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Marco Ceccarelli
Editors

International Symposium on History of Machines and Mechanisms

Proceedings of HMM 2008

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Preface

The International Symposium on the History of Machines and Mechanisms is the main activity of the Permanent Commission (PC) for the History of Mechanism and Machine Science (HMM) of the International Federation for the Promotion of Mechanism and Machine Science (IFToMM). The first symposium, HMM2000, was initiated by Dr. Marco Ceccarelli and was held at the University of Cassino (Cassino, Italy) on May 11–13, 2000. The second symposium, HMM2004, was chaired by Dr. Marco Ceccarelli and held at the same venue on May 12–15, 2004. The third symposium, HMM2008, was chaired by Dr. Hong-Sen Yan and held at the National Cheng Kung University (Tainan, Taiwan) on November 11–14, 2008.

The mission of IFToMM is to promote research and development in the field of machines and mechanisms by theoretical and experimental methods, along with their practical applications. The aim of HMM2008 is to establish an international forum for presenting and discussing historical developments in the field of Mechanism and Machine Science (MMS). The subject area covers all aspects of the development of HMM, such as machine, mechanism, kinematics, design method, etc., that are related to people, events, objects, anything that assisted in the development of the HMM, and presented in the forms of reasoning and arguments, demonstration and identification, and description and evaluation.

The HMM2008 Proceedings contain 26 papers by authors from all over the world. The topics include historical development on mechanism and machine theory, historical figures and their works, history of mechanical engineering, ancient machines and mechanisms, reconstruction design of ancient devices, mechanism and machine design, and engineering education. This book is of interest to researchers, graduate students and engineers specializing or promoting the history of science and technology, in particular on mechanism and machine science. It is believed that the book would provide the readers with extensive background information on the origin and the history of the invention of fundamental machines and mechanisms, and will undoubtedly provide further understanding and motivation for their own research and/or consultancy work.

The figure on the cover was provided by Dr. Tsung-Yi Lin. It shows a pictorial view of the water-powered armillary sphere and celestial globe invented by Su Song (蘇頌) of the Northern Song Dynasty in ancient China around 1088 AD. This was a water-powered mechanical clock with an escapement regulator. On the top was a massive spherical astronomical instrument for observing the stars. Inside the tower was a celestial globe, whose movements were synchronized with those of the sphere above. At the front of the tower was a pagoda-like structure of five floors, each with a door through which wooden puppets appeared at regular intervals throughout the day and night.

The evolutionists see history as the steady progression through time; the space enthusiasts press on with the exploration of the universe. However, by looking back in time, there is much to learn from the vast treasure of ancient science and technology, from the accumulated knowledge of our ancestors. And, we truly hope the publication of this book will create more interest from people around the world toward the research and publication of the history of machines and mechanisms.

Finally, we would like to express our sincere gratitude to the members of the Organizing Committee of the Symposium: Prof. Hanfried Kerle (Chair of the PC for History of MMS), Prof. Alexander Golovin (Russia), Prof. Teun Koetsier (The Netherlands), Prof. Carlos López-Cajún (Mexico), Prof. Jammi S. Rao (India), Prof. Jae Kyung Shim (Korea), Prof. Junichi Takeno (Japan), and Prof. Lu Zhen (China). We are grateful to the hard work of all the contributing authors and of the reviewers. We would also like to thank the sponsors of the Symposium: IFToMM, Ancient Chinese Machinery Cultural Foundation, National Cheng Kung University (NCKU) and the University Museum, Southern Taiwan University, and National Pingtung University of Science and Technology. Special thanks are also due to the following friends and colleagues for which without their generous support and help, this book would not have been possible: Dr. Sanly Hsin-Hui Huang, Dr. Tsung-Yi Lin, Dr. Kuo-Hung Hsiao, Dr. Sin Sin Hsu, Ms. Gretle Yu-Lin Chu, and students in the Creative Machine Design Research and Education Lab in the Department of Mechanical Engineering at NCKU.

November 2008, Tainan, Taiwan.

Hong-Sen Yan
Chairman, HMM2008
International Symposium on History of Machines and Mechanisms

Marco Ceccarelli
President, IFToMM
International Federation for the Promotion of Mechanism and Machine Science

Contents

History of Dynamics of Machines and Mechanisms from Leonardo to Timoshenko

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Abstract In this paper we review the use of dynamic analysis in the evolution of machine and mechanism design. Our thesis is that the application of analytical methods in dynamics to machines and mechanisms lagged behind the application of these methods to non-machine areas of science and engineering such as planetary dynamics and structural dynamics. The early works of Mertzalov, Den Hartog and Timoshenko are reviewed.

Keywords Dynamics, Machines, Mechanisms, Leonardo da Vinci, Reuleaux, Timoshenko

Introduction

Historical reviews of dynamics usually treat the motions of particles and rigid bodies but rarely mention applications to constrained rigid bodies in mechanisms and machines (see e.g. [24,83]). In the same spirit, historical reviews of kinematics of mechanisms do not discuss dynamical problems in machines. (see e.g. [61,62,33,27]) The author has recently published a book on the history of kinematics in machines from the time of Leonardo to Reuleaux. [63]. Often dynamics histories describe the evolution of general principles of physics but do not consider the application to technology. In this survey we attempt to put together an outline the history of technical dynamics as applied to mechanisms and machines.

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The histories of kinematics of mechanisms and dynamics have evolved on different paths and time tracks. In some cases the applied dynamics of mechanisms such as clocks were understood before theoreticians had a deep understanding of theoretical dynamics. Galileo described the motions of the pendulum and Huygens invented a pendulum clock in 1658 before Newton published his *Principia* in 1686 [39]. Even then it was not until 1760 before Euler had written his treatise on dynamics of rigid bodies. In addition to the history of general principles there are many dynamical phenomenon connected with machines that have only now been understood mathematically such as nonholonomic dynamics of rolling and control of robotic systems. Even in the realm of general principles, the phenomenon of unpredictable dynamics known of chaos theory has only recently been understood and even less so in its application to machines (see e.g. [59]).

Dynamics of mechanisms developed as a formal sub-area of the theory of machines around the beginning of the 20th century. For example in the textbook *Mechanisms* written by S. Dunkerley [25], who was Director of the Whitworth Laboratory at the University of Manchester, three areas of machine design are outlined: kinematics, machine element design and dynamics of machines. Some aspects of dynamics of machines can be found in the work of Rankine [67] and Redtenbacher [69] in which mention is made of the dynamic principal of virtual velocities. However in the major books of Franz Reuleaux who is often called the "father of kinematics" there is no discussion of dynamical principles in either *Kinematics of Machinery* [74–76] or *Der Constucktor* [73,77].

Dynamics vis a vis Kinematics of Mechanisms

Before we proceed too far it is necessary to define our terminology because in classical mechanisms the terms kinematics and dynamics of connected rigid links are sometimes used synonymously. We define a *dynamics-based* problem in machines and mechanisms when either accelerations are required to determine forces (*indirect* dynamics problem) or if differential equations of motion, based on the Newton-Euler principles of mechanics, must be solved to determine the motion of all the parts (*direct* dynamics problem). Included in the direct problems are regulated and controlled machines, including modern robotics that may require control theory in addition to Newton-Euler theory. On the other hand classical engine balancing is considered an *indirect* problem in dynamics of machines.

Dynamics of Machines in Antiquity

To begin our review we survey what is known about dynamics of machines in the historical records of the ancient Greeks and Romans and European civilizations.

Aristotle (384–322 BCE)
Of particular interest to us is his *MHXANIKA*, or *Mechanical Problems,* published in modern editions under the *Minor Works* of Aristotle. *Mechanical Problems* is more a mathematics text than an engineering manual. The focus of the Greek mathematics was on the force equilibrium nature of the simple machines and less on the motion or dynamics character of the devise. However the chariot, potters wheel and catapult were by nature dynamic machines. Aristotle's simple machines were focused on forces and not motions. The idea of the inherent kinematic nature of many mechanisms did not aappear until the time of the French school at the Polytechnique in Paris under Gaspard Monge at the end of the 19th century.

Archimedes (287–212 BCE)
His work as a designer of machines however is usually ascribed through other ancient writers. For example, Plutarch in writing about the Roman general Marcellus, tells how Archimedes designed machines for war against the Romans in 212 BCE. These included dynamic machines to hurl missiles and large stones at the enemy as well as an underwater mechanism of levers and pulleys that could destabilize and overturn a ship entering a harbor.

Ctesibius (2nd C. BCE)
Ctesibius' is another engineer schooled in Alexandria and who is often credited with inventions but of whom we have no extant works to document his contributions. Nevertheless, he has been identified with clock mechanisms and geared devices. In the Roman work by Vitruvius Pollio (circa 50 BCE), Ctesibius's water clock is described as the first to have a regulator that would maintain a constant head of water in the effluent part of the clock in order to improve the accuracy. Ctesibius is also recorded as inventing various automata or moving mechanical animals driven by his clock.

Hero of Alexandria (2nd C. BCE)
Hero is one of the few Greek engineer-mathematicians whose written works have come down to us. Among his dynamic machines are catapults and balisti. These devices could launch both stones and arrows. He also published a book on automata. An Italian translation of 1589 by Bernardino Baldi contains a drawing attempting to reconstruct one of these devices for a fountain offering wine and milk and having a rotating figure on top. The automata is driven by a hidden falling weight that creates a torque on a rotating cylinder.

Vitruvius Pollio (c. 37 BCE)
In *de Architectura libri decem (c. 37 BCE)* he proceeds in Book X to describe the existing machines of Roman times as well as their methods of construction. There is some discussion of pumps in Book VIII, as well as water clocks in Book IX. However in Book X we can find an encyclopedia of descriptions of many applications of machines. Here he described numerous dynamic machines of war including scorpions, catapultae and ballistae. In Chapter 11 he gave detailed instructions for a catapult capable of hurling stones. It is likely that he must have had experience in the

dynamics of such machines because his dimensions are very detailed and specific. In Chapter 13 he described a battering ram that is essentially a pendulum comprised of a large beam supported by ropes swung back and forth to develop sufficient kinetic energy to transfer into impact to knock down the enemies defenses.

Dynamics of Machines in the Manuscripts of Leonardo da Vinci

The Renaissance in the 15th century produced important machine engineers in both Siena and Florence (see Moon [63], for a review of history of machines in the Renaissance). Before the work of Leonardo, there was a school of machine inventors in Florence's rival city Siena; the principal engineers were Taccola and Francesco di Giorgio Martini. The latter's work was reproduced in several books and included dynamic machines such as catapults and trebuchets. One of these books was in the library of Leonardo da Vinci.

There has also much been written about Leonardo's writings on mechanics and dynamics. Criticism has been made of Leonardo's observations on the laws of dynamics, statics and fluid mechanics due to often contradictory writings (see e.g. [86]); in one place noting prescient observations of laws of physics that were discovered later, while in other places espousing outdated concepts from classical Aristotelian physics. However our focus here is on his observations of dynamics as it applied to constrained mechanical systems such as machines and mechanisms of which Leonardo made a few contributions.

For example, one of his most direct discussions of a dynamic nature is on flywheels, and particularly about masses on chains attached to a spinning axis (Fig. 1). Here is Reti's translation from *Codex Madrid I*;

"Why do the weights which hang perpendicularly at the beginning and at the end [of the motion] take up, together with their chains a horizontal line while they are in motion?"

[Observations about the use of flywheels can also be found in the machine book of Francesco di Giorgio, c. 1460.]

In remarks relevant to another drawing of a flywheel turned by a rope wrapped around a shaft and under a weight under gravity, he writes;

"The question here is: how many times would the wheel turn by itself, once the cord of the counterweight is completely unwound—?" This drawing is somewhat analogous to the sketch in 1589 by Baldi of Hero's automata fountain.

With respect to dynamics of machines, Leonardo only addresses dynamics issues in the context of specific machines and not in terms of general principles.

One of the more striking drawings and directed discussions of a dynamic mechanism is the perpetual motion wheel. (*Codex Madrid I* 147 verso and 148 recto). Leonardo seemed to describe a sequence of motions and impacts that might allow the wheel to continue moving. However in characteristic Leonardo style, on the second page, he emphatically states the impossibility of such a device.

"therefore, as it has been demonstrated, such a wheel is sophistical".

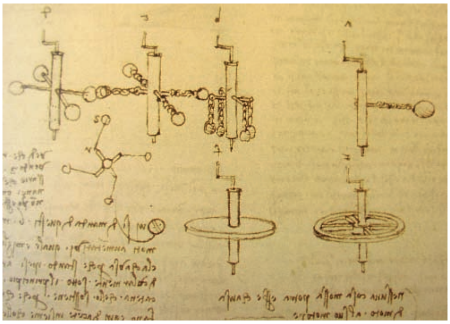
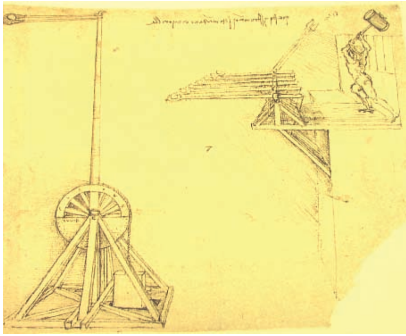



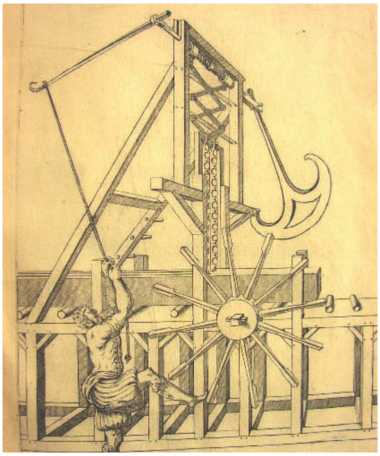
Fig. 1 Drawings of flywheels showing centrifugal effects from Leonardo da Vinci's Codex Madrid, Folio 114 recto (*left*)
Fig. 2 Leonardo da Vinci drawing of a double pendulum trebuchet war machine from the *Codex Atlanticus* (*right*)

This perpetual motion wheel appeared in other sources in the time of the Renaissance besides Leonardo and the concept of conservation of energy would not be formulated until the mid 19th century. His conclusion on the implausibility of this device was not made from general principles but as stated above, from his attempt to analyze the specific sequence of dynamic events were the wheel to work. It is interesting to note that although Leonardo da Vinci drew one of these perpetual motion wheels, he declared that they could not work. In later books, such as *Theatrum Machinarum Novum* by Böckler [14] and Jacob Leupold [49] [*Theatrum Machinarum Generale*], one can find machine designs that would supposedly run continuously without power input.

Among the most dynamic mechanisms is Leonardo da Vinci's work is his drawings of trebuchets in the Codex Atlanticus that are essentially nonlinear double pendulum devices (Fig. 2). Certainly Leonardo da Vinci's designs for human flying machines were dynamics dependent.

Theatre of Machine Books: Besson (1569) and Böckler (1661)

In the 16th, 17th and 18th centuries there were published books illustrating and describing a wide range of machines and applications. Some of these portray machines that use dynamic principles for their operation. For example in the 16th century Book of Besson called the "theatre of machines" he illustrated the use of pendulum resonance to actuate pumps using a mangle mechanism (Fig. 3). The worker supposedly applies a periodic torque through a crank on the pendulum at the resonance frequency of the pendulum thereby setting it into large oscillations that are used to drive the pump. A similar scheme can be found in later "theatre of machines" books. Another example is the use of large verge and foliot escapement to control a pump (Böckler, 17th C.) shown in Fig. 4.



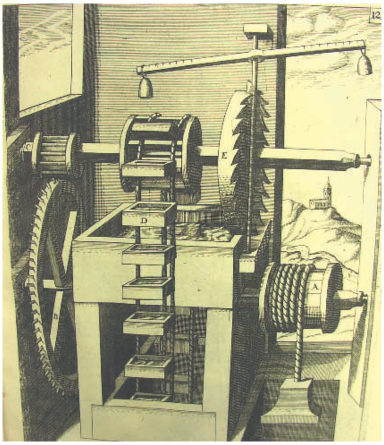


Fig. 3 Woodcut of a saw mill machine using the resonance of a pendulum [7] (*left*)
Fig. 4 Engraving of pump escapement [13] (*right*)

Analytical Dynamics in the Industrial Age

Although the greatest advances in analytical dynamics of particles and rigid bodies took place in the pre-industrial and industrial age, little of this theory was utilized in the design of machines by either the machine practitioners nor their theorists in the universities. Isaac Newton's *Principia*, published in 1686, was a treatise on dynamics of particles and their behavior in gravitational force fields. The Swiss mathematician Leonard Euler was the principal theorist on rigid body dynamics whose formalism we still use today. His major work in this area was *Theoria motus corporum solidorum seu rigidorum*, published in 1760, 40 years after Newcommen's steam engine was deployed in the Cornwall mines in England.

Joseph-Louis de Lagrange (1736–1813) in his *Mecanique Analytique* [44], developed powerful mathematical tools to study the motions of constrained systems such as connected rigid bodies in a machine or mechanism. This work was published during Watt and Boulton's monopoly on steam engine manufacture that saw the installation of hundreds of steam engines. Yet machine dynamics was not studied with these new techniques in the analytical dynamics community.

In the new technical universities such as Ecole Polytechnique in Paris, in the late 18th century, Gaspar Monge introduced descriptive geometry methods that became a mathematical underpinning of kinematics of machines. Ecole Polytechnique was established in 1894 and the mathematician Gaspard Monge was one of its founders. Shortly thereafter, Lagrange received an appointment to teach analysis there. He had a reputation however of being a poor lecturer as he had an Italian accent, having been born in Turin. Later books on mechanisms by Hachette, Lanz and Betancourt [30] and Borgnis [15], were inspired by the work of Monge in descriptive geometry, but did not include any material of a dynamics favor from Lagrange.

It is also interesting that Lagrange's analytical dynamics did not make it into the German texts in machine design though he spent 20 years at the Academy of Sciences in Berlin from 1767 to 1787. He also wrote his famous *Mecanique analytique* there in 1782 that was later published in 1788 in Paris. Lagrange had been recommended for the Berlin position by Euler who himself had been in Berlin and had moved to the court at St Petersburg. Euler, Lagrange, and D'Alembert all exchanged letters and ideas during this time, but somehow in the critical period of 1798–1810, these dynamical theories were not absorbed into the culture of machine theorists.

During the 19th century, theoretical work of Hamilton, Jacobi, Caughy, Navier, and Poincare in dynamics developed but again these methods were not incorporated into machine design teaching or practice until the mid 20th century.

Dynamics of Machines in the Industrial Age 1750–1900

James Watt (c.1780): Regulators

Historians of kinematics are quick to point out that James Watt's proudest invention was the approximate straight-line mechanism [87]. A portrait in the National Gallery of London of Watt shows him contemplating a drawing of this linkage applied to the steam engine. However, for those who write of the history of control engineering, it was his use of the rotating ball speed regulator that was his most important contribution and the first large scale use of feedback control (some might argue that the directional control of windmills was the earliest automatic controller. See Bennett [5]), Boulton and Watt did not seek patent protection for the ball governor but thought it might go unnoticed. However it was soon copied and improved as can be seen in the version of Poncelet from the mid 19th C. The ball mechanism was only a form of sensor-actuator and also required linkages and control valves. In some engine controllers, instead of maintaining constant speed there was the dynamic phenomenon of hunting. This sparked an effort by some to develop an analytical model to derive stable operating condition for these controllers [see discussion below on servomechanisms and Maxwell].

J.-A. Borgnis (1818)

The Italian J.-A, Borgnis in 1818 published a treatise in French in which he categorized machines into six orders as "recepteurs, communicateurs, modificateurs, supports, regulateurs and operateurs" [15]. It is within the class of regulators that he included dynamic mechanisms such as escapements. He wrote about their use in clocks and their connection with pendula. Borgnis discussed in detail the contributions of several figures in the history of clock design including Hugyens, Gramham, Berthoud, Tompion, Le Roy, Thomas, Mudge, Bre'guet and others. In particular he discussed clock regulator subcomponents such as the fusee, remontoir, and different types of escapements. He also discussed the temperature compensation of pendulums for clocks. This work is completely descriptive with 36 plates of about 8–10 figures each and no mathematical equations.

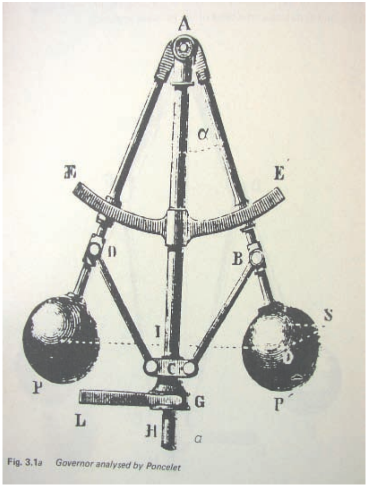


Fig. 3.1a Governor analysed by Poncelet

Fig. 5 Rotating ball governor of Poncelet (from [4])

Haton de la Goupillie're (1864)
This is a mid 19th century French book on the theory of mechanisms: *Traite des Me'canismes* [37]. Haton cites the work of Lanz and Betancourt [45], Willis [89] and Laboulaye [43]. The major part of this work discusses more than 200 mechanisms with over 250 drawings. However the second part of this book is titled "Etude Dynamique des Me'canismes". The major part of this section treats the laws of friction in machines. There is one section however that derives the differential equation of oscillation for a cylinder rolling inside of another cylinder in a style that anticipates vibration texts 80 years later such as Den Hartog [22]. Haton also discussed clock escapements including the anchor and cylinder escapements but did not give any analytical treatment of them. In a section on regulators he analyzed Watt's rotating ball regulator and similar devices and wrote equations of motion balancing the centripetal force moment with the gravity force moment. This is the extent of Haton's treatment of dynamics of mechanisms. It basically contains no general principles and a few ad hoc dynamics related problems.

Julius Weisbach (1848)
Julius Weisbach (1806–1871), like Redtenbacher and Rankine wrote general books that helped define the teaching of what would become mechanical engineering [88]. Weisbach's books were translated into English and thus his work was familiar to engineers in both Great Britain and North America. For example, his *Principles of Machinery and Engineering*, first published in America in 1848 was a two volume work that was expanded in its 1870 edition into three volumes. This work presented some general material on dynamics of rigid bodies, dynamic stability and the theory of oscillations.

Franz Reuleaux (1859, 1876, 1893)
The Reuleaux ‘‘School’’ of kinematics, which included Kennedy [41] in England and Burmester [18], Hartmann [36], and Grübler [29] in Germany, influenced the kinematics of machines to this day [72,75–77]. Although Reuleaux’s theory of machines were important contributions, his theories were based largely on geometric ideas, or Phoronomy, and not on dynamic principles, that were later incorporated into the theory of machines (see, e.g. [34]). Nor did Reuleaux treat the problem of nonholnomic constraints. In general, however, ideas about the importance of elastic vibrations, resonance, or structure-borne noise in machines did not make it into Reuleaux’s work.

There are examples in his oeuvre where he exhibited interest in dynamics and control. One was a 1859 paper in the new journal of the German society of engineers or VDI. He titled this paper [72] “Regulatorfrage” or regulator questions. Reuleaux also published a paper in 1876 titled, “Das Zentrifugalmoment: Ein Beitrag zur Dynamik”. [The centrifugal moment: A contribution to dynamics]. Reuleaux found a general equation for the centrifugal force of extended rigid bodies rotating about an axis. He used integration methods to relate the force moment to the principal moments of inertia of the rotating body and designed an experimental apparatus to measure this moment (Fig. 6). However, this result in dynamics did not appear in his major books.

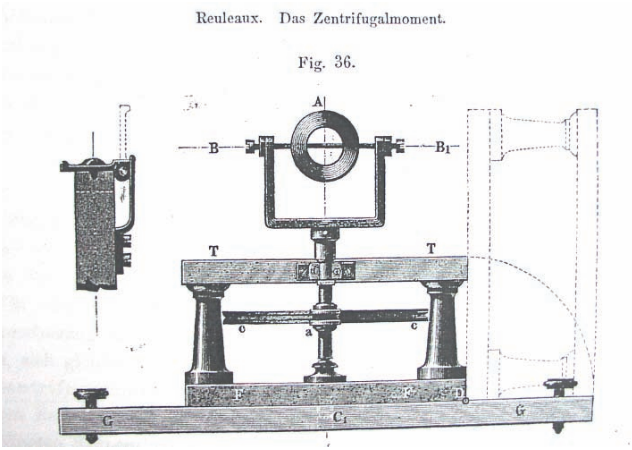


Fig. 6 Drawing of Reuleaux’s design for an experimental apparatus to measure the moment of inertia of balls for a Watt type governor

Reuleaux was also interested in the regulation of steam and gas engine motions which he discussed in the 4th Edition of his The Constructor (1893). In these engines, slide and rotary valves were opened and closed during each machine cycle to admit steam or air-fuel mixtures or to exhaust steam or gas from the engine cylinder. In an early 20th century book by Bevan [9], he refers to “The Reuleaux Diagram”, a phase diagram to describe the timing between the valves and crank motions of a steam engine. There is evidence that Reuleaux understood the concept of feedback control in a figure from The Constructor, Figs. 1012, 1213, p. 231, in which he tried to explain the workings of two coupled regulators of a commercial machine. This figure has the features of a block diagram, an idea that did not appear in control theory until several decades into the 20th century.

M. J. Callon (1875)

As an example of a French text on design of machines we examine the work of M.J. Callon whose course on machines at the L'Ecole des Mines de Paris largely dealt with the steam engine of mid 19th century Europe [19]. In Chapter 18 titled "Details on the parts of the steam engine" Callon discussed Watt's rotating ball speed regulator. He used the balance of the centrifugal force moment on the rotating balls and the gravity force moment to derive design equations (Figs. 255–265). This method converted a dynamics problem into a static equilibrium problem. However, it was Maxwell who about this time, examined the stability of governors in steam engines from a more modern point of view.

Alexander Kennedy (1886): Acceleration diagrams

Kennedy translated Reuleaux's major work in kinematics of machines in 1876, one year after the German publication. Both Kennedy [41] and Burmester [18] introduced the acceleration diagram that became a staple part of the kinematics pedagogy for the next half century.

One example in Kennedy's book describes the acceleration history of a piston in a pumping engine called the "Bull Engine" [Page 336, §45; see KMODDL website for digital copy; http://kmoddl.library.cornell.edu] Kennedy notes the importance of dynamics in this machine: "Kinematically the combination is nothing but a sliding pair of elements, there is no crank or rotating parts of any kind. Dynamically the machine is of much more interest, and its action much more complex. For although the form of the piston and cylinder prevent any relative motions—they do not in any way affect or control the velocity of motion and the length of the stroke of the engine is entirely dependent on the acceleration forces in action,—".

Ludwig Burmester (1888)

Burmester was an ardent admirer of Reuleaux's kinematics of machinery. In his *Lehrbuch der Kinematik,* he advanced and embellished Reuleaux's geometric theories especially in the area of centrode theory of rolling [18]. Unlike Reuleaux, Burmester included a long section on accelerations in mechanisms and presented graphical methods to calculate these terms especially four-bar and slider crank mechanisms [Chapter 11: "Die Lehre von der Beschleunigung und irhe Anwendung"]. It is odd that in his introduction Burmester mentions the work of Newton, D'Alembert, Euler, Carnot and Kant. He even cited Euler's 1765 theory on the motion of rigid bodies that was translated into German in 1853. However after an extremely detailed treatment of acceleration diagrams, Burmester did not present a general treatment of dynamics or vibrations in machines and mechanisms.

Clock Dynamics

The first pendulum clock is attributed to Huygens in 1657, although even here there is some posthumous claim to the invention by Galileo and his son. The Huygens clock is a combination of the verge and the pendulum. Huygens also recognized that the period of the pendulum increased with the amplitude and he designed a cycloidal clamp for the pendulum which decreased the effective length of the swinging bob to produce a constant period, independent of amplitude. This is one of the first solutions in nonlinear vibrations.

The next major improvement was the invention of the anchor escapement that replaced the verge with a two-arm device. Other contributors at this time were Pierre Le Roy and Ferdinand Berthoud of France as well as Arnold and Earnshaw in England. Many other escapements were invented such as the detent, cylinder, duplex, pin wheel, and gravity escapement, over a period of four centuries of clock invention, design and development [16] (see Fig. 7). Despite this progress, the historical record is replete with evidence and discussion of the irregularities, inaccuracies and unpredictability in the mechanical clock.

Early works on the dynamics of clocks include George Biddell Airy [1], James Mackenzie Bloxam [11], and Edmond Beckett Denison (Lord Grimthorpe) [23]. Other important mathematical analyses in the 20th century were those of the Russians Andronov, Chaiken and Witt (circa 1940–1960) [2]. Recently there have appeared a series of papers on the mathematical analysis of escapement dynamics such as, Kauderer [40], Kesteven [42], Lepschy et al. [48], Bernstein [6] and Roup and Bernstein et al. [78] as well as a work by the Author [64].

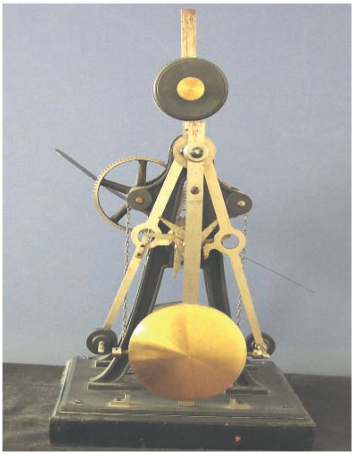


Fig. 7 Reuleaux model of a three pendula gravity escapement [from the Cornell Reuleaux kinematic models collection]

Governors, Servomechanisms and Control Theory

The two principal historical texts in this area are Otto Mayr's *The Origins of Feedback Control* [54] and S. Bennett's *A History of Control Engineering 1800–1930,* written in 1979 [4]. Mayr's work covers the period from antiquity to around 1800. There have been many other reviews of control engineering since. However for us the focus is how this subject of control and its associated questions of dynamics and stability entered the teaching of machine design. Many writers credit James Watt with the invention of the rotating ball regulator in 1788 to achieve speed control of the steam engine. However Mayr cites earlier use of the rotating ball governor for control in windmills by Mead around 1787.

In Maxwell's paper [53], which was published in the Proceedings of the Royal Society, there are no sketches or pictures of any governor mechanisms, although there are several in Bennett's book. There is reference to several governors of Watt, Jenkins, Siemens etc. but Maxwell's analysis uses general abstract terms to describe forces or torques in these machines and no specifics. He obtained a third-order dynamic system coupling the governor dynamics to the machine or "plant" motions and thus found a stability criterion for the controller to avoid instabilities. Although his mathematical models have some generality, it is not clear if they apply to actual devices since, none of the parameters are estimated by Maxwell. There is also a hint in Maxwell's paper that there was anecdotal evidence for engine instabilities with governors as Maxwell calls it, "oscillating and jerking motion, increasing in violence until it reaches the limit of action of the governor".

Maxwell and others such as E.J. Routh [79] and the Russian work of J. Wischnegradski (1876–1879) in St Petersburg and A.M. Lyapunov [50] laid out the ideas of stability of motion in mechanical and electrical systems by the end of the 19th century. It is interesting to note that Lyapunov was a student of Chebyshev at St Petersburg. The latter had spent many years analyzing the kinematic geometry of linkages and mechanisms. There is the question of whether the teaching of dynamics of machines and kinematics of mechanisms was more unified in Russia than that in Europe and North America.

As outlined in Bennett [4], the use of speed controllers in the 19th century, evolved into the field of servomechanisms (Fig. 8). Initially both feedback and control actuation were accomplished with mechanical linkages but were gradually replaced with electromechanical sensors and actuation in the early 20th century. Still, the teaching of control theory in the late 20th century was often devoid of specific machine knowledge. Two exceptions were in gyro design and aircraft control, in which detailed knowledge of the plant was part of the control culture.

Gyroscopes

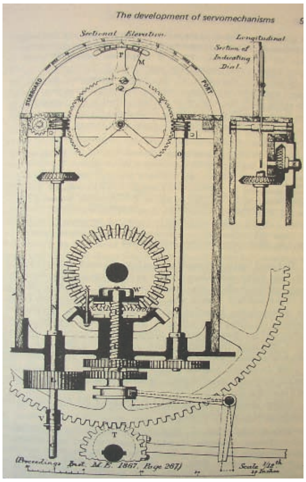
Spinning tops have always had a fascination with people and can be traced back to ancient civilizations in China and the Middle East and Mediterranean cultures. In 1760, The dynamic theory of rotating rigid bodies was first formulated by Euler.

A century later, J.B. Leon Foucault, using his famous pendulum in the Paris Pantheon determined that the spinning of the Earth could be detected in the precession of the plane of rotation of a pendulum. Around the same time he invented a spinning top that could also detect the Earth's rotation. He was the first to give such a device the name "gyroscope".

Despite Foucault experiments with the use of a spinning body as an angular reference, the first practical use of the gyro compass for navigation was developed in Germany by Hermann Anschütz around 1908. Later in 1911, Elmer Sperry in the US developed a gyrocompass for ship navigation that was easier to manufacture (see e.g. [91]).

A theoretical treatise on these principles appeared in 1897 by F. Klein and A. Sommerfeld; *Über die Theorie des Kreisels,* which was published later in several editions. Despite the span of theoretical and mathematical discussion of the dynamics of rotating bodies from Euler [26] to Klein, there remained technical problems to overcome before this technology became practical machinery. To quote the book by the MIT Draper lab engineers, Wrigley et al. [91]: "The history of precision gyro technology is, as is the case for most practical devices, a story of methods, materials, engineering skill, and perseverance rather than of scientific breakthrough or new physical principles".

However it still does not explain why the design of the gyro mechanism was absent from most kinematics of machines and machine design books of the 20th century.



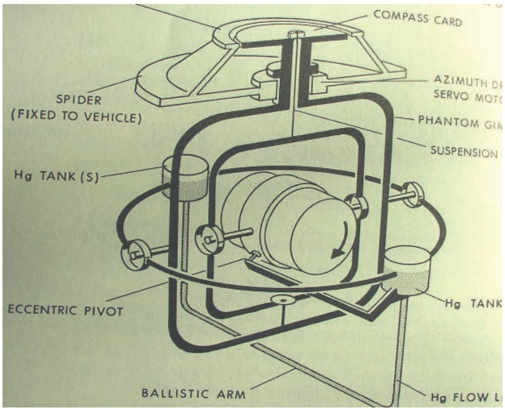


Fig. 8 Servomechanism for ship steerage of McFarlane Grey (from Bennett) (*left*)

Fig. 9 Sketch of design for gyrocompass of Sperry (from Wrigley et al.) (*right*)

Early 20th Century Dynamics of Machines

The lack of common ground between practitioners of analytical dynamics and technical mechanics of machines is illustrated in the career of Arnold Sommerfeld (1868–1951). Born and educated in Köingsberg, Prussia, he taught at Göttingen, Clausthal, Aachen and Munich. In Clausthal (1897–1899) he was professor of mathematics, while at Aachen (1899–1905) he held the chair of Technical Mechanics at the Technische Hochschule. Although known for his contributions in applied mathematics applied to quantum mechanics, Sommerfeld gave lectures in classical physics and mechanics. For example, his lectures in mechanics at Munich were published in English after World War II [81]. Scattered throughout this text are a number of examples relating to the dynamics of engines, including the slider-crank mechanism, balancing of a four piston marine engine and the equations of motion of an automobile differential, juxtaposed amidst mathematical exposition on Hamilton–Jacobi theory and the quantum treatment of Kepler's orbital mechanics. Although the first German edition of these lectures was published in 1942, it is likely that Sommerfeld's interest in dynamics of machines was born during his tenure at the Technical University at Aachen at the turn of the century. As in the case of Lagrange at the Ecole Polytechnique a century earlier, the mathematical theory that Sommerfeld brought to mechanics of machines was not incorporated into engineering textbooks and practice in a systematic way until the late 1920s and early 1930s. For example in Timoshenko's 1928 book *Vibration Problems in Engineering* [84], he references an experiment of Sommerfeld in 1904 on the resonant vibrations of an unbalanced rotor.

Dynamics of Engines: Inertia Forces and Balancing

Although there were a few serious mathematical studies of a dynamical nature in technology at the beginning of the 20th century, these tended to be carried out by mathematical scientists and not engineers or as in the case of Van der Pol for the new field of electric circuits. Practitioners in the field of kinematic design of machines generally took only small steps toward full dynamic analysis. One example of such books was by Ham and Crane [32] of the University of Illinois (Fig. 10). The text reviews all the standard elements of kinematic analysis, pairs, chains, inversions, point paths etc. Near the end of the text however there is an analysis of acceleration and "inertial forces". The problem of engine balancing became important with the expansion of the use of the automobile and became more prominent in machine engineering books such as Den Hartog [22]. *Dynamics of Machines: Den Hartog and Timoshenko (1928–1948).*

The reduction of dynamic problems in machines to equilibrium of static forces and "inertia forces" was soon replaced by full dynamic analysis with the recognition that machine elements are elastic components. This often involved the use of vibration theory, a mathematical method that appeared in the 19th century in works such as Rayleigh [68] in his theory of sound.

One of the important English books on the dynamics of machines was *Mechanical Vibrations* by J.P. Den Hartog of Harvard University written in 1934 [22]. Den Hartog had worked for the Westinghouse Corporation when he arrived from Europe in the 1920s as did Steven Timoshenko. Den Hartog's book acknowledges his indebtedness to his former colleagues at Westinghouse as well as to Professor Timoshenko who first went to the University of Michigan and then to Stanford University. Many of the problems in Den Hartog's book arose out of machine related problems including gear systems, vibration absorbers in machines, ship stabilization problems, automobile shock systems, multi-cylinder engine dynamics, balancing or rotors, hunting of steam engine governors, wheel shimmy and self excitation of fluid valves (Fig. 11). At the same time Den Hartog introduced advanced analytical methods such as coupled linear systems, subharmonic resonance, nonlinear vibrations, relaxation oscillations. Both Den Hartog and Timoshenko brought advanced analytical techniques to America from Europe and Russia and combined them with experience with practical problems in industry.

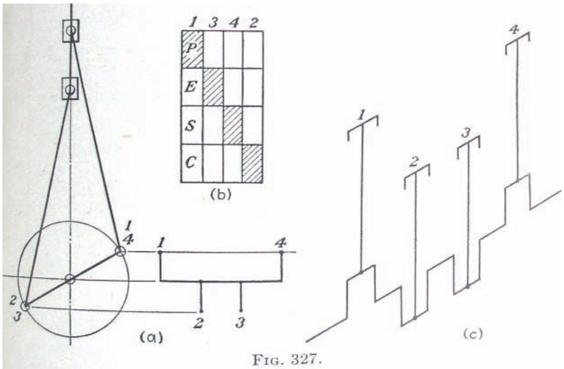


Fig. 10 Balancing of a 4 cylinder engine (Ham and Crane)

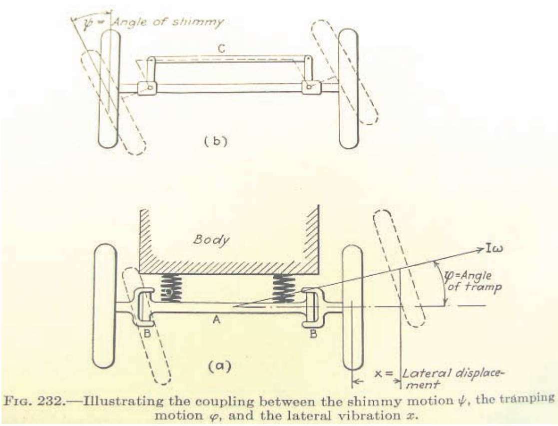


Fig. 11 Wheel Shimmy model from Den Hartog [22]

Steven Timoshenko (1878–1972) was born in the Ukraine and educated in St Petersburg. Ten years younger than Sommerfeld, he worked in railroad engineering. He came to the United States in 1922. His first dynamics book was published in 1928 under the title *Vibration Problems in Engineering*, when he was at the University of Michigan [84]. He also acknowledged his indebtedness to the Westinghouse Corporation as well as to Den Hartog with whom he had worked on several dynamics problems on electric generating systems for Westinghouse. His work not only dealt with linear systems, but also “non-harmonic vibrations”, using the dynamics of locomotives as an example. He also dealt with vibrations of turbine blades and described several vibration measuring instruments including seismic vibrographs that had a substantial mechanism component to them. A large part of the book treats the vibration of continuous beams and plates without much reference to specific machine applications however.

The 1948 book of S. Timoshenko and D.H. Young *Advanced Dynamics,* both at Stanford University at the time, truly combined advanced analytical methodology with many problems of direct machine dynamics [85]. This includes balancing of reciprocating engines, dynamics of rotating ball governors, dynamics of constrained systems including linkages, flywheel governors, gyroscopic motions, the gyrocompass, ship stabilizers, and vibration absorbers. Analytical techniques included Lagrange’s equations, linear systems, Mathieu’s equation, Rayleigh’s method, and nonlinear vibrations. The Authors acknowledged their access to several European books such as E.I. Nikolai’s *Theoretical Mechanics* [65], Routh’s *Elementary Rigid [Body] Dynamics* [80], and Biezeno and Grammel’s *Technische Dynamik* [10].

There were other works of this nature in the Russian and European literature during the quarter century, 1925–1950, that contained similar materials. The Author has come across a citation to a Russian work by N.I Mertsalov, *Dynamics of Mechanism* [55] which was a published set of lecture notes at the Imperial Technical School, in Russian. In a recent visit to Bauman Moscow State Technical University, the Author had an opportunity to examine a copy of Mertsalov’s lecture notes. There is certainly some aspects that relate to the dynamics of machines, but this work is not as comprehensive as the later texts of Timoshenko and Den Hartog. (This reference is from Prof. Alexander Golovin of the Bauman Moscow State Technical Univ.)

In the English speaking engineering community, the works of Timoshenko and Den Hartog had considerable influence on the study and design of machine dynamics. One example is the book by James B. Hartman of Lehigh Universty, *Dynamics of Machinery* [35].

The presentation of analytical methods in dynamics in the mechanisms textbooks, were much abbreviated during this period. However in defense of the kinematicians, although the technical dynamics books of the time used examples from machine design, these examples were often used as a way to illustrate the mathematical methods of vibrations. Engine balancing seems to be the exception. In general, there was no attempt to address a general theory of dynamic design in machines and mechanisms nor to use dynamics in the context of design optimization and synthesis.

Summary and Concluding Observations

In the 18th, 19th and early 20th centuries, advanced ideas of analytical dynamics and concomitant mathematical tools of dynamical systems were developed decades, sometimes a century, before their adaptation into the theory of mechanisms and machines. What can be the reason for this delay? It cannot be for lack of communication channels as this period coincided with major advances in telecommunication as well as land and sea travel. One possible thesis was the existence of different scientific, mathematical and technical communities between dynamicists and machine designers.

One can advance the theory that it takes a community of scientists, mathematicians and engineers to develop a new idea or theory or to create new machines and technologies. Throughout most of the 19th century, machines were developed largely in workshops and factories although academic engineers such as Willis, Rankine, Weisbach, Redtenbacher and Reuleaux were creating an engineering-science of machine design. However this mathematics and science-based design methodology took at least half a century to mature and to be accepted in industry as well as in the academic engineering communities that provided the talent for these machine industries. Westinghouse Corporation for example hired both Steven Timoshenko from Russia as well as Den Hartog from Holland in the early 1920s to work on dynamic turbine failures in electric generators. Both of these engineers went on to write famous books illustrating the application of analytical mechanics, dynamics and mathematics to the design of machine elements and structures. The ASME Journal of Applied Mechanics began to publish some machine dynamics research at this time.

On the other hand, the analytical dynamics community that emerged in the 18th century and early 19th century, seemed more interested in so-called “natural” dynamics problems in astronomy, fluid mechanics of air and water, acoustics and electromagnetic fields as they still do today. The members of this community seldom had any overlap with the community of machine theorists or builders. Maxwell seems to have been one of the exceptions to this because of his interest in machine regulator stability.

One reason for the increasing interest by machine theorists in dynamics in the 20th century may have been the increasing speed of prime movers and the attempt at increasing power to weight ratios. Higher speeds in machines placed a greater emphasis on dynamic forces as well as on dynamic instabilities and machine component vibrations.

References

(References are listed also for further reading, without citing them in the text).

1. Airy GB (1826) On the Disturbances of Pendulums and Balances and the Theory of Escapements, Trans. Cambridge Philos. Soc. 3(pt.I(1830)), 105–128.

2. Andronov AA, Vitt AA, Khaikin SE (1966) Theory of Oscillators, Pergamon Press, Oxford. Dover Publ., 1987.
3. Baillie GH, Clutton C, Ilbert CA (1956) Britten's Old Clocks and Watches and Their Makers, 7th Ed., Bonanza Books, NY.
4. Bennett S (1979) A History of Control Engineering 1800–1930, Institution of Electrical Engineers, London and Peter Peregrinus Ltd., Stevenage, UK.
5. Bennett (1979)
6. Bernstein D (2000) Escapements, Governors, Ailerons, Gyros, and Amplifiers: Feedback Control and the History of Technology, Michigan St. Univ. Report.
7. Besson (1569–1578)
8. Besson J (1569–1578) Theatre des Instruments.
9. Bevan T (1939) The Theory of Machines, Longmans, Green and Co., London.
10. Biezeno CB, Grammel R (1939, 1953) Technische Dynamik, 2nd Ed., Springer, Berlin.
11. Bloxam JM (1854) On the Mathematical Theory and Practical Defects of Clock Escapements, with a Description of a New Escapement; and Some Observations for Astronomical and Scientific Purposes, Mem. Roy. Astron. Soc. 22, 103–150.
12. Böckler (1661) Theatrum Machinarum Novum.
13. Böckler (1661)
14. Böckler (1661)
15. Borgnis JA (1818) Traite' Complet De Me'canique Applique'e Aux Arts: Composition des Machines, Bachlier, Libraire, Paris.
16. Bruton E (1979) The History of Clocks and Watches, Orbis Publ., London.
17. Buckingham E (1949) Analytical Mechanics of Gears, McGraw-Hill, NY.
18. Burmester L (1888) Lehrbuch der Kinematik; Erster Band. Die Ebene Bewegung, Verlag von Arthur Felix, Leipzig.
19. Callon MJ (1875)
20. Conway HG (1953–55) Origins of Mechanical Servo Mechanisms, Newcomen Soc. 29, 1953–1954, 1954-1955.
21. Crabtree H (1909, 1913) An Elementary Treatment of the Theory of Spinning Tops and Gyroscopic Motion 2nd Ed., Longmans, Green and Co., London.
22. Den Hartog JP (1934, 1940) Mechanical Vibrations, 2nd Ed., McGraw-Hill Book Co., NY.
23. Denison EB (1868) (a k.a. Lord Grimthorpe) A Rudimentary Treatise on Clocks and Watches and Bells.
24. Dugas R (1955, 1988) A History of Mechanics, Dover Edition, Dover Publ., NY.
25. Dunkerley S (1904, 1910) Mechanism, 3rd Ed., Longmans, Green and Co., London.
26. Euler L (1760) Theoria motus corporum solidorum seu rigidorum.
27. Ferguson ES (1962) Kinematics of Mechanisms from the Time of Watt, from United States National Museum Bulletin, 228, Smithsonian Institution, Washington, DC. paper 27, pp. 185–230.
28. Foucault (1853)
29. Grübler M (1917) Getriebelehre, Verlag von Julius Springer, Berlin.

30. Hachette et al. (1811)
31. Hachette JNP (1811) Traité Elementaire des Machines, Paris.
32. Ham, Crane (1927) Mechanics of Machines, McGraw-Hill, NY.
33. Hartenberg and Denevit (1964)
34. Hartenberg RS, Denavit J (1964) Kinematic Synthesis of Linkages, McGraw-Hill Book Co., NY, p. 75.
35. Hartman (1956) Dynamics of Machinery.
36. Hartmann W (1913) Die Maschinengetriebe, Stuttgart.
37. Haton de la Goupillie (1864) Traite des Mecanismes.
38. Headrick MV (2001) Clocks and Time: Clock and Watch Escapements http://ubr.com/clocks/educ/escapem.html
39. Huygens C (1658) Horologium.
40. Kauderer H (1958) Nichtlineare Mechanik, Springer-Verlag, Berlin, Second part, Section 4, pp. 415–423.
41. Kennedy ABW (1886) The Mechanics of Machinery, Macmillan and Co., London.
42. Kesteven M (1978) On the Mathematical Theory of Clocks, Am. J. Phys. 46(2), 125–129.
43. Laboulaye C (1849, 1864) Traite de Cinematique ou Theorie des Mechanismes, 2nd Ed., Gauthier-Villars, Paris.
44. Lagrange JL (1788) Mecanique Analytique.
45. Lanz, Betoncourt (1808) Analytical Essay on the Construction of Machines.
46. Leonardo da Vinci (c.1500) Codex Atlanticus.
47. Leonardo da Vinci (c. 1500) Codex Madrid I.
48. Lepschy AM, Mian GA, Viaro U (1992) Feedback Control in Ancient Water and Mechanical Clocks, IEEE Trans. Edu. 35(1), 3–10.
49. Leupold J (1724) Theatrum Machinarum, Leipzig.
50. Lyapunov AM (1892) The General Problem of the Stability of Motion.
51. Mach E (1893) The Science of Mechanics, English edition, The Open Court Publishing Co. Lasalle Illinois, 1960.
52. Martinek, Rehor (1996) Mechanische Uhren.
53. Maxwell JC (1867/1868) On Governors, Proc. Royal Soc. 16, pp. 270–283.
54. Mayr O (1969, 1970) The Origins of Feedback Control, English Edition, MIT Press, Cambridge, MA.
55. Mertzalov NI (1914)
56. Mertzalov NI (1914) [In Russian] Dynamics of Machines.
57. Mevel B, Guyader JL (1993) Routes to Chaos in Ball Bearings, J. Sound Vib. 162(3), 471–487.
58. Moll C L, Reuleaux F (1854) Constructionslehre Für Den Maschinenbau, (Design for mechanical engineering) Druck und Verlag von Friedrich Vieweg und Sohn, Braunschweig.
59. Moon FC (1992) Chaotic and Fractal Dynamics, Wiley, NY.
60. Moon FC (1998, 2008) Applied Dynamics: With Applications to Multibody and Mechatronic Systems, Wiley-VCH, Berlin.
61. Moon FC (2003) Franz Reuleaux; Contributions to 19th Century Kinematics and Theory of Machines, App. Mech. Rev. 56(2), 261–285.

62. Moon FC (2003) Robert Willis and Franz Reuleaux: Notes and Records, Roy.Soc.
63. Moon FC (2007) The Machines of Leonardo da Vinci and Franz Reuleaux, Springer, NY.
64. Moon FC, Stiefel PD (2006) Coexisting Periodic and Chaotic Dynamics in Clock Escapements, Phil Trans. Roy Soc A 364, 2539–2563.
65. Nikolai EI (1939) Theoretical Mechanics
66. Ord-Hume AWJG (1977) Perpetual Motion: The History of an Obsession, St. Marten's Press, NY.
67. Rankine WJM (1858, 1868) A Manual of Applied Mechanics, 4th Ed., Charles Griffin and Co., London.
68. Rayleigh [Lord] (1894–1896) The Theory of Sound, 2nd Ed., Macmillan, London.
69. Redtenbacher (1861) Resultate für den Maschinenbaau, Mannheim.
70. Redenbacher F (1865) Der Machinenbau Dritter Band, Verlagsbuchhandlung von Friedrich Bassermann, Mannheim.
71. Reti L (1974) The Unknown Leonardo.
72. Reuleaux F (1859) Regulatorenfrage, Zeitschtrift von deutscher Ingenuier, Vol 3.
73. Reuleaux F and Moll (1854)
74. Reuleaux (1875) Theoretische Kinematik.
75. Reuleaux F (1876) Das Zentrifugalmoment. Ein Beitrag zur Dynamik Verhandlungen des Verein zur Beförderung des Gewerbefleisses, Vol 55, (Sitzungsberichte), s. 50–88.
76. Reuleaux F (1876) Kinematics of Machinery; Outlines of a Theory of Machines, A.B.W. Kennedy, Transl., MacMillan and Co., London.
77. Reuleaux F (1893) The Constructor, 4th Edition, Translated by H. Suplee.
78. Roup and Bernstein et al. (2001) Analysis of the Verge and Foliot Clock Escapement, Michigan State Univ Report.
79. Routh (1905)
80. Routh EJ (1905) Dynamics of a System of Rigid Bodies, 6th Ed., Macmillan, London.
81. Sommerfeld A (1952) Mechanics.
82. Strada (1617) Künstlicher Abriss Allerand Wasser, Wind, Ross, und Handt Mühlen.
83. Szabo (1987) Geschichte der mechanischen Prinzipien, 3rd Ed., Birkhaüser Verlag, Basel.
84. Timoshenko S (1928) Vibration Problems in Engineering, D. Van Nostrand, NY.
85. Timoshenko S, Young DH (1948) Advanced Dynamics, McGraw-Hill, NY.
86. Truesdell C (1968) Essays in the History of Mechanics, Springer-Verlag, NY.
87. Watt (1780)
88. Weisbach J (1848) Principles of the Mechanics of Machinery and Engineering, First American Edition, Vol. 2 Lea and Blanchard, Philadelphia, 1848–1849.
89. Willis R (1841) Principles of Mechanisms, London.
90. Wood G (2002) Living Dolls, Faber and Faber Ltd., London.
91. Wrigley W, Hollister WM, Denhard WG (1969) Gyroscopic Theory, Design and Instrumentation, MIT Press, Cambridge US.

On the Historical Overview of Geometric Algebra for Kinematics of Mechanisms

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Abstract In this article, a historical survey of geometric algebra also called Clifford algebra is first undertaken in chronological order. This new algebra is ascribed to Grassmann and Clifford. The quaternion algebra originated from Hamilton can be considered as its special version. Next, in terms of geometric algebra notation, we further deal with the representation of the classical problems about the single finite rotation, first derived by Euler, and the composition formula of two successive finite rotations, originally proposed by Rodriques. Finally, the rigid body motion in the four dimensional geometric algebra $\mathscr{G}_4$ is introduced for the basis of possible future applications using geometric algebra and a general rigid body motion related to the 4×4 homogeneous transformation matrix in Euclidean space is then elucidated.

Keywords Historical survey, Geometric algebra, Clifford algebra, Quaternion algebra, Rigid body motion

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Historic Survey on Geometric Algebra

Geometry stemmed from two Greek words meaning "earth measurement". It was motivated by the need to make measurements of distances and areas on the Earth. Euclidean geometry has a broader meaning and the chief subject matter of the monumental 13-volume work called "The Elements", written about 300 B.C. by Greek mathematician Euclid (365–265 B.C., Fig. 1) [1]. Geometry, as developed in Euclid, was a systematic body of mathematical knowledge, built by deductive reasoning upon a foundation of the definitions, axioms, and postulates.

Algebra was associated with geometry from its beginning, but the French philosopher René Descartes (1596–1650, Fig. 2) was the first to develop it systematically into a geometrical language in 1637. He gave the Greek notion of magnitude a symbolic form and made significant improvements in algebraic notations, putting algebra in a form close to the one we use today. Descartes united algebra and geometry by treating the arithmetic of scalars as a kind of arithmetic of line segments. His application of algebra to geometry in the book of *La Géométrie* [2] leads to Cartesian geometry.

Fig. 1 Euclid of Alexandria (365–265 B.C.)

Fig. 2 René Descartes (1596–1650)

The introduction of complex numbers, generally attributed to Jean Robert Argand (1768–1822) in his work of 1806 but in fact anticipated by Norwegian Caspar Wessel (1745–1818) in 1799 [3], provided a valuable way of describing a rotation in algebraic terms, namely modulus and phase. These contributions promoted many attempts to develop an algebra of n-dimensional space by analogy with the representation of the plane using complex number in the future.

In 1840, French mathematician Olinde Rodrigues (1795–1851, Fig. 3) proposed the well-known half-angle relations for calculating the compound effect of two finite rotations [4]. Three years later attention was deflected from Rodriques's contribution by Hamilton's celebrated paper of 1843 describing the quaternions. The quaternions, introduced by Irish mathematician Sir William Rowan Hamilton (1805–1865, Fig. 4) form the oldest and best known non-commutative algebra, and can be regarded as a special case of geometric or Clifford algebra by expressing its basal elements as a binary product of geometric algebra bases. Quaternions yield the introduction of the ideas of vectors, and the cross product between them, but exist in three dimensions only. Quaternions are unsuited to representation of n dimensional rotations and after raising initial enthusiasm, influenced by Gibbs, were abandoned by most workers [5].

Fig. 3 Olinde Rodrigues (1795–1851)

Fig. 4 William Rowan Hamilton (1805–1865)

In 1844, the German mathematician Hermann Günter Grassmann (1809–1877, Fig. 5) discovered a rule for relating line segments to numbers that differed slightly from the rule adopted by Descartes. He chose to regard two line segments as equivalent if and only if one can be obtained from the other by a translation. This leads to the ideas of a "directed line segment" or vector. Trigonometry is founded on the Greek theories of proportion and perpendicular projection. But the principal ideas of trigonometry did not find their simplest symbolic expression until the invention of vectors and the inner product by Grassmann. With the abstract definition of the inner product $(a \bullet b)$, the principles and theorems of geometry can be completely expressed by algebraic equations without the need to use natural language. Moreover, trigonometry can be regarded as a system of algebraic equations and relations. The algebra of scalars and vectors based on the inner product has been so widely accepted as to be routinely employed, but this algebra is still incapable of providing a full expression of geometrical ideas. So a new kind of directed number, a directed plane segment (a parallelogram) also called a bivector (or 2-vector), was introduced to characterize the notion of directed plane segment. Since the bivector corresponding to a parallelogram is clearly uniquely determined by the geometrical construction, a new kind of multiplication to distinguish it from the inner product called the outer product $(a \wedge b)$ was defined.

Grassmann, who was the first person to define multiplication simply by specifying a set of algebraic rules, invented the outer or exterior product which can be defined on any vector space [5]. The outer product, a generalization of the idea of the cross product, is a new mathematical entity encoding an oriented plane and is called a bivector. Bivectors form a linear space and have the algebraic properties of being antisymmetric and distributive over addition. It can be visualized as the parallelogram obtained by sweeping one vector along the other. In modern notation, the outer or exterior product can be written as $a \wedge b$, or "*a* wedge *b*". Grassmann's considerable achievements are recognized as the first presentation of the abstract theory of vector spaces over the field of real numbers [6].

Clifford algebra, also named "geometric algebra" and sometimes called "hypercomplex numbers" to describe a generalization of the complex number and the quaternions [7], was introduced by the English mathematician William Kingdom Clifford (1845–1879, Fig. 6) in 1878. Clifford used Grassmann's ideas as the starting point for development of his geometric algebra and united the inner and outer products into a single geometric product, a new kind of product. Hence, geometric or Clifford algebra was formally introduced by Clifford in 1878 [8]. He called this algebra "geometrical algebra" and sometimes called the elements "hypercomplex numbers" as they generalize the complex numbers and the quaternions [9].

Fig. 5 Hermann Günter Grassmann (1809–1877)

Fig. 6 William Kingdom Clifford (1845–1879)

Geometrical algebra is a powerful mathematics with applications across a range of subjects in physics and engineering [5]. In the field of theoretical physics, Duffin-Kemmer algebra used to describe the behaviour of the π meson is a subalgebra of Clifford algebra. Clifford generalized the quaternions what he called the biquaternions and used them to study motion in "Clifford-Klein spaces". A general algebra denoted by C_n over a field of real number generated by any Clifford algebra base element. Every element of C_n can be regarded as a linear combination of 1 and products of basis vectors of the algebra. A general geometric algebra is classified into four cases based on the property of base elements [7]. Even subalgebra of a general algebra is closely related to the quaternions and we call this subalgebra "*n*-way algebra" and sometimes the second or special Clifford algebra.

Mechanics is most commonly formulated in terms of the vector algebra but for some applications of mechanics the algebra of complex numbers is more efficient than vector algebra, while in other applications matrix algebra works well. Geometric algebra integrates all these algebraic systems to retain their advantages and to produce new capabilities [9]. It encompasses both complex numbers and quaternions. Many distinct algebraic systems have been developed to describe geometric relations. They include the system of complex numbers, the quaternions, matrix algebra, vector, tensor and spinor algebra. Some of the more well-known mathematical applications of Clifford algebra which are adequately treated in the literature are historically mentioned in this work.

Briefs on Fundamentals of Geometric Algebra

Clifford's powerful idea was to introduce a product for vectors within a vector space. Starting with a space of dimension n and basis vectors $e_1, e_2, ..., e_n$, a larger space is formed of dimension 2^n whose basis elements are e_S where S is any subset of $\{1,2,...,n\}$. This new space is the Clifford algebra and it clearly contains the original space. The element $e_Ø$ where Ø is the empty set is identified with the unit scalar 1. The (non-commutative) product of original basis vectors is defined following that ideas that, for distinct subscripts i, j, k

$$e_ie_j = e_{ij}, \qquad e_je_i = -e_{ij}, \qquad e_ie_je_k = e_{ijk} \tag{1}$$

and that the square of any original basis element is a scalar, here taken to be the unit element

$$e_i^2 = 1 \tag{2}$$

The typical element of the larger space is a linear combination of the $\mathbf{e}_S$ and the multiplication extends naturally to these elements. The product also obeys the left and right distributive rules. The grade of the basis element e_S is the size of the subset S. If a general element is a combination of basis element only of a single grade, then that is also the grade of the element. Elements of grade 0 are simply multiples of $e_Ø$ and are regarded as scalars; elements of grade 1 are called *vectors*; elements of grade 2 *bivectors*; and elements of grade 3 *trivectors* to arbitrary dimensions.

The product is used to define an inner and an outer product of vectors of the algebra as follows.

$$a \bullet b = (ab+ba)/2 \tag{3a}$$
$$a \wedge b = (ab-ba)/2 \tag{3b}$$

It is clear that the original product can be written simply as follows,

$$ab = a \bullet b + a \wedge b \tag{4}$$

Note that in the case when a and b are vectors, this product is the sum of two distinct objects, a scalar and a bivector.

Consider an example when the original vector space has three dimensions. Suppose that $\{e_1, e_2, e_3\}$ form a right-handed frame of orthonormal vectors. Let $a = a_ie_i$ and $b = b_je_j$ be typical vectors, where the summation convention is used in this notation. It follows that

$$a \bullet b = (ab+ba)/2$$
$$= (a_i e_i) \bullet (b_j e_j) = a_i b_j \delta_{ij} \quad \text{where } \delta_{ij} \text{ is the Kronecker delta} \tag{5}$$
$$a \wedge b = (ab-ba)/2$$
$$= (a_i e_i) \wedge (b_j e_j)$$
$$= (a_2 b_3 - b_2 a_3) e_2 \wedge e_3 + (a_3 b_1 - b_3 a_1) e_3 \wedge e_1 + (a_1 b_2 - b_1 a_2) e_1 \wedge e_2 \tag{6}$$
$$a \wedge b \wedge c = (a_i e_i) \wedge (b_j e_j) \wedge (c_k e_k)$$
$$= \varepsilon_{ijk} (a_i b_j c_k)\, e_i \wedge e_j \wedge e_k \quad \text{where } \varepsilon_{ijk} \text{ is the alternating tensor} \tag{7}$$

which thus define the inner and outer products in terms of the geometric algebra and represents an oriented parallelepiped called a trivector. The orientation of a trivector depends on the order of its factors. Based on antisymmetry of the exterior product, the trivector $a \wedge b \wedge c$ changes sign under interchange of any pair of vectors. Therefore, the anticommutation rule together with the associative rule implies that exchange of any pair of factors in a product reverses the orientation of the result.

The full product of a vector a and a bivector B can be written as a sum of “symmetric” and “antisymmetric” parts in the following way

$$aB = a \bullet B + a \wedge B \tag{8}$$

where in terms of the geometric algebra, a generalization of the inner product of vectors $a \bullet B = (aB - Ba)/2$ and the outer product of vector and bivector $a \wedge B = (aB + Ba)/2$, because of $a \bullet B = -B \bullet a$ and $a \wedge B = B \wedge a$. The geometric product of a vector with a bivector results in the sum of a vector and a trivector. It is evident that outer multiplication by a vector raises the dimension of any directed number by one, whereas inner multiplication lowers it by one.

Furthermore, in the case of dimension n=3, introduce the following basis bivectors: $B_1 = e_2 e_3 = e_{23}$, $B_2 = e_3 e_1 = e_{31}$ and $B_3 = e_1 e_2 = e_{12}$. Then, their geometric products yield: $B_1^2 = B_2^2 = B_3^2 = -1$, $B_1 B_2 = -B_2 B_1 = -B_3$, and more generally

$$B_i B_j = -\varepsilon_{ijk} B_k \tag{9}$$

It is easily verified that these basis bivectors are the properties of the quaternion algebra generators i, j, k except that we have $B_1 B_2 B_3 = +1$. To set up an isomorphism, one can change sign in B_2. Hence, the quaternions are a left-hand set of bivectors.

Despite the American physicist Josiah Willard Gibbs (1839–1903) [10] being misguided in some of his objections to the quaternion product, two of the lasting legacies of the quaternion concept are the introduction of the idea of a vector, and the cross product between two vectors. In fact, the vector cross product is largely redundant now because there exists the exterior product and duality which can be used. By means of the unit right-handed pseudoscalar $I = e_1 e_2 e_3 = e_{123}$ for 3-dimensional space, the vector cross product can be defined as

$$a \times b = -I(a \wedge b) \tag{10}$$

This shows how the cross product of two vectors is a disguised bivector and the bivector is mapped to a vector by a duality operation [3]. By multiplying from the left or the right, the product of a unit vector e_i (i = 1, 2, or 3) with the unit grade-3 right-handed pseudoscalar I returns a bivector which represents the plane perpendicular to the original vector. This operation of multiplication is called the duality transformation and was originally introduced by Grassmann. It is independent of the order and holds for any basis vector. In fact, the pseudoscalar commutes with all vectors in the three dimensional case and squares to –1. This applied also to spaces of odd dimension, but I anticommutes with all vectors in the even dimensional case. In addition, the product of the pseudoscalar I with a unit bivector formed by e_1e_2, e_2e_3, or e_3e_1 is the minus the vector perpendicular to the original plane. Then, in terms of a definition by the exterior product and duality operation, the vector cross product is obviously redundant. It is now clear that a triple cross product of vectors is ready calculated by

$$a\times(b\times c) = -Ia\wedge[-I(b\wedge c)] = I\,[aI(b\wedge c) - (b\wedge c)Ia]$$
$$= -a \bullet (b\wedge c) = a \bullet bc - a \bullet cb \quad (11)$$

This turns out to be a very useful formula.

Here, some conventions are worth mentioning to simplify expressions in geometric algebra. For example, inner and outer products are performed before geometric products, and inner products are performed before outer products unless brackets specify.

An important operation in geometric algebra is that of reversion, denoted by the $^+$ symbol, which reverses the order of vectors in any product. Scalars and vectors are invariant under reversion, but bivectors and in three dimensions the pseudoscalar I change sign. For an example, a general multivector in the geometric algebra of three-dimensional space $\mathcal{G}_3$ can be written as

$$M = \alpha + a + B + \beta I \quad (12)$$

in which α and β are scalars, a is a vector and B is a bivector. Any element of the geometric algebra can be called a multivector. For all multivectors, addition is commutative, addition and multiplication are associative, and multiplication is distribution with respect to addition. There exists unique multivectors 0 and 1 and every multivector has a unique additive inverse. The whole algebra is algebraically closed, that is, the sum or product of any two multivectors is itself a multivector. By virtue of the definition, vectors always commute with trivectors. It follows that the pseudoscalar scalar commutes with all vectors in spaces of odd dimension but in even dimensions, the pseudoscalar anticommutes with all vectors.

Then, we see that the reverse of M, denoted as M^+, is

$$M^+ = \alpha + a - B - \beta I \quad (13)$$

This operation has the same effect as Hermitian conjugation applied to the Pauli matrices.

Two most powerful applications of geometric algebra are reflections and rotations. The result of reflecting an arbitrary vector a in the plane orthogonal to a unit vector n is the vector a', which can be expressed as

$$a' = -nan \quad (14)$$

The above formula is a quite general formula for a reflection and is valid in spaces of any dimension. Making use of the scalar product between two vectors and the cyclic reordering property of scalar part of geometric product [5], it is easily verified that this operation has the desired property of leaving lengths and angles unchanged.

A rotation in the plane generated by two unit vectors m and n is achieved by successive reflections in the planes perpendicular to m and n. On the other hand, two successive reflections in the hyperplanes perpendicular to m and n results a rotation in the plane $m \wedge n$. Simple trigonometry confirms that the angle between the initial vector a and the final vector c is twice the angle between m and n. Furthermore, we define a quantity $R{=}nm$ (or $R^{+}{=}mn$ is a reversion of R) so that the result of the rotation becomes

$$c = RaR^{+} \tag{15}$$

This transformation is a totally general way of handling rotations. It works in all spaces, whatever their dimension, and also works for any grade of multivector. Here, the quantity $R{=}nm$ is called a rotor, which provides a way of handling rotations that is unique to geometric algebra. Since a rotor is a geometric product of two unit vectors, we see immediately that $RR^{+} = R^{+}R = 1$. This also provides a proof that the rotation transformation has the property of preserving length and angles. Furthermore, in terms of the bivector B, we have

$$R = \cos\theta - B\sin\theta \tag{16}$$

This is equivalent to Euler's formula in complex number with $i = \sqrt{-1}$ replaced by the unit bivector B. With the exponential defined in its power series in the normal way, we can therefore write $R = \exp(-B\theta)$. Recall that our formula is for a rotation through $2\,\theta$. So the appropriate rotor to rotate through θ is

$$R = \exp(-B\theta/2) \tag{17}$$

This provides a clear geometric significance and gives the formula

$$a' = RaR^{+} = e^{-B\theta/2}\, a\, e^{B\theta/2} \tag{18}$$

which is for a rotation through θ in the B plane, with handedness determined by B. We can also see that the inverse transformation is given by $a = R^{+}a'R$.

Let the rotor R_1 transform the vector a into a vector b and then rotate b into another c, using a rotor R_2. This produces

$$\mathrm{c} = R_1 b R_1^{+} = R_2 R_1 a R_1 R_2 = R_2 R_1 a (R_2 R_1)^{+} \tag{19}$$

The composition rotor is given by $R = R_2 R_1$. This is the group combination rule for rotors. Rotors form a group, a continuous group or a Lie group [5].

Finite Rotations with Geometric Algebra

The Swiss mathematician Leonhard Euler (1707–1783, Fig. 7) was first to derive the finite rotation formula. Euler's theorem [11] states that the general displacement of a rigid body with one point fixed is a rotation about some axis. In terms of the angle of rotation ϕ and the unit vector **u** along the axis of rotation, the vector representation of the commonly used Euler finite rotation formula is expressed as follows.

$$\mathbf{r}' = \mathbf{r}\cos\phi + (\mathbf{u}\times\mathbf{r})\sin\phi + \mathbf{u}(\mathbf{u}\bullet\mathbf{r})(1-\cos\phi)$$
$$= \mathbf{r} + (\mathbf{u}\times\mathbf{r})\sin\phi + [\mathbf{u}\times(\mathbf{u}\times\mathbf{r})](1-\cos\phi) \quad (20)$$

where **r** and **r**′ are initial and final positions of the vector, respectively.

Fig. 7 Leonhard Euler (1707–1783)

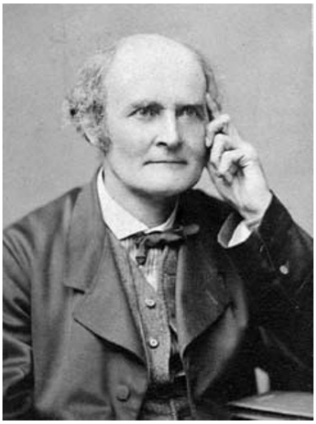

Fig. 8 Arthur Cayley (1821–1895)

In 1775, Euler considered a single finite rotation and obtained the finite rotation formula expressed in terms of the direction cosines of the rotation axis and the rotation angle. He did not solve the problem of finding the resultant of two successive finite rotations, although Euler's theorem affirms its existence. The composition formulae of rotations were actually derived by French mathematician Olinde Rodrigues (1795–1851, Fig. 3) [4]. Rodrigues proposed the well-known half-angle relations for calculating the compound effect of two finite rotations in 1840, three years before the invention of the quaternions [5], which were originated in Dublin, Ireland, on Oct. 16, 1843, by W.R. Hamilton (1805–1865, Fig. 4), who is famous because of his canonical functions and equations of motion that are important in both classical and quantum dynamics. The vector form of Rodrigues formula for two successive rotations [7] can be written as

$$\mathbf{u}_r \tan(\phi_r/2) = [\mathbf{u}_1 \tan(\phi_1/2) + \mathbf{u}_2 \tan(\phi_2/2) - \mathbf{u}_1 \tan(\phi_1/2) \times \mathbf{u}_2 \tan(\phi_2/2)]$$
$$/[1 - \mathbf{u}_1 \tan(\phi_1/2) \bullet \mathbf{u}_2 \tan(\phi_2/2)] \quad (21)$$

where $\mathbf{u}_1$, $\mathbf{u}_2$ and $\mathbf{u}_r$ and ϕ_1, ϕ_2 and ϕ_r are the unity vectors along the axes and the rotation angles of the first, the second and the resultant rotations respectively. Besides, it was Rodrigues who defined the Euler-Rodrigues parameters explicitly:

$$\mu_0 = \cos(\phi/2) \quad \mu_1 = u_x \sin(\phi/2) \quad \mu_2 = u_y \sin(\phi/2) \quad \mu_3 = u_z \sin(\phi/2) \quad (22)$$

where $\mathbf{u}=[u_x, u_y, u_z]^T$ is a unit vector, and used them to derive the composition formulae, which, in vector form, are

$$\mu_o'' = \mu_o\mu_o' - \boldsymbol{\mu}\cdot\boldsymbol{\mu}' \quad \text{and} \quad \boldsymbol{\mu}'' = \mu_o\boldsymbol{\mu}' + \mu_o'\,\boldsymbol{\mu} - \boldsymbol{\mu}\times\boldsymbol{\mu}' \tag{23}$$

in which the four Euler-Rodrigues parameters (μ_o'', μ_1'', μ_2'', μ_3'') are the resultant of two successive rotations (μ_0, μ_1, μ_2, μ_3) and (μ_0', μ_1', μ_2', μ_3'), and the vectors $\boldsymbol{\mu}$, $\boldsymbol{\mu}'$, and $\boldsymbol{\mu}''$ are defined as $\boldsymbol{\mu}=[\mu_1, \mu_2, \mu_3]^T$, $\boldsymbol{\mu}'=[\mu_1', \mu_2', \mu_3']^T$, $\boldsymbol{\mu}''=[\mu_1'', \mu_2'', \mu_3'']^T$. The application of Euler-Rodriques parameters further leads to the quaternion representation of the finite rotation formula,

$$\mathbf{r}' = q\mathbf{r}q^{-1} \tag{24}$$

with the unit quaternion $q=\mu_0 + \mu_1\, i + \mu_2\, j + \mu_3\, k$ and the initial and final position vectors $\mathbf{r}$ and $\mathbf{r}'$. This quaternion formula for the finite rotation itself was first derived by Hamilton [12]. However, the physical meaning of this quaternion form using Rodrigues parameters:

$$d_1 = \mathrm{u}_x \tan(\phi/2) \quad d_2 = \mathrm{u}_y \tan(\phi/2) \quad d_3 = \mathrm{u}_z \tan(\phi/2) \tag{25}$$

was discovered by English mathematician Arthur Cayley (1821–1895, Fig. 8) [13]. Hamilton then made the same composition formula which can be written as

$$\mathbf{r}'' = q'\mathbf{r}'q'^{-1} = q'q\mathbf{r}q^{-1}q'^{-1} = q''\mathbf{r}q''^{-1} \tag{26}$$

with $q''=q'q$.

The Rodrigues's composition formula of finite rotations mentioned above could be easily derived by just multiplying the rotors directly. Hence, the rotor composition rule is ready to provide a simple formula for the compound effect of two rotations in the following manner.

Suppose that we have

$$R_1 = e^{-B_1\theta_1/2} = \cos(\theta_1/2) - B_1\sin(\theta_1/2) \quad \text{and}$$
$$R_2 = e^{-B_2\theta_2/2} = \cos(\theta_2/2) - B_2\sin(\theta_2/2) \tag{27}$$

in which B_1 and B_2 are unit bivectors. The product rotor is $R=R_2R_1=\exp(-B\theta/2)$ [or $\cos(\theta/2) - B\sin(\theta/2)$], in which B is a new unit bivector,

$$\begin{aligned} R &= [\cos(\theta_2/2) - B_2\sin(\theta_2/2)][\cos(\theta_1/2) - B_1\sin(\theta_1/2)] \\ &= \cos(\theta_2/2)\cos(\theta_1/2) - [\cos(\theta_2/2)\sin(\theta_1/2)\, B_1 + \cos(\theta_1/2)\sin(\theta_2/2)\, B_2] \\ &\quad + \sin(\theta_2/2)\sin(\theta_1/2)\, B_2B_1 \end{aligned} \tag{28}$$

By using angled brackets $\langle\ \rangle_r$ to denote the r-grade onto which we want to project and dropping the subscript zero for the scalar part of a geometric product, we immediately see that

$$\cos(\theta/2) = \cos(\theta_2/2)\cos(\theta_1/2) + \sin(\theta_2/2)\sin(\theta_1/2)\,\langle B_2B_1\rangle \tag{29}$$

and

$$\begin{aligned} \sin(\theta/2)B = {} & [\cos(\theta_2/2)\sin(\theta_1/2)B_1 + \cos(\theta_1/2)\sin(\theta_2/2)B_2] \\ & - \sin(\theta_2/2)\sin(\theta_1/2)\,\langle B_2B_1\rangle_2 \end{aligned} \tag{30}$$

These expressions definitely confirm the half-angle relations for the composition of two finite rotations.

Rigid Body Motion in the Geometric Algebra $\mathcal{G}_4$

A general rigid body motion related to the 4×4 homogeneous transformation matrix in Euclidean space is briefly elucidated for the basis of possible future application using geometric algebra. Conventional mechanism analysis approach is the use of 4×4 coordinate transformation matrices indicated by means of the Denavit and Hartenberg parameters [14] or its varieties. These allow each type of rotation and translation to be combined using the ordinary matrix multiplication. Quaternions, which form a special geometric algebra, can also be used to represent rotations. The relation between the quaternion and matrix approaches has also been studied. However, recently, more attentions are taken to handle geometry and to represent geometric entities as actual elements within itself rather than as equations relating coordinates. As a consequence of the appearance of papers by Selig [15], Mullineux [16] working in the 4-dimensional (4D) geometric algebra $\mathcal{G}_4$ extend the definition of the inner and outer products, which were defined just for vectors, to apply for all elements in 4D geometric algebra. So, for any x and y in $\mathcal{G}_4$,

$$x \bullet y = (xy + yx)/2 \quad \text{and} \quad x \wedge y = (xy - yx)/2 \tag{31}$$

It turns out that if x, y, z have the same grade then,

$$(x \wedge y) \bullet z = (y \wedge z) \bullet x = (z \wedge x) \bullet y = (xyz + yzx + zxy - xzy - zyx - yxz)/6 \tag{32}$$

which agrees with Lounesto's definition [17] of $x \wedge y \wedge z$.

In Cartesian geometry, lines and planes are represented by equations involving the coordinates of points. In the work of [16], points, lines and planes are elements of a four dimensional geometric algebra $\mathcal{G}_4$ in their own right. Therefore, a geometric algebra can be used to handle translations and rotations in a way which preserves the natural representation of Euclidean space. The rigid body motions, which are combinations of rotations and translations can be represented in a natural way as elements of even grade within the geometric algebra $\mathcal{G}_4$. In this approach, one of four basis vectors has a square which is treated as infinite by defining it to be the reciprocal of an arbitrarily small number so that $e_0^2 = \varepsilon^{-1}$, where e_0 is the fourth basis of algebra element and ε is an infinitesimal, real number. This algebra is used to represent three dimensional space in a projective way. The typical point (x,y,z) is represented by the element $e_0+xe_1+ye_2+ze_3$ (and by any non-zero scalar multiple of this element). It turns out that all rigid body transforms are represented by even grade elements in the geometric algebra and act upon vectors which are the natural representation of Euclidean points.

Let b be a unit bivector and $b=q_1e_{23}+q_2e_{31}+q_3e_{12}$. Suppose that c and s are the abbreviations of cosine and sine of angle $\theta/2$, that is, $c=\cos(\theta/2)$ and $s=\sin(\theta/2)$. For convenience, an axis in the direction q is indicated as a unit vector

$$q = [q_1, q_2, q_3]^T = q_1e_1+q_2e_2+q_3e_3 \tag{33}$$

For the typical Euclidean point (x, y, z), let $r=xe_1+ye_2+ze_3$. so that the point is represented in the algebra $\mathcal{G}_4$ by the vector $p=e_0+r$. The element R of $\mathcal{G}_4$ is defined as $R=c+sb$, then the map that takes p to R^+pR (where $^+$ means the reversion), rotates the position vector r to a new position vector about an axis through the origin in the direction of vector q. Moreover, let T=1+$\varepsilon e_0 t$ where t=t_1e_1+t_2e_2+t_3e_3. The map that transform the point p=e_0+r to T^+pT take r to r+$2t$. In this way, the transformation represents a translation through $2t$. Thus a rigid body motion that rotates the angle θ about an axis through the origin in the direction of the vector q and followed by a translation 2t along the t-direction can be the element S of even grade in $\mathcal{J}_4$ as follows.

$$S = RT = (c+sb)(1+\varepsilon e_0 t)$$
$$= (c+sb) + \varepsilon(c+sb)e_0 t = c(1+\varepsilon e_0 t) + sb(1+\varepsilon e_0 t) \qquad (34)$$

Suppose now that the axis of rotation does not pass through the origin, but passes through the position u = e_0+2u_1e_1+2u_2e_2+2u_3e_3 and in the same direction cited above. Then, the rotation is represented instead by the following modified form of R. This formed as a combination of a translation, a rotation, and a translation, where the translation take the point u to the origin and back.

$$R = (1-\varepsilon e_0 u)(c+sb)(1+\varepsilon e_0 u)$$
$$= c + sb + \varepsilon cu^2 + 2\varepsilon s e_0(b\wedge u) + \varepsilon subu \qquad (35)$$

and in the limit as $\varepsilon \to 0$, this becomes

$$R = c + sb + 2\varepsilon s e_0(b\wedge u) = c + s[b + 2\varepsilon e_0(b\wedge u)] \qquad (36)$$

Thus, a rigid body motion that combines the rotation and translation is represented by

$$S = RT = [c + sb + 2\varepsilon s e_0(b\wedge u)](1 + \varepsilon e_0 t)$$
$$= c + \varepsilon c e_0 t + sb + \varepsilon s e_0 bt + 2\varepsilon s e_0(b\wedge u) - 2\varepsilon s(b\wedge u)t$$
$$= (c + sb) + \varepsilon e_0[ct + 2s(b\wedge u)] + \varepsilon s e_0 bt \qquad (37)$$

A kinematic model shown in Fig. 9 is the three-body open chain connected by two helical (or screw) pairs, in which ${}^1t$ (=${}^1t_1e_1$+${}^1t_2e_2$+${}^1t_3e_3$) and ${}^2t$ (=${}^2t_1e_1$+${}^2t_2e_2$+${}^2t_3e_3$) are the half translations for each screw revolution, and ${}^1q$=[${}^1q_1$, ${}^1q_2$, ${}^1q_3$]^T and ${}^2q$=[${}^2q_1$, ${}^2q_2$, ${}^2q_3$]^T are the direction of rotaion axes of screws. Hence, b_1 = ${}^1q_1e_{23}$+${}^1q_2e_{31}$+${}^1q_3e_{12}$ and b_2 = ${}^2q_1e_{23}$+${}^2q_2e_{31}$+${}^2q_3e_{12}$.

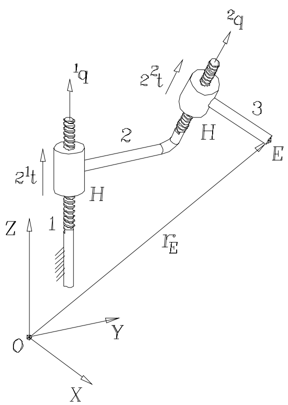

Fig. 9 The kinematic model of a HH open chain

Let u_1 and u_2 be points on the two axes (as above). Based on the previous discussions, this case can be simulated by using the geometric algebra approach. The vector $p_E=e_0+r_E$ indicated the position vector r_E of the end in the last link is moved to a new position by the following map

$$S^{+}p_E S = (S_1S_2)^{+}p_E S_1S_2 = S_2^{+}S_1^{+}p_E S_1S_2 \quad (38)$$

in which $^{+}$ means reversion and

$$S_1 = R_1T_1 = (c_1 + s_1b_1) + \varepsilon e_0(c_1^{\,1}t + 2s_1(b_1\wedge u_1)) + \varepsilon s_1e_0b_1^{\,1}t$$
$$S_2 = R_2T_2 = (c_2 + s_2b_2) + \varepsilon e_0(c_2^{\,2}t + 2s_2(b_2\wedge u_2)) + \varepsilon s_2e_0b_2^{\,2}t$$
$$S = S_1S_2$$

Summary

It is contended that Geometric Algebra as a method is more comprehensive and less artificial than and eventually in every way far superior to Coordinate Geometry. When, in the treatment of any particular question, scalars have to be adopted, geometric algebra solution can becomes identical with the Cartesian one. It must always be remembered that Cartesian methods are mere particular cases of geometric algebra. It is hoped that this historical survey of geometric algebra with originated with Grassmann and Clifford could lead to a kinematic interest in the mechanism community for the further applications.

References

1. Encyclopedia of Science and Technology, McGraw-Hill, New York, 1972.
2. Jullien V (1996) Descartes La ‘Géométrie’ de 1637, Paris.
3. Branner B (1999) Caspar Wessel on representing complex number (1799),” Eur. Math. Soc. Newsl. Vol. 33, pp. 13–16.
4. Rodriques O (1840) Des lois geometriques qui regissent le deplacement d’un systeme solide, J. du Math. Pures et Appliquées, Vol. 5, pp. 380–440.
5. Doran C, Lasenby A (2003) Geometric Algebra for Physicists, Cambridge University Press, Cambridge.
6. Stewart I (1986) Hermann Grassmann was right, Nature, Vol. 321, p. 17.
7. Shimpuku T (1988) Symmetric Algebra by Direct Product of Clifford Algebra, Seibunsha, Osaka.
8. Clifford WK (1878) Application of Grassmann’s extensive algebra, Am. J. Math. Vol. 1, pp. 350–358.
9. Hestenes D (1986) New Foundations for Classical Mechanics, Kluwer Academic Publishers, Dordrecht.
10. Gibbs JW (1901) Vector Analysis, E. B. Wilson, Ed., Scribner, New York, and Yale University Press, New Haven (1931).

11. Euler L (1775) Formulae generales pro translatione quacunque corporum rigidorum, Novi Commentari acad. Imp. Petrop. Vol. 20, pp. 189–207.
12. Hamilton WR (1853) Lectures on Quaternions, Hodges and Simth, Dulin.
13. Cayley A (1843) On the motion of rotation of a solid body, Cambridge Math. J. Vol. III, pp. 224–232.
14. Denavit J, Hartenberg RS (1955) A kinematic notation for lower pair mechanisms based on matrices, ASME Trans. J. Appl. Mech., Vol. 22, pp. 215–221.
15. Selig JM (2000) Clifford algebra of points, lines and planes, Robotica Vol. 18, pp. 545–556.
16. Mullineux G (2002) Clifford algebra of three dimensional geometry, Robotica Vol. 20, pp. 687–697.
17. Lounesto P (2001) Clifford Algebra and Spinors, Cambridge University Press, Cambridge.

Some Origins of TMM Arisen from Pseudo-Aristotle and Hero of Alexandria

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Abstract This paper is an attempt to investigate the remote origins of the theories of machines and mechanisms. The work "Mechanica" (Lindsay, Energy: Historical Development of the Concept, 1975; Dugas, A History of Mechanics, 1988), attributed to Aristotelian tradition and considered the first explanation of the behavior of machines, is studied and discussed. His author is known as "pseudo-Aristotle", probably a follower of the great Greek philosopher. The properties of the circle, according to the author explain that behavior.

Keywords History of mechanics, History of mathematics, Greek mathematicians, Aristotelian tradition, Theory of machines and mechanisms

Introduction

The studies conducted in this paper use the first four sections of the treatise "Mechanica" in an English translation by E.S. Forster in Volume VI of the works of Aristotle, edited by W.D. Ross, a Clarendon Press appeared in London in 1913, p. 847-a to 850-b. By using the properties of the circle the author explains the dynamical behavior of machines at some length, coming close to introducing the parallelogram law of composition of vectors. He also studies the balance as a lever in rotational motion about the fulcrum whose discussions anticipate the

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principle of virtual velocities [2,3]. The importance of the text “Mechanica” is not only because it geometrizes mechanical problems but also because it is in contrast with the statical method employed some years later by Archimedes (287–212 B.C.) and Euclides in mechanics. There is an Arabic manuscript of 970 A.C. called “Book on the balance” which remained unknown to the western Midle Ages. Dr. Woepke has brought this manuscript to light as referred by René Dugas [4].

This dynamical approach is a remarkable advance in terms of future works like the contributions of Hero of Alexandria [5] to machines studies. It seems that Hero lived at some time during the second century A.D. He wrote a treatise “Mechanics”, divided in three books. In book one he studies some geared systems to move weights. A clear influence of “Mechanica” in his studies is shown. To Hero of Alexandria is also attributed: “Pneumatics”, “Automata”, “Metrics” and “Dioptra”.

If we look at history of TMM the majority papers are of two categories. Some discuss their ancient origins [6] and others the modern contributions [7, 8].

“Mechanica”, the First Theory of Machines and Mechanisms

In p. 847-a, the author refers to the context where mechanical problems appear: “Instances of this are those cases in which the less prevails over the greater, and where forces of small motive power move great weights – in fact, practically all those problems which we call Mechanical Problems… Among questions of a mechanical kind are included those, which are connected with the lever. It seems strange that a great weight can be moved with but little force, and that when the addition of more weight is involved; for the very same weight, which one cannot move at all without a lever, one can move quite easily with it, in spite of the additional weight of the lever”.

The fact that “the less prevails over the greater” and where “forces of small motive power move great weights”, implies a force multiplication system, provided by the lever. The author attributed the original cause of “all such phenomena” to the properties of the circle. He considers that the circle has a great marvel that “contraries should be present together” and the circle is made up of contraries as a kind of dialectics inherent to this figure. He, then, made a detailed description of these contradictions: “The motion and rest, the concave and the convex, the peculiarity of moving in two contrary directions at the same time…”

To illustrate those properties he studies a system very similar to a gear train, as shown below in Fig. 1.

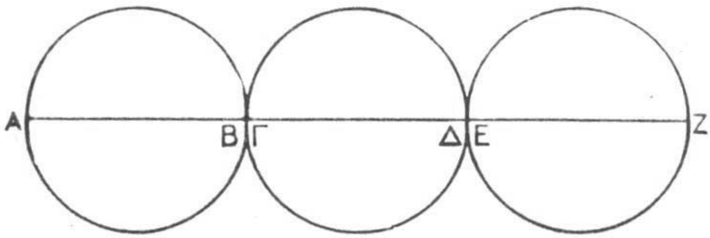

Fig. 1

In p. 848-a, one can read: “Because a circle moves in two contrary forms of motion at the same time, and because one extremity of the diameter, A, moves forwards and the other, B, moves backwards, some people contrive so that as the result of a single movement a number of circles move simultaneously in contrary directions, like the wheels of brass and iron which they make and dedicate in the temples. Let AB be a circle and ΓΔ another circle in contact with it; then, if the diameter of the circle AB moves forward, the diameter ΓΔ will move in a backward direction as compared with the circle AB, as long as the diameter moves round the same point. The circle ΓΔ therefore will move in the opposite direction to the circle AB. Again, the circle ΓΔ will itself make the adjoining circle EZ move in an opposite direction to itself for the same reason. The same thing will happen in the case of a large number of circles, only one of them being set in motion”.

In Fig. 2, an anticipation of the rule of the parallelogram and vectors composition is presented as follows:

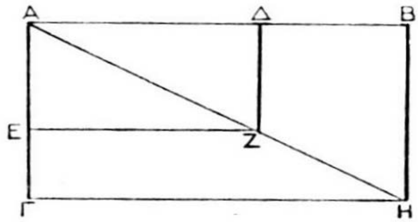

Fig. 2

“Now if two displacements of a body are in any fixed proportion, the resulting displacement must necessarily be a straight line, and this line is the diagonal of the figure, made by the lines drawn in this proportion. Let the proportion of the two displacements be as AB to AΓ and let A be brought to B, and the line AB brought down to HΓ. Again, let A be brought to Δ and the line AB to E; then, if the proportion of the two displacements be maintained, AΔ must necessarily have the same proportion to AE as AB to AΓ. Therefore, the small parallelogram is similar to the greater, and their diagonal is the same, so that A will be at Z”.

Obviously, if the proportion of the sides is not obeyed, the point will not move along the diagonal but following a curve. A circular or circumferential path is explained by the author, as a resultant of two components motions, related to each other according to a constantly changing ratio. Other properties of the circle come from Aristotelian tradition as "natural" and "unnatural" components. He refers to "natural" component that directed along the tangent at every point of the circle. The "unnatural" component, in the sense that it interfered with the "natural" tangential movement, is that directed toward the center of the circle, and thus, at a right angle to the tangential component. As we mention, the author considers that the ratio between the "natural" and the "unnatural" components changed continuously, resulting in a curved arc. In connection with his analysis of the lever, he inquired why the end point on a rotation radius traveled more quickly than some intermediate point on the same radius. Using Fig. 3, this analysis is made.

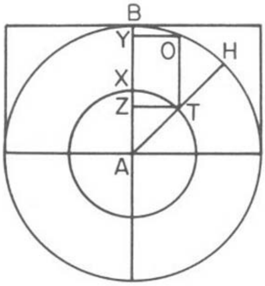

Fig. 3

Let the equal perpendiculars ZT and YO represent the natural tangential components of arcs XT and BO. Let the vertical projections XZ and BY of the same arcs represent their respective unnatural components. Take ZT = YO, so that arc XT, described by the shorter radius, can be compared with arc BO, apart of arc BH described in the same time by the longer radius. Since XZ > BY, it follows that $n_2 / u_2 > n_1 / u_1$. By n and u we are designating the two components of the movement: the natural (n) and unnatural (u). Or if we put the argument in terms of physical objects, a weight on the end point of a rotating radius moves more rapidly than a similar weight at an intermediate point because it is less interfered with. The analysis has some deficient points. YO represents the tangential component even when the radius is no longer at B on the circumference, but at O, where YO is by no means tangential. In order to express the greater velocity of the radius on the other arc, the author compares radius AX when it is at point T to AB, an extension of the same radius, when it is at point O, where it was formerly but is no longer. He asserts, but cannot prove, that the inequality between the ratios n_2 / u_2 and n_1 / u_1 when the radii are at T and O holds everywhere on the circumferences.

For the analysis made above, it is the following the author's conclusion: "The reason why the point further from the center is moved quicker by the same force, and the greater radius describes the greater circle, is plain from what has been said; and hence the reason is also clear why larger balances are more accurate than smaller… Therefore by the same weight the end of the balance must necessarily be moved quicker in proportion as it is more distant from the cord (the fulcrum), and some weight must be imperceptible to the senses in small balances, but perceptible in large balances…"

To finalize the part of the manuscript under consideration, the author studies the balance with two kinds of restriction. The first one with the cord attached to the upper surface. The other with the cord attached to the lower surface. He intends to prove that, for the first case "if one takes away the weight when the balance is depressed on one side, the beam rises again", while for the second, "it does not rise but remains in the same position". It is explained in Figs. 4 and 5, below.

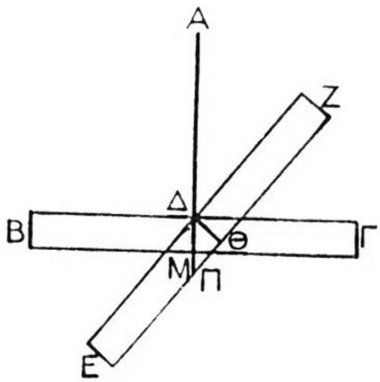

Fig. 4

"Let BΓ be a straight beam, and AΔ a cord. If AΔ were produced it will form the perpendicular AΔM. If the portion of the beam towards B be depressed, B will be displaced to E and Γ to Z; and so the line dividing the beam into two halves, which was originally ΔM, part of the perpendicular, will become Δθ when the beam is depressed; so that the part of the beam EZ which is outside the perpendicular AM will be greater by θH than half the beam. If therefore the weight at E be taken away, Z must sink, because the side towards E is shorter".

"Let NE be the beam when horizontal, and KAM the perpendicular dividing NE into two halves. When the weight is placed at N, N will be displaced to O and E to P, and KA to Aθ, so that KO is greater than AP by θAK. If the weight, therefore is removed the beam must necessarily remain in the same position; for the excess of the part in which OK is over half the beam acts as a weight and remains depressed".

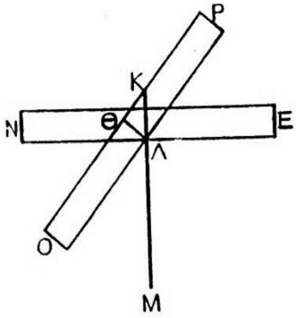

Fig. 5

The Influences of "Mechanica" in Hero of Alexandria

"The Mechanics", a famous book of Hero of Alexandria, is known only by means of an Arabic manuscript from the IX century, translated into several languages. In this paper, we use the translation to French language by Carra de Vaux with comments by A.G. Drachmann, published by "Les Belles Lettres", in 1988.

In book one, Hero studies gear-trains mechanisms in order to move weights. These mechanisms are very similar to those studied by "pseudo-Aristotle". The first mechanism is shown in Fig. 6, below.

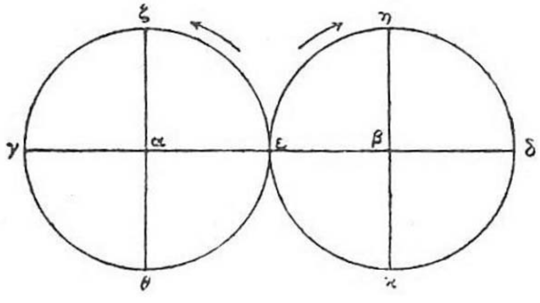

Fig. 6

In p. 63, Hero wrote: "Lets move two equal circles, one ηεξδ, the other ζγθε, with centers in α and β, respectively and the point of contact of both ε. They move starting by this point and after some time, they turn a half-circumference. During this time, the point ε displaces the arc εηδ, arriving in δ the same displacement of the point γ. There are points turning in the same direction and others in opposite directions. Similar points in the two circles have opposite movements and those symmetrically placed have movement in the same direction".

In Fig. 7, the author studies a similar mechanism but with circles of different diameters.

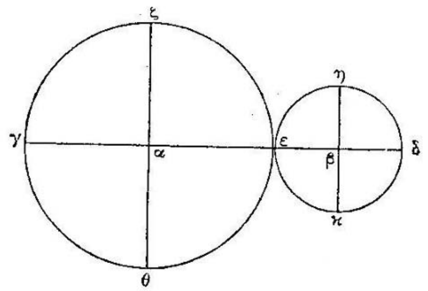

Fig. 7

In p. 65, one reads: "Now, lets suppose two different circles with centers in α and β, respectively. The relationships are not perfect like in the previous case. By considering two points that turn from ε and, as an example be the diameter γε the double of diameter εδ. The arc εξδ will be the double of the arc εηδ as demonstrated Archimedes; then, the time elapsed by the point ε to describe the arc εη moving towards the point γ, the same point ε moving in opposite direction describes the arc εηδ; the same time that the point starting at ζ describes the arc ζγ, one point starting at δ describes the arc δξε and arrives at point ε".

The considerations above made by Hero of Alexandria are very similar to those made by pseudo-Aristotle" in Fig. 1 about the properties of the circle.

In p. 69/70, Fig. 8, one can read considerations quite similar to the parallelogram law discussed in "pseudo-Aristotle".

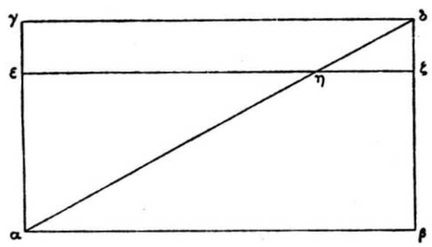

Fig. 8

Lets suppose the motion of one point described by two regular motions belonging to lines of different lengths. Looking at Fig. 8, the parallelogram αβγδ; αδ being the its diagonal. The point α described by one regular motion αβ, and the line αβ itself being transposed by a regular motion over the lines αγ, βδ such that this line is maintained parallel to the line γδ. The time elapsed by the point α to arrive in β is equal to the line αβ to arrive in γδ. Consequently, the motion of point α describes two lines of different lengths and when the line αβ is displaced during any interval like εζ, the point α moving over the line αβ in the same time is over the line εζ; the relationship between αγ and αβ is δγ which is equal to the relation between the length αε to the length of the line over that the point is moving. Or the relation αγ /γδ is equal to relation αε /εη. Hence, the point which is moving over the line αβ is going towards η over the line αδ, the diagonal. It is then proved that the point which describes the line αβ stays ever over the line αδ; during that travel the point is moving over the lines αβ and αδ and that point with a regular motion describes two lines of different lengths. Therefore, the motion of the point over the line αβ that is simple, while the motion along the diagonal αδ is composed of motion of αβ over the lines αγ, βδ and the motion of α over the line αβ. Yet, the point α described by the same time and the regular motion of two lines of different lengths.

Conclusions

The dynamical tradition where we can identify the origins of the theories of machines and mechanisms began with the Greek author of "Mechanica" usually thought to have been among the first few generations of Aristotelians. As shown in this paper he devoted considerable attention to mechanical systems like mechanisms, especially systems that operate like a gear train in a modern sense. He then created a conceptual basis to explain the kinematics involved by the properties of the circle. He also studied the balance, whose principles it was asserted, illuminate a wide range of mechanical problems. In this context "pseudo-Aristotle" contained several important and original contributions like an appreciation of compound motion, for which the author developed a primitive sort of vector analysis with the first known statement of the parallelogram of forces. His attempt to geometrize the constrained movement of a rotating beam to study the balance is also an incipient formulation of the principle of virtual velocities [9–11], very useful and important tool for the study of mechanisms of articulated bars and others similar. These ideas consolidated some of the general notions of Aristotle mainly your dynamical approach to the science of motion [12].

With respect to the analysis of mathematical properties of circular motion and its applications to the behavior of the lever or balance, some remarks must be done. The analysis of circumferential path, as he explained, was a resultant of two component motions related to each other according to a constantly changing of ratio. He denominated these two components by "natural", and directed along the tangent at every point of the circular trajectory. The other component "unnatural", in the sense that it interfered with the previous one, the natural and tangential, was directed toward the center of the circle, obviously at right angle to tangential component. In the author's definitions, the ratio between the natural and the unnatural components changed continuously and the resultant was a curved arc. When the ratio is constant between the two components acting in an angle, the resultant will be a straight line, the diagonal of the parallelogram.

The characterization of the circular motion as presented above by "pseudo-Aristotle" is in contrast with Aristotle point of view for the natural motion. In Aristotle "Physics", natural motion of a heavy body was defined as motion directed toward the center of the universe, which is the vertical fall. Motion in any other direction was unnatural. As shown here, however it was the tangential motion that was natural. Thus, the two points of view are quite different.

In spite of the different approaches to mechanical problems, there is an important similitude between "pseudo-Aristotle" and Archimedes. Both made at the same time a geometrization of mechanics and a mechanization of geometry. This appears in "Mechanica" in the study of balance or lever as well as in Archimedes study of lever and in centers of gravity of figures [13].

A good overview on recent history of TMM is given by Ceccarelli [8]. He divided the contributions to TMM starting from early years works arisen at Polytechnic School in Paris since that it was established in 1794. The author considers that date the foundation of modern TMM.

The evolution of TMM continues until to become a discipline in the XX-th century. Subsequent periods can be identified in the 1960s years and finally in 1990s years when TMM assumed a character of engineering science.

References

1. Lindsay RB (1975) Energy: Historical Development of the Concept, Dowden Hutchingson & Ross, Inc.
2. Lindberg DC (1992) Science in the Middle Ages, Chapter 6, The University of Chicago Press.
3. Oliveira ARE (2006) History of the Principle of Virtual Works, Seminar at Cornell. University, NY.
4. Dugas R (1988) A History of Mechanics, Dover Publications Inc., NY.
5. Vaux Carra de (1988) Heron d'Alexandrie, Les Mechaniques ou L'élevateur des Corps Lourds, Les Belles Lettres, Paris.
6. Ceccarelli M (2006) Early TMM in Le Mecaniche by Galileo Galilei in 1593, Mechanisms and Machine Theory, Vol. 4, No. 12, pp. 1401–1406.
7. Dimaragonas AD (1993) The Origins of the Theory of Machines and Mechanisms in Modern Kinematics, Developments in the Last Forty Years, Ed. By A. G. Erdman, Wiley, New York, pp 3–18.
8. Ceccarelli M (2004) Evolution of TMM (Theory of Machines and Mechanisms) to MMS (Machine and Mechanism Science), An Illustration Survey.

9. Fourier JBP (1798) Memoire sur la Statique Contenant la Démonstration du Principe des Vitesses Virtuelles et la Théorie des Moments, Journal de l'École Polytechnique, Paris.
10. Poinsot L (1975) La Théotie Génerale de l'Equilibre et du Mouvement des Systèmes, Patrice Bailase, LibrairiePhilosophique J. Vrin, Paris.
11. Lagrange JL (1989) Mécanique Analytique, Éditions Jacques Gabay, Paris.
12. Aristote (1999) La Physique, Librairie Philisophique J. Vrin, Paris.
13. Heath TL (2002) The Works of Archimedes, Dover Publication, Inc., NY.

Kurt Hain – An Outstanding Personality in the Field of Applied Kinematics and the Accessibility to his Scientific Work

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Abstract Dr.-Ing. E.h. Kurt Hain (1908–1995) belongs to the pioneers of Applied Kinematics in Germany. He published an extensive scientific work which contains 13 books and more than 380 papers on nearly all partial fields of kinematics. The paper gives a survey of the lifework of Kurt Hain and describes a national research project to store and to provide his heritage for all people who are interested in kinematics.

Keywords Lifework of an outstanding personality, Prevention of scientific heritage, Digitalization and enhancement of scientific sources, Open access to scientific knowledge, Internet-based digital library

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Biographical Notes

Kurt Hain (Fig. 1) was born on May 24, 1908 in Leipzig (Saxony, Germany) [1]. After having finished his apprenticeship as a mechanic and turner he studied mechanical engineering at the *Höhere Maschinenbauschule* in his native town. The then highly appreciated Paul Knechtel taught him and evoked in him the interest in kinematics as the basic knowledge for the increasingly developing mechanization period. This meant a key experience for Kurt Hain and fixed his future professional career. After his studies he worked several years with different companies in Leipzig, Dessau and Dresden until he moved with his family in 1939 to Braunschweig where he worked as a research and test engineer in the National Aviation Research Institution. This institution changed just after the war into the *Forschungsanstalt für Landwirtschaft* (Research Institution of Agriculture). Kurt Hain became head of the Department of Kinematics in the *Institut für Landtechnische Grundlagenforschung* (Institute of Agro-Technical Basic Research) of the FAL and made for example also major improvements in the design of tractor-drawn farm implements. He retired in 1973.

Fig. 1 Kurt Hain (1908–1995)

Personality and Activity

Kurt Hain is well known in the community of *Mechanism and Machine Science* (MMS) both for his personality and activity. His works are still considered as an important background and even source of inspiration, as outlined in [2].

Main activities of Kurt Hain were:

- promoter of IFToMM spirit
- honorary IFToMM member
- great scientist personality in MMS (published more than 500 works, formed and directed young researchers, directed national and international initiatives, received honours and awards)

Today Kurt Hain is a part of MMS history. His masterpiece "Angewandte Getriebelehre" was soon translated into English in "Applied Kinematics" by several USA friend-colleagues of him [3]. The book summarizes most of his work in the field of kinematics, as based on an approach bringing theory into practice.

The research activity of Kurt Hain was aimed to practical applications and to a teaching of both the solutions and approach for the formation of clever professionals. Thus, he continued the German tradition of using models of mechanisms (Fig. 9 and 11) to explain design aspects and operational features, even when computer technique was emerging as a potent means both for teaching and design research. He always preferred the possibility to control and to guide computations with models and he preferred a formulation that could also help to interpret the results and the intermediate steps.

Mentor of HMM

Kurt Hain can be considered as a mentor and promoter of IFToMM since with his open-minded attitude and ability for cooperation he was a brilliant example of an IFToMMist. Within this frame he contributed considerably and got benefit of the cultural environment that gave the Second Golden Age for *Theory of Machines and Mechanisms* (TMM, today MMS), whose main characters are outlined in [4]. The First Golden Age can be identified in the second half of the 19th century with great developments in theory and practice of mechanisms which enhanced engineering during the Industrial Revolution. Relevant contributions were given by the German Schools of Kinematics of Mechanisms within which Kurt Hain was formed and inspired.

Kurt Hain was not directly involved in the foundation of IFToMM. However, his activity was directed to collaboration and dissemination of engineering for the benefit of the society which made him recognized as if he would have been in the group of the IFToMM founding fathers. For those of the third generation of IFToMMists he is a brilliant example of the significance of the IFToMM spirit for worldwide collaboration and promotion of TMM in order to achieve personal satisfaction and useful goals for the community.

The Reflection of the Lifework of Kurt Hain at the DMG-Lib

Since 2005 the *Deutsche Forschungsgemeinschaft* (DFG, German Research Foundation) funds a project called "Digitale Mechanismen- und Getriebe-bibliothek" (Digital Mechanism and Gear Library; abbreviated DMG-Lib, www.dmg-lib.org). The focus is on:

1. development and realization of powerful infrastructures including required tools for digitization, preparation, accumulation and suitable presentation of information,
2. the selection, collection and preservation of knowledge in the mechanical engineering field of mechanical motion systems which is available in heterogeneous sources (Fig. 2),
3. design of an internet-based, multilingual digital library for the mechanism and gear technology being the central information memory in motion technology.

Fig. 2 Insight into the variety of sources from which contents is integrated into the DMG-Lib

As a pioneer of Applied Kinematics Kurt Hain doubtlessly belongs to the most significant German researchers in the field of motion technology. He left behind a considerable lifework with his 13 books, approximately 380 academic writings, 176 gear models as well as several other writings and drawings which are nearly completely publicly available in digital form through the DMG-Lib project.

The following sections give an overview of the lifework of Kurt Hain at the DMG-Lib.

Hereby, based on findable general search results in the DMG-Lib with the term "Hain" different documents belonging to Kurt Hain are presented. The documents are sub-divided into personal description, literature, models, and interactive animations. For more information about the DMG-Lib project see [5].

General Search

Searching the DMG-Lib with the term "Hain" results in a list with 538 documents (Fig. 3). These include 522 works of primary and secondary literature, 55 model descriptions, 41 interactive animations (including “Hain” in their name) and a personal description as well. In addition, some documents are origins for access to further information and resources concerning “Hain”. For example, model descriptions are typically connected with interactive animations and videos to comprehend the kinematics of the described gear models in a better way.

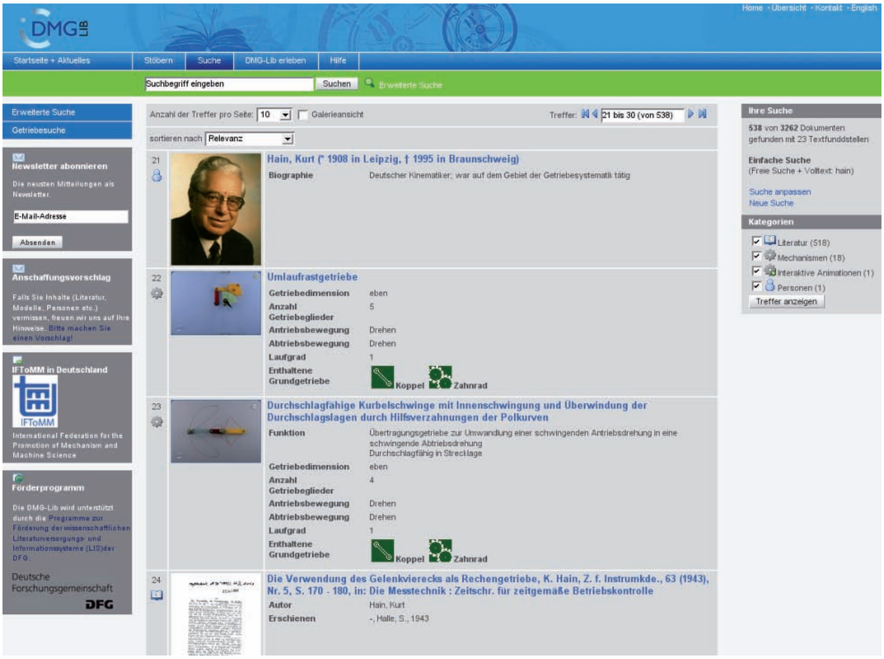

Fig. 3 A snapshot of the results by searching for the term “Hain”

Besides a simple search a differentiated or advanced search can be carried out. Here, the highlight is particularly the full text research in the total stock of works. Among other things this allows for the finding of sources or citations of Kurt Hain in works of other authors.

Personal Description

Personal descriptions with short biographies and tabular résumés take a central position at the DMG-Lib. Information about Kurt Hain is displayed in Fig. 4. Publications relating to persons as well as supplementary literature are added in chronological order to the personal descriptions. Based on this numerous works are accessible in full text.

Fig. 4 Snapshot about information concerning the person Kurt Hain

Literature

Kurt Hain is with his lifework momentarily the most frequently represented author in the DMG-Lib. His 508 visible works approximately correspond to half of all examinable and searchable works. According to Fig. 5 Hain had a very creative period particularly at the beginning of the 40s. Solely in 1944 he wrote more than 40 articles.

Even after the Second World War till his death in 1995 he continuously developed a considerable quantity of publications. Within these 50 years of his scientific work this corresponds to approximately 10 publications each year.

A large part of Kurt Hain's publications are scientific papers. This explains why the momentarily number of visible pages is not dominated by Hain's publications (Fig. 6). However, more than 5000 pages of Hain's lifework are reflected in his wishes to gather expertise in the field of motion technology as well as adjacent research areas and to convey it to his readership.

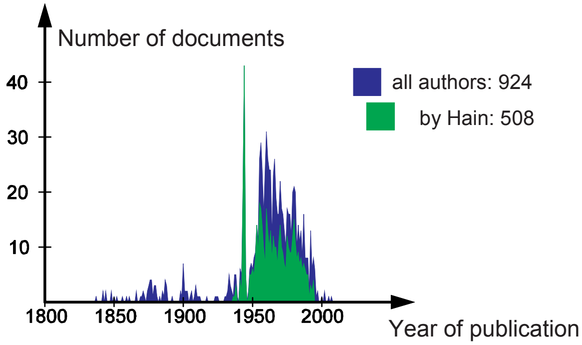

Fig. 5 Number of examinable works per year of publication at the portal (Status: March 2008)

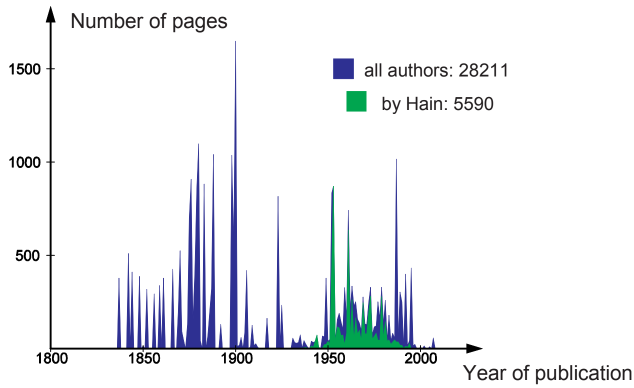

Fig. 6 Number of examinable pages per year of publication at the portal (Status: March 2008)

From the librarian point of view it should be noted that even documents that are not seen as publications in the narrower sense are publicly available through the DMG-Lib. This involves e.g. reviews, course material, unpublished manuscripts and handwritings.

A book viewer is available at the DMG-Lib-Portal for work with text documents. It combines usual standard features known from PDF displaying software as well as specific features adjusted to the needs inside the DMG-Lib.

Figure 7 shows one page of the Hain book “Getriebelehre: Grundlagen und Anwendungen” [6] as seen in the book viewer. This figure shows exemplarily the search results after terms starting with “Fadengeber” (English: thread take-up lever) for the viewed page as well as for the entire book.

An important DMG-Lib specific feature is to embed animations into book pages. It allows the reader e.g. to view the “Fadengebergetriebe” shown in Fig. 7 in motion (Fig. 8). The book “Getriebelehre: Grundlagen und Anwendungen” includes 62 embedded animations for a better understandability of kinematic properties. The used software for generation of embedded animations is MASP (Modeling and Analysis of Solution Principles, see [7, 8]).

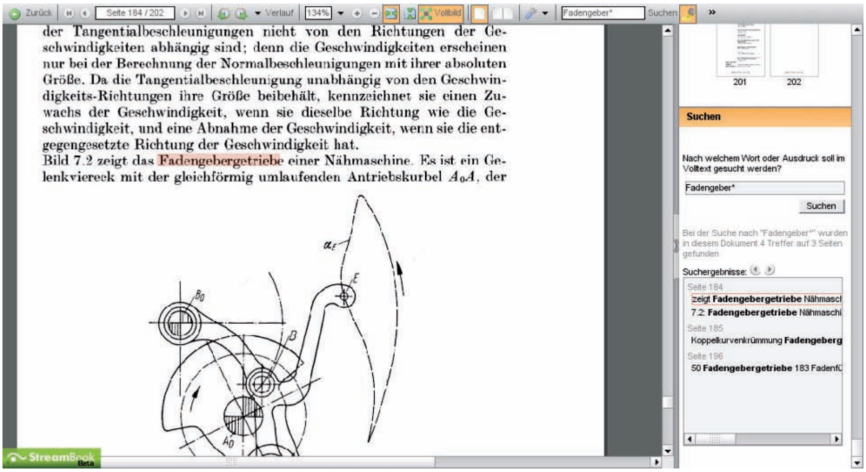

Fig. 7 Term search inside the book viewer with corresponding results

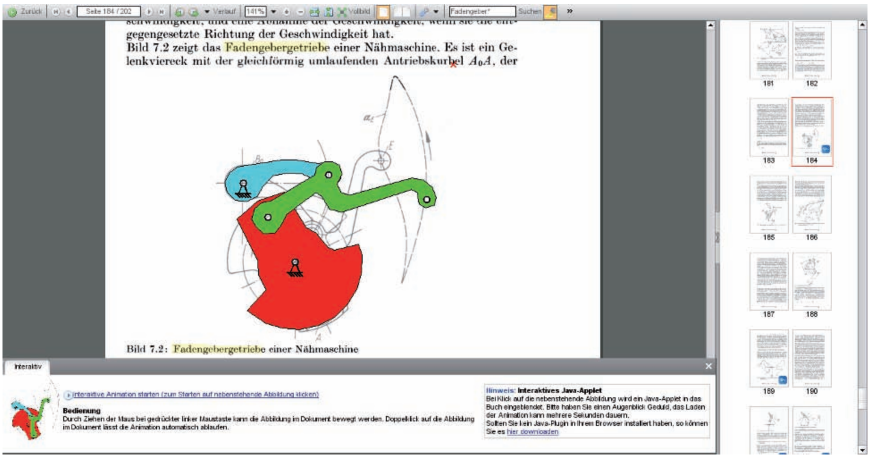

Fig. 8 Interactive illustration of a model inside a book

Models

Kurt Hain designed 176 display models in the course of his scientific work. Only 97 of them (among them 76 original models) exist as physical models (Figs. 9

and 10). At the DMG-Lib 61 of these Hain models among them are 11 of similar design are prepared as interactive animations for the public.

Fig. 9 Cabinet with Hain models at the TU Dresden

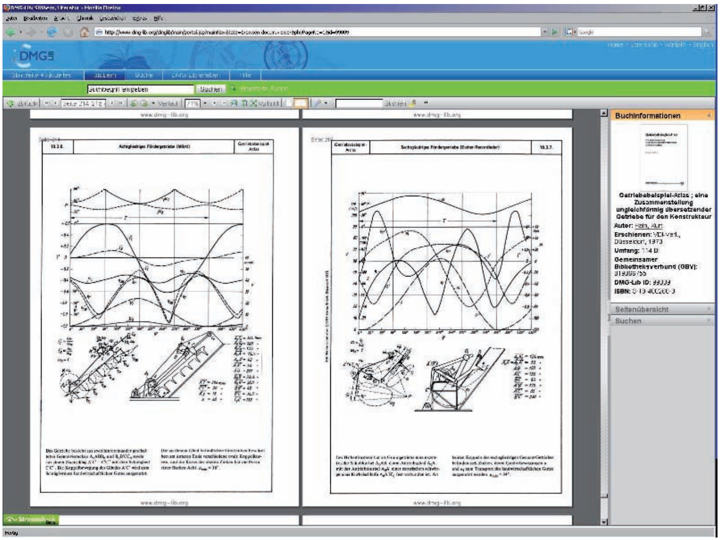

Fig. 10 Example from the mechanism atlas by Kurt Hain containing drafts of mechanism models

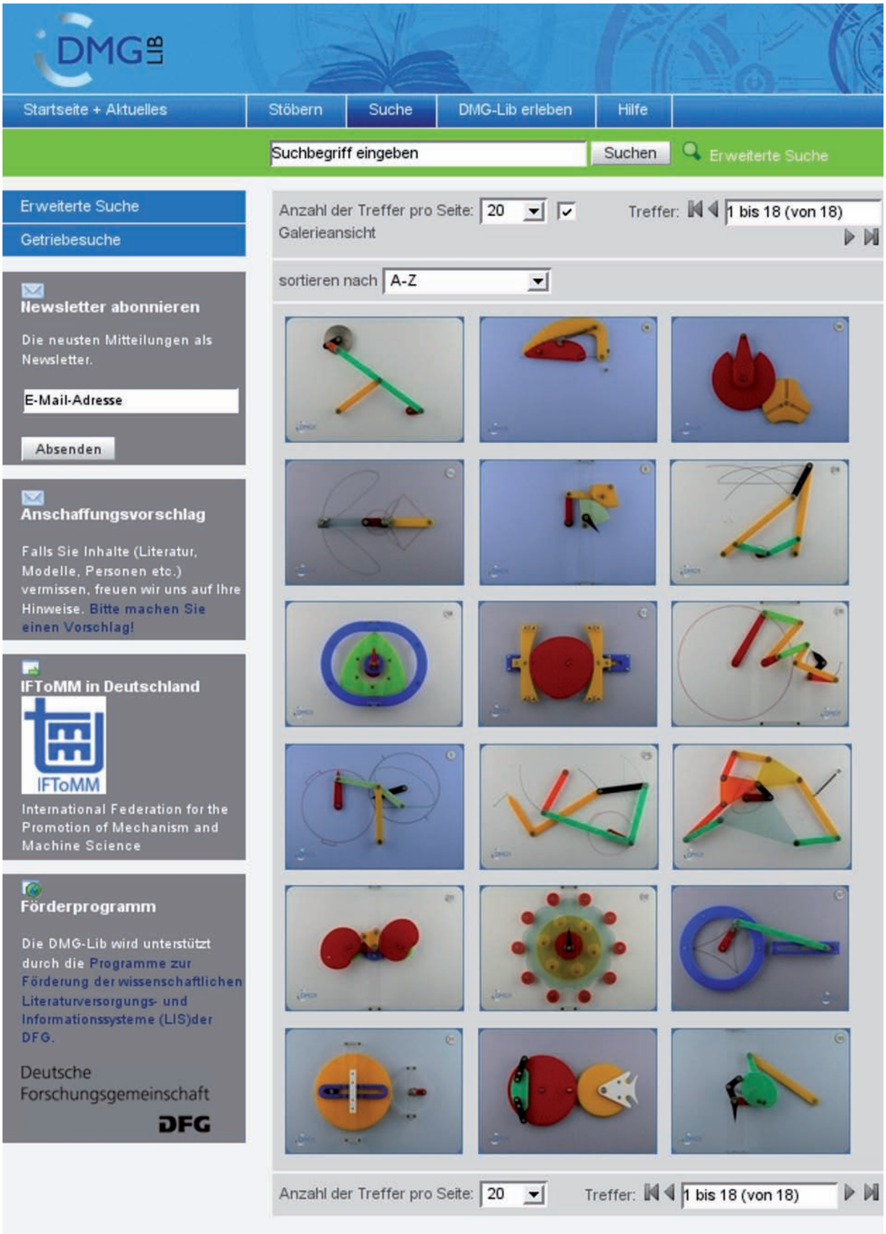

Fig. 11 Search results for Hain models in the gallery mode

Furthermore, 18 model descriptions of Hain models are placed at the disposal in the DMG-Lib portal. Figure 11 shows thumbnails of described models in a gallery mode to provide the user with an insight into the stock. The model description can be displayed by a click on the thumbnail which is shown in Fig. 12 for an eight-bar linkage (8-gliedriges Koppelgetriebe).

To describe a model currently 43 metadata are considered like formal (e.g. builder, location, used material), functional (e.g. type of the drive movement), structural (e.g. number of links, gear dimension), application related (e.g. use cases) and referring (e.g. further sources like interactive animations, figures, videos) attributes.

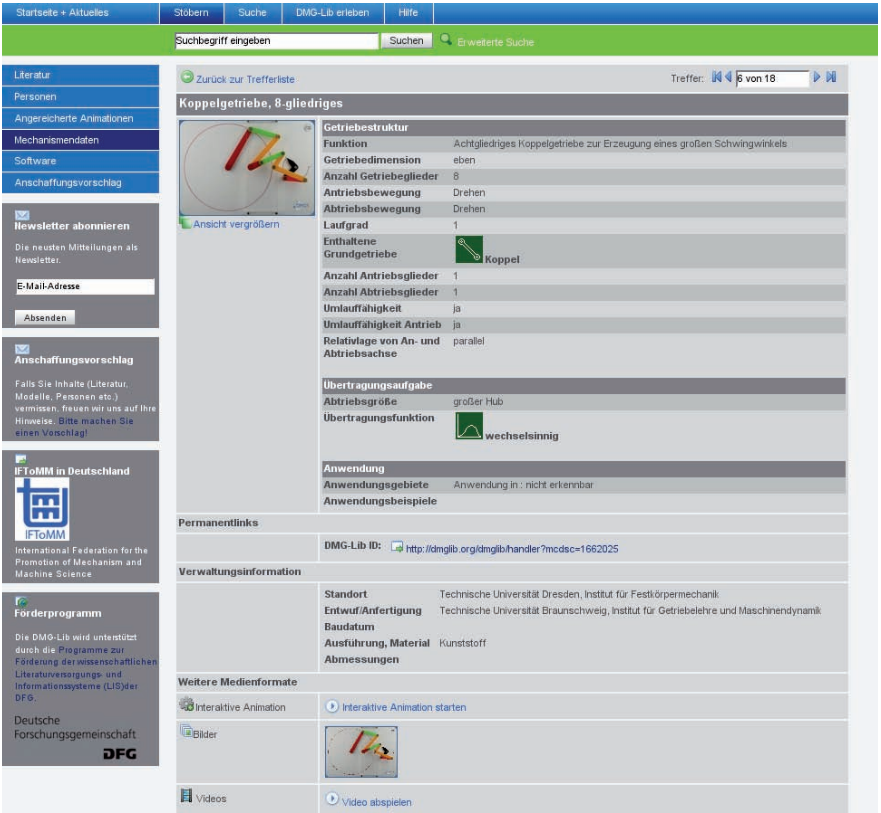

Fig. 12 Visible metadata for a model in the portal

Interactive Animations

Another DMG-Lib feature is the provision of interactive animations of selective gears and mechanisms (Fig. 13). Here, purpose-processed animations approve an interactive adjustment of the pictured mechanism or gear dependent on the position of the mouse cursor. This significantly improves the comprehension of the mechanism model functionality and hence the identification of common kinematic coherences. For the generation of interactive animations the software MASP is also used [7,8].

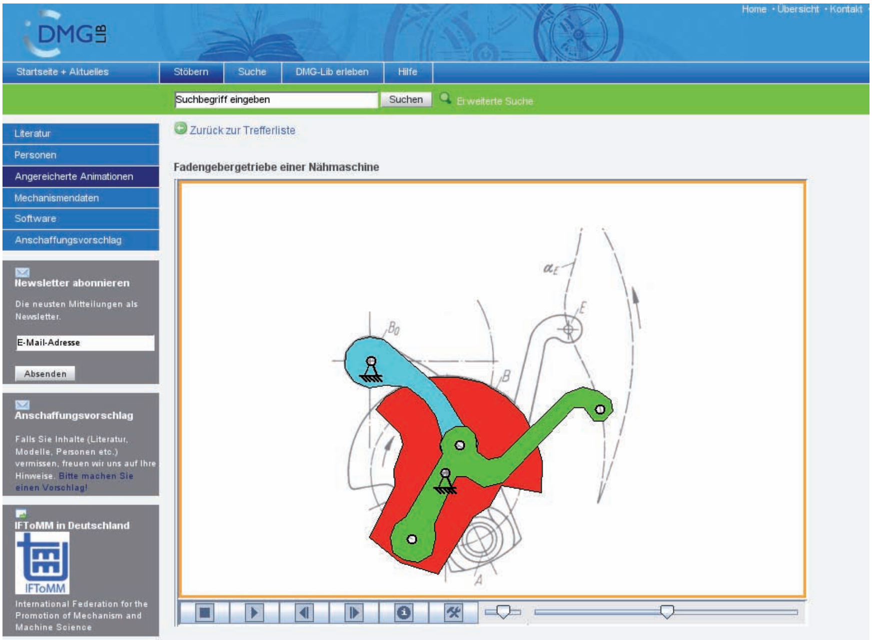

Fig. 13 Accumulated animation for a "Fadengebergetriebe" (thread take-up lever) from [6]

Source material for interactive animations can differ. The animation displayed in Fig. 13 is based on an engineering drawing. In contrast, the source material in Fig. 14 is taken from a sequence of 400 different mechanism positions that were recorded automatically. At this stage, more than 500 interactive animations are included in the DMG-Lib. More than 120 of them are based on figures or models of Kurt Hain.

Each interactive animation can be treated as a video allowing to use common video recorder features (play, stop, pause, speed control etc.). However, the quality of freeze-frames is in accordance to its original material better than conventional video material due to the avoidance of motional blur.
Another surplus yields the realization of metadata ( ), and the modification of viewer settings ( ), like e.g. the fade in and masking of background images or additional information.

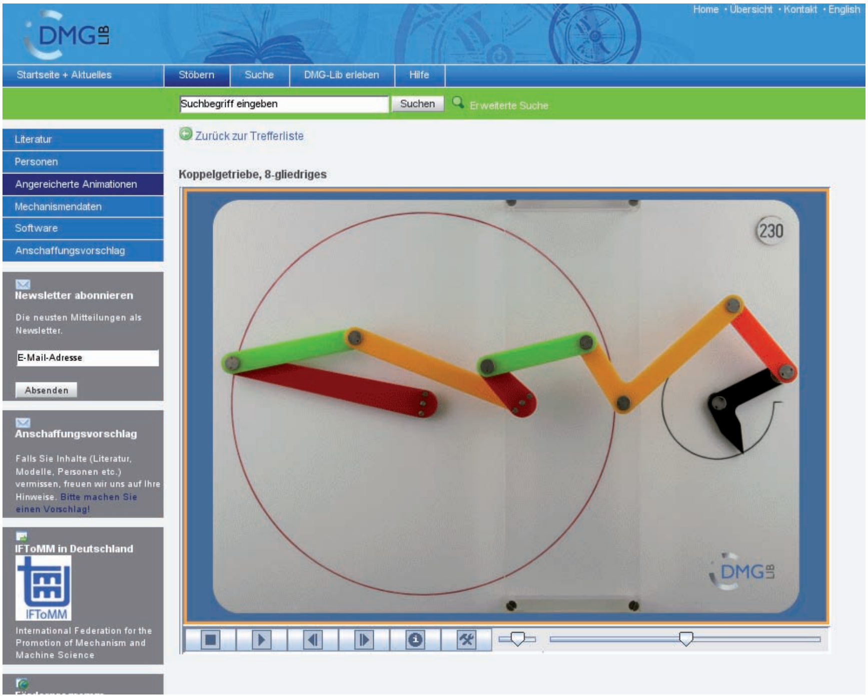

Fig. 14 Accumulated animation for an eight-bar linkage (8-gliedriges Koppelgetriebe)

Conclusions

Kurt Hain belongs to the pioneers of Applied Kinematics in Germany. He leaves a considerable lifework in nearly all fields of motion technology behind. By means of the DMG-Lib project the internet-based publication of his works is accomplished. The aim of the DMG-Lib project is to collect, save, systematize, and digitize the knowledge of gears and mechanisms and make it available in an appropriate and researchable way in the internet.

The way of the internet-based representation of contents provided by the DMG-Lib is demonstrated by taking the example of Kurt Hain's lifework. This is not only done by a targeted search for relevant text passages in full texts but also with the help of interactive animations for a better understanding of motion sequences, by the possibility of target-oriented gear retrieval or by links to continuing information (e.g. in life data and other works of authors of a specific work).

An extension of the DMG-Lib contents is aimed for in the future. Qualitatively new approaches for the retrieval and representation are intended alongside. The aim is to design a solution memory for motion systems (see [9]).

References

1. Kerle H, Brix T, Modler KH (2006) Presentation of the Lifework of Kurt Hain – Pioneer of Applied Kinematics in Germany, Proceedings of DETC´06, ASME, Design Engineering Technical Conferences and Computers and Information in Engineering Conference, Philadelphia (USA), September 10–13.
2. Kerle H (2007) Kurt Hain, Distinguished Figures in Mechanism and Machine Science – Part 1, Springer, pp. 183–215.
3. Hain K (1967) Applied Kinematics, McGraw-Hill, NY.
4. Ceccarelli M (2004) Evolution of TMM (Theory of Machines and Mechanisms) to MMS (Machine and Mechanism Science): An illustration survey", Keynote Lecture, 11th IFToMM World Congress in MMS, Vol. 1. pp. 13–24, Tianjin, China.
5. Brix T, Ulf Döring, Corves B, Modler KH (2007) DMG-Lib: The Digital Mechanism and Gear Library – Project, Proceedings of the 12th World Congress in MMS, IFToMM 2007, June 18–21, Besancon, France.
6. Hain K, Getriebelehre (1963) Grundlagen und Anwendungen: Getriebe-Analyse, Hanser, München. http://www.dmg-lib.org/dmglib/handler?docum=86009
7. Internet page for the download of MASP Free Edition: http://www.dmg-lib.org/dmglib/main/portal.jsp?mainNaviState=browsen.software.maspfreeed
8. Brix T, Reeßing M, Döring U (2005) Constraint-based Computational Kinematics, Intern. Workshop on Computational Kinematics, Cassino, Italy.
9. Döring U, Brix T, Reeßing M (2006) Application of Computational Kinematics in the Digital Mechanism and Gear Library DMG-Lib, Mechanism and Machine Theory, 41(8):1003–1015.

The Development of Machine Design as a Science from Classical Times to Modern Era

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Abstract Developments in natural philosophy and the scientific method in the 6th and 5th Centuries *BC* led to rapid development of engineering design in the 4th to 1st Centuries *BC* in the Greek and Hellenistic world, reaching maturity in the Roman Empire after the 2nd Century *AD* when Greek mathematical works started being translated into Latin. Design rules and concepts were practiced extensively by the engineers of ancient times leading to machine design from machine elements to the design of a machine as a system. Purely mechanical treatises on machinery go back to the 4th century *BC*. For the solution of mechanical problems and the design of equipment many basic scientific principles had to be explained at this time, and also trial and experimentation was established. The process of engineering design evolution from the 4th century *BC* up to modern era is discussed here.

Keywords Machine design, Origins of machine and mechanism designs

Introduction

The principles underlying design activity were investigated very early in history Dimarogonas. This process is confined with the machines and mechanisms which were designed in a systematic way and not arrived at empirically through a process of long evolution. This is a point that separates engineering science

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from technology and crafts. The first design theory was part of aesthetics, where aesthetic (beautiful) included also functional (useful) and ethical (the good) attributes. Function and ethical were inseparable from form. The philosophical foundation of knowledge, aesthetics and ethics are discussed in the works of Dimarogonas [11,12,14–16] in order to identify their implications in engineering design. After 2005 that the contents of the Archimedes Palimpsest were retrieved [43,44], new evidences for the influence of natural philosophy and the scientific method in the 6th and 5th Centuries BC in the development of engineering as a science in the 4th to 1st Centuries BC can be traced.

The Miletian (Ionian) philosophers in the cities of Ionia, the Greek-inhabited coast of Asia Minor, sought the principle of the universe in the concrete material substance that is perceivable by the senses [36]. The Ionian philosophers are also referred to as pre-Socratic philosophers [47], as much of their work was completed before the time of Socrates (469–399 BC). In the 6th century BC, Thales (620–546 BC), founded the Miletian School of natural philosophy and developed the scientific method to investigate the basic principles and the question of the originating substances of matter (Diogenes Laertius) [18,8,20,19,28]. Thales, Anaximander (ca. 610 BC) and Anaximenes (ca. 560–528 BC), developed their ideas about the Universe and the laws describing its behavior.

The later Ionians were Heraclitus (ca. 550–475 BC), Anaxogoras of Clazomenae, in the coast of Asia Minor, (500–428 BC), Empedocles of Acragas (in Sicily) (492–432 BC) and the Atomists Leucippus (5th century BC) and Democritus from Abdera (460–370 BC). Anaxagoras speculated that in the physical world everything contains a portion of everything else and Mind (Nous) is the initiating and governing principle of the cosmos [17,42,30].

Leucippus is regarded as the founder of atomic physics, and is reported to state that the atoms are always in motion [17,42,2]. Democritus expanded the atomic theory of Leucippus [17,23,42]. He maintained the impossibility of dividing things ad infinitum. From the difficulty of assigning a beginning of time, he argued the eternity of existing nature, of void space, and of motion. Epicurus borrowed the principal features of his philosophy from Democritus. Pythagoras of Samos (ca. 569–475 BC) made important developments in mathematics, astronomy, and the theory of music. The rigorous proof was introduced by Pythagoreans, based in deductive logic and mathematical symbolism. Experimentation was established as a method for scientific reasoning (Proclus Diadochos 410–485 AD).

Heraclitus of Ephesus (ca. 550–475 BC), was a contemporary of Pythagoras, Lao-Tzu, Confucius, and Siddhartha, the Buddha. He is best known for his doctrines that things are constantly changing (universal flux), that opposites coincide (unity of opposites), and that fire is the basic material of the world. Similar theories with those of Heraclitus concerning world views and philosophy were developed by Lao-Tzu in China without any known way of correspondence [37]. Heraclitus appears to have been the first to separate the study of motion itself from dynamics, the forces causing the motion, and introduced the principle of retribution, or change, in the motion of celestial bodies [46].

The Eleatic philosophy was founded by Xenophanes of Colophon who lived in various parts of the ancient Greek world during the late 6th and early 5th centuries

BC. Parmenides of Elea (515–450 BC), Zeno of Elea (490–420 BC), and Melissus of Samos (475–410 BC), apparently a student of Parmenides, are considered to be the Eleatic philosophers [9,47]. In the search for truth, the Eleatics, in contrast with the Ionian philosophers rejected any input from sensory experience. The Eleatics felt mathematics to be the method of arriving at the truth. They argued that the true knowledge of being can be discovered through reason, beyond the false impressions of the senses. Zeno, according to Aristotle was the inventor of "dialectic" and the so called "indirect proof". Aristotle reproduced Zeno's argument for the impossibility of motion in his Physics [31]. Empedocles, Anaxagoras, and Philolaus, tried to meet the same challenge, and did so in very different ways.

Although the Eleatic thinking was not perfect, important beginnings of logic were developed. Platon (429–347 BC) and Aristoteles (ca. 384–322 BC) formulated the Eleatic philosophy into a science that served as an instrument for the parallel development of the natural sciences, especially mathematics and physics [11,12].

The search for Reason led to the development of a generalized science as distinct from a set of unrelated empirical rules.

Aristotle's from Stagirus, Thrace (384–322 BC) at the age of 17 joined the Academy and studied under Plato. Later, he set up his own school, the Peripatetic school, at a place called the Lyceum [21]. In his definition of "substance" states that it is "the being which exists by itself and does not need anything else for its existence" yielding the ontological, Cartesian definition. This definition of substance considered both the Heraclitus philosophy, everything is changing, as well as the Eleatics philosophers' inquiry of truth through mathematics. Aristotle's works on natural science include Physics, which gives a vast amount of information on astronomy, meteorology, plants, and animals.

Xenocrates of Chalkedon (396–314 BC) was explicit about the division of philosophical topics implicit in Plato, into "physics", "ethics", and "logic"; this became the norm in Stoicism [21]. Strato (Straton) of Lampsacus (d. 269 BC) was the second successor of Aristotle in the Lyceum, following Aristotle's successor Theophrastus in about 286 BCE. Strato's origin was Lampsacus, a Greek city on the eastern side of the Hellespont in northern Troas (now part of Turkey). He was known in Latin as Strato Physicus. His extensive writings included a non-teleological reinterpretation of Aristotle's physics, which influenced Alexandrian philosophers such as Hero. Strato introduced an important kinematic criterion of equilibrium, the principle of virtual velocities. Strato's other theories included the notion space was porous, objects containing different amounts of the void (which accounted for differences in weight); he also corrected Aristotle's claim that bodies fall at a constant speed, noting that in fact they accelerate [3].

The subject of philosophy, as it is often conceived – a rigorous and systematic examination of ethical, political, metaphysical, and epistemological issues, armed with a distinctive method – can be called a Plato's invention. The most fundamental distinction in Platon's philosophy is between the many observable objects that appear beautiful (good, just, unified, equal, big) and the one object that is what beauty (goodness, justice, unity) really is, from which those many beautiful (good, just, unified, equal, big) things receive their names and their corresponding characteristics. Plato seems to have used Heraclitus' theory (as interpreted by Cratylus) as a model for the sensible world, as he used Parmenides' theory for the intelligible world. Both Plato and Aristotle viewed Heraclitus as violating the law of non-contradiction, and propounding an incoherent theory of knowledge based on a radical flux [22]. The philosophical inquiry developed in parallel with the establishment of the principles involving the initial steps of the mechanisms and machines design theory, from the 6th century BC, are discussed here in a chronological order.

The Origins of Machines and Mechanisms Design

Reuleaux [33] suggested as the earliest machine the twirling stick for starting fire and discussed further other early machinery such as water mills. The lever and the wedge are technology heritage from the paleolithic era. The first known written record of the word machine appears in Homer (ca. 800 BC) and Herodotus (ca. 484–425 BC), to describe political manipulation [14–16, 5]. The word was not used with its modern meaning until Aeschylus ca 450 BC used it to describe the theatrical device used extensively in the ancient Greek theatre as a stage device to lift actors, chariots or flying horses in the air, as though flying, portraying the descent of gods from the sky and similar purposes. The mechane is also known with the Latin term Deus Ex Machina. Mechanema (mechanism), in turn, as used by Aristophanes (448–385 BC), means "an assemblage of machines".

Purely mechanical treatises on machinery go back to the 4th century BC. One of Plato's contemporaries and friends and a student of Pythagoras, Archytas of Tarentum (ca. 400–365 BC), is said to have written the first systematic treatise on machines based on mathematical principles. This is lost. Archytas built an air-propelled flying wooden dove (Aulus Gellius, ca. 150 AD). Details about Archytas's dove are not known but it seems to be the first flying machine [15,16].

The simple pulley, used not to gain mechanical advantage but just to change the direction of pull, is first known from the 9th century BC and may well have been known to the Greeks before they began to build in megalithic masonry in the late seventh century BC. About 400 BC the Greeks had put to use compound pulleys. The earliest indisputable evidence for knowledge of compound pulley systems is referred in the Mechanical Problems attributed to Aristotle around 330 BC. Aristotle mentions gears, (wheel drives in windlasses). He said that the direction of rotation is reversed when one gear wheel drives another gear wheel. Philon of Byzantium (ca. 250 BC), a student of Ctesibios at the Museum was one of the first who used gears in water raising devices. Archimedes around 260 BC, used gears in various constructions and were well-known to the Alexandrian engineers.

The principles of statics and dynamics were discussed by Aristotle (ca. 384–322 BC) in Mechanica (Problems of Machines), the first extant treatise on the design of machines, probably written by one of Aristotle's students in Lyceum. Mechanica starts with the definition of machine, which in that era was synonymous with mechanism. In fact, mechanisms were the only machines known. Mechanica contains remarkable discussions of the mechanics of the lever, the balance, the wedge, rolling friction, the strength of beams, impact, mechanical advantage, and the difference between static and kinematic friction. Aristotle, further discusses several purely kinematic aspects of mechanisms. such as: the vectorial character of velocity, the superposition of velocities, and the parallelogram law for velocity addition, the concepts of absolute and relative velocity of points along a link of a machine. Strato (Straton) of Lampsacus (d. 269 BC) known in Latin as Strato Physicus the second successor of Aristotle in the Lyceum, following Aristotle's successor Theophrastus in about 286 BCE introduced an important kinematic criterion of equilibrium, the principle of virtual velocities [15,16].

Ctesibius (ca. 283–247 BC), was the designer of the precision water clock. He left many writings, which were subsequently lost, and only references to them by his students, notably Philo and Hero, are extant. Vitruvius (De Architectura) described the method used by Ctesibius to design a device for lifting a mirror for a barber shop. In fact this can be considered the first original mechanism that has been designed to order on the basis of engineering reasoning.

Archimedes (287–212 BC) contributed to knowledge concerning the five simple machines – winch, pulley, lever, wedge, and screw-known to antiquity, systematized their design and the study of their functions, and developed a rigorous theory of lever and the kinematics of the screw [6]. He invented the entire field of hydrostatics with the discovery of the Archimedes' Principle. Archimedes studied fluids at rest, hydrostatics, and it was nearly 2000 years before Daniel Bernoulli took the next step when he combined Archimedes' idea of pressure with Newton's laws of motion to develop the subject of fluid dynamics [10,39]. He provided a theoretical explanation of the pulley kinematics. The Antikythera mechanism was analyzed by Derek De Solla Price of Yale University [7], who concluded that it was an ancient planetarium in which the positions of the heavenly bodies were indicated by dials on the face of the device. The gearworks are about as complicated as those in a modern mechanical clock and represent the earliest physical evidence of an advanced metallic mechanism. Price gives evidence that this mechanism was in the Archimedean tradition and strongly suggests that Archimedes' planetarium was its forerunner.

Euclid's Elements, written about 300 BC, a comprehensive treatise on geometry, proportions, and the theory of numbers, is the most long-lived of all mathematical works. This elegant logical structure, formulated by Euclid based on a small number of self-evident axioms of the utmost simplicity, undoubtedly influenced the work of Archimedes ([36], Proclus). Archimedes introduced step-by-step logic combined with analysis and experiments in solving mechanical problems and the design of machines and mechanisms.

Philo of Byzantium (ca. 280–220 BC) also known as Philo Mechanicus (Engineer in Greek), was a student of Ctesibius at the Museum. Some fragments of an extensive treatise, Mechanike syntaxis (Compendium of Mechanics) exist. His treatise dealt among other things with the idea of machine elements, a small number of simple elements that constitute every machine. Different machines are constituted from different syntheses of these basic machine elements [26,27]. A section of Philo's Pneumatics which has so far has been regarded as a later Arabic interpolation, includes the first description of a water mill in history [24,48].

Hero of Alexandria born possibly in Alexandria, Egypt (ca. 10–70 AD) almost three centuries after Archimedes, expanded on his laws concerning levers. Heron wrote a number of important treatises on mechanics. They give methods of lifting heavy weights and describe simple mechanical machines. Heron separated the study of particular machines and the general concepts of machines from the study of standardized elements. He introduced five simple mechanical elements for the solution of the general problem of moving a weight with a given force: wheel and axle, lever, windlass, wedge, and screw. Heron's Mechanica is based quite closely on ideas due to Archimedes. Mechanica gave the first systematic development of design solutions to a given mechanism problem. Heron has developed a great number of automata, including vending machines. It is to be noted that these devices were original designs employing advanced principles such as feedback control and not devices made on the basis of long evolution of a craft. There are, rather remarkably, descriptions of over 100 machines such as a fire engine, a wind organ, a coin-operated machine, and a steam-powered engine called an aeolipile, Heron's aeolipile, which has much in common with a jet engine [26,27].

The Greeks from Syracuse developed the first catapults, as a result of engineering research financed by the tyrant Dionysius the Elder of Syracuse in the fourth century BC. To mechanize the archer's motions the catapult engineers incorporated a number of appropriate design features [38,12,13,6]. One of the crucial steps in designing the torsion springs was establishing a ratio between the diameter and the length of the cylindrical bundle of elastic cords. This optimization of the cord bundle yielding a complex stone-thrower formula was completed by roughly 270 BC, perhaps by the group of Greek engineers working for the Ptolemaic dynasty in Egypt, Thera and at Rhodes. Philo of Byzantium, Archimedes of Syracuse and Hero of Alexandria, were famous for their work on catapults. Most of the group of the solvers of the cube-root problem had either a direct or an indirect connection with catapults. Pappus of Alexandria (290–350 AD [29]), the last of the great Greek geometers wrote commentaries on Euclid's Elements and Ptolemy's Almagest. In his treatise Mathematical Collection, discusses the study of mechanics "examining bodies at rest, their natural tendency, and their locomotion in general, not only assigning causes of natural motion".

Commentators on the classics flourished in Rome. They not only preserved most of the classical culture but made substantial advances of their own. Vitruvius ten books De Archetecture (on Architecture) contained important material on the history of technology and on the design of machinery. Vitruvius defined a machine as "a combination of timbers fastened together, chiefly efficacious in moving great weights". Vitruvius studied Greek philosophy and science and gained experience in the course of professional work.

The diffusion of Roman culture into highly religious medieval Europe shifted the emphasis to the practical needs of worshipping God. The influence of the works of the pioneers of science and engineering in classical times in medieval and the early modern era was due mainly to Latin and Greek–Latin versions handwritten, and then printed from the 13th to the 17th centuries. Design methodology returned to the level of a craft, and no noticeable advancements were recorded until the time of Leonardo da Vinci (1452–1519). The early modern era is highlighted by the works of Galileo (1564–1642) and Newton (1642–1727) and includes the early stages of mechanization and the Industrial Revolution. The subjects of Mechanical Engineering have attracted more and more interest since early Renaissance both for practical applications and from a theoretical viewpoint in response to an increase of societal needs. Le Mecaniche is considered as a minor work of Galilei's since it is regarded as a preliminary step in the development of the masterpieces of Galilei in the field of experimental mechanics. In Le Mecaniche, Galilei approaches the analysis of fundamental machines for lifting weights, namely lever ('lieva'), capstan ('argano'), pulleys ('taglie'), and screw ('vite').

Newton, further, was the first to place dynamics on a satisfactory basis, and from dynamics he deduced the theory of statics: this was in the introduction to the Principia published in 1687 [34]. Design of machines and mechanisms in modern times were established in 1794 when The E cole Polytechnique in Paris established the separate study of kinematics from the study of machinery. Releaux in 1875 published Theoretische Kinematik on an attempt to systematize and classify a great number of different machines and mechanisms, a "mechanical alphabet" [15,16].

The contribution of Leonardo Da Vinci, Galilei and Newton, the redefinition of classical physics and mechanics, the separation of the study of kinematics and the study of machinery in the 18th century, the early mechanization and the progress during the Industrial Revolution yielded the development of engineering design as a systematic process in modern era. Various methods by which the different approaches and requirements of engineering design can be synthesized and evaluated appeared: mathematical analysis, computer modeling and simulation, experimental prototyping and testing, and extrapolating information from past experience [15,16].

Conclusions

Beginnings of logic were developed by Plato and Aristoteles into a science and served as an instrument for the parallel development of the natural sciences, especially mathematics and physics, by such pioneers as Pythagoras, Heraclitus, Euclid and Archimedes. The search for Reason in classical times led to the development of a generalized science as distinct from a set of unrelated empirical rules. Rigorous proof was introduced, based in deductive logic and mathematical symbolism. Experimentation was established as a method for scientific reasoning. Kinematics and machine design have a distinct place in the history of engineering because they comprised a rational step-by-step logic to receive further a mathematical foundation.

Developments in natural philosophy and the scientific method in the 6th and 5th Centuries BC led to rapid development of engineering design in the 4th to 1st Centuries BC in the Greek and Hellenistic world, reaching maturity in the Roman Empire after the 2nd Century AD when Greek mathematical works started being translated into Latin. Design rules and concepts were practiced extensively by the engineers of ancient times leading to machine design from machine elements to the design of a machine as a system. Purely mechanical treatises on machinery go back to the 4th century BC. Abstract reasoning based on mathematical analysis and engineering science, distinguished from mere empiricism, formed the basis for engineering design as a science using mathematics and reason.

References

(References are listed also for further reading, without citing them in the text).

1. Archimedes A (2002) The Works of Archimedes, Vols. 1–6, Kaktos Publications, Athens. (in Greek)
2. Berryman S (2004) Leucippus Stanford Encyclopedia of Philosophy, Metaphysics Research Lab, CSLI, Stanford University.
3. Blackburn S (1996) Oxford Dictionary of Philosophy, Oxford University Press, Oxford.
4. Ceccarelli M (2006) Early TMM in Le Mecaniche by Galileo Galilei in 1593, Mechanism and Machine Theory, Vol., 41, pp. 1401–1406.
5. Chondros TG (2004) Deus-Ex-Machina, Reconstruction and Dynamics, International Symposium on History of Machines and Mechanisms, Proceedings HMM2004, Edited by Marco Ceccarelli, Kluwer Academic Publishers, Dordrecht, pp 87–104.
6. Chondros TG (2007) Archimedes (287–212 BC) History of Mechanism and Machine Science 1, Distinguished Figures in Mechanism and Machine Science, Their Contributions and Legacies, Part 1. Edited by Marco Ceccarelli, University of Cassino, Italy, Springer, Netherlands.
7. De Solla Price D (1975) Gears from the Greeks, The Antikythera Mechanism-A Calendar Computer from ca. 80 BC. Science History Publications, NY.
8. Diels H, Kranz W (1951) Die Fragmente der Vorsokratiker, 6th ed. Berlin.
9. Diels, Kranz (1952)
10. Dijksterhuis (1987)
11. Dimarogonas AD (1991) The Origins of the Theory of Machines and Mechanisms. Proceedings 40 Years of Modern Kinematics: A Tribute to Ferdinand Freudenstein Conference. Minneapolis, MI.
12. Dimarogonas AD (1993) The Origins of Engineering Design. In: ASME Design Engineering Conferences, Albuquerque NM, Vibrations of Mechanical Systems and the History of Mechanical Design, DE-Vol. 63, pp. 1–18.
13. Dimarogonas (1995)
14. Dimarogonas AD (1997) Journal of Integrated Design and Process Science, 1 54–75, Philosophical Issues in Engineering Design.
15. Dimarogonas AD (2001) Machine Design A CAD Approach, John Wiley and Sons, NY.
16. Dimarogonas AD (2001) History of Technology, Macedonian Publications, Athens. (in Greek)
17. Diogenes L (1925) Lives of Eminent Philosophers, tr. R.D. Hicks (Loeb Classical Library: Cambridge MA), Book 9. 30–33.
18. G1adett P (1955) Greek Science in Antiquity, Aberland-Schuman, Inc., NY.

19. Graham DW (2006) Anaximenes, The Internet Encyclopedia of Philosophy.
20. Guthrie WKC (1962) A History of Greek Philosophy, Vol. 1, Cambridge U. Pr. Cambridge, pp. 115–140.
21. Hicks RD (1925) Diogenes Laertius: Lives of Eminent Philosophers, 2 vols. Harvard University Press, Cambridge, MA; William Heinemann Ltd, Loeb Classical Library, London (Greek with facing English translation).
22. Kahn CH (1979) The Art and Thought of Heraclitus, Cambridge University Press, Cambridge.
23. Kirk GS, Raven JE, Schofield M (1957) The Presocratic Philosophers, 2nd ed., Cambridge University Press, Cambridge.
24. Lewis (1997)
25. Netz R (2004) The Works of Archimedes, Cambridge University Press, UK.
26. O'Connor J, Robertson EF (2006) Archimedes, MacTutor History of Mathematics archive, University of St Andrews, School of Mathematics and Statistics, Fife, Scotland.
27. O'Connor J, Robertson EF (2006) Philo of Byzantium, MacTutor History of Mathematics archive, University of St Andrews, School of Mathematics and Statistics, Fife, Scotland.
28. O'Grady (2006)
29. Pappus of Alexandria. (Fourth century AD)
30. Patzia M (2007) Anaxagoras, The Internet Encyclopedia of Philosophy.
31. Preus (2001)
32. Proclus D (1970) A Commentary on the First Book of Euclid's Elements, Translated with an Introduction and Notes by Glenn R Morrow. Princeton University Press, Princeton.
33. Reuleaux F (1872) Der Konstructeur, J. Vieweg, Braunschweig.
34. Rouse Ball WW (1908) A Short Account of the History of Mathematics, 4th Ed., Dorer, Newyork.
35. Saccheri's Girolamo (1986) Euclides Vindicatus, Chelsea Publishing Company, NY.
36. Schofield (1997)
37. Sih G (2004) Opening Address xiv–xv. Multiscaling in Applied Science and Emerging Technology, Fundamentals and Applications in Mesomechanics, Proceedings of the Sixth International Conference for Mesomechanics, Patras, Greece, Edited by G.C. Sih, T.B. Kermanidis, S.G. Pantelakis.
38. Soedel W, Foley V (1979) Ancient Catapults, Scientific American, 240, 120–128, 150–160.
39. Stamatis E (1973) Archimedes–Apanta, Vols. 1–3, Technical Chamber of Greece, Athens. (in Greek)
40. Stamatis ES (1981) Pythagoras of Samos Technical Chamber of Greece, Athens. (in Greek)
41. Taylor CCW (1997) Anaxagoras and the Atomists, From the Beginning to Plato: Routledge History of Philosophy, Vol. I. Ed. C.C.W. Taylor. New York, NY: Routledge, 208–243.
42. Taylor CCW (1999) The Atomists: Leucippus and Democritus. Fragments, A Text and Translation with Commentary, Toronto.
43. The Archimedes Palimpsest (2005) (www.archimedespalimpsest.org)

44. The history of the Archimedes Palimpsest, at the website of the Walters Art Gallery, http://www.thewalters.org/archimedes
45. Vitruvius MP, 1st Century AD, De Architectura (On Architecture) BOOKS I–V Loeb Classical Library, Translator Frank Granger.
46. Vlastos G (1955) On Heraclitus, American Journal of Philology, 76, 337–378, Stanford Encyclopedia of Philosophy, Metaphysics Research Lab, CSLI, Stanford University.
47. Warren J (2007) Presocratics: Natural Philosophers Before Socrates, University of California Press, Berkeley.
48. Wilson (2002)

The Evolution and Development of Mechanical Engineering Through Large Cultural Areas

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Abstract Mechanical Engineering is probably the forerunner of many branches of Engineering and has persistently been their companion up to the present. For this reason, the History of Machines embraces a very broad period of the History of Mankind, and can be studied from many perspectives. This paper attempts to link progress in Mechanical Engineering to the great cultures that have arisen throughout the History of Mankind.

This paper begins with the anonymous mechanical developments that appeared in Prehistory and opened up the way to the first civilisations, marked to a large extent, maybe, by Greco-Roman culture in Europe and by China in Asia. After them came the Islamic world, which, in the Middle Ages stimulated society to find new mechanical devices and set the foundations that would lead to the Renaissance.

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Outstanding in this period was the expansion of Italian, French and German creative and innovative thinking with its “Treatises on Machines”, which, for a short time, coincided with the advance of the Iberian Empire and the development of machinery for the New World. Finally, the Industrial Revolution became the climax of all previous developments and a period of rapid mechanical evolution began that was to be highly interesting from a historical and technological point of view. This was accompanied by a parallel interest in reflecting on and analysing machines, which has led to the appearance of countless “Treatises on Machines”.

Keywords History, Machine, Treatise on machines, Cultural area

Introduction

The History of Mankind is also the History of Technology. Any culture moves forward at a rhythm imposed by its technology. Scientific knowledge itself requires a pre-existing technological substratum in order to move forward. Political and military affairs are also underpinned by technological development. Economic history goes hand in hand with the technological development, products and transport that make trade possible. On both a large and small scale, Engineering takes advantage of the existing technology of every period and makes it tangible. Engineering makes technological knowledge a reality and places it at the service of society by creating useful objects.

Mechanical Engineering is, together with Architecture, Civil and Military Engineering, the forerunner of newer types of engineering, which means the History of Machines embraces a very extensive period of the History of Mankind, all of which makes compiling a Machine Compendium extremely difficult. An eight section framework has been chosen, each section of which more or less corresponds to historical periods focused on large cultural areas; this inevitably leads to time overlaps. Each period receives a cultural inheritance from the previous ones and each culture receives cultural influences from other cultural areas, but the overall result is a compendium that presents a reasonably coherent sketch of the global development of the human race. This point of view has been dealt with in the book entitled “A Brief Illustrated History of Machines” [1] published by the authors, where the contents and chapters are set out in this paper are dealt with in more detail.

In general, a whole range of Prehistoric devices exist under the chapter name of “Anonymous Developments”, whose inventors, for many reasons, are unknown to us. The Neolithic revolution also has a part in the anonymous development of machinery.

Looking at historical epochs, the great Mesopotamian river cultures, of southeast Asia or the Chinese plains, developed mechanical devices after they had discovered the written word. The Chinese cultural area that spread from the Ancient

World to the beginning of Modern Times has been chosen in order to describe "Chinese Inventions and Machines".

Likewise, Greco-Roman culture is of particular relevance for "Mechanical Engineering in Antiquity". Latin and Greek have always been accessible languages for western European peoples, for which reason most references to Middle Eastern and North African cultures originate from Greek and Roman authors, who lived in, and came into direct contact with extensive cultural zones of the ancient world. The influence of this ancient world reached out to the Middle Ages passing through Byzantium and Islam and penetrated the Renaissance with the study of authors such as Vitruvius.

So the way was opened up for "Medieval Machines and Mechanisms" where Arab authors were outstanding, since Islam spread to the confines of the known world during the Middle Ages, and Arabic became the vehicle of culture in its area of influence.

The title, "The Machine Renaissance" refers to the tremendous impulse given, mainly from Italy, to all spheres of knowledge and also to the study of machines. Thus a considerable technological difference began to be marked between European culture and other cultures, which has lasted up to present times.

Additionally the technological impulse of the Renaissance led firstly to the great geographical discoveries and then to the founding of the European colonial empires that spread to large parts of the world. Very soon after, the "Machines in the First Colonial Empires" took advantage of the technological achievements of the Renaissance in order to exploit the resources at their disposal.

European political policy boosted industrial development by creating new ever more science-based technologies. The abundant "Machinery of the Industrial Revolution" reflects the achievements attained in this period. Technology was the travelling companion of political hegemony.

Recent history, particularly that referring to machines, has been considered to be sufficiently known, and therefore lacking in the "historical" interest that remote periods might have. On the other hand, the increasing speed at which technology is developing would make any systematic processing of the present-day period difficult and certainly ephemeral.

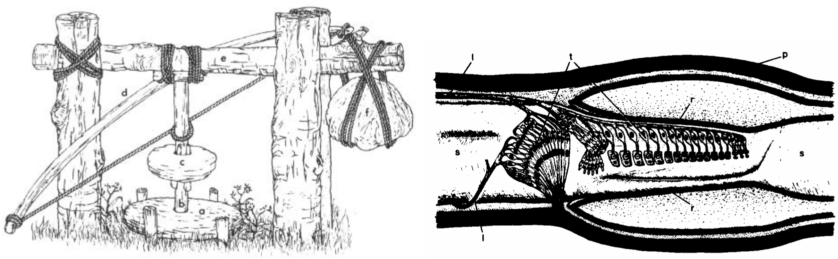
However, after the Industrial Revolution, an unusual event took place in Europe that marked a difference in respect of what happened in other cultures: "A Reflection on Machines" mainly led by the French enlightenment whose influence at the time spread to all European countries. These Reflections obviously had roots in the past, mainly in the Renaissance, and gave rise to systematisations for ever more mathematically-based personal machine study, which resulted in this material being included in higher study programmes. We are of the opinion that this qualitative leap deserved a separate chapter.

Anonymous Developments

No matter how far back in time we go, there is a considerable number of machines and mechanisms that are common cultural heritage. These study of ancestral developments is relate to two basic areas: Archaeology and Biology.

Archaeology has enabled the mechanisms used since Prehistory to be discovered through an exhaustive analysis of the remains from sites. These remains are not usually one object but an ordered set of parts, which gives rise to different theories and interpretations resulting from the innumerable studies carried out. Moreover, it is unusual for any archaeological remains to be found intact, which means that an adequate interpretation of many of them is difficult, particularly as the concept of a machine is linked to the relative motion of the various constitutive parts. Although current Archaeology lends more importance to the context of a site than to the object in isolation, there continues to be an intrinsic difficulty in recognising various scattered, incomplete parts as being the parts of a mechanism. The examples of machine development resulting from collective, popular resourcefulness in prehistoric times are innumerable. Figure 1 a shows a prehistoric drill, compiled by Strandh in 1998 [2].

As for the biological axis, it may be said that the most important development of anonymous mechanisms was based on biological shapes, as highly effective mechanisms can be found in both plants and animals. Their variety, complexity and evolution are also irrefutable evidence of mechanical design that induces us to include these "biological mechanisms" in the History of Machines. Figure 1 b shows the hearing "mechanism" of a grasshopper, depicted by Hass in 1979 [3].



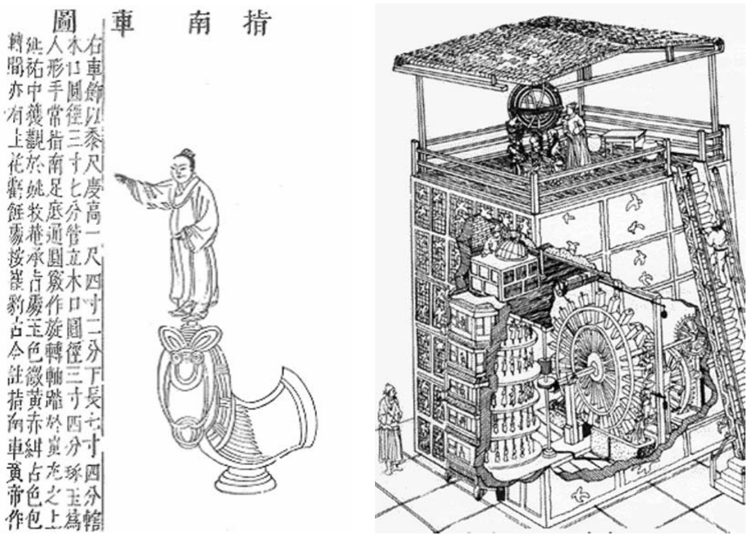
a) b)

Fig. 1 (**a**) Bow drilling machine. Reconstruction from "Machines, an Illustrated History" by Sigvard Strandh; (**b**) Ear in a grasshopper's front leg, from "From Fish to Man" by H. Hass

Chinese Inventions and Machines

Ideographic writing and a concern for calligraphy has been successful in revealing that Chinese technology had surprisingly evolved, on many occasions, beyond what was to be found in Europe up to the 16th century. Extremely ancient documents like the “Kao Gong Ji” (“Book of Diverse Arts”, 770–221 BC), reveal a concern for the development of science in all its forms: Astronomy, Biology, Mathematics, Physics and Engineering.

Numerous written examples followed this work: compendiums on war machines, agricultural and hydraulic machines, textile machinery, clocks and automatons follow one another through countless pages of diagrams and explanations. Two excellent examples of this technological progress are shown in Fig. 2: “the south pointing chariot”, a series of gears and gear wheels that always kept the figure’s finger pointing south, which dates from 2600 to 1100 BC and Su Song’s astronomical clock built in 1089, which, with its more than four hundred parts was undoubtedly a technological wonder. Additional examples can be found in the book “Qi Qi tu Shou” by Schreck and Wang Cheng which includes copies, sketches and improvements of machines from the European Renaissance.



a) b)

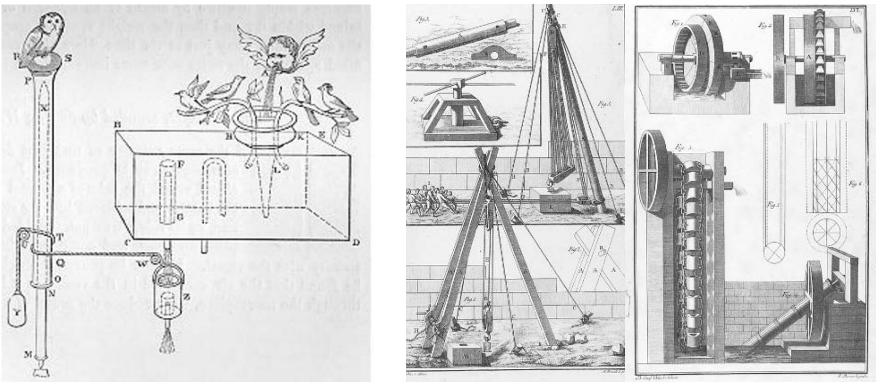
Fig. 2 (**a**) Drawing of the “south pointing chariot” from the “San Tshai Thu Hui” [4] by Wang Chhi, 1609; (**b**) Su Song’s astronomical clock from the “History of the Sung Dynasty” [5] by Shen Yueh, 500 AD

Mechanical Engineering in Antiquity

Some documents, artistic representations, and even humanistic literature reveal the existence of numerous automatic mechanisms during Antiquity, although most of them not been preserved, The Greco-Roman world adopted a large part of the technology developed by previous cultures such as the Egyptian civilisation.

Greece attained a high level in technical fields, one of the most outstanding examples being the School of Alexandria (from the 3rd century BC), where celebrities as famous as Archimedes, Euclid, Philo (Fig 3a) and Hero received their training. Some historians consider the latter to be the first real engineer because of his detailed and precise diagrams and explanations. His work entitled “Pneumatics” [6] brings together a series of automatic machines that were studied not only during his time, but subsequently rediscovered and used during the Renaissance.

The evolution of Greek culture had a determining influence on Roman technology. Its technology became more in-depth and wider-ranging with a study of different fields like public works and military applications. The most remarkable figure of this period was undoubtedly Vitruvius (80–70 BC.–25 BC.) with his “De Architectura” [7], a work containing his knowledge on architecture, including explanations and drawings of the machines used for this craft. This book was reproduced during Renaissance by authors like Daniele Barbaro and many others. Figure 3b shows a later representation by J. de Ortiz y Sanz from 1787 [8].



a) b)

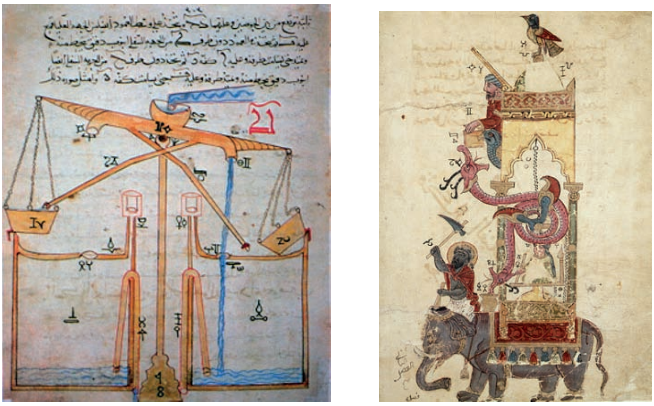
Fig. 3 (**a**) Hero’s “Singing birds” from Bennet Woodcroft’s translation of “Pneumatics”[6], 1851; (**b**) Reconstruction of machines for raising water and loads from Vitruvius’ book, by J. Ortiz y Sanz [8], 1787

Medieval Machines and Mechanisms

Islam spread to the confines of the known world during the Middle Ages and Arabic became the vehicle of culture in its area of influence. The “House of Wisdom”, founded in Baghdad (9th century), contributes to the apparition of the book entitled “Ingenious Devices” [9] written by the three Banu Musa brothers, whose pages contain the diagrams of one hundred machines and mechanisms. Some machines were copies of those produced by Hero and Philo but many others were improvements of these or new models.

Following in their footsteps came the most significant name in Islamic technology: Al-Jazari (1136–1206). His “Book of Knowledge of Ingenious Mechanical Devices” [10, 11] shows fountains, clocks, water wheels and automatons with a precision of detail in both drawings and explanations that had been unknown up to that time. His machines reveal an increasing complexity that turned out to be not only useful but also of spectacular appearance, as was the case of the elephant clock that combines mechanical engineering and design in equal parts. Figure 4 presents two examples of machines from the cited Al-Jazari’s book.

Although it was the Islamic world that most disseminated its knowledge, Europe was moving slowly forward along the road to the Renaissance. Walking this road was Villard de Honnecourt, who, in the 13th century, produced a notebook [12] where he drew the machines and mechanisms he had seen on his travels, such as catapults, saws and lifting devices.



a) b)

Fig. 4 (**a**) Fountain; (**b**) Elephant clock. Both from the book written by Al-Jazari

The Machine Renaissance

The Re-birth of Western Europe in the14th, 15th and 16th centuries marked a stage of renewed activity and vitality on a level of arts, sciences and literature, as it was sought to leave behind the stagnation of the Middle Ages. Unlike what happened in the Middle Ages, the opening up of Renaissance society paved the way to the spread of machines.

The 15th century can be taken as the high period of machine development, with celebrities like Leonardo da Vinci [13, 14] and Francesco Di Giorgio [15], whose success was partly due to an environment that was open to their creativity and new ideas. Parallel to this an interest in the theoretical aspects of machines led to a recovery of the knowledge of Antiquity with the study of authors from the Greek and Roman culture.

The publication of knowledge in the form of treatises began at the end of the 15th century. A first line of activity was the study of machine mechanics as an application of physics, by well-known figures such as Guidobaldo del Monte [16, 17] and Galileo Galilei [18]. The second line consisted of a development towards a discipline in the shape of a rational collection of machines, outstanding of which were the machine collections of the aforementioned Francesco Di Giorgio and Agostino Ramelli.

The Machine Renaissance, from Italy, spread throughout Western Europe from the second half of the 15th century with outstanding works such as Georgius Agricola's "De Re Metallica" [19] and Jacobus Strada's "Kunstliche Abris allerhand Wasser" [20]. Figure 5 shows the title pages of some relevant "Machine Treatises".

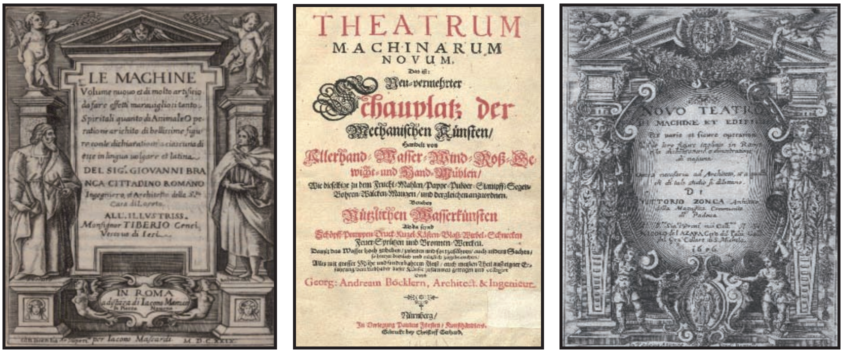


Fig. 5 Title pages of some "Machine Treatises" [21–23]

The printing press was a decisive factor in the dissemination of these treatises. Not only the text but also the accompanying illustrations attained a quality hitherto unknown in the previous books on machines that had been painstakingly copied by scribes. Although some significant treatises have survived to the present in the form of manuscripts, most authors published printed books whose readers no longer needed to belong to the privileged classes. Machine knowledge became popular and spread on a qualitatively different scale from previous periods.

Machines in the First Colonial Empires

For various known historical reasons, in Modern Times Europe set out on a process of expanding its political and cultural influence over large geographical areas, founding European colonial empires that have endured to the present. In this sense, Castile and Portugal had overtaken all other European nations from the end of the 15th century, which meant that the first colonial empires were basically Iberian.

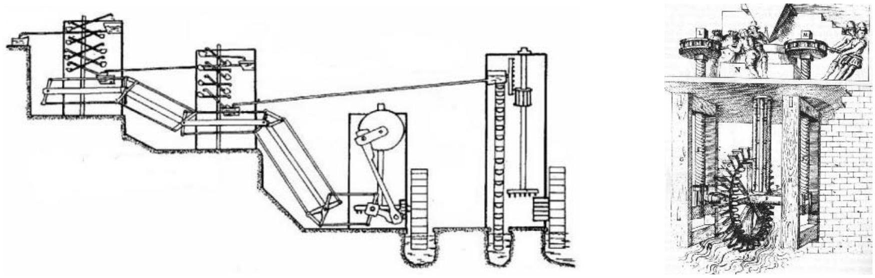
Going round the world was a feat requiring mechanical engineering, but keeping the new spice trade routes open meant that engineering was here to stay. The overseas mineral resources needed new machinery to exploit them. All this gave rise to specific centres for the study of science and technology, which facilitated this global geographic expansion.

Further clear proof of the strategic interest in mechanical engineering was the publication of Juanelo's "The Twenty-One Books of Devices and Machines" [24], ordered written by "the Catholic King Philip II, King of Spain and the New World", in about 1570. Among other knowledge, the book contains a large number of machines of the time ordered according to function with a surprising number of pumps, mills, cranes and other machines, particularly those driven by water, wind-energy, gravity or animal traction.

Considered to be a machine encyclopaedia by many historians, the author of this work is unknown. Since Juanelo Turriano was famous at the time for being the inventor of a well-known device in Toledo for raising water called "the dancing machine" (Fig. 6a), it was initially attributed to him. However, later studies have shown that it might have been by Pedro Juan de Lastanosa [25].

Other outstanding figures were Jerónimo de Ayanz y Beaumont [26], who was awarded a patent in 1606 for over fifty devices and Francisco Lobato [27], who, in less than forty pages made notes on technology from 1547 to 1585.

Figure 6b below, of one of the most common and used machines of the period, is shown by way of example: the mill. In this example, it was convenient to be able to adjust the height of the water wheel and adapt the position of the paddles according to the level of the water.



a) b)

Fig. 6 (**a**) Diagram of Juanelo's device in Toledo: "The dancing machine". Reconstruction by L. Reti; (**b**) Mills from "The Twenty-One Books of Devices and Machines", 1570

The Machinery of the Industrial Revolution

This period in history arose after the accumulation of knowledge from preceding eras and due to the coming together of a series of factors that resulted in a period of continuous advancement and progress that led to a change of focus, both social and engineering.

The construction of the steam engine by J. Watt (1736–1819) was a turning point, but on a mechanical level maybe establishing the search for automation in every field was more important. The machines began to replace people as a result of the new technologies that were being discovered in agriculture, mining or textile industry. A fine example of this generalised progress came about in the sphere of textile engineering, where developments arose in every field (spinning, weaving and sewing), thanks to men like Arkwright, Hargreaves and Crompton [28].

Figure 7 shows two examples of these machines: Arkwright's "Water frame" (or continuous motion machine) and Hargreaves' "Spinning Jenny". Evolution was continuous and in very few years all industries that were unable to move forward with technology became obsolete.

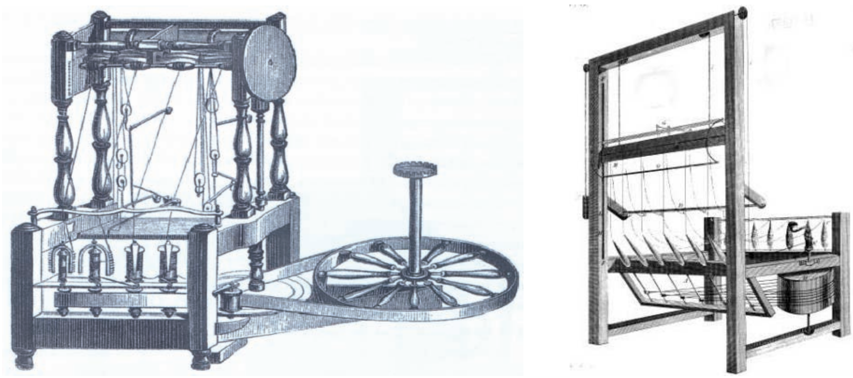


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Fig. 7 (**a**) Arkwright's "Water frame"; (**b**) Hargreaves's "Spinning Jenny"

It should also be emphasised that the industrial revolution did not spread and appear everywhere at the same speed. For example, while England was the pioneer in introducing mechanised and automated industries, neighbouring France was caught up in a social conflict that set it aside from this type of progress.

A Reflection on Machines

Throughout the above section, it has been seen how machines evolved alongside the cultural, social and often political circumstances. After the Industrial Revolution, mechanical development embraced a whole range of subjects.

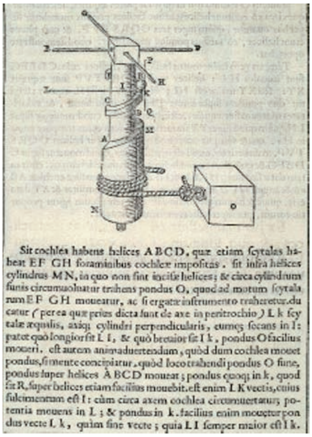
Even so, after the Industrial Revolution, there appeared, or rather, reappeared, a new "History of Machines": one made up of the theoretical treatises begun in the Renaissance but consigned to oblivion by the writings of the French Enlightenment, and which set out a series of essays and treatises on the composition of mechanisms and machines or theoretical studies of mechanical models.

One of the first was by the Spaniard Agustín de Betancourt, who moved to France to study. In his "Essay on Machine Composition" [29] (together with José María de Lanz) he puts forward a classification of movements which still continues to be valid.

Many are the engineers who followed in his footsteps: M. Hachette [30], J. Weisbach [31], Labouyale [32], F. Redtenbacher [33] and F. Reuleaux [34,35], not only used the books of their time but also those of their much older predecessors, such as G. del Monte [16,17] and G. Galilei [18] who, in the midst of the Renaissance, took it upon themselves to reflect on the study of Mechanics.

From modern authors the works of Artobolevsky on "Modern Technical Mechanisms" and Needham on "Chinese Engineering" are really noteworthy.

Figures 8 and 9 include a few examples, by different authors, regarding remarkable contributions on the machines and mechanism science.



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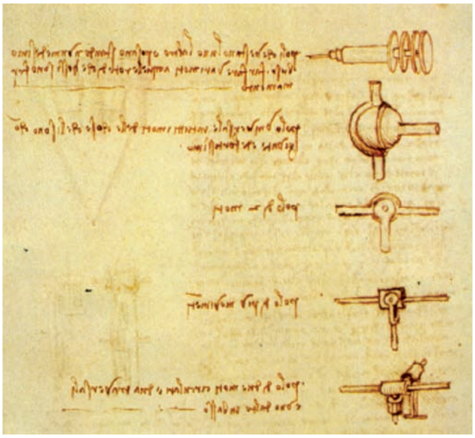

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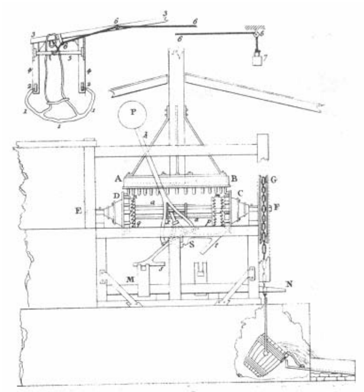
Fig. 8 (**a**) Page from "Le Mechaniche" by G. Del Monte, 1581 [16]; (**b**) Machine classification from "Madrid Codex" by L. Da Vinci, 1493 [14]



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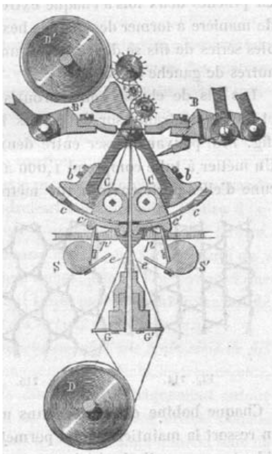

b)

Fig. 9 (**a**) Figure from "Essay on Machine Composition" by A. de Betancourt and J.M. de Lanz [29], 1808; (**b**) Mechanism from "Traité de cinématique" by Labouyale, 1861 [32]

Conclusions

Comparing the "History of Mankind" with the "History of Machines" reveals a parallel evolution that results in political and economic hegemony going along with the most technologically developed cultures. Technical progress has led man to use his imagination and resourcefulness not only for his own benefit but also as a way of providing help in tasks or work requiring skilled operatives. This work has always been done jointly and under the considerable influence of the scientific and political environment of the time. Perhaps the most appropriate example of this type of development is the Industrial Revolution, which, as we have seen, gave way to automated industries and the replacement of men by machines.

A "History of Machines" will never be complete, but this lightweight review [1] will help understand how the minds of "mechanical engineers" gradually evolved and changed, adapting to their era while looking to a "beyond" that led them to discover new and improved machines and mechanisms that would become a new step on an endless flight of stairs.

References

1. Bautista E, Ceccarelli M, et al. (2006) Breve Historia Ilustrada de las Máquinas, Sección de Publicaciones de la E.T.S.I.I. Universidad Politécnica de Madrid.
2. Strandh S (1998) Machines: Una historia ilustrada, Raíces.
3. Hass H (1979) Del pez al hombre, Salvat.
4. Chhi W (1609) San Tshai Thu Hui.
5. Yueh S (500) History of the Sung Dynasty.
6. Woodcroft B (1851) Pneumatics.
7. Vitruvius PM (1511) De architectura, Published by Fra Giocondo, Verona (reprinted in 1513, 1522 and 1523).
8. Ortiz y Sanz J (1787) Tratado sobre máquinas de Vitruvio, 1787.
9. Banu Musa, The book of ingenious devices: Kitab Al-Hiyal, 10th Century.
10. Al-Yazari, Al-Zaman (1974) The Book of Knowledge of Ingenious Devices, D. Reidel Publishing Co., Dordrecht.
11. Hill D (1998) Studies in medieval Islamic technology: from Philo to al-Jazari: from Alexandria to Diyar Bakr, Variorum Reprints.
12. V de Honnecourt (1991) Cuaderno. Siglo XIII, Akal.
13. L da Vinci, Atlantic Codex, 15th Century.
14. L da Vinci (1493) Madrid Codex, 1493.
15. F di Giorgio, Trattato di architectura e machine, 15th Century.
16. G del Monte (1577) Mechanicorum Liber.
17. G del Monte (1581) Le Mechanique.
18. Galilei G (1643) Les Mechaniques, Re-published by Brunetti, Turin, 1964.
19. Agrícola G (1556) De re metallica, Reprinted in 1950 by Dover Publishing.

20. Strada J (1617) Kunstliche Abrís allerhand Wasser – Wind Rosz- und Handt Muhlen, Gedruckt durch Paulum Iacobi in Verlegung Octavii de Strada.
21. Branca G (1629) Le machine.
22. Böckler G (1661) Theatrum Machinarum Novum, In Verlegung Paulus Fürsten, Gedruckt bey Christoff Gerhard.
23. Zonca V (1607) Novo teatro di machine et edificii per uarie et sicure operationi, Appresso Bertelli.
24. Anonymous (1570) The 21 Books of devices and Machines, (Published in 1997 in Spanish and English in a 7 volume edition), Fundación Juanelo Turriano.
25. García Tapia N (1988) Pedro Juan de Lastanosa y Pseudo Juanelo Turriano.
26. García Tapia N (2001) Un inventor navarro. Jerónimo de Ayanz y Beaumont, Departamento de Educación y Cultura de Pamplona.
27. García Tapia N y García Diego JA (1990) Vida y Técnica en el Renacimiento: Manuscrito by Francisco Lobato, of Medina del Campo, in the 16th century, Valladolid: Secretariado de Publicaciones, D.L.
28. Various authors (1993) Crónica de la técnica, Plaza y Janés.
29. Lanz J, Betancourt A (1808) Ensayo sobre la composición de las máquinas, Editorial Castalia, Colegio de Caminos, Canales y Puertos.
30. Hachette M (1811) Traite Élémentaire des Machines, Corby.
31. Weisbach J (1848) Principles of the Mechanics of Machinery and Engineering, Lea and Blanchard.
32. Labouyale (1861) Traité de cinématique ou Théorie des mécanismes, E. Lacroix.
33. Redtenbacher F (1866) Die Bewegungs-Mechanismen, Heidelberg.
34. Reuleaux F (1875) Kinematics of Machinery, F. Savy.
35. Reuleaux F (1876) Lehrbuch der Kinematik, V.1 Theoretische Kinematik, F. Savy.

A Brief Account on Roman Machines and Cultural Frames

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Abstract A brief account of Roman machines is presented by looking at the historical development of a technical culture and its practice, with a specific focus on the main available sources. A few examples of designer personalities and machine designs are discussed with the aim to illustrate the specific professional approach that made the Roman Engineering very successful from practical point of view.

Keywords History of machines, Antiquity, History of engineering, Roman machines

Introduction

The Roman culture lasted near one thousand years, since the time of the mature Republic in 4th century B.C. until the end of the Empire in the 5th century A.D. It is usually said that the power of the Romans was based on a strong military organization and a successful development of infrastructures all around the Roman

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Empire. Both aspects got great benefits from a cultural flexibility of Romans in accepting but absorbing populations and their cultures through an integration process that was motivated by practical goals for a successful organization of the state.

Beside the many studies on the historical developments of the Roman culture, organization, and politics in a very rich literature, no great attention was addressed to the technical developments in terms of machines by looking at their designs and operations. Only recently in the last decades interest has been directed in examining the technical developments even from some engineering viewpoints. Significant examples in the Italian literature of this specific interest are the Encyclopedia on History of Science [3], and the book The Roman Boats [18]. A larger interest in this field exists from the community of History of Science since many years, but with no deep technical engineering insights, as stated for example in [2,14,11,12,17]. In Italy, interest on the technical Roman culture has been addressed since the Renaissance time with the discover of the works by Roman engineers. In particular the treatise by Vitruvius caused large discussions both from cultural and technical viewpoints [2,10–14,19–21]. Indeed, that interest was a mixture of humanistic investigation and practical curiosity whose aim was directed both to identify a technical literature and a source for successful machinery to be copied or reinvented.

Unfortunately no original Roman machines have been preserved since they were made of perishable material. Thus, most of the arguments are based on interpretation of literature works, and mainly on those handbook-like books with technical contents that were available as copies made without figures during the Middle Ages. Recently, there is also a search in archaeological discovers in order to understand the technical content and expertise level of the Roman society.

In this paper we have attempted to outline the peculiar characters of the Roman technique referring to machines by looking at the cultural frame and to some designs through few significant examples.

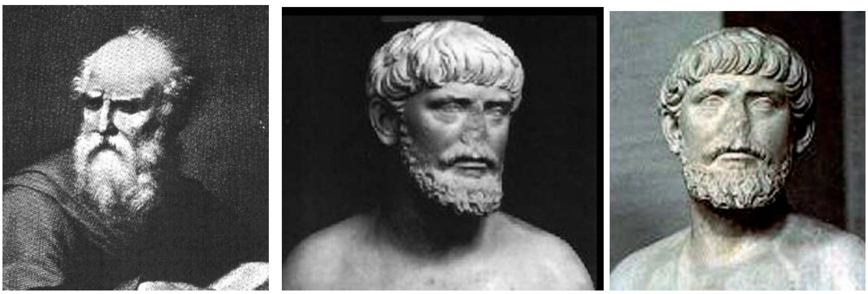
Biographical Notes of Main Personalities

Most of the Roman engineers remained unknown since the engineering practice was not used to be made visible with work's paternity and written publications. In addition, engineering practice was carried out mainly within state frames in military corps. Furthermore, most of technical developments were achieved by practitioners, who were named or identified as *machinatores* for their skills as technicians more than as educated engineers. They were figures who were related with design and construction of machines even with different specialties, as we can understand by terms like e.g. *faber automatarius*, *clepsydarius*, *mensor,* that indicate a specific machined design skill. These *machinatores*, who may recall the Greek *mechanikoi*, seems to be those experts for practical applications of the machines with a full expertise from the design and construction up to operation work. But we have not Roman names that are related with specific designers of machines as inventors.

Nevertheless, we have evidence of the Roman Engineering not only from the very durable infrastructures of Civil Engineering that required machines but even from few technical publications that reached us through manuscript tradition during the Middle Ages and reconsideration during Renaissance times. Beside these few works, there is great memory of personalities who contributed considerably to the Roman Engineering and its visibility through the centuries. In this survey we shall address attention briefly on biographical notes and characters of Marcus Vitruvius Pollio (80/70 B.C. circa – 25 B.C.); Sextus Julius Frontinus (30–103/104 A.D.); Apollodorus of Damascus (2nd century A.D.), Fig. 1. But others could be mentioned, although very little is known on many others who contributed, even considerably, to Roman Engineering.

Marcus Vitruvius Pollio (80/70 B.C. circa – 25 B.C.), Fig. 1a, is known as an architect and engineer. Indeed in the Antiquity and in the past up to the Industrial Revolution there was not a distinction between architect and engineer and only the term architect was used to identify technical experts in design and construction of systems (machines or buildings), as pointed out in Ceccarelli [5]. Indeed, a figure of architect was used to identify expertise on machines that were needed for the architect profession.

Vitruvius was an officer for war machines under Julius Cesar and then architect under Augustus. He wrote the treatise *De architectura* in ten books (today we shall say chapters) very probably between 27 and 23 B.C., since he dedicated it to Augustus. The treatise (perhaps already used in the Carolingian Age) was rediscovered in the Renaissance and since the translation into Italian in 1414 by Poggio Bracciolini until the later in 1584 by Daniele Barbaro, it has addressed lot of attention both from technical and literature viewpoints. The significance of the treatise can be recognized also by the fact that it was cited in other works in the Antiquity, like in the work by Frontinus.



a) b) c)

Fig. 1 Portraits of Roman Engineers: (**a**) Marcus Vitruvius Pollio (80/70 B.C. circa – 25 B.C.); (**b**) Sextus Julius Frontinus (30–103/104 A.D.); (**c**) Apollodorus of Damascus (2nd century A.D.)

The treatise *De architectura* is composed of ten books dealing with: I – education and formation of an architect, II – origin and developments of construction techniques, III and IV – holy buildings, V – public buildings, VI and VII – private buildings, VIII – hydraulics engineering, IX – solar clocks with elements of astronomy and astrology, X – machines and elements of mechanics. The aim of Vitruvius' work was to outline the figure and formation of a clever architect with a strong cultural basis and a very complementary knowledge of machines, as indicated by the fact that only one book over ten is dedicated to machines.

Sextus Julius Frontinus (30–103/104 A.D.), Fig. 1b, is a typical figure of a Roman technical expert. He was a senator and his political carrier was very brilliant since he was governor of Britannia from 74 to 78 where he was a successful general in defeating local population. In 97 he got the position of *curator* of the water supply in Rome during the empire of Nerva. He was also consul in Rome in 74, 98 and 100. He wrote several treatises but today we have only *De aquaeductu urbis Romae* and *Stratagemata*. The last is a history of military facts over the time. The *De aquaeductu urbis Romae* deals with problems and solutions to bring water to Rome.

Apollodorus of Damascus (died ca. 130 A.D.), Fig.1c, lived between the first and the 2nd century carrying out activity of engineer, architect, and sculptor. He had Syrian origins coming from Damascus and he worked under the emperor Trajan. It is known that he built a bridge in 104 on the Danube during the war against the Dacians and then public buildings in Rome such as the Trajan's Forum, Trajan's column; he is also credited to be the designer of the third Pantheon's rebuilding, achieved under Hadrian. He also wrote a treatise on war machines.

In addition to these engineers and architects who left important handbooks dedicated to the basic principles of their disciplines, we have further few information about other technicians, who supervised complex works, both in military and civil building, as Cocceius Nerva, architect in service of Agrippa, who built tunnels in the Phlegraen area, or Severus and Celer, architects of the neronian *Domus Aurea*.

Cultural and Technical Frames

Roman culture was oriented to efficiency of society and State. Thus, engineering was considered and used as a fundamental means for achieving practical goals without recognizing any scientific aim or social status to the practitioners.

We have mainly literature sources, and then other evidence coming from archaeological findings or ancient iconography. The literature nature of available sources reveals a more oriented 'ideological' approach, with philosophical remarks about the use of science and technology in human life. On the other side, the archaeological and iconographic evidence does not fill the lack of specific and technical information. For this reason a general overview shows a substantial dichotomy between science and technology. In the Roman world, in fact, these two kinds of knowledge were quite distinct: science was considered as a higher level of knowledge, that was deserved to people from the upper classes; technology held a lower importance and rank, and for this reason it was dedicated to people belonging to a lower social level. A key role in this strict distinction was played by the substantial contempt of any kind of manual labor which was widely spread in the Roman society, where only the intellectual work was considered worthy for ruling classes activity. On the other side, science was strictly connected with the philosophical thought and therefore considered as higher intellectual activity, far distant from technology that was considered at the same level of any hand labor.

According to many modern scholars, the Roman science was completely based on Greek studies and Roman scientists do not provide any new idea in comparison with Greek scientists. Roman treatises on scientific topics are only compilations, that were drawn with a massive and sometimes uncritical use of Greek sources. On the contrary, even the most critical scholars cannot avoid to remark that Romans reached a far higher technological level if compared to the Greek one. This apparent contradiction can be explained through the above mentioned dichotomy between science and technology. Science had a more abstract attitude, that was deserved to solution of theoretical questions and was devoted to explain phenomena of nature or physical laws, without trying any practical application. On the other hand, technology was more practical oriented, with a strong pragmatic approach, which did not often use the results of theoretical science. In this framework it is useful to remark that the scarce use of scientific knowledge in technical applications was caused also by social and economic factors: first of all because it was not necessary to develop advanced technological tools in a society where the slaves provided a very cheap labor and, for this reason, it was not profitable to develop machine-tools for a large utilization. A largely spread 'naturalistic' outlook of human life, that was proposed by many ancient philosophers, refused any artificial tool asserting that nature provides to human beings anything is necessary for their life.

In the ancient science, physical laws and phenomena of nature are only described through the *observatio*, namely by framing general rules from observation of phenomena themselves. For this reason, at the end of ancient world, the settlement of the canonical seven liberal arts, that were directed to a basic educational pattern even in the Middle Ages, divides teaching subjects between humanistic disciplines of Trivium (Grammar, Logic, and Rhetoric) and scientific disciplines of Quadrivium (Arithmetic, Music, Geometry, and Astronomy), by choosing for the last ones the more theoretical arts and leaving out the disciplines which could have a practical or technological approach.

The most representative figures of scientific and technological approaches in the Roman culture can be considered Seneca and Vitruvius.

Lucius Annaeus Seneca (4 B.C.–65 A.D.) may be considered as a perfect synthesis of above mentioned features of ancient science: he was a philosopher, mainly oriented to moral speculation. Seneca explains in several works that scientific research is anyway subject to an ethic evaluation; science must drive human beings to a better understanding of good and evil and any tool that is found or invented by men through science has to be used with moral purposes and not to fulfill perverted or corrupted instincts. In a well known passage of his *Epistulae ad Lucilium*, he claims that invention of technical tools is due to men who have only the gift of *sagacitas* but who are not in possession of *sapientia* (namely the philosophers, intellectual people of the highest level). Seneca believes that it is useless to apply the human thought to technology, because the real wise man does not try to invent unnecessary tools, since nature already provides men with everything is essential for their life.

In the technological side, Vitruvius is the most interesting figure. He was conscious indeed of enormous potentiality of technology, but he experienced in a very suffered way the 'inferiority complex' of technicians against the outstanding humanistic culture. In his work *De architectura*, Vitruvius tries to re-evaluate the architect work. Vitruvius emphasizes the necessity of a wide and versatile formation that is not limited to technical subjects but open to humanistic education too. In this way architecture obtains a preferential position if compared with other technical disciplines and Vitruvius can claim an intellectual role for himself and for the architect profession as well defined inside the official culture. The awareness of the role and of cultural level of architects leads Vitruvius to a rather positive attitude towards machines and human technology, against the opinion of philosophers like Seneca. Vitruvius believes in a positive function of machines, because they are useful for men and because they succeed to fill the lacks of nature. Thus, a Roman engineer is able to recover an old Hellenistic way of thinking, which underlined the strict connection between nature and technique.

The sharp division between science and technology in the Roman world caused different results. In this perspective we can consider the main scientific and encyclopedic Roman works, like *Naturalis Historia* by Pliny the Elder or *Naturales Quaestiones* by Seneca. The same remark can be made about several scientific works on specific topics, like handbooks on Geography by Pomponius Mela (*De chorographia*), Solinus (*Collectanea rerum memorabilium*), and Vibius Sequester (*De fluminibus, fontibus, lacubus, etc.*); on Astronomy and/or Astrology (not quite distinct in the ancient tradition) by Hyginus (*Astronomia*), Censorinus (*De die natali*), and Firmicus Maternus (*Matheseos libri VIII*).

On the contrary, we can find a less homogeneous level in the treatises dealing with practical technical subjects, like handbooks on Agriculture by Cato the Elder (*De agri cultura*), Varro (*De re rustica*), Hyginus (*De agri cultura* and *De apibus*), Columella (*De re rustica*), Gargilius Martial (*De hortis*), Palladius (*Opus agriculturae*), as they were based even on not Greek sources, as the agricultural treatise by the Carthaginian Mago; the several medical works (Scribonius Largus, *Compositiones*; Gargilius Martial, *Medicinae ex oleribus et pomis*; Avianus Vindicianus; Theodorus Priscianus; Caelius Aurelianus; Cassius Felix; Antimus, *De observatione ciborum*) or veterinary handbooks (Vegetius, *Mulomedicina*; Pelagonius, *Ars veterinaria*; Palladius, *Opus agriculturae*).

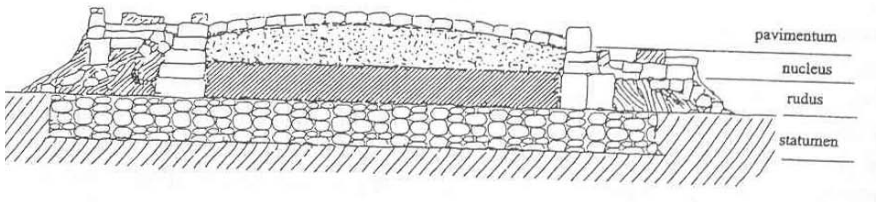
Technical results by Romans, especially in machines production, are quite different and really impressive in the more technical oriented handbooks. Roman technology reached a very high level especially in the field of military engineering, as we can see in historical works and in specific treatises, as Vegetius' *De re militari* or Frontinus' *Stratagemata* (Frontinus wrote also a work *De re militari*, unfortunately now lost); to these works we can also add the anonymous treatise *De rebus bellicis*, the final chapters of Book X of Vitruvius' *De architectura*, and a treatise *Peri mechanematon* (On Machines) by the military engineer Athenaeus Mechanicus as mainly devoted to siege war machines.

Although the extensive use of slaves likewise in other societies in Antiquity, the Romans developed machines as tools or systems to increase the operations power. Thus, typical main Roman machines can be considered cranes for lifting weights (stones for roads and buildings, loads for boats, etc.), pumps for water supply, mills for grinding floor and other materials; and war machines. Those machines were somehow originally imported from conquered countries but they were soon improved in efficiency for very practical specific applications.

The Romans were also attracted from the technical culture beside the specific machines and it is well known that military corps, i.e. the legions, were used to be fully autonomous even from technical viewpoints through soldiers who worked with several different technical skills. In fact, military corps were used to build roads and anything they needed in war campaigns and even in diary peace life, such as bridges, houses, chariots, towers, and of course weapons and war machines. In the Roman social frame technical needs were also considered with proper organizations under the supervision and responsibility of very high political positions, who had the power to ask activity of military corps too. They were the *aediles,* high officers under the direct control of a *consul*, who was sometimes even involved in important activity with technical contents.

Beside the above-mentioned great consideration of machinery techniques, there is not evidence of formation frames for those experts. Very probably most of the training was developed within military frames or, for civil technicians, directly on the field. Thus, the few written treatises seem to be likely handbooks or reports of activity. This is the case for the works by Vitruvius and Frontinus, respectively.
The work by Frontinus ([8]; the only existing medieval manuscript is [9]), is a kind of report of his work as 'water commissioner' in Rome by indicating problems and solutions for such a complex task due to the geography but due to also the size of the required water flow for the huge population living in Rome. In the 1st century A.D., Rome population is estimated to be more than one million, and some hypotheses give even two millions. Thus, the problem of having enough water was really a huge task and it was ensured through brilliant solutions that can be still admired as remains of aqueducts, not only in the city of Rome.

Another relevant work for Roman engineers can be considered the construction and maintenance of roads, Fig. 2. A Roman road is composed of several layers as shown in Fig. 2a, although its appearance does not reveal them, like in the example in Fig. 2b. The construction of the several layers required a considerable work of men and machines that can be thought necessary to achieve the accurate technical results and the power to move so many materials, even as pieces of relevant weight. The need and construction of roads ere considered so fundamental for the state efficiency that they were somehow considered ordinary works of engineering for military corps with specific expertise.



a)

b)

Fig. 2 Roman roads: (**a**) general design scheme [16]; (**b**) a detail from Via Sacra, a road from 2nd century B.C. in Nemi near Rome

Roman Machines

At the beginning of liber X Vitruvius defines: «A machine is a combination of materials and components that have the capability of moving weights» [1], than can be understood with a modern view as «A machine is a combination of timbers fastened together, chiefly efficacious in moving great weights» [13]. Thus, he addressed his attention to machines whose aim is the movement of mechanical parts for load transportation. This is a quite common viewpoint concerning with the Roman machines and more in general in Antiquity. Namely, machines have been developed to move weights with suitable performance that could not be achieved by human labor at the most in term of load capacity and positioning precision.

In this paper, we shall observe examples of machines from applications for load movements, water engineering, and war machines by looking at available sources from literature, illuminated manuscripts and archeological evidence. Consideration of sources either than in engineering products makes necessary interpretation from several viewpoints, like for example history of representation and history of society development, that are beyond the scope of this paper, although they could be important complementary aspects for a full understanding of Roman machines and their role in the society. Because of space limits, we shall limit discussion by referring to few figures for outlining considerations from technical viewpoints.

Figure 3 shows examples of Renaissance interpretation of those Roman machines that, indeed, were used and gave inspiration for theoretical studies and practical applications during the Renaissance yet [6,7]. In Fig. 3a attention is focused on components of cranes in terms of pulley systems, cables, and capstans with different solutions for high-ratio reduction of force transmission for man-powered tasks. In Fig. 3b a water pumping station on a river is shown with details of mechanical design of functional parts as hydraulic turbine and two valve-equipped pumps that are activated by two slider-crank mechanisms. Relevant is the size of the machine as compared with a human figure. A proper in-parallel operation is indicative of suitable expertise in operating slider-crank mechanisms at any scale of machines.

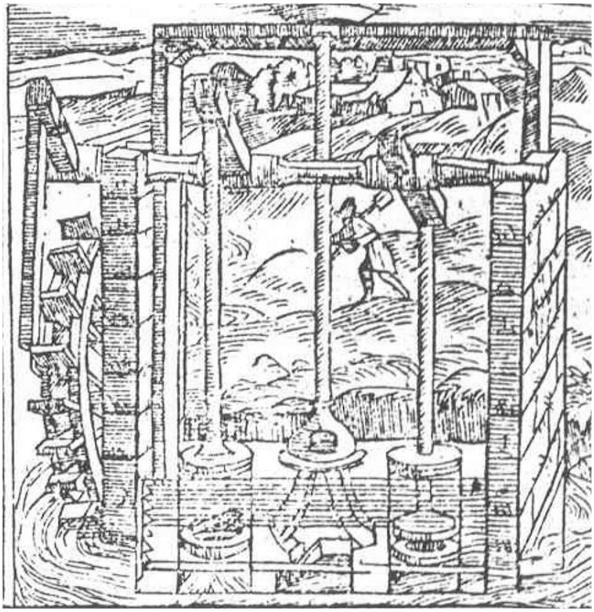
Joints were considered carefully both for motion capability and transmission efficiency. Roman used properly and efficiently ball bearings, even in no-conventional applications. Relevant is the case in Fig. 4a in which a platform for very heavy loads can rotate because of suitable joints made of metallic spheres. Platforms with cylinder roller elements were also found elsewhere.

Different hydraulic machines were developed for different tasks with different sizes, namely a flow regulator as the tap in Fig. 4b and a portable water feeder as the *noria* in Fig. 4c. The tap shows a compact body with a precise manufacturing for efficient operation of flow regulation and closure as a result of combining technology and theoretical design. A *noria* is obtained as a combination of a pulley system with suitably shaped water containers as a result of a practical mechanical design with an efficient transmission system, that could be used by one human operator only.

It is quite curious how Romans could find innovative solutions for special situations. Emblematic examples are shown in Fig. 5 in which boats are represented with unconventional power systems. Namely in Fig. 5a a boat is not equipped with oars and neither with sails. Probably the boats was powered with alternative not shown mechanical systems or by a pulling system tha was operated by cows from the river banks. In Fig. 5b an alternative power systems is clearly shown as composed by turbine wheels that are moved by on-board cows through a gear transmission.

Water paddle-wheels were used in Antiquity and Roman engineers extended their use in many fields, even with different paddle/blade designs. Significant new applications, other than pumping systems, can be recognized for measuring systems, like clocks and naval odometers, but also for more conventional tasks, like grinding mills. In all these systems brilliant designs are obtained by combining water wheels, gear transmissions, and linkage mechanisms. In particular, grinding mills were also designed with particular gear arrangements to obtain suitable operation speed and proper mill installation with vertical axis to facilitate grinding operations and system maintenance.

a)

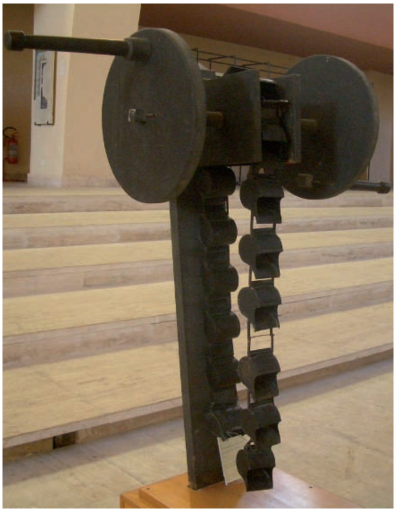


b)

Fig. 3 Drawings of Roman machines in the De Architectura by Vitruvius: (**a**) a crane by C. Cesarione in 1521; (**b**) a pump by D. Barbaro in 1584

a)

b)



c)

Fig. 4 Technical means in Roman boats in Nemi [18]: (**a**) a ball-bearing platform; (**b**) a bronze tab; (**c**) a manual noria

Other important machines were cranes that were developed at several scales for building constructions, load movements, and road constructions, with a wide-spread diffusion that has been recorded even in diary life. In Fig. 6 a crane is shown as a part of a scene in a building construction in two different situations.

In Fig. 6a a crane is shown with similar architecture like in Fig. 3a, but with several pulley and a large orientating wheel that is powered by several human operators (that is why is usually named *calcatoria* for the actuation by pedestrian actions). In addition, the crane carries two men on the top, as an indication of the variety of possible tasks.

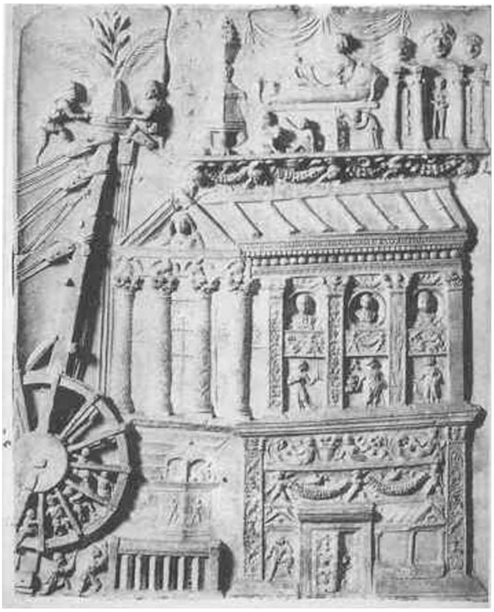
In Fig. 6b main components are drawn as a geared tower beam and a wheel that is connected to the tower beam. It is remarkable the size and even the location of the crane on the roof of another building.

a)

b)

Fig. 5 Examples of unconventional boat propulsion: (**a**) a river boat from the Museum of Roman boats in Mainz; (**b**) a mechanical powered boat from De rebus bellicis in 4-th century A.D.

A small crane with a simple particular structure is shown in Fig. 7 for road construction purposes. The crane is made of essential parts and has the aim to be easily displaced for moving and locating stone blocks for the pavement of roads. The crane supporting frame is made as an arc from a deployable system whose locking bar is shown near the top of this rod, indeed, can be also understood as a linear guide to facilitate the positioning of the loaded road stone. The pulley system is shown in detail with the two joints in the small capstan and a grasping system is illustrated as a two finger gripper with locking mechanisms. Thus the human operator is aimed only to guide the loaded stone, even without any additional help.



a)

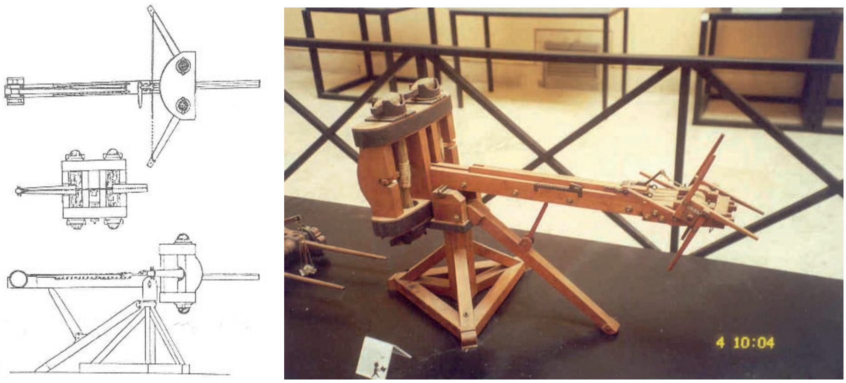
b)

Fig. 6 A crane for civil constructions: (**a**) for the construction of Haterii monument in 1-st century A.D.; (**b**) an artistic representation in a miniature from the codex Vigilius Vaticanus; in 4-th century A.D.

Fig. 7 Construction of Roman road Via Appia near Terracina on 3-rd century B.C. in a basso-relievo

Roman engineering capability is even more evident in war machine designs that are and were considered highs of Roman technical culture.

A brilliant example of war machines is a *ballista* that although known since the Antiquity was enhanced by the Romans. The machine design combines systems made of flexible components with high-ratio transmissions and accurate joint constructions, Fig. 8. They were completed with locking mechanisms and other mechanisms for releasing even with multiple arrows shooting like the modern rifles. In addition, the Roman war machines had the well-known peculiarity to be built on site and this demonstrates the accuracy of the design but even a widespread culture on machine techniques at several levels.



a) b)

Fig. 8 Example of Roman war machines: (**a**) a drawing from Renaissance reconstruction; (**b**) a reconstruction at Roma Museum of Roman culture

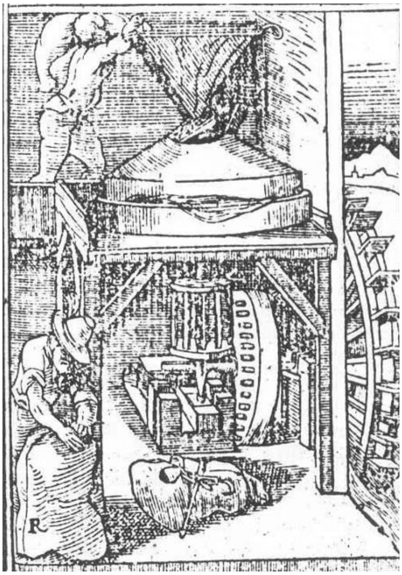
Figure 9a shows war machines in Trajan column in Rome as a monumental memory of the war against Dacians by showing them as usual means available in the Roman Military force [15]. In this case the significance of the machines can be understood even as emphasized with respect to the number of the nearby shown soldiers. However, the war machines are not fully depicted but their capability is stressed through details of their portability by means of wheels and repeated figures of them. The operation is not fully explained since the military purposes of those machines. In the same monument, in the top of scene in Fig. 9b it is possible to identify an individual carrying an instrument. It seems to be for angle measurements or for level determination. Remarkable is that this operator is not a soldier, as for the cases of war machines. This could give an idea that such a mechanism needed high-education and/or was of strategic significance so that it could be suitable only for high-level officers or even for special consultants. The machine is portable and has an out-side structure that does not show the mechanism.

a)

b)

Fig. 9 Machines in the Traianus column in Rome: (**a**) a war machine; (**b**) a measuring instrument

Machines were also considered part of the Roman society in its day life and developments, when one observes representation of machines in memorial monuments, like the example in Fig. 9, in production aspects, like in the example in Fig. 10a and in artistic works, like in the examples in Fig. 10 b.



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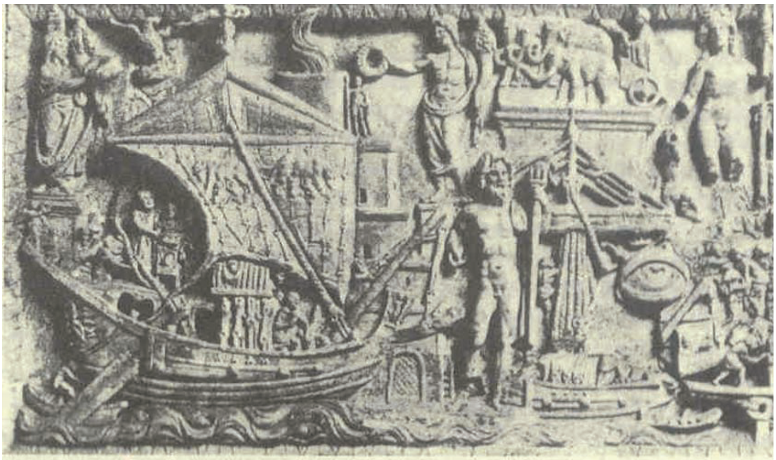

b)

Fig. 10 Roman machines in a diary life: (**a**) floor mill from reconstruction by D. Barbaro [1]; (**b**) a crane mechanism for loading and downloading boats in Ostia harbor in a sculpture of 1-th century A.D.

In Fig. 10a, that is a Renaissance reconstruction from Vitruvius' treatise, a mill is shown as operated by common people who seem to be familiar with the complex geared system that transform the hydraulic power from a river through a paddle turbine to a grinding force.

In Fig. 10b it is remarkable how the scene of the Ostia harbor (the port of Rome) is crowed of several elements, from holy symbols to typical boats, but including a crane with several pulleys. The crane is quite well depicted as to show familiarity of the public to such devices in a harbor.

Conclusions

Existence and characteristics of Roman machines can be known basically from literature works, even with specific technical contents and by analyzing representations in artistic and monumental works, like it has been reported in this paper. Few examples (but many more could be pointed out) have been discussed in this paper with the aim to outline the peculiar characters of diffusion and familiarity of machines in the Roman culture and society. Machinery were considered by the Romans as a necessary means for achieving successfully practical goals. Although theory was known and still investigated somehow, Roman engineers were much more attracted to practical applications and their knowledge and skills were considered and used as a well-established practice for community needs.

References

1. Barbaro D (1584) I Dieci Libri dell'Architettura di M. Vitruvio, Venezia.
2. Campbell DB (2003) Greek and Roman siege machinery, Osprey Publishing, Oxford.
3. Capocaccia AA (Editor) (1973) History of Technique – From Prehistory to the Year One Thousand, UTET, Torino. (in Italian)
4. Capocaccia (1989)
5. Ceccarelli M (2004) Evolution of TMM (Theory of Machines and Mechanisms) to MMS (Machine and Mechanism Science): An Illustration Survey, Keynote Lecture, 11th IFToMM World Congress in Mechanism and Machine Science, 2004, Vol.1, pp. 13–24, Tianjin, China.
6. Ceccarelli M (2006) Greek Mechanics of Machinery in the Early Works on Modern TMM, Proceedings of 2-nd Int. Conference on Ancient Greek Technology, Technical Chamber of Greece, pp. 361–368, Athens.
7. Ceccarelli M (2007) Renaissance of machines: from Brunelleschi to Galilei through Francesco di Giorgio and Leonardo, 12th World Congress in Mechanism and Machine Science IFToMM'07, paper no. A236, Besançon.
8. Frontino (2004) De aquae ductu urbis Romae, introd., testo crit. trad. e comm.. a c. di F. Del Chicca, Herder Editrice, Roma.

9. Frontinus (1930) De Aequaductu Urbis Romae, cur. M. Inguanez, Montecassino. (Reproduction of Montecassino Ms. 361)
10. Gara A (1994) Tecnica e tecnologia nelle società antiche, La Nuova Italia Scientifica, Roma.
11. Green M (1979) Roman technology and crafts, Longman, London.
12. Klemm F (1959) A history of Western technology, Scribner, NY.
13. Morgan MH (ed.), Vitruvius Pollio (1914) The Ten Books on Architecture, Cambridge, Mass. – London. (repr. New York 1960)
14. Oleson JP (1984) Greek and Roman water-lifting devices, The history of a technology, Univ. of Toronto Pr., Toronto.
15. Popescu I, Ceccarelli M (2005) The Machines, Structures, and Mechanisms on the Traian's Columns, The 9th IFToMM International Symposium on Theory of Machines and Mechanisms, pp. 283–288, Bucharest.
16. Quilici L (1989), Via Appia – da porta Capena ai Colli Albani, Fratelli Palombi Editori, Roma, 2nd Ed. (in Italian)
17. Singer CH, Holmyard EJ, Hall AR (1956) A history of technology, II, The Mediterranean civilizations and the middle ages c. 700 B.C. to c. A.D. 1500, OPU, Oxford.
18. Ucelli G (1996) Le Navi Romane (The Roman Boats), Istituto Poligrafico dello Stato, Roma, 3rd Ed. (1-st Ed 1940)
19. Veneziani M (Editor) (2005) Machina – Proceedings of XI International Coloquium in Rome 2004, Olschki Publ. Firenze.
20. Vitruvius (1997) De architectura, edited by P. Gros, Einaudi, Torino.
21. White KD (1984) Greek and Roman technology, Thames & Hudson, London, UK.

Devices for Distance and Time Measurement at the Time of Roman Empire

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Abstract In this paper, devices for measuring distances and time intervals are presented as conceived and used during Roman Empire since they represent the most important means of practices and developments both for scientist and engineers. The constructions and operations of main devices are discussed by using modern reconstructions and interpretations with the aim to sow the expertise in mechanism design at the time of the Roman Empire.

Keywords Roman machines, Odometers, Water clocks, Ctesibius, Vitruvius

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Introduction

As many people know, the Roman Empire was one of the widest empires ever existed in the human history. On the other side, most people suppose that, at that time, technology and science were quite primitive and the study of them almost neglected. The study of the History the Engineering gives a great help to recognize that, on the contrary, knowledge of Mechanics and its application was rather advanced. In addition, it can help also to recognize the use and function of some archaeological discovers by interpreting their operation and technical performance. In particular, by joining efforts of Archaeologists and Engineers it can be possible to understand that many devices of common use at the present days were invented and built about twenty centuries ago. From a general point of view, the study of the History of Engineering is a great help to understand the present through the understanding of the past. In addition, it is probable that deeper studies in this field could lead up to important new discoveries. Anyway, in order to correctly understand the past, it is necessary that Archaeologists and Engineers work together.

The attention to machines of Antiquity has been addressed in several works within the History of Science and Technology, like for example in [5,7,8,3,14], but mainly from general viewpoints, even when with technical observations. In some cases, the analysis has been even limited to bibliographic search with no engineering comments, like for example [6,10]. Only recently, interest is arose to technical investigations to understand design, operation and manufacturing of machines in Antiquity, like for example in [9,4,11,12,13] by looking at the mechanisms and their operations through numerical analysis for performance evaluation. This paper is within this research frame as an attempt to rediscover mechanisms that were invented and/or implemented in instrument devices at the time of Roman Empire.

In the wide Roman Empire, the measurements of distances, both in the ground and sea, played certainly a very important role as related to the road developments. The wide road system can be considered one of the most important constructions that the Roman have built in Europe. Most of those roads are still in use at present days. In addition, since sextants and marine chronographs were not jet invented, the only way to know distances was to measure the space run by a ship in the sea.

Even for the measure of time intervals, some devices of that time were rather advanced from a mechanical point of view.

Devices for Distance Measurement

Among the many Roman devices for distance measurement, like stadia and dioptre, this paper addresses specific attention to odometers that make use of mechanisms as invented at the Roman time both for ground and sea applications.

The Odometer by Heron

The invention of the odometer device is attributed to Heron of Alexandria, [1]. The biography of this very important ancient scientist and engineer is not very clear for what the dates are concerned. The century in which he lived, can be individuated by dating on March 13, 62 A.D. a moon eclipse that he described. Thus, he was probably born on 10 B.C. and died on about 70 A.D. He studied the works of Ctesibius, Philon, Euclid and Archimedes. His activity is recognized as scientist and practical engineer since a lot of inventions are attributed to him, mainly in the field of Pneumatics, Mechanics and Automatics as applications of his studies. In addition to the odometer, he was probably the inventor also of optical devices for distance measurement.

The odometer by Heron can be considered, without any doubt, the predecessor of the modern mechanical mileometer and tripmeter that has been used in modern motor vehicles untill less than ten years ago. Although it was designed about two thousand years ago, it works with the same principles of modern tripmeters.

The odometer device was of great importance during the Roman Empire since it was used to locate the mileage stones indicating miles along roads. This permitted to plan the movements of the army units and to estimate military costs. In addition, it is reported that an odometer was installed on the chariots of emperors.

The description of the odometer by Heron is given from Vitruvius in Barbaro [2]. Vitruvius was an officer of the Roman Army Engineers and an inventor himself. From the description of Vitruvius it is possible to propose the perspective reconstruction in Fig. 1. The ring R is connected to the wheel and moves a pin of the input wheel through a small flap. On the axle of this first wheel is installed a pointer that indicates the steps named as “passus”. A dial (indicated as 1 in Fig. 1) was graduated from 0 to 9. This first axle moves a second axle by means of worm gears with a gear ratio 10. On the second axle w a second pointer is installed to indicate the ten steps. This axle (indicated as 2 in the Fig. 1) moves a third axle again with a worm gear, and so on.

A kinematic scheme of the mechanism is shown in Fig. 2. Because of such a kinematic scheme, the odometer can be understood to have up to five pointers that indicated units, tens, hundreds, thousands, and thousand tens of steps. Of course, the gear ratios will be all equal to 10. This means that probably the worms could have 2 principles and, consequently the wheels had 20 teeth.

As for the pins on the input wheel and wheel of the carriage, Vitruvius wrote that the standard wheel diameter of a roman chariot was 4 roman feet. Since a roman feet was 0.2964 m, the wheel circumference was 3,725 m. Therefore, we can suppose that, for a correct continuous transmission between chariot wheel and input wheel, the latter should have 8 pins. Thus, the distance measurements can be computed through the following expression

$$8 \text{ chariot wheel revolutions} = 10 \text{ roman steps} = 14.785 \text{ m}$$

Consequently, with 8 pins, the wheel diameter can be computed as

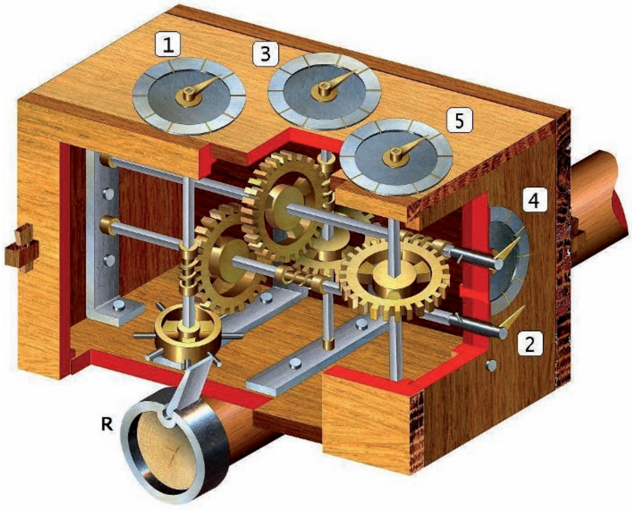


Fig. 1 A perspective modern reconstruction of the odometer by Heron

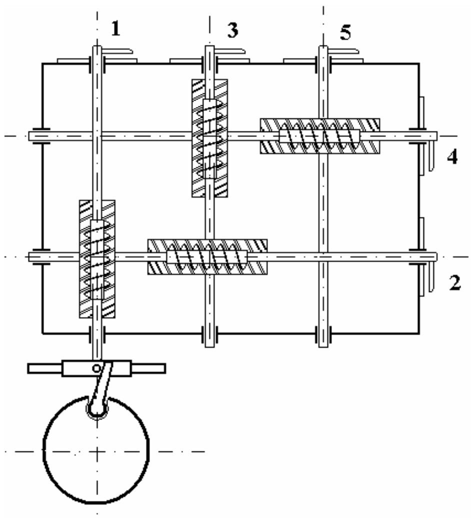


Fig. 2 A kinematic scheme for gear connections in the Heron odometer in Fig. 1

$$14.785 / (8 \cdot \pi) = 0{,}588 \text{ m} \cong 2 \text{ roman feet}$$

This is exactly one half of the standard wheel.

It must be observed that the small flap is not rigidly installed to the axle but it can rotate, with a certain amount, with respect to it. This particular, that is shown in Fig. 3, is not reported in some later designs by later technicians but it was very useful for a correct working of an odometer.

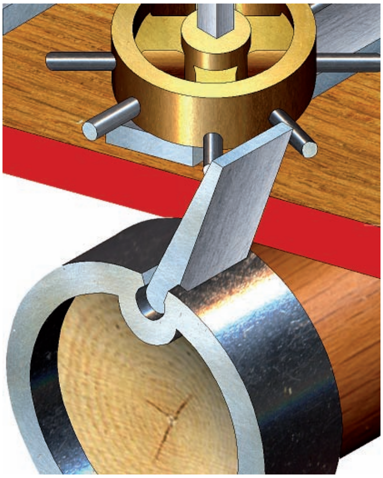


Fig. 3 A zoomed view of a detail for flap connector in the Heron odometer in Fig. 1

The Odometer by Vitruvius

It is well-known that at the time of the Roman Empire it was not possible to determinate the position of a ship by astronomical device. For this reason the only way to determinate the distance that were run by a ship was to measure its displacement. A first device for this task can be considered the naval odometer that was designed by Vitruvius. A perspective reconstruction is shown in Fig. 4. A paddle wheel was installed at each side of a ship so that it was moved by the ship's motion. Both the paddle wheels were fitted on an axle that moved the mechanism of the odometer.

Each revolution of the paddle wheels causes one teeth rotation of the first gear wheel, which through other gears (that are not represented in the reconstruction drawing) moves the counting pointers. A scheme is reported in Fig. 5, in which the axle 1 is that one of the paddle wheels.

As far as we know, this devices can be considered as the first log example for measuring ship speed. It has to be pointed out that "log" in English indicates the piece of wood that was tied to a small rope and was thrown outboards. The rope had a number of knots, that were located 1/10 of nautical mile from each other. By means of an hourglass, the number of knots in the unit of time where counted, hence the speed was computed. This device, in the shape that has been just described, was considered as invented in the 18th century. That is to say more than 18 centuries after the naval odometer by Vitruvius, and it is clearly much more unsophisticated. The term "log" is still used for mechanical or electrical devices that are used to measure speed and distances in the sea in more recent times.

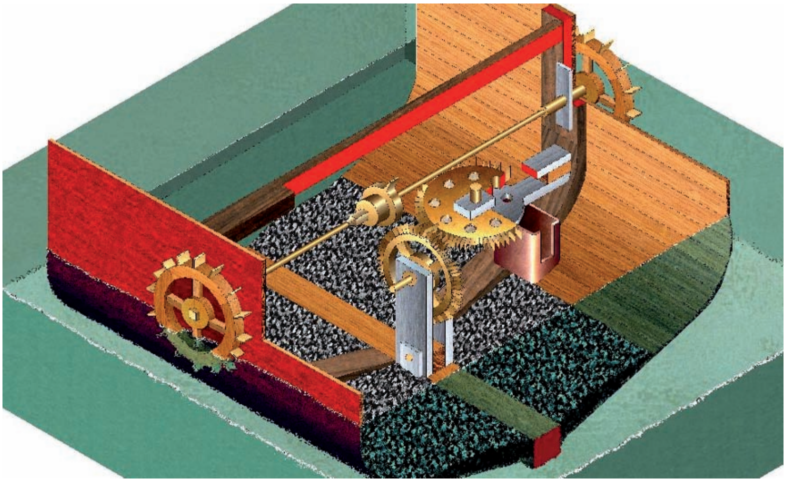


Fig. 4 A perspective modern reconstruction of the naval odometer by Vitruvius

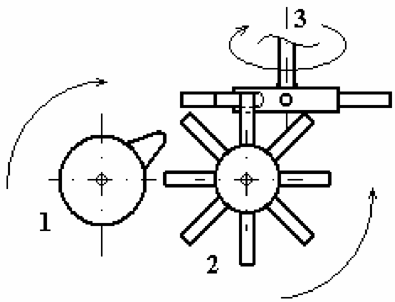


Fig. 5 A scheme of the first three axes in the mechanism of the naval odometer in Fig. 4

Before the (very recent) use of the GPS, the coastal navigation, both for sporting and professional activity, was made possible by log and compass until the present days. At the time of the Roman Empire, the navigation was mainly coastal as they were helped by a wide system of long range lighthouses.

Topographic Instruments

Other relevant instruments for distance measurements were developed for topography purposes. They may have not been based on mechanisms but on the geometry properties which are strongly linked with displacement evaluation. In this paragraph we have reported some of those ancient devices which made possible the developing of topography during the Roman Empire.

A Groma is an instrument that was used intensively by Roman engineers. It would be difficult to determine when the Groma was invented since it may have been originated in Mesopotamia, from where it may have been imported by Greeks around the IV century B.C., an indicated as gnomona or little star. Then, Etruscans brought it to Rome and named it as cranema or ferramentum. It was made of a cross made of iron or bronze, whose arms supported four plumb weighted lines, as represented in Fig. 5 a. Looking through the opposite pairs, the instrument could identify two perpendicular directions, which were used to subdivide the land into orthogonal alignments. In Fig. 5 a modern reconstruction of a Groma is proposed as compared with an artistic representation in bas-relief from roman imperial time.

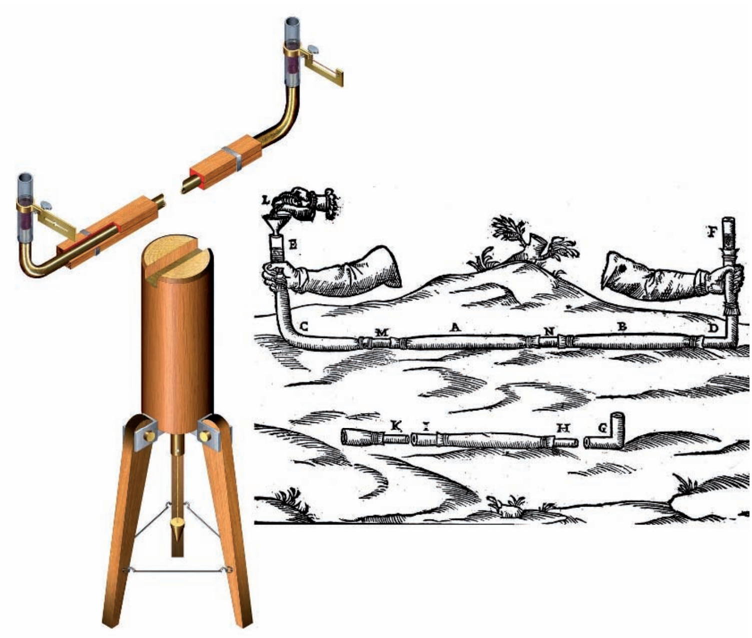
a) b)

Fig. 6 A Groma instrument: (**a**) a modern reconstruction; (**b**) an artistic representation in archeological found

Although this instrument was invented in other civilization, it was used for many centuries in the Antiquity and was extended during the Roman Empire. Proof of the instrument and its uses are found in the remains of a Groma discovered in Pompeii and its illustration is reported on several funerary steles of the time of Roman Empire. As far as we can understand, the approximately two meter long rod supported the cross well above the eye level of a user, who could therefore look freely through the plumb weighted lines. The real limitation of the instrument can be identified in a situation when there was even a weak wind that could cause the lines to oscillate and prevent a correct observation of line alignment.

Another important instrument for topography purposes was considered the Heron's lever. In Fig. 6 (a) modern reconstruction of Heron's level is reported by showing communicating pipes and slots for optical sightseeing that were the basic components for the mechanism and its operation. In Fig. 6b a reconstruction is reported for a similar devices as proposed by Giovanni Branca in the table XXXIX of the book "Macchine", that was published in Rome in 1629.

The basis of the instrument is the Mechanics of levers which will require long rod for proper accurate measurements. Obviously a topographic instrument six meters long, even though precise, was too cumbersome to transport in a filed or even during a military campaign. In addition, rain and wind could prevent its practical use.



a) b)

Fig. 7 Reconstruction of Heron's level: (**a**) a modernperspective; (**b**) from G. Branca in 1629

A real innovation was made when Hero succeeded in constructing a dioptre fitted with a special accessory in lieu of the alidade. Thus he transformed the instrument in a compact design even with a high precision operation. In many ways this is the forerunner of the theodolite. Etymologically, *dioptre* in Greek comes from two words: *dià*= through and *opteuo*= observe: *observe or look through*. This definition is suitable for all sighting instruments that are used to identify a direction. These instruments were replaced by telescopes only in modern times.

Hero wrote a very detailed description of the instrument in his *Treatise on Dioptrics*, translated from the Greek by Giambattista Venturi in 1804. The instrument was intended for angular measurements by using an alidade or dioptre that could rotate both horizontally and vertically. Two semi-cogged wheels used two worm screws with knobs to rotate in the horizontal and vertical directions. In this manner, they could achieve lines of sightseeing with target rods in order to determine azimuth or elevation angle. By using a crosswire at the ends of the dioptre, they were able to improve precision apparently up to 30 min of a degree. A small tripod column, rather like our trestle, was used to support the instrument and a plumb weighted line or bob along its side ensured perfect verticality.

In his interpretation Venturi supposed that, in addition to the goniometric plate to measure the azimuth angles, in the instrument there must have been installed also a vertical semi-disk to measure elevation angle. In effect, the device would resemble a modern inclinometer. However, since there is no mention or supposition to this in the Hero's treatise, we prefer to believe that the sight slot only had a vertical rotation and that it occurred in the traverse fork on the goniometric plate. Such a location makes the functionality of the instrument as similar to a today telescope, which makes the dioptre even more modern.

As for its operation for a level measurement, this occurred by replacing the sight slot with a wood rule containing a small copper tube with U shape. At the ends of the U rod tube two transparent glass pipes were installed. When an opaque liquid, such as red wine, was used, the two cursors could be made to coincide perfectly with the level of the liquid. In effect, this was two communicating vessels with one index.

The cursors were actually two metal ties, each one with a line of sight that could slide along the exterior of the glass tubes. Once the liquid was stationary, these cursors were moved to align with the liquid. The regulus containing the tube is described as being 12 fingers long, approximately 25 cm, as a measure that is perfectly suited to its purpose.

The most interesting and least known accessory is the pair of leveling rods that completed the dioptre. However, since it was not possible to read the rod from a distance without a telescope, a solution was found to allow for a direct reading. By looking through the sight slots of the level tube, a mobile pointer along the rod was brought to coincide with its direction. Since this had a wide disk that was half white and half black, collimation was not particularly difficult. In fact, once the assistant had blocked the disk after it had been aligned, the measurements could be read on the rod, as registered by a lateral pointer.

In Fig. 7 reconstructions are reported for an Heron's dioptre and a Roman stadia, according to Heron's description.

In 1907, the remains of a Roman ship was found off the coast of Mahadia. Many decades later, when it became possible to bring the ship cargo out of the sea, among the several valuable works of art they found also several bronze flanges, two of which were semi-cogged. This was a symmetrical pair and was most likely intended to rotate the horizontal plane of a dioptre, as a ship instrument.

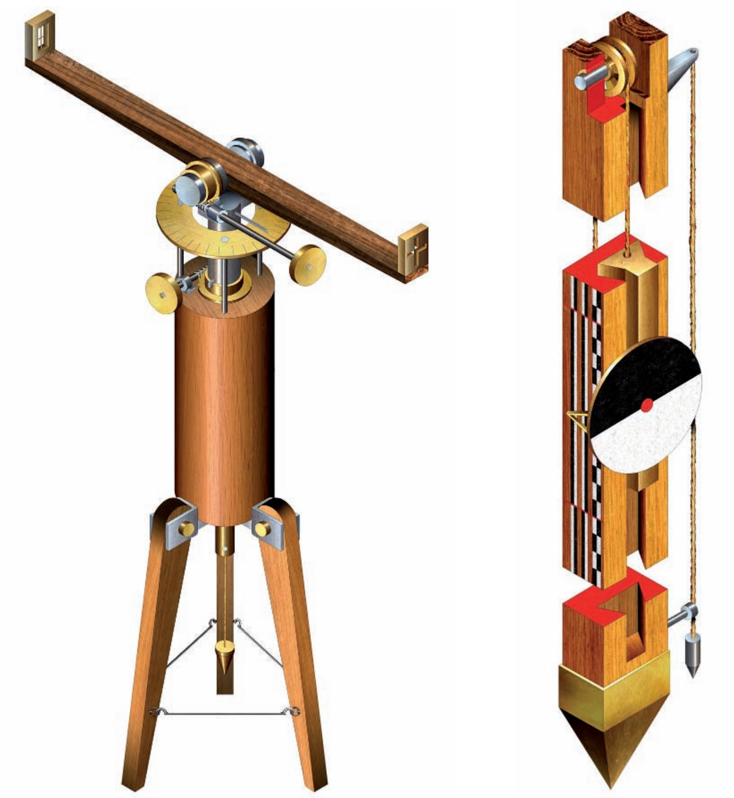

a) b)

Fig. 8 Modern reconstructions of topographical instruments: (**a**) Heron's dioptre; (**b**) a Stadia

The Water Clock by Ctesibius

Water clocks were quite common two thousand years ago but generally they were very simple and not very accurate. Essentially they consisted in an upper water tank that filled a lower one through a regulated water flow. In the lower tank a ball cock was activated by the water flow and moved a pointer that indicated the time.

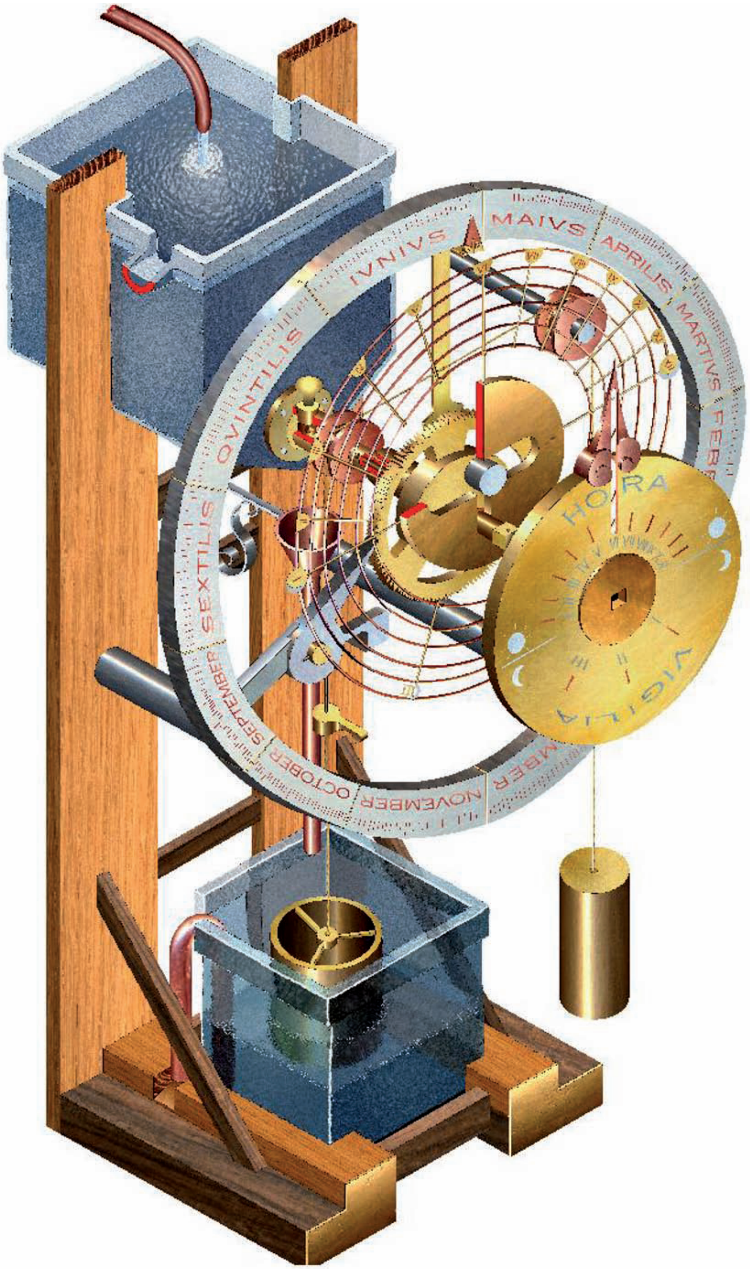


Fig. 9 A perspective reconstruction of Ctesibius' water clock

Beside the motion and power transmission, there was another problem to solve. The length of a roman hour was not constant since it was defined as 1/12 of the time between sunrise and sunset during the day and 1/12 of the time between sunset and sunrise during the night. Thus, the time duration of one hour was different from day and night (except at the equinoxes) and from a given day to another one. The water clock that was designed by Ctesibius, solved this problem. A perspective modern reconstruction of it is shown in Fig. 8 on the basis of what was described by Vitruvius.

A bottom tank was filled by a constant water flow from a top tank that is continuously maintained full. An yarn was connected to the ball clock and to a counter weight and was wrapped in coil around the pointer axle. Daily the bottom tank was drained and the cycle started again. The main parts of the mechanism are shown as an orthogonal section in Fig. 9.

The problem of measuring hours of variable length was solved by Ctesibius by fitting the dial on a shaft that was off the centre of the pointer shaft and by moving the dial during the year. The mechanism is shown in Fig. 9b.

Any time the ball cock passes through a certain position (once a day), it moves a rod that pushes one tooth of a gear. This last gear has 365 teeth, so it made a revolution in one year, and was fitted on an hollow shaft coaxial to the pointer shaft and connected to a rod, as shown in Fig. 9b.

The dial was installed on an hub having two orthogonal slots. Through the vertical slot passed the pointer shaft and in the horizontal one a crank was connected to the gear shaft. While the crank rotates, the dial could move just along the vertical direction. In this way, the dial centre moves with respect to the pointer axis from the higher position to the lower position to the higher again, once in a year. The 365 teeth gear moved also another pointer to indicate the day of the year.

Conclusions

The presented devices show that twenty centuries ago the knowledge in the field of mechanics, and specifically in measuring time and distances, was much more advanced than what is commonly supposed. In this paper, measurement devices are presented and discussed in order to understand their designs and operations as important examples of high technical level in Mechanism Design at the time of Roman Empire.

Measuring distance, together with the measuring of mass and force, represented the first steps in developing science and technology in Antiquity. In addition, the first western scientists and engineers (e.g. Thaletes, Pitagoras, Archimedes, etc.) were very deeply interested in the study of Geometry, as fundamental for the study of Mechanics and design of mechanical systems. It is also well-known that an accurate measuring of distances is also essential for civil engineering in building temples and towns. A relevant impulse in this field of knowledge and its practical application was given during the Roman Empire, as discussed in this paper through few significant examples.

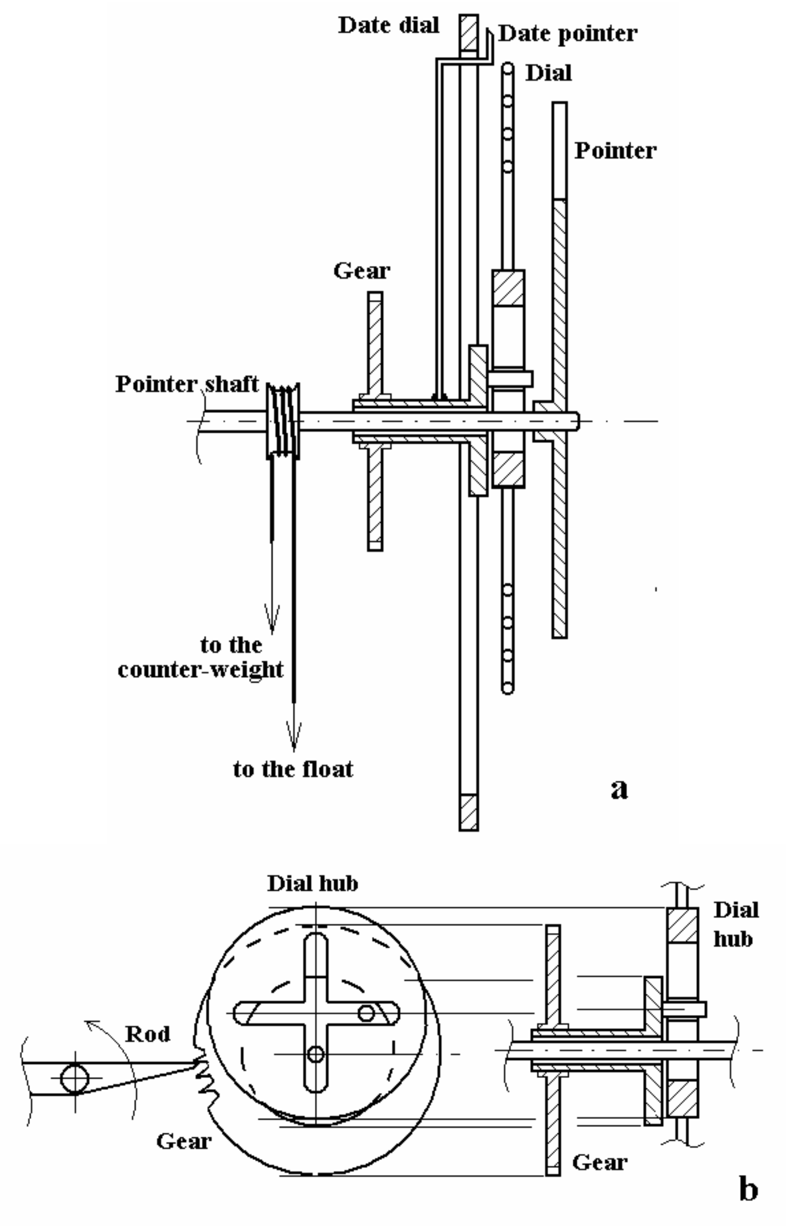


Fig. 10 A kinematic scheme of Ctesibius' clock in Fig. 8: (**a**) the clock mechanism; (**b**) a details of the mechanism for the dial motion

References

1. Baldo B (1616) Heronis Ctesibis Belopoetica id est, telifactiva, Augustae Vindelicorum, typu Davidu Franci.
2. Barbaro D (1584) De Architectura, by Marcus Vitruvius Pollio, traduced by Daniele Barbaro in ancient Italian as "I Dieci Libri dell'Architettura di M. Vitruvio", Venezia.
3. Capocaccia AA (Editor) (1973) History of Technique – From Prehistory to the Year One Thousand", UTET, Torino. (in Italian)
4. Ceccarelli M (2007) A Note on Roman Engineers and their Machines, CD Proc. of 2007 Bangalore IFToMM Workshop on History of MMS, Bangalore.
5. Chasles M (1875) Apercu historique sur l'origin et le développement des méthodes en géométrie ..., Mémoires couronnés par l'Académie de Bruxelles, Vol. 11, 1837 (2nd Ed.), Paris.
6. De Groot J (1970) Bibliography on Kinematics, Eindhoven University, Eindhoven.
7. Dimarogonas AD (1993) The Origins of the Theory of Machines and Mechanisms, in Modern Kinematics – Developments in the Last Forty Years Ed. by A.G. Erdman, Wiley, New York, pp. 3–18.
8. Hartenberg RS, Denavit J (1956) Men and Machines … an Informal History, Machine Design, May 3, 1956, pp. 75–82; June 14, 1956, pp. 101–109; July12, 1956, pp. 84–93.
9. Koetsier T, Blauwendraat H (2004) The Archimedean Screw-Pump: A Note on Its Invention and the Development of the Theory, Proc. of Int. Symposium on History of Machines and Mechanism (HMM04), Kluwer, Dordercht, pp. 181–194.
10. Marchis V (1994) History of Machines – Three Thousands Years of Technological Culture, Ed. Laterza, Milano. (in Italian)
11. Popescu I, Ceccarelli M (2005) The Machines, Structures, and Mechanisms on the Traian's Columns, The 9th IFToMM International Symposium on Theory of Machines and Mechanisms, Bucharest, pp. 283–288.
12. Russo F, Russo F (2007) POMPEI: A Course Towards Transformation – the Forgotten Contributions of Roman Naval Technology, NATO, CCMAR Naples, ISBN 978-88-95430-05-8.
13. Russo F, Russo F (2006) 79 A.D. Course for Pompeii, Inquiry on the Death of an Admiral, NATO, CCMAR Naples, ISBN 88-88-419-56-X.
14. Veneziani M (Editor) (2005) Machina – Proceedings of XI International Coloquium in Rome 2004, Olschki Publ. Firenze.

The Twenty-One Books of Devices and Machines: An Encyclopedia of Machines and Mechanisms of the 16th Century

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Abstract Progress in Engineering and Architecture has been decisive in the birth and duration of empires throughout History, and Mechanical Engineering has always played an important role. For long periods of the 16th and 17th centuries the Spanish Crown became the World's leading political and economic power, so extensive that in the domains of King Philip II, "the Sun never set".

The strategic interest in Mechanical Engineering became clear with the appearance of "The Twenty-One Books of Devices and Machines of Juanelo" (Anonymous (Los Veintiún Libros de los Ingenios y Máquinas de Juanelo Turriano, 1997)), whose compilation was ordered by King Philip II around the year 1570 [1]. Among other knowledge exposed, the book contains a large number of machines of the period. The devices and machines are classified according to its function, with a surprising number of pumps, mills, cranes and other machines, particularly those driven by water, wind-energy, gravity or animal traction.

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This work sets out some reflections on the importance of this book and takes a detailed look at the main mechanisms and machines described, while making comparisons with similar devices of the period or those that may have had an influence on the contents.

Keywords Machine encyclopedia, Spanish crown, 16th Century, Twenty-one books

Introduction

The complex process of founding empires that has existed throughout History, has always been an object of study due to the profound political, economic, demographic, religious and social changes involved. It is important to point out that almost all empires have arisen out of a situation of scientific-technological superiority. Progress in Engineering and Architecture has been decisive in the birth and duration of empires throughout History, and Mechanical Engineering has always played an important role [2, 3].

Every empire has needed to develop communication and trade networks, advances in the means of transport, in the exploitation of agricultural and mining resources, and in the building of cities and infrastructures, so as to address the population's needs. In addition fortifications and defense structures needed to be continuously improved against potential enemies. In order to meet all these requirements, the use of efficient machinery and resourceful devices has always been paramount.

For long periods during the 16th and 17th centuries, the two Iberian empires became unified, whereupon the Spanish crown became the World's number one political and economic power, so extensive that in the domains of King Philip II, "the Sun never set".

In the framework of this empire a need arose for the Spanish Crown to have highly qualified professional experts at its disposal. The scarcity of which is made clear in a letter by Francés de Álava, written to Philip II in the second half of the 16th Century: "The persons that I know in Spain employed in the service of Your Majesty as qualified engineers […] are all foreigners and I know not a single Spaniard who knows anything as near as much as any of them".

The strategic interest in Mechanical Engineering became clear with the appearance of "The Twenty-One Books of Devices and Machines of Juanelo", whose compilation was ordered by King Philip II around the year 1570 and is nowadays preserved in the National Library in Madrid (www.bne.es). Among other knowledge, the book contains a large number of machines of the period. The devices and machines are classified according to its function, and a surprising number of pumps, mills, cranes and other machines, particularly those driven by water, wind-energy, gravity or animal traction is included.

It is regrettable that the book was not published at the time due to a lack of consent by Philip II. Had it been published, it would undoubtedly have become as well-known as the most famous European Renaissance treatises. Known and probably used by engineers and architects such as Gómez de Mora, Teodoro Ardemans and Benito Bails, it remained in relative oblivion until the 60s of the last Century when various historians in Technology showed an interest in it.

This work sets out some reflections on the importance of this book and takes a detailed look at the main mechanisms and machines it describes, while making comparisons with similar devices of the period or those that may have had an influence on the contents.

On the Authorship of the Twenty-One Books

The School of Civil Engineering prepared an edition of "The Twenty-One Books of Devices and Machines" in 1983 and the Juanelo Turriano Foundation, founded by José Antonio García-Diego in 1987, produced a facsimile edition in 1997. However, the continuing efforts of publishers and researchers have failed to reveal the authorship of the codex.

Round about 1645, Gómez de Mora, the royal architect, chose the title page shown in Fig. 1 for "The Twenty-One Books", where it reads, "The Twenty-One Books of Devices and Machines of Juanelo". This reference to Juanelo on the title page contributed initially to Juanelo's being attributed the authorship of this work.

"The Twenty-One Books of Devices and Machines of Juanelo, ordered written and demonstrated by King Philip II, Catholic King of Spain and New World. Dedicated to John of Austria.".

Fig. 1 Title page of the Twenty-One Books

Later on, the words "Machines of Juanelo" was thought to be only a way of alluding to the quality of the machines described in the work, due to his renown at the time and the reputation that grew around him. Moreover, it seems strange that Juanelo Turriano would not include his most important work in this great Machine Encyclopedia: the famous device for raising water from the river Tagus to the Citadel in Toledo, the old capital of Spain, overcoming a difference in level of ninety metres.

In view of the features of the text, written in a Spanish full of Aragonese expressions, with numerous and precise references to Aragón (Spain), José Antonio García-Diego and Juan Antonio Frago reached the conclusion that the author was of Aragonese origin but his identity remained still unknown.

After some additional and detailed research, Nicolás García Tapia put forward Pedro Juan de Lastanosa (1527–1576), from Aragón, as the author, an inclination that has gained strength in recent years. On the other hand, not everyone accepts this hypothesis, which has given rise to heated polemics that have promoted an even more extensive study of this work, which in turn has led to new studies being published on the matter [4–8].

A relevant argument contributed by Antonio T. Reguera, refers to the contradiction that Lastanosa left no proof of his authorship, when, for instance, his recognition as legitimate holder of a patent for a mill is well-known.

At present, various authors are of the opinion that "The Twenty-One Books" may have been written by different authors, one of whom would have been Lastanosa, according to Nicolás García Tapia's version. This hypothesis is supported by the existence of considerable differences between chapters of the work regarding style, degree of detail and scientific-technical quality.

New events have occurred recently that open up new lines of future research. María Teresa Cacho located an undated and unsigned manuscript preserved in the national Library of Florence, entitled "Trattato dell'acque". This is a treatise on Hydraulic Engineering written in Spanish that bears a remarkable similarity to "The Twenty-One Books" preserved in the National Library of Madrid. Much shorter with only 84 pages, it contains 350 illustrations of which 315 appear in the Madrid manuscript. The faint definition of some of the illustrations suggests that the Florentine version is older.

A third manuscript has also been discovered belonging to a private collection in Barcelona, and therefore less known than the previous ones. This Catalan Codex comes close to the Madrid version, having 609 pages and 404 illustrations compared to the 949 pages and 509 illustrations of the Madrid manuscript.

Structure and Contents of the Twenty-One Books

The compendium kept in the National Library of Madrid deals with numerous themes related to Mechanical Engineering, Civil Engineering, Naval Engineering and Architecture, as well as how to obtain and process different raw materials used extensively in these disciplines. All this knowledge is grouped together in five related books, following the structure set out below:

Books One to Five: On the properties of water, methods for finding it and evaluating its quality.

Books Six to Ten: On how to extract, transport and store water. On the construction of aqueducts, dams, cisterns and tanks.

Books Eleven to Thirteen: On mills, how to build them, the different types and their use for grinding corn, sifting flour, extracting water and washing fabric.

Books Fourteen to Eighteen: On the use of wood and stone for building. On the properties of these raw materials and how to obtain them. On the construction of stone and wooden bridges and boats.

Books Nineteen to Twenty-One: On building structures on the sea and about harbour defenses. On other works of Hydraulic Engineering and water clocks.

Below are listed the main developments described concerning Mechanical Engineering, together with a comparative study of other similar inventions existing towards the end of the 16th Century, when this Machine Encyclopedia was produced.

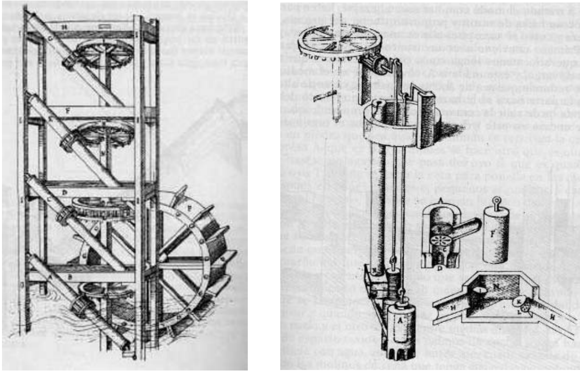
Some of the Main Devices and Machines Included in the Twenty-One Books

These Books include detailed descriptions of machines and devices, mainly water raising machines, different kinds of mills and building machinery; in order to give this work a practical character according to its historical context.

Water Raising Machines

The need to supply cities with water together with the requirements to remove water from mine workings, especially in the territories in the Viceroyalty of New Spain, promoted the compilation of many references to hydraulic devices such as pumps, and to water raising devices in general.

Some references are about improvements to machines known and used since Antiquity. Figure 2a shows a set of four Archimedes screws driven by a common hydraulically powered shaft, with a remarkable water-raising capacity. Figure 2b shows a crown-lantern gear that drives a crankshaft to power a force pump similar to Ctesibius', which works by alternately sending a flow to a collector tank from each of the two compartments in which the pump is divided. Due to this principle, a more uniform flow is obtained since the two pumps take turns to raise the water, which flows out through some side openings in the pistons themselves.



a) b)

Fig. 2 (a) Archimedes screws; (**b**) Force pump; from “The Twenty-One Books”

The text of “The Twenty-One Books” recommends using these pumps for raising water to great heights, but only in small amounts due to the weight of water. Also emphasized is the importance of using the correct size machine parts.

Figure 3 shows other water raising devices, this time animal-powered, which provides information as to the size and power of the machines.

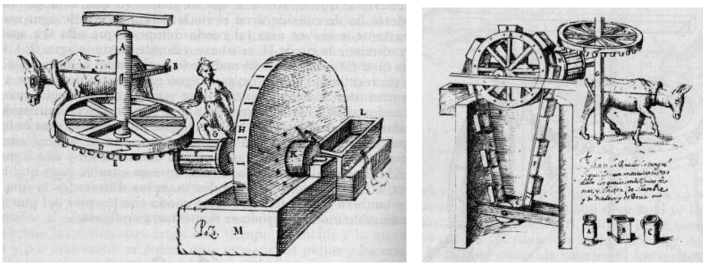
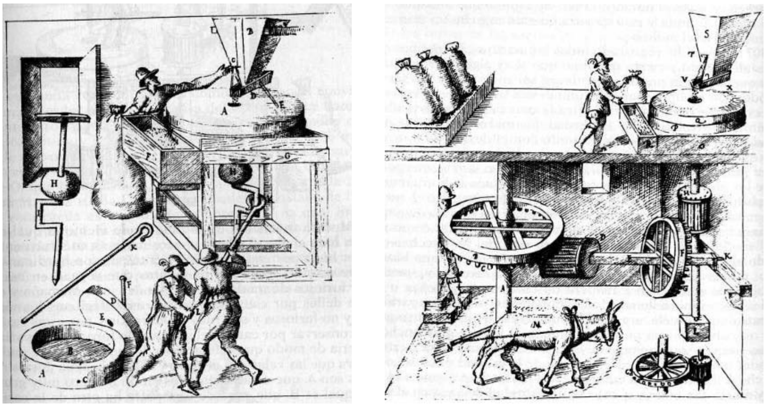


Fig. 3 Animal-powered water raising devices, from “The Twenty-One Books”

Iberian Empire Mills

Milling was of vital economic importance in these first colonial empires, because various sectors of industry and agriculture depended on it. Wheat and oil were the staple diet of the native population of the Iberian empires. In addition, mills were linked to colonial mining and therefore to the financial support of the conquering and expansion activities.

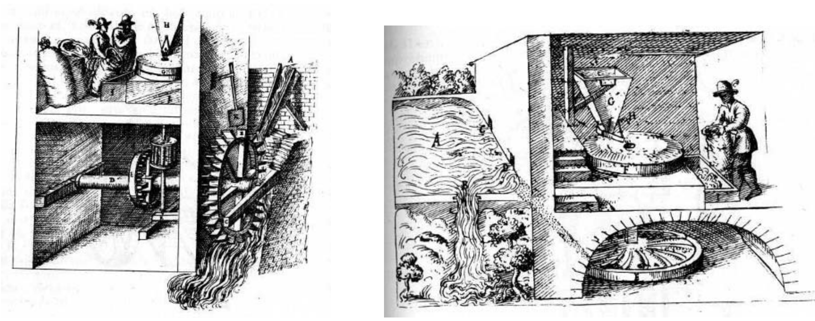
The descriptions found in “The Twenty-One Books” start out from some simple mechanisms like the hand-operated flour mill in Fig. 4a, or the animal-powered one in Fig. 4b.



a) b)

Fig. 4 Flour mills from “The Twenty-One Books”; (**a**) Hand-operated; (**b**) Animal-powered

Hydraulic power drive is also frequently described, using both vertical wheels (Fig. 5a) and horizontal wheels (Fig. 5b). There is a section in “The Twenty-One Books” devoted to a study of the appropriate layout and spatial location for water pipes carrying water to the wheels so as to improve operating efficiency.



a) b)

Fig. 5 Water wheel-driven flour mills, from “The Twenty-One Books”; (**a**) Vertical wheel; (**b**) Horizontal wheel

On other developments explained the mill is driven by wind-power, as in Fig. 6, which the writer assures, “is very common in Flanders, Germany and France, but not in Spain or Italy because the winds in these regions are not suitable for driving them as they are not constant when they blow”.

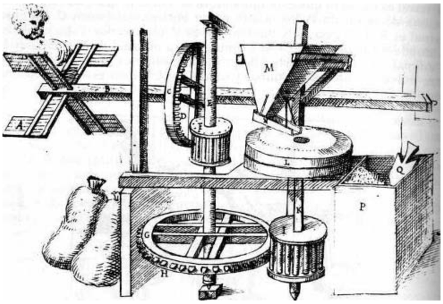
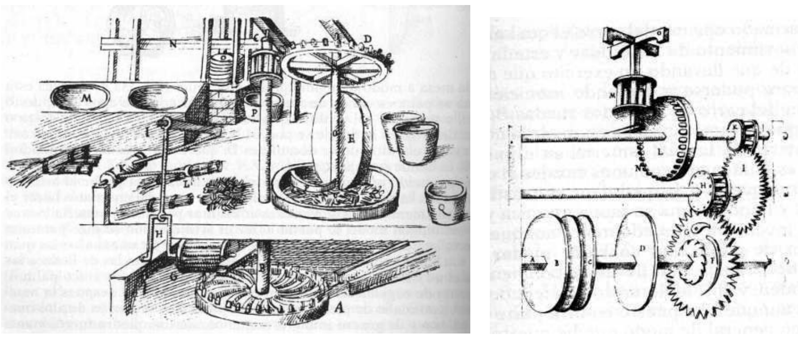


Fig. 6 Windmill, from “The Twenty-One Books”

When sugar cane began to be exploited overseas, milling machines were also required, which led to the development of more complex high production systems. The set up shown in Fig. 7a presents a drive wheel that in turn powers the milling and automatic sugar cane cutting mechanism, enabling the cutting and milling operations to be synchronised.

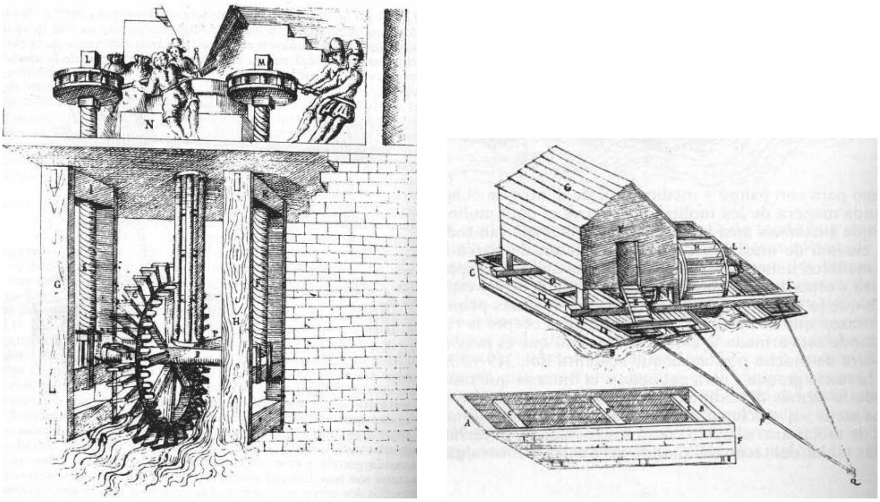
The attempts to develop ever more productive mills becomes clear in other machinery presented in the text, like the device shown in Fig. 7b for milling flour. The author himself warns that the high efficiency means that the parts may often suffer damage. The transmission mechanism is more complex, with three horizontal shafts, one vertical and including several reduction stages. Also noteworthy is the addition of fly wheels and a ratchet mechanism on one of the wheels. This mill with counterweights gave rise to litigation, concerning patent rights, between the Spaniard Pedro Juan de Lastanosa and the New World Spaniard Ruy Lope de Luna, which ended in a judgement of Solomon with the profits being divided between both of them.

Moreover, the machine in Fig. 7b works with counterweights, using large weights set at a considerable height. It is an example of the efforts made in the 16th century to use not only animal or hydraulic energy but also gravity, as additional support.



a) b)

Fig. 7 (**a**) Mill for producing sugar; (**b**) High efficiency flour-milling mechanism, from “The Twenty-One Books”



a) b)

Fig. 8 (a) Flour mill adjustable to the level of flow of the water; (**b**) Floating mill

Another way of improving productivity was to endow the machines with a capacity to work in more demanding conditions:

Figure 8a shows a flour mill that can be adjusted in case the wheels are powered by highly changing currents. In such a situation, it is useful to be able to adjust the height of the water wheel and to adapt the position of the paddles according to the water level, which was performed by operating two screws. The great length of the lantern means that it will always engage the crown mounted on the water wheel although its height may vary.

Figure 8b shows floating flour mills that the author of "The Twenty-One Books" claims to have seen in many parts of Italy. The anchorage allowed them to be adapted to the amount of water of the river. The wheels powered by water from beneath had to be placed in pairs or be wider than other types of mill wheels, since the slow running water often did not provide enough power to move them. Consequently, it was quite usual for them not to be able to grind much grain, unless they were driven on fast-flowing rivers.

"The Twenty-One Books" include new designs based on grouping together other devices and discuss the feasibility of these novel designs. One example of this is the sophisticated machine shown in Fig. 9, which performs numerous tasks at the same time: crushing gunpowder, polishing and cleaning weapons and milling flour.

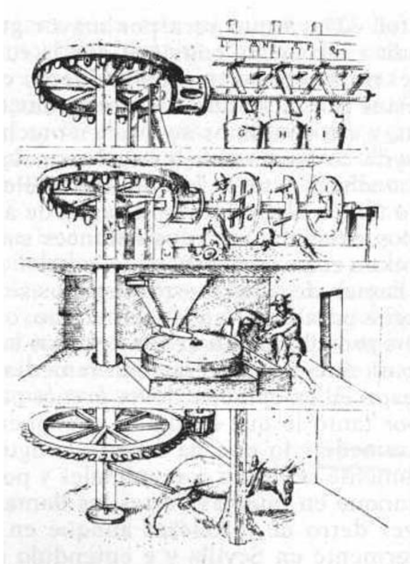


Fig. 9 Machine for performing numerous operations simultaneously, from "The Twenty-One Books"

Building Machinery

The great works of architecture carried out in the age of splendour of the Iberian Empire also required lifting machines with important mechanical requirements. "The Twenty-One Books" contributed to the spread of some of these cranes, like the one in Fig. 10, used for lifting building workers in a kind of cage. Elevation was achieved by some manually operated drums that took up the rope using a pulley system. It could also be used for lowering persons, down to mining galleries, for example. Other different cranes are depicted in Fig. 11.

The text sets out the advantages of using pulleys and multiple ropes to reduce the weight borne by each cord when lifting very heavy weights.

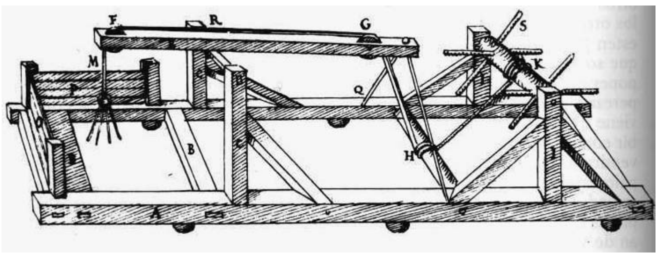


Fig. 10 Machine for lifting and lowering workers

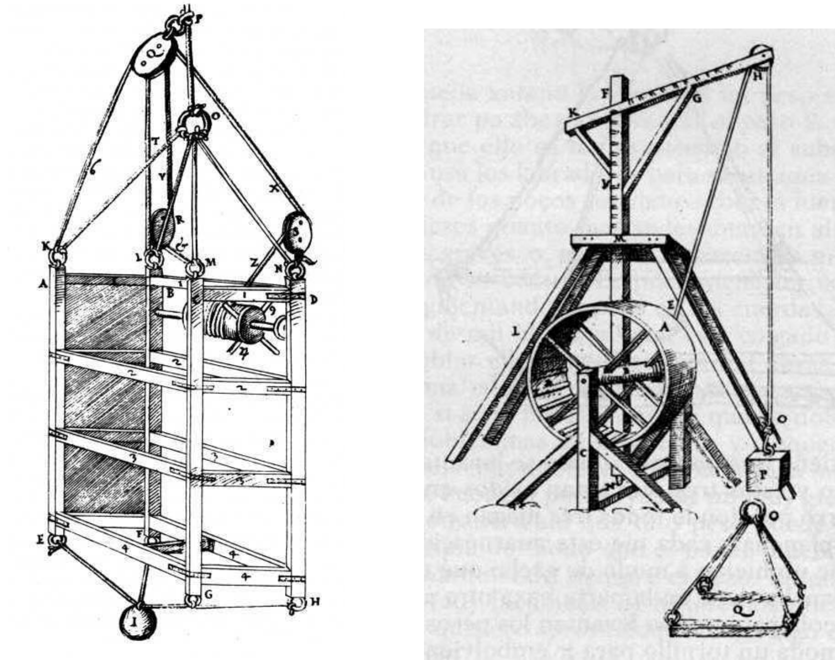


Fig. 11 Cranes, from "The Twenty-One Books"

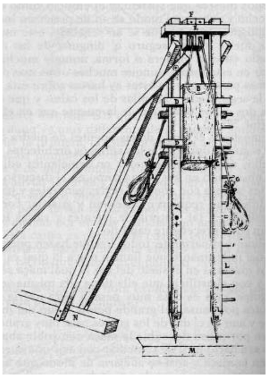
Other Machines and Mechanisms in the Compilation

It is difficult to summarise the contents of the "Twenty-One Books of Devices and Machines" in relation with other types of devices and machinery, which is why only a few examples are given below.

Overseas relations meant that harbours had to be enlarged and in many cities built. Pile driving machines were frequently used in the period; Fig. 12a depicts one of the machines of this kind explained in these books. It was manually operated by pulling on ropes to raise the hammer with the use of pulleys. The way of joining the ropes to the pulleys and hammer is shown in detail in Fig. 12b.

The machine in Fig. 13a consists of a hydraulic press, with a crankshaft to drive an articulated rod mechanism. These move some swing hammers that strike a wedge to produce pressing by means of a crossbeam. The machine can be seen in operation in Fig. 13b.

Another device shown is one for beating and washing clothes with water, as in exposed the diagram of Fig. 14. A small flow of water halfway up a water wheel suffices to set the device in motion, by producing movement in a shaft bearing two radial actuators to act as cams to cause the pendulum motion of the washing tools.



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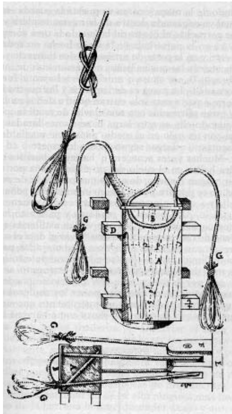
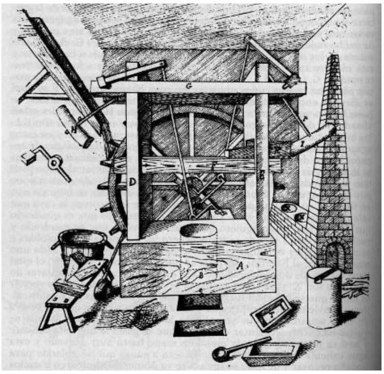


b)

Fig. 12 (**a**) Pile driving machine; (**b**) Detail of the device, from "The Twenty-One Books"



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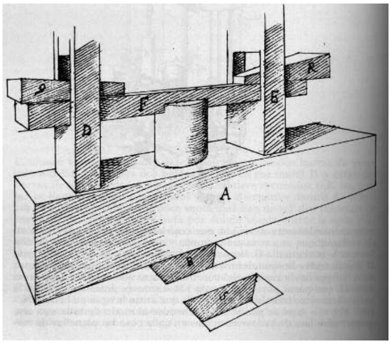

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Fig. 13 (**a**) Wax press; (**b**) Detail of pressing, from the Twenty-One Books

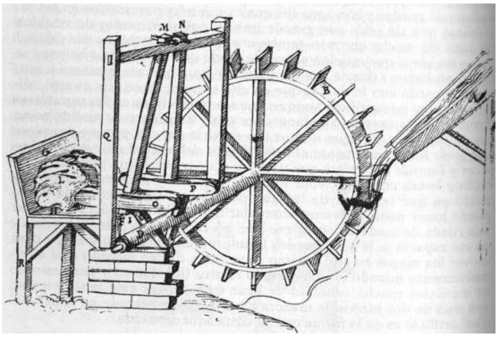
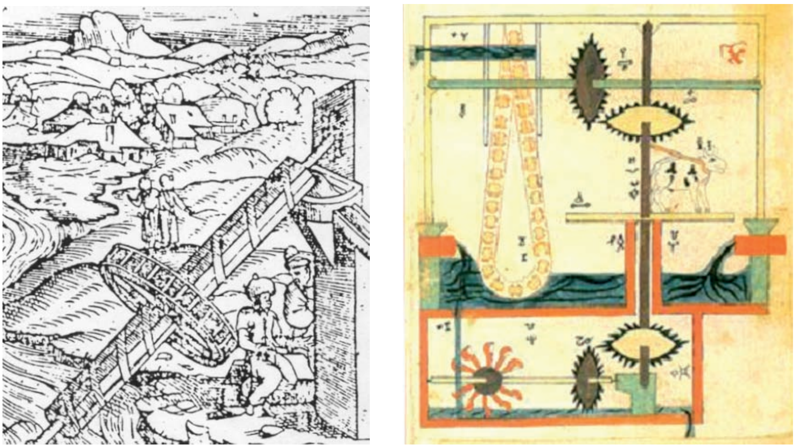


Fig. 14 Clothes washing device, from the Twenty-one Books

Comparison with Other Machine Treatises During the Renaissance

The Machine Renaissance, starting from Italy, reached extent areas of Occidental Europe in the second half of the 15th century, where the development of relevant machines and devices rose very quickly. The main developments were hydraulic devices, mills, building machinery and other useful machines, in line with the machines included in "The Twenty-One Books". Nevertheless, the interest in other less practical devices such as clocks or automatons was reduced [9].

The treatises of the Renaissance include mainly new machines and reviews of past works in order to improve their capacity, accuracy and efficiency. For example, though the Archimedes screw is supposed to be known and used since the Antiquity, this system was reproduced later in many works during the Renaissance [2], like shows the Fig. 15a depicted by Daniele Barbaro in 1584 or the cited modification of this machine presented in the Twenty-One Books (Fig. 2a). Other hydraulic devices included in the Twenty-One Books (Figs. 2b and 3), show correlations not only with machines from the European culture but also with preceding illustrations from Medieval Islam [10]. For example, the machines of Al-Jazari reveal a high interest in hydraulic machines, like the one depicted in Fig. 15b, from Al-Jazari's "Book of Knowledge of Ingenious Mechanical Devices", finished in 1206. In addition, Di Giorgio's "Trattati di architettura ingegneria" ("Architecture and machines treatise") published in 1484, includes examples of water suction machines like the hand-operated dual piston pump depicted in Fig. 16 which reminds the pump shown in Fig. 2a.



a) b)

Fig. 15 (**a**) Archimedes screw, by Daniele Bárbaro (1584); (**b**) An hydraulic machine from Al-Jazari's book

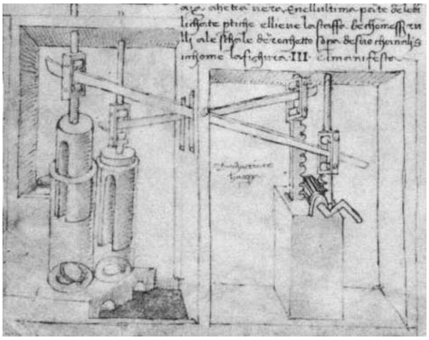
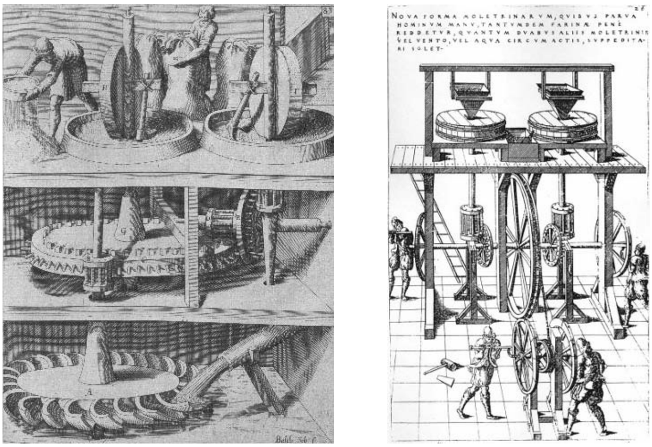


Fig. 16 Di Giorgio's water suction machine from "Trattato di architectura e machine"

In the same way, the mills included in "The Twenty One Books", like the examples shown in Figs. 4, 5, 6, 7, 8 and 9, bear numerous similarities to other Renaissance works. A remarkable example due to Jacobus Strada is the flour mill in Fig. 17a included in his work "Kunstliche Abrís allerhand Wasser – Wind Rosz- und Handt Muhlen" from 1617 [2]. In this new design some considerations have been taking into account in order to enhance previously existing designs. On the one hand, a horizontal water wheel is used, which constitutes an authentic turbine with spoon-like blades designed so that the flow will hit the blade and leave in the precise direction to obtain the maximum efficiency. On the other hand, the machine is improved for proto-industrial applications, by using a large horizontal tooth wheel and two lanterns, in order to distribute the power transmitted to two different mill wheels. Another example is shown in Fig. 17b concerning a hand-operated mill with two mill wheels, included in Jacobus Bessonus's "Theatrum Instrumentorum et Machinarum", published in 1578 [2].

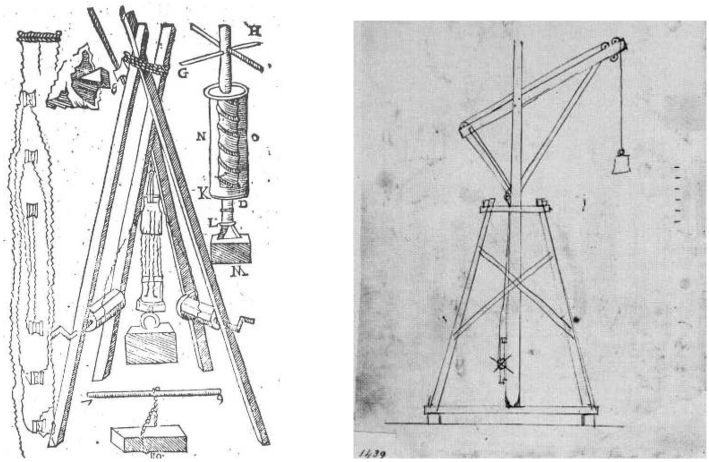


a) b)

Fig. 17 Mills by renaissance authors; (**a**) Jacobus Strada; (**b**) Jacobus Bessonus

The same considerations regarding technical solutions similar to other authors are common in the chapters of “The Twenty-One Books” devoted to lifting machinery for building applications. The appearance of the devices shown in Figs. 10 and 11 reminds for example a machine depicted by Daniele Barbaro in 1584 (Fig. 18a), considering the comments in Vitruvius’ book “De Architectura” [11,12] and a machine scheme (Fig. 18b) present in Antonio Da Sagallo’s collection of sheets from 1526 approximately [2].

It is possible to find many additional examples of machines with equivalent mechanical developments in other Renaissance and Pre-Renaissance works [2,13,14].



a) b)

Fig. 18 (**a**) Vitruvius’ elevator represented by Daniele Barbaro; (**b**) A crane, by Antonio da Sangallo

Finally, the similitude between many devices included in “The Twenty-One Books” and other remarkable manuscripts of the Renaissance is shown through the Figs. 12, 13 and 14, compared respectively to the pile driving machine shown in Fig. 19, the press depicted in Fig. 20a and the washing device shown in Fig. 20b. Figure 19 has been taken from Giovanni Branca’s “Le machine” from 1629 [15]. Figure 20a,b have been obtained from Zonca’s work [16] entitled “Novo teatro di machine et edificii “written in 1607.

The machines found in “The Twenty-One Books” are in line with many other remarkable books of the Renaissance, though some designs exposed are simpler than those of Strada, Bessonus or Branca. The major contribution of “The Twenty-One Books” is the compilation, as a kind of Machine Encyclopedia, of many useful machines and devices used at that time in several application areas and for numerous practical tasks. The dissemination of the machines is highly promoted with this compendium, because of the detailed figures and comments on each one of the hundreds of designs exposed, including guidelines for the construction, comparisons between machines, advantages and disadvantages of each design.

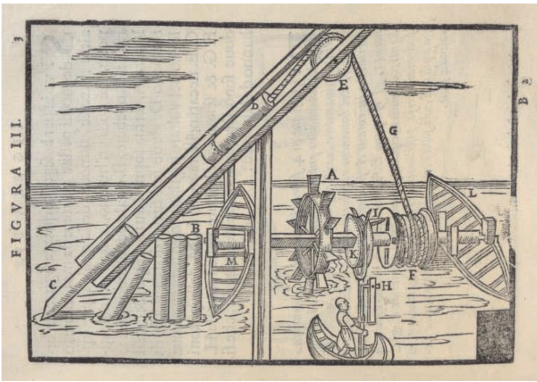
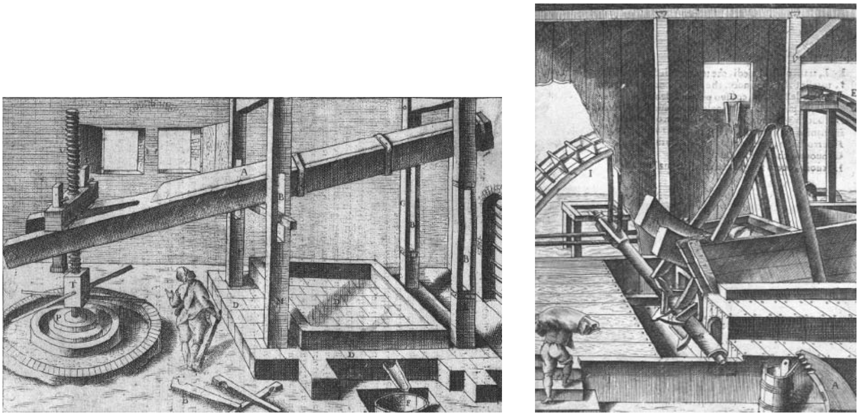


Fig. 19 Pile driving machine by Giovanni Branca, from “Le machine”



a) b)

Fig. 20 (**a**) Zonca’s press; (**b**) Zonca’s washing device; from “Novo teatro di machine et edificii”

Conclusions

The “Twenty-One Books of Devices and Machines” is the first and most important Encyclopedia of Machines and Mechanisms written in Spain. It was ordered to be written by King Philip II around the year 1570, as a sign of the strategic interest that Mechanical Engineering has always had in the birth, expansion and defense of any empire. This work sets out some reflections on the importance of this book and takes a detailed look at some of the main mechanisms and machines described, while making comparisons with similar devices of the period or those that may have had an influence on the contents.

Despite the fact that most of the machines and mechanisms described in "The Twenty-One Books" do not represent any significant technological progress regarding to devices already existing at the time, the large number of themes dealt with and their detailed analysis is remarkable. Additionally, the detailed schematic drawings included in "The Twenty-One Books" provide insight on the size and power of many different machines of the 16th century. It was undoubtedly written as a reference for all the engineers of the Spanish Crown for providing advised on how they should optimize their tasks with the help of Machines and Mechanisms.

Who wrote, copied, edited or compiled this compendium of Engineering and Architectural Knowledge is really of no special importance; what really bears relevance is that the manuscript has been preserved. Therefore we can continue its detailed examination and many of the devices and machines described can even be reproduced, thanks to the high level of detail devoted to its production.

We hope the reflections exposed help to call the attention, of foreign specialists on History of Machines and Mechanisms, on the largest compendium produced on this subject in Spain. We also would like to increase the technological and teaching interests on the machines and devices explained in the work.

References

1. Anonymous (1997) Los Veintiún Libros de los Ingenios y Máquinas de Juanelo Turriano, Facsimile of the manuscript (circa 1570) in the National Library in Madrid, Fundación Juanelo Turriano.
2. Bautista E, Ceccarelli M, et al. (2007) Breve Historia Ilustrada de las Máquinas, Sección de Publicaciones de la E.T.S.I.I. Universidad Politécnica de Madrid.
3. Kaiser W, König W (2006) Geschichte des Ingenierus: Ein Beruf in sechs Jahrtausenden, 150 Jahre Verein Deutsche Ingenieure 1856–2006, Carl Hanser Verlag.
4. García Tapia N (1994) Ciencia y Técnica en la España de los Austrias, Una visión desde la perspectiva de las investigaciones actuales, Cuadernos de Historia Moderna, Editorial Complutense, Madrid.
5. García Tapia N (1990) En Defensa de Lastanosa, Revista de Obras Públicas.
6. García Tapia N (1989) Técnica y poder en Castilla durante los siglos XVI y XVII, Consejería de Cultura y Bienestar Social.
7. García Tapia N (1988) Pedro Juan de Lastanosa y Pseudo Juanelo Turriano.
8. García Tapia N (2001) Un inventor navarro, Jerónimo de Ayanz y Beaumont, Departamento de Educación y Cultura de Pamplona.
9. García-Diego JA (1982) Los relojes y autómatas de Juanelo Turriano, Albatros.
10. Hill D, al-Hassan A (1986) Islamic Technology: An Illustrated History, Cambridge University Press, Cambridge.
11. Ortiz y Sanz J (1787) Tratado sobre máquinas de Vitruvius.
12. Vitruvius PM (1511) De architectura. Published by Fra Giocondo, Verona. (reprinted in 1513, 1522 and 1523)
13. Banu Musa, The book of ingenious devices: Kitab Al-Hiyal, 10th Century.

14. Al-Yazari, Al-Zaman B, Hill D, (1974) The Book of Knowledge of Ingenious Devices, D. Reidel Publishing Co., Dordrecht.
15. Branca G (1629) Le machine.
16. Zonca V (1607) Novo teatro di machine et edificii per uarie et sicure operationi, Appresso F. Bertelli.

A Contribution to the History of Cam Mechanisms – From Leonardo da Vinci Till Today

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Abstract Cams and cam mechanisms are widely spread in mechanical engineering design, mostly to transform uniform rotary motion into non-uniform rotary motion or into linear motion. Sometimes cams and cam mechanisms are coupled with linkages, thus giving a broader variety of output motions and applications. From the historical point of view it is possible to derive cam mechanisms from some of the "mechanical abilities" in the antiquity. The present paper tries to reveal the roots of cams and cam mechanisms starting in the time of *Leonardo da Vinci* and ending with some well-known applications of today. It refers to two preparatory papers (Müller and Mauersberger, Zur Entwicklungsgeschichte der Kurvengetriebe, 1988; Müller and Mauersberger, LEONARDO DA VINCI – Seine Beziehungen zum Kurvengetriebe im Vorfeld der Technikwissenschaften, 1990) written in 1988 and 1990 by the late Prof. Jörg Müller (Rostock, Germany) and the second author as co-author. The rather concise retrospective is mainly taken from a post in Germany.

Keywords History of cam mechanisms, Machine books, Machine age, Old models of cam mechanisms

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Introduction

Cam mechanisms with at least three links and one cam joint or so-called higher pair form a very common and most useful part of a machine, because the shapes of the two pair elements in contact can be given almost any arbitrary form dependent on the geometric-kinematic task to be fulfilled. Normally a cam joint represents maximally five joint d.o f. in space and two joint d.o f (rolling and sliding) in plane. But of course, there may be mechanical restrictions that reduce the number of d.o f. Especially with planar higher pairs it is possible and well known to give the two element shapes in contact the forms of corresponding rolling centrodes and thus create a one d.o f. higher pair with pure rolling behaviour and theoretically no friction and wear. Figure 1 shows some design example types of planar and spatial cam mechanisms.

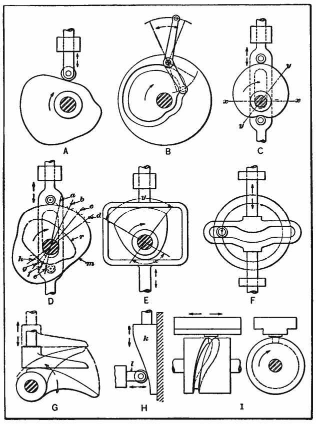

Fig. 1 Some exemplary types of planar and spatial cam mechanisms

Following the line of time and personalities as generally scheduled in [1] concerning on the one hand the early mechanical developments in Mechanism and Machine Science (MMS) and on the other hand a period especially described as the "Renaissance of Machines" [2], an approach similar to [3] is the goal of this historical contribution to MMS, but this time with the focus on cams and cam mechanisms [4]. The origin of these mechanisms must be closely seen in connection with the development of technical and manufacturing processes and with the first machines that could transmit and transform human and later natural mechanical power sources, like water and wind streams. In the antiquity five simple machines or so-called "mechanical abilities" were known which could amplify the human arm force considerably, i.e. lever, wedge (inclined plane), wheel (roll, axle), screw (thread, helix, spindle) and pulley. These "mechanical abilities" are shown, for example, on the cover page of the German translation of the books "Mechanicorum Libri" written by the Italian artist-engineer *Guido Ubaldo del Monte* (1545–1607), Fig. 2 (left) [5].

If we make rotate a wedge around a central axis, we get a screw or a helix; if we make rotate the helix, we can transport water in properly shaped grooves or pipes from a lower to a higher level, as already described in detail by the Roman *Marcus Vitruvius Pollio* (80, 70–25 BC) for use in a mine. The sketch in Fig. 2 (right) is taken from a book of *W. Ryff* in 1548 [6] who explained and translated from Latin into German *Vitruvius´* ideas and inventions from a text without pictures (they got lost). Instead, *Ryff* added pictures of his own to illustrate essential geometric relations. It is also possible to move up and down a load by means of a nut on a properly shaped thread. Thus, we can take the thread as a collection of cam joints put in series.

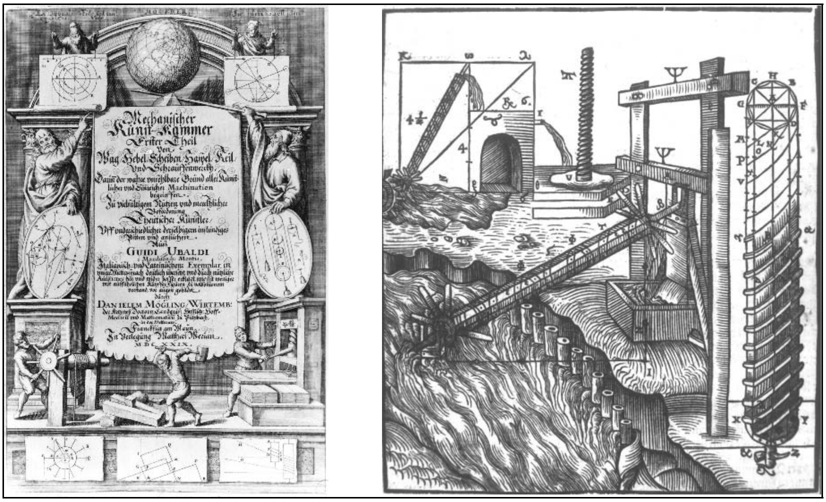

Fig. 2 Cover page of the German translation of the book of *Guido Ubaldo del Monte* (*left*) and *Archimedes* helix for lifting water in a mine (*right*)

This historical contribution starts with *Leonardo da Vinci* (1452–1519), one of the most famous artist-engineers of the Renaissance, the period between 1350 and 1550. From Leonardo the mechanism and machine science engineer community inherited a big number of sketches and proposals of machine parts including cam mechanisms for the transformation of rotary motion into linear motion. Especially the Codex Madrid I, translated into English by the Leonardo scholar *Ladislao Reti* and rediscovered in 1965 has revealed to be also a mine for many applications of cam mechanisms, e.g. in hammer mills, clock escapements, locks, water lifts and pumps. We will make an intermediate stop with *Franz Reuleaux* (1829–1905), the famous German pioneer of kinematics and machinery, in the period of the Age of Machines leading to the Industrial Revolution in Europe and the USA [7]. Within the last 100 years of the recent past the development of cam mechanisms is essentially determined by new manufacturing processes, more theoretical basic knowledge of mathematics and mechanics and finally also by the use of computers and computer programs.

The Sketchbooks of Leonardo da Vinci

Leonardo da Vinci, who was born 1452 in Vinci near Florence (Italy) and died 1519 in Amboise near Tours (France), was a genius of mankind. He thought and worked in his period of life as a drawer, painter, sculptor, architect and engineer in the broadest sense. Moreover, he also dealt with topics and problems on almost all fields of natural sciences, medicine included. In the context of the present paper the interest in *Leonardo´s* legacy is restricted to his genial works on the fields of mechanics, mechanisms and machines.

The sketchbooks of *Leonardo da Vinci* are not completely preserved today, they were spread all over Europe after the death of his scholar and heir *Francesco Melzi* who took care of the books for fifty years. The rests of his legacy in different European countries were recollected during the last centuries and put in so-called “codices”. The important codices concerning mechanisms and machines are as follows [8–10]: The “Codex Atlanticus (CA)” [11] is preserved in the Biblioteca Ambrosiana in Milan (Italy), the “Codices Madrid (CM) I and II” [12] in the National Library in Madrid (Spain), the “Codex Forster” [13] in the Victoria & Albert Museum and the “Codex Arundel” [14] in the British Museum, both in London (UK). Additionally, there are also some smaller sketchbooks (manuscripts) labelled A–M [15] which were looted in Milan by Napoleon´s troops in 1796 and now reside at the Institut de France in Paris.

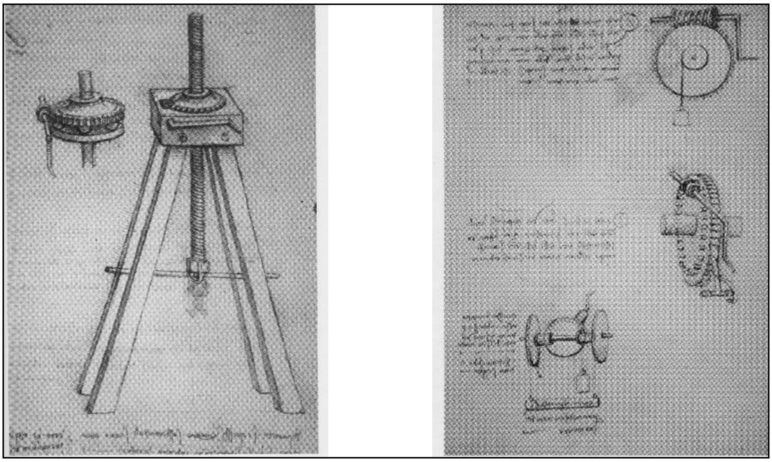

Fig. 3 Screw jack (*left*) and three different load lifts (*right*)

As already pointed out two bodies in contact form a general cam joint and from this point of view we find in CM I a manually driven winch or screw jack for lifting loads with three different cam joints (Fig. 3, left, [8,16]): The first cam joint belongs to a worm gear or endless screw, the worm rotates by a crank, and the worm wheel is at the same time nut and part of the second cam joint combination with a screw mechanism; finally there a several balls between the lower plate of the worm wheel and a fixed plate on top of the winch stand; thus a ball bearing in a protective box between worm wheel and stand is introduced to reduce the influence of friction.

Also in CM I we discover three interesting machines for lifting loads from the ground (Fig. 3, right, [10,16]). The first one (above) is based again on a worm gear, the second one (in the middle) represents a pin-teeth gear with one lantern pinion and a crown wheel. There is also an additional ratchet mechanism to prevent the load from falling back to the ground. The third machine (below) belongs to the group of reversing or mangle mechanisms [8]. As the middle wheel on the crank axis with only a half circle of pin teeth rotates, say, in clockwise direction, it first forces the right wheel to lift the bar load, the left wheel does the same, because it is attached to a common axis. During the next half rotation of the crank, the left wheel is now forced to let the load go down, and then a second lift process follows a half circle later, and so on. The crank is normally turned by a worker, but his turning activity is supported by a counterweight acting on the middle wheel.

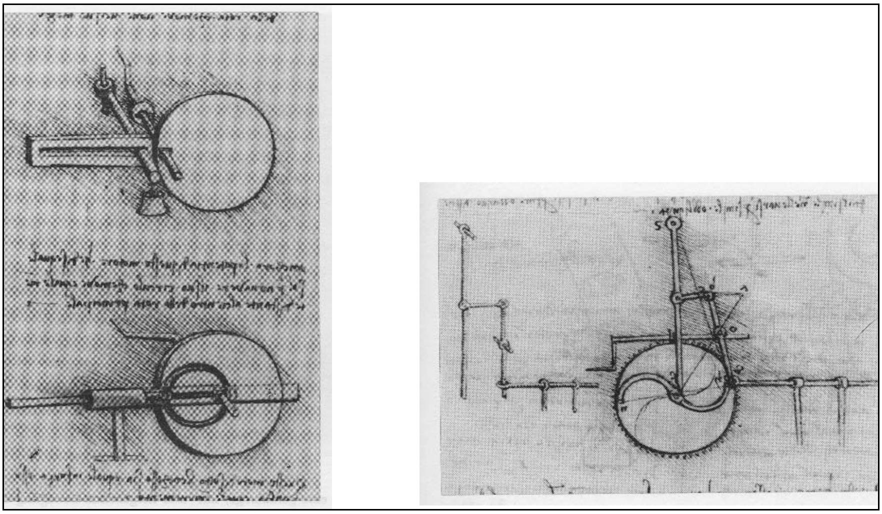

Fig. 4 Two cam mechanisms with translating follower (*left*) and cam linkage combination (*right*)

Leonardo was fond of cam mechanisms being very compact mechanical devices to transform rotary into linear motion. Sometimes we wonder what could have been the use then of types of cam mechanisms that turn out to be very familiar to the mechanical engineer of today. Two cam mechanisms based on eccentrically rotating circular disks are depicted on the left side of Fig. 4 (CM I) [10]. The mechanism above is of the type “disk cam with translating flat-faced follower, force-closure", the mechanism below belongs to the group "grooved disk cam with translating pin-follower, form-closure". *Leonardo* also designed a cam-linkage combination as shown on the right side of Fig. 4 (CM I) [10]. A disk cam with a groove forming a mirror image of the letter "S" is driven by a worm gear. Two pins match with the groove and belong to two different links of a planar five-bar linkage having two degrees of freedom. The range of motion of both pins is always one half of the letter "S" alternately. If one pin has reached the rim of the worm wheel, the other pin is in the centre of the worm wheel and unable to move. During operation the pin at the rim moves to the centre and the pin in the centre is forced by the linkage to move to the rim, this process occurs twice during one full rotation of the worm wheel resulting in a motion of the horizontal rod back and forth.

With many of his inventions *Leonardo da Vinci* was ahead of his time. Craftsmen around him were not able to realize the majority of his design ideas, proper tools and proper materials were not yet developed or found. So, somehow *Leonardo* was a clairvoyant mechanical engineer in his ideas and drawings. His genius to make three-dimensional drawings and his skill and ability to take details apart from the whole machine or mechanism was incomprehensible, but helped to preserve his ideas for coming generations of mechanical engineers.

The Machine Books of the 16th to the 18th Century

Theodor Beck gives a very good and impressive survey of famous engineers of the old past in his book [17]. The period he viewed and discussed ranges from *Heron of Alexandria* (10–85) to *James Watt* (1736–1819), the inventor of the steam engine. Some of these "artist engineers" wrote so-called "machine books" with wonderful drawings, page by page. The machine books were works of art with fine copperplate engravings comprising the contemporary technical and technological knowledge about machines and their use or – more precisely sometimes – about their purpose. A very important question at that time was, for example, how to transport water and how to transform water flow energy into mechanical (kinetic) energy of wheels and sliders, all designed for use in hydraulic machines, e.g. scoop devices, water wheel drives for grain and oil mills, and water pumps.

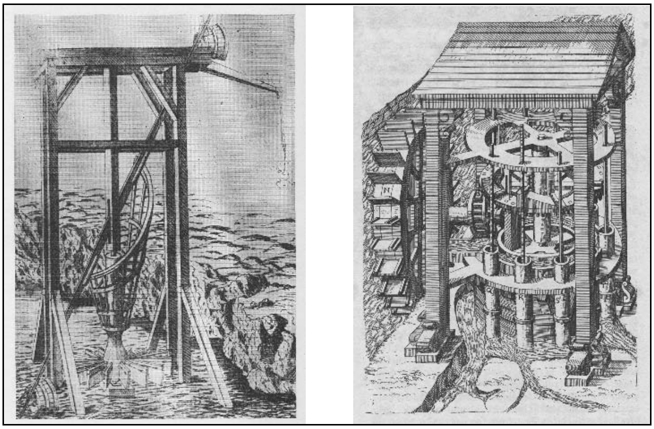

Fig. 5 Two examples of cam mechanisms in machines taken from different machine books

Jacques Besson (1500–1569), professor of mathematics and natural philosophy at the University of Orléans (France), designed in his "Theatrum instrumentorum et machinarum" a gigantic machine for scooping water from a lower to a higher landscape level by means of a balanced beam with two tubs at its ends (Fig. 5, left). The beam is rotated by the water wheel and moves at the same time along a fixed spatial spiral cam and thus lifts the lower tub filled with water to its highest position. The paddles of the water wheel are hinged in order to allow alternate turn of the water wheel for the rise and fall of the beam.

The Italian *Agostino Ramelli* (1530–1590), also working for the French king as a military engineer like *Leonardo da Vinci* half a century before, presents in his machine book titled "Le diverse et artificiose machine" a special multiple piston water pump (Fig. 5, right) [18]. The pistons are moved upwards by cam segments forming a multi-threaded screw. The cam segments are mounted on a circular disk with a pin-wheel turned by a lantern pinion on a common shaft with a driving water wheel.

The two aforementioned machine books show drafts of machines, technical experiments and possibilities. There are no comments on actual realizations of the machines presented.

In a different way, *Jacob Leupold* (1674–1727) from Leipzig (Germany) wrote a ten-volume machine book titled "Theatrum machinarum" [19] and thus created a new category of literature about machines. Not every machine in his books was his own invention, but he added critical remarks to the then known machines and machine concepts the functions and purposes of which he had studied and understood. He also drew details of machine parts and machine elements that could help to explain and to build the machine. *Leupold* belonged to a new generation of mechanics who did not only want to describe a machine, but tried to dismantle it into its different parts of function and design. An example of *Leupold´s* novel systematic approach as regards cams is shown in Fig. 6 (left).

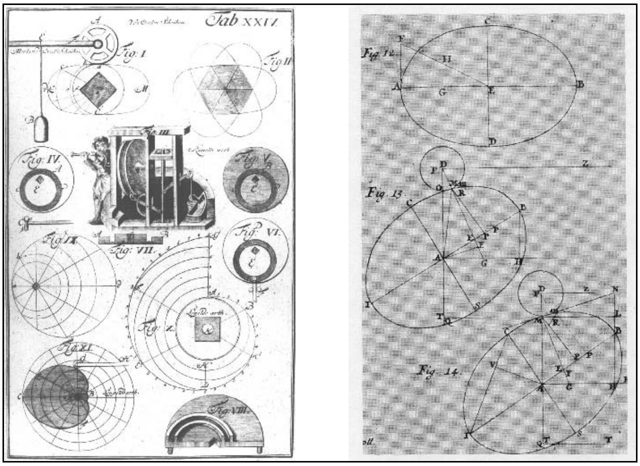

Fig. 6 Cam studies of *Leupold* (*left*) and of *Bélidor* (*right*)

The French engineer officer *Bernard Forest de Bélidor* (1697–1761) also dealt with the idea to move pistons in water pumps by means of cams and improved in his machine book "Architecture hydraulique" [19] two cam versions of two famous French, the geometrician *Girard Desargues* (1593–1662) and the physician *Philippe de la Hire* (1640–1718), the latter pointing out the epicycloidal cam profile.

Instead, *Bélidor* recommended to use ellipses because of an even transmission of pressure forces and consequently less friction influence. He also presented the geometric fundamentals of such elliptic cams, Fig. 6 (right). So *Bélidor* at this early time did not only describe cams and followers, but already wrote a theoretical treatise on this subject.

Finally, it must be emphasized again and again the fact that the material prevailing at that time was wood. Therefore, load-bearing capacity, strength, stability and the resistance against wear of such base material were on a minimal level. Consequently, most of the ideas of the authors of the machine books mentioned could not be set into practice and tested at once, but had to be left to and placed into the minds of future engineer generations of the mechanization era.

Cam Mechanisms in the Period of the Machine Age

The period of the Machine Age is equivalent with the 19th century, and especially its last third is marked by the "Industrial Revolution" in Europe and USA. The kernel process can be defined by the notion "mechanization of production". The machine systems of this century consisted almost without exception of the three parts input or drive unit, transmission unit, output or driven unit. The drive unit or power engine of that time is the steam engine which made the production independent of water streams. The steam engine is closely connected with the name of

James Watt, even though he was not alone involved in the design, development, improvement and industrial introduction of this new power source [20]. The problem concerning the transmission of power had reversed: With water wheels rotary motion had to be transformed into linear motion, now with steam engines linear motions of the pistons had to be transformed into rotary motion.

Modified or further developed mechanisms became necessary which even often could be taken from the old machine books, concerning pumps for example. At that time of mechanization a new solution found had to be patented at once because of the existing rivalry between industrial companies.

For example: To avoid patent quarrels *Watt* invented two different transmission mechanisms with cam joints. The first mechanism called “inclined wheel” had a rod-belt combination acting as a linear drive unit to make rotate the inclined wheel by means of friction rolls, Fig. 7 (left) [21]. This solution strongly depends on a flywheel effect of the inclined wheel to guarantee a constant angular velocity, a condition which *Watt* could not fulfil in a satisfactory way, and so he dropped the inclined wheel. The second mechanism called “eccentric wheel” with three circular disks worked like a cam-roller combination and was kinematically similar to the expansion of the two elements of a rotary joint, Fig. 7 (right).

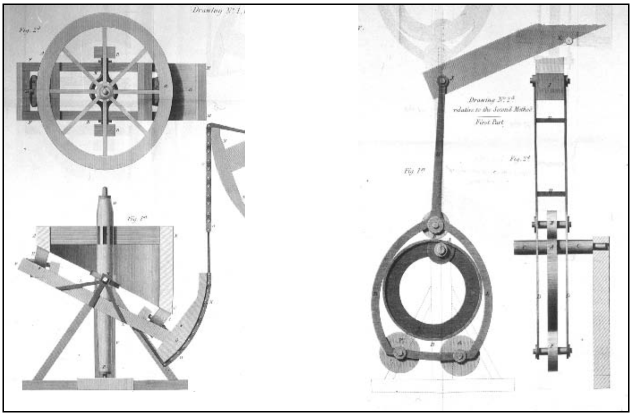

Fig. 7 *James Watt's* cam mechanism solutions to transform linear into rotary motion: Inclined wheel (*left*), eccentric wheel (*right*)

Classical machinery science started in France in the course of the French Revolution (1789–1794) at the École Polytechnique in Paris. *Gaspard Monge* (1746–1818) taught kinematics as part of his subject “Géométrie descriptive”. His scholars *Jean Nicolas Pierre Hachette* (1769–1834), *José Maria Lanz* (1764–1839) and *Augustin de Betancourt* (1758–1824) became protagonists of a “kinematic machine science”. They classified all relevant mechanisms of their time concerning the type and direction of motion (input/output) and treated them as elements of a “mechanism matrix” which also included cam mechanisms, Fig. 8 [22].

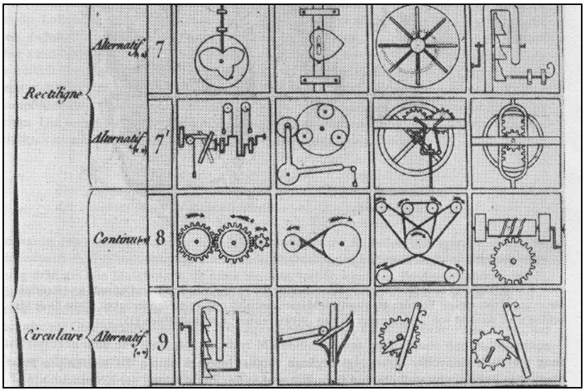

Fig. 8 The "matrix of mechanisms", part of a catalogue by *Lanz* and *Betancourt*

Hachette also dealt with the synthesis of cam mechanisms from the geometric point of view, Fig. 9 (left). Later on, *Jean Victor Poncelet* (1788–1867) who belonged to the "dynamics group" at the École Polytechnique took into account also dynamical aspects of cam mechanisms and pointed to the "pressure angle" α with a translating roller follower as an important characteristic quantity for the optimal transmission of forces, Fig. 9 (right) [23]. Because of his two-track education *Poncelet* was capable of combining geometric-kinematic concepts with dynamic-energetic demands.

The interest in the development of new mechanisms and machines grew more and more in the Machine Age, and parallel to this increased the trend to create mechanism catalogues. The building of mechanism models formed the next step of polytechnical education of students. In England *Robert Willis* (1800–1876) taught kinematics at Cambridge University using mechanism models for experimental purposes. In his book [24] we find cams being classified as rolling *and* sliding pairs.

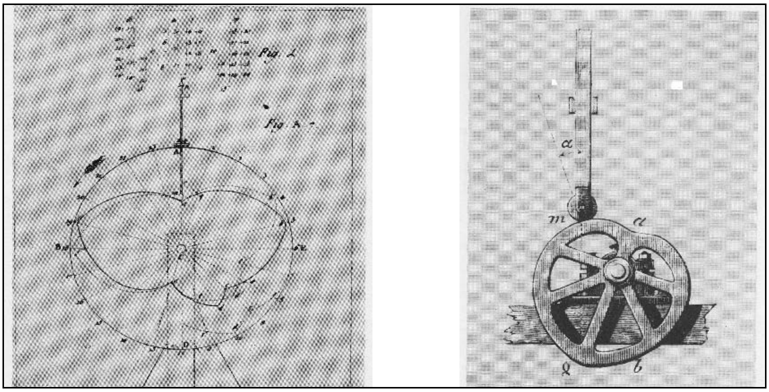

Fig. 9 Cam synthesis design by *Hachette* (*left*) and pressure angle α with a translating roller follower by *Poncelet* (*right*)

Fig. 10 Eight *Redtenbacher* mechanism models from Karlsruhe (Germany)

Ferdinand Redtenbacher (1809–1863) laid the foundations of the scientific mechanical engineering in Germany (and beyond). *Redtenbacher* was professor at the Polytechnic School in Karlsruhe. He established a metal mechanism model collection with as many as 100 specimen [8]. These models were capable of loads and are mostly listed and described by *Redtenbacher* himself in one of his books [25]. Eight specimen are shown in Fig. 10.

Parallel to *Redtenbacher* lived and worked *Johann Andreas Schubert* (1808–1870), professor at the Polytechnic School in Dresden (Germany). Cams and cam mechanisms belonged to his category of elements of machine science [26], Fig. 11 (left). Also *Schubert* used models to explain complex motions of links and points in mechanisms to his students. But till today only nine mechanism models could be preserved [27, 28]. In Fig. 11 (right) a swash-plate cam mechanism made of cedar wood is depicted exemplarily.

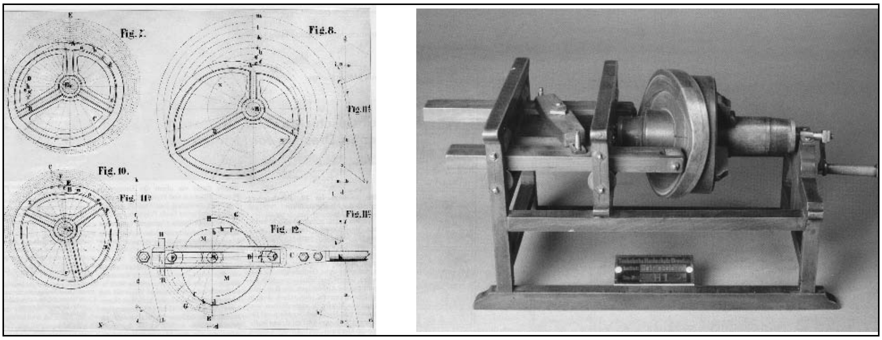

Fig. 11 Planar cams and cam mechanisms (*left*) and a spatial swash-plate cam mechanism (*right*) designed by *Schubert* in Dresden (Germany)

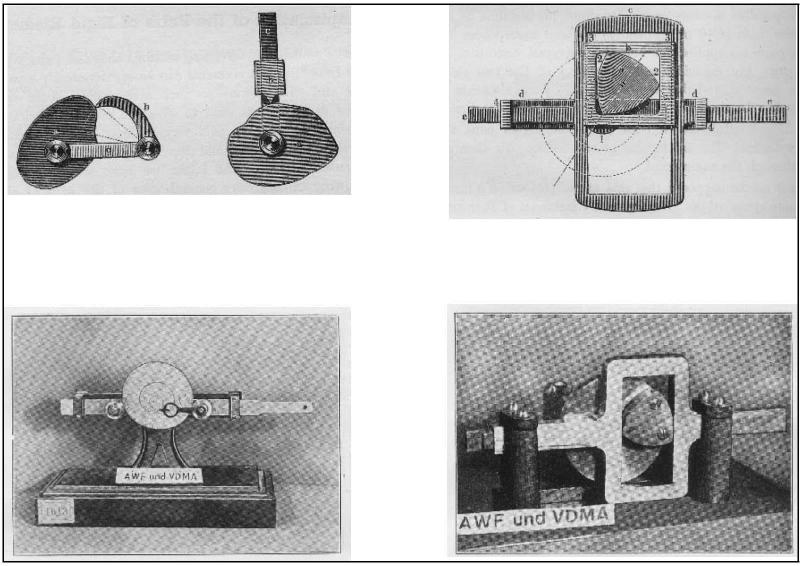

Fig. 12 *Reuleaux* cam mechanisms and models from Berlin

The German *Franz Reuleaux* (1829–1905) studied mechanical engineering in Karlsruhe and became a scholar of *Redtenbacher*. Later on, he got professorships at the Zurich Polytechnic Institute in Switzerland and at the Königliche Gewerbeakademie (Royal Trade Academy) in Berlin. *Reuleaux* was the "father" and pioneer of the "kinematics of machines" in Germany and outside of Germany. With his two-volume work [29,31] in German about "Theoretical Kinematics" he produced a unique jewel of the "systematics of mechanisms" based on the theory of constraints within a kinematic chain of links and joints. Moreover, he defined a machine that transformed motions as well as forces. The first volume of this work was also translated into English [7].

Most famous is *Reuleaux´s* large collection of nearly 800 mechanism models, 350 of them were marketed to universities around the world [8]. In the upper part of Fig. 12 we look at two simple three-link cam mechanisms and one triangle-cam/scotch-yoke combination taken from [29]; in the lower part of Fig. 12 two original Reuleaux models are shown taken from a catalogue published in 1928 [32].

Developments in the Last Century

At the beginning of the 20th century there is the death of *Franz Reuleaux* in 1905, but his ideas of mechanism design and systematics survived in many of his followers who worked in industrial companies and universities all over the world. His successor in Berlin became *Wilhelm Hartmann* (1853-1922) who even designed complex cam mechanisms for the study of planetary motions [30].

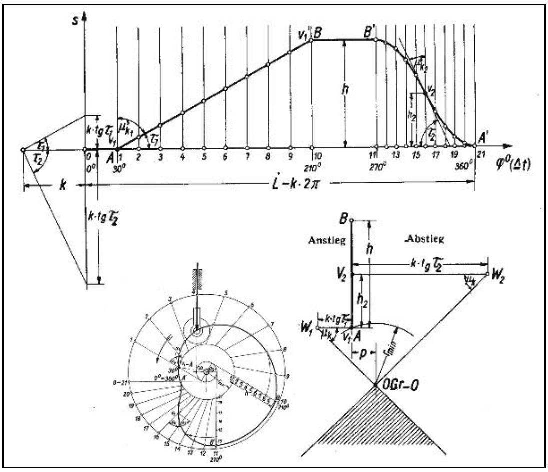

Fig. 13 *Flocke* design procedure for cams with offset translating roller follower

In the thirties of the last century there was again a peak period of mechanization in Europe and USA, culminating in mass production of capital goods. It became more and more important in the industrial world to develop compact machines with a high performance-to-weight ratio, for automobiles as well as for manufacturing machines and machine tools. Mechanism theory or kinematics became one of the outstanding subjects in the curricula of schools and universities for mechanical engineers. The state of the art of mechanism design at that time is given with two books. The first book titled "Grundzüge der Getriebelehre" and consisting of two parts (volumes) was published by *Willy Jahr* and *Paul Knechtel*. It contains a very extensive part about cam mechanisms [33]. As regarded the synthesis of disk cams with radial or oscillating followers the two authors made use of a design procedure that was developed by *K. A. Flocke* [34] for finding disk cams of minimal size. The procedure is based on the coherence of the minimal radius r_{min} of the base circle with the chosen transmission angles (complementary to the pressure angles) μ_{k1} for the rise and μ_{k2} for the fall, Fig. 13.

The second book titled "Technische Kinematik" [35] was published by *Rudolf Beyer* (1892–1960), a very gifted theorist and estimated university teacher, besides a specialist for spatial mechanisms. The part he wrote about cam mechanisms is only very short, but *Beyer* was at that time editor of the famous RM/AfG – Reuleaux-Mitteilungen/Archiv für Getriebetechnik (Reuleaux News/Archive of Kinematics). The series started in 1933 and ended in 1944, with a slightly changed title and since 1939 also under the roof of the VDI – Verein Deutscher Ingenieure (Association of German Engineers).

Here we have a mine of publications concerning cams and applications based on cam mechanisms. First example: The mass production of cams was performed by using a template cam on a milling machine (Fig. 14, left). In order to reduce manufacturing errors, the template cam profile had to be as precise as possible and bigger in dimensions than the product cam [36].

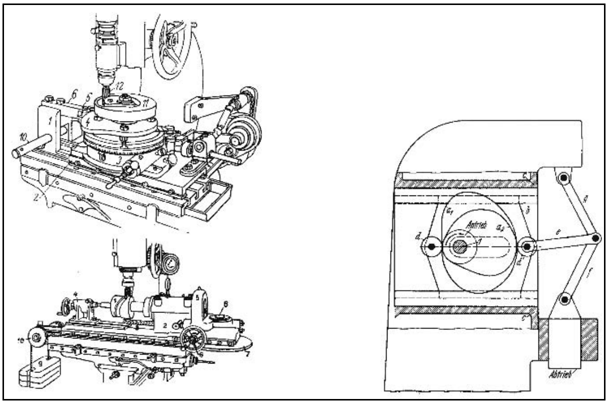

Fig. 14 Milling machines for the manufacture of cams (*left*) and cam-activated toggle-press (*right*)

Second example: On the right of Fig. 14 there is a press with a five-bar toggle mechanism that is activated by two conjugate cams. The main load during the press operation is taken by the slider-crank part of the press [37].

After World War II the technical development in all industrial countries began again, in a very stormy and exciting way, and this became also true for the development of theoretical fundamentals and industrial applications of cams and cam mechanisms. The best motion laws including complicated mathematical functions with smooth transitions between different motion sections for different followers were traditionally used for valve controls in automobiles (cf. Fig. 15, [38]) and – still more challenging because of the extremely high number of camshaft revolutions per minute – in motorcycles. High speed motion of crank- and camshafts causes vibrations in mass-elastic systems and must be encountered by properly chosen motion laws and – most important – by cams manufactured with highest quality and precision.

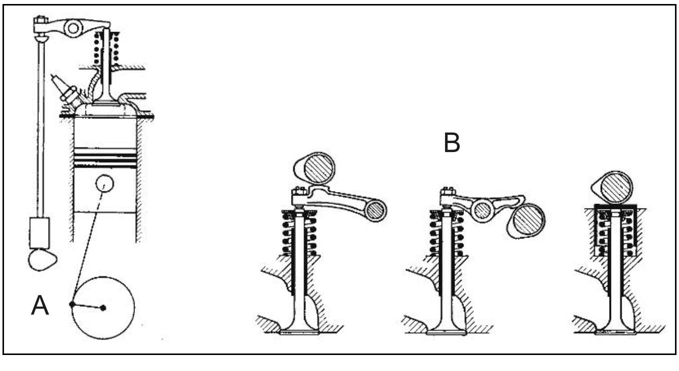

Fig. 15 Some types of cam mechanisms in automobile engines: (**A**) Overhead valve (OHV) and (**B**) overhead cam (OHC)

Gradually these ideas and possibilities were also transferred to cam mechanisms in machines for manufacturing and production processes. *Harold A. Rothbart* pioneered with his book in 1956 [39] and *Preben W. Jensen* wrote another one nine years later [40]. *Kurt Hain*, the German pioneer in applied kinematics, showed how to develop cam mechanisms alone and in combination with linkages in a most systematic and efficient way, cf. for example [41].

A big thrust in research and application for cam mechanisms – and not only for them, of course, but generally for all technical sciences – came with the use of computers and computer programs. The introduction of computer hardware and software marked the beginning of the period of automation, and especially automated production. Now there were new chances to calculate, simulate, optimize and manufacture cams and cam mechanisms to achieve optimal performance and running quality for a given mechanical task. Starting exemplarily with the books of *Delbert Tesar/Gary K. Matthew* [42], *Johannes Volmer* [43] and *Fan Yu Chen* [44] who all formed the middle generation of cam experts, we now look back at the last monographs from *Jorge Angeles/Carlos S. López-Cajún* [45] and *Zdeněk Koloc/Miroslav Václavík* [46] asking ourselves what could come next? Is it really the electronical solution with one single or multiple rotating shafts?

Conclusions

Cams and cam mechanisms were already known to *Leonardo da Vinci* in the 15th century. But at his time and centuries thereafter there was only the chance of realizing simple cam mechanisms by using wood material. Nevertheless the idea of applying cam mechanisms in machines was kept and substantially developed in the machine books of the 16th to the 18th century. Finally, in the Machine Age of the 19th century, in the course of the invention of the steam engine by *James Watt*, and later on in the course of the development of the automobile engines, cam mechanisms could be calculated, designed, manufactured and applied in a way that is familiar to the mechanical engineer of today. Revolutionary ideas of the design of cam mechanisms concerning and combining geometric-kinematic with dynamic aspects came from researchers at the École Polytechnique in Paris, went around the world and finally paved the way for mechanization and mass production of the recent past.

References

1. Ceccarelli M (2004) Evolution of TMM (Theory of Machines and Mechanisms) to MMS (Machine and Mechanism Science): An Illustration Survey, Proc. 11th IFToMM World Congress in Mechanism and Machine Science, Tianjin, China, Vol. 1, pp. 13–24.
2. Ceccarelli M (2007) Renaissance of Machines in Italy: from Brunelleschi to Galilei through Francesco di Giorgio and Leonardo, Proc. 12th IFToMM

World Congress in Mechanism and Machine Science, Besançon, France, paper No. A236.
3. Koetsier T (1983) A Contribution to the History of Kinematics, Mechanism and Machine Theory, Vol. 18, No. 1, Pergamon Press Ltd., Oxford (UK), pp. 37–42 (Part I) and pp. 43–48 (Part II).
4. Müller J, Mauersberger K (1988) Zur Entwicklungsgeschichte der Kurvengetriebe, Wissenschaftliche Zeitschrift der Wilhelm-Pieck-Universität Rostock, N-Series, Vol. 37, No. 7, Rostock, Germany, pp. 56–88.
5. Mauersberger K (1992) Exkurs in die Geschichte der Maschinenlehre, Wissenschaftliche Zeitschrift der TU Dresden, Vol. 41, No. 4, Dresden, Germany, pp. 6–15.
6. Ryff W (1548) Vitruvius Teutsch, Nürnberg, Germany.
7. Reuleaux F (1876) The Kinematics of Machinery – Outlines of a Theory of Machines, Macmillan & Co., London, UK.
8. Moon F C (2007) The Machines of Leonardo da Vinci and Franz Reuleaux – Kinematics of Machines from the Renaissance to the 20th Century, Springer Co., Dordrecht, Netherlands.
9. Mauersberger K (1989) Leonardo da Vincis Entwürfe von Kurvenmechanismen – Studie, Dresdener Beiträge zur Geschichte der Technikwissenschaften, No. 18, Dresden, Germany, pp. 53–102.
10. Müller J, Mauersberger K (1990) LEONARDO DA VINCI – seine Beziehungen zum Kurvengetriebe im Vorfeld der Technikwissenschaften, Wissenschaftliche Zeitschrift der Universität Rostock, N-Series, Vol. 39, No. 6, Rostock, Germany, pp. 99–141.
11. Il Codice Atlantico di Leonardo da Vinci nella Biblioteca Ambrosiana di Milano, pubblicato dalla Regis Accademia dei Lincei, Hoepli, Milan, Italy, 1894–1904.
12. Codex Madrid or Tratado de Estatica y Mechanica en Italiano, Madrid, Spain, 1493.
13. Il Codice Forster del Victoria and Albert Museum, Edizione Minori, a cura della Regis Commissione Vinciana, Danesi e Libreria dello Stato, Rome, Italy, 1930.
14. I manoscritti e i disegni di Leonardo da Vinci, Codice Arundel 2631, pubblicato dalla Regis Commissione Vinciana sotto gli auspici del Ministero della Pubblica Istruzione (4 volumes), Danesi, Rome, Italy, 1923–1927.
15. Les manuscrits de Leonardo da Vinci, manuscrits de la Bibliothèque de l´Institut, Tome 6, Quantin, Paris, France, 1881–1891.
16. Cianchi M (1995) Le macchine di Leonardo da Vinci, Becocci Editore, Florence, Italy.
17. Beck T (1899) Beiträge zur Geschichte des Maschinenbaues, Julius Springer, Berlin, Germany.
18. Ramelli A (1588) Le diverse et artificiose machine del capitano Agostino Ramelli, dal Ponte della Tresia, ingeniero del christianissimo Re di Francia et di Pollonia, Paris, France.
19. Mauersberger K (1989) Bewegungswandlung als wissenschaftliches Maschinenproblem im Vorfeld der industriellen Revolution, NTM-Schriftenreihe

Geschichte der Naturwissenschaften, Technik, Medizin, Vol. 26, No. 1, Leipzig, Germany, pp. 91–107.
20. Mauersberger K (1990) Bewegungswandlung im Entwicklungsprozeß der Betriebsdampfmaschine, NTM-Schriftenreihe Geschichte der Naturwissenschaften, Technik, Medizin, Vol. 27, No. 2, Leipzig, Germany, pp. 57–79.
21. Muirhead J P (1854) The Origin and Progress of the Mechanical Inventions of James Watt, Vol. III, London, UK.
22. Lanz J M, Betancourt A de (1808) Essai sur la Composition des Machines, Paris, France.
23. Poncelet J V (1826) Cours de Mécanique Appliquée aux Machines, Paris, France.
24. Willis R (1841) Principles of Mechanism, John W. Parker, London, UK.
25. Redtenbacher F (1857) Die Bewegungs-Mechanismen, Friedrich Bassermann, Heidelberg, Germany.
26. Schubert J A (1842) Elemente der Maschinenlehre, Dresden and Leipzig, Germany.
27. Mauersberger K (2001) Zur Geschichte der Getriebetechnik an der TH Dresden vor Lichtenheldt, Wissenschaftliche Zeitschrift der TU Dresden, Vol. 50, No. 3, Dresden, Germany, pp. 9–18.
28. Blechschmidt C, Kramer R (1984) Getriebemodelle von Johann Andreas Schubert", Wissenschaftliche Zeitschrift der TU Dresden, Vol. 33, No. 1, Dresden, Germany, pp. 51–57.
29. Reuleaux F (1875) Lehrbuch der Kinematik, Vol. 1: Theoretische Kinematik – Grundzüge einer Theorie des Maschinenwesens, Vieweg & Sohn, Braunschweig, Germany.
30. Hartmann W (1913) Die Maschinengetriebe, Vol. 1, Deutsche Verlags-Anstalt, Stuttgart/Berlin, Germany.
31. Reuleaux F (1900) Lehrbuch der Kinematik, Vol. 2: Die praktischen Beziehungen der Kinematik zu Geometrie und Mechanik, Vieweg & Sohn, Braunschweig, Germany.
32. AWF/VDMA, Getriebe und Getriebemodelle, Beuth-Verlag, Berlin, Germany, 1928.
33. Jahr W, Knechtel P (1938) Grundzüge der Getriebelehre, Vol. 2, Jänecke Verlagsbuchhandlung, Leipzig, Germany.
34. Flocke K A (1931) Zur Konstruktion von Kurvenscheiben bei Verarbeitungsmaschinen, VDI-Forschungsheft No. 345, Berlin, Germany.
35. Beyer R (1931) Technische Kinematik, Johann Ambrosius Barth, Leipzig, Germany.
36. Grodzinski P (1934) Wirtschaftliche Herstellung von Kurvenscheiben, Reuleaux-Mitteilungen/Archiv für Getriebetechnik, Vol. 2, No. 4, Berlin, Germany, pp. 30–33 and plate No. 7.
37. Rasenberger O (1938) Kniehebelpressen für Sonderzwecke, Reuleaux-Mitteilungen/Archiv für Getriebetechnik, Vol. 6, No. 1, Berlin, Germany, p. 43.
38. Bensinger W D (1955) Die Steuerung des Gaswechsels in schnellaufenden Verbrennungsmotoren, Springer-Verlag, Berlin/Göttingen/Heidelberg, Germany.

39. Rothbart H A (1956) Cams – Design, Dynamics, and Accuracy, John Wiley & Sons, Inc., NY.
40. Jensen P W (1965) Cam Design and Manufacture, The Industrial Press, New York, NY.
41. Hain K (1960) Systematik mehrgliedriger Kurvengetriebe und ihre Anwendungsmöglichkeiten, MASCHINENBAUTECHNIK (Getriebetechnik), Vol. 9, No. 12, Berlin, Germany, pp. 641–649.
42. Tesar D, Matthew G K (1978) The Dynamic Synthesis, Analysis, and Design of Modeled Cam Systems, Mechanical Publications Ltd., Suffolk, UK.
43. Volmer J (ed.) (1976) GETRIEBETECHNIK – Kurvengetriebe, VEB Verlag Technik, Berlin, Germany.
44. Chen F Y (1982) Mechanics and Design of Cam Mechanisms, Pergamon Press, NY.
45. Angeles J, López-Cajún C S (1991) Optimization of Cam Mechanisms, Kluwer Academic Publishers, Dordrecht, Netherlands.
46. Koloc Z, Václavík M (1993) Cam Mechanisms, Elsevier Science Publishers, Amsterdam, Netherlands.

Steam Locomotives in the History of Technology of Mexico

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Abstract Mexican history is full of interesting facts connected not only to social and political issues but also to engineering practice and technology development. This was the case with steam locomotives during the first half of the twentieth century. An essential means for the transportation of persons and goods, especially in a country with such a difficult terrain and agriculture land situation, railroad transportation played an important role on the years before and during the 1910–1923 civil revolution war. They also were essential to the conciliation and reconstruction times after the war, and to the industrialization in the years to come, supported by the foundation of the railroad workers unions and their outstanding participation in steam locomotives construction, as is reviewed in this paper.

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The large railroad network expansion during the last and the first decades of the 19th and 20th centuries respectively, contributed enormously to set the beginning of the industrial growth of the country, in particular the iron industry, so important for construction and other productive activities. Nevertheless, those times were of social turmoil and effervescence that turn into a period of civil war among different revolutionary ideologies, mainly motivated by the need for a socioeconomic change, especially in the land ownership regime and the agriculture activities, with consequences to industry and commerce. The opposing armies used the railroad to move large number of troops from one region in the north to another region in the central part of the country, and vice versa. They also used the trains as for many strategic and support activities (noteworthy was the medical hospital-train in the army of Pancho Villa). Therefore, the railroads, the cars and the engines themselves were also the target to infringe important damages to a given enemy.

Once a new federal constitution was signed and the pacification of the country begun, there was a period of reconstruction and social renewal, especially in relation to industrial workers. Unions and the like organizations were founded and a new spirit of the working class settled in. The railroad workers participation was remarkable as they not only took part in the organization of the transportation companies but also in the equipment construction and technology improvements. This paper explores these experiences and facts that ended with the full design and fabrication of two large steam locomotives by a group of enthusiastic and well trained and organized railroad workers.

Keywords Railroads in Mexico, Locomotives

Historical Review of the Railroads in Mexico

The railroad transport has played an important role in the socio-economic development of Mexico, given its orographical features, with large desert lands in the center and north of the country and jungle regions in the south, connected by huge and intricate mountains systems. It should be pointed out also that there are some cities at sea level and some of them up to 3,000 m above sea level, whereas distances, in the same direction, of more than 4,000 km.

The first complete railroad track in Mexico was inaugurated in 1873 joining Mexico City and Veracruz. The latter is an entry harbor in the Gulf of Mexico that has served for commercial, cultural and political interchange with Europe and the USA. The first constructions related to railroad activity actually started from 1837. Some workshops for foundry and mechanical construction were set at several places of the country. Clearly, the investments were minimal and even the low technology being used was imported. Nevertheless, it was recognized since then the importance that could have had the development of this mean of transportation.

With the economic difficulties, due to the lack of foreign investments, joined to the political instability and to the frequent foreign interventions, the construction of different railroads was very slow, until the culmination of the abovementioned route (Mexico City-Veracruz). Actually, the infrastructure required for that railroad was an important masterpiece of engineering due to the terrain irregularities, including slopes of up to 5.5%. It required huge bridges and very sharp curvatures. This railroad was built by foreign and Mexican engineers. There were 26 steam locomotives (some of them with double boiler), mainly of British manufacture, with 200 different types of wagons. However, this first stage of the Mexican railroad was not problem-free. Indeed, the track beds were inadequate to the region's climatic conditions. Moreover, most of the locomotives lacked of the necessary power for the steep slopes as well as for the load being transported. Furthermore, most of the equipment was either, too old or, in bad shape. The facilities and workshops were provisional and had capacity only for minor repairs.

The railroad branching achievement in almost 30 years allowed to communicate the country from North to South, and much less from East to West, due to the orographical difficulties already mentioned. Thus, by the year 1880, the railroad network expanded to more than 1,000 km. However, the great impulse was given in the next decade, achieving approximately 12,000 km by 1890 and reaching more than 19,000 km in 1910. The North border and the Gulf of Mexico had thus communicated to the centre of the country via the railroad. In Emma Yanes-Rizo's words, "…The steam railroad changed the country's geography, the commerce, the production rhythm, the sense of time and the social relations" [1]. Parallel to the growing of the railroad network, and the concessionaries foreign enterprises, facilities and repair workshops also grew and they reached the technical capabilities for manufacturing steam locomotives in the country. Clearly, this was outside of the railroads enterprises.

Indeed, at the first stage of the great expansion of railroads, Government's policy was oriented mainly to foment by all possible means the construction of railroads tracks in such an extensive country and complex orography; even if this implicated enormous sacrifices and concessions that would favor investments. Clearly, this was a marketing integration with a fiscal regime favorable to the capitalistic development, in order to attract foreign investments for industry and commerce. At the second stage, the General Law for Railroads was issued and helped to regulate operations of the concessionaries enterprises, by stating some construction and equipping norms, oriented towards railroads modernization.

With the advent of the railroad in the second half of the XIX century, the railroad system was consolidated, as well as the agricultural and live-stock production in the great "latifundio" country state properties, a heritage from the colonial times (1521–1810). In addition, rules for the important industrialization, which reached its peak in the XX century, with the oil industry, great development of the hydroelectricity, and the highway network, were set.

During the colonial time, mining was also a very important economic activity. This led that at the second half of the XIX century Mexico stepped in towards its industrial development. Thus, several manufacturing companies were set, which used machines being powered by steam, like the same mining industry, textile, paper, sugar, shoe and leather, glass and steel industries, among others.

At the turn of the XX century, there was a remarkable urbanization, mainly in Mexico City, and an important industrial production with a diversified market and self-sustained based on offer and demand. For obvious reasons, the steel industry was very important. At the beginning of the XX century, the company “Fundidora de Fierro y Acero de Monterrey” was started with a strong integration of iron and steel activities and a strong capacity (a furnace with a daily production of 500 metric tons, coke and several furnaces, rolling mills, etc.) for the production of several iron and steel goods, particularly useful for the development of railroads like tracks and also for building construction. The company had implemented the technological elements for the several stages for iron and steel production, starting from coke and iron mines extraction up to the finishing of steel profiles for structures. In addition of the high capacity furnace, it had also coke furnaces, steel furnaces, rolling mills workshops, all of them with a capacity of up to 1,000 daily metric tons. There was also equipment for pieces of cast bronze for self provisioning and to provide other industries. Facilities were in good condition for producing all the materials and equipment required for locomotives and passengers and load wagons.

At the beginning of the social turmoil (1910s revolution), the iron and steel enterprise had the capacity for producing tracks and accessories, but also the fabrication of locomotives and other specialized equipment as well. On the other hand, the Mexican transportation company “Ferrocarriles Nacionales de México” was more interested in the huge debt due to the recent nationalization, and very little interested in the possibility of investing in equipment fabrication inside the country, even though the important capacity in workshops and facilities of high technological level that had spread out in several places of the country. In other words, there were the given conditions for producing all the necessary material for a sustained development of this mean of transportation. However, the Mexican policy and economy were too weak to react to foreign pressure as well as the social internal conditions. There was not economic capacity neither political actions necessary to hold the economic development of a country pointing towards a railroad technological development.

The railroad network served as a mean of transportation for agricultural goods, merchandises and people, helping notoriously to the economic integration with the USA, but also to the communication and spreading of the liberal and social liberation ideas. Given the closeness of the USA and Mexico, the latter was taken as a place to perform espionage activities of the European countries, the USA, and Japan while the First World War [2] and the political revenge showing up along the XX century (for example the killing of Trotsky).

But moreover, railroads in Mexico played an important role in the Mexican revolution 1910–1917. This civil war among antagonist revolutionary factions was at first highly motivated by the need for a change in political issues. Thereafter a socioeconomic change was sought, especially in the land ownership regime and the agriculture activities, with consequences to industry and commerce. The opposing armies used the railroad to move large number of troops with horses and cannons, from one region in the north to another region in the central part of the country, and vice versa. They also used the trains as for many strategic and support activities: Noteworthy was the medical hospital-train in the army of Pancho Villa [3]. Therefore, the railroads, the cars and the engines themselves were also the target to infringe important damages to a given enemy (Figs. 1, 2 and 3).

The Railroad Union in the Post-Revolution

The first railroad unions emerged since the last decade of the XIX century and were consolidating in the previous years to the starting of the revolution of 1910. Some organizations of important workers' unions had been settled through the continuous search for better working conditions, before the military fight. Besides, they struggled for having access to education and technical training for workers. This would allow them to get working places being occupied for foreigners, which represented a strong brake for workers improving. These two last aspects were very important for the posterior workers' rights, and also in the development of technological and management skills for managing railroads companies. Close to the end of the "maderista" stage (1910–1913), the railroad workers achieved, through a strike, several labor reinvindications, above all in relation with the technical training and the right to occupy higher hierarchical jobs. But, because of the revolution, the above implementation was stopped and workers had to learn authentically "on the walk" for developing their creativity and any other skills; these were converted actually in surviving requisites.

The military war between antagonist groups affected strongly the quotidian life and working relations in the railroads working class, many times originated for the lack of technical knowledge of the militaries of intermediate rank and the power they exerted. In the new phase of the fight, trains were strategically and tactically important. Those who controlled and dominated the tracks and the trains had extraordinary offensive and retractile capacities. The mechanical and railroad destruction/construction was commonly practiced. The revolutionary "guerrilleros" and their commandants had taken the power of the railroads. The above resulted in enormous difficulties for railroads workers, especially for the machinists and operators. War divided the most skilled workers, who were the most valuable for the revolutionary bosses. As a consequence, the fidelity to "caudillos" and the campaign successes substituted the requisites of salary scale, anciently, and knowledge for workers. In the workers jargon, this gave rise to the so-called "carabina rights", as pointed out clearly in [1].

Fig. 1 Military train (ca. 1910)

Fig. 2 Military train (1913)

Fig. 3 Military train (ca. 1914)

Once a new federal constitution (1917) was signed and the pacification of the country begun, there was a period of reconstruction and social renewal, especially in relation to industrial workers. Unions and the like organizations were founded and a new spirit of the working class settled in. The railroad workers participation was remarkable as they not only took part in the organization of the transportation companies but also in the equipment construction and technology improvements.

With the triumph of the constitutionalist revolution, the railroad management went back to the hands of the State and the system had new challenges. On the one hand, the tracks, locomotives, and rolling equipment reconstruction, and on the other hand the workers organization.

During Álvaro Obregón's administration (1920–1924) the institutions raised from the revolutionary upholding started to consolidate, namely, the class alliances, the strong presidential role and a capitalistic model with strong State's participation, who survived up to the decade of 1980. The revolutionary chiefs privileged to their closest collaborators with public jobs, especially those from the railroad company: it was part of the politics and the same time a military tactic, a fashion for body guarding. The country pacification was not yet complete and the railroads continued being strategic for controlling the frequent military rebellions and to keep the communication with the North border.

The railroad traffic was resettled and it was oriented to the activity of workers for repairing and track reconstruction, bridges, train stations, and workshops. Wagons and locomotives were purchased (it was acquired what the US wanted to sell). The equipment had to be readapted according to the needs of the country; locomotives of wood for coal; from coal for oil, etc. Domes, mechanisms, valves, etc., were changed in order to function according to the geographical characteristics of the divisions to which they were assigned. Nevertheless, the contracts signed with private companies for repairing and reconstruction of wagons and locomotives do not have success because they were no exempt of speculation between concessionaries and state officers; corruption and bribing; and few personnel being hired. The above rose, among other things, the lack of significant investments in workshops of the national railroad company, thus these were underused. Because of the above, the railroad dependence with the USA increased with important effects on the amortization of the debt and the management of enterprises. Anyway, parallel to equipment renovation and administrative reorganization of the company, the railroad activity increased and also the diversity of the job functions. In the workshops, the learning was given in the master-pupil relation, thus increasing the importance of the mechanical master.

The period 1924–1929 of president Calles' administration, the political stability was broken several times (Huerta and Escobar rebellions, "Cristeros" war, Serrano's plot, and the murder of Obregón). The crisis was stopped with the foundation of the PNR (PRI antecessor) as a first step to build a system that would allow to pacifically find a remedy to the presidential succession. The PNR was centered in the conciliation and national unity and the execution of two of the most important articles of the 1917s constitution.

On the economic viewpoint, the State participated actively in the industrial development without stopping the growth of the national burgess. The railroad company was given back to foreign private companies (1928) with the control of the 51% of assets belonging to the government, etc. Several agreements were signed with the railroad sector. The railroad debt was separated from the public debt. The company had a modern organization structure and the main preoccupation of the investors was the reorganization of railroads. Adjustments on salaries, tariffs and expenses in order that the company could satisfy its financial obligations were made. The policy of the company was oriented neither to the purchase of new rolling material, nor to the locomotives repairs in private shops, but the foreign rent of locomotives and wagons continued. With the growing of the company, an internal complex organization of the working process was also developed. This was due to the multiplicity of professions and specialties demanded by the railroad growing. The mechanical workers were in intimate contact with the locomotives. They were highly trained, with a great experience, and a deep knowledge regarding to the functioning, reparation and reconstruction of machine tools and rolling materials. To move up in the ranking was regulated besides the corresponding boss, by a real knowledge of technical matters.

The Lázaro Cárdenas administration (1934–1940) modified the orientation of the Post-revolution development already set by the previous regimes. Indeed, a nationalist policy was set as the leading direction. The local "cacicazgo" was eliminated and turned back to centralize the power at the presidential figure. It searched to achieve the two main revolution's objectives, namely, the agrarian distribution and the workers' rights. Workers and agricultural groups were motivate to organize and make use of the strike to defend their rights and make a front against national and foreign investment, giving rise to one of the politic-economic most important nation's event: the oil expropriation. However, the pretension of the oil union to administrate this resource was unaccepted.

It was not the same with the railroads. In 1937, the government nationalized them, with the corresponding indemnification to the companies, so to say, recognizing its debt. The measure was apparently too radical, but the railroads being nationalized were those broken and the State trying to liberate of them, left them on workers hands. The delivery of the company to the workers implied autonomy to reorganize it as a State's decentralized dependency; workers would be the administrators, but not the owners. The Government thus tied the new administration's hands leaving the whole debt during nationalization. Moreover, the State make no investments, nor loans; neither collaborated with the debt's payment. Instead, inappropriate concessions were given to mining companies related to the prices of loading mining being transported: less than 50% of the actual transport load cost. Devaluation, and wagons and locomotive rentals increased the foreign debt. The economic difficulties forced the company to stop salaries increases causing grieve among workers. The economic situation of the company was a disaster because it could pay only half of the invoices with a serious deficit of equipment and locomotives.

In the period 1940–1946 when Manuel Avila Camacho was in power, the system of only a single political party was getting consolidated, all of the different ideological trends were discussed inside that party. The Government got farther of the proposed original plans, favouring more to the party's right wing and allowing the conformation of a capitalistic economy, with State intervention, but with a diminished participation of the workers organizations and their socioeconomic demands.

All of the above was given in the frame of the Second World War, in which Mexico was with the allies and declared war to the Berlin-Rome-Tokyo axis. This situation encouraged an accelerated economy growth, with high demand of Mexican goods and an increase in industrial production. The State support was given basically to manufacturing and transformation industries, but not to transport, where investments were destined more to the widening and improvement of roads and the purchase of automotive vehicles.

Even though the investments and widening capacities of the railroad network was limited during that period, an intensive use of the railroads was achieved, with an increase of the transported load. This was the result of an important stage of negotiations between workers and the company, which in 1941 was constituted as a decentralized State company. To this contributed the spirit of national unity that prevailed in that epoch, the collective effort of workers and the attitude of the administration of railroads for listening the union demands, particularly those related with the need of repairing and building new locomotives at the company's workshops and not in the USA.

The Workers' Technological Creativity

Railroads workers' union besides having played an essential role in the fights for labor rights in Mexico, it also implied a technological development, given the workshop activities, transportation and commerce that this sector signified for the economy of the epoch. For the year 1935 the only one railroad workers union had about 35,000 workers. They served as a technological structure, and therefore socioeconomic, for the workers turmoil that there were in the reconstruction and development of the country. The experiment of the workers' administration lasted two years and a half and the company could not get rid off of its heavy load debts. Very often the workers' administration is minimized albeit their efforts for making it theirs and developing their labor creativity. During this period, there were big efforts to come back to the personnel training and modernization of workshops for eliminating contracts for performing repairs outside the company, and rolling material rentals as well. The benign results rose and by the end of the year 1937 several locomotives had been reconstructed and also the starting of the fabrication of the first passengers wagons. To the initiative to modernize facilities and workshops, followed a policy of support to labor creativity with several interesting technological results, going from novel designs and more economic mechanisms for the operation locomotive's boiler, up to safety devices for locomotive combustion.

The development of the capacities of railroad workers had its origin in the railroad expansion at the second half of the XIX century. This was so, because many railroad workshops masters came from the epoch' artisans workshops. In these workshops, they had acquired the experience for working with iron, foundries, wood, etc., and some of them had the knowledge in mechanical work from the mining workshops and the textile industry. With the coming of railroads, they encountered new devices and tools that had to learn by developing their capacities and take advantage to the diversity of machines being in front of them. The trained personnel were in charge of teaching new workers within the traditional structure of the artisans' workshops. The same happened with the jobs for handling the locomotives. Indeed most of the machinists were foreigners and there was a continuous fight that motivated workers since the first organizations demand the work training and the nationalization of the railroads. So, in 1907, the first training schools were open. This was a fundamental requisite in order to substitute the foreign personnel. Several books on diverse themes were written for helping to the workers' training. For example, in [4] were presented several aspects from design and construction of boilers, pressure recipients, domes and fire tubes, with definitions and parameters of geometry, tanks construction and reservoirs; physical principles of locomotives operation; several mechanisms used in the machines, types of fuels, and the like. Throughout these books the monopoly of knowledge ended and the traditional training fashion via master-pupil. The union's organization also contributed to the spreading of knowledge via its newspapers and gremial publications (Figs. 4, 5, and 6).

Locomotive Construction in Acámbaro's Workshops

A history, very little known, was the goal from the union organization about the possibility to contribute to the technological development of the national railroads by manufacturing in the country steam locomotives to propel its growing. In the city of Acámbaro (Guanajuato), especial conditions were given that would had favored a development in this sense, as described in [5], because it was a joining place of the railroads between Mexico's central plateau and the Pacific Basin, since 1883. Given the different tracks' widths joining there, it was necessary the change of merchandises from one system to another. The railroad station had a large patio for maneuvers and a round workshop with capacity for width and narrow tracks locomotives. Thus, Acámbaro was converted in a very important railroad center given its geographical situation and its workshops with machine-tools and furnaces of adequate capacity.

Even the closeness of Celaya and Leon, region where several battles took place, and in which Obregón fought against Villa, thus insuring the final triumph to the moderated wing of the revolutionaries, in Acámbaro there were neither rapping nor important battles, the railroad facilities were undamaged and the workshops kept machinery and tools from the pre-revolution times. In the following years there were not new locomotives, but none of the assigned to that division was lost.

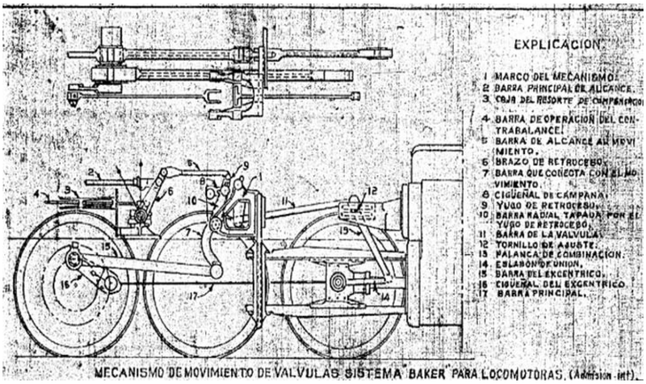

Fig. 4 Locomotive valves mechanism (Source: Acámbaro's Museum)

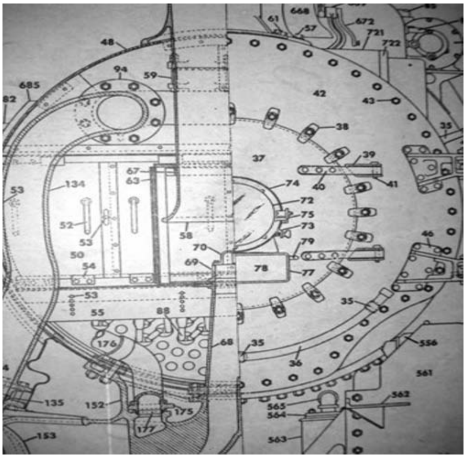

Fig. 5 Locomotive drawing (Source: Acámbaro's Museum)

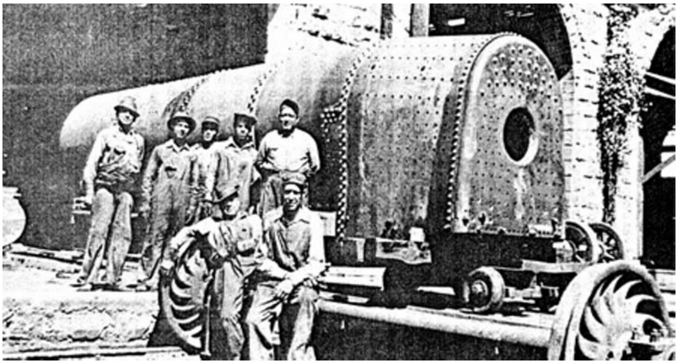

Fig. 6 Locomotive shop workers (Source: Acámbaro's Museum)

Thus, Fidelita—nickname given to the locomotive by the railroad workers in remembrance of the dead girl of the company's managers—and "her sister" were born. Two locomotives wholly built at Acámbaro's workshops. Fidelita still exits and it is placed as a landmark at Acámbaro's Railroad Museum; her sister was dismantled. The fact exemplifies how the workers organization was able to hit into the organization structure of a national enterprise to set the basis for a plausible technological development.

The locomotive 295 was inaugurated in September of 1942 (Fig. 7). This was a product to a large process where the characteristics of Acámbaro's workshops, their workers, and the national railroad company were mingled, but above all, a great collective willingness effort. The initiative for building the locomotive in Acámbaro was due to the master José Cardoso, who struggled for producing new locomotives with improved traction with respect to the rebuilt ones and because in those workshops there were a wide experience in reconstruction and repair many locomotives in the previous years.

The construction was done under engineering procedures and the supervision of the workshops' mechanics workers, with compromises for the participants workers that can be resumed in the fulfillment of ordinary work with the same personnel and same time schedule with extra hours assigned to foundry's personnel, mechanics workers, warehouse, and design of the Acámbaro's workshops, only for two months.

Fig. 7 Inauguration of 295 engine (September 1942)

The construction of the locomotive 295 caused a great deal of enthusiasm among Acámbaro's workshops workers, who immediately proposed that two more locomotives were built, with the possibility of producing them in series. Their main argument was that the fabrication time would be reduced from 150 days to only 20 days, thus avoiding to import new locomotives from the USA. The company accepted the construction of only one more locomotive: the 296, baptized as Fidelita (Fig. 8). The main technological changes were overheated steam, the use of a Stephenson mechanism for opening the valves, and the substitution of bushings by roller bearings.

Fig. 8 “La Fidelita” in Acámbaro´s museum (today)

Years 1942–1944 were little favorable to the workers union, especially in their requests related to productivity and construction of rolling equipment. This period coincides with the peak of the Second World War. Mexico’s compromises with allies were, for the national railroads, among other things, to assure the load traffic towards the USA, and the creation of war cooperation commissions. These were integrated by members of the union and the company, organized in such a way for guaranteeing an increase in production and efficiency in the services, in a similar fashion as the commissions in US factories, through the War Production Board. The workers’ effort allowed the increase in productivity and the fulfillment of the abovementioned compromises. When the war ended, Mexico had become part of the modern capitalism, with an annual economic growth of 7% in the period 1940–1945.

By the end of 1946, Miguel Alemán became the new president. At the beginning of this administration, the automotive industry was supported rather than the railroads. This automotive industry, with mostly foreign investment, started the production of trucks. In turn, in the railroad sector, the company’s policy was oriented towards the change of narrow tracks to wider ones and the acquisition of diesel locomotives, in a process that should have been slow for the adequate workshops technological adaptation and the technical personnel. Nevertheless, it was carried out in a quick way, thus discarding the technological experience of many workers and condemning prematurely to many steam locomotives to the trash.

As pointed out by Yanes-Rizo [6], it makes no sense talking about history of the scientific or technological contributions in a society, if these are not linked with the social environment where they are developed.

Conclusions

The manufacture of locomotives in Mexico emerged as the result of a process in which several circumstantial aspects were mingled: the experience acquired in the continuing repairs of locomotives in national workshops during the period of the social revolution; the organization of railroad workers and, in particular the insistency of Acámbaro's workers, who fought for technical training and the construction of rolling equipment in their workshops; the diverse agreements between the enterprise and the union in the period of the II World War, that made possible the organized development of the creativity and the enormous labour capacity of Mexican railroad workers. Having lived in difficult times, where violence and scarcity and the direct exposition to warlike actions and their effects, including the lack of materials supply and technological knowledge, evidently influenced in the generational surviving of the Mexican railroad workers. Thus, the history of science and technology in a country as Mexico, is also an economic and political history, it is the history of its dependency and its inhabitants' creativity, their needs and proposals, their advances and obstacles, of the working people and their people in the government. The necessary link of the technological evolution with the country socio-political structure and the history of workers and their working fashion in a certain period, makes it possible a social history of the technology. It is indeed, a history of men related to machines. Machines lack of history, except in their relationship to men, to the workers and the context where they were produced.

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References

1. Yanes-Rizo, Emma (1991) Vida y muerte de Fidelita, la novia de Acámbaro Una historia social de la tecnología en los años cuarenta: el caso de los Ferrocarriles Nacionales de México, CONACULTA, México.
2. Katz F (1981) The Secret War in Mexico: Europe, the United States, and the Mexican Revolution, The University of Chicago Press, Chicago.
3. Reed J (1914) Insurgent Mexico. (Available as ISBN-10: 9997995031.)
4. Alzati S (1907) La locomotora moderna en México. (Unpublished.)
5. Meyer F (1985) Acámbaro, Guanajuato, sede de la Superintendencia de la División Pacífico de los Ferrocarriles Nacionales de México. (© by F. Meyer.)
6. Yanes-Rizo, Emma (2002) Me matan si no trabajo y si trabajo me matan, Historia de la comunidad ferroviaria en México, 1850–1950, INAH, Mexico.

The First Steam Machine in Cuba: Little-Known Pages of Agustin de Betancourt's Work and Life

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Abstract The purpose of this paper is to prove that the first steam machine used in sugar industry of Cuba was designed by Agustin de Betancourrt, the outstanding Spanish engineer, one of the founders of "Theory of Machines and Mechanisms" science.

Keywords History of MMS, Steam machine, Agustin de Betancourt

Introduction

This year (2008) we have celebrated the 250 anniversary of Agustin de Betancourt's birth. He was a great inventor and engineer, architect and constructor of cities and one of the founders of science "Theory of Machines and Mechanisms".

He was born on February 1, 1758 on the island of Tenerife, in the city Puerto de la Cruz in a noble family. Later he received good education in Spain, France and Great Britain and at the end of the nineties of the XVIII century was considered one of the greatest and known engineers of Europe.

Before going to Russia Agustin de Betancourt had a plan for working in Cuba but the wars and hidden intrigues prevented him from following Columbus` steps and he had never come to Cuba. But, nevertheless, the Spanish engineer played an important role in the development of innovative technical ideas in Cuba.

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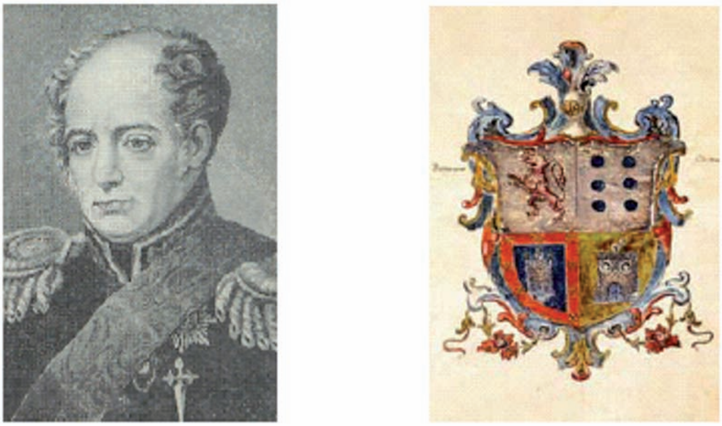
Brief Biographical Notes

Agustín José Pedro del Carmen Domingo Candelaria de Betancourt y Molina (his full name) (Fig. 1) was born on February 1, 1758 in Puerto de la Cruz (Tenerife, Canary Islands, Spain) in a noble and aristocratic family. From 1778 to 1784 he studied in Madrid in the "Reales Estudios de San Isidro" and in the "Real Academia de Bellas Artes de San Fernando" [1].



(a) (b)

Fig. 1-2. Agustin de Betancourt and his family coat of arms [2]

In March 1784 as a capable student he was sent to Paris where he participated at the activity in the School of Bridges and Channels (École des Ponts et Chaussées). But very soon he went back to Madrid and after an interview with the Secretary of State D. Jose Monino, Count de Floridablanca, he was asked for the establishment in Spain of a new school, namely, the "Escuela de Caminos y Canales" (School of Roads and Channels).

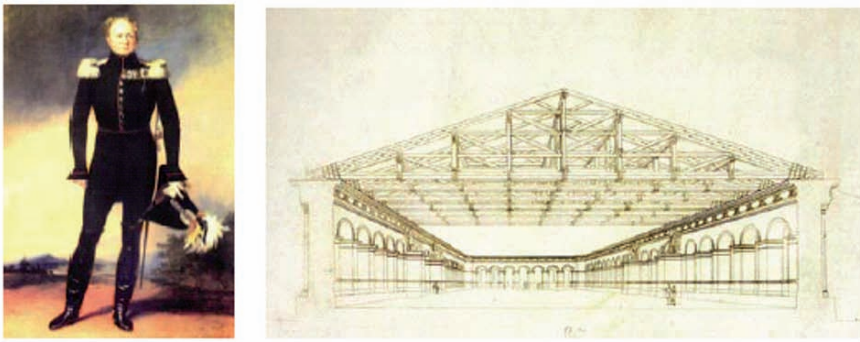
The agreements included to select students for the "École des Ponts et Chaussées" in Paris in order to obtain the degree of Hydraulic Engineers; to form experts in mechanical (industrial) engineering; and to collect models of machines of general utility in public works and industry. On September 10, 1785, Betancourt went again to Paris, where he was well accepted from the Director of the School Jean Rodolphe Perronet (1708–1794) and Professor Gaspard François de Prony (1755–1839).

In April 1788 the Spanish ambassador, Count Fernan-Nunez (Conde de Fernán-Núñez in Spanish), by chance visited the home-workshop of Betancourt was very impressed of the many scale models he collected and in a letter to the Secretary of State dated 23 April, he proposed the creation of a Cabinet of Machines in Madrid [3,4]. In 1791 since the situation in France, the king of Spain Carlos IV decided that Betancourt should return home, to Madrid, and he would have brought with him the collection of drawings and scale models. The whole collection (including

42 drawings) was received in Spain between July and September. In April 1792 the Cabinet, located in the kings' house "Palacio del Buen Retiro", was opened to the public. The 14th October Betancourt was officially appointed Director of the Cabinet. The whole collection was composed of 271 models, 359 drawings and 99 memories, library of rare books and manuscripts [5]. Thus, first-ever museum on Science and Techniques History was established. By the end of 1790th Betancourt was already considered as the greatest engineer of Spain.

Activity in Russia

In October 1808 because of the unstable political situation in Spain and family reasons, Agustin de Betancourt went to Russia to work under the auspices of the Czar and Emperor Alexander I (Fig. 2a). In Russia he spent great efforts to develop successfully an engineering framework through several activities in designing, teaching, and organizing in many fields of engineering until his death in 1824 in Saint Petersburg. This activity was fully recognized to Betancourt and still today there is great memory of him in Russian history of Mechanical Engineering.



(a) (b)

Fig. 2 Emperor of Russia Alexander I and Moscow Riding-School (project) [2]

It is impossible to enumerate in a short article everything that Betancourt could do in his new motherland. Being an engineer of talent and a great organizer, he tried, as his own words, to turn Russia in one of the most advanced countries of that time. For example, in 1817, according to his project, the Riding-School of Parades (Manege) was built in Moscow (Fig. 2b). It is a very big building with dimensions of more than a hundred sixty six by forty fours meters without any supporter inside. Seemingly, there are no similar buildings in the world [2].

In 2003, according to the initiative of the higher schools of Saint Petersburg and with the aim of glorifying the name of the Spanish-Russian engineer appeared in the register of small planets of the solar system, the planet "Betancourt" under the number 11,446. At the end of the nineties of the XVIII century Agustin Betancourt had a plan for working in Cuba before going to Russia but the wars and hidden intrigues prevented him from following Columbus` steps and he had never been to Cuba. But, nevertheless, the Spanish engineer played an important role in the development of innovative technical ideas in Cuba.

Cuba as a Part of Spain Empire at the End of the XVIII Century

At the end of XVIII century Luis de las Casas, Spanish, the Governor, who had ruled since 1790 up to 1796, greatly contributed to the prosperity of Cuba. There appeared some institutions, which made important contributions into the development and instruction in the country. There was founded the Economic Society of Friends of the Country (SEAP) and the Royal Society of Agriculture, Industry and Trade.

Fig. 3 Luis de las Casas, the Governor of Cuba (1790–1796)

Luis de las Casas also received with goodwill the refugees from Haiti after the rebellion of slaves, which took place there in 1791 and gave them lands and credits in the eastern part of the island Cuba. The new colonists had great experience in the production of coffee and sugar. In this way, more and more plantations and sugar-mills or "ingenios" appeared in Cuba. At the end of the XVIII century Cuba overcame Haiti as the most important producer and exporter of that time.

King Charles III died in 1788 and the throne was occupied by Charles IV, the one who was weak and without real power. Spain was governed by Maria Luisa and her favorites; the main of them was Manuel Godoy (Fig. 5), officer of the guard. At the age of twenty-five, he was named prime minister. Under his tutelage the power in Cuba passed into the hands of the powerful Cuban bourgeoisie, sometimes known as "saccharocracia", related to the sugar production.

Fig. 4 "Ingenio" or Sugar-mill in Cuba

One of their most prominent representatives was Francisco de Arango and Parreno (1765–1837) (Fig. 6) owner of vast lands and an intellectual. He was born in Havana on May 22, 1765 in a family of ancestry and with large economical resources. Francisco de Arango was at the head of Havana's saccharocracia and became one of the most prominent fighters of reforms in Cuba [6].

Fig. 5 Manuel Godoy

Fig. 6 Francisco de Arango y Parreño [6]

We could suppose that Francisco de Arango and Parreno met Agustin de Betancourt in 1794. This conclusion is based on existing data and documents with regard to his long trip with Count de Casa Montalvo to Portugal, England and its colonies, Barbados and Jamaica, to become familiar with the new technical inventions. His visit to England coincides with Betancourt's staying in London.

On October 14, 1795 after having finished his trip, Francisco de Arango and Parreno spoke about the steam machine ordered in England by Count de Casa Montalvo in one session of Royal Society and he showed a little pattern and some designs of mechanisms of the machine. We have to point out that one of the passions of Betancourt was the construction of the machine patterns, practically exact copies but to a much reduced scale. The existence of this pattern points indirectly to authorship of Betancourt in the creation of the mentioned machine because he had great experience in this occupation.

Fig. 7 Count de Casa Montalvo and his family coat of arms

In the funds of Don Perez Beato [7] of the National Library of Cuba in Havana (BNC), it's preserved, under the number 968, the original letter (Fig. 8) written by Francisco de Arango y Parreno with the instructions on revision and transportation of the steam machine to Cuba under the name *The instruction which was left by D. Fransisco Arango to Sr. D. Fransisco de Enquino to keep his correspondence about everything pendent and the rest that happens.* Here are some fragments of it:

> It's not necessary to say anything about the fire bomb (the steam machine) and the way to make its payment because it has been said enough in the document which I've signed with Count de Casa Montalvo and I also signed an agreement with Don Agustin de Betancourt who has been the supervisor of these works….
>
> …I left everything to Don Agustin de Betancourt's discretion who will receive 200 pounds…
>
> …If Count de San Juan de Jaruco, with residence in Madrid, had to make some variation on these topics or to communicate some instructions for a better transportation of the fire bomb (the steam machine) or trapiche, his will should be followed in everything.
>
> …After having received the money from Havana for fulfilling our obligation, Don Betancourt will pay my bills with Reynolds. It will be also paid Don Equino's debt and the receipts will be sent in two copies. One of them will be sent to Havana and the other to Count de Jaruco for handing to that that will make the payment in Spain.

This letter is the unique document where we can see that Francisco de Arango y Parreno and Agustin de Betancourt subscribed an agreement, which was on the production of the new steam machine set for grinding of sugar cane.

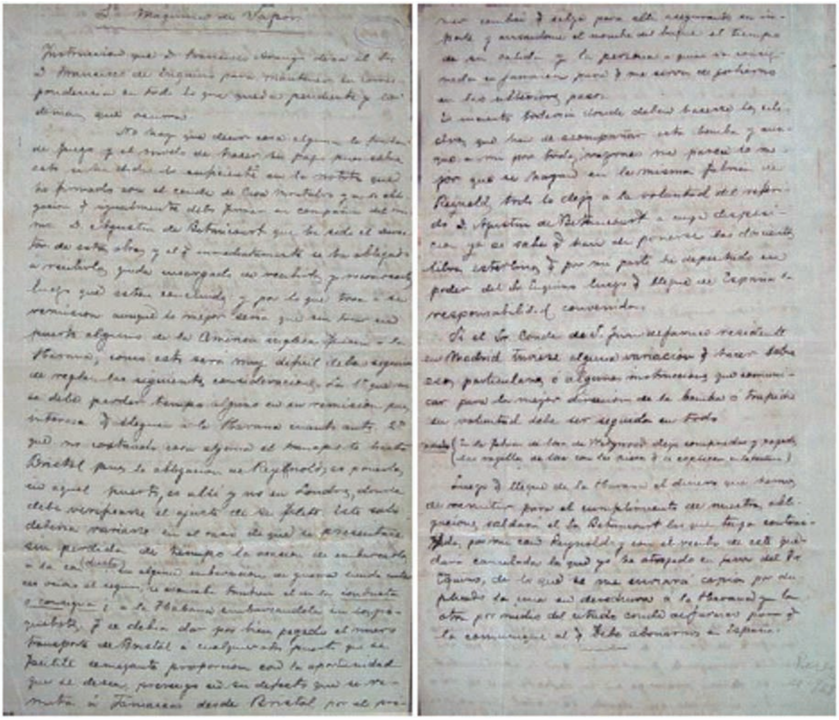


Fig. 8 The original letter written by Francisco de Arango and Parreno [7]

This contract also responded to Betancourt's plans to construct steam machines for different purposes. In those times, the steam machines of Watt (Fig. 9) were unknown in Cuba and the machines which used the power of animals or Negro-slaves (Fig. 10) were not profitable because of their low productivity.

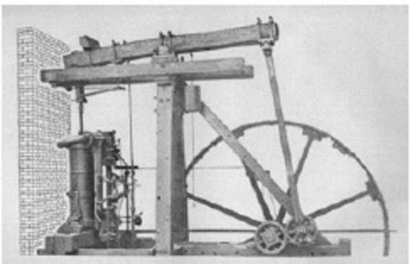


Fig. 9 The steam machines of Watt

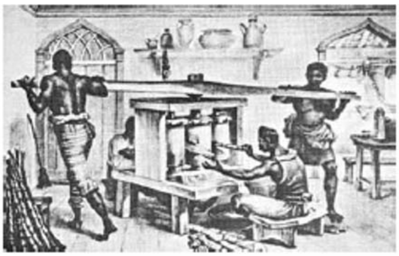


Fig. 10 Using power of Negro-slaves

There is also a letter which Betancourt wrote in French on December 10, 1794 to his friend Breguet (Bregue) mentioning the received order. This letter, preserved in the archives of Breguet [8], serves as a proof. Among others, it says:

> This summer two friends from the Spanish America have been here and I proposed them the project of installing the steam machines in their possessions to avoid the use of oxen and negroes for expelling juice from the sugar cane; I did some calculations and they asked me to produce two of these machines designed by me and they are being done now… Two of these machines will be finished soon and I hope their effectiveness could be seen on the islands and the owners would leave the ones they have now.

It is seen from the text that the order was made by two travellers from "Spanish America" who probably were Cubans. It is obvious that the new machines were designed for grinding the sugar cane and they planned to use them on their lands. Francisco de Arango and Parreno and Count de Casa Montalvo were the owners of vast lands and were interested in the use of modern technology and new machines in their sugar mills. Betancourt's plans for using the machine, constructed by him, show that it was Cuba where the production of sugar was the principal line of its economy and the country was turned into a "world wide sugar-bowl" while the saccharocracia keeping the economical power in their hands were thinking about increasing the productivity of this industry.

The Sugar-Mill in Cuba

In the book "The Sugar-mill" written by Manuel Moreno Fraginals [9], an outstanding investigator of the history of sugar industry, we can read the following:

> Finally, in 1796, the motive power of the large industry, the steam, arrived in Cuba. It was a machine bought in London with Count Jaruco`s money. Its installation became a singular event surrounded by an atmosphere of tense expectation. It was seen working for the first time on January 11, 1797 at Seybabo sugar-mill and it had been grinding for several weeks. The experiment wasn't a success but the saccharocrates didn't lose heart. They understood that the main problem wasn't in the bomb itself but in the type of grinding machine (trapiche) that moved and in the absurdity of the system of the installed transmission.

It's significant the fact that the first steam machine was installed at Seybabo sugar-mill, which belonged to Count de Mopox and de Jaruco (Fig. 11), who led the scientific expedition in which Betancourt and his Spanish colleagues would have participated [10]. Count de Mopox and de Jaruco was also the son in law of Count de Casa Montalvo [11] who accompanied Francisco de Arango y Parreno in his trip to England. These coincidences make us think that Betancourt was the creator of the first steam machine used for grinding cane in Cuba.

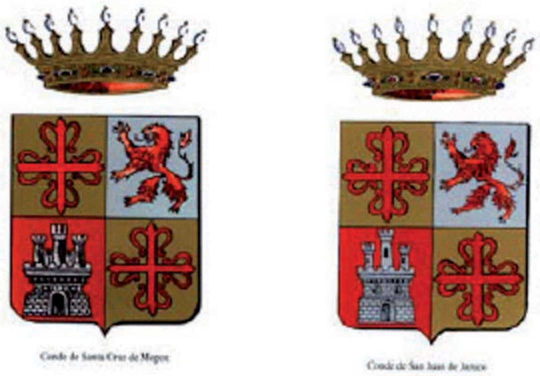


Fig. 11 Count de Mopox and de Jaruco's family coat of arms

The before mentioned machine was broken because there were neither qualified operators nor competent engineers. Count de Mopox and de Jaruco made his expedition to Cuba, which lasted six yeas, and he could hardly attend the problems related to the new equipment. In those years, Agustin de Betancourt dedicated himself to the construction of optic telegraph and to the organization of the School of Roads and Canals in Madrid. The wide use of steam machines, in the production of sugar in Cuba, began much later, after 1827.

Conclusions

The investigation proves convincingly that the author of the first steam machine made in England and used in the sugar industry in Cuba in 1796 was the Spanish engineer Agustin de Betancourt. His ideas made a great influence on the development of modern technique in Cuba and indirectly on the use of steam machines in the sugar industry of the island in the XIX–XX centuries. Steam machines got popularity and later in 1837 Cuba became the first country in Latin America to have a railway from Havana to a region Guines [12].

References

1. Rumeu de Armas, Antonio (1980) Ciencia y tecnología en la España ilustrada. La escuela de caminos y canales. Ediciones Turner, Madrid, pp. 29–32.
2. Egorova OV (2006) Moscow Manege. Past and Present. Globus, Moscow (in Russian).
3. A.H.N.: Estado, leg. 4088, lib.2, doc.153.
4. Cioranescu, Alejandro (1965) Agustín de Betancourt. Su obra tecnica y científica. Instituto de estudios Canarios en La Universidad de La Laguna, La Laguna de Tenerife, vol. XX, pp. 20–21.

5. Rumeu de Armas, Antonio (1990) El Real Gabinete de Máquinas del Buen Retiro, una empresa técnico de Agustín de Betancourt. Ediciones Castalia, Madrid
6. Francisco Arango y Parreño, Obras (2005) vol.1, Ensayo introductorio compilación y notas de Gloria García Rodríguez, impreso en la Empresa Gráfica «Juan Marinello», Editorial de Ciencias Sociales, La Habana.
7. BNC, Fondo Pérez Beato, Manuscritos C. M. Pérez, no.968, (no dates).
8. García-Diego JA (1985) En busca de Betancourt y Lanz. Ediciones Castalia, Madrid, p. 28.
9. Moreno Fraginals, Manuel (1986) El ingenio. Complejo económico social cubano del azúcar. Editorial de Ciencias Sociales, La Habana, tomo 1, p. 87.
10. Expediciones, exploraciones y viajeros en el Caribe. La Real Comisión de Guantánamo en la isla de Cuba 1797–1802. Conferencia Científica por el Bicentenario (2003) Ediciones Unión, La Habana.
11. Cornide, María Teresa (2003) De La Habana, de siglos y de familias. Editorial de Ciencias Sociales, La Habana, pp. 114–119.
12. Guzmán, Indalecio González (1955) El Ferrocarril Cubano, Enciclopedia UTEHA, Barcelona, España.

A Historical Overview of Japanese Clocks and Karakuri

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Abstract This paper describes the history of clocks and *karakuri* (mechanisms) in Japan. In particular, it touches on the application of clock technology to *karakuri ningyou* (Japanese automata) and introduces the works of Hisashige Tanaka, a *karakuri* master in the Edo period (1603–1867) and also a clockmaker. It also discusses the contribution of Hisashige Tanaka to the modernization of Japan through his contributions to the development of *karakuri* and clock technology.

Keywords History, Clock, *Karakuri*, Automata

Introduction

Karakuri means "mechanism" or "system" in Japanese. In the narrow sense, however, it refers to *karakuri ningyou* (automata) and the mechanical mechanisms of machines such as clocks and watches. On the other hand, clocks of the Edo period (1603–1867) have attracted little attention (except among some clock collectors interested in *wadokei* (Japanese clocks)). *Karakuri ningyou* and clocks, however, brought about a sea change in the Edo Period and subsequently, influencing each other and triggering the beginnings of the vigorous modernization and industrialization of Japan following the Meiji Restoration (1868). In this report, therefore, we describe the history of *karakuri* and clocks in Japan and show their effects on the modernization of Japan by following the footsteps of Hisashige Tanaka, founder of the predecessor of Toshiba Corporation.

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History of Clocks and Karakuri in Japan (Prior to the Edo Period)

The first record of a clock in Japan is found in *Nihon Shoki* (The Chronicles of Japan) completed in around 720. It is recorded in it that Emperor Tenchi made a *rokoku* (water clocks or clepsydras) in 660 [1] and 671 [2] (Fig. 1). In the Heian period (A.D. 794–1185), officials measured the time using water clocks, and it seems they measured the time in more detail according to the speed of incense burning on the basis of the time signals. Another important development occurred in 1551 during the Sengoku period when the Spanish Society of Jesus missionary Francisco de Xavier introduced Western mechanical clocks to Japan [3].

The *Nihon Shoki* also contains the earliest record of *karakuri*. It states that the South Pointing Chariot was made in 658 [4]. The advent of the *karakuri ningyou* is recorded in *Konjaku monogatari shu* [5] – a collection of tales, ancient and modern – compiled in the late Heian period, which states that Prince Kaya made *karakuri ningyou*. Prince Kaya is thought to have lived in the 8th century although the historical record is unclear. These *karakuri* were greatly influenced by developments in China and there is a high possibility that they were composed of gears only. In subsequent literature, there are several descriptions about marionettes, suggesting that the technology was handed down. *Karakuri* underwent a revolution in the Edo period.

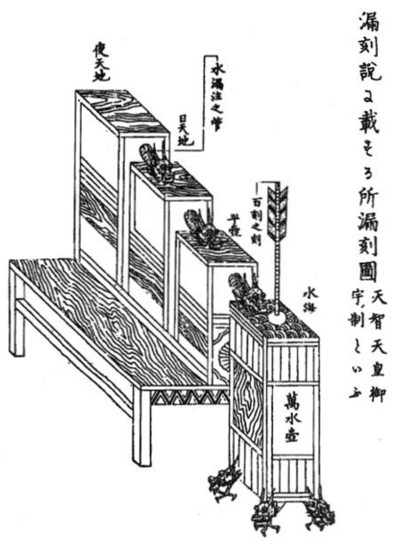


Fig. 1 *Rokoku* (water clock) [6]

Fig. 2 A clockmaker in the Edo period [7]

Introduction of Mechanical Clocks and Their Application to *Karakuri*

As mentioned above, the first western mechanical clock introduced to Japan is recorded in 1551. It was presented to OUCHI Yoshitaka, one of Sengoku daimyo (regional lords), by the Spanish Society of Jesus missionary Francisco Xavier. Subsequently, there is documentary evidence that clocks were presented to ODA Nobunaga in 1569 [8] and TOYOTOMI Hideyoshi in 1591 [9] by envoys dispatched to have audiences with the Pope by the order of Sengoku daimyo OHTOMO Sourin, and to TOKUGAWA Ieyasu in 1606 by the missionary Rodrigues [10] and in 1611 by the Portuguese governor of Indian Goa [11].The oldest clock existing in Japan is one presented to Shogun Ieyasu in 1612 by the viceroy of New Spain (Mexico). It is a spring-driven clock made in Madrid in 1581. It is said that already in 1598, TSUDA Sukezaemon made a mechanical clock [12]. It is also said that while he repaired many Western clocks already imported, he came to understand the mechanism and made a clock on his own (Fig. 2). By the beginning of the 17th century, clockmaking technology had been disseminated in part because clockmaking was taught by missionaries living in Japan. In Japan, however, temporal hour system (Appendix) had been adopted, and clocks based on the fixed time method were not useful. Therefore, *wadokei*, clocks corresponding to the temporal hour system were devised, which are rare and of unusual design. By incorporating a new mechanism, practical clocks were made. This is not unrelated to the fact that many clockmakers at the time already possessed clockmaking technology. Indeed, in China where the temporal hour system was used, western clocks remained the toys or ornaments of emperors.

As mentioned above, craftsmen skilled in *karakuri* techniques became the clockmakers, and in due course, the clockmaking techniques were applied to *karakuri*. The most influential techniques concerned springs and the crown-shaped escapement. A spring is, of course, a means of storing energy, which enabled *karakuri* to move unaided. The performance of fixed motion sequences was achieved by incorporating the escapement. One of the most famous examples of *karakuri ningyou* is the *Chahakobi ningyou* (tea-serving doll) (Fig. 3 and 4). Spring-driven and equipped with balance, the *Chahakobi ningyou* performs the following actions.

1. A cup is placed on a tray held by the doll’s hands.
2. The doll moves toward a guest.
3. It stops in front of the guest.
4. The guest takes the cup and drinks.
5. When the empty cup is placed back on the tray, the doll turns and returns to the starting point.

This *Chahakobi ningyou* is described in a book published in 1690 [13]. Although it draws heavily on clockmaking techniques, the spring is made of whale baleen.

Fig. 3 *Chahakobi ningyou* (replica) [14]

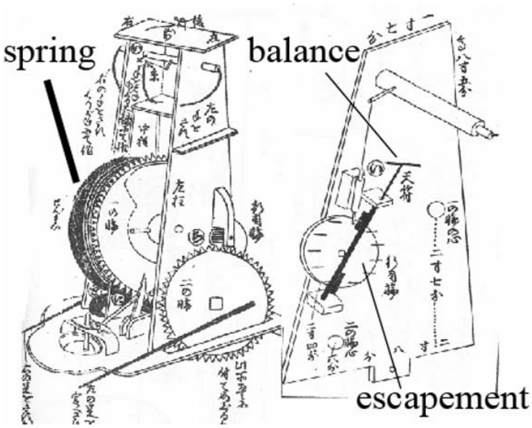


Fig. 4 Mechanism of a *chahakobi ningyou* [15]

Progress of *Wadokei* and *Karakuri*

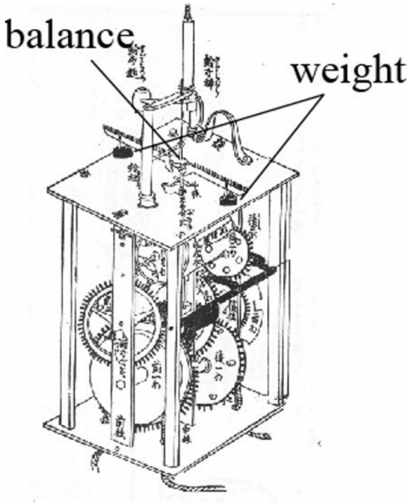
The *wadokei* corresponding to the temporal hour system are of two types: those with a clock hand that moves at a fixed speed in the usual manner, but with a dial whose time interval is adjusted to the temporal hour system (Figs. 5 and 6), and those whose design is such that the time indication of the dial is at equal intervals, but the speed of the hand changes (Fig. 7). The temporal hour system poses a problem in that the time interval differs between day and night within a day and it changes continuously throughout the year. For the former type, there was a system of replaceable dials for the different seasons or the interval of the plates with figures indicating the time was adjusted. The disadvantage is that it is necessary to prepare many dials. For the latter type, the frequency of the escapement is changed by changing the position of the weight (Fig.7). The disadvantage is that it is necessary to replace the weight in accordance with the day/night and season. Although these *wadokei* corresponded to the temporal hour system, it seems that they were troublesome and unsatisfactory. Around 1780, therefore, an improved *wadokei, Nicho-temp tokei* was made [16]. *Nicho-temp-tokei* have two pieces of *temp* (balance) that automatically change the position of the weight for day and night are prepared and automatically changed (Fig. 8). Clocks of this type dispensed with the troublesome task of changing the position of the weight each day. In the latter part of the Edo period, various types of clocks (for example, ring type watch and clock with a music box) were made.

A turning point in the development of *karakuri* occurred in 1662 when TAKEDA Ohmi started *karakuri ningyou* performances (marionette performances featuring *karakuri*). He was originally a clockmaker. Scenes of well-known stories were expressed by means of *karakuri* or various *karakuri*-like mechanical devices. These *karakuri* entertainments, which enjoyed widespread popularity, were performed by many troupes and persisted into the Meiji period (1868–1912).

A milestone in the development of both clocks and *karakuri* was the publication in 1796 of *Karakuri-zui*, a three-volume work on mechanical engineering by HOSOKAWA Hanzo. One volume is about clocks and the remaining 2 volumes explain the structure and fabrication methods of *karakuri ningyou*, including *chahakobi ningyou*. They include illustrations that are in perspective and are rendered with accurate scale. *Karakuri-zui* can be used as a manual for making *karakuri ningyou* and *wadokei*. It is not known how many copies of this work were printed.

Fig. 5 *Wadokei* (*Syaku-dokei*) [14]

Fig. 6 *Wadokei* (*Makura-tokei*) [14]



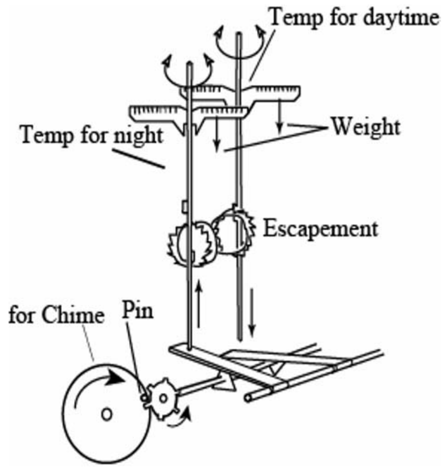


Fig. 7 Mechanism of a *wadokei* [17] **Fig. 8** Mechanism of *Nicho-temp tokei* [18]

However, the fact that *karakuri ningyou* of similar design have been found throughout Japan and that the work was issued many times by different publishers suggest it enjoyed wide circulation. Many of the *karakuri ningyou* makers who have been identified are thought to have referred to *karakuri-zui*. Actually, there is evidence confirming that some *karakuri ningyou* makers possessed the work. It seems increasing numbers of people tried to make *karakuri ningyou*. This view is supported by the strong desire for knowledge and eagerness to learn evident among ordinary people at that time. In the twilight of the Tokugawa shogunate, the literacy rate for men in the towns is thought to have reached almost 80%, and even in the countryside it was 20%–50%. Reflecting these high literacy rates, the total print runs of some books exceeded 10,000 copies. Moreover, book-lending shops were commonplace, suggesting that the readership may have greatly exceeded the number of copies printed. This was a society where ordinary people could acquire knowledge if they had the will to do so. In the countryside, *wasan*, a distinct form of mathematics developed in Japan, was a popular, essentially free, pastime among farmers during the slack season.

The *Man-nen dokei* (Fig. 9) [19] is generally considered to be a masterpiece of the *wadokei* tradition. In 2005 the *Man-nen dokei* was exhibited at Aichi Expo, and in June 2006 it was designated an important cultural property of Japan. This clock is about 60 cm tall and weighs 38 kg. The clock is composed primarily of a hexagonal column accommodating six clock faces, a hemispheric glass container at the top to accommodate the celestial globe, and a pedestal housing in which spiral springs that drive the mechanism. The clock has two sets of spiral springs (a total of four springs), one set for driving the indicators of the clock, and the other for striking the bell. The springs are made of brass.

Six clock faces of the *Man-nen dokei* are as follows:

· First face: *Wadokei* and the 24 astronomical seasons indicator (Fig. 10)
· Second face: Memo (writing the date of the 24 astronomical seasons)
· Third face: Seven days of the week
· Fourth face: Ten calendar signs and twelve signs of the Chinese zodiac (*Jikkan* and *Jyuunishi*)
· Fifth face: Lunar calendar and lunar age
· Sixth face: Western-style clock

A feature of the design of the *Man-nen dokei* is that *warigoma* (split plates), each showing a designated time, are arranged on the circumference of a disc (a clock face) which completes one turning at constant speed in one day, and the time is shown by the *warigoma* indicated by a fixed clock hand on the fixed plate supporting the *wadokei*. Since the clock hand is fixed, changes of time in day and night and also in each season are expressed in the temporal hour system by adjustment of the clearance between the *warigoma*. Each *warigoma* is driven by a spiral spring and gears only and it is possible to display the time automatically throughout the year. The *Man-nen dokei* represented the pinnacle of the *wadokei* tradition. However, with the advent of the Meiji period, the temporal hour system was abolished and *wadokei* ceased to be made.

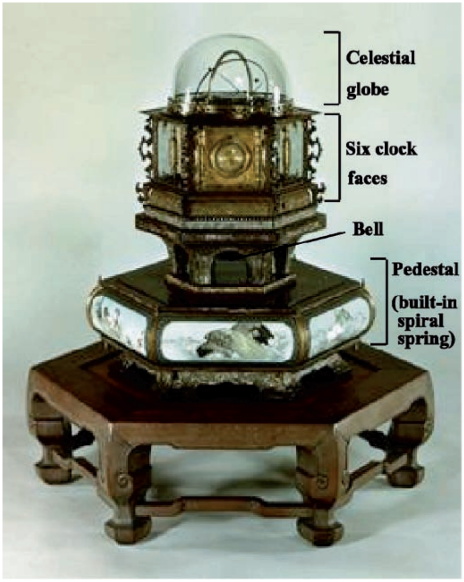


Fig. 9 *Man-nen dokei* [19]

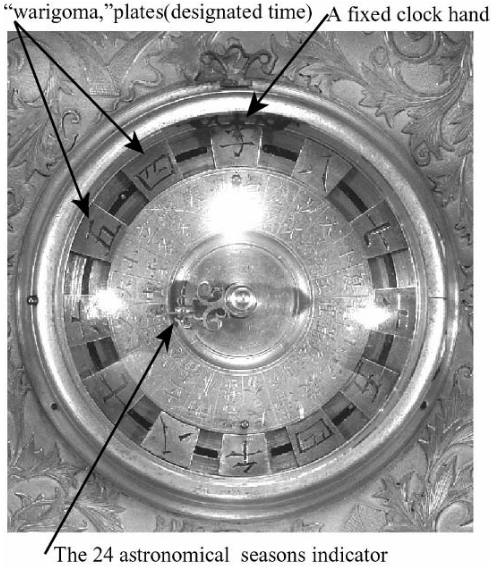


Fig. 10 First face of the *Man-nen dokei* [19]

The *Chahakobi ningyou* is cited above as a famous example of *karakuri*. Another celebrated example, featuring a similar system, is the *Sake-kai ningyo* (sake-buying doll) made by IIDZUKA Igashichi, but unfortunately no examples have survived (Legend has it that the doll automatically walked to a sake shop to buy sake!). Also of great significance is the *Yumi-iri-douji* (bow-shooting doll) made by Hisashige TANAKA (Fig.11). This doll picks up an arrow from a table, fixes it to a bow and shoots at a mark, and repeats the steps. It is composed of a spring, a fusee, a cam/lever, a speed governing mechanism, and the doll itself. The limbs of the doll are moved by strings attached to the lever moved by the cam. The *Yumi-iri-douji* is admired not only for its smooth action, but also for two other features. One is that the doll's face is like a *Noh* mask. The eyes and mouth don't move, whereas those of western automata typically do move. Only the direction of its face can express its feeling. The other feature is that it fails. One arrow is deliberately designed so that it does not hit the mark, presumably to maintain the interest of the audience. According to Kazuyoshi SUZUKI of the National Science Museum senior curator, "In the West, they would have adopted a mechanism centering on gears to prevent failure. I think Hisashige TANAKA used the strings instead of the gears, despite the fact that he had sufficient expertise in gear technology as is evident from the *Man-nen dokei*, because he wanted to realize the delicate movement and facilitate the adjustment" [20]. Another notable example of Hisashige Tanaka's work is the *Moji-kaki ningyou* (writing doll). (Fig. 12), which was recently discovered and has been restored (by Susumu HIGASHINO). This is similar to the automata called The Writer made by Jaquet-Droz, which is on display at the Museum of Art and History located in Neuchatel, Switzerland.

Fig. 11 *Yumi-iri-douji* (replica) [14]

Fig. 12 Moji-kaki ningyou [21]

In the case of The Writer, however, the elbow and lower parts move when it writes a character, giving it an appearance reminiscent of that of a plotter, whereas, in the case of the *Moji-kaki ningyou*, the movement of the shoulder and lower parts is akin to that of a person who is actually writing a character. In addition, the *Moji-kaki ningyou* uses a writing brush and executes large changes in terms of the brush pressure and speed. It realizes motion similar to that of a human being in combination with the delicate movement of the face that matches the movement of the arm.

Karakuri Master TANAKA Hisashige

As mentioned above, Hisashige TANAKA was a distinguished clockmaker and karakuri master. Indeed, the biography of Hisashige TANAKA coincided, in important respects, with the development of mechanical engineering in Japan. He was born in 1799, the eldest son of a tortoiseshell craftsman, at Kurume in Kyushu, far from Edo (Tokyo), Osaka, and Kyoto, the major cities of Japan in the Edo period. However, it seems itinerant *karakuri* entertainers performed during the annual shrine festival and gained popularity among the local people and that he also watched the performances in his childhood. It is not known whether he was influenced by them, but he made various inventions utilizing *karakuri* from his childhood. In his early twenties, he traveled as an itinerant *karakuri* entertainer throughout Japan. The *Yumi-iri douji* is thought to have been made during this period.

In his thirties, he opened a shop in Osaka. The purpose was to sell his inventions utilizing his expertise in mechanical engineering, and the name of the shop was *Kikou-dou* (*Karakuri* shop). He produced two hit products there. One was *kaichu-syokudai* (portable pocket candle-stand) (Fig. 13), which is said to have gained popularity among merchants and doctors who made house calls at night, The other was *mujin-to* (automatically fueled lamp) (Fig. 14), which assured long lighting and improved brightness by continuously supplying oil from a tank by means of an air-pressure pump. The design is thought to be influenced by the structure of air guns from Europe. This was also very popular among merchants who wanted to work at night. The shop subsequently relocated to Kyoto, where it seems he became interested in clocks. While making various clocks, he also devoted himself to the study of astronomy and physics from the West. In 1851, he completed the *Man-nen dokei*, fusing the clock technology of the West with *wadokei*, and astronomy with the Japanese calendar.

Fig. 13 *Kaichu-syokudai* [14]

Fig. 14 *Mujin-to* [14]

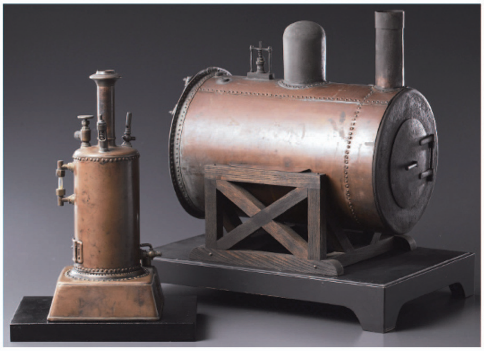


Fig. 15 Steam engine [14]

Fig. 16 Predecessor of Toshiba Corporation (approximately 1880) [14]

Versed in the latest knowledge from the West, he gained a reputation as an accomplished engineer and designer of machines, including *karakuri*. He was invited to the Saga domain in Kyushu, which had long been eager to adopt Western technology, where he took the lead in developing working models of a steam locomotive, a screw-driven steamship and a paddle steamer, as well as a full-scale steamship, telegraph equipment, etc (Fig. 15). In addition, he established production of Armstrong's rifled breech loader in the Kurume domain.

As modernization progressed after the Meiji Restoration, the Meiji government called him to Tokyo in order to utilize his expertise. He set up a factory in Tokyo in 1872 to produce Henry telegraph equipment. In 1875, he opened a shop-cum-factory in the Ginza district of Tokyo (Fig. 16). This year was made the foundation year of present Toshiba. Thus, Hisashige TANAKA is the founder of Toshiba.

As described above, Hisashige TANAKA was a superlative craftsman, a *karakuri* master who became a master clockmaking, and moreover, contributed to the rapid modernization of Japan by applying his engineering expertise.

Conclusions

I have described the history of clocks and *karakuri* in Japan, focusing on their development during the Edo period, and, in particular, on the contributions of Hisashige TANAKA not only to the development of clock and *karakuri* technologies, but also to the modernization of Japan.

Acknowledgements In writing this paper, I referred to two excellent books, *Karakuri* [22] by Shouji TATUKAWA and *Karakuri–Ningyou* [20] by Kazuyoshi SUZUKI. In particular, I benefited greatly from the ideas of Mr. SUZUKI, one of the leading experts on *karakuri*, and I am grateful to him. I wish to thank Susumu HIGASHINO for the photographs of the *Moji-kaki Ningyou*.

Appendix

Temporal Hour System Formerly Used in Japan

In the temporal hour system formerly used in Japan, the day and night were each divided into six hours of equal duration. The daytime was counted from dawn to dusk, not from sunrise to sunset. Therefore, the unit hour of daytime was not equal to that of night-time during a day. Furthermore, the length varied with the seasons. In the temporal hour system, counting of the hours of a day began at midnight (Table 1) [19].

Table 1 Numerical designation of temporal hour

Numerical designation of the temporal hour	Time of the present hour system	
9(Kokonotsu)	Midnight	Noon
8(Yatsu)	Approx. 2:00	14:00
7(Nanatsu)	Approx. 4:00	16:00
6(Mutsu)	Dawn	Dusk
5(Itsutsu)	Approx. 8:00	20:00
4(Yotsu)	Approx. 10:00	22:00

References

1. Nihon Shoki (The Chronicles of Japan, first national history), around 720, reprinted edition: Kokushi-Taikei 1–2 Nihon-Shoki, (1967), Yoshikawa-koubunkan, p. 273. (in Japanese)
2. Nihon Shoki, (The Chronicles of Japan, first national history), around 720, reprinted edition: Kokushi-Taikei 1–2 Nihon-Shoki, (1967), Yoshikawa-koubunkan, p. 299. (in Japanese)
3. Crasset RP, Histoire de l'Eglise du Japon/par le R. P. Crasset de la Compagnie de Jesus. – Seconde ed. – A Paris : Chez Francois Montalant, 1715. Nihon-Seikyou-shi 1, p. 177, Hakubunsya, Tokyo, 1878, National Diet Library Collection. (in Japanese)
4. Nihon Shoki, (The Chronicles of Japan, first national history), around 720, reprinted edition: Kokushi-Taikei 1–2 Nihon-Shoki, (1967), Yoshikawa-koubunkan, p. 268, 291. (in Japanese)
5. Konjyaku-Monogatari-syu, compiled in the late Heian Period, reprinted edition: Kokushi-Taikei 17 Konjyaku-Monogatari, (1967), Yoshikawa-koubunkan, pp. 641–642. (in Japanese)
6. Sasaki K (2003) The principle of "Rokoku (Water Clocks)" and the numerical calculation of their water level, Bull. Natn. Sci. Mus., Ser.E, 26, pp. 21–31.
7. Genzaburou, Jinrin-kinmou-zui, 1690, Kendou-bunko, Reprinted edition: Kinmou-zui-syuusei 13 Jinrin-kinmou-zui, p. 200, Ohzora-sya, Tokyo, 1998. (in Japanese)
8. Luis Frois, Historia de Iapam, established in 16C, Japanese translation: Nihon-shi (History of Japan), 2, p. 154, Chuuou-kouron-shinsya, 2000. (in Japanese)
9. Luis Frois, Historia de Iapam, established in 16C, Japanese translation: Nihon-shi (History of Japan), 5, pp. 121, Chuuou-kouron-shinsya, 2000. (in Japanese)
10. Crasset RP, Histoire de l'Eglise du Japon/par le R. P. Crasset de la Compagnie de Jesus. – Seconde ed. – A Paris : Chez Francois Montalant , 1715. Japanese translation: Nihon-Seikyou-shi 2, p. 342, Hakubunsya, Tokyo, 1878, National Diet Library Collection.
11. Tsukada T (1960) Wadokei, p. 28, Toho-syoin, Tokyo. (in Japanese)
12. Tsukada T (1960) Wadokei, pp. 36–37, Toho-syoin, Tokyo. (in Japanese)
13. Ihara S, Haikai H (2001) reprinted edition: Nihon-koten-bungaku-zensyuu, 61, Rengasyuu-Haikaisyuu, p. 462, Shougakukan, Tokyo. (in Japanese)
14. Toshiba Science Museum Collection
15. HATTORI Hanzo, Karakuri-zui, 1797, National Diet Library Collection Reprinted edition: Kinmou-zui-syuusei 23, pp. 90–94, Ohzora-sya, Tokyo, 2000, in Japanese
16. Hisashige TANAKA, Man-nen dokei zuben, Kyoto, National Science Museum Collection.
17. HATTORI Hanzo, Karakuri-zui, 1797, National Diet Library Collection Reprinted edition: Kinmou-zui-syuusei 23, p. 170, Ohzora-sya, Tokyo, 2000, in Japanese
18. Tsukada T (1960) Wadokei, p. 123, Toho-syoin, Tokyo. (in Japanese)

19. Yokota Y et al. (2007) Mechanism of “Man-nen dokei,” a Historic Perpetual Chronometer Part1: Celestial Globe and Japanese Traditional Clock, 12th IFToMM World Congress, Besançon, France.
20. Suzuki K (1997) Karakuri ningyou, pp. 73–76, Gakusyu-kenkyu-sya, Tokyo. (in Japanese)
21. Susumu HIGASHINO (Nippon Karakuri-automata Society) Collection.
22. Tatukawa S et al. (2002) Karakuri, Kawade-syobou, Tokyo. (in Japanese)

An Introduction to the Spinning and Weaving Devices and Tools of the Miao Ethnic Group in the Northeast of Yunnan Province

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Abstract Based on information collected from field surveys carried out from Sept. 2006 to Aug. 2007 in Longzuishi, a village of Miao ethnic group in Yunnan province, this paper described sets of spinning and weaving devices and tools used by Miao women to spin hemp, reel hemp thread, wind weft thread on a spool and weave hemp thread into cloth.

Keywords Miao people, Hemp, Spinning and weaving devices and tools

Introduction

Miao is one of the largest amongst the 25 minority ethnic groups in Yunnan province. They mainly live in Wenshan Zhuang and Miao People Autonomous Prefecture, Honghe Hani and Yi People Autonomous Prefecture in the southeast of Yunnan province and in Zhaotong city in the northeast of Yunnan Province. Miao people still use traditional spinning and weaving devices and tools to make their own traditional clothes, usually made of ramie and hemp.

During the period from Sept. 2006 to Aug. 2007, the author visited Longzuishi village in Yunnan province five times to study their traditional spinning and weaving devices and tools. There were 93 families in this village, and each family with a middle-aged woman almost always had spinning and weaving devices and tools, most of which were still in use. The author met several

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middle-aged women, including LONG Meifang, an expert in spinning and weaving, her sister-in law, her aunt and another woman. The author surveyed the traditional devices and tools they were using, watched how they used them and tried operating some of them.

Spinning Devices and Tools

Spinning Wheel

A foot-operated spinning wheel, called "Jiao Ta Fangche" in Mandarin, was invented in the Donghan Dynasty (25–220 A.D.). In Yunnan province, Foot-operated spinning wheel with more than one spindle was only used by Miao people [1]. In Miao language, they called this type of spinning wheel "Darchan". In this village, women used four-spindle-foot-operated spinning wheel, which, except for the additional spindle, was similar to the traditional Chinese three-spindle-foot-operated spinning wheel depicted in the ancient book *Nong Shu*, literally A Book on Agriculture, written by WANG Zhen in 1313.

Based on an eccentric, a foot-operated spinning wheel could convert up–and–down movement into circular movement to run the spindles inserted into it when its treadle was operated. The wooden spinning wheel the author saw was 145 cm long and 108 cm high. It was mainly joined with tenons, mortises, wedges and dowels except for some parts bound with iron wires. It consisted of a base, two vertical posts, a treadle, a wheel and a head as shown in Fig. 1.

Fig. 1 A four-spindle-foot operated spinning wheel (Jan. 2007)

The shape of the base was the same as the Chinese character—"丁" (ding) (some base was shaped like "工" (gong)), and it was made of two pieces of wood. One was 120 cm long, 6 cm wide and 6 cm thick; the other 58 cm long, 5.5 cm wide and 4.2 cm thick. A 108 cm-high-6 cm-long-and-5 cm-wide vertical post was placed 14 cm away from its wide end, on which the wheel was fixed. 10.5 cm away from the narrow end was a 27 cm high vertical rod with a tapered head. The treadle was a 118 cm-long wood. One end of it was big and flat, and had a small hole in it; the other end was small and pointed, and was inserted into a small hole in the middle of one of the spokes of the wheel. Inserted into the hole in the treadle, the shorter vertical rod supported this pedal lever (see Fig. 1).

The wheel was built with two canes and two flat pieces of wood. Its width was 13 cm. It had an inside and outside diameters of 62 cm and 67 cm. The canes were shaped into the two rims of the wheel while the two flat pieces of wood were used as the spokes. One wood was thinner than the other. The thin wood traversed a rectangular hollow in the centre of the thick one and formed a cross, which was the spokes of the wheel. Outside the spokes, four small flat pieces of wood were joined to the rims and spokes together by iron wires. Between these flat pieces of wood, there was another small flat piece of wood respectively which joined the rims with iron wire to make the wheel firm. One end of a thick wood was carved into the hub of this wheel while the other end was carved into a rectangular tenon that was inserted into the mortise in the vertical post to form the bracket of this wheel.

The head of the spinning wheel sat above the wheel and was comprised of two long, flat pieces of wood whose shape was similar to a bow (see Fig. 1). They were rabbeted together by means of three small pieces of flat wood and some dowels. The flat wood in the middle was also the bracket of the head which was joined to the vertical post with a tenon, a mortise and a wedge. In the outer wood of the head, there were four pairs of u-cuts. Correspondingly, there were four pairs of holes in the inside wood. Four driven shafts with spindles were inserted into them when spinning. Some thin reinforcing steel rods with a small round wood on one end and a spindle on the other end were used as the driven shafts. During weaving process, only four u-cuts and holes were required. They would be replaced by the other four when they became too hot from friction heat. With the help of a leather transmission belt and the driven shafts, the spindles were turned by the wheel.

Reel

A hemp thread was rich in glue. The glue had to be dissolved before it was weaved into cloth. Therefore a reel was required. A reel was a revolving frame, called "Dargelee" by Miao people or "Guangzi" in Mandarin. By means of a reel, a hemp thread was wound into a reel, making it easier to boil and wash off the glue on the hemp thread. The reel was made up of two parts (see Fig. 2a). One part was a stump with several branches around one end and an axle at the

Fig. 2 (**a**) A reel (Jan. 2007) (*left*); (**b**) A woman reeling off a hemp thread with a reel (Photo taken by PU Luping in Sept. 2006) (*right*)

top of the other end, which was used as a base; the other was a wooden cross wheel with a small rod inserted into each end and a hole at the center. It was typically 40 cm high and of 120 cm diameter. When winding a hemp thread, a woman sat next to it, turned the cross wheel with one hand and held a spindle with the hemp thread in her other hand. A reel was also used to reel off the washed hemp thread, which was later put into a small round bamboo basket (see Fig. 2b).

Woof Reel

Fig. 3 (**a**) A woof reel (Jan. 2007) (*left*); (**b**) A woman winding a hemp thread on a spool with a woof reel (Jan. 2007) (*right*)

A woof reel, also called "Darchan" in Miao language but called "Weiche" or "Luoche" in Mandarin, was a device for winding the washed hemp thread on a spool from the small bamboo basket. The spool would be set into a shuttle and the hemp thread on it would be used as weft. The structure of a woof reel was the same as that of a common wooden one-spindle-hand-operated cotton spinning wheel, but with a smaller driver as shown in Fig. 3. A woof reel was composed of a base, a driver with a small shaft, a driven roller and a transmission belt. The base was of the form of the Chinese character—"工" (gong). Some used just a piece of thick rectangular wood as its base. Whatever the shape, its main function was to hold the frame steady. The base was typically 50 cm long with a vertical post at each end. The vertical post, on which the driver was fixed with tenon, mortice and wedge, was about 35 cm high while the other vertical post was twice as wide but a little shorter. The axle of the driven roller was fixed onto the shorter post with a cane or was inserted into it directly. A hemp string was used as a transmission belt. The driver was made of one piece of flat wood and its diameter was from 20 to 25 cm. Along its rim was a v- or u-groove for the transmission belt. There was a small wooden handle on the outside face of the wheel near the rim. There was more than one shallow groove around the driven roller for the transmission belt, which could be used in turns in order to prolong the service life of the driven roller. When using a woof reel, a woman put a spool on the axle of the driven wheel, then stepped on the base with one foot, turned the driver with her right hand and lifted the hemp thread from the basket with her left hand. The hemp thread was thus rolled on the spool which would be set into a shuttle (see Fig. 3).

Loom

According to Mr. YAN Enquan's study, it was a foreign missionary and his wife who taught Miao people to make a platform loom in the 1930s [2,3]. And the people in this village also said that some foreign missionaries had brought them a platform loom.

Nowadays, Miao people used two kinds of loom: a loom connected to the waist of a weaver, called "DoDolyesar" in Miao language and "Yaoji" in Mandarin; the other was a platform loom named "Darjarjar" in Miao language and "Taishi Zhibuji" in Mandarin. The purposes of these two kinds of loom were different. A waist loom was used to weave colored belts or satchels while a platform loom was used to weave hemp cloth for making clothes or skirts. Generally, the colored woven cloth was only 7.5 cm wide but the hemp cloth was typically 43–45 cm wide.

Waist loom

A waist loom was the most ancient loom in the world and was also the origin of a platform loom. Although platform loom was popular in this village due to its efficiency, waist looms were so convenient for carrying around that Miao women seemed to always take them when they were out or grazing herds on hills. In their spare time, the women would continuously weave with the waist looms. There were only a few differences between Miao people's waist loom and that of other ethnic groups. A waist loom consisted of a woof tightener, a shuttle, a heddle, a wood to separate and guide warp threads and a warp reel (see Fig. 4).

It did not have a cloth reel or a waistband, making it more convenient to carry. The woven colored cloth was tied to the waistband of a woman's skirt directly as shown in Fig. 4.

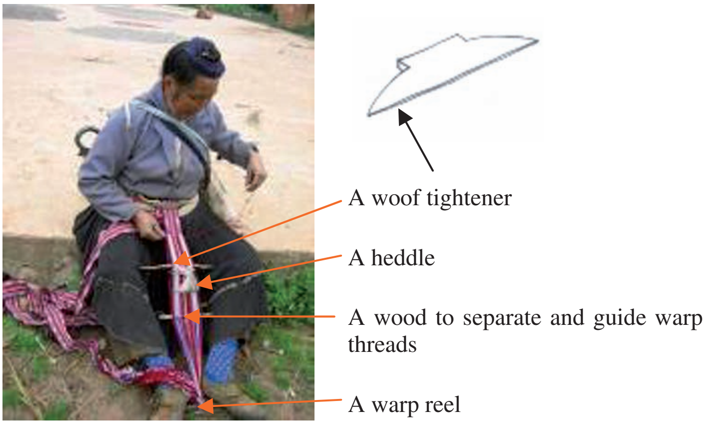

Fig. 4 A Miao woman weaving a belt with a waist loom (Photo taken by PU Luping in Sept. 2006)

Fig. 5 Figures on the Treasure Container excavated from the site of Shizhaishan, Jinning County, Yunnan province [1]

The heddle was made of some hemp threads, and only lifted and guided the lower (even) warp threads while the wood to separate and guide warp threads controlled upper (odd) warp threads. Every odd warp thread would be wound around this wood once in order to fix it. Thus the wood could lift and guide all odd warp threads. The woof tightener of a waist loom was a piece of wood. It was about 25 cm long, 10 cm wide, and was shaped like a boat but its bottom heaved a little and its top was a little sharp like a knife. The heaving bottom widened the path for a shuttle to run through while the sharp edge helped to tighten the weft. The shuttle of a waist loom was not like a boat but a slip of wood with a u-cut at each end in which the woof thread was wound. Some weavers did not use a shuttle but a ball of woof thread when weaving. The warp reel was typically a wood rod, one end of which was flat and the other pointed. It was easy to stick the pointed end into the ground when arranging warp threads. In fact, warp threads were not wound onto this warp reel but were only knotted and tied to it. When weaving, the warp threads were tightened as the weaver stepped on them as shown in Fig. 4.

When weaving with a waist loom, Miao women looked like the figures on the Treasure Container excavated in the site of Shizhaishan, Jinning County, Yunnan province as shown in Fig. 5. This Treasure Container was made approximately in the second century.

Fig. 6 A woman weaving with a platform loom (Jan. 2007)

Platform loom

All the platform looms in the village were made of wood and were quite similar. The platform loom the author surveyed was 148 cm high, 130 cm wide and

166 cm long. It had a base, a warp reel, a support rod of warp threads, two pieces of heddle, two pedals, a reed, a trough for a shuttle to run through, a support rod of cloth, a cloth reel and a moveable seat board (see Fig. 6).

The base was a cuboid framework of 130 cm long, 67 cm wide and 60 cm high. However, the height of the vertical posts at its two ends was different: one was 67 cm high while the other 97 cm high. The shorter posts were the bearing of the moveable seat board; the taller ones shored up the support rod of warp threads. The warp reel was set outside the taller posts. There was another frame measuring 88 cm-high-and-65 cm-wide vertically rabbeted onto the base, which was located 35 cm away from the taller posts. The roller of the two pieces of heddle and the pulley of the shuttle were near or at the top of this framework. The reed, the trough for a shuttle to run through, and their support were integrated into another vertical frame which was under the vertical form with the roller and the pulley on and toward the cloth reel. The cloth reel, its bearing and the support rod of cloth were positioned between the trough and the moveable seat board. The warp reel was set almost at the same level as the seat board to balance the whole loom.

There were two kinds of wrap reel in the village. One was a hexagonal axle with 6 wood bars rabbeted at each end (see Fig. 6); the other was a tetragonal axle with two pieces of cross wood joined to the two ends by means of tenons, mortices and dowels (see Fig. 7[1]).

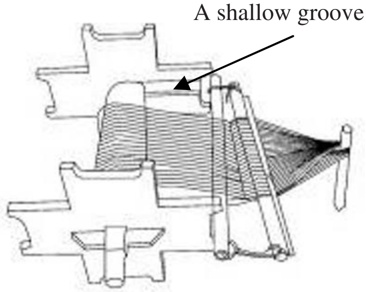

Fig. 7 A tetragonal-axle warp reel

The hexagonal-axle warp reel was 40 cm wide inside and its diameter was 60 cm. The twelve slips of wood rabbeted at the two ends of the axle were to assist in fixing the wood rod or bamboo rod to which warp threads were tied, to prevent them from slipping, and to prevent the warp reel from turning during the weaving process. A tetragonal-axle warp reel was different in shape. Two pieces of wood, 40 cm long and 18 cm wide, were interlocked as a cross before they were joined to any end of the tetragonal axle with a tenon, a mortice and a dowel. Each piece of wood had two protuberances on its edge for the convenience of controlling the turning of the warp reel with a long rod, which was put on the base closely in front

[1] Figures 7, 12, 13 and 14 were drawn by Yan Junhua who works in Yunnan City and Town Planning Institute.

of the warp reel during the weaving process. On the surface of the tetragonal axle was a shallow-40 cm-long-and-1.5 cm-wide groove in which the wooden rod or bamboo rod with warp threads could be positioned. In the inside wall of the cross wood at the two ends of the axle were two corresponding shallow grooves for the wooden or bamboo rod to be pushed in (see Fig. 7).

The rod supporting the warp threads was located at the top of the taller vertical posts, to which the wood to separate and guide warp threads was tied. It could lift the level of the warp threads a little higher than the reed making it easier for the operator to weave and to look out for any broken thread.

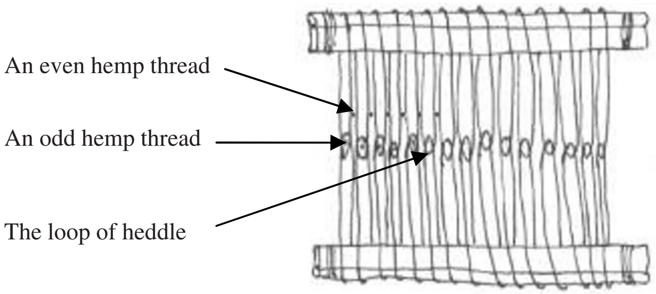

Fig. 8 A piece of heddle

There were two pieces of heddle on a platform loom. They could lift the odd and even warp threads in turn to make a path for a shuttle to run through when the two pedals linked to them were pressed down in turns. One piece of heddle comprised of two bamboo rods, two wooden bars and some hemp threads, which formed a 54 cm-long-and-23 cm-wide frame (see Fig. 8). The upper hemp threads always hooked the lower hemp threads to form loops in the middle of the hemp threads. Through the loops of one of the heddles there were only odd warp threads while the other only held even warp threads (see Fig. 8)

To make a piece of heddle, a special tool called the heddle-making wood, or "Darharzaimarbitsau" by Miao people, was required. It was a piece of wood for winding hemp threads measuring 55 cm-long-and-1.5 cm-thick with one end wider than the other. The wider end was 8 or 9 cm wide and the other 5.5 cm wide. It had typically two styles (see Fig. 9). The sloping edge was to help take off the hemp threads after winding them on a bamboo rod. Figures 10 and 11 showed how hemp threads were rolled with this tool. One piece of heddle was made by winding all hemp threads twice. Each time only one half of the heddle was wound and each time the hemp thread only hooked one odd or an even warp thread. After finishing one half, the heddle-making wood was slipped off, and the wooded bar was used to press the hemp thread firmly onto the bamboo rod. The wooden bar and the bamboo rod were then bound together with some hemp strings. Then, the warp reel was turned upside down to roll the other half of the piece of the heddle.

The next steps were the same as before. Another hemp thread was guided through all the hemp thread loops to hook all the odd or even warp threads one by one. A piece of heddle was thus completed (see Fig. 8).

Fig. 9 Two types of heddle-making wood

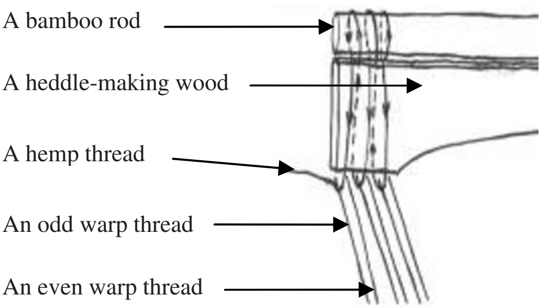

Fig. 10 Making a piece of heddle

Fig. 11 A woman making a piece of heddle with the help of a piece of heddle-making wood (Sept. 2006)

The two heddles were connected by a hemp string tied to each upper corner. Therefore, two strings hung these two pieces of heddle on the roller near the top of the tall vertical frame. There were three styles of roller as shown in Fig. 12. The lower corners of the two heddles were connected to the two pedals with two strings separately. The pedals were 54 cm long, 10 cm wide and 3 cm thick. When one pedal was depressed, the heddle connected to it would move down while the other moved up, creating a wide path for the shuttle to run through smoothly. When the two pedals were pressed down constantly in turns, the two heddles would keep moving up and down correspondingly. The back of the two pedals was set between four small iron circles on a thick wood that was rabbeted to the base. One thin bamboo rod or iron wire was inserted into these four iron circles to fix the pedals so that they could not move sideways but could be lifted with the entire device when moved.

The reed and the trough for a shuttle to run through were integrated into a frame measuring 130 cm long and 89 cm high. The reed was used to comb warp threads and tighten woof threads. It was 46 cm long and 7.3 cm high, made up of two pieces of long and flat bamboo bars, two short pieces of bamboo, many bamboo flakes and some hemp strings. The hemp strings were rolled on the flat bamboo bars between which the bamboo flakes were inserted into the hemp strings. The two short pieces of bamboo were put at the two sides and bound to the two flat bamboo bars with hemp strings. The reed was inserted into the middle of the top of the trough for a shuttle to run through and fixed with two wood dowels.

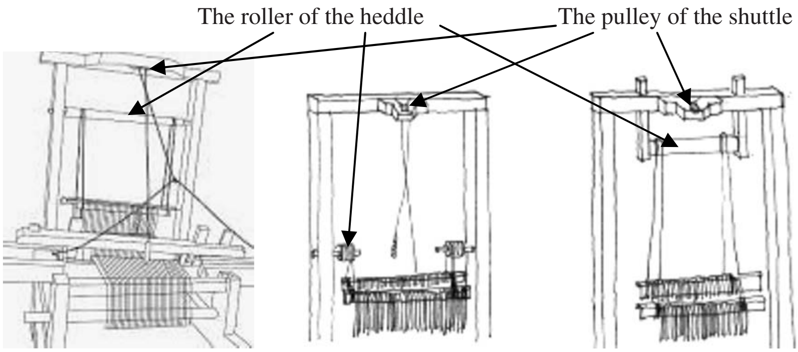

Fig. 12 The three styles of vertical wooden frame for fixing the roller with the heddles and the pulley of a shuttle

The support of the trough could move back and forth and had two styles: one had four legs linked to the inside of the two pieces of lower wood of the base framework with four iron nails; the other only two legs with a n-cut at the feet that rode on two pegs. The pegs were on the outside of the two pieces of lower wood of the base framework.

There were two slideways in the inside wall of the trough at each end for a circle to slide and hit the shuttle into operation. The circle was made of leather and was fixed onto a small square piece of wood with two sloping edges, which fitted into the slideways perfectly so that it could move smoothly when the string tied to it was pulled down. A string was tied to the two circles and another string with a handle was connected to this string through a pulley at the top of the tall vertical frame. When weaving, the operator pulled and drew the reed in turns with her left hand, drew down the handle with her right hand while her feet pressed down the pedals in turns simultaneously. These actions caused the circles to constantly hit the shuttle so that it came and went smoothly along the trough.

The shuttle was 35 cm long, 4 cm wide and 4 cm high. There were two wood rollers set in the bottom to ensure the shuttle move more quickly and smoothly. Furthermore, how a weft went in the shuttle could keep it moving quickly and sending the woof smoothly (see Fig. 13).

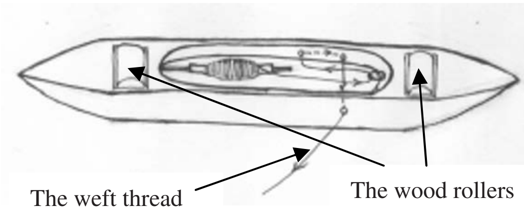

Fig. 13 The bottom of a shuttle

The cloth reel was a 77.5 cm-long wood rod with a diameter of 5 cm. One of its ends was hollowed out in the shape of a cross. It was set between the trough and the moveable seat board. Its bearing was two holes in the base of the support rod of cloth. Outside of the base on the right side was a small trough with more than ten iron bars inside. A slip of wood that ran through the hollow cross in the cloth reel was inserted in between the iron bars to control the turning of the cloth reel so that the warp threads and cloth could be tightened (see Fig. 14).

The support rod of cloth was located above the cloth reel. Just as the support rod of wrap threads lifted the level of all warp threads, the cloth support rod lifted the level of cloth. Generally, there was no support rod of cloth in a traditional loom. The support rod of cloth in Miao people's loom was related to the control device of the cloth reel (see Fig. 14). Furthermore, it could relieve the weaver from having to lower her head and bending forward.

The seat board was usually 56 cm long, 16 cm wide and 3 or 4 cm thick. It was very unique in that it was moveable with the aid of rollers at its two ends. During the weaving process, it moved with the weaver back and forth, thereby reducing fatigue.

Typically, the Miao women commenced spinning and weaving when there was not much work in the fields in summer and winter. When not in use, the looms were taken apart to free up some space in the house. Therefore, their looms couldn't be seen in other seasons in their houses.

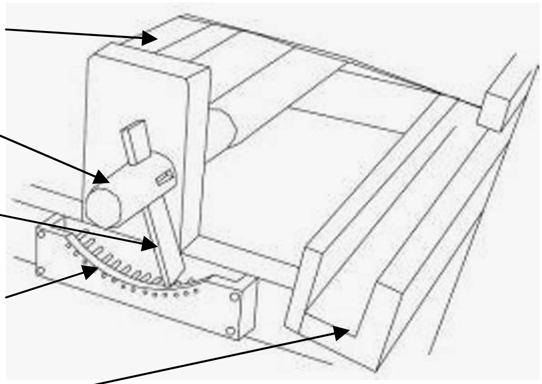

Fig. 14 The trough and the slip of wood to control the turning of the cloth reel

Conclusion

Although nowadays girls in this village were not required to learn how to spin and weave as their mothers did when they were young, spinning and weaving devices and tools were still popular in Miao people's daily life. In fact, almost all middle-aged women could spin and weave. It was some historical reasons of Miao people and their preference for traditional clothes that kept these spinning and weaving devices and tools working.

References

1. LUO Yu and ZHONG Qiu （2000）Spinning and Weaving, The Material Culture of Yunnan (in Chinese), Yunnan Education Publishing House, Kunming.
《云南物质文化·纺织卷》；罗钰、钟秋著，云南教育出版社，昆明，2000年
2. YAN Enquan (1993) Clothes Adornment's Tradition and Change of Yun Nan Province's Miao People (in Chinese), The Tonsan Publications, Taipei.
《云南苗族服饰文化的传统与发展》；颜恩泉著，唐山出版社，台北，1993年

3. YAN Enquan (1999) The Influence of Foreign Religion on Miao People's Area in the Southwest of China (in Chinese), Yunnan Ethnic Publishing House, Sout-west China Culture Studies, Kunming, No. 4, pp. 47–66.
颜恩泉，“外来宗教对西南苗区的影响”，中国西南文化研究，云南民族出版社，第四辑，昆明，第47-66页，1999

Ancient Chinese Windmills

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Abstract Early records of wind-driven water-lifting devices were first discovered in a book written in the twelfth century in China. In the Ming Dynasty of China (1368–1644), windmills became popular in the Southeastern area of the country. Windmills back then could be classified into two types, the vertical-axle windmill, also know as the vertical-sail windmill, and the horizontal-axle windmill. They had vanes like the cloth sail on a Chinese sailboat and were mainly used to drive water-lifting devices. The most ingenious part of the vertical-axle windmill was the self-adjustment of the sail direction in response to wind as the windmill rotated. In 1992 and in 2006, an ancient vertical-axle windmill was rebuilt by the CAS Institute for the History of Natural Science.

Keywords Vertical-axle windmill, Horizontal-axle windmill, Reconstruction

Introduction

One of mankind's important inventions from thousands of years ago is wind driven boats or machines. Historic recordings of sailing boats and windmills can be found in many countries around the world. One of these about sailing boats is a Chinese article written in the Eastern Han Dynasty (A.D. 25–220) [1].

A story written in the 9th century revealed that vertical-axle windmills were built by Persian craftsmen in the 7th century [2]. Yeluchucai 耶律楚材 (1190～1244), a Khitan official from Mongolian-ruled China, composed a poem [3] about windmills that he saw in Samarqand. Joseph Needham [4] wrote that Persian windmill technology was transmitted into China during the Western Liao State (Qarã-Khitãi, 1124–1211).

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However, Needham's viewpoint is debatable. Before the 13th century, a water-lifting device driven by a windmill was mentioned in Chapter 3 of a book entitled Shaoxi Ji (苕溪集), which was written in the twelfth century by Yizhi Liu (劉一止) (1078–1161) in the South Song Dynasty of China [5]. In the 17th century, windmills were recorded in important technical books such as the Nongzheng Quanshu 農政全書 (Book on Agriculture, 1639) by Guangqi Xu's (徐光啓) and Tiangong Kaiwu (天工開物), 1637, translated as Natural Skills Exploiting Things, by Yingxing Song's (宋應星).

Generally, a windmill is a device consisting of vanes, a shaft, a gear wheel and other parts that when subjected to straight-line motion of air current (wind) rotates its vanes. There are two types of windmills in China, especially in coastal areas. One is a vertical-axle windmill, also known as a vertical-sail windmill, and the other, a horizontal-axle windmill. Both are mainly used to drive water-lifting devices. The vanes of these two sorts of windmills are like the cloth sail on a sailboat. The following two sections describe the windmills in more details.

The Vertical-Axle Windmill

A vertical-axle windmill is also known as a standing-sail windmill, or so-called 'walking-horse lantern' or the great windmill. 'Walking-horse lantern' is the Chinese-styled hot-air zoetrope with a running chimney driven by the heat of a candle in it [6]. It is somewhat similar with the vertical-axle windmill in form.

Generally, records on windmills in ancient China were too brief with little mention of any details of the structural construction, such as the number of vanes or sails. In the Ming Dynasty, there was a description of the action of a water-lifting device, driven by wind-wheel with a diameter of about 3 zhang (~ 10 m), used in Lingling in the essay Shuiche Xing (水車行), translated as Watemillts Run, written by Ji Tong (童冀) [7]. In a publication by Tsing Hua University [8], it was noted that in the middle of the Qing Dynasty (1644–1911), Qingyun Zhou (周慶雲) recorded in Chapter 36 of his book entitled Yanfa Tongzhi (鹽法通志), translated as General Records on How to Produce Salt, the structure and principle of a windmill. In his book, he said that a windmill with the aid of wind-power, ran to be used [8]. The diameter of this kind of windmill was more than 8 m and its height more than 6.7 m. The shear size of the device, suggests to the author that it must be a vertical-axle windmill, similar to the those shown in a painting of the littoral of China by a Dutch painter in 1656 (Fig. 1) [9].

During the late Qing Dynasty, Changyi Lin 林昌彝 introduced the arrangement and use of a vertical-axle windmill in Chapter 13 of the book Yan Gui Xu Lu (硯耒圭) (Fig. 2) [10].

If a windmill is constructed on level ground, [it] is able to replace manpower used by a water-lifting swape. It is not necessary to change its position as the sails on a ship do at any moment. The sails of the windmill is made of cloth or thin bamboo strips, [they] may be supported on level ground where wind comes from any direction….In addition, two pieces of covering are added over and under the windmill. The covering inclines to the inside and is installed to enable wind to enter the windmill more efficiently.

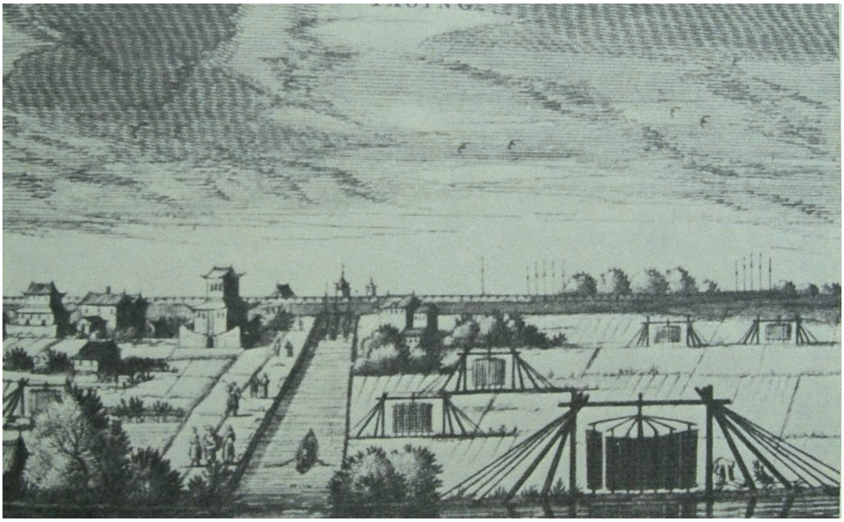

Fig. 1 The Chinese vertical-axle windmills by a Dutch painter in 1659 [9]

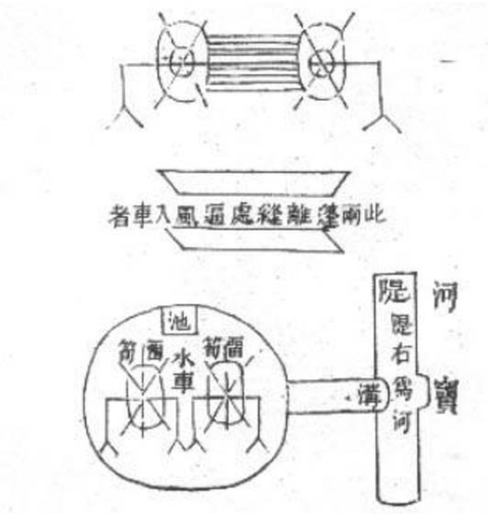

Fig. 2 Ancient schematic of the arrangement of the vertical-axle windmill [10]

There were 600 vertical-axle windmills only in the Saishang District and Tangda District of Hangu along the shore of the Bohai Sea in the early 1950s [11]. The structures of gearwheel and vanes (sails) can be seen in pictures taken by Li Chen (陳立) and shown here in Figs. 3,4 and 5. The supporting frame of these windmills appeared to be of an octagonal prism shape. Inserted at the upper end of the vertical axle are eight spokes. There was a driving wheel on the shaft to drive a water-lifting device.

The structure of the vanes of a windmill had the same shape as the sail on a Chinese sailboat. Each vane was linked onto its mast with a vine circle, and was tied to a pulley on each spoke with a 'running rope' on its upper end. The side of a sail near the vertical axle was tied to the bottom of a mast close by with a thick rope. The height and area of the sail, which was exposed to the wind could be adjusted by drawing in or letting out the running rope. Wind pressure was related to the size and height of the sails and the fixing angle. When wind blew on the sails, the mast was pushed to rotate the vertical axle and a big horizontal gear, the latter of which drove the water-lifting device connected to it. When the wind was strong, one big horizontal gear could drive two or three water-lifting devices.

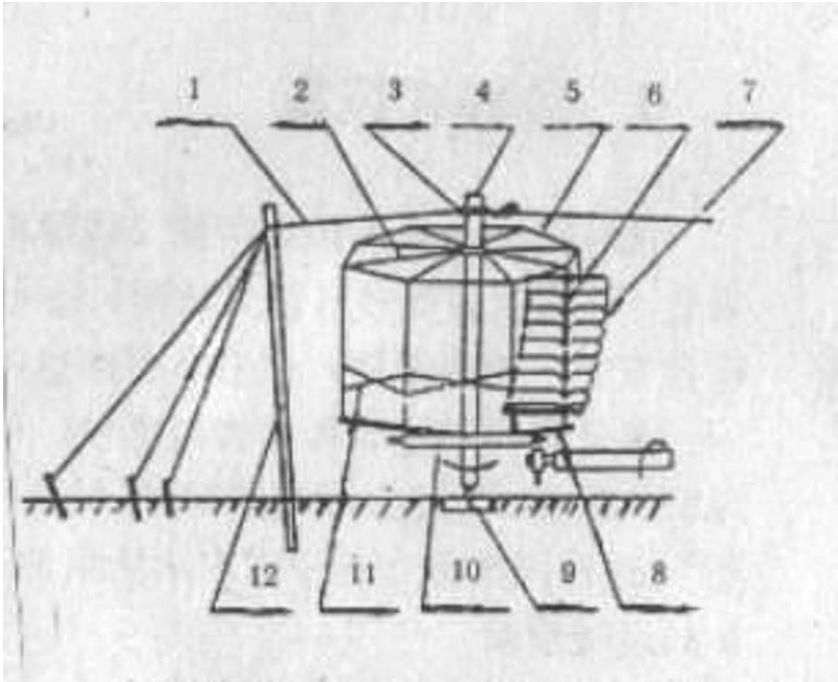

Fig. 3 The basic structure of a great windmill (drew in the 1950s)

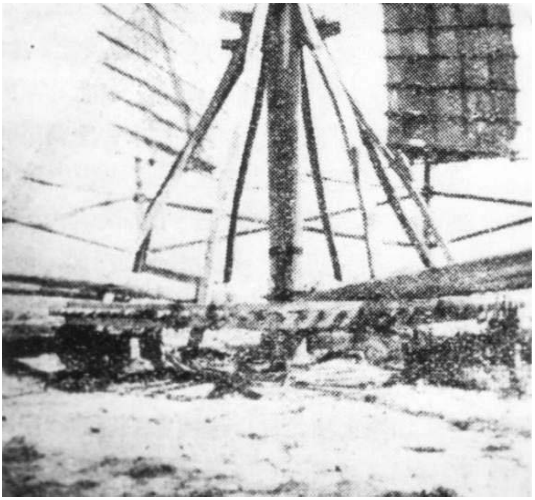

Fig. 4 Big gear wheel of a great windmill (photograph taken in the 1950s)

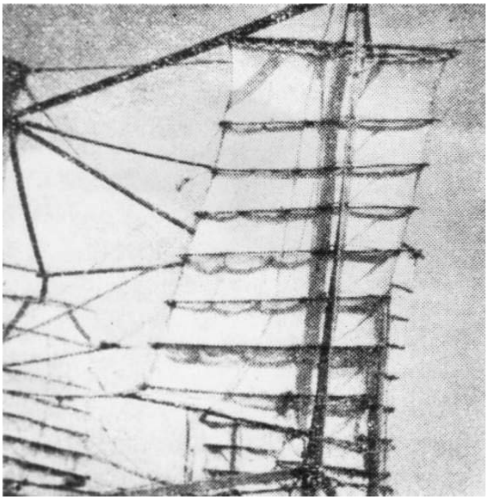

Fig. 5 The sail of a great windmill (photograph taken in the 1950s)

To start the windmill, a rope fasten to its frame was used to mesh the gear teeth of the horizontal and vertical gears. Depending on the strength of the wind, the sails were then lifted to an appropriate height with the help of a running rope. The running rope was tied onto a small wood nail on its mast, and the rope tied to the frame was loosened to allow the windmill to commence driving a water-lifting device. To stop the windmill, a pole was set not far away from the outside of the frame, which would knock off the rope-hanging woods from the wood nails in turn. This would cause all the sails to lower and the windmill would then stop running.

Before starting a windmill, the rotating speed was adjusted by hoisting the wind sails to an appropriate height or by shortening the length of the rope, which changed the included angle between the sails and the thick ropes. Generally, the rotating speed was about eight turns per minute. If the wind was too strong, the windmill was stopped to prevent the structure from being destroyed if the rotating speed exceeded the allowable limit of the water-lifting device and its rotating system.

The most ingenious part of the vertical-axle windmill was the self-adjustment of the sail direction in response to the wind as the windmill rotated. With one side of a sail tied to the bottom of a close by mast with a thick rope, each time the sails moved to the wind-facing side, they would automatically meet the wind at right angle, catching the strongest wind power. As the sails turned to the opposite side, they would automatically become parallel to the wind and be subjected to the least resistance. This principle ensured the windmill rotated in the same direction, capturing the maximum wind force and not affected by the wind direction.

In the 1950s and 1960s, many vertical windmills also existed in Yancheng, Jiangsu province, as captured in the film, The Story of Liubao (柳堡的故事). Those windmills were also big in size and became extinct in the middle of the 1980s when they were completely replaced by electric pumps or internal-combustion engine-driven pumps. Jingyan Lu (陸敬嚴) and Yingqi Yi (易穎琦) published an article from their field investigation on the vertical-axle windmill and constructed a model of the windmill at Tongji University in the early 1990s [12].

The Horizontal-Axle Windmill

The book, Wuli Xiaoshi (物理小識), written by Yizhi Fang (方以智) a scholar living in the period from the end of the Ming Dynasty to the beginning of the Qing Dynasty, described six wind vanes (six-wind-sail windmills) used to lift water to irrigate farmlands [13]. The windmills were also present in fields near rivers at Huai and Yang. In Chapter 7 of a book entitled Yinyi Biantong (音譯辯同), Tingmei Zeng (曾廷枚) written in the Qing Dynasty described water-lifting devices and swapes set near reservoirs of water, with five or six vanes made of bamboo strips in the shape of wind sails. The windmills were connected to each other and assisted [people] with water lifting by virtue of the wind [14].

Comparing historical records, it was likely that the abovementioned device was a horizontal-axle windmill with three to six wind sails. It could also be called an inclined pole windmill because its axle was an inclined wooden pole. The wooden pole has since been replaced by steel tubes in modern time. This type of windmills was mainly used in the Southeast littoral of China. In the film, Yi Jiang Chunshui Xiangdong Liu (一江春水向東流), translated as A River Running to the East in Spring, made in 1947, the windmills were shown in action.

In May of 1993, the author and Lisheng Feng (馮立昇) went to Northern Jiangsu province to study traditional windmills. In the salt field in Xilinzi village, Ganyu (贛榆) county, there were more than ten horizontal windmills driving water-lifting devices to carry salt water. These were soon to be replaced by modern propeller wind-driven machines. Photographs of a horizontal-axle windmill with a water-lifting device, situated by a beach much further away from the village were taken (Figs. 6, 7, 8 and 9) [15]. Figure 7 shows the operation of the water-lifting device and the gear wheels; Fig. 8 shows the operator adjusting the engagement of the gear teeth. A few components of the windmills and water-lifting devices were piled on the side of the salt field and they included wooden gears, the driving chain wheels of a man-driven water-lifting device and its rock handle (Fig. 9).

Fig. 6 A horizontal-axle windmill driving a water-lifting device [15]

Fig. 7 A water-lifting device and the gear wheels [15]

Fig. 8 Adjusting the engagement of the gear teeth [15]

Fig. 9 Unused gear wheels and driving chain wheels [15]

The dimensions of the windmill shown in Fig. 6 were taken to produce a mechanical drawing. The windmill had a driving gear, whose horizontal axle was connected to the vertical axle of the driven gear through a so-called 'lying pillow'. All the gears had the same diameter and the same number of teeth. Except for a few iron parts, the whole windmill in its original form was made of fir wood. In order to prolong its life, the wooden parts were puttied first, and then painted with Chinese wood oil.

The horizontal axle of the windmill was now replaced with a steel tube, the diameter of which was 75 mm. From an abandoned original wooden horizontal axle, the diameter of its bigger end (the gear was set on this end) was about 180 mm and the other end, 100 mm.

The wind sails of a horizontal-axle windmill were also similar to the sails of a traditional Chinese sailboat. A thick adjusting rope (the rope to hoist a sail) and the circum-gyration plane of the wind wheel met to form an included angle of about 10º. The principle of torque generation was the same as that of a tower windmill in Holland in that the blowing of the air current against a wind sail makes a force component that is right-angled to the main axle. According to the users of the windmills, when the wind intensity reached the third or fourth order, the rotating speed of a wind wheel was over 20 turns per minute; when the wind intensity ranged from the fourth to the sixth order, the operation of a windmill was optimum, with the rotating speed ranging from 40 to 50 turns per minute. When the wind intensity reached the eighth order, the rotating speed would be 80 turns per minute, an unsuitably high speed to drive a water-lifting device. In accordance with the direction of the wind, operators would move the horizontal axle around the lying pillow within 300º on ground plane with a shaft strut to make sure that the wind wheel was arranged against the direction of the wind. The method of setting the sails was similar to that used on a vertical windmill.

Except for the inability to automatically adjust the sail in response to the change of wind direction, a horizontal-axle windmill had several advantages: its structure was simple; it was convenient to operate and it occupied a smaller space. In 1959, there were more than 200,000 vertical-axle and horizontal-axle windmills in Jiangsu province. There were 3,735 windmills in the salt fields of Northern Huai in 1958, which lifted four hundred million cubic meters of water each year [16]. Since the late 1960s, heat and electric power gradually took over the place of windmills. A few traditional windmills are still in use in counties such as Yancheng, Jianhu, Dafeng, Funing, Xiangshui, Sheyang and Ganyu. In 1984, with four traditional windmills and seven workers, the salt field ran by Bodong Salt Field Middle School in Xiangshui county produced more than 700 tons of salt and conserved 10,241 kwh each year [17]. Until 1993, apart from a very small number of horizontal-axle windmills used in Northern Jiangsu province, there were at least 200 horizontal-axle windmills in Putian Salt Field, Fujian province. The required wind speed of this sort of windmills ranged from 3.5 to 10.7 ms^{-1}; the utilization coefficient of wind power was between 0.15 and 0.20 and the output power ranged from 0.3 to 5 hp. The diameter of its wind wheel was 6 m and it had six wind sails, the number of which could be increased or decreased in order to adjust the speed of the wheel. The lift of the water-lifting devices driven by this kind of windmills was from 0.4 to 2.1 m and the capacity to carry water was from 5.5 to 120 m^3h^{-1}.

Conclusions

Early historical records showed that Chinese windmills were invented later than those in Persia. If Persian windmills had possible influence on the invention of Chinese windmills, it is thought that the transmission of the idea about windmills from western or middle Asia to China was of the stimulus diffusion type. There are no historical records on the construction details of the Persian-styled windmills.

Traditional Chinese windmills possessed their unique technical tradition. The Chinese combined the sail-making technology and sail-controlling skills with power devices to invent the unique vertical-axle windmill. Rotating devices such as water-wheels probably influenced the design of these windmills. Based on the technology of vertical-axle windmill, early craftsmen constructed the horizontal-axle windmills.

The most important creation of Chinese windmill-makers was the self-adjusting mechanism of the sail of a vertical-axle windmill in response to the wind direction. This mechanism was significantly different to the sail-adjusting device of the Persian or European windmills. Traditional Chinese windmills were used to drive square-pallet chain-pumps, whilst those in Persia and Europe were to drive millstones to grind grains or pigments in.

References

1. Chinese Society of Navigation, A History of Navigation in China (in ancient time), People's Communication Press, Beijing, pp. 92–93.
   中國航海學會（1988）. 中國航海史（古代航海史）. 人民交通出版社，北京，第92－93頁
2. Needham J (1965) Science and Civilization in China (Volume IV: 2), Cambridge University Press, Cambridge, pp. 557–568.
3. Research group for the history of science and technology at the library of Tsinghua University (1985) A Selected Collection of Historical Materials for the History of Science and Technology: Agricultural Machines, Tsinghua University Press, Beijing, p. 314.
   清華大學圖書館科技史研究組（1985）. 中國科技史資料選編——農業機械. 清華大學出版社, 北京, 第314頁
4. Needham J (1965) Science and Civilization in China (Volume IV: 2), Cambridge University Press, Cambridge, p. 560.
5. Research group for the history of science and technology at the library of Tsinghua University (1985) A Selected Collection of Historical Materials for the History of Science and Technology: Agricultural Machines, Tsinghua University Press, Beijing, p. 161.
   清華大學圖書館科技史研究組（1985）. 中國科技史資料選編——農業機械. 清華大學出版社, 北京, 第161頁
6. Liu XZ (1962) A History of Mechanical Engineering Inventions, Science Press, Beijing, pp. 71–73.
   劉仙洲 (1962) 中國機械工程發明史(第一編). 科學出版社, 北京, 第71-73頁
7. Research group for the history of science and technology at the library of Tsinghua University (1985) A Selected Collection of Historical Materials for the History of Science and Technology: Agricultural Machines, Tsinghua University Press, Beijing, p. 169.

清華大學圖書館科技史研究組（1985）. 中國科技史資料選編——農業機械. 清華大學出版社, 北京, 第169頁

8. Research group for the history of science and technology at the library of Tsinghua University (1985) A Selected Collection of Historical Materials for the History of Science and Technology: Agricultural Machines, Tsinghua University Press, Beijing, p. 224.
   清華大學圖書館科技史研究組（1985）. 中國科技史資料選編——農業機械. 清華大學出版社, 北京, 第224頁
9. Needham J (1965) Science and Civilization in China (Volume IV: 2), Cambridge University Press, Cambridge, Fig. 688.
10. Research group for the history of science and technology at the library of Tsinghua University (1985) A Selected Collection of Historical Materials for the History of Science and Technology: Agricultural Machines, Tsinghua University Press, Beijing, p. 213–214.
   清華大學圖書館科技史研究組（1985）. 中國科技史資料選編——農業機械. 清華大學出版社, 北京, 第213–214頁
11. Chen L (1951) Why Were Wind Power Not Generally Used in North China? – An Investigation Report on the Windmill of the Coastal Area near Bohai Sea, Chinese Science Bulletin, 3: 266–268.
   陳立 (1951). 爲什麼風力沒有在華北普遍利用——渤海海濱風車調查報告. 科學通報 3: 266–268
12. Yi YQ, Lu JY (1992) An Textual Research and Rebuilding of Chinese Ancient Vertical-axle Great Windmill, Agricultural Archaeology 3: 157–162, 321.
   易穎琦, 陸敬嚴 (1992) 中國古代立軸式大風車的考證與復原. 農業考古, 3: 157–162, 321
13. Research group for the history of science and technology at the library of Tsinghua University (1985) A Selected Collection of Historical Materials for the History of Science and Technology: Agricultural Machine, Tsinghua University Press, Beijing, p. 186.
   清華大學圖書館科技史研究組（1985）. 中國科技史資料選編——農業機械. 清華大學出版社, 北京, 第186頁
14. Research group for the history of science and technology at the library of Tsinghua University (1985) A Selected Collection of Historical Materials for the History of Science and Technology: Agricultural Machines, Tsinghua University Press, Beijing, p. 202.
   清華大學圖書館科技史研究組（1985）. 中國科技史資料選編——農業機械. 清華大學出版社, 北京, 第202頁
15. Zhang BC (1995) A New Research on the Structures and Principles of Chinese Wind-Driven Square-Pallet Chain-Pumps, Studies in the History of Natural Science, 3: 287–296.
   張柏春 (1995). 中國風力翻車構造原理新探. 自然科學史研究, 3:287–296
16. Li MX (1993) History and Present Situation of the Development and Use of Wind Energy Source in Northern Jiangsu Province (Draft), A literature gift from Li to the author in 1993.

李敏新（1993）. 蘇北風能開放利用的歷史和現狀（文稿）. 1993年作者贈送給張柏春

17. Li MX (1993) History and Present Situation of Development and Use of Wind Energy Source in Northern Jiangsu Province (Draft), A literature gift from Li to the author in 1993.
李敏新（1993）. 蘇北風能開放利用的歷史和現狀（文稿）. 1993年作者贈送給張柏春

An Interpretation of a *Shui Lun Fu* 水輪賦 (*Rhapsody on Waterwheel*)*

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Abstract A *shui lun* is a water wheel with buckets attached to its rim for use to raise water from a stream for transfer to an irrigation channel. When and where did it originate and when was it first applied in China are not yet clear to date. It might have been employed in China no later than the Tang Dynasty according to ancient literature such as *ji ji ji* written by Liu Yuxi and *shui lun fu* written by either Chen Tingzhang or Chen Zhang. However, the text in both scripts had not been carefully studied. This paper presented a preliminary interpretation of *shui lun fu* with an attempt to understand the technical details of the waterwheel described in the text. This may clarify the origin of the Chinese waterwheel.

Keywords *Shui lun fu* (*Rhapsody on Waterwheel*), *Shui lun* (waterwheel), Technical knowledge

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* This paper presents the author's interpretation of the text of *shui lun fu* (*Rhapsody on Waterwheel*) given at the reading group during an invite to PD Dr. Schaefer's Research Group at the Max Planck Institute for the History of Science from September 2007 to February 2008. The author would like to express his sincere appreciation to all members of the reading group their great patience with the readings, suggestions of many illuminating ideas, and constructive criticisms and advice to improve the author's comprehension of the text. The author would also like to emphasise that he is responsible for any errors found in this paper.

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Introduction

Shui lun (水輪) in this paper refers to a water wheel with buckets attached to its rim, with the function of raising water from a stream or pool for transfer to an irrigation channel. It is unclear to date when was *shui lun* invented and when was it first applied in China. According to descriptions in ancient literature such as *ji ji ji* 《機汲記》 (*The Note for Drawing Water by Machine*) and *shui lun fu* 《水輪賦》 (*Rhapsody on Waterwheel*), *Shui lun* might have first been employed in China no later than the Tang Dynasty (618–907 AD). The former text was written by Liu Yuxi (劉禹錫, 772–842 AD) while the author of the latter was either Chen Tingzhang (陳廷章) or Chen Zhang (陳章). However, the text in both scripts had not been carefully studied. This paper presented a preliminary interpretation of *shui lun fu* with an attempt to understand the technical details of the waterwheel described in the text, which may clarify the origin of the Chinese waterwheel.

Who was the author of *Shui Lun Fu? Shui lun fu* was mentioned in a few compiled writings such as *wen yuan ying hua* 《文苑英華》 (*The Best Selected Texts before the Northern Song Dynasty*) and *quan tang wen* 《全唐文》 (*The Completed Texts of the Tang Dynasty*). The author of *shui lun fu* was noted as Chen Zhang in the former but recorded as Chen Tingzhang in the latter.

Wen yuan ying hua was compiled by Li Fang (李昉) between 982 AD and 987 AD in the Northern Song Dynasty (960–1127 AD). It consisted of one thousand volumes, with almost twenty thousand pieces of writings contributed by approximated two thousand and two hundred authors. Nine-tenths of the writings in *wen yuan ying hua* were from the Tang Dynasty. The version cited in this article was a photocopied edition published by *zhong hua shu ju* (中華書局) in January, 1966. It collected a hundred volumes of the block-printed edition of the Northern Song Dynasty and eight hundred and sixty volumes of the Ming Dynasty's edition. The Ming's edition was based on the hand-copied edition of the Northern Song Dynasty which was littered with errors. The edition of *wen yuan ying hua* referred by *quan tang wen* was the edition of the Ming Dynasty's block-printed edition published in Fujian Province.

Quan tang wen was compiled from March, 1808 to 1814, and collected works from *tang wen* 《唐文》 (*The Texts of Tang Dynasty*), which was a hand-copied edition reserved in the Palace, consisting in total of one hundred and sixty books. It also included some versions of *si ku quan shu* 《四庫全書》, *tang wen cui* 《唐文粹》, *wen yuan ying hua*, chorography and many other materials and sources.

There were six rhapsodies in Volume 948 in *quan tang wen*, namely, *shui lun fu*, *dou niu jian you zi qi fu* 《斗牛間有紫氣賦》, *fu cao wei ying fu* 《腐草爲螢賦》, *ai ren fu* 《艾人賦》, *feng bu ming tiao fu* 《風不鳴條賦》 and *bing quan fu* 《冰泉賦》 in the name of Chen Tingzhang. These six rhapsodies could all be found in different volumes of *wen yuan ying hua*. For example, *shui lun fu* was in Volume 33, *dou niu jian you zi qi fu* was in Volume 102, *fu cao wei ying fu* in

Volume 141, *ai ren fu* in Volume 149, *feng bu ming tiao fu* in Volume 13 and *bing quan fu* in Volume 38. The author of these rhapsodies was listed as Chen Zhang in the content list, but the author of *bing quan fu* was written in the text itself as Chen Tingzhang.

It was uncertain whether Chen Tingzhang and Chen Zhang was the same person, nor were there any details about his birth date, his life and his death. Furthermore, it is still a mystery as to where the *shui lun* described in the rhapsody existed. There was a famous poet named Sikong Tu (司空圖) who was born in 837 AD and died at the end of the Tang Dynasty in 908 AD. In one of his writings *zhong tiao wang guan gu xu* 《中條王官谷序》 (*The Preface of zhong tiao wang guan gu*), he mentioned a rhapsody of waterwheel written by his grandmother's brother whose family name was Chen. If this Chen mentioned by Sikong Tu were Chen Tingzhang or Chen Zhang, perhaps it would shed some light to the period as to he lived. According to *zhong tiao wang guan gu xu*, Sikong Tu's mother had a brother called Liu Quan, who could recite *shui lun fu** written by his uncle, Chen, at an age of four, and who had written the book *liu shi dong shi* 《劉氏洞史》 (*The History of Liu Family*) when he was sixteen years old. *Liu shi dong shi* was recorded as twenty volumes in Volume 58 of *xin tang shu* 《新唐書》 (*The New Book on the History of the Tang Dynasty*).

If Chen was indeed the brother of Sikong Tu's grandmother, he would be two generations above Sikong Tu, which is to say, he might be about fifty to sixty years older than Sikong Tu. That puts his birth time around 770–780 AD, almost the same period as Liu Yuxi. Regardless if Chen was the author of *shui lun fu* as Cheng Tingzhang or Chen Zhang and *shui lun fu** was the same as *shui lun fu*, what is clear is that Chen did indeed wrote a rhapsody on waterwheel. Liu Yuxi may have named the machine for drawing water he saw as *ji ji* (汲機), the author of *shui lun fu* or *shui lun fu** had named the machine as *shui lun*. It reflected the different background and experience between Liu Yuxi and Cheng Tingzhang, maybe Chen Zhang or Chen.

The Content of *Shui Lun Fu*

In this section, an explanation of *shui lun fu* based on the edition of *quan tang wen* and referred to in the edition of *wen yuan ying hua* to aid in understanding the text. The title of the text is *shui lun fu*, translated as *the rhapsody on waterwheel*. It was written in the rhyme of *ji yin zhi dao, cheng yu yun lun* ([汲引之道，成於運輪]), which literally translates to 'the ways for drawing up water and conducting it from one place to another, could be put into practice by applying the waterwheel'.

The whole text consists of three hundred and three Chinese characters, and the text, arranged into thirty five sentences herein, is explained sentence by sentence:

1. 水能利物，輪乃曲成。

Water can benefit things, [water] wheel is made into the shape of roundness.

2. 升降滿農夫之用，低徊隨匠氏之程。
Its rise and fall satisfies the needs of peasants, it circles round and round following the rules of artisans.
3. 始崩騰以電散，俄宛轉以風生。
It sounds like thunder when it begins to move, then before long it rotates engendering breeze.
4. 雖破浪於川湄，善行無迹；
While breaking through waves, it moves swiftly without any traces.
5. 既斡流於波面，終夜有聲。
As it generates current at the water surface, the sound persists through the night.
6. 觀夫斲木而爲，憑河而引，箭馳可得而滴瀝，輻湊必循乎規准。
As you can see, waterwheel is made of wood and is set up alongside a river. It could draw up water in a very short time, and its spokes converging at a hub following regulations of the craft.
7. 何先何後，互興而自契心期；
No matter which bucket comes first, they rise mutually to satisfy people's expectation naturally.
8. 不疾不徐，迭用而寧因手敏。
Not too fast and not too slow, they work one by one due to the skillful design.
9. 信勞機於出沒，惟與日而推移。
Let the arduous waterwheel work at the riverside with its buckets wheeling in and out of the stream, working continuously moving along with time.
10. 殊轆轤以致功，就其深矣；
Differing from *lu lu* (轆轤, windlass) in work, waterwheel could bring water from deep depth like the windlass could.
11. 鄙桔槔之煩力，使自趨之。
Scorning *Jiegao* (桔槔, a labor-saving lever device with unequal arms) a labour intensive device, waterwheel could rotate by itself.
12. 轉轂諒由乎順動，盈科每悅於柔隨。
Waterwheel rotates on its hub driven by the moving stream, gutter and pits will be fully and smoothly filled with water.
13. 遠望蹄涔，詎有朱殷之色；
From afar, splashes of water near the waterwheel appearing to gleam in bright blackish red.
14. 挹茲鱗起，終無塗附之期。
When the scalelike water is lifted up, there is no worry of the wheel being covered with mud.
15. 作霖或自於斯干，流濕更彰乎就燥；
Persistent rain perhaps comes from ghyll, and the moving wetness appears more obviously to come close to dry.
16. 回環潤乎嘉轂，洊至踰於行潦。
The fine hub of the waterwheel is lubricated by its rotation, as water is ceaselessly drawn up and travels through a long journey over the gutter.

17. 鉤深致遠，沿洄而可使在山；
Water is drawn and transferred far away, transported to mountain fields through winding roads.
18. 積少之多，灌輸而各由其道。
Many a little makes a mickle, water is transferred to their respective paths of irrigation.
19. 爾其揚清激濁，吐故納新，輾桃花之活活，搖杏葉之鱗鱗。
By bringing in fresh water drained of mud, getting rid of the stale and taking in the fresh, it turns the flowers of peaches vivacious and shakes the leaves of apricots scaly shining.
20. 一勺每勞於濡軌，三材必賴於工人。
A scoop of water should always be transferred through wet path, three kinds of materials should depend on the craftsmen.
21. 浴海上之朝光，升如日御；
Bathing in the morning sunlight at the side of the river, [a rotating waterwheel] appears like the rising sun.
22. 泛江中之夜影，重似月輪。
Its shadow reflects on the river in the night, appearing as a down moon.
23. 常虛受以載沈，表能圓於獨運。
Waterwheel often keeps its buckets empty to load more weight; its round surface makes it self-revolving.
24. 低徊而涯岸非阻，委曲而農桑是訓。
Waterwheel lingers away and not interrupted by high riverbanks, bends to rotate as crops and mulberries benefit.
25. 惠可周於地利，空霑負郭之田；
Waterwheel spreads its benefit all over rich lands, but barely irrigates the fertile field in the suburbs.
26. 材足任於天津，多寄臨川之郡。
They are made of materials worthy of tasks in the Milky Way; mostly they are placed on countryside by rivers.
27. 池陂無漉，畎澮既瀦；
[By using waterwheel,] the ponds will not run dry; the field ditches storing the water.
28. 用能務實，勢欲淩虛。
It is practical, and always ready to fire up to heaven.
29. 罄折而下隨崟彼，持盈而上善依於。
Bowing down, buckets from the waterwheel follow the water flow. Drawing full of water to rise up, they are efficiently interdependent.
30. 當浸稻之時，寧非沃壤；
When paddy fields are irrigated, wouldn’t they become fertile soil?
31. 映生蒲之處，相類安車。
At places where reed grows, a waterwheel should be based.
32. 異矣哉！
What a miracle!

33. 俯此溝塍，潤於原隰。
Overlooking the irrigation canals, ditches and small dikes, waterwheels are irrigating farmlands all over the plain and lowland.
34. 成形必仰乎膏雨，屈已且安於卑濕。
To accomplish such an achievement waterwheel should rely on timely rainfall; it should descend itself to stand willingly in low and wet places.
35. 苟量遠大之功，庶無慙於甕汲。
If considering its great contribution, waterwheel perhaps would not feel ashamed of drawing and transferring water as compared to a *weng* (甕, earthen pot).

The Technical Knowledge in *Shui Lun Fu*

Some technical knowledge about waterwheel was included in the text of *shui lun fu*. The material, structure, appearance, shape, working characteristic, sound, setting location, work efficiency, function and influence of waterwheel were described in the text at different levels. For example, *shui lun* was made of wood; it comprised of a hub and spokes; and it was set up at the bank of a stream; *shui lun* was driven to rotate engendering wind by water which was different from the operation of *lu lu* (轆轳) and *jie gao* (桔槔). The text suffices in providing an outline of the basic structure of the waterwheel but the information is not enough for a detailed reconstruction of the structure.

To further understand the waterwheel described in the text, the history of the application of waterwheels in China since the Northern Song Dynasty was studied. Substantial available materials and literature were available that described and mentioned waterwheels. They included those by famous poets, high-ranking officials and distinguished scholars such as Li Chuquan (李處權), Mei Yaochen (梅堯臣), Fan Zhongyan (范仲淹) and Su Shunqin (蘇舜欽) of the Northern Song Dynasty, Zhang Xiaoxiang (張孝祥) of the Southern Song Dynasty (1127–1279 AD), Wang Zhen (王禎) of the Yuan Dynasty (1206–1368 AD), Lu Rong (陸容), Wang Linheng (王臨亨), Song Yingxing (宋應星) and Xu Guangqi (徐光啓) of the Ming Dynasty (1368–1644 AD), Gu Yanwu (顧炎武), Qu Dajun (屈大均) and Zha Shenxing (查慎行) of the Qing Dynasty (1616–1911 AD) [1]. These works brought forth a meaningful phenomenon of the widely applied waterwheel in the history of China from the Northern Song Dynasty to the Qing Dynasty. During the Ming and Qing Dynasties, the application of waterwheel was very popular in many provinces such as Jiang Xi, Zhe Jiang, Guang Dong, Guang Xi, Yun Nan, Gan Su and Ning Xia. Waterwheels were still broadly used in China during the 1950s–1960s. When electric power became widely available in China, traditional irrigational methods, such as waterwheels, were soon replaced by electric pumps. Waterwheels gradually disappeared, leaving only a few still in operation at present.

Waterwheels can be divided into four categories based on the structure and the driving method according to the record of *nong shu* 《農書》 (*The Book on Agriculture*) written by Wang Zhen in the Yuan Dynasty [2]:

(a) *liu shui tong lun* (流水筒輪)–a single wheel driven by water flow, transferring water from streams to fields near banks, Fig. 1 [3];

(b) *lǘzhuan tong che* (驢轉筒車)–a waterwheel driven by a donkey or ox and had an addition pair of joggled gears including a horizontal and vertical gear; The animal circled the vertical axle under the horizontal gear to drive the vertical gear, which transmitted power to the waterwheel to draw up water, Fig. 2 [4];

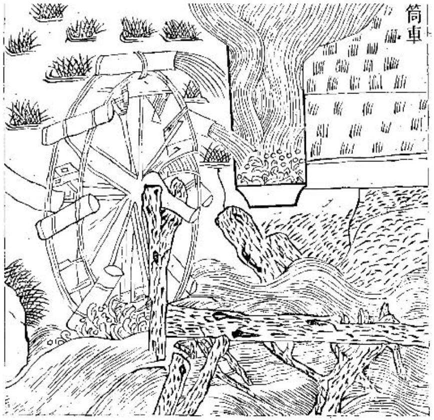

Fig. 1 Liu shui tong lun

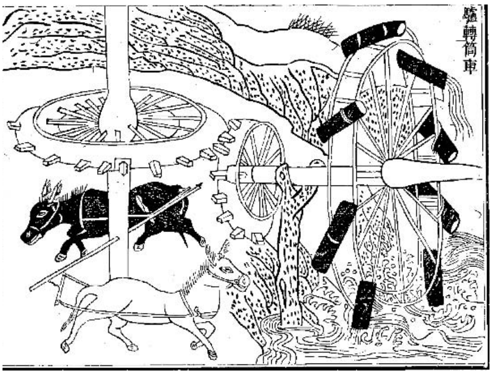

Fig. 2 Lǘ zhuan tong che

(c) *gao zhuan tong che* (高轉筒車)–a waterwheel used on fields by streams with very high banks; two wheels were fixed at the spot, one next to the stream and the other on the high bank; cables connected these two wheels and buckets were attached to the cables. When the upper wheel was driven by an operator or by an animal, the buckets dropped down to draw up water one by one, Fig. 3 [5];

(d) *shui zhuan gao che* (水轉高車)–This waterwheel was similar to the *gao zhuan tong che*; two wheels were fixed at the high side of a flowing stream; the lower wheel was driven by water flow to raise water to the high side, Fig. 4 [6].

Types (a) and (d) suited for areas with running water, whilst types (b) and (c) were for drawing water from a static pool and lake. The structure of (a) and (b), (c) and (d) were similar, but their driving methods and power were different because of the difference in water sources.

Fig. 3 Gao zhuan tong che

Fig. 4 Shui zhuan gao che

Shui lun portrayed in *shui lun fu* might be similar to type (a) stated above and *ji ji* depicted in *ji ji ji* was clearly of type (c). The two texts were perhaps the earliest descriptions of waterwheel as far as the author was aware, and they successfully demonstrated that different types of waterwheels were adapted to suit different surroundings and resources in China from as early as the Tang Dynasty.

Conclusions

The descriptions in *shui lun fu* of waterwheels included important technical information, although there were insufficient details on the structure design. From this prospective, it well deserved careful scrutiny by technology historians. Through vast historic literature on the technical application of waterwheels from the Northern Song Dynasty, it could be surmised that waterwheels had evolved from predecessors as early as the Tang Dynasty, the era of advancement of traditional crafts that inherited and adapted the surroundings, materials, and other influencing factors. The waterwheel described by the author of *shui lun fu* or *shui lun fu** was certainly a well-adapted Chinese traditional craft.

References

1. The Research Group of the History of Science and Technology of Tsinghua University Library (1985) The Materials and Sources of the History of Science and Technology of China-Agricultural Machine, Tsinghua University Press, Beijing, P. R. China, pp. 148–223. (in Chinese)
   清華大學圖書館科技史研究組. 中國科技史資料——農業機械. 清華大學出版社, 1985年, 第148～223頁.
2. Wang Z (Yuan Dynasty) The Book on Agriculture (農書), Volume 19, The Charts of Agricultural Tools 13, The Category of Irrigation.
   [元]王禎.《農書》卷十九”農器圖譜十三”之”灌溉門”.
3. Ren JY (1994) The Selected Classical Texts of Science and Technology in China, Agriculture, Volume 1, He Nan Education Press, Zheng Zhou, China, pp. 650.
   任继愈主编《中国科学技术典籍通汇・农学卷一》，郑州：河南教育出版社，1994年，第650页.
4. Ren JY (1994) The Selected Classical Texts of Science and Technology in China, Agriculture, Volume 1, He Nan Education Press, Zheng Zhou, China, pp. 653.
   任继愈主编.《中国科学技术典籍通汇・农学卷一》，郑州：河南教育出版社，1994年，第653页.

5. Ren JY (1994) The Selected Classical Texts of Science and Technology in China, Agriculture, Volume 1, He Nan Education Press, Zheng Zhou, China, pp. 653.
任继愈主编.《中国科学技术典籍通汇・农学卷一》，郑州：河南教育出版社，1994年，第653页.
6. Ren JY (1994) The Selected Classical Texts of Science and Technology in China, Agriculture, Volume 1, He Nan Education Press, Zheng Zhou, China, pp. 654.
任继愈主编.《中国科学技术典籍通汇·农学卷一》，郑州：河南教育出版社，1994年，第654页.

“*Lei Si Jing*”（耒耜经）and the Curve-Beam Plough of the Tang Dynasty of China

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Abstract The curve-beam plough, widely used in the region of the lower reaches of Yangtze River towards the end of the Tang Dynasty (about the 9th century A.D.) occupies an important position in the development of agricultural machinery in China. The curve-beam plough was recorded in the book “*Lei Si Jing*”（耒耜经）, composed by Lu Guimeng, a scholar from the Tang Dynasty. Based on the records in “*Lei Si Jing”* and a review of available literature, the author studied the shape, structure, size of the curve-beam plough, and identified the following issues: (1) The curve-beam plough was in fact measured with the short ruler of the Tang Dynasty; (2) The length of the curve-beam plough should be reasonable; (3) The curve of the curve-beam plough should be reasonable. Based on these viewpoints, the author carried out a full-size reconstruction of plough in 1998.

For the purpose of comparison, the pictures of the plough by Watabe (渡部武) and the one by Bray are also shown in the paper.

Keywords *Lei Si Jing*（耒耜经）, The curve-beam plough, Tang dynasty of China, Reconstruction

Brief Introduction on *Lei Si Jing*

China is an area in the world, where ploughs and animal-ploughing originated the earliest. Historically, Chinese ploughs were the most advanced in the world. According to archaeological finds, in the second century B.C., Chinese already used various types of iron mould-board on their plough [1]. Historians found that

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ploughs back then had a straight beam pulled by two oxen and operated by two or three persons [2]. The art of ploughing was not yet proficient. Gradually, the tools improved and up to the 9th century A.D. (the end of the Tang Dynasty), a new type of curve-beam plough was widely employed in most areas south of the Yangtze River in China. This type of plough was advanced both in structure and in function. It could be pulled by one ox and operated by one person. This type of curve-beam plough can be seen in ancient wall-pictures. The earliest complete record is in the book titled "*Lei Si Jing*".

"*Lei Si Jing*" was composed by Lu Guimeng, a scholar from the Tang Dynasty. The book was short, containing only 630 words, and recorded nothing else but farming tools. The book is somewhat hard to understand, but it has strict structure and clear management. It detailed and accurately recorded the names, shape, structure, size and the material of the parts of the curve-beam plough used then. As it contained the earliest complete record of ploughs of China, "*Lei Si Jing*" is of an important value in the history of farming tools both in China and in the world.

Lu Guimeng took on an alias Lu Wang. He was from Wujun (now Suzhou, Jiangsu province of China) and was a famous poet in the late Tang Dynasty. Lu's birth date was unknown and he died probably in the first year of Zhonghe (881 A.D.), when Emperor Xizong was in throne. Lu was a proud man, who disliked touring the country without an entourage of officials. Lu took part in some farm work and became familiar with local agricultural production. He then started composing "*Lei Si Jing*" to introduce farming tools to more people. At that time, intellectuals looked down upon people involved in agricultural production and farming. Lu, despite his privileged background, recognized the importance of agriculture and took up farming tools as a research subject. On his final days, he lived in seclusion in Puli, Songjiang (now southeast of Wuxian, Jiangsu province) with 100 µu of farmland.

At the start of "*Lei Si Jing*", Lu expressed his aim of composing the book, i.e. to make more people know and master farming tools. He made it clear that no one, whatever the status of the person, could do without farming tools. Lu explained that "*Lei Si*" was a scholarly term used in agricultural treatises, but farmers called it plough (『耒耜，农书之言也。民之习，通谓之犁。』). The literal translation of "*Lei Si Jing*" was "*On Ploughs*".

The main content of "*Lei Si Jing*" is as follows:

> The share lies flat below and the mould-board slops back above; the share is sharp on top and the mould-board curved at the base [to fit tightly against the share]. The part which carries the share is called the slade (*di* 底): the very front of the slade fits into the share, and carpenters call this part the "turtle flesh" (*bie rou* 鳖肉). The part adjoining the slade is called the "share press" (*ya chan* 压镵). [The mouldboard] has two lugs on its back joined to either side of the share-press. The part adjoining the share is called the *ce e* (策额), and it protects the mould-board. All these parts are connected.

The part which comes down from the *ce e* to the slade, into which it is morticed at right anles, is called the strut or "arrow" (*jian* 箭). The part at the front of the plough which is curved like a carriage-shaft is called the beam (*yuan* 辕), and the part at the back rising up like a handle is called the stilt or "rudder" (*shao* 梢). Above the beam projects an extension of the strut which can be tightened or loosened; along the top of the beam there is a groove corresponding to [a slit in] the strut, [into which fits] a piece that is cut into steps high in front and lower behind, which can be pulled back or forward [as necessary]; this piece is called the wedge or "adjustor" (*ping* 评). When it is pushed forward the strut is loosened and so the plough bites deeper into the soil; when it is pulled back the strut is raised and the depth of ploughing is shallower. The strut is called "arrow" because its height is adjusted like [an arrow in a cross-] bow; the wedge is called "adjustor" because it is adjusted to exactly the right position. The piece that transfixes the top of the wedge is called the bolt (*jian* 建); it holds beam and wedge together and without it the two pieces would spring apart and the strut would not stay in place.

The piece across the end of the beam is called the whipple-tree (*pan* 槃); it can pivot, and it is attached on either side by traces (*qian* 掔) to the yoke (*e* 轭). The very back of the beam is called the "mid-stilt" (*shao zhong* 梢中), which is where the plough is actually held [3].

『镵引而居下，壁偃而居上。镵表上利，壁形下圆。负镵者曰底，底初实于镵中，工谓之鳖肉。底之次曰压镵，背有二孔，系于压镵之两旁。镵之次曰策额，言其可以扞其壁也，皆貤然相戴。

『自策额达于犁底，纵而贯之曰箭。前如桯而樛者曰辕，后如柄而乔者曰梢。辕有越，加箭可驰张焉。辕之上又有如槽形，亦如箭焉。刻为级，前高而后庳，所以进退曰评。进之则箭下，入土也浅，以其上下类激射，故曰箭。以其浅深类可否，故曰评。评之上曲而衡之者曰建。建，揵也，所以柅其辕与评。无是，则二物跃而出，箭不能止。

『横于辕之前末曰槃，言可转也。左右系以掔乎轭也。辕之后末曰梢，中在手所以执耕者也。』[4]

On the basis of "*Lei Si Jing*", the curve-beam plough, when compared with the straight-beam plough used before, had the following clear advantages:

1. The beam was short and curved, which made it easy to handle and therefore conserved energy.
2. The whipple-tree was added to the plough, with two ropes tied to both ends of it. It could turn towards both sides, making it more easily operated by the farmer in the fields and by the field side.
3. The depth of the ploughing could be changed by means of an adjuster.
4. The plough-share was narrower and the mould wider. The mould-board was fixed straight upon the plough-share instead of forming a constant curve surface. It was therefore easier to break clods and form ridges while ploughing.

It is fair to say that the curve-beam plough was a good representation of the advanced production tools at the end of the Tang Dynasty. Being well-adapted for rice fields south of the Changjiang River, where the clay was sticky and the plots small, it became widely use and promoted the development of the agriculture production in the south of China [5].

On the Reconstruction of the Curve-Beam Plough of *Lei Si Jing*

Based on the writings in "*Lei Si Jing*", many modern researchers were able to construe their own version of the curve-beam plough in drawings. The drawings were, however, very different, which led to arguments and discontentment.

The curve-beam plough recorded in "*Lei Si Jing*" was made up of 11 parts. The names and functions are described as follows:

Two pieces of metal part:

Plough-share—to cut through the earth

Mould-board—to replace the clay clods raised by the plough

Nine pieces of wooden part:

Sole or slade—as the base of whole structure of the plough, its fore-part holding the share

Press-share—to fix the mould-board

Mould-board brace—to fix the press-share

Plough-beam—the main part for receiving and carrying the force

Strut—for linking the sole and the mould-board brace, and then fixing them to the beam, the strut is used to tighten the adjuster.

Adjustor—fixed to the joint part and could be adjusted step by step

Bolt—goes through the upper end of the strut to control the adjuster and the beam, and to prevent them from moving away from the strut.

(The strut, adjustor and bolt together form a system adjusting the depth of ploughing.)

Stilt—for the plough operator to hold on to

Whipple-tree—for tying on ropes and transmitting the force of the ox to the beam

The written record is clear, but what was the plough really like? There were no archaeological specimens. This inspired the zeal of researchers to imagine and reconstruct the plough. At the end of the 1950s, Yan Wenru (阎文儒) from China first reconstructed the curve-beam plough with the ratio of 1–2. This created great excitement with interested academics. Twenty years on, however, Yan realized inaccuracies in his model and went on to remake a new model in the 1970s [6]. Song Zhaolin (宋兆麟) [7] and Yang Ronggai (杨荣垓) [8], both from China, Watabe (渡部武) [9] from Japan and Bray [3] from Britain also studied "*Lei Si Jing*" and they each drew a picture of the curve-beam plough, according to their own understanding. It was because of the differences in the interpretations that led to the author's decision to reconstruct a full-scale curve beam plough in this paper.

As far as the author was aware, this would be the first reconstruction of the original size. While carrying out the reconstruction and consulting references, the following issues were encountered.

The Curve-Beam Plough Was In Fact Measured with the Short Ruler of the Tang Dynasty

Former researchers of "*Lei Si Jing*" thought that ploughs were measured with a long ruler, according to "The History of Laws and Rules" [10]. However, this would make the plough humongous. A few scholars doubted the use of a long ruler, but they failed to explain the reasons. After much research, the author realised that the curve-beam plough was in fact measured with a short ruler, in which, one chi was 24.6 cm. The bases for this argument are:

(1) Think of the size of the rudder, if a long ruler was used. The rudder would be too long for the operator to work. In another word, the plough would not be in coherence with the principle of ergonomics (the design and construction must be good for the human's operation)

(2) Think of the reasonable usage of animal force, if measured with a long ruler, the plough would be gigantic and too heavy for one ox to pull. It would be difficult to plough deep. All those mentioned above are contradictory with the record in "*Lei Si Jing*" that one ox was used. From historic records, the areas south of the Changjiang River had the tradition of using a short ruler [11]. When making ploughs, they must have used the short ruler for convenience as there was no need for them to use the long ruler.

The Length of the Curve-Beam Plough

How should one understand the length of curve-beam plough? This used to be a problem troubling many researchers. "*Lei Si Jing*" wrote: "The plough is one zhang (丈) and two chi（尺） long from head to end"（"犁之终始丈有二"） [12]. The words seemed to have expressed it clearly. However, careful computing revealed problems: if the beam was 9 chi long, considering the curve, the distance from the front of the beam to the joint between the beam and stilt would have been become 7 chi long. Adding the horizontal distance formed by the leaning stilt, the whole length would have been no more than 9 chi, much less than "one zhang and two chi". Even if it reached "one zhang and two chi", the curve-beam plough would be 355 cm long based on the measurement of a long ruler, a gigantic matter; it would be 299 cm long based on the short ruler, which is unbelievably large too. What was wrong then?

In the author's opinion, "one zhang and two chi long from head to end" did not refer to the length of the plough (i.e. the distance from the handle to the whipple-tree), but referred to the distance from the handle to yoke. That is, about 7 chi from the handle to the whipple-tree and about 5 chi from the whipple-tree to the yoke. If the ox was 8 chi long, and the length from its shoulder to its tail was 2/3 of the ox's length, the actual distance from the yoke to the whipple tree was about 6 chi (think also of the gulp between the ox's tail and the whipple-tree). Adding this length to the length of the plough, it should be nearly "one zhang and two chi" (”丈有二”).

The Curve of the "Curve-Beam Plough", Should Be Reasonable

According to the record in "*Lei Si Jing*", the hind part of the beam was curved. What was the curve like? Earlier researchers did not mention the size of the curve. The author thought that a reasonably curved wood would not easily come by naturally. It would not explain the fact that the curve beam plough was widely used in the history, suggesting that the material was easily available. If the curve was too shallow, it would not look like the curve beam plough. How should one decide on the curve? By reading into the saying in "*Lei Si Jing*": "Between the beam and the rudder-center, yan four chi" ("辕至梢中间掩四尺"), the author interpreted that "rudder-center" (梢中) referred to the joint between the beam and the rudder. From the rudder-center, a line segment can be drawn parallel to the slade reaching the beam. The line segment corresponded to a bow, which was called "yan"（掩） and was "four chi" long. According to this understanding, the curve on the curve-beam plough could be decided. From that, a reasonable position for the hole to carry the strut on the beam and the strut length could also be estimated. However, in terms of actual reconstruction, this statement did not make sense.

Based on these viewpoints, a reconstruction was created (Fig. 3). For the purpose of comparison, the pictures of the reconstruction by Watabe (Fig. 1) and the one by Bray (Fig. 2) are also shown.

Additional Remarks

The author reckoned that the curve-beam plough in the Tang Dynasty was a long curve-beam plough. In the Song and the Yuan Dynasties, there was great improvement in the plough design shown from ancient drawings due to the rapid development of agricultural production. The beam was shorter, the overall size smaller and the structure simpler. The *ce e* (策额), *ya chan* (压镵), *ping* (评) and *jian* (建) were removed, making it lighter and more handy.

In the book "Agricultural Treatises" by Wang Zhen in the Yuan Dynasty, there was a picture of the curve-beam plough and the words extracted from "*Lei Si Jing*". But reading carefully, it was found that the words did not correspond to the picture. The picture was clearly the plough from the Song and the Yuan Dynasties.

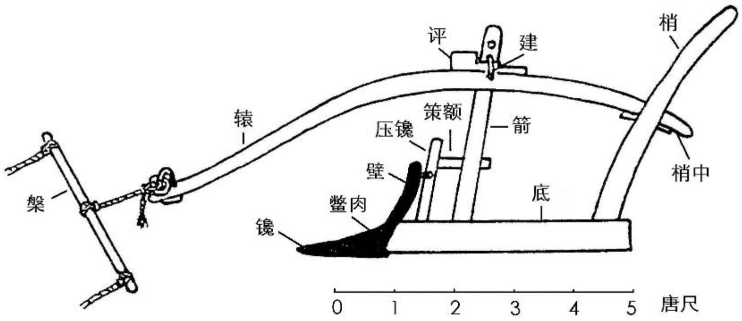

Fig. 1 Reconstruction drawing by Watabe (渡部武) based on his interpretation of the structure of the curve-beam plough in "*Lei Si Jing*"

1. *shao* 梢——stilt
2. *shao chung* 梢中——mid-stilt
3. *di* 底——sole or slade
4. *jian* 箭——'arrow 'or strut
5. *ya chhan* 压镵——'press-share'
6. *ce e* 策额——mouldboard brace
7. *bie rou* 鳖肉——'turtle flesh'
8. *bi* 壁——mouldboard
9. *chan* 镵——share
10. *ping* 评——'adjustor' or wedge
11. *jian* 建——bolt
12. *yuan* 辕——beam
13. *pan* 檠——whipple-tree

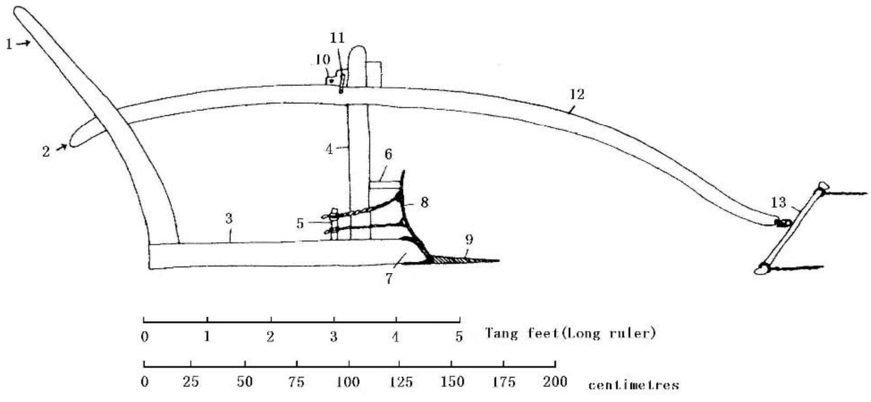

Fig. 2 Reconstruction drawing by Bray [3]

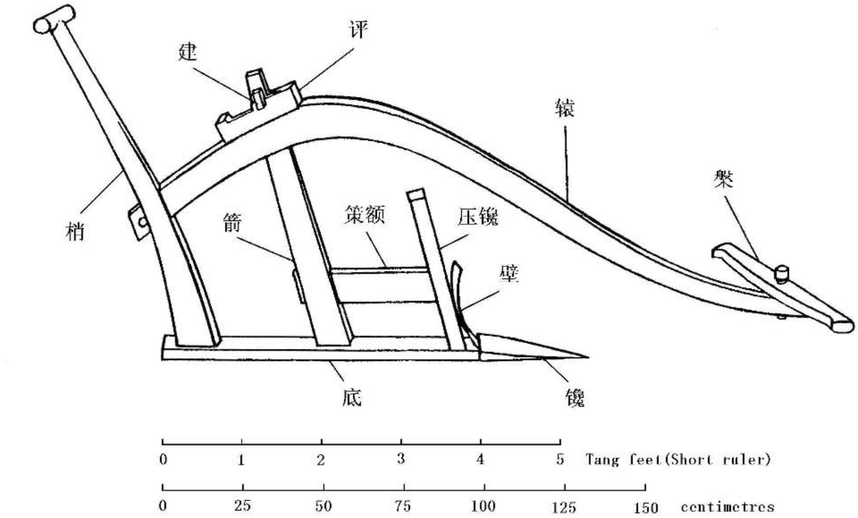

Fig. 3 Reconstruction drawing of the curve-beam plough by the author

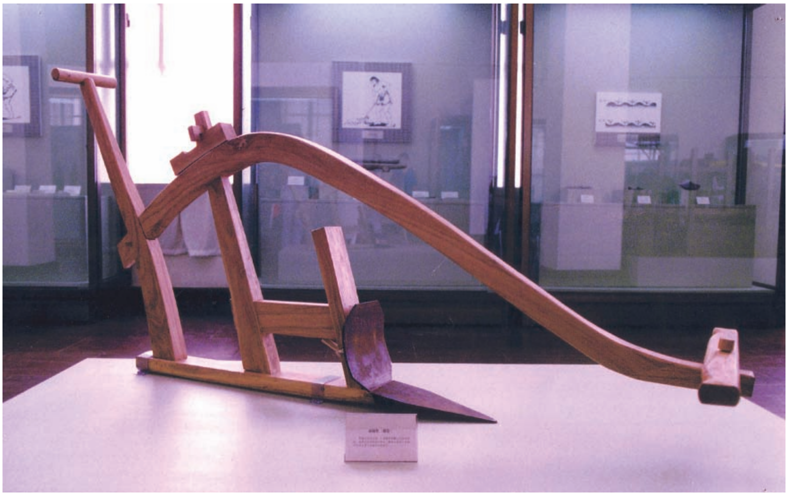

Fig. 4 The reconstructed curve-beam plough in exhibition

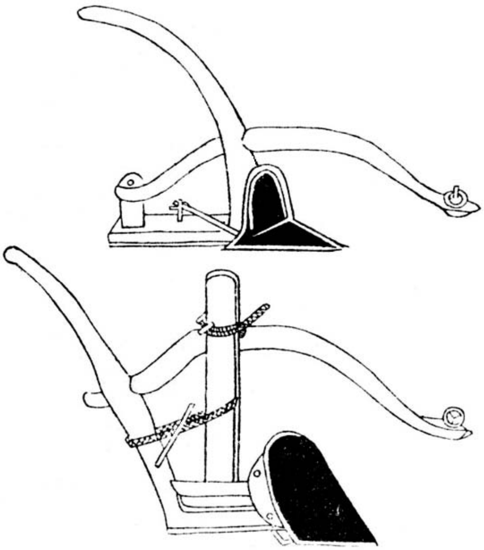

Fig. 5 Ploughs in the Song and the Yuan dynasties

References

1. Shanxi Museum and Historical Relics Management Committee (1966) The Plough-Share and Mould-Board of the Han Dynasty Are Found in Shanxi, in “Historical Relics”, Vol. I.
2. Zhang CH (1998) Appendix Ⅱ, the History of the Invention of Agricultural Machinery in Ancient China, Tsinghua University House, Beijing, China.
3. Bray F (1984) Science and civilization in China Vol. Ⅵ: 2(J. Needham), Cambridge University Press, pp. 181–182.
4. Si Ku Quan Shu·Fu Li Collection.
5. Liang JM (1989) The History of Chinese Agricultural Science and technology, p. 320, Agricultural Publishing House, Beijing, China.
6. Yan WN, Yan WS (1980) The annotation of ‘Lei Si Jing’ by Lu Guimeng, in the Tang Dynasty, The Journal of Chinese Historical Museum, Vol. 2, pp. 49–57.
7. Song ZL (1979) The Study of the Curve-beam Plough of the Tang Dynasty, The Journal of Chinese Historical Museum, Vol. 2, pp. 62–72.
8. Yang RT (1988) New Research of Curve-Beam Plough, Agricultural Archaeology, Vol. 2, pp. 225–234.
9. Watabe (1989) Lu Guimeng’s ‘Lei Si Jing’ and the Structure of Curve-beam Plough, Japanese History Research Vol. 48, No. 3, pp. 480–508.

10. Du Y (Tang Dynasty) This is the earliest record of Chinese laws and rules from the very beginning to the author's time.
11. Qiu GM (1982) The Study of Metrology Along the History of China, Beijing, Science Publishing House, p. 82.
12. In ancient China, 1 zhang（丈）= 10 chi（尺）, one zhang and two chi means 12 chi.

Crank-Connecting Rod Mechanism: Its Applications in Ancient China and Its Origin

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Abstract Crank-connecting rod is the most fundamental and typical mechanism, classifying as one of the most important inventions in ancient China and in the history of mechanical technology. This paper firstly describes the three applications of this mechanism in ancient China, i.e. agriculture, textile, and blowing-engines. This paper then discusses the origin of the mechanism through reviewing ancient Chinese literature and unearthed cultural relics.

Keywords Crank-connecting rod, Agricultural machinery, Textile machinery

Introduction

Generally, a connecting-rod, which connects to the frame indirectly, is the middle link that connects driving parts and driven parts. In mechanical principles, a linkage mechanism formed by links connected by a connecting-rod is called a connecting-rod mechanism. Linkage mechanism is the most fundamental and typical transmission-mechanism in mechanics. The invention of the crank-connecting rod is an important achievement in the history of mechanical technology. Doctor Joseph Needham pointed out: "Of all mechanical discoveries that of the crank (*chhü huai* 曲拐) is perhaps highest in importance, since it permits the simplest interconversion of rotary and reciprocating (rectilinear) motion". He further explained

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the importance of crank and the difficulties of its application, citing Lynn White, historian of technology: “Continuous rotary motion is typical of inorganic matter, while reciprocating motion is the sole form of movement found in living things. The crank connects these two kinds of motion; therefore we who are organic find that crank motion does not come easily to us…. To use a crank, our muscles and tendons must relate themselves to the motion of galaxies and electrons. From this inhuman adventure our race long recoiled”[1]. According to Karl Marx, the rotary motion of quern is unnatural, as it forms circles—regular mechanical patterns. In light of the views of the Western historians, it is perhaps the reason why the application of crank in Europe is relatively late. However, rotary motion did not prevent ancient Chinese people from adopting crank mechanisms. Specific typical machines in which crank mechanisms were adopted in ancient China are described in the following sections. The origin of crank-connecting rod mechanism and the differences between its application in the East and the West are then discussed at the last section of this paper.

The Application of Crank-Connecting Rod Mechanism in Agricultural Machinery

Manually Operated Quern and *Long*

Quern is a processing instrument for squashing grain. *Long* (砻), also called *long mo* (砻磨), which looks like a quern, is an instrument used for decortications of cereal grains. *Long* was at first made of stone—as was quern—but was later replaced by wood, soil or other materials. *Tu long* (土砻), which is made of soil, is usually surrounded by a weaving bamboo circle. Quern and *long* consist of two parts, the lower part fixed and the upper part moving during operation. Quern first appeared in the period of the Warring States of China (475–221 BC), and *long* appeared in the Western Han Dynasty. Manually operated ancient *long* and quern were recorded in the stone relief (画像石) in the Western Han Dynasty, unearthed in Chonggang (重岗) and Sihong (泗洪), in the Jiangsu province. According to a facsimile (Fig. 1), it is clear that an ancient *long* had an eccentric lug and a pushing rod, similar to the *long* and quern used in contemporary rural areas (Fig. 2). An ancient pottery quern with a pushing rod was unearthed in a tomb of the Eastern Wu (东吴) Dynasty, at Echeng (鄂城), in the Hubei province (Figs. 3 and 4) [2]. The same type of quern was also introduced in J. Rawson’s works (Fig. 5) [3].

Records and images of manually operated *long* can be found in the following ancient books; *Nong Shu* (《农书》), translated as the Treatise on Agriculture, by Wang Zhen (王祯) in the Yuan Dynasty; *Nong Zheng Quan Shu* (《农政全书》), translated as The Complete Treatise on Agriculture, by Xu Guangqi (徐光启); and the book *Tian Gong Kai Wu* (《天工开物》), translated as The Exploitation of the Works of Nature, by Song Yingxing (宋应星) in the Ming Dynasty. Figure 6 shows the image of a manually operated *long* from the book *Nong Shu*. Both sides of the cross bar were tied to a rope hanging from a beam, and the horizontal pushing rod tied to the cross bar was connected to the crank on the *long*. When pushing the cross bar reciprocally with a little sway, the crank-connecting rod forced the upper part of the *long* to rotate.

Figure 7 shows a manually operated quern used by a farmer in the Bama (巴马) county of the Guangxi Autonomous Region. The transmission mode and working principle are the same as manually operated *long*. In the book *Tian Gong Kai Wu*, a stone quern used for making candles was also introduced, as were a *mu long* (木砻), a *long* made of wood and a *tu long* (土砻), a *long* made of soil. The principle of this kind of mechanism is the same as an eccentric wheel system. The eccentric lug is actually a crank, also a kind of crank-connecting rod mechanism. So far as we know, the eccentric lug system of manually operated quern and *long* in the Han Dynasty was the earliest crank mechanism in China; it was also the earliest application of the crank and connecting rod in the world, making it a significant achievement in the history of mechanical technology.

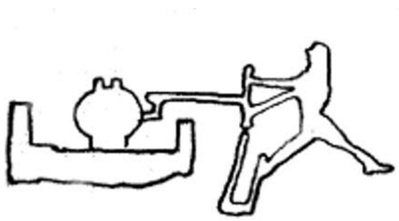
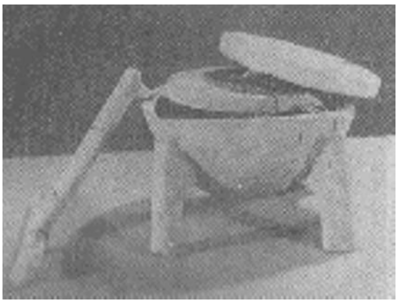


Fig. 1 A manually operated *long* in a stone relief of Han Dynasty (facsimile) (*left*)
Fig. 2 Operation of a *long mo* in Sihong, Jiangsu Province, China (*right*)



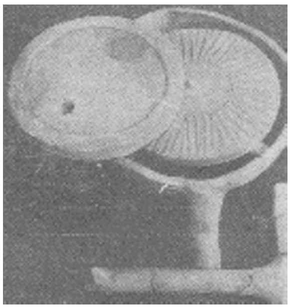


Fig. 3 A pottery quern with a pushing rod from the Eastern Wu Dynasty (*left*)
Fig. 4 A pottery quern from the Eastern Wu Dynasty (top view) (*right*)

Fig. 5 Model of a quern with a pushing rod from the Eastern Han Dynasty (*left*)
Fig. 6 A manually operated *long mo* (*right*)

Fig. 7 A manually pushed quern in Wenqian (文钱) village, Dongshan (东山), Bama county, Guangxi, China (credited by Zhang Baichun)

Jiao Da Luo, or Foot-Treadle Flour-Sifter (Man Power)

For sifting powder, the treadle-operated flour-sifters (*jiao da luo*, 脚打罗) with rocking motions have long been in use in China. Foot-treadle flour-sifter makes use of part of the body's gravity. Figure 8 is the illustration of a foot-treadle flour-sifter in the book *Tian Gong Kai Wu*. The flour-sifter hung upon a big flour-box (大面箱). On both sides of the flour-sifter there was a rod, and a cross rod that connected the two rods was linked to a rocker. The rocker was installed on a lateral axis with a treadle rod. When tapping both sides of the treadle rod alternatively, the rocker swayed from left to right and in the mean time created the reciprocating motion of the flour-sifter. There were two short cross-bars between the two rods, and the distance between them was in the range of the reciprocating motion. In the middle, a strike post was installed. The strike post was hit each time when the rocker swayed back and forth in order to strengthen the effect of the sifter. The transmission-mechanism of the foot-treadle flour-sifter is also a connecting-rod mechanism. Figure 9 shows a photograph of a foot-treadle flour-sifter used in rural areas of Zhejiang province in the 1920s taken by Rudolf Hommel. The structure is exactly the same as that recorded in *Tian Gong Kai Wu*.

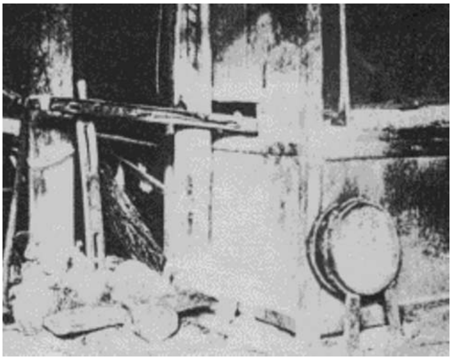
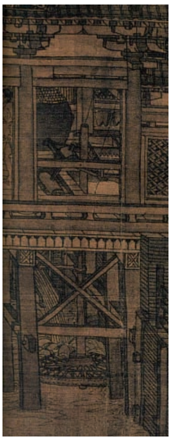


Fig. 8 A foot-treadle flour-sifter illustrated in *Tian Gong Kai Wu* (*left*)
Fig. 9 A foot-treadle flour sifter used in rural areas in Zhejiang province, China in the 1920s (*right*)

Shui Ji Mian Luo

The same mechanism was adopted in another traditional machine called the *shui ji mian luo* (水击面罗), a flour-sifter driven by a piston-rod, a connecting-rod and an eccentric lug of a horizontal water-wheel. A drawing of a *shui ji mian luo* appeared in a brushwork of Weixian's (卫贤) *Zhakou Panche Tujuan* (《闸口盘车图卷》), a traditional Chinese painting shown in Fig. 10, and kept in the Shanghai Museum of the Five Dynasties. Zheng Wei (郑为) did a construction drawing of the *shui ji mian luo* according to the picture in Fig. 10 [4] and shown in Fig. 11. An illustration of *shui ji mian luo* was also included in *Nong Shu*, and it is clear that its transmission-mechanism was the same as that applied in horizontal water-power blowing-engines (水排) as shown on Fig. 12.



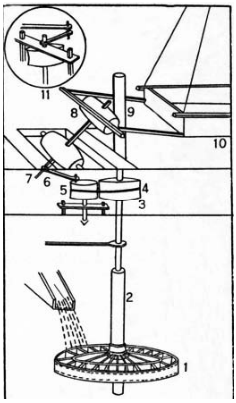


Fig. 10 A *shui ji mian luo* in *Zhakou Panche Tujuan* (*left*)
Fig. 11 Assumed structure of *shui ji mian luo* (*right*)

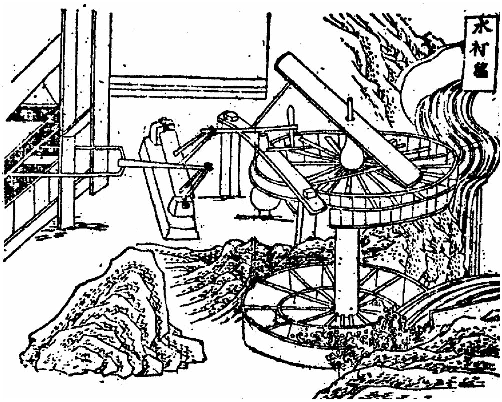


Fig. 12 *Shui ji mian luo*, from *Nong Shu*

The Application of Crank-Connecting Rod in Textile Machinery

Treadle Spinning-Wheel

The Chinese treadle spinning-wheel appeared as early as the Han Dynasty. The earliest image showing the spinning-wheel was on a stone relief of the Eastern Han Dynasty unearthed in Caozhuang (曹庄) at Sihong county, Jiangsu province in 1974 (Fig. 13). The treadle spinning-wheel composed of a treadle mechanism and a spinning mechanism. The treadle mechanism, which has the equivalent effect of a crank-connecting rod, had a crank and a treadle rod, and spinning was provided by a rope transmission.

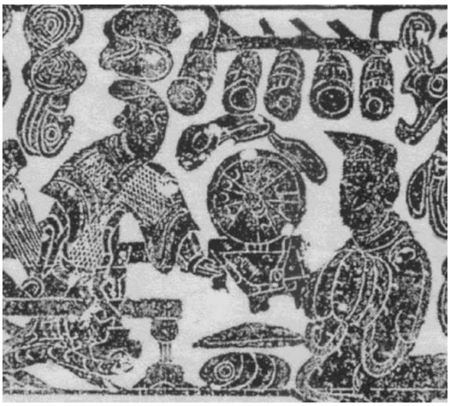


Fig. 13 Part of a stone relief of the Eastern Han Dynasty unearthed in Caozhuang

Images of a treadle spinning-wheel were recorded in many ancient scripts. For instance, Gu Kaizhi (顾恺之), a painter of the Eastern Jin dynasty, did a treadle spinning-wheel illustration for Liu Xiang's (刘向) book written in the Han Dynasty, titled *Lie Nü Zhuan* (《列女传》), translated as Biographies of Famous Ladies. Although the original version was lost, there were several replicas in the years that followed. An illustration in a Song Dynasty block-printed book *Xin Bian Gu Lie Nü Zhuan* (《新编古列女传》), translated as the New Compiled Biographies of Ancient Famous Ladies, demonstrated the operation of a spinning-wheel (Fig. 14). Three types of treadle spinning-wheel recorded by Wang Zhen's *Nong Shu* had accompanying images, one of which is shown in Fig. 15.

Fig. 14 Treadle spinning-wheel, from the book *Xin Bian Gu Lie Nü Zhuan* (left)
Fig. 15 Treadle spinning-wheel, from *Nong Shu* written by Wang Zhen (right)

According to records and images, a few of which were faded and therefore unclear, the treadle mechanism consisted of a treadle rod, a projecting nail and a crank. The iron projecting nail was installed in the connecting part of the treadle rod and the nail base, forming a sliding mechanism, similar to the structure installed on a boat to make the yuloh sway from left to right. In the middle of the treadle rod there was a carving of a small concave slot to fit the projecting nail. One end of the crank was installed at the wheel axle, and the other end connected to the treadle rod. When the treadle rod was tapped on both sides (the projecting nail was used as fulcrum), the crank would then drive the wheel to operate the spinning machinery. Besides the sliding movement described above, there was a treadle mechanism with a long history called the aperture-style structure. It appeared in an Eastern Han's stone relief unearthed in Caozhuang.

Treadle Silk-Reeling Machine (*Sao Che*)

The transmission system of a treadle silk-reeling machine was the typical two dimensional crank-connecting rod mechanisms. Qin Guan (秦观) of the Northern Song Dynasty made detailed descriptions about silk-reeling machines in the book *Can Shu* (《蚕书》), translated as the Book of Sericulture, but no illustration or explanation about the treadle mechanism was given. In the book *Nong Sang Ji Yao* (《农桑辑要》), translated as the Fundamental of Agriculture and Sericulture, compiled by Si Nong si (司农司, a government department in charge of agriculture) in the early Yuan Dynasty, there was a short description of the structure and working principle of a treadle silk-reeling machine. In the book *Nong Shu*, there was description and diagrams of North and South *sao che*. Figure 16 shows the South *sao che*

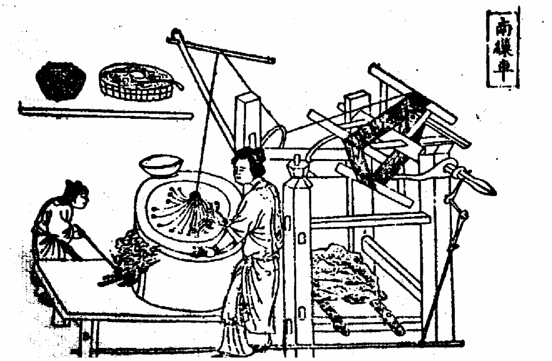


Fig. 16 South *sao che*

The treadle silk-reeling machine was developed on the basis of manually operated silk-reeling machine. Between the Tang and Song Dynasties, the treadle mechanism was commonly used in silk-reeling machines.

Pedals and treadle rods were different. In *Nong Shu*, South silk-reeling machine had a long treadle rod lying on the ground, while North silk-reeling machines adopted pedals. Figure 17 is an illustration from *Can Sang He Bian* (《蚕桑合编》) written in the Qing Dynasty by Sha Shi'an (沙石安), which clearly shows the pedals and treadle mechanisms.

Doctor Joseph Needham discussed the structure and operating procedure of the silk-reeling machine described in the book *Can Sang He Bian*. His explication is extracted as follows:

> The individual fibres of silk are drawn from the cocoons in the heated bath, passing through guiding eyes and over rollers before being laid down on the main reel. There they form broad bands, the fibres oscillating from side to side because they pass under hook on the simplest form of flyer, the ramping-arm. All the motion of the machine originate from a single treadle action of the operator; this rotates the main reel by means of a crank but at the same time also a small pulley (at the other end of the frame) which is fitted with an eccentric lug, thus effecting the regular excursion of the ramping-arm. The power is transmitted by a driving-belt [5].

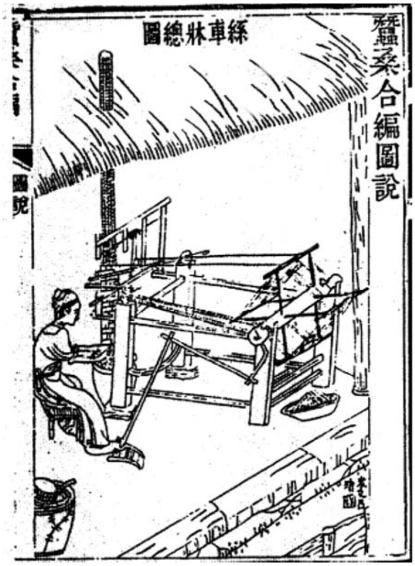


Fig. 17 Illustration of a *sao che*, from *Can Sang He Bian*

Figure 18 shows a *sao che* in the Chinese Silk Museum. Its structure corresponds with evidence from ancient Chinese literature.

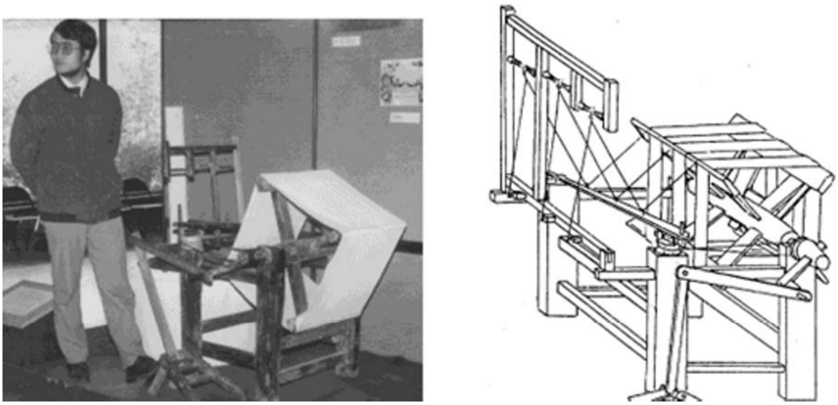


Fig. 18 A *sao che* in the Chinese Silk Museum

The Application of Crank-Connecting Rod Mechanism in Water Powered and Animal-Powered Blowing-Engines

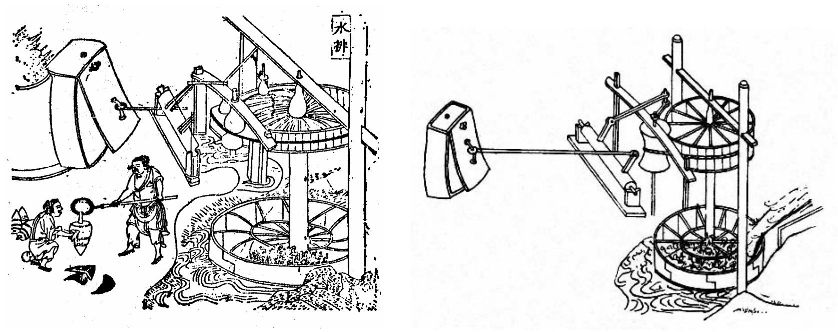
Shui pai, a water-powered reciprocator, generally shown with hinged fan-bellows, was driven by a piston-rod, a connecting-rod and an eccentric lug of a horizontal water-wheel. It is a type of water powered blowing machine. By using the crank-connecting rod mechanism, rotary motion was converted into reciprocating motion. The structure and transmission mechanism of *ma pai* (马排) are the same as *shui pai* but was instead driven by a horse.

Records on *shui pai* first appeared in the ancient texts like *Dong Guan Han Ji* (《东观汉记》) and *Hou Han Shu* (《后汉书》), translated as History of the Later Han Dynasty. *Du Shi Zhuan* (《杜诗传》), the Biography of Du Shi (杜诗) in *Hou Han Shu* recorded that in the seventh year of the Jian-wu (建武) reign-period (+31), Du Shi was promoted as the Prefect of Nanyang (南阳). He devised or at least sponsored the construction of water-powered blowing engines in the form of hydraulic reciprocators or *shui pai* for blast furnaces and the forging of ironworks for making agricultural implements [6]. During the era of the Three Kingdoms, *shui pai* was further promoted. In the book *San Guo Zhi* (《三国志》), translated as History of the Three Kingdoms, it was recorded that horse power was used to drive blowing-engines, and each picul (a weight equal to 100 catties) of refined wrought iron required the work of a hundred horses. Man-power was also used, but that was exceedingly strenuous. So Han Ji (韩暨) adapted the furnace bellows to use abundantly available flowing water, and achieved three times greater efficiency than before. It was suggested in the book that Han Ji also used water power as the power of blast apparatus and that *ma pai* was very popular in the Central Plains. At that time, a hundred horses were needed in mineral melting, which suggested that iron smelting mills had reached a considerable scale. During his seven year of office, iron implements became very sufficient [7].

Early *shui pai* was built according to the structure of *ma pai*, the wheels of which were both horizontal. In *Nong Shu*, there was a description of the structure of *shui pai* with horizontal water-wheels. It was written that previously leather bag bellows (韦囊) were used, which were replaced by wooden fans (木扇). "A place beside a rushing torrent is selected, and a vertical shaft (立轴) is set up in a framework with two horizontal wheels (卧轮)". "The lower one is rotated by the force of the water. The upper one is connected by a driving-belt (絃索) to a smaller wheel (旋鼓) in front of it, which bears an eccentric lug (lit. oscillating rod, 掉枝)". "Following the turning of the driving-wheel, the connecting-rod (行桄) attached to the eccentric lug pushes the rocking roller (卧轴), the levers (攀耳) to left and right of which assure the transmission of the motion to the piston-rod (直木). Thus this is pushed back and forth, operating the furnace bellows far more quickly than what would be possible with man-power" [8].

As there was peculiarity in the illustration in the Ming dynasty's version of *Nong Shu* (Fig. 19a), Liu Xiangzhou (刘仙洲) produced an improved picture based on the original texts (Fig. 19b). The early *shui pai* with horizontal water-wheels was working to almost perfection when *Nong Shu* was finished, with the connecting rod mechanism always the main transmission-mechanism converting rotary motion into reciprocating motion.

It is not difficult to infer the basic structure and transmission principles of *ma pai*, according to the structure of *shui pai*. One or two cross rods were installed on the vertical shaft for a horse to drive the cross rod into a circular motion. The big wheel (大绳轮) was installed on the vertical shaft, and the small wheel (小绳轮) was driven by a belt (绳套). A crank was installed on the wheel, and a connecting rod and another crank transmitted the power to the horizontal shaft, which moved back and forth. The crank on the horizontal shaft and another connecting rod pushed the leather bag to and fro. Figure 19 is the assumed structure of the trans-mission-mechanism of *ma pai*.



a) b)

Fig. 19 S*hui pai*, with a horizontal wheel

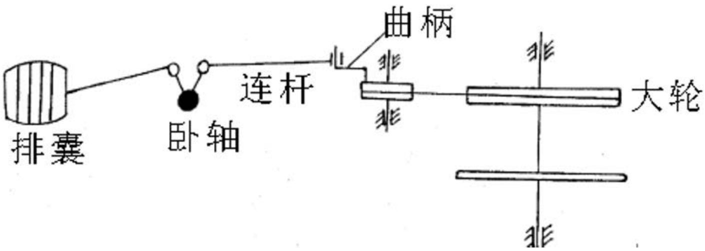
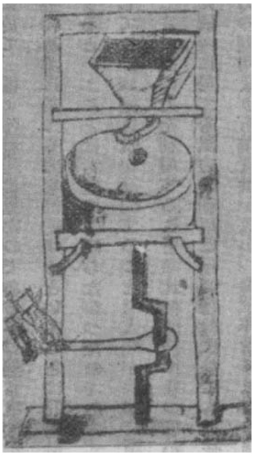


Fig. 20 Schematic diagram of the transmission mechanism of *ma pai*

The Origin and Popularization of the Crank-Connecting Mechanism

Texts and archaeological data showed that it was not until 4 or 5 AD that manually operated quern with a vertical handle appeared in Europe. However, the appearance of a crank was much later according to conclusive evidence; it was not until 9 AD that it was recorded in literature. As the predecessor of crank, the handle was first used in querns in Europe. It was in the 15th century that crank and connecting-rod were used together.

While concluding the development of European mechanical technology in his book, mechanical historian Usher noticed that basic types of mechanical transmission system and components existed before the Mediaeval period, but the only missing part was the crank. He said that there were no evidences that indicated the existence of any form of crank before the Medieval period in Europe [9]. The earliest evidence in Europe was found in the Bible of Utrecht written in 830 AD, in which it wrote that a handle was installed in a rotating quern. In the first half of the century, Theophilus Presbyter described hand handles being used for cutting casting cores. Till the 15th century, crank became common [10]. Figure 20 is a type of manually operated quern which used crank and connecting-rod in the 15th century in Europe. Figure 21 is an illustration of the manually operated quern used in Europe in the 15th century (from Jacob de Strada, *Kunstliche Abriss*, 1617–1618). Similar to the Chinese manually operated *long* and quern, European quern adopted the crank connecting-rod mechanism, but the crank was a crankshaft, demonstrating a different style.



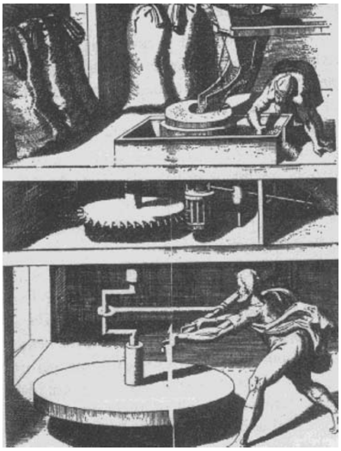


Fig. 21 Manually operated quern in Europe from the15th century (*left*)
Fig. 22 Manually operated quern in Europe from the 17th century (*right*)

According to the dates in historic records, the appearance of the crank connecting-rod in China was much earlier than in Europe. But regarding the time of its first appearance in China, there were different opinions.

For a long time, Chinese scholars generally accepted Liu Xianzhou's view that the crank connecting-rod was first used in *shui pai* invented by Du Shi in the Eastern Han dynasty. However, the illustrations of *shui pai* and *shui ji mian luo* in *Nong Shu* in the Yuan dynasty indicated that crank connecting-rod was adopted in 31 AD. Few Western scholars agreed; Lynn White regarded *shui pai* in 31 AD as a reliable example of crank motion. But Joseph Needham thought otherwise. He said: "In the present state of our knowledge we cannot assume that the Han system was the same as that of the Sung and Yuan; it may well have been much simpler, the bellows being operated simply by lugs on a horizontal water-driven shaft. Just when the more complex machinery came in we do not yet know, but by the beginning of the Thang period might be a good guess" [11]. Chinese scholars considered the *shui pai* of the Eastern Han and Yuan Dynasties to be similar, so Joseph Needham's query seems reasonable at that time. In fact, Wang Zhen clearly indicated in *Nong Shu* about their major differences that blowing-engines used leather bag bellows (韦囊) in ancient times, but in the Yuan dynasty they used wooden fans (木扇). The manually operated *long* shown in the stone relief of the Han Dynasty dated the time of invention of the crank-connecting rod back to an earlier period—the Western Han. Therefore, it is meaningless to argue whether the crank appeared in the Eastern Han period or not.

Crank mechanism evolved from the rotary handle, which is accepted amongst technical historians. Joseph Needham and Lynn White both noticed the use of the crank handle in the pottery winnowing-fan (陶风车) of the Han dynasty. In Atkin Museum of Kansas city, where a pottery model of a farmhouse was housed, there were models of a treadle rice-huller (脚踏碓), a rotary-quern (转磨) and a winnowing-machine (风扇车). Needham and White thought the crank handle of the rotary-fan and winnowing-machine were the oldest in record. Needham claimed: "The crank-handle for working the rotary-fan of the winnowing-machine is the oldest representation of true crank-handle from any civilisation" [12]. Since the 1970s, models of pottery winnowing-machines have been unearthed continually in Jiyuan and Luoyang, at the Henan province and in Ruicheng, at the Shanxi province. Among them, a winnowing-machine model unearthed in Sijiangou, Jiyuan could be traced back to the period of the Western Han (Fig. 23) [13]. Figure 24 is the photo of a pottery winnowing-machine model unearthed in an Eastern Han Tomb in Luoyang [14]. In the Han dynasty, another important application of crank handle was in crank spinning-wheels, which was very popular at that time.

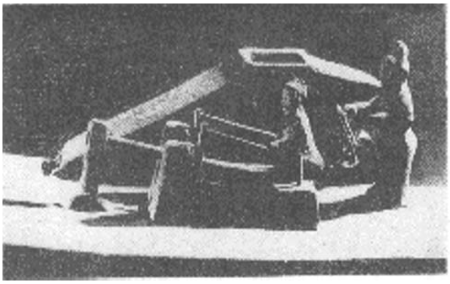
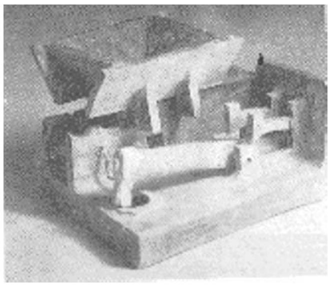



Fig. 23 A pottery winnowing-machine model in the Western Han Dynasty (*left*)
Fig. 24 A pottery winnowing-machine model in the Eastern Han Dynasty (*right*)

The emergence of quern with a crank handle could be traced back to the Period of the Warring States, and the use of hand-crank rotary quern (手摇转磨) or hand-pushing rotary quern (手推转磨) was very common in the Han dynasty. Therefore, it can be concluded that hand-crank (旋转手柄) was invented and widely used in the Han dynasty.

Joseph Needham did not differentiate between hand-crank and crank. In actual fact, the combined installation of the crank and connecting-rod could create the crank motion. More precisely, it was the combination of the crank and connecting-rod that permitted the simple conversion of the rotary motion and reciprocating (rectilinear) motion. It was the application of the composite crank and connecting-rod in *long* and quern that converted a person's reciprocating motion into the rotary motion of the quern and *long*. When a hand-crank and a push-and-pull connecting rod (推拉连杆) were connected by a hinge, the handle became a crank.

The composite mechanism of connecting-rod and crank was first used in the hand-pushing rotary quern and *long*, but was much overlooked by technical historians. The main reason was that they failed to estimate the exact time of its appearance. Joseph Needham noticed that *long mo* and traditional hand-pushing rotary quern were widely used in China, and was recorded in *Nong Shu*. However, due to limited available history records, he failed to trace the time of its appearance. He inferred that connecting rods of various lengths were installed in hand-pushing querns long ago in China, not later than the Song dynasty. Chinese scholars also placed the appearance of this kind of hand-pushing quern as after *shui pai*. Dai Nianzu (戴念祖) indicated that quern was further developed in the Eastern and Western Han periods, when *shui pai* was invented [15]. This assumed that they were found later than it was in Needham's argument. But there were insufficient evidence to show that it was inspired by the crank and connecting-rod in *shui pai*. *Shui pai* was more complicated and more advanced than manually operated quern in terms of working principles, structure and the transmission system. On the contrary, the argument that the emergence of *shui pai* was inspired by the crank and connecting-rod used in manually operated quern was more reasonable. Apparently, *shui pai* synthesized several simple techniques in that period, including the crank and connecting-rod mechanism used in manually operated quern and the rope transmission system adopted in a crank spinning-wheel. Joseph Needham later realized the importance of tracking back the appearance of crank in manually operated quern. In his book *Science and Civilisation in China*, he added the discussion concerning manually operated quern in the appendix: "The quern connecting-rod is obviously an important ancestor of the full assembly of crank, connecting-rod and piston-rod as seen in the standard method of interconversion of rotary and longitudinal motion. It seemed likely to be old, but we could not date it from book illustrations earlier than +1210. The Chiangsu Historical Museum at Nanking, however, possesses an excellent model of the quern connecting-rod and handle taken recently from a tomb of the Nan Chhao period (between +420 and +589) at Têng-fu Shan very near Nanking. A photograph of the model (ca. 9 in. long) is available. This strengthens our view that the standard method was a Chinese development with a long historical background" [16]. Now, according to new history records, the origin of the quern connection-rod can be dated back to the Western Han Dynasty, and the origin of crank connecting-rod is then explainable.

The inventions of manually operated quern, *shui pai* as well as *sao che* are of significant importance in the history of machinery. Karl Marx thought that quern could be regarded as the earliest tool that applied the machinery principles, and it was easier to apply machinery principles on quern than on a spinning-wheel, because quern was used to overcome the resistance on a spinning-wheel. The original quern had nothing to do with hands and did not require manual intervention [17]. Based on modern mechanical principles, manually operated quern and *long* possessed basic features of machines. It can, therefore, be said that manually operated quern is the earliest machine invented by human beings. The appearance of *shui pai* and *sao che* symbolized high levels of mechanical transmission in ancient China and the greatest achievement during that period. Needham pointed out: "and the latter (sill-reeling machine) is a machine of great importance in the history of technology for it embodied, so far as we can see, the first appearance of that fundamental combination of eccentric, connecting-rod and piston-rod used afterwards in all steam and internal combustion engines" [18]. From the above discussion, the crank and connecting-rod mechanism featured with eccentric lug was adopted for a long period of time in ancient Chinese blasting apparatus, textile machinery and agricultural machinery, and its appearance was not later than the Western Han Dynasty. It was first applied in manually operated quern and *long*, and then gradually evolved into different crank connecting-rod devices, used in the inter-conversion of rotary and reciprocating (rectilinear) motion in specific situations.

References

1. Needham J (1965) Science and Civilisation in China, Volume 4, Physics and Physical Technology, Part 2, Mechanical Engineering, Cambridge University Press, pp. 111–112.
2. Chen WH (1994) Illustrations of Chinese Agricultural Archaeology (in Chinese), Jiangxi Science & Technology Press, 370–371.
《中国农业考古图录》；陈文华撰，江西科学技术出版社，1994 年，第 370–371 页。
3. Needham J (2000) Science and Civilisation in China, Volume 6, Biology and Biological Technology, Part 5, Fermentations and Food Science, Cambridge University Press, p. 465.
4. Zheng W (1965) Zhakou Panche Tujuan, Cultural Relics (in Chinese), Vol.2, p. 25.
郑为，"闸口盘车图卷"，文物，北京，1965 年第 2 期，第 25 页。
5. Needham J (1965) Science and Civilisation in China, Volume 4, Physics and Physical Technology, Part 2, Mechanical Engineering, Cambridge University Press, Illustration of Fig. 409.
6. 《后汉书》卷三一《杜诗传》；范晔[南朝]撰。译文引自 Needham J (1965) Science and Civilisation in China, Volume 4, Physics and Physical Technology, Part 2, Mechanical Engineering, Cambridge University Press, p. 370.

7. 《三国志 • 魏书》卷二四《韩暨传》；陈寿[晋朝]撰。译文引自 Needham J (1965) Science and Civilisation in China, Volume 4, Physics and Physical Technology, Part 2, Mechanical Engineering, Cambridge University Press, p. 370.
8. 《农书》；王祯[元朝]撰，"农器图谱集之十四·利用门"。译文引自 Needham J (1965) Science and Civilisation in China, Volume 4, Physics and Physical Technology, Part 2, Mechanical Engineering, Cambridge University Press, pp. 374–376.
9. Usher AP (1988) A History of Mechanical Inventions, Dover Publications, Inc., New York.
10. Needham J (1965) Science and Civilisation in China, Volume 4, Physics and Physical Technology, Part 2, Mechanical Engineering, Cambridge University Press, p. 111.
11. Needham J (1965) Science and Civilisation in China, Volume 4, Physics and Physical Technology, Part 2, Mechanical Engineering, Cambridge University Press, p. 119.
12. Needham J (1965) Science and Civilisation in China, Volume 4, Physics and Physical Technology, Part 2, Mechanical Engineering, Cambridge University Press, PLATE CLVI.
13. 河南省博物馆，"济源泗涧沟三座汉墓的发掘"，文物，北京，1973 年第 2 期，第 50 页。
14. 余扶危、贺官保, "洛阳东关东汉殉人墓"，文物，北京，1973 年第 2 期，第 54 页。
15. 《中国力学史》；戴念祖撰，湖北教育出版社，1988 年，第 281 页。
16. Needham J (1965) Science and Civilisation in China, Volume 4, Physics and Physical Technology, Part 2, Mechanical Engineering, Cambridge University Press, p. 759.
17. 《机器。自然力和科学的应用》（中译本）；马克思撰，人民出版社，北京，1978 年，第 67 页。
18. Needham J (1965) Science and Civilisation in China, Volume 4, Physics and Physical Technology, Part 2, Mechanical Engineering, Cambridge University Press, p. 118.

The Development of Knowledge on Levers in Ancient China

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Abstract The lever is the simplest yet the most basic mechanical device. It was used in many ancient cultures around the world, each of which developed their machine-making technology and mechanical knowledge based on its own culture and tradition. A thorough study of the process and characteristics of the development of knowledge concerning levers may help to gain insight into the influences of cultures on technology. In China, in the book *Mozi* (墨子) from the the 5th to 4th century BC., a theoretical discussion about the function of lever was given. A chapter in the book *Zhuangzi* (the 4th – 3rd century BC.) revealed that in the 3rd century BC., a swape, called *Jiegao* (桔槔) in Chinese, was already commonly used for water-lifting. In later texts, devices with levers as the main components, such as a device to raise signal fire or trebuchet, were generally named *Jiegao*. There were written records that Chinese had developed complicated devices using levers by the 11th century. In this paper, based on extensive evidences, including archaeological excavation, paintings, philosophical and historical works, the development of the knowledge of levers of practitioners and academics in ancient China was analysed. The viewpoints on the characteristics of ancient Chinese lever technology were also presented and compared with that of Greece.

Keywords Jiegao, Lever, Mechanical device

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Introduction

Lever is the simplest yet the most basic mechanical device. It was used in many ancient cultures around the world, each of which developed their machine-making technology and mechanical knowledge based on its own culture and tradition. The design of a lever thus provided important information of the means technological knowledge was acquired and produced. In Greece, in Aristotelian tradition, “the Law of Lever” was the main theoretical principle used to explain the relation between force and the effect of almost every mechanical device. Lever was also one of the basic machines in the classifications of the Hero of Alexandria (fl. 2 C.E.), and was used as elements for analysing any complex machinery [1,2]. There were various devices with lever as their main component as shown and recorded in ancient Chinese materials. Were Chinese aware of the similarity of the basic structures of such devices? Were levers intentionally applied in the design of more complicate instruments? Another question was did the Chinese discovered the Law of Lever? In this paper, answers to these questions were explored.

Jiegao: Lever as Used by Traditional Practitioners in China

Jiegao as a Water-Lifting Device

In ancient Chinese literature, *jiegao* was commonly defined as a water-lifting device (swape), and was cited as one of the most important implements by Chinese philosophers, the main supporter being *Master Zhuang* (庄子) (Zhang Zhou, 396 BC–286 BC). *Jiegao* was described by *Master Zhuang* in two sets of text:

> Carve a piece of wood to make a mechanism (*ji* 機) which is heavy in the back and light in the front. It can raise water by drawing it up with such great speed as water boiling over. Its name is a *gao* (槔, a counter-balanced bailing lever) [3]
>
> Have you never seen a *Jiegao*? Pull it, then down it comes; let go then up it swings [4]

In summary, this *Jiegao* was made of wood and was divided into two sections by a fulcrum. A force by an operator acted on the lighter section. When the force was withdrawn, the deadweight of the heavier section made it descend. This description exactly fitted with a lever used for raising water. Similar descriptions could be found in different scripts. For example, in a chapter in *Fanzhi* of *Shuoyuan* (反質說苑), Liu Xiang (77 BC–6 BC) mentioned:

> To make a mechanism, make its back [section] heavy and its front [section] light. It is called *qiao* (beam). It can tirelessly irrigate a hundred *qu* of chives [field] the whole day long [5].

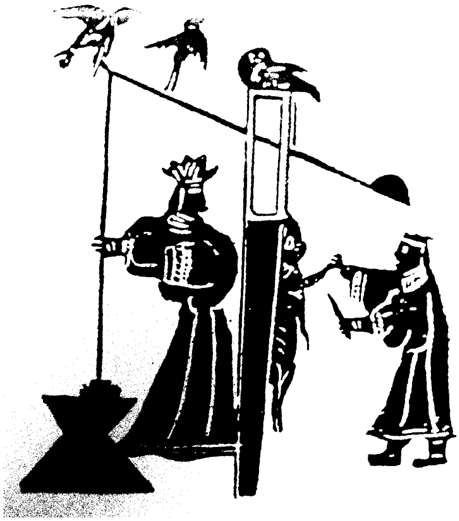

Fig. 1 An illustration of Jiegao in Wuliangci painting dated as the western Han Dynasty (206 BC–24 AD) [6]

The above painting (Fig. 1) clearly illustrates a water-lifting device, which had an identical structure with the one described by *Master Zhuang* and in *Shuoyuan*. This device had a beam supported by a column and divided into two non-equiponderant parts. A weight was fixed at the end of shorter part of the beam and a rope was fixed at the end of the longer one. A vessel was attached to the other end of the rope. A man pulled at the rope. The function of the device was clear. The appended weight helped reduced the force required for lifting the vessel.[1] It is

[1] A weight is fixed to one end of the beam of the swape while a vessel is hung by a rope at the other end of the beam. Supposing the beam is of uniform quality and size, the distance between the weight and the fulcrum is l_1, the distance between the vessel and the fulcrum is l_2, the difference in weight between the two sections of the beam is w_1, the weight of the empty vessel is w_2, the counter-weight weighs w. As long as $w > \frac{(w_1 + 2w_2)l_2}{2l_1} - \frac{w_1}{2}$, the operator may make use of the weight to conserve his force. In extent sources related to the swape, there is no discussion about the relation between the counterweight and the applied force. However, this does not necessarily mean that Chinese people never acquired such knowledge.

reasonable to assume that this illustration reflects the basic structure of a *jiegao*, the water-lifting swape. It is worth noting that the man pulled at the same side of the weight he intended to lift, whilst the counterweight was fixed at the opposite end at the longer part. At first sight, the function of *jiegao* was different to a standard lever[2]. A closer look revealed that it had the same working principle as a lever, and furthermore, the design of *Jiegao* was practical and convenient. A long horizontal distance between the well-mouth and the fulcrum was necessary for water-lifting from a deep well. A certain length of the part of the beam between the point the vessel was tied and the column permitted the end of the beam to draw a long and straight arc as the beam swung. If the operator wanted to make use of the difference in lengths between the arms of the force and the weight, he had to lengthen the beam to a certain extent, which could make the *jiegao* quite large. By adding a weight to the end of the beam opposite to the one the vessel was attached, the design of *Jiegao* could overcome such a problem. Considering another factor of lifting-water, this solution is advantageous in practice than using a standard lever. For water-lifting, a person was required to empty the vessel as well as adjust the position of the vessel. That meant that there should constantly be a man stood around the well-mouth. In the illustration, a person stands near the well-mouth and pulls the vessel up instead of a person standing at the other end of the beam and pulling the beam down. According to this design, with the help of the weight, the operator can conserve force when pulling up the vessel as well as when lowering the vessel by pulling down the beam and the weight as that moment arm on his side is longer than the one on the other side. In this operation, the *Jiegao* acts exactly as an ordinary lever. No sources revealed how the *Jiegao* was invented but it is reasonable to assume that the inventor had extensive technical knowledge of the lever.[3]

In fact, *jiegao* (swape) was mainly used as a low-lifting tool in history. Windlass or pulley was a more popular water-lifting device for deep wells. However, *jiegao* was very popular and continued to exist until the modern time for water-lifting from low wells or pools to irrigate in agriculture. It was mentioned in various books and poems, such as Wang Zhen's *Book on Agriculture* （1313） [7].[4]

[2] The function of a standard lever could be expressed as the following: applied force and the weight were attached to different ends of the beam. If one hopes to conserve his force, the moment arm of the applied force should be longer than the resistant arm of force.

[3] It is admitted that both *Master Zhang* and *Shuoyuan* stressed that the weight lifted should be fixed at the lighter part of a *Jiegao*. The effect of the beam length of a *jiegao* was not mentioned. It may therefore be assumed that their authors did not have the knowledge the effect of longer arm length of the applied force on conserving energy.

[4] It is possible that Wang Zheng compiled the majority of the section on Nongqi tupu of Nongshu (the Book on Agriculture) from the book Nongqi pu written by Zeng Zhijin in the Southern Song Dynasty [8].

According to a description of spring by Zhang Guowei (張國維) (1595–1646), the land in Zhejiang province was almost covered by a great number of *jiegao* [9].

The *Jiegao* for Other Purposes

Jiegao was generally defined as a water-lifting tool, but some ancient sources showed that other lever-styled devices were also named as *jiegao*. In the commentaries on *Shiji* (史記) by Wen Ying (文穎) of the 3rd century AD, a device for enkindling signal fire in the Han Dynasty（202BC–220AD）was described as:

Construct a high wooden watchtower, at which a *jiegao* is constructed. At the head of the *jiegao* is a bag, into which hay is put, it is called *feng* (signal fire). At ordinary times make it low. If invaders come, then enkindle and raise it [10].

In this text, *jiegao* was a device for lifting signal fire instead of lifting water.

Zhang Yan (張晏) of the 3rd century AD mentioned that such devices of lifting signal fire was also named as *quanhuo* (權火), and had a shape similar to *jiegao* used for lifting water from a well [11]. *Quan* could be interpreted as the tendency of motion, and the counterweights of balance and steelyards were also named *quan*.[5]

In the book *Liushu Gu* of the 13th century, *zeng* (罾), a kind of fish catcher, was described as a device for lifting fishnet with *Jiegao* [12]. A picture dated from the Song Dynasty (960–1279) illustrates such a device, Fig. 2 [13].

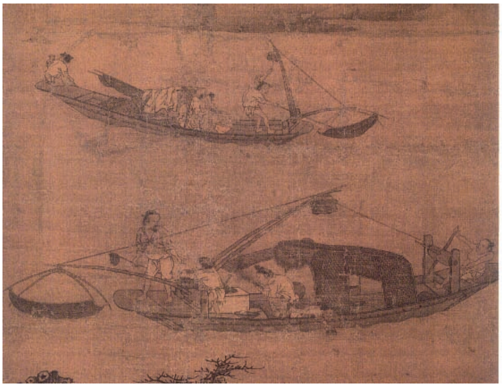

Fig. 2 Illustration of a fish catching device of the Song Dynasty, as preserved in the Palace Museum, Taipei [13]

In fact, non-water-lifting lever was a very ancient invention in China. In a site dated as the late Western Zhou Dynasty (11 century BC–771 BC), a few remnant parts of a lever were excavated [14]. Amongst them, a wooden pole of 2.6 m length was named by the archaeologist as *jiegao* 88:1. There was an arc-shaped

5 The meaning of *quan* is further discussed at the conclusion of this paper.

notch located at 1.66 m from the thin end of the pole. A remnant column that had a diameter of 14 cm stood beside the pole. All the facts presented such as the location of the column, the pole and bamboo baskets full of ore sand suggested that the pole must have been the beam of a lever. It was used to lift scrap ore sand in the mineral separation field. The notch of the beam working as a fulcrum must have been tied to the column. A bamboo basket must have been hung at the end of the short section of the beam. Similar columns and beams as well as wooden shovels were uncovered in ancient mines next to the Tongling mines. The above archaeological discovery revealed that levers were used to lift ore or stones in low mine-driving locations before 771 BC at the latest.

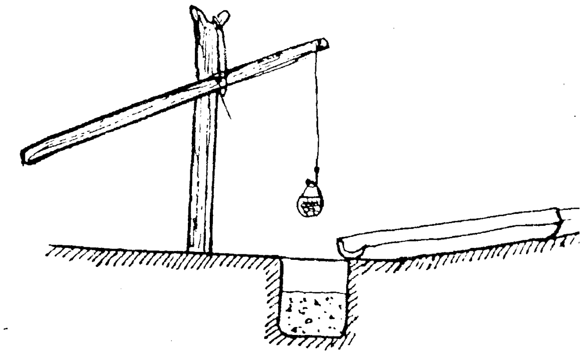

Fig. 3 Reconstruction of the lever excavated in 1988 at Tongling, Jiangxi province [14]

Trebuchet: Military *Jiegao*

The beam of a swape will swing at a certain speed when the difference in weight between the two parts of the beam is large enough or when a strong force acts at one end of the beam. Moreover, if the beam swings in a certain speed, it can make an object attached to it fly off. No theoretical description of this phenomenon had been found in ancient Chinese writings, but Chinese long before had acquired such experiential knowledge. Based on that knowledge, they invented the military *jiegao*. Modern historians believe that *jiche* (藉車) described in section 52 of *Bei chengmen* (備城門) written by *Mozi* must be a type of trebuchet. In his commentary on the biography of Gan Yanshou's (甘延壽) in the book *Hanshu* (汉书) translated as Book on the Han Dynasty, Zhang Yan (張晏) of the 3rd century AD introduced a device in the lost book *Fanli Bingfa*, literally the Military art of Fan li, he wrote "Launched by a mechanism, a stone weighs two *jin* may flys two hundred *bu* away" [15,16].

Jinshu (晋書) translated as the Book on the Jin Dynasty, 646 AD, mentioned the application of *jiegao* in wars. From 311 to 315 AD, Du Tao (杜弢), an insurrectionist, often used *jiegao* as a weapon. In 315 AD, Du constructed a *jiegao* for attacking military warships [17,18]. This *jiegao* should be a kind of trebuchet. In the 7th century, this kind of device was systematically named *pao* (砲). In the Tang Dynasty, Li Quan of the 8th century depicted the structure of *pao* in his book *Taibai Yinjing*:

> For the *paoche* (trebuchet mounted on carriage) on the wall of city, [they] use large blocks of wood to make a framework, four wheels are arranged below the framework. [They] build two posts on [the framework]. Between them [there are] horizontal bars, through which a pole stands alone. The top of [the device] is like a *jiegao* (swape). The height, length and size of the pole depend on the city as a yard-stick. At the top of [another] pole a sling [lit. nest,] is used to hold a stone or stones, size and number [of the stone] are restricted in force (the strength) of the pole. Men [suddenly] pull [ropes attached to the other] end, and so shoot it forth [19,20].

There were no mention of the sizes of each part and the stone weights as balls. The length of the pole depended on the structure of the city wall; the philosophy of the design was identical with the Chinese technological tradition of "adjusting measures to suit local conditions". The ancient Chinese knew that an overweight stone would break the pole, therefore they emphasized that the relation between the weight of the stone and the strength of the pole should be equivalent. They must have gained the experiential knowledge from the use of a trebuchet in war. The author of *Wujing Zongyao* written in the 11th century described and drew a *paoche*, the structure of which was identical with the description in *Taibai Yinjing*.

Besides trebuchet mounted on carriages, the authors of *Wujing Zongyao* drew and explained the structure and usage of two series of trebuchets and several special trebuchets. For example, one series of trebuchets was respectively named *danshaopao* (單梢砲), literally one-branch trebuchet, *shuangshaopao* (雙梢砲), literally twin-branch trebuchet, *wushaopao* (五梢砲), five-branch rectangular trebuchet and *qishaopao* (七梢砲), seven-branch trebuchet. The number attached with the *shao* was "applied to the number of component wooden [or even bamboo] poles which formed the arm".[6]

[6] The author of *Science and Civilisation in China* pointed out that the wooden poles could be bound with metal bands [21]. This may be true for the pao mentioned in other sources. In *Wujing Zongyao*, it was clearly recorded that bands were made of hemp [22].

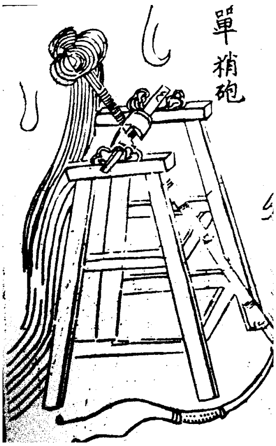

Fig. 4 Danshao Pao, from *Wujing Zongyao*

Danshaopao had only one pole as arm (Fig. 4). The author of the book drew and explained the detailed structure of its frame. The entire arm was one *zhang* (丈) long in total and its stone ball weighed two *jin* (斤), but there were no mentions on the distance between any ends of the arm to the fulcrum. The author explained that there were nine truss ropes along the arm. According to his drawing, it is known that the fulcrum was located at the seventh truss rope; therefore the proportion between the two sections of the arm is 1:3. According to the description, there should be forty people pulling the 45 ropes, which were tied at the other end of the arm. When all these forty people pulled the ropes at the same time, a huge momentum was imparted to the stone. The author of *Wujing Zongyao* described that the stone can be flung 50 *bu* (步) away, and such a trebuchet was intended to be located in the city for attacking enemies outside the city [22].

It is clear that the more wood was used for the arm, the more was the power of the arm, enabling heavier stones to be shot by the *pao*.[7] For the seven-branch trebuchet, the weight of the stone increased to 90 or 100 *jin*, which would then require about 250 people to pull the ropes [22,23].

For each *pao* introduced in the *Wujing Zongyao*, the range of its shot was explicitly given. This showed that as early as the middle of the 11th century, Chinese military engineers had already noticed that the firing range depended on the structure of a *pao*, including the weight of the ball, the length of the arm and the force applied to shoot the ball. The results must have been attained through field tests, and were recorded in the *Wujing Zongyao* as guidelines, and consequently, were handed down to later generations.

[7] This is in accordance with the principle of choosing a stone given by the guidelines by Li Quan. This meant that this experiential knowledge was handed down and was accepted by the author of *Wujing Zong Yao*.

Up to the Yuan Dynasty (1206–1368), Chinese often named this type of *pao* (trebuchet) *jiegao*. In the book *Liushu Gu* (六書故), *pao* was explained as follows:

> Raise a stone to throw. Now in army, jiegao is used to turn a stone to beat [enemy], [and] it is named pao [24].

Besides trebuchets, ancient Chinese named other lever-shaped military devices as *jiegao*. For example, in *Wujing Zongyao*, the *feiju* (飛炬), a flying torch, which held down a burning object by means of an iron chain to obstruct enemy, was named *jiegao* too [25].

The above materials showed that ancient Chinese consciously named lever-shaped devices that were used to raise or to throw or to hang an object as *jiegao*, or any related devices. This suggested that ancient Chinese had in fact noticed that these devices had a common mode of function. Although no written theoretical knowledge, such as a formula for *jiegao* for hoisting heavy objects, nor quantitative systematic analyses of the force or strength of a trebuchet existed, they demonstrated extensive experiential knowledge about levers through real-life practice and engineering.

There was a story about the famous man, Great Yu, trying to control rivers four or five thousand years ago. The story was drawn out by *Dayu Zhishui Tu* (no later than the 12th century) which is currently housed in Taipei Palace Museum [26]. The devices for stone-cutting reflected the technology and mechanical experience relating to the use of levers (Fig. 5). The painter carefully drew simple crowbars, lever and wedges and complicated leverage. The lever in Fig. 6 is supported by a wheel and consists of two levers and ropes.

Fig. 5 *Dayu Zhishui Tu*, presently housed in Taipei Imperial Palace. Photo by Tian Miao and Zhang Baichun [26]

Fig. 6 Dayu Zhishui Tu [26]

From facts, the lever had become a part of complicated machines for a long time. One typical example in ancient China application was the water-powered armillary sphere and celestial globe tower built by Su Song (蘇頌) and his collaborators in the 11th century [27]. The *tianheng* (the celestial balance) as an escapement mechanism of clockwork controlled the turning of a waterwheel, and made the waterwheel rotated equably intermittently [28].

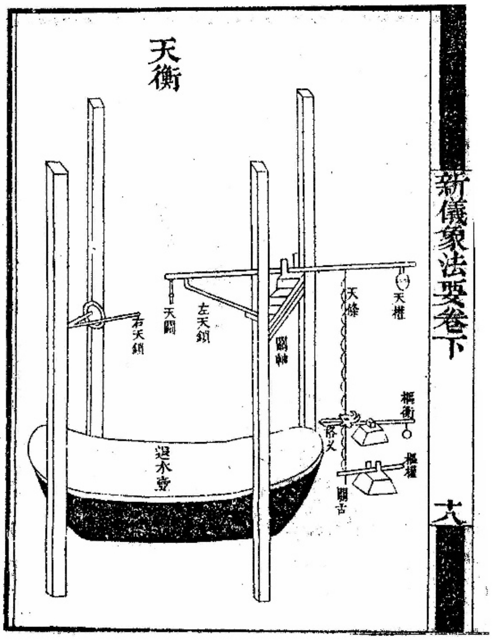

Fig. 7 Illustration of the celestial balance of the water-powered armillary sphere and celestial globe tower [28]

Mathematical Approach of the Law of Lever: Balance and Steelyard

In the preceding section, the historic existence of levers was discussed. This included to a certain extent the thoughts put into the designing, making and using of levers of ancient craftsmen. There were also discussions on trebuchet, which contained detailed quantitative information. Nevertheless, the available information did not provide solid proof as to whether the designer or the user of various kinds of lever acquired the basic theory of lever, namely the Law of Lever. In this section, the invention and structure of the Balance and steelyard are analysed to provide insight into the technology thinking of the Chinese and their use of the Law of Lever.

The Invention of Lever and Steelyard in China

If a fulcrum divides an object into two weight-unequal parts, the heavier part will descend. If a fulcrum divides an object into two parts that are equal in weight, the object will be in balance. These are the two states of a lever-shaped object. The former state is easier to determine, and it is clear that the invention of *Jiegao* was based on this knowledge. The latter can be deduced from the former. Based on the above experiential knowledge, the arm-equal balance was invented. With this device, man was able to compare the weight between two objects and even to weigh objects. As early as the Warring States Period (403 BC–221), Chinese knew how to construct and use an arm-equal balance, called *heng* (衡), to weigh an object.[8] Two special bronze beams of balance discovered in a tomb of the Chu State in Anhui province (about the 5th century BC) revealed important information. The beams contained well-proportional scales. One beam was 23.1 cm long[9] and the other slightly longer at 23.5 cm long. Both beams were divided into ten equal sections with each section further divided into two equal parts by a line [31].[10] Historians believed that these beams reflected a transitional form between an arm-equal balance and a steelyard [32]. Using such beams, one may either move the object to be weighed or the hung weight to a position so that the beam is in level. Then, one could calculate the weight of an object based on the proportional relation between the weight, the hung weight, and the length of the arms. The precise scale on the

[8] It was recorded in the book *Guanzi* ,that “Counterweights and balances are used to measure weight” [29]. In 1975 archaeologists discovered ring-shaped bronze counterweights in the Yutai tomb at Jiangling of Hubei province. The tomb was dated as the Warring States Period. Apart from this one, quite a few counterweights and balances were excavated from different sites [30].

[9] 23.1 cm is exactly the length of a standard one *chi* 尺 in China during the Warring States Period, when the beam was believed to be constructed.

[10] Both beams were preserved in the Museum of Chinese History.

beams revealed that the inventor had acquired knowledge equivalent to the Law of Lever.

The invention of arm-unequal balance, namely steelyard is of great significant in the evolution of mechanical knowledge. It necessary means that the inventor fully mastered the knowledge that the weight of object, the hung weight, and the distances from the points the object and hung weight tied to the fulcrum are in proportion.[11] That is a special case of the Law of Lever.

There were no evidence demonstrating the earliest existence of steelyard but the fact remained that it existed very earlier on. The majority of unearthed counterweights before the 25 AD were stamped with their weights, while those from during or after the Eastern Han Dynasty were mostly not stamped and their weights were also not of a regular ratio relation. This situation indicated that each independent counterweight was only applicable to the scale on a special beam. Some counterweights became moving weights of unequal-armed balances, namely the steelyard [30]. There were further evidence demonstrating the existence of steelyard during the Eastern Han Dynasty. For example, a hook and rotten wood bar unearthed from a tomb of the Eastern Han Dynasty were probably a steelyard hook and the beam of a steelyard. An illustration of a steelyard during the Eastern Han Dynasty was reprinted in a Japanese book (Fig. 8) [31]. The archaeological relics and writings evidenced that the steelyard became popular before 220 AD.[12]

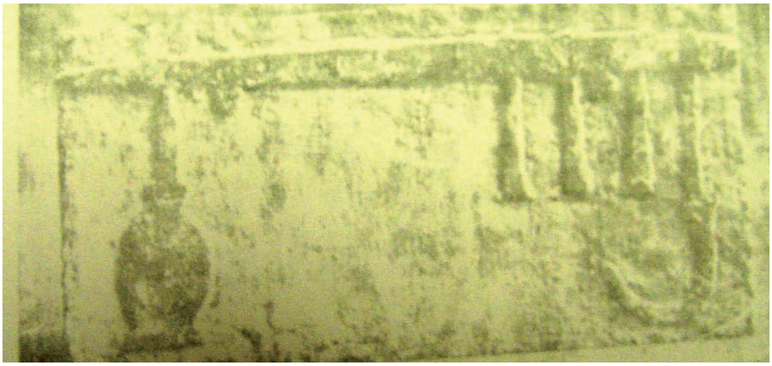

Fig. 8 Illustration of a steelyard of the eastern Han Dynasty [35]

[11] The making of a steelyard presented another problem, the position of the zero point of the scale. The Chinese must have solved this problem based on experien tial knowledge. Anthropological investigations revealed more information about the Chinese steelyard [33,34].

[12] In the Eastern Han Dynasty, Zheng Xuan (郑玄) of AD 127–200 annotated the book *Li Ji* (禮記), translated as The Book of Rites, and used the technical term *cheng* (稱), the steelyard. He mentioned "the upper part of the steelyard is named *heng*" and "*chengchui* (*chui* of steelyard) is named *quan*" (稱錘曰權). *Chengchui* was supposed to be the moving weight [36–38].

There were evidence demonstrating the Chinese applying the mechanical knowledge of steelyards in other devices, for example, in a water clock. The design of this water clock was based on two theories, the change in amount of water that flowed into or out a vessel that reflected the elapse of time and the other the weighing of water. This technology existed as early as the Southern and Northern Dynasties. During the Northern Wei period (386 AD–534), Taoist Li Lan (李蘭) described a steelyard-styled clepsydra in his book *Louke Fa* (漏刻法), translated as The Method of Clepsydra, that was cited by Xu Jian (徐堅) in his book *Chuxue Ji* (初學記) written in the Tang Dynasty:

> Store water in a vessel; make a siphon of copper, which has the shape as a hook. Use it to draw water from the vessel. [The water] was spitted from the mouth of a silver dragon into a vessel for weighing. When the volume of water is up to one *sheng*, and the weight is weighed as one *jin*, that means time elapses one *ke* [39][13] (Fig. 9).

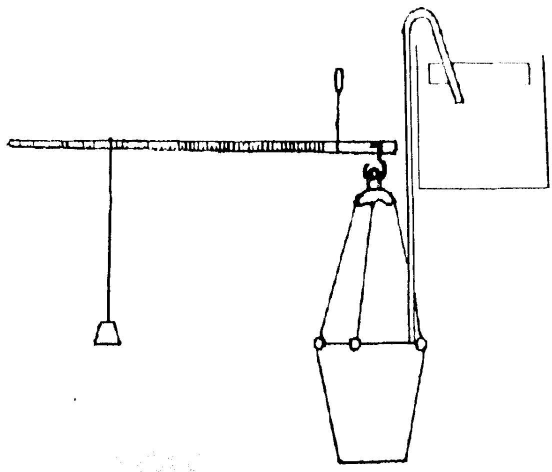

Fig. 9 Steelyard styled clepsydras, cited from [40]

Steelyard-styled clepsydras were also constructed during later dynasties. For example, in the early 7th century, the then emperor ordered the construction of a steelyard-styled clepsydra according to Li Lan's method [41]. Besides using steelyards in clepsydras, Chinese also used them in measuring the strength of bows and crossbows.

[13] *Sheng* was a unit of volume, *Jin* was a unit of weight, and *ke* was a unit of time.

Theoretical Study on Levers in China – As the Conclusion

In the above section, the presented evidences were mainly descriptive or material ones. Did Chinese make any effort in terms of theoretical approach on the knowledge of lever, and if they did, was this approach different from the one developed in the West? Several paragraphs in *Mozi* (the 5th century BC–the 4th century BC) provided important information on this issue. One of them is presented here to demonstrate the Chinese philosophy of the levers.

The Moist, one of the most influential philosophical schools, paid great attention to practical technology and the daily lives of common people. The function of levers attracted the attention of the Moist. They provided the following theoretical interpretation for the operation of the canon:

> [Canon] To pull (*Qie* 挈) and to let go (*shou* 收) are opposites which can be explained through *quan* 權 (positional advantage).
>
> [Explanation] Pulling (*qie* 挈) requires force (*li* 力); letting go (*yin* 引) does not require force. When not balanced, [a lever] that will be pulled up rests at an incline. Using a rope to pull is like using an awl to pierce. Pulling (*qie*): [From an initial condition when] the long or heavy side [of a lever] is below and the short or light side is above [as one pulls up the long and heavy side to balance the lever] the upper side gains tendency (quan) while the lower side loses tendency (quan). [When] the rope is perpendicular [to the lever], the amount of tendency (*quan*) [on both sides] is equal; then [the lever] is balanced. Letting go: the upper side [falls and] loses tendency (quan) while the lower side gains (quan). Once the upper side has exhausted its tendency of weight (quanzhong 權重) [the process] is finished [and the lever returns to its initial condition at an incline] [42].

The interpretation focussed on the tendency of motion of each part of a lever, and the way the force acted on it. It did not explicitly mention using a lever one can conserve force, nor the reason for the lever motion and its relation to force. Nevertheless, one may conclude that if one acts a force in accordance with the tendency of the motion of the lever, one may conserve force from the discussion about *quan,* the tendency.[14]

This theoretical approach is obviously different from the one in the *Mechanical problem* of Aristotelian tradition. In Aristotelian tradition, using devices such as a lever can conserve force, meaning one can suspend the relation between force and effect. This was regraded as unnatural and violented the Aristotelian orthodox theory of motion. Thus, this phenomenon had to be interpreted in theories in accordance with Aristotelian philosophy. However, in China, as well as Moist philosophy, there was not an orthodox theory about motion, the reason of motion or even nature. What happened in nature was commonly accepted as natural. As a result, Chinese did not find anything abnormal in the fact that by using a device one can conserve force, which was in fact the aim of Chinese practitioners from the very beginning.

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[14] From a study on the concept of force in China, see [43].

From the above discussion, it may be concluded that Chinese practitioners acquired basic knowledge concerning levers. They knew that by using levers, man may conserve force, and they used such knowledge to construct different kinds of devices. They had also accrued knowledge equivalent the Law of Lever. Noting the fact that the Chinese used the term *Jiegao* to name and interpret devices with lever as its main component, it is believed that they regarded lever as a basic device. This revealed the similar characteristic of using and making levers in Chinese and Western traditions. However, in relation to the theoretical approach to lever, Chinese and Greek philosophers obviously followed different paths.

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References

1. Emest AM, Marshall C (1960) The Medieval Science of Weights, Madison: University of Wisconsin Press.
2. Peter D, Juergen R, Mechanics and the Science of Motion, In publication.
3. Zhuang Z (War Period) Master Zhuang (Zhuangzi), Ming edition, reprinted by: Shanghai, Shangwu Yinshu guan, 1936. Chapter of Tiandi, Section 12.
   莊周 [戰國]，《莊子》，明刊本，上海商務印書館重印，1936，天地篇。
4. Zhuang Zhou, Master Zhuang. Chapter 5.
5. Liu X (Western Han Dynasty) Shuoyuan, Sikuquanshu edition. Chapter 20, 3
   劉向 [西漢]，《說苑》，文淵閣四庫全書本，卷 20，第 3 頁
6. Lu JY, Hua JM (2000) History of Technology in China, Volume of machines, Beijing, China, Kexue Chubanshe, p. 47.
   陸敬嚴，華覺明，《中國科學技術史》，機械卷，北京：科學出版社，第 47 頁，2000
7. Wang Z (1313) Book on Agriculture, Chapter 18.
   王禎[明代]，《農書》，卷 18，四庫全書本，1313。
8. Zheng XS (2003) An investigation on the influence of the book on agriculture of Mr. Zheng on the Wang Zhen's book on Agriculture, in Nongye Kaogu, Issue 1.
   曾雄生，王禎《農書》中的《曾氏農書》試探，農業考古，第 1 期，2003。
9. Zhang GW (1639) Completed work on the irrigation works in the middle of ZHengjiang province, Siku Quanshu edition, Chapter 24, 15.
   張國維[明代]，《吳中水利全書》，文淵閣四庫全書本，卷 24，第 15 頁，1639。

10. Wen Y (220) Commentary of Shiji, in Pei Yin, An collected commentaries of Shiji, Siku Quanshu edition, Chapter 77, 1b.
文穎[漢魏之際], 史記注, 引自, 裴駰[宋代]，《史記集解》，文淵閣四庫全書本，卷 77，第 1 頁。
11. Zhang Y (Three Kingdom Period) commentary of Shiji, in Pei Yin, An Collected commentaries of Shiji. Chapter 28, 12a.
張晏[曹魏], 史記注，見：裴駰[宋代]，《史記集解》，.文淵閣四庫全書本，卷 28，第 12 頁。
12. Dai T (Song Dynasty) Liushu Gu. Siku quanshu edition, Chapter 31. 24a.
戴桐 [宋代]，《六書故》，四庫全書本，卷 31，第 24 頁, 。
13. Liu FR (editor) (2008) The Art of Mounting Chinese Painting and Calligraphy, Taipei: National Palace Museum, p. 181.
劉芳如，主編，《書畫裝池之美》，臺北：國立故宮博物院，第 181 頁，2008
14. Lu BS, Zhang BC, Liu SZ (1996) Tong Ling's Mining Sweeps and Pulleys and Their Use during the Shang and Zhou Dynasties, China Historical Materials of Science and Technology, Vol. 17, No. 2, pp. 73–80.
盧本珊, 張柏春, 劉詩中. 銅嶺商周礦用桔槔與滑車及其使用方式. 中國科技史料, 1996 年（第 17 卷）第 2 期, 第 73–80 頁.
15. Zhang Y (Three Kingdom Period) Commentary. in: Ban Gu, Qian Hanshu, Siku quanshu edition. Chapter 70. 6b.
張晏[曹魏]，前漢書注，《前漢書》，四庫全書本，卷 70，第 6 頁。
16. Needham J, Robin DSY (1994) Science and Civilisation in China, Vol.5, Part VI, military technology: missiles and sieges, Cambridge University Press, Sydney, pp. 207–208.
17. Fang XL (Tang Dynasty) Jinshu, Siku quanshu edition, chapter 58, 14a.
房玄齡[唐代]，《晉書》，四庫全書本，卷 58，第 14 頁，648。
18. Li Q (Tang Dynasty) Taibai Yinjing (Dark Classic of Planet Venus), Sikuquanshu edition, Chapter 4, 1b–2a.
李荃[唐代]，《太白陰經》，四庫全書本，卷 4，第 1-2 頁，768？。
19. Lu JY (2000) Hua Jueming, Zhongguo Kexue Jishu shi, Volume of machines, Beijing, Kexue Chubanshe, p. 47.
20. Needham J, Robin DSY (1994) Science and Civilisation in China, Cambridge University Press, Vol. 6, p. 221.
21. Needham J, Robin DSY (1994) Science and Civilisation in China, Cambridge University Press, Vol. 6, p. 214.
22. Zeng GL, Ding D (North Song Dynasty) Wujing Zongyao (Classic of the Most Important Military Techniques), Chapter 12, pp. 37a–38a.
曾公亮[北宋]，丁度 [北宋]，武經總要，卷 12，第 37–38 頁。
23. Needham J, Robin DSY, Science and Civilisation in China, Cambridge University Press, Vol. 6. pp. 216–217.
24. Dai T, Liushu Gu. Siku quanshu edition, Chapter 5, 25a.
25. Zeng GL (North Song Dynasty) Wujing Zongyao, Siku quanshu edition, Chapter 20, 52a–53a.

26. Tian M, Zhang BC (2008) Technological and Mechanical knowledge contained in Dayu Zhishui tu, in Technology as Culture Heritage (Zhang Baichun, Jiang Zhenhuan, ed.), Jinan: Shandong Jiaoyu Chubanshe.
田淼，張柏春，大禹治水圖反映的技術與機械知識，《技術發展與文化遺產》（張柏春，姜振寰主編），濟南：山東教育出版社，2008。
27. Su S (North Song Dynasty) Xinyixiang fayao, Sikuyuanshu edition, Chapter 2.
蘇頌[北宋]撰，《新儀象法要》；新儀象法要，台灣商務印書館，台北，1969 年。
28. Needham J, Science and Civilisation in China. Vol.4, part II, mechanical engineering, Cambridge University Press, pp. 446–465.
29. Guan Z (War period) Guanzi, chapter 21, Siku Quanshu edition, 17a.
管仲 [戰國]，《管子》，四庫全書本，卷 21，第 17 頁。
30. Qiu GM (2005) Zhongguo Gudai Jiliang Shi Tujian, Hefei: Hefei Gongye Daxue Chuban She.
丘光明，《中國古代計量史圖鑒》，合肥：合肥工業大學出版社，2005。
31. Qiu GM (2005) Zhongguo Gudai Jiliang Shi Tujian, Hefei: Hefei Gongye Daxue Chuban She, p. 32.
32. Qiu GM (2005) Zhongguo gudai Jiliang Shi Tujian, Hefei: Hefei Gongye Daxue Chuban She, p. 30.
33. Renn & Schemmel (2000) Preprint 136: Waagen und Wissen in China, Bericht einer Forschungsreise, Berlin: Max-Planck-Institut fuer Wissenschaftsgeschichte.
34. Qiu GM (1993) Zhong-Guo Du-liang-heng (Length, Capacity and Weight in Ancient China), Beijing, China, p. 85.
丘光明，《中國度量衡》，北京，第 85 頁，1993。
35. Qiu GM, Qiu L, Yang P (2001) Zhongguo kexue Jishu Shi (History of science and technology in China), the Volume of Weights and Measures, Beijing: Kexue chubanshe, p. 257.
丘光明，丘龍，楊平，《中國科學技術史》，度量衡卷，北京：科學出版社，第 257 頁，2001。
36. Zheng X (Han Dynasty) annotated. Liji Zhushu,Siku Quanshu edition. Chapter 15. 7 a-b.
鄭玄 [汉代]注，《禮記注疏》，四庫全書本，卷 15，第 7 頁。
37. Renn & Schemmel (2000) Preprint 136: Waagen und Wissen in China, Bericht einer Forschungsreise, Berlin: Max-Planck-Institut fuer Wissenschaftsgeschichte.
38. Qiu GM, Qiu L, Yang P (2001) Zhongguo kexue jishu shi. Duliangheng. Beijing: kexue Chubanshe, p. 257.
39. Xu J (Tang Danasty) Chuxue Ji, Siku quanshu edition, Chapter 25, P. 2, 728.
徐堅[唐代]，《初學記》，四庫全書本，卷 25，第 2 頁，728。

40. Hua TX (2004) Chenglou de Jiegou Jiqi Wenlin Yuanli, Ziran Kexue shi Yanjiu, Vol. 23, Issue 1. 16–24.
華同旭，稱漏的結構及其原理， 自然科學史研究，卷 23。 第 1 期，第 16–24 頁，2004。
41. Wei Z (Tang Dynasty) History of the Sui Dynasty (Suishu), Suishu, Siku Quanshu edition, Chapter 19. 36.
魏征 [唐代]，隋書，四庫全書本，卷 19，第 36 頁，656。
42. Mo D (War Period) Moist Canon, Dao Zang edition. Chpater 10, P. 4a.
墨翟 [戰國]，《墨子》，道藏本，卷 10，第 4 頁。
43. Zou DH (2005) The concept of Force in Early China, Transformation and Transmission: Chinese Mechanical Knowledge and the Jesuit Intervention, pp. 11–36. (Zhang Baichun, Juergen Renn ed., Berlin: Max-Planck-Institut Fuer Wissenschaftsgeschichte. Preprint 313)

Phases in the Unraveling of the Secrets of the Gear System of the Antikythera Mechanism

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Abstract In November 2006 Tony Freeth et al. published a new reconstruction of the gear system of the Antikythera mechanism in the journal *Nature*. Important earlier reconstructions had been published by Derek de Solla Price in 1974 and Michael Wright in 2005. In this paper I will discuss the three reconstructions. Price did important work, but his reconstruction turned out to be seriously flawed, as Wright has shown in considerable detail. Wright's work was a great advance on De Solla Price's and resulted in a largely correct reconstruction of the topography of the wheelwork. He had identified a pin and slot mechanism that could model the anomaly of the Moon and he had discovered that the back dials consisted of spirals. Wright had got hold of most of the pieces of the puzzle, but some of the pieces didn't fall into place. Freeth *et al.* gave the final solution. In the National Archeological Museum in Athens they discovered the so-called Fragment F of the mechanism. It yielded data that led to the discovery of the way in which the central wheelwork of the mechanism had functioned. I will argue that, while Wright was close to the solution, the 2006 paper in *Nature* represents a great step forward that was not taken easily. The creation of a team of 17 experts, engaging support from high-tech companies, can be considered an important change in research methodology. Wright worked alone; in Freeth's team different kinds of expertise are represented by different individuals. The new approach has been very fertile: in July 2008 a second paper by Freeth and three others appeared in *Nature*.

Keywords History of gearing, History of planetaria, Antikythera mechanism

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Introduction

Shortly before Easter of 1900 a party of Greek sponge fishers from the island of Syme near Rhodes returned from their normal fishing grounds near Tunisia. In the channels between the islands of Kythera and Crete they were driven off course by a gale and found shelter close to Kythera, near the barren island of Antikythera. After the storms had subsided the divers explored the shallow rock shelves below them on which they had dropped their anchor. At a depth of 42 meters they found a 50 m long ship wreck containing a plainly visible pile of bronze and marble statues.

In November 1900 a difficult salvage operation started that lasted until the end of September 1901. Eight months after the end of the salvage operation, Spyridon Staïs, a prominent Greek archaeologist, discovered an inscription on one of the pieces of corroded bronze from the wreck in the National Museum in Athens. Traces of gear-wheels were clearly visible as well. The pieces turned out to be parts of a complicated mechanism. It is remarkable that this wasn't discovered earlier. Some uninteresting looking lumps may have only revealed their significance in the museum after they had cracked.

This was the beginning of an exciting story. The mechanism had obviously been a complicated astronomical instrument, a kind of astrolabe or a planetarium. However, what was it exactly? It took a long time before the first satisfactory answers could be given. With the completion of the reconstruction by Freeth et al. published in 2006 in *Nature*, research on the mechanism has entered a new phase [7]. As a result we now basically know how the mechanism works. It is highly improbable that future research will lead to more than minor modifications in the reconstruction of the gearing system. On the other hand, further investigation of the inscriptions may still yield surprising results, as the publication of [8] in 2008 proves.

The publication in *Nature* in 2006 was the climax in an exciting development that I will describe below. Three phases can be distinguished. Phase 1 culminated in Price's reconstruction in 1974 [12]. Phase 2 culminated in the publication of Wright's reconstruction in the years 2003 through 2005 [18–22]. Phase 3 culminated in the publication by Freeth et al. in 2006 [7].

Price's Reconstruction

Although scholarly interest was immediately considerable, it was only in the 1950s, with the involvement of Derek de Solla Price (Yale), that the Antikythera mechanism began to draw public attention. In particular the article published by Price in June 1959 in *Scientific American* under the title "An Ancient Greek Computer" had a considerable impact. Yet Price's *Scientific American* article raised more questions than it provided answers.

In 1971 there was a breakthrough. Price engaged the help of the Greek Atomic Energy Commission. The radiographer Charalambos Karakalos undertook the cumbersome work of preparing gamma-radiographs and fine x-radiographs. The radiographs were inspected visually. Karakalos and his wife Emily made counts of gear teeth. In 1974 Price published a definitive account of the results that had been achieved [12].

The fragments fitted together in such a way that Price assumed that the original mechanism had been in a rectangular box with a dial on the front of the mechanism in the middle of the rectangular front surface and two dials on the back of the mechanism. The two back dials each had a subsidiary dial. There were plates over the dials and Price conjectured that they were joined as doors (See Fig. 1).

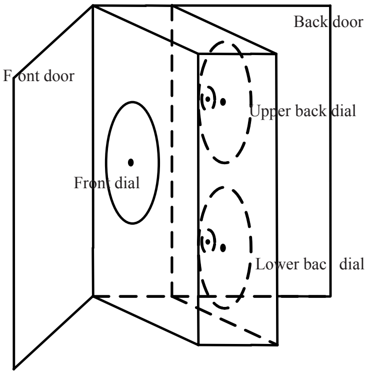

Fig. 1 Rough sketch of the case of the Antikythera mechanism with front and back doors open. The two back dials each had a subsidiary dial

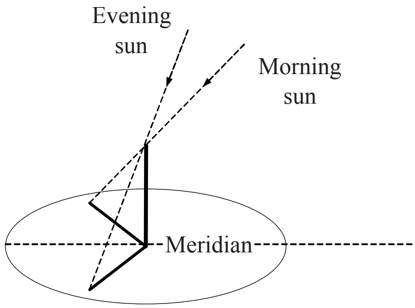

Fig. 2 A gnomon

The mechanism was driven by means of a drive axle. Price gave a reconstruction of the gearing system. He identified the mechanism as a calendrical Sun and Moon computing system ca. 80 BCE. The date and the position of the Sun and the Moon in the Zodiac could be read off the front dial plate. A remarkable part of Price's reconstruction is a differential gear system with a large differential turntable in the centre. This was an amazing result because differential gears are conceptually sophisticated and their occurrence in antiquity was a complete surprise. Below we will look at the details. First, however, we must turn our attention to Greek astronomy.

Greek Astronomy 1: Counting Days, Months and Years, the Metonic and Calippic Calendars

The behaviour of the celestial bodies is in many ways cyclical: the same phenomena repeat themselves with a certain period. Counting days is easy. Measuring the number of days in a month, for example a synodic month (also called a lunation: from Full Moon to Full Moon or from New Moon to New Moon) is less easy. Measuring the number of days in a year is difficult as well, although a simple instrument can help. According to Herodotus the Babylonians taught the Greeks the use of the gnomon (see Fig. 2). The gnomon is merely a pole erected vertically on a horizontal plane. Its use is simple: on a sunny day one registers the behavior of the shadow of the pole.

By means of a gnomon the North-South direction can be found easily. One determines the direction of the shadow in the morning and in the afternoon at moments when the two shadows are equally long: The bisector of the two directions gives the direction of the meridian. The moment at which the shadow coincides with the meridian corresponds with the highest position of the Sun on that particular day. However, much more can be done with this simple instrument if we register the shadow corresponding to the highest position of the Sun in the course of the year (see Fig. 3). This provides a way to measure the tropical year.

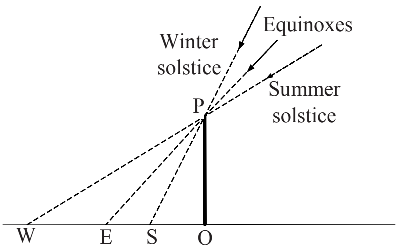

Fig. 3 PE is the bisector of the angle WPS

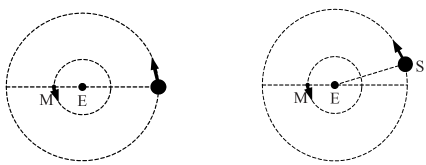

Fig. 4 Sun and Moon in opposition (*left*). One sidereal month later (*right*): the moon has completed a revolution about the earth. However, in the mean time the Sun has moved on: opposition is only reached after two more days, after a synodic month

By means of the gnomon it is possible to establish the dates of the summer solstice (the longest day), the winter solstice (the shortest day) and the two equinoxes (day and night are equally long). Ancient astronomers were looking for ways to relate the length of a year and the length of a month. However, a synodic month is not equal to an integral number of days. And a tropical year is not equal either to an integral number of days, nor to an integral number of synodic months. The precise relation between these periods of time was a problem.

When one considers the motion of the Sun and the Moon not with respect to the earth but against the backdrop of the stars yet again other periodicities show up. Clearly the Sun participates in the rotation from east to west of the fixed stars: one full rotation takes exactly one day. However, the Sun also moves from west to east with respect to the fixed stars; this seems to be a circular motion whereby the Sun moves through twelve constellations of stars. The lengths of the seasons determined by the Greek astronomers, however, make it clear that this latter motion is only approximately a uniform circular motion. The Greeks called the belt of twelve constellations of stars through which the Sun moves the Zodiac. For the Greeks, who introduced geometrical modeling in astronomy, the Zodiac corresponded to a big circle on the sphere of the fixed stars.

There are other heavenly bodies moving against the background of the fixed stars: the Moon and the planets; they all seem to be moving from west to east. The actual period of the Moon's orbit as measured with respect to the Zodiac, is known as a *sidereal* month. Figure 4 illustrates that a sidereal month differs from a synodic month. It takes the Moon extra time after completing a sidereal month to catch up and return to the same position with respect to the Sun and complete a *synodic* month.

Hipparchus discovered that the length of the year determined by the four seasons, the tropical year, differs slightly from the sidereal year, determined by the position of the Sun against the backdrop of the stars. This is his famous discovery of the precession of the equinoxes. It is so called because over of the years the position of the equinoxes changes very slowly relative to the stars. Hipparchus introduced an important change in the description of the heavens: he separated the Zodiac from the stars, coupled the Zodiac to the tropical year and as a result of this he had to accept the fact that the Zodiac slowly moves with respect to the stars. This implies that we must, strictly speaking, distinguish the tropical year from the sidereal year and the tropical month from the sidereal month. Below we will not do this because the precession of the equinoxes is extremely slow (one rotation in about 25,770 years).

In the 5th century BCE the famous Athenian astronomer Meton defined the cycle that was afterwards called the *Metonic cycle* in which 19 tropical years are made to correspond with 235 synodic months (or 254 sidereal months). In the cycle the 235 synodic months (or 254 sidereal months) represent 6940 days. The basic idea is that 19 is the smallest number of tropical years that is close to an integral number of both synodic and sidereal months. The cycle implicitly gives the Metonic length of the year: 6940 divided by 19 is 365 5/19 days. To keep a 12-month lunar year in pace with the tropical year, a 13th month must be added seven times during the nineteen-year period.

Yet the 6,940 days of the Metonic cycle of 19 years happen to exceed 235 lunations by almost a third of a day. A century later Callippus, an associate of Aristotle, multiplied the 19-year cycle by 4 and then dropped 1 day from the last 19-year cycle. Thus he constructed a cycle of 76 years that contains 940 lunations and 27,759 days. It has been called the *Callippic* cycle after him. It leads to a year of exactly 365 ¼ days, which is as we know more accurate than the Metonic length of the year. The Calippic calendar was used for astronomical dating by many of the Hellenistic astronomers. Hipparchus used it and so did Ptolemy.

Mechanical Modeling of Astronomical Phenomena

In 1983 the Science Museum in London acquired four fragments of a Byzantine portable sundial with a geared calendar dating from between the fourth and the seventh century CE. This was a spectacular find because it showed that between the Antikythera mechanism and al-Biruni's *Book on the Full Comprehensiveness of the Possible Methods for Constructing the Astrolabe* from about 1000 CE geared planetaria or calendars had been built. The mechanism is discussed in detail in [4]. The gearing of the Byzantine sundial calendar resembled that of a calendrical device described by al-Biruni in his book. Gearing similar to that described by al-Biruni is found in a Persian astrolabe dating from 1221/2 that is now in the Museum of Science in Oxford (Inventory number CCA 5). The earliest Latin example of gearing that served the same purpose occurs in an astrolabe from about 1300 CE, now in the Science Museum in London (Inventory number 1880-32). It seems probable that the Antikythera mechanism is part of a tradition of making representations of the motions of the heavenly bodies by means of gear trains. This tradition started in antiquity and continued in the Byzantine Empire and in Islamic culture.

The existence of this tradition in Antiquity is confirmed by a few other sources. I will give one example. Cicero spent two years on Rhodes from 79 to 77 BCE with the stoic philosopher Posidonios of Apamea. In Cicero's *De natura deorum* II, he discusses the views of thinkers who doubt that the universe is guided by reason. The text says (Rackham's translation quoted by Price [12] p. 57):

> Suppose a traveler to carry into Scythia or Britain the orrery recently constructed by our friend Posidonius, which at each revolution reproduces the same motions of the Sun, the Moon and the five planets that take place in the heavens every day and night, would any single native doubt that this orrery was the work of a rational being? These thinkers however raise doubts about the world itself from which all things arise and have their being, and debate whether it is the product of chance or necessity of some sort, or of divine reason or intelligence; they think more highly of the achievement of Archimedes in making a model of the revolutions of the firmament, than of that of nature in creating them, although the perfection of the original shows a craftsmanship many times as great as does the counterfeit. (*De natura deorum* II,88)

This quotation shows that in Antiquity planetaria existed. As an illustration I will describe the gear trains of an instrument described by al-Biruni which displays the Age of the Moon and the positions of the Moon and the Sun in the Zodiac in three separate displays (see Fig. 5). An axle driven by hand is rotated once a week. It carries two pinions, A1 with 7 and A2 with 10 teeth. The wheel with 10 teeth drives a wheel B1 with 40 teeth giving the position of the Moon in the Zodiac. The wheel A1 with 7 teeth drives a wheel C1 with 59 teeth. On the axle of C1 there is C2 which drives a wheel D1 with 24 teeth. On the axle of D1 there is D2 with 24 teeth which drives E1 with 48 teeth representing the position of the sun in the Zodiac.

Clearly, one rotation of the input axle represents a week of 7 days. 4 weeks correspond to one rotation of the B-axle representing a month of 28 days. The wheel with 59 teeth on the C-axle turns once in 59 days. It represents the Age of the Moon, which is important in the Islamic calendar. The Islamic calendar is based on a lunar year of 12 months in which months with a length of 30 and 29 days alternate. The Age of the Moon, measured from the time of the New Moon, tells us where we are in this cyclical process which has a two-month period of 59 days.

The wheel with 48 teeth on the E-axle turns once in (48/24).(59/19).(59/7) = 52.35 weeks = 366.42 days. As a matter of interest, al-Biruni elsewhere, in his *Astrology*, gives 365.24 days for the length of the year (Cf. [4]).

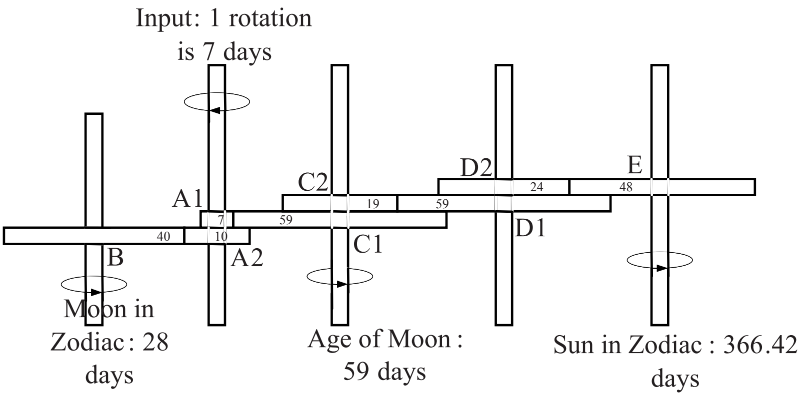

Fig. 5 Gear system of al-Biruni's calendrical device (based on [4], Fig. 12)

As we shall see, this idea of modeling cyclical astronomical phenomena by means of gear-wheels goes back to antiquity. The gear system of the Antikythera mechanism is similar but much more sophisticated.

Price's Reconstruction: General Remarks

Before turning to the gear system of the Antikythera mechanism I will summarize aspects of Price's reconstruction. The front dial plate contains two annuli. The inner annulus is immovably fixed in position. It undoubtedly carried in 30º intervals the Greek names of the signs of the zodiac proceeding clockwise. The word ΧΗΛΑΙ (chelai, the claws of the scorpion), the name of the sign nowadays called Libra, is clearly visible in one of the intervals. The movable outer annulus must have carried the 12 names of the 12 months in the Graeco-Egyptian year. The name of the 9th month ΠΑΧΩΝ = pachon is still visible. This year consisted of 12 periods of 30 days followed by a period of 5 days without adjustment for leap years. Because the tropical year is slightly longer, it is understandable that the outer annulus was made movable. The modern calendar corrects the asynchronicity of the 365 calendars years and the 365 ¼ tropical years by means of a leap year every four years. In the Antikythera mechanism the outer annulus had to be moved once every four years over 1/365 of a turn in an anti-clockwise direction.

The fragments show that on the back of the rectangular mechanism there was a plate with two dials. Each of the two back dials consists of a central plate with a 44.3 mm radius surrounded by a series of annuli. Price clearly discerned four annuli in the upper back dial (held together by a bridge) and three (held together by a bridge) in the lower dial. In the upper dial Price saw something that looked like a dial pointer, which was 55 mm long (and may have been longer originally). The lower back dial has a fixed and inscribed outer limb. Price thought that it was unlikely that there was a fourth annulus in the lower dial because of the presence of the outer limb. He could not tell whether the upper dial had an outer limb as well.

Price had considerable difficulties with the inscriptions. The upper back dial is heavily inscribed but Price could not read the inscriptions on it. The lower back dial had comparatively few inscriptions. Only a small piece of the back door is extant. Yet, because of the mirror inscription as a result of the huge pressure that the mechanism experienced for centuries, part of the inscription on the lower half of the back door was somewhat legible. See [12], p. 50. The Metonic and the Callipic cycles are mentioned. The front door inscription was not sufficiently legible.

Then there are *parapegma* inscriptions. A parapegma is a list of dates – with holes for placing a marker pin – of seasonally regular weather changes, first and last appearances of stars or constellations of stars at sunrise or sunset. They were composed for centuries in antiquity.

In Price's reconstruction the front dial showed the *mean* position of the Moon and the Sun with respect to the Zodiac. If the movable calendar annulus was given the right position, the future tropical mean positions of the Moon and the Sun could be calculated.

On the basis of his reconstruction of the gear system Price came to the conclusion that the lower back dial counted the synodic months and the lunar years.

Price rejected the possibility that the upper back dial could have displayed the period of the planets or the 223-month eclipse cycle which is referred to on one of the instrument door panels ([12], p. 44). In his rejection of the possibility that the dial displayed the eclipse cycle he was wrong, as will become apparent in the relevant section in the part on the reconstruction by Freeth *et al*. The tooth count led Price to conclude that the main part of the upper back dial corresponded to one revolution approximately every four tropical years. He did not succeed in drawing further firm conclusions.

Price's Reconstruction: The Gearing System: The Gear Trains Driving The Sun and Moon Position Wheels

Price gave the reconstruction of the gear trains shown in Fig. 6. Price assumed that the crown wheel with which the mechanism was driven had 45 teeth and that the main drive wheel B1, driven by the crown wheel, had 225 teeth. These numbers do not have any astronomical significance. On the shaft connected to the main drive wheel B1 there is wheel B2 (with 64 teeth), which drives C1 (with 38 teeth) which has on its axle C2 (with 48 teeth), which drives D1 (with 24 teeth), which has on its axle D2 (with 127 teeth), which drives B4 (with 32 teeth). B4 is on a shaft inside the axle carrying B1 and B2.

Consider one revolution of the main drive wheel. This produces n revolutions of the inner shaft with n = (64/38).(48.24).(127/32) = 254/19. So 19 revolutions of the main drive wheel lead to 254 revolutions of the inner shaft.

In the Metonic cycle 19 tropical years (consisting of 6,940 days) correspond to 254 sidereal revolutions of the Moon (of about 27 ⅓ days). Thus a "Sun position wheel" of the same size as the drive wheel, rotating, however, in the opposite direction, and a "Moon position wheel" connected to the inner shaft would represent the tropical years and sidereal months of the Metonic cycle. The two position wheels would represent the positions of the Moon and the Sun with respect to the Earth.

Price's Reconstruction: The Gear Trains Connecting to the Lower Back Dial

The fragments show that there were two dials on the back of the rectangular mechanism. In Price's reconstruction the upper back dial corresponded to the gear train at the bottom left of Fig. 6 (axles M, N and O), and the lower back dial corresponded to the gear train at the bottom right of Fig. 6 (axles F, G, H and I). Let us look at the bottom right gear trains.

A *sidereal* month has a duration of about 27 ⅓ days. The *synodic* month, the period based on the appearance of the Moon from the earth, has a duration of about 29 ½ days. The rotating inner shaft carrying B4 corresponds to the sidereal month. An axle corresponding to the synodic months needs to make 235 revolutions during the 19 tropical years of the Metonic cycle. In Price's reconstruction the bottom right part in Fig. 5 yields an axle that makes 235 revolutions. Price assumes that in the Antikythera mechanism the 235 was obtained by subtracting 19 from 254 by means of a differential gear. The possibility that the clearly visible large central gear-wheel had been a differential turntable was already mentioned in Price's 1959 paper in *Scientific American*. In 1974 Price provided the details. He proposed that the differential system was connected to the lower back dial where full rotations of the two pointers would correspond to a synodic month and a lunar year (of 12 synodic months).

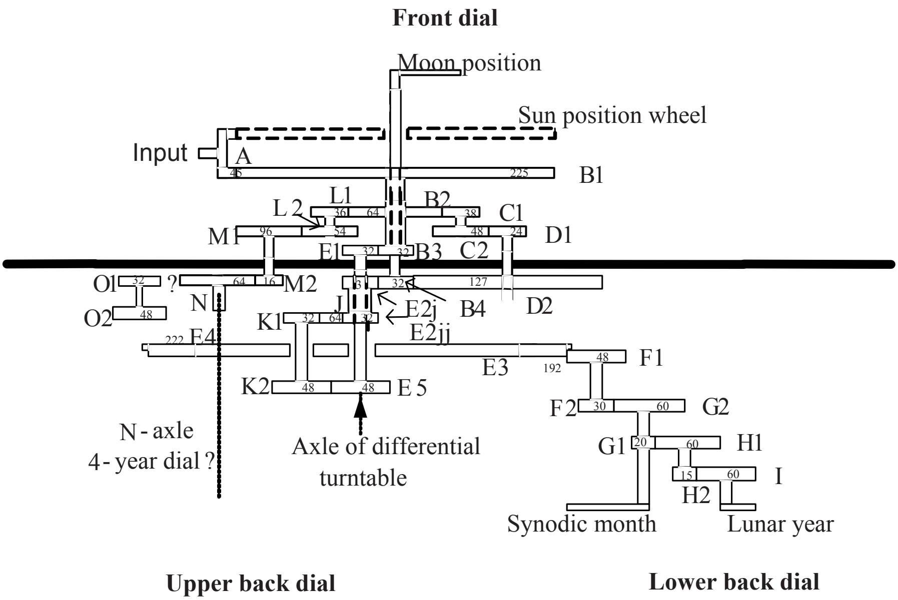

Fig. 6 Price's reconstruction of the gear system ([12], p. 43)

Price's Reconstruction: The Differential Gear

Consider Fig. 8. A straight bar W_1 can rotate about a centre O. A wheel W_2 can rotate about O and W_2 drives another wheel W_3 that can rotate about a centre on the bar W_1. System W_0 is the system of reference at rest, the World. The radius of the wheels W_i is equal to r_i.

We use the following notation. The angular velocity of system W_i with respect to System W_j is ω_{ij}. The anticlockwise direction is positive. Consider the point where the wheels W_2 and W_3 touch. It is a point of W_2 and as such its velocity with respect to the World W_0 is

$$r_2.\omega_{20}.$$

It is a point of W_3 as well and as such its velocity with respect to the World W_0 is

$$r_2.\omega_{10} - r_3.\omega_{31}.$$

Because W_2 drives W_3 without slipping these two velocities are equal. This yields an important equation:

$$\omega_{31} = (r_2/ r_3) . (\omega_{10} - \omega_{20}) \text{ or } \omega_{10} = (r_3/ r_2)\omega_{31} + \omega_{20} \qquad (1)$$

The effect of the rotation ω_{10} is that from the point of view of the rotating bar W_1 it merely slows down the rotation of the driving wheel W_2. This means that if, instead of the short train $W_2 - W_3$, we consider the train $W_2 - W_3 - W_4 - \ldots - W_n$ of wheels, we get the formula

$$\omega_{n1} = (-1)^{n+1} . (r_2/ r_n) . (\omega_{10} - \omega_{20}) \text{ or } \omega_{10} = (-1)^{n+1} (r_n/ r_2)\omega_{n1} + \omega_{20}. \qquad (2)$$

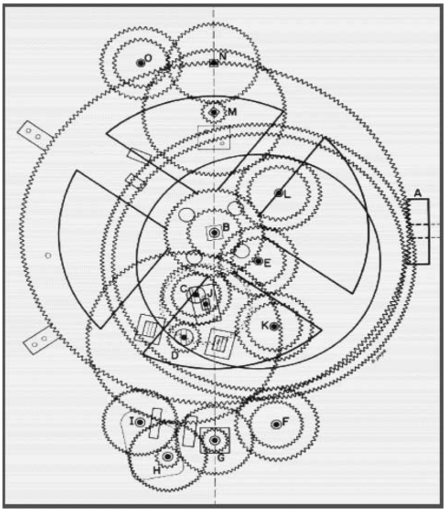

Fig. 7 Top view of the wheelwork in Price's reconstruction ([12], p. 37)

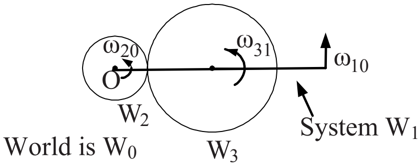

Fig. 8 Rotating gear chain

Now consider Price's gear trains. Suppose the inner B-shaft makes 254 revolutions per unit of time. Then the wheel B4 makes 254 revolutions per unit of time, which means that the wheels E2j and E2jj make 254 revolutions as well. In the same unit of time E1 and E5 driven by B3 make 19 revolutions.

We now consider gear trains E2jj, J and K1, on the one hand, and E5 and K2, on the other hand. Their inputs are, respectively, +254 and –19 revolutions per unit of time. Nota bene: the opposite signs are important! The output wheels K1 and K2, are fixed to and rotate about the same axle K. If the two gear chains would not rotate about the common axle of the input wheels, this would be impossible. However, they are allowed to rotate and in fact drive the differential turntable E4/E3. E4 is a disc, E3 is smaller annulus fixed to the turntable. Suppose its angular velocity is ω_{table}. Applying the formula (2) for a rotating gear chain twice, we get:

$$\omega_{table} = -\omega_K + 254 \qquad \text{and} \qquad \omega_{table} = \omega_K - 19$$

So $\omega_{table} = (254-19)/2 = 235/2$. This means that the G axle makes $(192/48).(30/60).(235/2) = 235$ revolutions per unit of time.

Bromley and Wright Refute Price

In the first half of the 1980s Michael Wright developed serious doubts about Price's reconstruction which he shared with Alan Bromley ([1,2], p. 26). They obtained permission from the National Museum in Athens and Wright had build a tomograph at home which they used on several visits between January 1991 and April 1994 with an X-ray tube in the National Museum in Athens to make some 700 images of the fragments. Bromley took the data with him to Australia and fell ill. Bromley died in 2002. The plan was that Bromley would have the radiographic plates scanned and digitized but he never achieved this. At the end of 2000 Wright succeeded in retrieving most of the material. Until autumn 2003 he analyzed the plates by peering at them through a magnifier. Only in 2003 he succeeded in having the plates scanned.

Bromley and Wright first of all showed beyond reasonable doubt that Price's reconstruction of the gear system was seriously flawed. In particular the spectacular differential gear was never there. Its existence could even be refuted on the basis of Karakalos's radiographs. It became clear that Price had been carried away by the assumption of the existence of a differential gear. It explained the existence of the large turntable and it enabled him to make sense of the lower back dial, but careful consideration revealed serious problems related to Price's assumption that the big central gear-wheel had been a differential turntable. Price thought that he needed the differential gear in order to get a wheel that makes 235 rotations while the outer axle B and the inner axle B, respectively, make 19 and 254 rotations. The differential gear does this by subtracting 19 from 254. Bromley and Wright showed that there are much easier ways to solve this particular problem by using plain fixed axle gear without using wheels of extraordinary size ([18], p. 273). For example, if we put a wheel D3 with 20 teeth on axle D engaging a wheel Y1 with 32 teeth on an a new axle Y, a wheel on Y2 with 94 teeth engaging a wheel Z1 with 16 teeth on an axle Z, this axle Z gives us the synodic months, as B2-C1+C2-D1+D3-Y1+Y2-Z1 gives the ratio (64/38).(48/24).(20/32).(94/16) = 235/19.

Bromley and Wright took this argument even further. A display of the synodic month could have been added to the front dial without any extra wheels. In other words, in Price's reconstruction a highly complicated mechanism plus an extra dial are used to do something that can actually be done quite simply. There is more, however. In Price's reconstruction the system is driven from the slow-moving end of the train. This means that relatively high loads develop in the chain. This point was already made in the 1980s by Wright (cf. [1], p. 26) and by Zeeman [23]. Those who built models of Price's reconstruction, even though they used modern wheelwork, experienced problems as a result. They found it hard to make their models work. G. White even claimed that Price's reconstruction could not have worked at all [14,15]. In his paper White proposes changes in Price's reconstruction that leave its basic structure intact.

Clearly Price's reconstruction was in serious trouble. The tomograms supplied the final and most convincing argument against Price's reconstruction. A detailed description of the argument is to be found in ([18], pp. 275–277). Consider the wheels K2 and E5 in Fig. 6. Karakalos noticed the double thickness of both wheels. He saw K2 definitely as a double wheel and he counted more teeth on E5 (50–52) than on K2 (48 or 51). Price chose to overrule Karakalos' observations ([12], p. 34) because "the apparent purpose is simply to provide a 1/1 gear ratio". Distortion and corrosion, said Price, hide the fact that there are two gear-wheels of equal size, each with 48 teeth. Wright had another good look and saw double wheels.

Sometimes Price had to alter Karakalos's results drastically in order to make them fit. Karakalos counted 54 or 55 teeth on gear-wheel G2, but Price needed 60 to make the mechanism fit his interpretation. So 60 it became ([12], p. 35). Similarly in the case of wheel F1. Karakalos had counted 54 teeth, but Price needed 48 teeth, and so it became 48. Of course, when the numbers teeth of each gear-wheel are counted on the basis of radiographs of fragments, there are various potential sources of error. Yet Wright convincingly argues that Price definitely allowed himself too much latitude ([18], pp. 278–279). Price seems not to have counted the teeth himself but to have taken the figures offered by Karakalos and altered them to suit his model. Moreover, the axles E, B and D lie in a triangular pattern. The tomographic plates do not show E2j, B4 and D2 engaged as Price suggested. The images show that D2 is engaged directly with a wheel on axle E and another wheel on E engages B4. The two wheels on axle E both seemed to have 32 teeth ([17] p. 83). With good reason Price himself had called the differential gear the most spectacular part of his reconstruction ([12], p. 44). Unfortunately that part was wrong. Bromley and Wright had to abandon the central element of Price's reconstruction, the differential gear. In the end Wright came up with a new reconstruction.

Competition

Only at the end of 2003, twenty years after he developed his first doubts about Price's reconstruction, Wright had the tomograms that had been made in 1994 scanned and he had the software for viewing and inspecting them. Things had been moving very slowly indeed. At the same time others had become interested in the secrets of the gear system of the Antikythera mechanism. In 2000 Mike Edmunds and Philip Morgan wrote a paper in which they discussed speculative planetary mechanisms that could have been part of the wheelwork of the Antikythera mechanism [3]. In 2002 Tony Freeth, mathematician and documentary film maker in London, published two papers on the mechanism [4,5]. In his papers Freeth severely criticized Price's reconstruction and he advocated a novel approach to the questions involving the engaging the most sophisticated recent technology. These early papers do not contain new answers to the questions. At the time Michael Wright was still undoubtedly the number one expert on the Antikythera mechanism in the world. However, change was in the air. As we shall see below, Edmunds and Freeth maintained their interest in the mechanism. Before we can discuss the ensuing developments we need to have another look at Greek astronomy.

Greek Astronomy 2: Eclipses and the Saros Cycle

The Babylonians had a great interest in eclipses. They recorded them and they studied them. They knew, for example, that in order to have a lunar eclipse a Full Moon is needed and that for a solar eclipse a New Moon is needed. Some time before 575 BCE they discovered that the pattern of lunar eclipses repeated itself after 223 synodic months. This means that if there are records of the eclipses that occurred in a past cycle, we can predict eclipses. Because solar eclipses are only visible locally the precise prediction of solar eclipses is difficult. The Babylonians realized that the cycle yielded potential solar eclipses, but no certainty of solar eclipses. This period of 223 synodic months is now called the *Saros cycle*. The ancient astronomers called it the *Periodic* ([13], p. 175) The name *Saros* was coined by Sir Edmund Halley. It has no significance related to Antiquity. The Saros cycle corresponds to 6585 1/3 days. In order to obtain a period with an integral number of days astronomers before Hipparchus tripled the *Periodic* and obtained a period of 19756 days which they called *Exeligmos*.

The Greeks used the astronomical data of the Babylonians and they adopted their approach, but they added the element of geometrical modeling, which greatly advanced the understanding of the phenomena. They realized that the Moon, the Sun and the Earth could be considered as large spherical bodies. In addition they realized that, for an eclipse to occur, the Sun, the Moon and the Earth must be collinear. A lunar eclipse will only occur at Full Moon: the Sun and the Moon must be in *opposition*. A solar eclipse will only occur at New Moon: the Sun and the Moon must be on the same side of the Earth; they must be in *conjunction*. However, a situation of *syzygy* (opposition or conjunction) is not enough for the centers of the three bodies to be collinear. This is because the plane in which the Moon rotates does not coincide with the plane of the Sun (see Fig. 9). The angle between the two planes is approximately 5 degrees. The points of intersection of the orbit of the Moon with the ecliptic are called nodes. An eclipse can only occur when the Moon is in or close to a node. Actually the fact that the ecliptic and the orbital plane of the Moon do not coincide is clearly visible in the sky. An observer who watches the Moon and the Sun in the course of time will notice that once every synodic month the Moon seems to overtake the Sun (see Fig. 4). This usually happens either above the Sun or below the Sun.

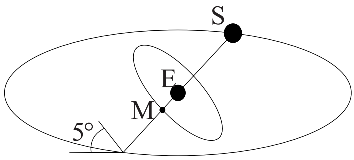

Fig. 9 A lunar eclipse occurs when the Moon and the Sun are in opposition and the Moon is in or sufficiently close to the plane of rotation of the Sun

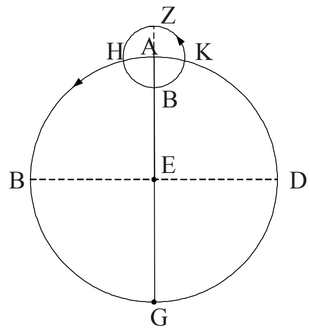

Fig. 10 Hipparchus' epicycle model

In addition to the Sun and the Moon being in opposition or conjunction and the Moon being in a node one more condition must be fulfilled for a solar eclipse to occur. For a total eclipse of the Sun it is necessary that the Moon is in its perigee, i.e. in the point of its orbit where it is closest to the earth. If the Moon is close to the earth and in a node in conjunction with the Sun its conical umbral shadow, consisting of all those points not reached by any sunlight, will touch the surface of the earth. There we can see a total solar eclipse.

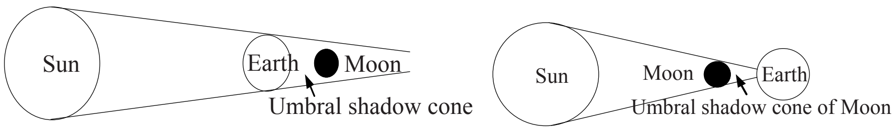

Fig. 11 Total lunar eclipse (visible everywhere on the right side of the earth) and a total solar eclipse (only visible locally)

Because of the difference in size between the Moon and the earth there is a major difference between solar and lunar eclipses, which is particularly important if one wants to predict eclipses, namely that during a lunar eclipse the entire Moon is covered by the umbral shadow of the earth, while during a solar eclipse the umbral shadow of the Moon falls only on a small part of the earth (see Fig. 11). This means that the prediction of the visibility of a solar eclipse must take the observer's position on earth into account.

The Saros cycle can be understood in terms of the Greek geometrical way of looking at the celestial phenomena. The two necessary conditions for an eclipse, viz. opposition or conjunction and the Moon being in a node, correspond to two cyclical phenomena:

(i) The *synodic month* (New Moon to New Moon or Full Moon to Full Moon) of 29.5306 days.

(ii) The *draconitic or draconic month* of 27.2122 days, which is the time the Moon needs to return to the same node. The draconic month differs from the sidereal month, because the nodes move. The line of intersection of the two orbital planes of Moon and Sun rotates slowly backward because the plane of the Moon does so.

A period of 223 synodic months is nearly equal to 242 draconic months. Moreover this period is also approximately equal to 239 anomalistic months (the time the Moon needs to go from perigee to perigee). This period of approximately 18 years, 11 days and 8 hours is obviously exactly the *Saros cycle*.

Hipparchus

From the period between 350 BCE and the year 0 many Babylonian astronomical cuneiform tablets are extant. They contain calculations and predictions concerning the phases of the Moon, the positions of planets etc. This was an arithmetic tradition in astronomy which kept a close track of the phenomena and differed from the more speculative tradition in which Eudoxus and Apollonius were working. These two great Greek mathematicians developed kinematical models of astronomical phenomena, but unlike the Babylonians they did not go beyond a qualitative comparison between the model and the phenomena. In this respect Hipparchus (about 150 BCE) represents a revolution. Hipparchus was familiar with Greek geometry and with Babylonian observations. As far as we know he was the first to try to really adapt the models to the actual, observed data.

Consider the epicycle model in Fig. 10. Two circles are involved: the *epicycle* and the *deferent*. The *epicycle* ZHBK, or rather its centre, moves on the circle ABGD with centre E. This circle ABGD is called the *deferent*. The body moves on the epicycle ZHBK. It is quite obvious that seen from the point of view of the terrestrial observer the composition of these two uniform rotations is non-uniform. Suppose the epicycle moves in the direction from A to B. If the body on the epicycle is in the position K it appears to lag behind, if it is in H it appears to move faster than the epicycle.

In Hipparchus' model for the motion of the Sun the angular velocity corresponding to the epicycle (the anomalous motion) is equal to the angular velocity corresponding to the deferent (the motion of the Mean Sun). This means the sidereal year (return to the same fixed star) is equal to the anomalistic year (return to the same velocity). The anomaly is the phenomenon of the deviation from the uniform rotation. The anomalistic year is, for example, the time it takes between two moments of minimal angular velocity.

This model for the motion of the Sun can be rather simple because the Mean Sun and the anomaly have periods that are sufficiently similar for the difference not to be easily noticeable.

Unfortunately the motion of the Moon is more complex. Hipparchus used exactly the same model but the two periods are unequal: the period of the anomaly, the anomalistic month is larger than the sidereal month. In other words the epicyclic angular velocity is less than the velocity of the Mean Moon. Against the backdrop of the Zodiac the Moon moves at a velocity that fluctuates around a mean of some 13 degrees per day. As a result, the Moon moves back and forth over a distance of 6 degrees either way. The period of this fluctuation is the anomalistic month. A familiar method in Antiquity uses an anomalistic month of 248/9 days [9,10,11]. Clearly this anomalistic month is equal to the period from perigee to perigee. It is also the period of time between two moments of minimum velocity as seen from the Earth.

Conclusion: the motion of the Moon in Hipparchus' model is the combination of a uniform rotation with a period of one sidereal month and a sinusoidal back and forth motion with an amplitude of 6 degrees and a period somewhat greater than a sidereal month. This means that when the mean motion in longitude completes 360 degrees the mean motion in anomaly still has roughly 3 degrees to go.

For the calculations it is important to realize that the Moon is large and has a considerable daily parallax of almost twice its own diameter: observations by different observers are different. The most suitable observations to be used as data are observations of lunar eclipses. They take place at Full Moon when the Sun and the Moon are diametrically opposed. The longitude of the Sun at the exact moment of the eclipse can be taken from the table of the longitude of the Sun (made on the basis of the theory of the Sun) and 180 degrees is added.

Wright's Reconstruction 1

In the course of time Wright correctly identified all visible gear-wheels and counted the number of teeth on each gear-wheel.

Only the simple parts of Price's reconstruction were still standing after Bromley and Wright criticized it. The assumption that on the front dial the positions of the Sun and the Moon were represented remained untouched by the criticism. Yet the precise manner in which this happened had to be corrected. In Price's reconstruction wheel D2 drove wheel B4 on the central axle. Bromley and Wright discovered that this happened indirectly via two wheels on the E axle (wheels that Price used for the differential gear). The only effect of these two wheels was in Wright's reconstruction the reversal of the direction of rotation of the Moon position pointer. This made Price's Sun position wheel superfluous because the Sun position pointer received the same motion as the drive wheel B1.

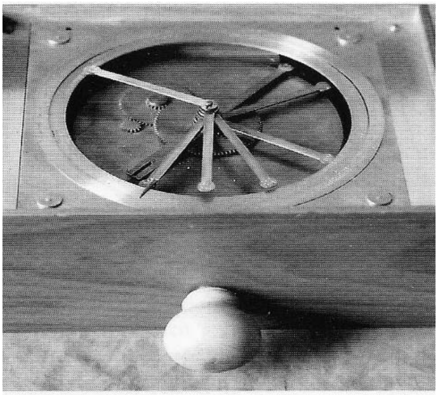

Fig. 12 Wright's model of the front dial including a display of the motion of the planets [18]

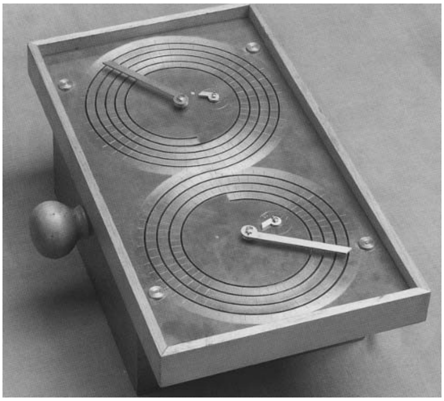

Fig. 13 Wright's 2005 reconstruction of the back-dials of the Antikythera mechanism [20]

Wright made sense of the upper back dial: in his reconstruction the main pointer counts the months in the Metonic cycle. The Metonic cycle of 19 tropical years is one of the well-known astronomical cycles from Antiquity. Price had suggested it but Wright defined the complete gear train. In Wright's reconstruction the subsidiary dial tells us where we are in the Calippic cycle of 76 years, which consists of 4 Metonic cycles.

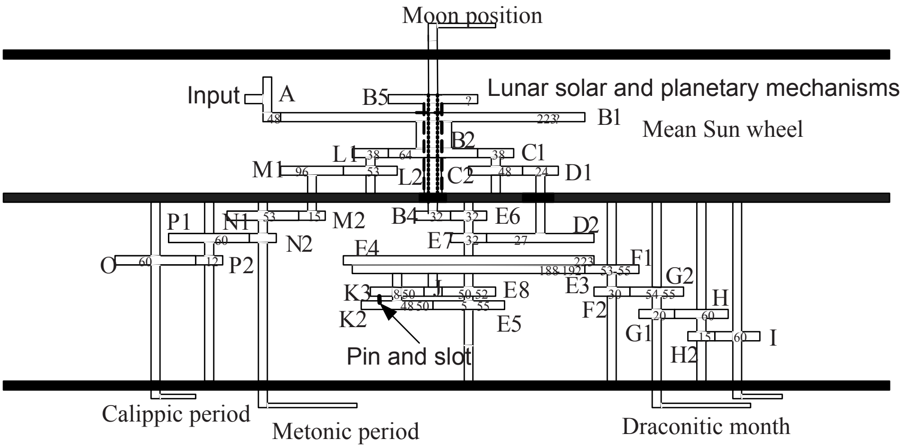

Fig. 14 Wright's reconstruction [21]

Wright had observed that what he called the Mean Sun Wheel (B1 in Figs. 6 and 14) carried a structure and that the central boss around which it turned was stationary and carried a wheel (B5 connected to the base plate of the mechanism); so there was an epicyclic mechanism going round at the rate of the Mean Sun.

This could easily have generated the motion of the inferior planets. Moreover there was the observation that Fragment C (front dial) does not join Fragment A (frame plate with all the gearing), which leaves room for further gearing representing the motion of the superior planets. Wright showed that the mechanism may indeed very well have included a display of the motions of the Superior Planets, Mars, Jupiter and Saturn by building a working model of the resulting conjectural design in which the Moon and the Sun moved in accordance with Hipparchus' theories and the five planets in accordance with the epicyclic theory prevalent at the time ([16, 17]).[1] It is part of Wright's methodology that he systematically constructs models of the gear chains that he observes. He preferably uses very simple tools of the kind that would have been available in Antiquity. The planetarium display he has built in this way for the Antikythera mechanism is more than mere speculation.

Wright drew the provisional conclusion that the mechanism that replaced the differential gear drove a pointer on the lower back dial with a rotational period equal to one draconitic month. He drew the conclusion that the lower back dial functioned to predict eclipses. See [18] and [20].

Wright analyzed the geometry of the remaining fragments of the two back dials. He noticed that they did not consist of concentric circles but of continuous spirals of five and four turns, respectively on the upper and the lower back dial ([20], p. 59).

As for the function of the upper back dial Wright discovered that one revolution of the main pointer represented 47 months with a scale laid out as a five turn spiral containing 47 divisions in each turn. It represents the 235 months (235 = 5 times 47) of the Metonic cycle. He suggested, moreover, that the subsidiary dial indicated in which of the four Metonic cycles one was that make up a 76-year Calippic cycle [21].

Wright's Reconstruction 2

Wright replaced the differential turntable by a large gear-wheel with 223 teeth. On top of this large gear-wheel he discovered an arrangement of two epicyclic wheels, the one directly above the other, but turning about separate axles on a stepped stud, coupled by a pin that projected from the face of the lower wheel into a radial slot in the upper one. See Figs. 17 and 18. Nota bene: In Wright's model in Figs. 17 and 18 there is a hypothetical extra wheel between E5 and K2; it has the same size as E5 and K2 and it is there merely in order to change the direction of the rotation. It would turn out to be superfluous. The stepped stud is fixed to the large gear-wheel. Let us consider E5 as the input. E5 engages K2. K2 engages K3 by means of the pin on K2 that slides in a slot in K3 and finally K3 engages E8. See Fig. 13. All four wheels have fixed centres on the turntable E4.

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[1] Price suggested this line of research in [12], p. 28. Wright was the first to develop the idea seriously, but others worked on it as well. See [3] and [6].

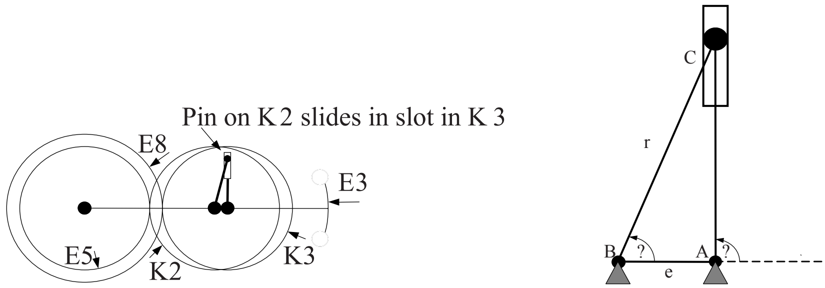

Fig. 15 The pin and slot mechanism

This was a fascinating discovery. It is the earliest occurrence of a slider-crank mechanism in history that we know of. Let us look at what it does. The sine-rule applied to triangle ABC yields:

$$\frac{r}{\sin(\pi - \alpha)} = \frac{e}{\sin(\alpha - \beta)} \tag{3}$$

or

$$\sin(\alpha - \beta) = \frac{e}{r}.\sin\alpha. \tag{4}$$

If β is the input angle and α the output angle, then θ = α – β is the angle that is added to the input by the pin and slot mechanism. If *e*/*r* is small, sin x is approximately equal to x and we can write

$$\theta = \frac{e}{r}\sin\alpha. \tag{5}$$

Indeed a roughly sinusoidal wave is introduced into the velocity ratio of the train, as Wright remarked (in [20] on p. 62).

Let us look at the whole mechanism. E8 engages K3. K3 engages K2 by means of the pin in the slot mechanism and finally K2 engages E5.

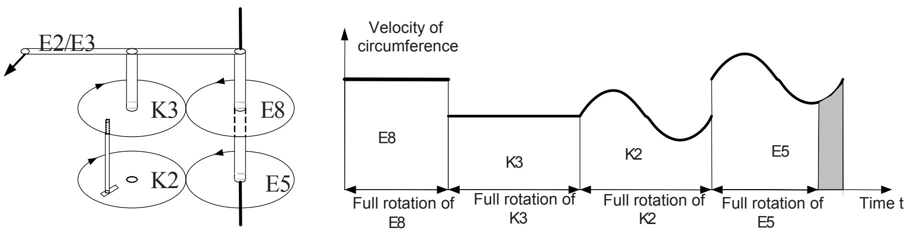

Fig. 16 The effect of the epicyclic pin-and-slot mechanism, on an input rotation of E8

We assume that the four wheels in the chain E8–K3–K2–E5 are of equal size. A uniform input velocity of E8 leads to a lower uniform velocity of K3 because the point where E8 and K3 touch shares the velocity of the epicyclic turntable. Nota bene: The rotations of K3 and K2 are considered with respect to the turntable and not with respect to the frame of the mechanism. In Fig. 16 (right) the area E8 is equal to the area K3; the two areas measure the length of the circumference of the wheels E8 and K3. The pin-and-slot mechanism changes the uniform rotation of K3 into the wave of K2. Yet a full rotation of K2 takes as much time as a full rotation of K3. The area K2 measures the circumference of K2 and is equal to the area K3. At the point where K2 engages E5 the velocity that is transferred to E5 is increased by the velocity of the turntable. This means that a full rotation of E5 is completed before the period of the wave brought about by the pin and slot mechanism is completed.

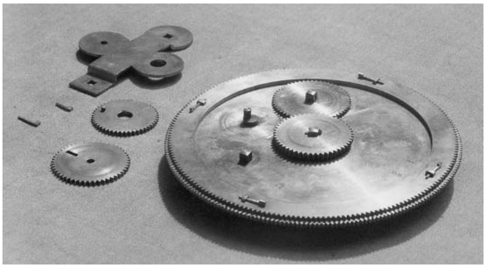

Fig. 17 The epicyclic gearing showing the pin and slot coupling between the wheels on the K-axle [20]

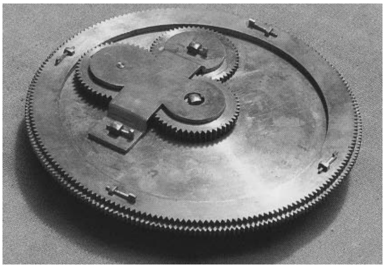

Fig. 18 The epicyclic gear assembled [20]

Wright realized that such a mechanism could be used to model one of the anomalies figuring in astronomical theory, and as he wrote “the only possibility in this train, concerned with months, is lunar theory”. However, he added that the wave’s period was determined by the rate of rotation of the wheels relative to the epicyclic turntable and that neither period nor amplitude could be matched to the anomaly of Hipparchus’ lunar theory with the turntable going round at the rate he had conjectured. 19 revolutions of B1 corresponded to 254 revolutions of E6 and E8. How about the epicyclic turntable? Consider the chain E3–F1+F2–G2. In Wright’s reconstruction one rotation of the turntable corresponds to roughly 2 rotations ((190/54).(30/54) is approximately 2) of the main pointer on the lower back dial.

Wright could not make sense of the function of the gear train E5–K2+K3–E8. In his reconstruction of the gear trains Wright had got hold of all the pieces of the puzzle, but some of the pieces didn’t fall into place, they didn’t seem to make sense/ seemed to make no sense. For example, the large gear-wheel may be considered as composed of two concentric gear-wheels fixed together; one is slightly smaller than the other. The large one was unused in Wright’s reconstruction. The pin and slot mechanism did not seem to make sense either in the position it has. Unable to completely solve the puzzle Wright saw himself forced to suppose that the Antikythera mechanism had to a certain extent been constructed from reused parts derived from another, older mechanism. In old pieces of mechanism from before the introduction of mass production redundant features are often found.

The Reconstruction by Freeth et al.

Wright had the correct topography of the wheels and the correct understanding of most of the moving parts. He also had the correct layout of both back dials and the correct function of the main upper back dial. He had correctly identified the pin and slot mechanism. In addition, he had identified most of the details correctly, although some of them made no sense. In a sense he was close to the correct solution, but he was not quite there.

The clue to the final solution was in Athens in the National Archeological Museum. Wright had observed that some of the fractures were encrusted and/or eroded while others were bright and clean suggesting that they dated from after the salvage operation. Wright suspected that matching pieces that he had not seen might be present in the National Museum in Athens. He was right. Fragment F turned up in the Museum when the Antikythera Mechanism Research Project was started. Tony Freeth and others enlisted the help of Hewlett Packard (USA) and X-Tek Systems Ltd[2] (UK) and assembled a team of 17 individuals. The team published its results in November 2006 in *Nature* [6]. They confirmed the correctness of many of Wright's results. However, there was more. The microfocus computed tomography (CT) by X-Tek Systems yielded a scan of Fragment F which showed some of the scale divisions on the lower back dial. Combining what they saw on Fragment F with the scale divisions visible on Fragments A and E. Freeth et al. estimated the number of scale divisions round the whole 4-turn spiral scale (observed by Wright) to be 223, exactly the number of months in a Saros cycle.[3] The assumption that the dial displayed a Saros cycle was reinforced by the discovery of characters on the dial separated by gaps of five or six months, precisely the gaps that separate eclipses.

Once it is known that the lower back dial shows where one is in a Saros cycle one can work back through the gear trains to see that an extra gear-wheel on the M axle can engage the unused gear-wheel in such a way that the Saros-cycle is generated at the right place.

Let us look at the details. The pointer of the Saros dial makes 4 rotations in 223 synodic months. In 19 years there are 235 synodic months. So when the wheel B1 corresponding to the position of the Sun makes 19 rotations, the axle G must make 4 times 235/223 rotations. What is needed is a gear train B2 to G2 that produces

[2] X-Tek Systems is now part of the Metris group.

[3] Freeth wrote to me that although Fragment F was the route by which the Antikythera Mechanism Research Group discovered that the lower back dial is a Saros dial all the evidence is already visible on Fragment A.

the right ratio using the wheels from the system of Fig. 13. Wheel E4 is so far unused and it has 223 teeth. The train E4+E3–F1+F2–G2 is certainly the last part of the train we are looking for. The idea of introducing an extra wheel M3 on the M axle is now within reach, because there is no other simple way to get from B2 to E4.[4] On the basis of Wright's data it now follows that 19 rotations of B2 give

$$19 \times \frac{64}{38} \times \frac{53}{96} \times \frac{X}{223} \times \frac{<188-192>}{<53-55>} \times \frac{30}{<54-55>} \tag{6}$$

rotations of the Saros pointer. Here X is the number of teeth of the new wheel M3 and <x–y> denotes an integer n in the interval x–y. This number must be equal to 4 times 235/223. It is easily verified that this implies that $26 \leq X \leq 29$. The precise values can be found by trial and error: M3 has 27 teeth, E3 has 188, F1 has 53 and G2 has 54 teeth.

As we have seen, Wright had been aware of the fact that the pin-and-slot mechanism could be used to generate an anomaly (a deviation from uniform motion in the orbit of a celestial body), but this made no sense to him at the time. However, as soon as the Saros cycle is supposed to be represented, the pin-and-slot mechanism and the large gear-wheel it is mounted on run roughly at the right speed for the anomaly of the Moon. With hindsight everything makes perfect sense. One of the two wheels E6 or E7 seemed superfluous. Not anymore. E7 rotates at the speed of the Mean Moon. So does E8 which is rigidly connected to it. The anomalous motion of the Moon is superimposed on this motion by the pin-and-slot mechanism. The result is the motion of E5 which is connected to E6 by means of an axle inside the axle of E7 and E8 (see Fig. 19).

Although with hindsight things look easy it took Tony Freeth and Mike Edmunds many months to draw the right conclusions about the function of the pin-and-slot mechanism. They published their findings in 2006 in *Nature*.

The New Methodology and its Results

The team that finally provided answers to the last remaining questions had seventeen members. In the team, led by Mike Edmunds (Cardiff University), two individuals from the National Archeological Museum of Athens catalogued and measured the fragments aided by an astronomer from Thessaloniki University. Six individuals from X-Tek Systems Ltd (Tring, Herts, U.K.) dealt with the building and operation of a Bladerunner CT machine that performed the 3-dimensional X-ray microfocus computed tomography (CT). They provided the CT reconstructions. Three individuals, two from Hewlett-Packard Inc. (California) and one

[4] Wright informed me that the model of the mechanism that he built before the results of Freeth et al. became known had an empty square wheel-seat on axle M "ready to receive wheel M3". He had observed it, seen the possibility that it suggested, and shelved it for later consideration.

from Foxhollow Technologies Inc. (California) built, operated and provided the software for the Polynomial Texture Mapping which was used to reveal surface details. Three Greek specialists read and translated the inscriptions. The first author, Tony Freeth (Cardiff University and Images First Ltd., London) took care of the analysis of the structure and its interpretation.

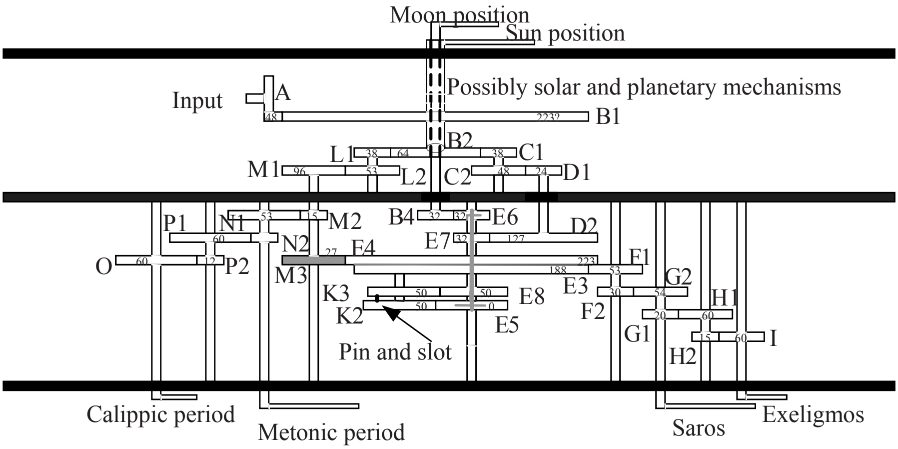

Fig. 19 The reconstruction of the gear system by Freeth et al. The grey elements, wheel M3 and the inner E axle represent essential modifications of Wright's scheme

The contrast with Wright's approach could not be greater. Essentially Wright did everything alone. The approach of Freeth *et al*. was entirely different. Creating a group consisting of different specialists and engaging the most up-to-date technology available indeed represents a considerable methodological shift.

It was not clear in advance that this new approach would yield fruit. Jo Marchant reported in *Nature* that Freeth had said: "My main fear was that we'd throw all this technology at it and we wouldn't do more than dot the i's and cross the t's" ([9], p. 537). There was, indeed, a lot of technology. The team, for example, shipped an X-Tek machine of 12 tonnes to Athens in 2005. There is therefore a certain irony in the fact that the breakthrough in the interpretation of the gear trains and their interactions was largely the result of chance: the team had access to Fragment F.

In the mean time it has become clear that the new approach is yielding impressive results. In July 2008 Freeth et al. published a letter in *Nature* with the latest results concerning the two back dials. It turns out that the upper subsidiary dial is not the 76 year Calippic dial but follows the 4 year period of the Panhellenic games in Olympia, the predecessor of the Olympic games. A further discussion of these results falls beyond the scope of this paper. For more information on this paper and the Antikythera Mechanism Research Project I refer the reader to the site http://www.antikythera-mechanism.gr/

Conclusion

The first serious reconstruction of the gear system of the Antikythera mechanism was proposed by De Solla Price. It's most spectacular feature was a differential gear, which, however, proved to be a figment of the imagination. Yet, as Francis Bacon said, truth emerges more readily from error than from confusion, and Price's bold hypothesis gave a major stimulus to work on the mechanism. The next major step forward was Wright's reconstruction published in 2005. Wright had correctly identified most of the important details, but he was two essential steps away from the correct interpretation. Wright is convinced that if he had had access to "Fragment F", he would have been able solve the riddle of the unused large gear-wheel and he would have understood the function of the mysterious pin and slot mechanism as well. His frustration that he didn't have access is understandable. The final solution was published in 2006 by the team of Freeth *et al.* It is not just the latest in a series of closer and closer approximations to the truth and more and more sophisticated interpretations of the Antikythera mechanism, but it is likely to be the last in the series, and final in the sense that it is basically correct.

Acknowledgements I am very grateful to Michael Wright and to Tony Freeth for reading an earlier version of this paper and commenting on it. In fact they supplied me with so much information that I have undoubtedly failed to do justice to some of their remarks. I am also grateful to Tjeerd B. Jongeling for discussing several parts of the paper with me which led to some important changes.

References

1. A.G. Bromley, Notes on the Antikythera Mechanism, *Centaurus* 29, 1986, pp. 5–27
2. A.G. Bromley, Observations on the Antikythera Mechanism, *Antiquarian Horology* 18, 1990, pp. 641–652
3. M. Edmunds and P. Morgan, The Antikythera Mechanism: Still a mystery of Greek astronomy?, *Astronomy & Geophysics*, 41, 2000, pp. 6.10–6.17
4. J. V. Field & M. T. Wright, Gears from the Byzantines: a portable sundial with calendrical gearing, *Annals of Science* 42, pp. 87–138. 1985 (reprinted in J. V. Field, D. R. Hill & M. T. Wright, *Byzantine and Arabic Mathematical Gearing*, London, Science Museum, 1985)
5. T. Freeth, The Antikythera Mechanism: I. Challenging The Classic Research, *Mediterranean Archaeology & Archaeometry* (MAA) Vol. 2, 2002, pp. 21–35
6. T. Freeth, The Antikythera Mechanism II: Is it Posidonius' Orrery?, *Mediterranean Archaeology & Archaeometry* (MAA) Vol. 2, 2002, pp. 45–58
7. T. Freeth et al., Decoding the Ancient Greek Astronomical Calculator Known as the Antikythera mechanism, *Nature* 444, 2006, pp. 587–591

8. T. Freeth *et al.*, Calendars with Olympiad Display and Eclipse Prediction on the Antikythera Mechanism, *Nature* 454, 2008, pp. 614–617
9. A. Jones, The Development and Transmission of 248-Day Schemes for Lunar Motion in Ancient Astronomy, *Archive for History of Exact Sciences* 29, 1983, 1–36
10. J. Marchant, In Search of Lost Time, News Feature in *Nature* 2006, pp. 534–538
11. O. Neugebauer, *The Exact Sciences in Antiquity*, Dover Edition, New York 1969
12. D. de S, Price, Gears from the Greeks, The Antikythera Mechanism – A Calendar Computer from ca. 80 B.C., *Transactions of the American Philosophical Society*, New Series, Vol. 64, Part 7, 1974
13. G. J. Toomer, *Ptolemy's Almagest*, Duckworth, London, 1984
14. G. White, Antikythera Gearing – A Different Solution, *Horological Journal* 144, 2002, pp. 358–363
15. M. T. Wright, Rational and Irrational Reconstruction: The London Byzantine Sundial-Calendar and the Early History of Geared Mechanisms, *History of Technology*, 12, 1990, pp. 65–102
16. M. T. Wright, A Planetarium Display for the Antikythera Mechanism, *Horological Journal*, 144, 2002, pp. 169–173 and p. 193
17. M. T. Wright & A. G. Bromley, Towards a new reconstruction of the Antikythera mechanism, S. A. Paipetis (editor), *Extraordinary Machines and Structures in Antiquity*, Peri Technon, Patras, 2003 , pp. 81–94.
18. M. T. Wright, Epicyclic Gearing and the Antikythera mechanism, Part I, *Antiquarian horology* 27, 2003, pp. 270–279
19. M. T. Wright, The Scholar, the Mechanic and the Antikythera Mechanism, *Bulletin of the Scientific Instrument Society*, 80, 2004, pp. 4–11
20. M. T. Wright, Epicyclic Gearing and the Antikythera Mechanism, Part II, *Antiquarian Horology* 29, 2005, pp. 51–63
21. M. T. Wright, The Antikythera Mechanism: A New Gearing Scheme, *Bulletin of the Scientific Instrument Society*, 85, 2005, 2–7
22. M. T. Wright, Counting Months and Years: the Upper Back Dial of the Antikythera mechanism, *Bulletin of the Scientific Instrument Society*, 87, 2005, pp. 8–13
23. E. C. Zeeman, The Antikythera Mechanisms, *Proceedings of the Royal Institution of Great Britain*, 58, 1986, pp. 137–156.

An Investigation and Reconstruction of Traditional Vertical-Axle-Styled "Chinese Great Windmill" and Its Square-Pallet Chain-Pump

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Abstract From 2004 to 2006, in the north of Jiangsu Province, the Institute for the History of Natural Science (IHNS, CAS), in collaboration with Southern Taiwan University of Technology (STUT), carried out a field survey and reconstructed a vertical-axle "Chinese Great windmill" (CGW) complete with its square-pallet chain-pump (SPCP). An experienced carpenter, Master Ya Chen, who once made and repaired CGWs in the 1950–1960s, was recruited to assist with the reconstruction of the CGW using only traditional craftsmanship. The authors recorded the entire reconstruction process and at the same time investigated related local folk-custom. In this article, the process of investigation and reconstruction of the CGW were reported and the technical issues involved were also discussed.

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Keywords Vertical-axle Chinese great windmill, Square-pallet chain-pump, Field survey, Reconstruction

Introduction

Traditional vertical-axle Chinese great windmill (CGW), shown in Fig. 1, is also called the vertical-sail great windmill, great windmill or Chinese great windmill. A square-pallet chain-pump (SPCP) is also called a watermill (水車), keeled watermill (龍骨車) and trough bucket (槽桶). The CGW was a wind-driven device invented by ancient craftsmen based on the operating principle of a sail on a boat, which could adjust and adapt automatically to different wind directions. This mechanism as applied on the CGW is illustrated in Fig. 2. Operators were able to run and stop the great windmill, and to control its rotational speed by simply adjusting the ropes of the sails. The structure and operating principle of the CGW are quite different to traditional windmills in Europe and West Asia. This type of windmill with clear local characteristics and technical characters was the prime mover of a SPCP for the purpose of irrigation and the production of salt on the coast of Southeast China and the Bohai Sea area (渤海).

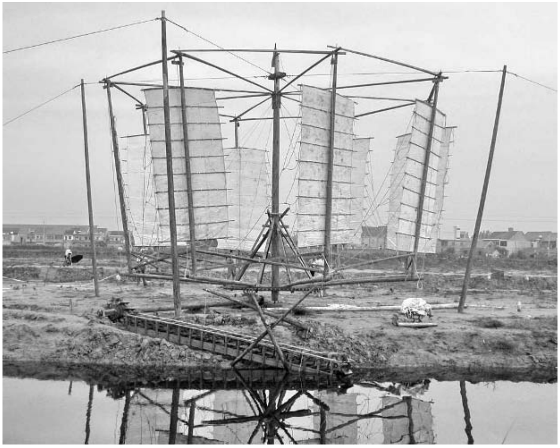


Fig. 1 Typical Chinese great windmill (CGW) with a square-pallet chain-pump (SPCP)

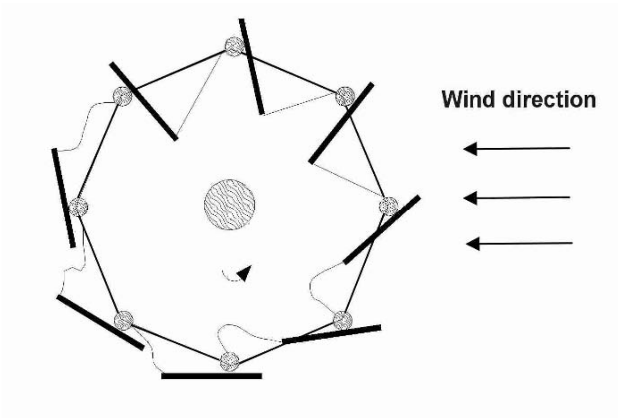


Fig. 2 Movement of the eight sails of a CGW and their ropes

For over fifty years, historians of science, such as Li Chen (陳立) [1], Xianzhou Liu (劉仙洲) [2], Joseph Needham [3], Jingyan Lu (陸敬嚴) [4], Yingqi Yi (易穎琦) [5] and Baichun Zhang (張柏春) [6], have studied the vertical-axle great windmill. By the end of the 1960s, with the popularization of modern mechanical irrigation and drainage modes in agriculture, CGWs had become rare. On account of the limited record on CGW in ancient literature, it is of scientific value to carry out an on field survey of existing CGWs. In 1985, Prof. Jingyan Lu studied the hangovers of a CGW in the north of Jiangsu province [7]. In the early 1990s, Baichun Zhang and Lisheng Feng (馮立昇) also surveyed and carried out technical analysis of windmills at that region.

In July, 2004, Tsung-Yi Lin (林聰益) from Southern Taiwan University of Technology (STUT, 南台科技大學) and Su-Hua Wu (吳淑華) from National Science and Technology Museum (NSTM) (国立科學工藝博物館, 台湾高雄) of Science and Technology visited the Institute for the History of Natural Science, Chinese Academy of Sciences (IHNS, 中國科學院自然科學史研究所) and the Institute of China Agriculture Museum (中國農業博物館). In a discussion with Baichun Zhang and Xingsui Cao (曹幸穗), it was mentioned the desire to acquire and reconstruct traditional mechanisms for NSTM. Of those traditional devices mentioned, there were CGW, water wheel, watermill and water grind. At the beginning of that November, Zhizhong Zhang (張治中), an engineer who was interested in the history of mechanisms reported on the possible existence of a traditional windmill maker in Haihe town (海河鎮), Sheyang county (射陽縣) in the north of Jiangsu province. At the beginning of 2005, the collaboration between NSTM and mainland China was stopped. To ensure the project continued, Tsung-Yi Lin and Baichun Zhang agreed that STUT would raise money for IHNS to continue to manage and record the entire reconstruction process. The reconstruction project was completed at the end of 2006. Fig. 3 shows the flow chart of the reconstruction process.

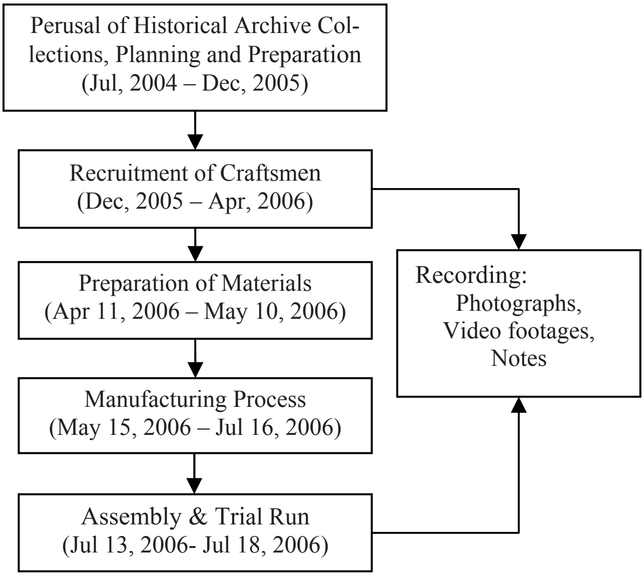


Fig. 3 The reconstruction and field survey process of a CGW

Recruitment of Traditional Craftsmen

The framework of traditional windmill was timberwork. The prime task was therefore to recruit a master in traditional carpentry. With some difficulties, Master Ya Chen was located at the end of 2005.

Ya Chen 陳亞 (Fig. 4), from Qinghe village (清河村), Haihe town, Sheyang county Jiangsu province, was seventy-two years old and had elementary education. He was very fit, quiet, prudent, capable and, most importantly, experienced. Through conversations with Chen, it was revealed that he was familiar with the structure of a CGW and remembered the exact sizes of main components. Especially, Chen had kept a set of special measures for decades. With his enthusiasm and experience, he was the perfect choice for the job.

Once the key worker had been identified, the reconstruction process commenced without ado. The process included three main stages: preparation of material, manufacturing and assembly.

Material Preparation

Material preparation mostly involved choosing and buying raw materials and preliminary processing. More specifically, it included the following stages: selecting, transporting, storing and cutting, and aging rough parts. The raw material selection process was vital as it not only directly affected the quality of the structure but also determined the degree of resemblance of the reconstruction to the original device. All required raw materials and the main technical requirements are shown in Table 1.

a) Master Ya Chen b) Chen and an inquirer

Fig. 4 Master Ya Chen and an investigator, Lie Sun (孫烈) at work (2006)

Manufacturing

Manufacturing was the key stage of the reconstruction processes. Traditional carpentry skills were the primary processing technique. Master Chen did not have any available drawings, so all the technical details came from his memory, experience and the set of special measures that he had possessed for decades. In terms of difficulty and work effort, the main components such as the big gear wheel, spindle, transmission shaft, driven gear and driving sprocket, required the most time and effort than the supporting and linking components such as the masts, frames and so on. Fig. 5 shows the procedure for the carpentry work.

The big gear wheel was a large spoked spur gear, whose outside perimeter was typically 3.2~3.5 m. The cogs of the gear were called "Chui (棰)". The big gear wheel, driven gear, driving sprocket, chain and driven sprocket, collectively formed the transmission chain, as shown in Fig. 6.

Of all the manufactured components, the big level gear wheel was the most difficult to shape and took the most effort. The shaping of this gear demonstrated the characteristic of how a great windmill was made. Due to the great size of the whole rim, this component was made up of bonded pieces for the convenience of selecting the raw material and the fabrication process. The big gear (Fig. 7) was entirely made of mulberry and composed of six big rims, six small rims and 88 cogs by jointing. Fabricating the rims required seven processes: pre-forming, accomplishing and gouging of grooves in the big rims, processing the small rims and tenons and mortises, chiseling 88 holes in the rims and 8 mortises for spokes (穿子孔), processing and fixing the clubs, and adjusting the mesh position of the cogs.

Table 1 Main raw materials required for the great windmill

Name	Main Purposes	Size/quantity
Mulberry (桑木)	Gear wheel rim (大輞, 小輞), Driven gear (旱撥), Driving sprocket (水撥), Driven sprocket (杌掇子), SPCP, Bearing sleeve (將軍帽), Pulleys (鈴鐺), Bearing Pedestal (遊子), Cogs (棰)	Φ≈70–110 cm, L ≈180–220 cm
Fir (杉木)	Spindle (車心), Transmission shaft (跨軸), Masts (桅子), Wheel spokes (穿), Frames (幢子木), Top spokes (撐心), Base bars (柭擔), Hanging rods (掛), Horn (羊角), Head hoops (箍頭), Crossing rods (剪)	Φ≈20–40 cm, L≈6~8 m, Tot. ≈40
Willow (柳木)	Square boards (梻板)	Φ≈40 cm, L≈2.5 m
Bamboo rods (細竹竿)	Sail's framework (蓬竹子)	Φ≈10 mm, L >2~3 m, Tot. ≈40
Cattail (蒲草)	Sail material（蒲草）	~40 kg
Rice straw (稻草)	Ropes（草繩）	~5 kg
Reinforced steel bar (洋元)	Hawsers (大纜)	Φ=10 mm, L= 30 m
Steel wire (鐵絲)	Wire suspensions (軟吊)	Φ=8 mm
Tung oil (桐油)	Timber coat (木料油漆)	~20 kg
Cast iron (鑄鐵)	Bearings (釧)	~8 kg
Wrought iron (鍛鐵)	Hoops (鐵箍), Cleeks (鐵鉤), Nails (釘), Bottom pole (母轉), Iron needle (公轉)	~15 kg
Rock (石塊)	Stone stake (石樁)	~500 kg

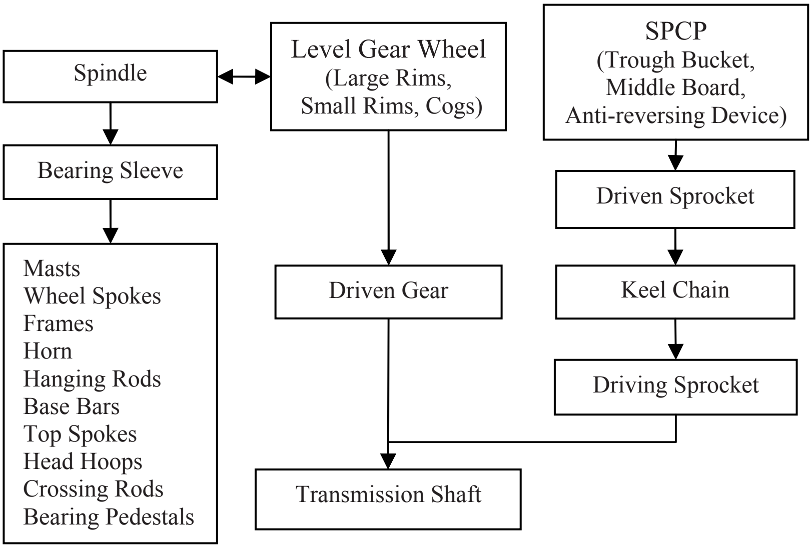


Fig. 5 Procedure for the carpentry work

Fig. 6 Position of the main transmission components

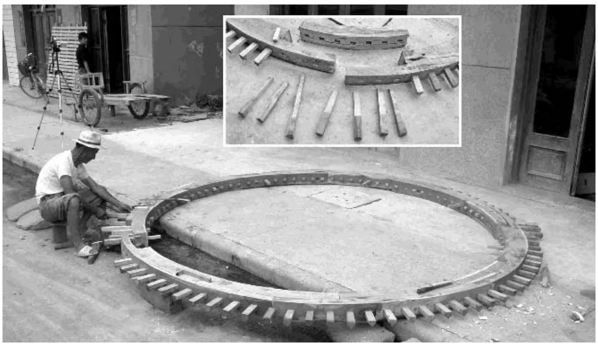


Fig. 7 Trial-installation and adjustment of the level gear wheel (driving gear)

Both the driven gear and the driving sprocket were a columniform body surrounded by many evenly distributed cogs. They were located at the two ends of the transmission shaft, jointed to the big gear and a square-pallet chain pump respectively, shown in Fig. 8. The fabrication process for the driven gear, the driving sprocket and the driven sprocket was similar to that of the big gear. However, compared to the big gear, these three components were smaller in size, simpler in structure, and therefore easier to manufacture. During manufacturing, it was necessary to ensure the precision of the space (2~3 mm) between the cogs of the big gear and the driven gear, driving sprocket and driven sprocket.

a) Assembling driven gear and transmission shaft

b) Adjusting driving sprocket and keeled chain

Fig. 8 Transmission shaft, driven gear, driving sprocket, and keeled chain

a) Processing spindle

b) Assembling a bearing sleeve

c) Measuring some rods

d) Processing some poles

Fig. 9 Processing the spindle and others rods and poles

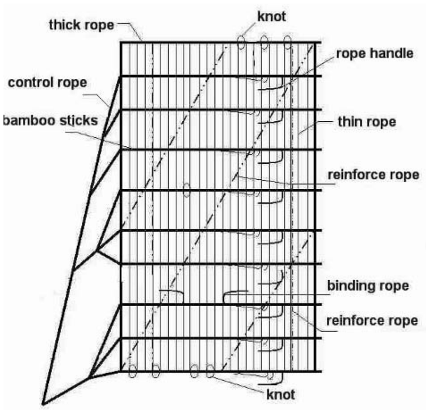
The framework of the CGW was made up of many rods and poles, which were jointed together. Amongst them, the spindle was the rotor of the whole windmill and the hinge for jointing other rods. The spindle was not only one of the largest rods but also one that required the most effort. All the rods were made of straight fir, which was soft and easy to shape. Figure 9 illustrates the process.

Sails, also called Fengfan (蓬,風帆) in Chinese, were mostly made of cattail leaves and rice straw, and weaved by hand in a traditional method, which usually included weaving, binding of the sails with bamboo sticks, inserting reinforcement for balancing, tying of rope handles (包梔) and knots (蓬紐子), and controlling the ropes (駕繩). This process is illustrated in Fig. 10a–c. The structure of one sail is shown in Fig. 10d.

a) Weaving a sail

b) A weaved sail

c) Tying bamboos sticks and ropes

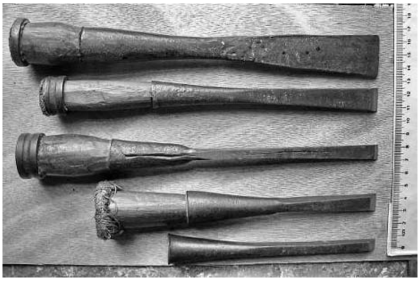


d) Schematic of a Sail

Fig. 10 Fabrication process and structure of a sail

The hand tools used in the fabrication process were so-called "the Big Four Tools of a Carpenter" – plane, chisel, axe and saw, shown in Fig. 11a–d. The ancillary tools included ruler, square, Chinese ink dipper (墨斗) and pencil. Having the set of measures from Chen was most extraordinary. They were used to process and adjust the big gear, shown in Fig. 11e.

a) Planes



b) Chisels

c) Axes

d) Saws

e) A set of Special Measures

Fig. 11 Main tools for the carpentry work

The reconstruction work started on the 11th April, 2006 and the sails were finished at the end of that year. It took eight months but the contracted man-days for this project were 70 days. The work on the big gear took almost 60 percent of the total labour; the rods about 20 percent; 10 percent of work was to build the SPCP; another 10 percent to make the sails.

Assembly and Trial Run

The assembling process included locating the site for the great windmill, leveling the ground, performing a traditional worshipping ritual, setting up the windmill and testing it. The process is illustrated in Fig. 12. Amongst them, setting up the windmill was the key process, which involved the following steps: erecting the spindle (Fig. 13a and b), fixing the framework (Fig. 13c and d), setting up the transmission shaft and the SPCP, and tying and hanging the sails. After the framework was fixed, the SPCP was suspended and properly secured. The windmill was then ready to be operated. A person and a buffalo were employed to run the windmill. When the buffalo was whipped and started to move, the person stood on the big gear and assisted in driving it, as shown in Fig. 13e.

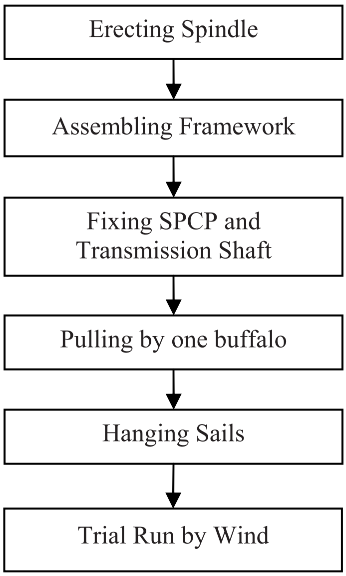


Fig. 12 Procedure of the assembling process and trial run

a) Erecting spindle

b) Spindle's iron needle and stone pedestal

c) Fixing framework

d) Framework and pump

e) Buffalo and driver

f) Bound sails and brake rope

Fig. 13 Main assembling process and trial run

When tying and operating the sails, experience was necessary especially in adjusting the length of the control ropes in order to ensure the sails turned at optimal angles against wind. If the windmill encountered strong wind, the sail halyards would be pulled out from the framework and the sails would fall immediately. If the windmill had to be stopped, all sails had to be lowered first and tied to the framework, followed by fastening of the framework and pole respectively with a so-called brake rope to prevent the windmill from turning (Fig. 13f).

The success of the assembling and trial run symbolized the accomplishment of the task of reconstructing a CGW, shown in Fig. 14. The assembling process took about 400 man-hours.

Fig. 14 The reconstructed traditional CGW and Its SPCP in a field in Sheyang County, Jiangsu Province (2006)

Conclusions

CGWs and their SPCPs were traditional Chinese wind-driven mechanisms with appreciable size and complexity. They gradually disappeared on the coast of the Southeast China, quickly being replaced by compact, efficient and economical modern motor-pumps in the 1960–1980s.

The CGWs and its SPCPs were regarded as “traditional” mechanisms not because they represented “pre-modern” devices but because of the ancient technical tradition and culture that they, their makers and users have inherited [8]. The aim of the reconstruction exercise was not just to preserve the implement but to understand and pass on the traditional techniques and the cultural heritage that came with it.

References

1. Chen L (1951) Why Were Wind Power Not Generally Used in North China? – An Investigation Report on the Windmill of the Bohai Sea area. Chinese Science Bulletin 3:266–268.

陳立 (1951) 爲什麼風力沒有在華北普遍利用——渤海海濱風車調查報告. 科學通報 3:266–268

2. Liu XZ (1962) A History of Mechanical Engineering Inventions, Science press, Beijing, China, pp. 59–60.
   劉仙洲 (1962) 中國機械工程發明史(第一編). 科學出版社, 北京, 第 59–60 頁
3. Needham J (1965) Science and Civilisation in China (Volume IV: 2), Cambridge University Press, Cambridge, pp. 555–568.
4. Lu JY (1999) Ancient Vertical-axle-styled Windmill, Root Exploration 3:39–41.
   陸敬嚴(1999) 古代的立軸式大風車 . 尋根 3:39–41
5. Yi YQ, Lu JY (1996) Vertical-axle Great Windmill and the Analysis of Its Force, Journal of Tongji University (Natural Science) 3:287–292.
   易穎琦, 陸敬嚴 (1996) 立軸式大風車及其受力分析. 同濟大學學報(自然科學版) 3:287–292
6. Zhang BC (1995) A New Research on the Structures and Principles of Chinese Wind-Driven Square-Pallet Chain-Pumps, Studies in the History of Natural Science 3:287–296.
   張柏春 (1995) 中國風力翻車構造原理新探. 自然科學史研究 3:287–296
7. Yi YQ, Lu JY (1992) An Textual Research and Rebuilding of Chinese Ancient Vertical-axle Great Windmill, Agricultural Archaeology 3:160.
   易穎琦, 陸敬嚴 (1992) 中國古代立軸式大風車的考證與復原. 農業考古 3:160
8. Zhang BC, Zhang ZZ, Feng LS, Qian XK, Li XH, Renn J (2006) The Complete Works of Chinese Traditional Crafts · Investigations of Traditional Chinese Machines, Elephant Press, Zhengzhou, p. 3.
   張柏春, 張治中, 馮立升, 錢小康, 李秀輝, 雷恩 (2006) 中國傳統工藝全集 ·. 傳統機械調查研究. 大象出版社, 鄭州, 第 3 頁

On the Mechanism Analysis of the Vertical Shaft Type Wind-Power Chinese Square-Pallet Chain-Pump

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Abstract Vertical shaft type wind-power Chinese square-pallet chain-pumps are Chinese square-pallet chain-pumps that are powered by vertical-sail-type Chinese windmills (Chinese great windmills). These apparatuses had been widely-used for raising water in agricultural fields and salt fields along the coast of China since the 12th century until the 1980s, when they went completely extinct. While there is a lack of detailed records of the techniques and craftsmanship used in building these chain-pumps, there still survive some master craftsmen who are skilled in designing and building them, though most of them are quite old. Following a plan for their revival, we have successfully preserved the dying technique and craftsmanship. This article is an analysis of the mechanisms of these chain-pumps and the principles underlying their functionality based on our reconstruction research.

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Keywords Reconstruction research, Vertical-sail-type Chinese windmills, Chinese square-pallet chain-pump, Mechanism analysis

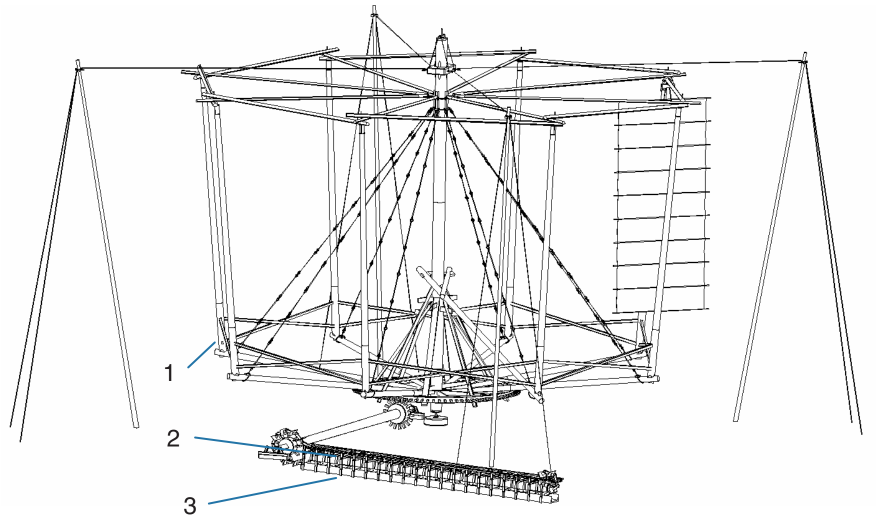
Introduction

The earliest record of the Chinese great windmills (i.e. vertical-sail-type Chinese windmills) was written in the Southern Song dynasty (circa the early 12th Century) [1], which documented that they were used to power one or more Chinese square-pallet chain-pumps (龍骨水車) for irrigation or salt-making in areas along the coast of the mainland China (as Fig. 1 shows) [2–4]. With electrical and internal combustion engine-driven pumps growing more popular since the 1950s, however, these chain-pumps became completely obsolete in the 1980s [5–6].

In mid-July of 2006, the first real-size giant windmill to be seen in more than 20 years was successfully rebuilt and field-tested on an open field in Haihe (海河鎮) in the northern Jiangsu province in China using the traditional technical knowledge gathered from field surveys and studies[1] (as Fig. 2 shows). This completely functional structure, with a height of 8 m and a diameter of over 10 m, now stands on the campus of the Southern Taiwan University (as Fig. 3 shows) as a successful example of reconstruction research.

Having been used for over hundreds of years, the design of the vertical shaft type wind-power Chinese square-pallet chain-pumps has been perfected and greatly simplified. However, although scholars of history of technology attempted to keep alive their techniques and craftsmanship, the records on these chain-pumps in the forms of models and diagrams are of questionable verity as many of these records are based on conjectures, rather than real-size reconstruction manufacturing [5–7]. With this reconstruction research on technological field surveys, we have collected a great amount of data to allow us to confirm the previous assumptions as well as making the necessary corrections. We will analyze the structure and the mechanisms by dividing the structure into three components: a propulsion system, a transmission system, and a pumping system.

[1] The preliminary research for the "Reconstruction Research and Manufacturing of the Vertical Shaft Type Wind-Power Chinese Square-Pallet Chain-Pump" project was initiated in late 2002. The field surveys went under way in April of 2004, and the actual building and field-testing were done between April and December of 2006. The research was completed with funding from the Southern Taiwan University and the National Science Council (Taiwan). It reconstructed the windmill in collaboration with CAS Institute for the History of Natural Science, whose help opens a door to future cooperative efforts between the two sides of the Strait in rescuing important cultural heritage.



1 vertical-sail-type Chinese windmill (立帆式大風車, Chinese great windmill)　2 transmission shaft (跨軸)　3 Chinese square-pallet chain-pump (龍骨水車)

Fig. 1 The vertical shaft type wind-power Chinese square-pallet chain-pump

Fig. 2 The field-test of the vertical shaft type wind-power Chinese square-pallet chain-pump in Haihe in the northern Jiangsu province

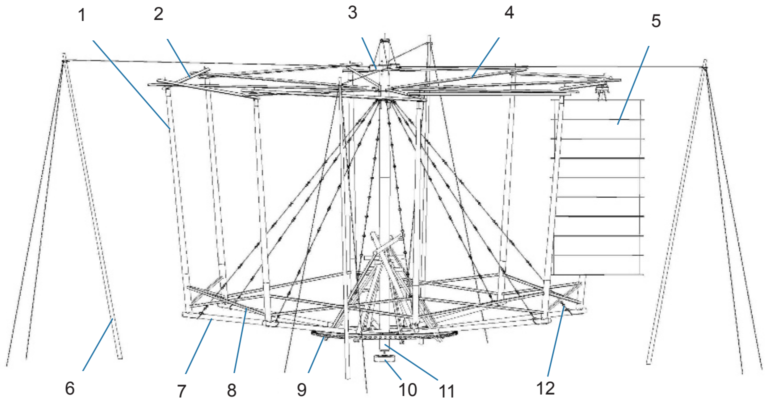
Fig. 3 The vertical shaft type wind-power Chinese square-pallet chain-pump stands on the campus of the Southern Taiwan University

Propulsion System

The propulsion system, simply stated, is the windmill itself, which is basically a giant wood wheel held up horizontally to the other parts by a central spindle. It functions by allowing sails to take on wind to rotate the wheel, which in turn turns the transmission shaft via a gear system.

As Fig. 4 shows, the wheel is a framework made up of a set of rods arranged in the shape of an octahedron. The spindle (車心), which is the windmill's central axis, is also its main power control. Its nickname, the Big General (大將軍), which is the popular name for the main mast of a Chinese sailboat, suggests that the idea for the windmill's design came from sailboats. The spindle is not only the largest part of the entire wheel, it is also the part that needs most processing since it is connected to the most parts as Fig. 4 shows. As a result, the size and the appearance of the windmill are dependent on how the spindle is designed.

Jointed to the level gear wheel (平齒輪) at the bottom of the spindle are eight spokes as Fig. 5 shows. The two longer ones (通穿) pass through the spindle and the four shorter ones (支穿) are jointed to the spindle. These spokes, along with eight hanging rods (掛) that are jointed to the horn (羊角) on the spindle and the longer cogs (掛棰, longer tooth) of the level gear wheel, are used to hold up the level gear wheel and share the burden of its weight.

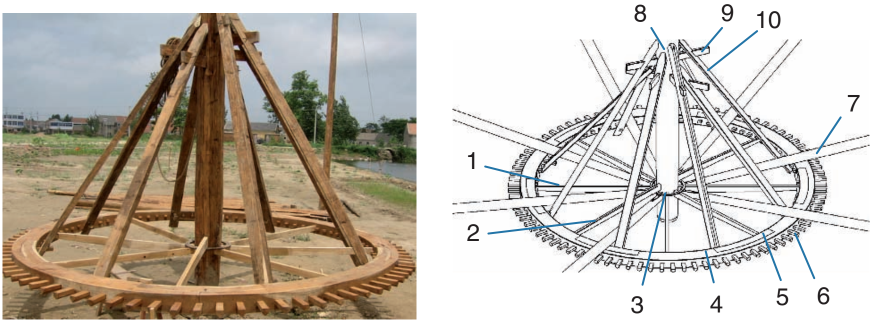


1 mast (桅子)
2 head hoop (箍頭)
3 bearing sleeve (將軍帽, "general's hat")
4 top spoke (撐心, "heart-supporter")
5 sail (帆篷)
6 frame (幢子木, 大柱)
7 base bar (枕擔)
8 crossing rod (剪)
9 level gear wheel (平齒輪)
10 stone pedestal (車心石)
11 spindle (車心, 大將軍, "Big General")
12 steel wire (軟吊) or iron chain (鐵鏈)

Fig. 4 The vertical-sail-type Chinese windmill

There are eight base bars (枕擔) sitting on top of the level gear wheel at the bottom of the windmill wheel. They are hooked to the crowbar ring (撬盤) on one end and are jointed to a mast on the other. In the absence of wind, one of the base bars is unhooked from the crowbar ring and hung on the horn (hence its name 吊枕擔, "suspension base rod") to make enough space for a bubalus (水牛) to pull forward the wheel as Fig. 6 shows. To lessen the bending force exerted on these bars, the outer end of each of these eight base bars is held up by a iron chain (鐵鏈) or a steel wire (軟吊), which is hooked to the steel bracelet (金剛鐲) on the upper end of the spindle.

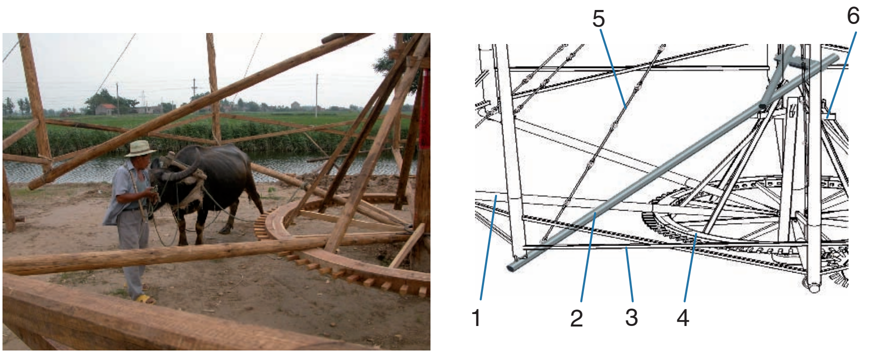
The eight top spokes (撐心, "heart-supporter") that are on the upper side of the wheel are hooked to the flat ring (花盤) on the top of the spindle on one end and are jointed to the iron tenon (鐵桅榫) of the upper mast on the other end (as Figs. 7 and 8 show). The masts are jointed by head hoops (箍頭) on the top end and are jointed by two crossing rods (剪) at the bottom, both of which are helpful in holding together the windmill wheel.



a) b)

1 shorter spoke (支穿)
2 longer spoke (通穿)
3 crowbar ring (撬盤)
4 big rim (大輞)
5 small rim (小輞)
6 cog (棰, tooth)
7 base bar (枕擔)
8 spindle (車心)
9 horn (羊角)
10 hanging rod (掛)

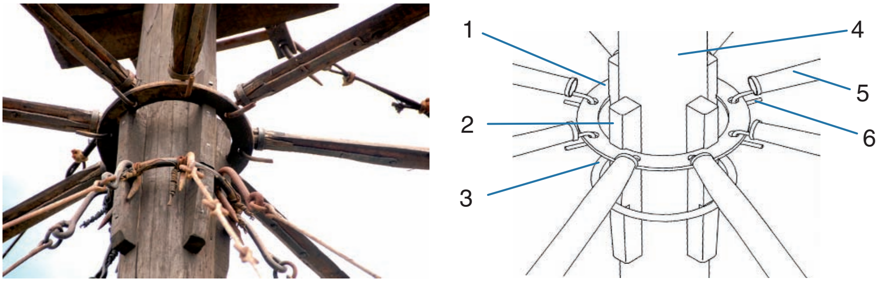
Fig. 5 The installation of the level gear wheel



a) b)

1 base bar (枕擔)
2 suspension base rod (吊枕擔)
3 crossing rod (剪)
4 level gear wheel (平齒輪)
5 steel wire (軟吊) or iron chain (鐵鏈)
6 horn (羊角)

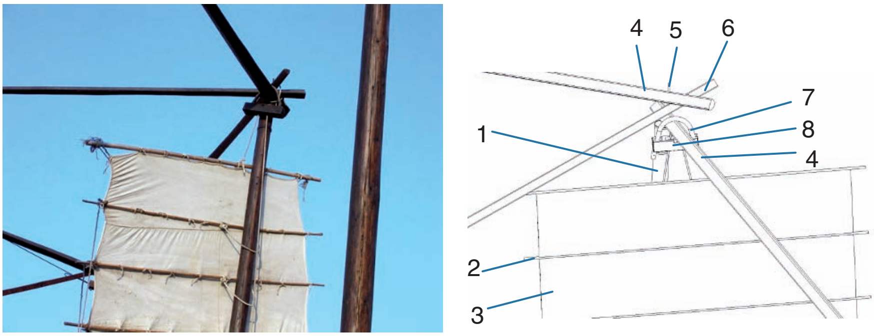
Fig. 6 The design of the “suspension base rod” to make enough space



a) b)

1 flat ring (花盤)
2 fastening bar (定科)
3 steel bracelet (金剛鐲)
4 spindle (車心)
5 top spoke (撐心)
6 cleek (鐵鉤)

Fig. 7 The installation of the top spoke



a) b)

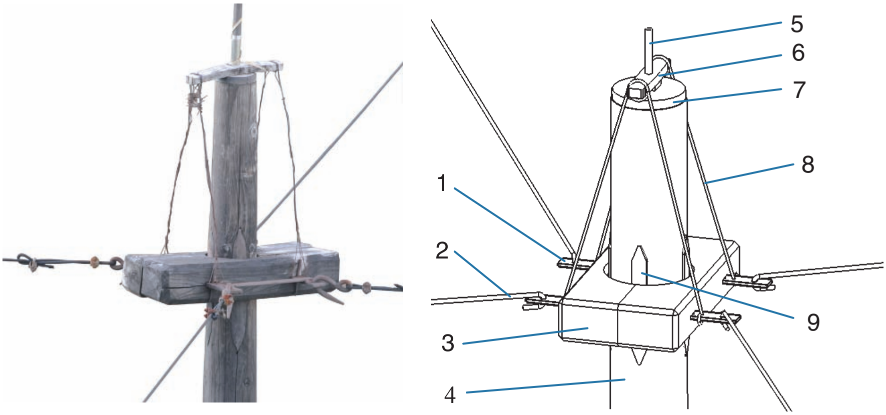
1 mast (桅子)
2 bamboo stick (蓬竹)
3 sail (風帆)
4 head hood (箍頭)
5 iron tenon (鐵桅榫)
6 top spoke (撐心)
7 handle (提頭)
8 pulley (鈴鐺)

Fig. 8 The installation of the top of the mast

A bearing sleeve (將軍帽, “general’s hat”) that is consisted of two wood blocks is placed near the shaft collar (鐵角, iron sheath) on the upper end of the spindle, as Fig. 9 shows. It forms a sliding bearing system, which allows the spindle to rotate freely in the circular hole in its center. The bearing sleeve is held in place by tying four big cables (大纜) through the holes on the two iron latches (閂子) that hold together the two wood blocks. The four cables have iron rings that can go onto the frame (幢子木). From the iron rings two additional cables are extended downward and tied to iron pegs.[2] Inserted at the lower end of the spindle is a bottom pole (母轉, “female turn”) whose interaction with the iron needle (公轉, “male turn”) on the stone pedestal (車心石). It forms a bearing device (as Fig. 10 shows), allows the spindle to spin freely atop the iron needle by minimizing the friction and the resistance generated by the rotation of the windmill while the iron needle upholds the windmill’s weight of more than 700 kg.

The sails (風帆) on the windmill, like the leaves on the water wheels, are used to collect energy. The design for the sails is inspired by the Chinese vertical sails (fore-and-aft sails). There are eight masts and eight sails, allowing the windmill to be driven by winds from all directions without being influenced by any change in wind direction, thus making it a unique propulsion system as Fig. 11 shows. Two kinds of materials were used to make sails in our research: cloth and bulrushes (蒲草, the stem or leaf of cattail). The cloth sail has a length of 4 m and a width of 2 m. Because sails made of bulrushes are more permeable, the length is increased to 4.5 m. On the surface of the sails there are in all ten bamboo sticks (蓬竹), which form the sail’s framework (桁骨) as Fig. 8 shows. Each sail is hung on the mast by the use of rope handles (包桅, “mast wrapper”) and knots (蓬紐子, “bamboo button”). Tied to the top of each sail is a halyard (升帆索), which is hung above the pulley (鈴鐺) on the head hoop that connects two masts on top. Tied to the halyard is a looped rope (力索) that can be tied to the base rods at the bottom of the windmill wheel, can be used to adjust the height of the sails of the windmill as sails on a boat. With the masts as the axes, the sails can be divided into a longer and a shorter side. The bamboo sticks that form the sail’s framework on the longer side has a sheet (帆腳索) tied to it, and the other end of the sheet is tied to the neighboring mast and its crossing rods (剪). The sheet is used to change the size of the windward surface. Thus, depending on the wind velocity, the halyard can be used to control the height of the sail and the length of the sheet to change the angle between the sail and the wind direction to control the rotation speed of the windmill. If the wind is strong, the looped rope on the base rods at the bottom of the windmill wheel can be released one by one so that the sails are lowered gradually to keep the windmill from getting destroyed by the sudden drop in velocity.

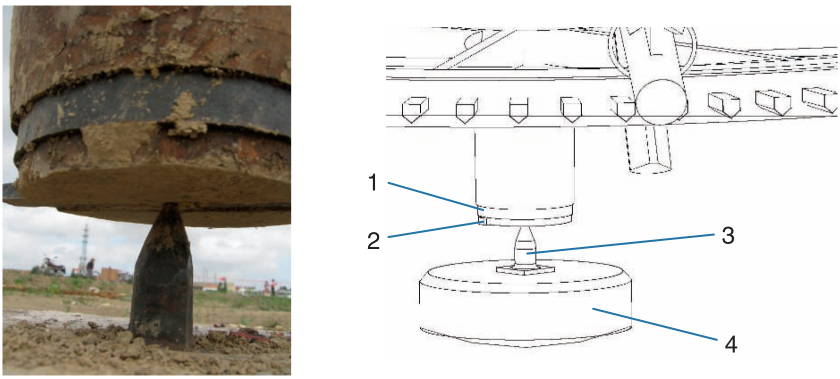
2 In the first model built in Haihe, only one extension cable was used to tie to the stone column on the nearby ground.



a) b)

1 iron latch (閂子)
2 big cable (大纜)
3 bearing sleeve (將軍帽)
4 spindle (車心)
5 top axle (天軸)
6 top pole (天扁擔)
7 top hoop (天龍箍)
8 top wire (天纜)
9 shaft collar (鐵角, iron sheath)

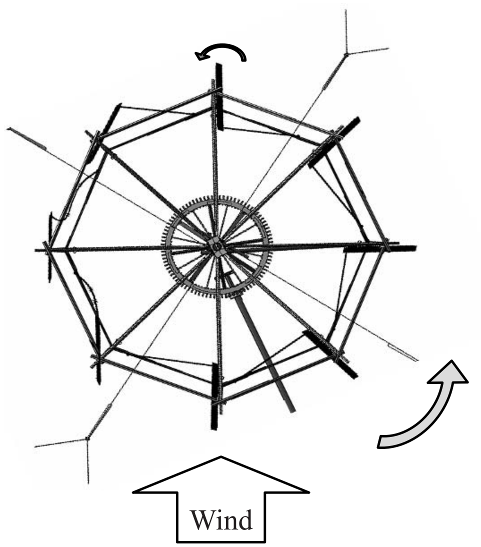
Fig. 9 The bearing device of the top of the spindle



a) b)

1 bottom hoop (地龍箍)
2 female turn (母轉) or bottom pole (地扁擔)
3 male turn (公轉) or iron needle (踏針)
4 pedestal stone (車心石)

Fig. 10 The bearing device of the bottom of the spindle



a)

b)

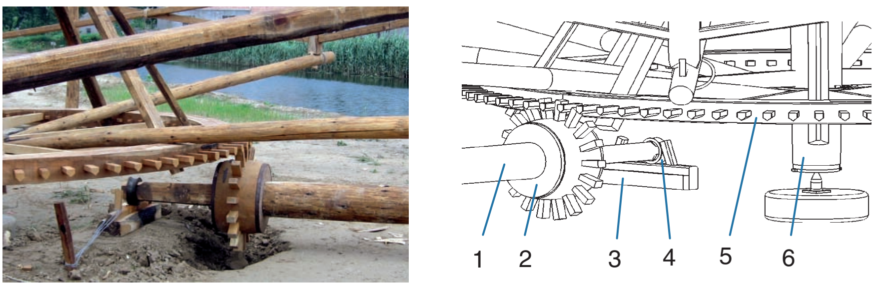
Fig. 11 (**a**) The position of the sails while against the wind; (**b**) The bulrush sails and its rig

Transmission System

The transmission system includes a gear mechanism, the transmission shaft, and a keeled chain drive (龍骨鏈條傳動).

The gear mechanism is made up of a level gear wheel (平齒輪) and a "land gear" (旱撥) as Fig. 12 shows. The level gear wheel is actually a big "spoke-type spur gear wheel" (輪幅式正齒輪) with 88 cogs (棰, tooth). The diameter of its outer circumference is typically about 3.5 m. Because of its large size, its rim (車輞) is generally multiple-spline. The body of the rim is made up of six arc-shaped sections (大輞, large rim) that are jointed together by small wood arcs (小輞, small rim) and are fastened by its cogs. The rim is made from mulberry wood, whose large size, high density, and hard texture allow it to be processed multiple times. The land gear is a vertical gear wheel that is shaped like a flattened barrel. It has 18 equally-distributed cogs on its side and is attached to near the end of the transmission shaft. As the level gear wheel drives it to turn, it in turn rotates the transmission shaft.

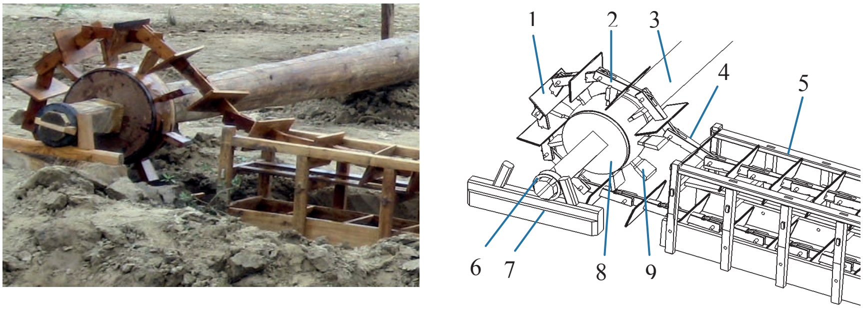
The transmission shaft interacts with the windmill and the pump through the aforementioned land gear (旱撥, driven gear) and a water gear (水撥, driving sprocket) attaching near its two ends, respectively. An iron bearing (旱撥釧 and 水撥釧) with an inner octagonal hole is attached by a trapezoidal wood block to each of the two ends of the transmission shaft (as Figs. 12 and 13 show). The groove in its circular rim allows it to roll and spin freely on the bearing pedestal (遊子). As with other traditional roller bearing systems, vegetable oil is often used when lubricating the groove, which makes meshing between gears tighter and the rotations more smooth.



a) b)

1 transmission shaft (跨軸)
2 land gear (旱撥, driven gear)
3 bearing pedestal (遊子)
4 iron bearing (釧,旱撥釧)
5 level gear wheel (平齒輪)
6 spindle (車心)

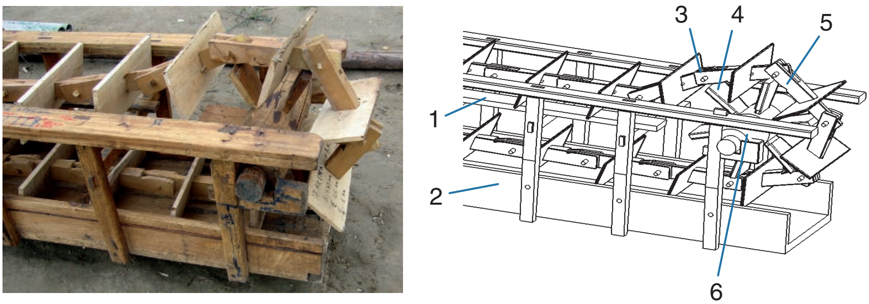
Fig. 12 The installation of the gear mechanism



a) b)

1 square board (柫板)
2 chain-piece (鶴子)
3 transmission shaft (跨軸)
4 keel chain (龍骨)
5 trough (槽筒)
6 iron bearing (釧,水撥釧)
7 bearing pedestal (遊子)
8 water gear (水撥, driving sprocket)
9 water tooth (水齒)

Fig. 13 The installation of the land gear



a) b)

1 middle board (行柫)
2 trough bucket (槽筒)
3 keel chain (龍骨)
4 water tooth (水齒)
5 chain-piece (鶴子)
6 small wheel (杌搬子, driven sprocket)

Fig. 14 The installation of the small wheel (杌搬子)

The keeled chain drive is composed of the water gear, the keel chain (龍骨), and the small wheel (杌棳子, driven sprocket). The water gear, rotated by the moving transmission shaft, is the "driving sprocket" of the system as its movements drive the keel chain and the driven sprocket. Both its main body and the diameter of its center hole which the transmission shaft goes through are smaller than those of the land gear. Unlike the cogs on the land gear, the nine water teeth (水齒) on the water gear are flat and wide. The transmission system operates basically by having the chain-pieces (鶴子) meshing with the water gear and small wheel (i.e. the driving and the driven sprockets). The upper parts (top land) of the water teeth of the water gear mesh with the notches on the tail end of the chain-pieces, as Fig. 13 shows, while the upper parts of the water teeth of the small wheel mesh with the point where two connects, as Fig. 14 shows. This form of meshing is seldom seen in the modern chain systems.

The Pumping System

The pumping system is essentially the chain transmission system plus the trough bucket (槽筒). With its scraper chain transmission (刮板式鏈條傳動裝置), it is one of the most unique chain-pumps in the world as Fig. 15 shows.

The water pump is composed of the trough bucket, the keel chain, the water gear, and the small wheel. The tail of the trough bucket is hung from a wood tripod, with the lower part of the small wheel immersed in the water, while its front section is connected to the water gear on land. The rotation of the water gear causes the keel chain and the small wheel to move, allowing the square boards (桲板) of the keel chain (龍骨) to continuously "pump" water.

The trough bucket (槽筒) is box-shaped, with its width set to match with that of the square boards. The trough bucket is divided into an upper and a lower section by a middle board (行桲), which prevents the moving square boards in the upper section from crashing into the square boards that take up water in the lower section and thus halting the entire process. The trough built for the reconstruction project measures 6 m in length, which is suitable to use with a higher water source. Instead of being perfectly linear as most modern diagrams show, the trough is actually slight arched to reduce the space between the distance between the square boards and the bottom of the middle board to ensure the efficiency of the pumping system. The small wheel at the tail end of the trough bucket has six water teeth, which are flat and wide like the water teeth on the water gear rather than rod-like as those on the land gear.

The keel chain is made up of a series of interchangeable links. Each link has four parts: a square board, a chain piece, a circular wood pin (梘子), and a smaller wood pin (逼桲). The chain piece is a part of the transmission, the square board is a workpiece. Thus, each link of the keel chain is that a transmission part is a workpiece too.

a)

b)

Fig. 15 The installation of the Chinese square-pallet chain-pump

Each chain piece is convex in the front end and concave in the tail end, with a hole in each of the two ends. A circular wood pin is inserted into the hole to hold two chain pieces together; it also allows the chain piece to be rotated at an angle. The square board is fastened by a smaller wood pin to the front end of the chain piece. The tail end of the chain piece has a small notch, which the water tooth of the water gear can fit in to propel movement as Fig. 13 shows. It is sometimes necessary to check if the water gear meshes with the keel chain and determine if the length of the chain is appropriate by doing a test run; and the extra chain pieces from the overlong chain can then be removed and used as spares. Within the trough bucket there is also a anti-reversing device (搭楔子), which prevents the chain from moving backward, thus ensuring that the windmill can move in one direction only.

Conclusions

The vertical shaft type wind-power Chinese square-pallet chain-pump is the culmination of the Chinese traditional irrigational technology. It epitomizes China's most representative and influential traditional technologies, encompassing knowledge in woodwork, metalwork (casting and forging), sailing, mechanics, gear mechanism, bearing, rope/pulley and chain drive. It further illustrates the most important characteristics of Chinese traditional technology: its innovativeness, generalizability, easy adaptedness to local conditions, and versatility. As the techniques and craftsmanship for these chain-pumps and Chinese great windmills are finally documented and preserved, their principles and mechanisms are also becoming better understood. And as the full meaning behind the old folk song that [2]

> "The Big General stands imposingly against winds from all sides
>
> Each of its eight masts turns with the wind
>
> With a hat on top and a needle underneath
>
> It spins freely on both land and water, bringing water to everywhere.

(大將軍八面威風，小桅子隨風轉動，上戴帽子下立針，水旱兩頭任意動。)

finally being fully appreciated, the knowledge gained from the reconstruction research will no doubt keep the chain-pumps and Chinese great windmills alive well into the future.

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References

1. Liu YZ (Southern Song dynasty), Tiao xi ji – Wenyuange Siku Quanshu (苕溪集 – 收入《文淵閣四庫全書》), Taiwan Commercial Press, Taipei, 1983, No. 1132.
2. Chen L (1951) "Why Were Wind Power Not Generally Used in North China? – An Investigation Report on the Windmill of the Coastal Area near Bohai Sea", Chinese Science Bulletin, Beijing, China, No. 3, pp. 266–268.
3. Liu XZ, (1962) History of Chinese Ancient Mechanical Engineering, Science press, Beijing, China, pp. 59–60.
4. Needham J (1974) Science and civilization in China (Volume IV: 2), Cambridge University Press, London, UK.

5. Lu JY (1999) Ancient Vertical-axle-styled Windmill, Root Exploration, Zhengzhou, China, No. 3, pp. 39–41.
6. Yi YQ, Lu JY (1992) An Textual Research and Rebuilding of Chinese Ancient Vertical-axle Great Windmill. Agricultural Archaeology, Nanchang, China, No. 3, pp. 157–162.
7. Zhang BC (1995) A New Research on The Structures and Principles of Chinese Wind-Driven Square-Pallet Chain-Pumps, Studies in the History of Natural Science, Beijing, China, No. 3, Vol. 14, pp. 287–w296.

An Approach for the Reconstruction Synthesis of Lost Ancient Chinese Mechanisms

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Abstract This paper presents a systematic approach for the reconstruction of all possible topological structures of lost ancient Chinese mechanisms. This approach utilizes the idea of creative mechanism design methodology to converge the divergent conceptions from the results of literature studies to a focused scope, and then applies the mechanical evolution and variation method to obtain feasible reconstruction design concepts that meet the scientific and technological standards of the subjects' time period. Three examples, such as south pointing chariots, Zhang Heng's seismoscope, and Su Song's escapement regulator, are provided.

Keywords Mechanism, Reconstruction synthesis and design, History of machinery, Creative mechanism design

Introduction

In the long history of Chinese civilization, many ingenious machines were invented. However, due to incomplete documentation and loss of finished objects, most of the original machines cannot be verified and many of the inventions did not pass down to later generations. In past years some reconstruction designs of lost machines in ancient China were brought into existence based on literature studies, and with or without the help of modern science and technology. However,

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these designs were mainly based on personal knowledge and judgment, and the results may not be solidly functional and proven. Furthermore, very few scholars studied lost ancient machines, those with some literary records but without surviving hardware, especially based on a systematic approach.

In the past several decades, some major methodologies were developed for the structural synthesis of mechanisms [1–3]. The objective here is to briefly present a systematic approach, based on a methodology for creative mechanism design [2,3], to re-generate the topological structures of mechanisms of lost ancient machines that are consistent with historical records and the levels of ancient technology and craftsmanship subject to design specifications, requirements, and constraints [4].

Procedure of Reconstruction Synthesis

Figure 1 shows the procedure of reconstruction synthesis [4]. It includes the following four steps:

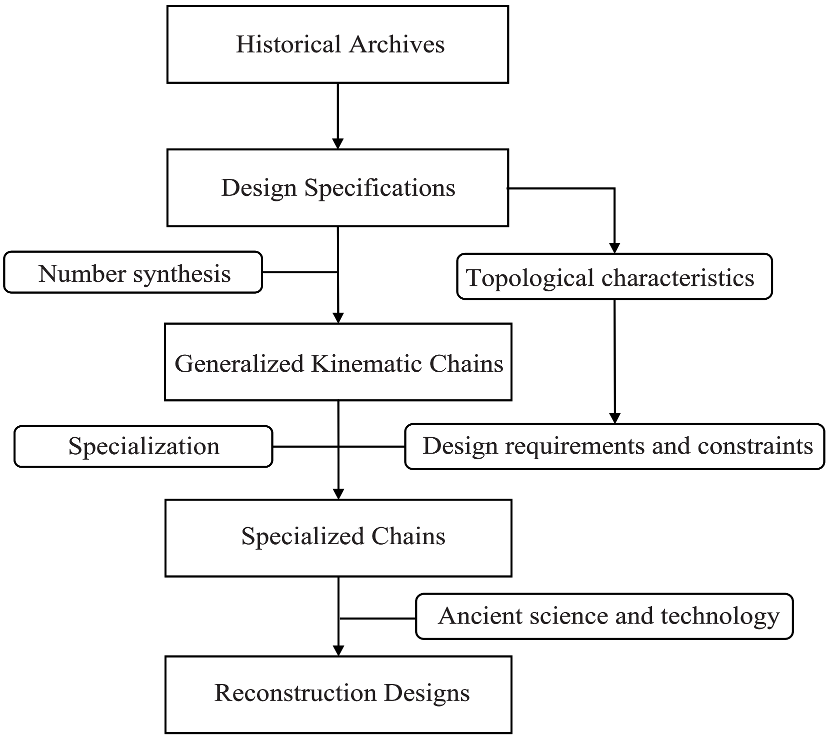


Fig. 1 Procedure of the reconstruction synthesis [4]

Step 1. Develop design specifications of the mechanism of the lost machine based on the study of available historical archives, and conclude the topological characteristics of the mechanism.

Step 2. Obtain the atlas of generalized kinematic chains with the required numbers of members and joints as specified in Step 1, based on the algorithm of number synthesis.

Step 3. Assign required types of members and joints to each generalized kinematic chain obtained in Step 2, and based on the process of specialization, to have the atlas of specialized chains subject to concluded design requirements and constraints.

Step 4. Particularize each specialized chain obtained in Step 3 into its corresponding schematic format to have the atlas of reconstruction mechanisms that meet the science and technology standards of the subject's time period by utilizing the mechanical evolution and variation theory to perform a mechanism equivalent transformation.

The reconstruction of ancient machines requires exhaustive literature study to clearly recognize and define the problem in order to develop design specifications. It is also important to be familiar with the available science and technology of the subjects' time period. Mechanical elements and mechanisms of lost ancient machines may be different in different dynasties. Based on the developed design specifications or by studying the topological characteristics of mechanisms of available existing designs, design requirements and constraints can be concluded. They are normally identified based on technology reality and designers' decisions. Different design requirements and constraints result in different atlases of specialized chains.

The second step of the reconstruction synthesis methodology is to obtain the atlas of generalized kinematic chains with the required numbers of members and joints as specified in the concluded topological characteristics of mechanisms [2, 5]. A generalized joint is a joint in general; it can be a revolute joint, spherical joint, or some others. A generalized link is a link with generalized joints; it can be a binary link, ternary link, and etc. A generalized kinematic chain consists of generalized links connected by generalized joints. It is connected, closed, without any bridge-link, and with simple joints only. The topological structure of a generalized kinematic chain is characterized by the number and the type of links, the number of joints, and the incidences between links and joints.

The core concept of this methodology is specialization [2, 6]. The process of assigning specific types of members and joints in the available atlas of generalized kinematic chains, subject to certain design requirements and constraints is called specialization. And, a generalized kinematic chain after specialization is called a specialized chain.

In what follows, three examples for the reconstruction synthesis of the topological structures of mechanisms of lost ancient Chinese machines are presented based on the process shown in Fig. 1.

South Pointing Chariots

Many ancient Chinese legends refer to the mysterious invention of the south pointing chariots. And, there were various literary works regarding south pointing chariots in different dynasties in ancient China [4,7,8]. An important one is as follows [9]: *The south pointing chariot originated from the Yellow Emperor. During the battle of Zhuolu, Chi You conjured up thick fog that blurred the vision of the Yellow Emperor's men. The Yellow Emperor thus invented a south pointing chariot to find direction, and captured Chi You.*『指南車起於黃帝。與蚩尤戰於涿鹿之野，蚩尤作大霧，兵士皆迷，於是作指南車以示四方，遂擒蚩尤。』

According to legend and historic records, it was said that Yellow Emperor (黃帝, ~ 2697–2599 BC) successfully invented south pointing chariots. However, they were not recorded in official literature and there was not enough evidence to support the argument. South pointing chariots appeared in some official literature from the time of the Three Kingdoms (220–280 AD) to the Jin Dynasty (1115–1234 AD). A solid design by Ma Jun (馬鈞) first appeared in the era of Three Kingdoms. And, there were two detailed records about the exterior shape and the interior structure of south pointing chariots in Song Shi《宋史》, including one design by Yan Su (燕肅) in 1027 AD and another by Wu De-ren (吳德仁) in 1107 AD. No records regarding south pointing chariots were found after the Yuan Dynasty (1206–1368 AD).

Yan Su's south pointing chariot, reconstructed by Z.D. Wang [10], contains ropes and pulleys for pulling the gears. In fact, in ancient China, the developments of labor-saving devices were very mature and had various applications, especially the rope-and-pulley mechanisms. Besides, the friction wheels have the function of transmitting continuous rotational motion and the advantage of simplicity in structure. Therefore for the reconstruction synthesis of the fixed-axis wheel south pointing chariots with ropes, pulleys, gears, linkages and friction wheels, design specifications are defined as:

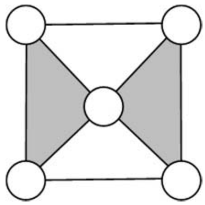
1. The number of links is four.
2. The degree of freedom is one.
3. The mechanical components are links, gears and frictional wheels.

For a planar mechanism with one degree of freedom and four links (three members and one rope), the number of joints is five (one joint with two degrees of freedom, two joints with one degree of freedom and two fixed joints). Therefore, the generalized kinematic chain has four links and five joints, Fig. 2a.

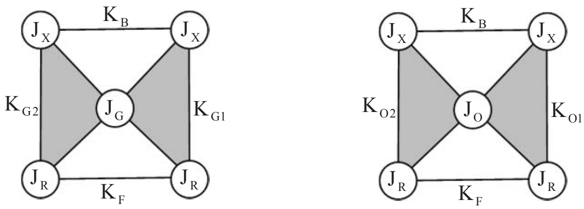
Here, the design requirements and constraints of the rope and fixed joint are:

1. The rope must be a binary link.
2. The rope can not be adjacent to the frame.
3. Any joint incident to the rope must be a fixed joint.

And, only the link which is not adjacent to the frame can be assigned as the rope. Two results are obtained as shown in Fig. 2b.



a) Generalized chain



b) Specialized chains

Fig. 2 Atlases of generalized kinematic chains and specialized chains of south pointing chariots

Based on the process of specialization, the characteristics of members and joints are assigned. The simplest solution with a direct connection is chosen. As a result, six specialized chains are obtained. Figure 3 shows the corresponding design concepts from the atlas of specialized chains, in which Fig. 3e is Wang's design. And, Fig. 4 shows a physical reconstruction design of differential type south pointing chariots [7].

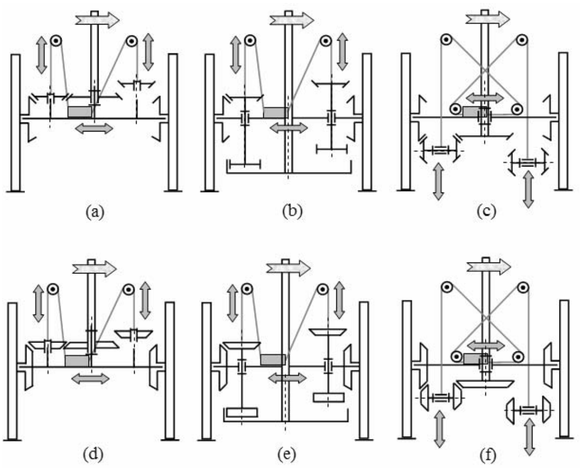


Fig. 3 Synthesized mechanisms of south pointing chariots

Fig. 4 A reconstruction design of differential type south pointing chariot [7]

Zhang Heng's Seismoscope

Researches in the relevant literature show that the earliest seismoscope named *Hou Feng Di Dong Yi* (候風地動儀) was invented by Zhang Heng (張衡) in the Eastern Han Dynasty (25–220 AD) [4,11,12]. This instrument was designed to indicate not only the occurrence of an earthquake but also the direction to its source. The historic records in the Biography of Zhang Heng in the History of the Later Han Dynasty《後漢書·張衡傳》[13] are the most complete ones about Zhang Heng's seismoscope, such as the following description: ...*The instrument was cast with bronze. The outer appearance of it was like a jar with a diameter around eight chi. The cover was protruded and it looked like a wine vessel. ... There was a du zhu (a pillar) in the center of the interior and eight transmitting rods near the pillar. There were eight dragons attached to the outside of the vessel, facing in the principal directions of the compass. Below each dragon rested a toad with its mouth open toward the dragon. Each dragon's mouth contained a bronze ball. The intricate mechanism used was hidden inside the device. When the ground moved, the ball located favorably to the direction of ground movement would drop out of the dragon's mouth and fall into the mouth of a bronze toad waiting below. ... The direction faced by the dragon that had dropped the ball would be the direction from which the shaking came. ...*『… 以精銅鑄成，圓徑八尺，合蓋隆起，形似酒尊，…。中有都柱，傍行八道，施關發機；外有八龍，首銜銅丸，下有蟾蜍，張口承之。其牙機巧制，皆隱在尊中，覆蓋周密無際。如有地動，尊則振、龍機發、吐丸，而蟾蜍銜之。振聲激揚，伺者因此覺知。唯一龍發機，七首不動，尋其方面，乃知震之所在。… 』

However, the records that have passed down through history give a detailed account only of the outside of the instrument, Fig. 5 [14]; and with very few practical details regarding the mechanism inside the instrument, except for noting that inside there was a central pillar named *du zhu* (都柱) which was capable of lateral displacement along tracks in eight directions, and so arranged that it would operate a closing and opening mechanism.

Fig. 5 External appearance of Zhang Heng's seismoscope [14]

Based on the study of historical archives, the design specifications of Zhang Heng's seismoscope can be defined as:

1. There is one pillar in the center of interior and eight transmitting rods near the pillar.
2. The basic concept that a switch ball located on the top of the pillar is adapted. And, when an earthquake occurs, the switch ball can move on the transmitting rod.
3. The design must detect the direction of the first motion, no matter whether it is compressing or expanding.
4. There are eight devices in the design to detect eight principal directions. Each device has an interior mechanism as a seismometer inside and a recording system outside.
5. Each interior mechanism has a pillar as the ground link, a sensing link to respond to ground shake, a lever mechanism as a magnifier, and a transmitting rod at least. It is a planar mechanism with one degree of freedom.

And, the design requirements and constraints are:

1. It has a pillar as the frame in the center of the interior, and it has eight transmitting rods as channels near the pillar.
2. The switch ball which can move on the transmitting rod is held with the eight transmitting rods on the top of the pillar.
3. The design must detect the first motion of P-waves, no matter if it is compressing or expanding.
4. There are eight devices in the eight principal directions of the design. Each device has the interior mechanism as a seismometer and a recording system.
5. Each interior mechanism has at least a ground link, a sensing link, a connecting rod, a lever arm, and a transmitting rod.
6. It is a planar mechanism with one degree of freedom.

For the reconstruction synthesis of feasible mechanisms of Zhang Heng's seismoscope with a rope-and-pulley and with six members and eight joints, the design consists of a ground link (1), a sensing link (2), a pulley (3), a rope (4), a lever arm (5), a transmitting rod (6), a prismatic joint, a wrapping joint, a pin-in-slot joint, and five revolute joints.

Based on the procedure of reconstruction synthesis shown in Fig. 1, six interior mechanisms are synthesized, Fig. 6. And, Fig. 7 shows one of the reconstruction designs.

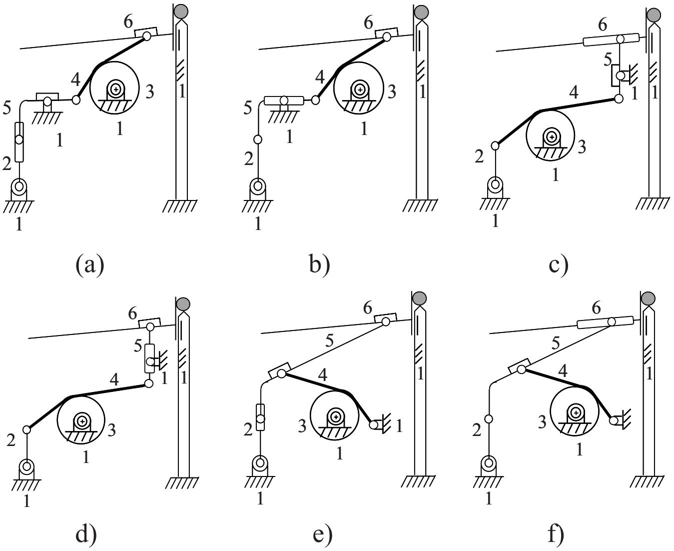


Fig. 6 Synthesized interior mechanisms Zhang Heng's seismoscope

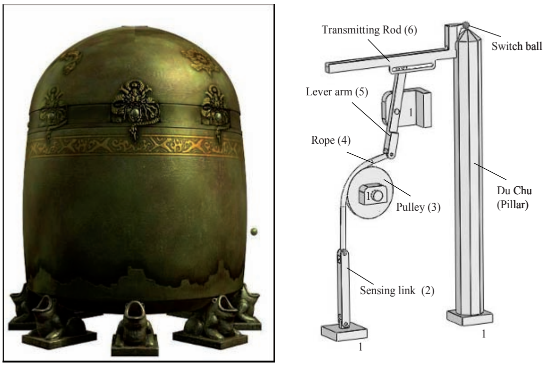


Fig. 7 A reconstruction design of Zhang Heng's seismoscope [4]

Su Song's Escapement Regulator

Su Song (蘇頌) of the Northern Song Dynasty invented a water-powered armillary sphere and celestial globe (水運儀象臺) around year 1088 AD, Fig. 8 [4,15–17]. This device was working based on a water-powered mechanical clock with an escapement regulator. Literary records are available for this invention, but unfortunately surviving hardware is lacking. However, several reconstruction designs have existed in the past century.

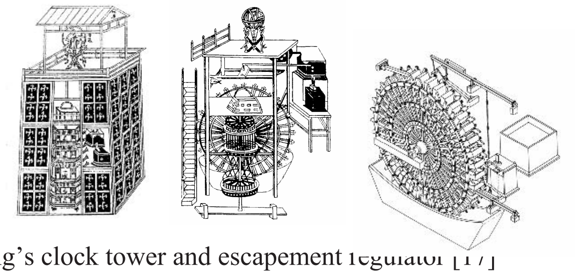


Fig. 8 Su Song's clock tower and escapement regulator [17]

Su Song wrote a book named New Design for an Armillary Sphere and Celestial Globe《新儀象法要志》during the period of 1088–1096 AD, documenting in detail the structure, components, and diagrams of the motion and structure of the water-powered clock tower. The book enabled the escapement regulator using the waterwheel and steelyard clepsydra mechanism to be handed down to future generations. The book read [17]: *The constant-level tank had a water-level marker. Water was lifted to a reservoir and poured into the upper reservoir. A constant-level tank was used to regulate water flow to maintain constant the speed and amount of water flowing from the upper reservoir. Water then flowed into the water-receiving scoops on the driving wheel. Since the water flow was maintained constant throughout the day, accurate time measurement was ensured. ... A lower balancing lever and a lower weight were located above the stopping tongue of the upper balancing lever. A free-spinning axle was located at the center of the lower balancing lever, which was held in place by two plates installed at the crossbar located at the north-south direction of the stand holding the constant-level tank. The tip of the lower balancing lever was a checking fork, which alternately checked and released the water-receiving scoops on the driving wheel. The lower weight was located on the opposite end of the lower balancing lever, which would rise or lower itself in accordance with the amount of water inside the water-receiving scoop.*『平水壺上有準水箭，自河車發水入天河，以注天池壺。天池壺受水有多少緊慢不均，故以平水壺節之，即注樞輪受水壺，晝夜停勻時刻自正。… 樞衡、樞權各一，在天衡關舌上，正中爲關軸於平水壺南北橫桄上，爲兩頰以貫其軸，常使運動。首爲格叉，西距樞輪受水壺，權隨於衡東，隨水壺虛實低昂。』

The development of ancient Chinese escapement regulators lies in the knowledge of clepsydra and lever technologies. In ancient China, applications of clepsydra and lever mechanisms were ubiquitous, with steady improvements in the structures, forms, and accuracy documented in historical records. The clepsydra, utilizing the steady flow of water from a reservoir and an arrow to indicate time, was the predominant timer used in ancient China. As for their structures, the floating clepsydra and the steelyard clepsydra were the two major types. The most popular lever mechanisms in ancient China were the *jie gao* (桔槔, a labor-saving lever with unequal arms) and *heng qi* (衡器, a weighing apparatus). An escapement can be made by integrating the *jie gao* as a force amplifier and the *heng qi* as a weight comparator to control the motion of the waterwheel. Thus, the design specifications of a water wheel steelyard-clepsydra device can be defined as:

1. It is an escapement regulator.
2. It has a waterwheel.
3. It has an independent input that has an isochoric and intermittent motion.
4. It has an escapement that can control the waterwheel motion.

And, the characteristics of the topological structure of this design are concluded as:

1. It is a planar six-bar mechanism with eight joints.
2. It has a ground link (member 1), a waterwheel (member 2), an upper balancing lever (member 3), a connecting rod (member 4), an upper stopping tongue (member 5), and a water-receiving scoop (member 6).
3. It has one upper stopping joint, one cam joint, and six revolute joints.
4. It has one degree of freedom.
5. It has one ground link with multiple incident joints.

Based on the procedure of reconstruction synthesis shown in Fig. 1, eight feasible designs for the waterwheel steelyard-clepsydra device with four-bar linkage are synthesized, including the original design shown in Fig. 8; and four of them are shown in Fig. 9. Furthermore, Fig. 10 shows a physical reconstruction design.

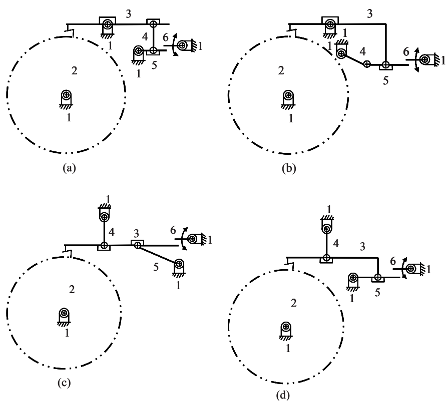


Fig. 9 Four feasible designs of the waterwheel steelyard-clepsydra device

Fig. 10 A reconstruction design of Su Song's waterwheel steelyard-clepsydra device [4]

Conclusions

This work is devoted to presenting an innovative methodology in the area of mechanical historiography for the systematic reconstruction synthesis of all possible topological structures of mechanisms of ancient Chinese machines that have been lost to time. If the concluded design specifications, topological characteristics, and design requirements and constraints are feasible, one of the resulting reconstruction designs should be the original concept. Such an approach provides a logical tool for historians in ancient mechanical engineering and technology to further identify the possible original designs according to proven historical archives.

References

1. Freudenstein F, Maki F (1979) The creation of mechanism according to kinematic structure and function, Environment and Planning B, Vol. 6, pp. 375–391.
2. Yan HS (1992) A Methodology for creative mechanism design, Mechanism and Machine Theory, Vol. 27, No. 3, pp. 235–242.
3. Yan HS (1998) Creative Design of Mechanical Devices, Springer, Singapore.
4. Yan HS (2007) Reconstruction Designs of Lost Ancient Chinese Machinery, Springer, Netherlands.
5. Yan HS, Hwang YW (1990) Number synthesis of kinematic chains based on permutations groups, Mathematical and Computer Modeling, Vol. 13, No. 8, pp. 29–42.
6. Yan HS, Hwang YW (1991) The specialization of mechanisms, Mechanism and Machine Theory, Vol. 26, No. 6, pp. 541–551.
7. Yan HS, Chen CW (2006) A systematic approach for the structural synthesis of differential-type South Point Chariots, JSME International Journal, Series C, Vol. 49, No. 3, pp. 1–10.
8. Yan HS, Chen CW (2007) Structural synthesis of South Pointing Chariots with a fixed axis wheel system, Transactions of the Canada Society for Mechanical Engineering, Vol. 31, No. 3, pp. 255–272.
9. Chi Bao (Jin Dynasty) (1966) Gu Jin Zhu – Notes on the Antiquity and Present Days (in Chinese), Taiwan Commercial Press, Taipei.
《古今注》；崔豹[晉朝]撰，台灣商務印書館，台北，1966年。
10. Wang ZD (1937) Investigations and reproduction in model form of the south pointing chariot and the hodometer (in Chinese), Beiping Academy of Sciences, Historical Journal, Beijing, No. 3, pp. 1–47.
王振鐸，”指南車記里鼓車之考證與模製”，史學集刊，科學出版社，第3期，北京，第1-47頁，1937年。
11. Yan HS, Hsiao KH (2007) Reconstruction design of the lost seismoscope of ancient China, Mechanism and Machine Theory, Vol. 42, pp. 1601–1617.
12. Yan HS, Hsiao KH (2008) Reconstruction design of Zhang Heng’s seismoscope with a rope-and-pulley mechanism, Journal of the Chinese Society of Mechanical Engineers (TAIWAN), Vol. 29, No. 2, pp. 89–97.

13. Fan Ye (Eastern Jin Dynasty) (1977) The History of the Later Han Dynasty (in Chinese), Ding Wen Publishing House, Taipei.
《後漢書》；范曄[晉朝]撰，鼎文出版社，台北，1977年。
14. Wang ZD (1936) Conjecture of Zheng Heng's Seismoscope, Yenching University Journal of Chinese Studies (in Chinese), Beijing, Vol. 20, pp. 577–586.
王振鐸，"漢張衡候風地動儀造法之推測"，燕京學報，第20卷，北京，第577–586 頁，1936年。
15. Yan HS, Lin TY (2002) A systematic approach to reconstruction of ancient Chinese escapement regulators, Proceedings of ASME 2002 Design Engineering Technical Conferences and Computers and Information in Engineering Conference (DETC'02), Montreal, Canada.
16. Yan HS, Lin TY (2002) A study on ancient Chinese time laws and the time-telling system of Su Song's clock-tower, Mechanism and Machine Theory, Vol. 37, No. 1, pp. 15–33.
17. Su Song (Northern Song Dynasty) (1969) Xin Yi Xiang Fa Yao (in Chinese), Taiwan Commercial Press, Taipei.
《新儀象法要》；蘇頌[北宋]撰，新儀象法要，台灣商務印書館，台北，1969年。

Robotics for Minimally Invasive Surgery: A Historical Review from the Perspective of Kinematics

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Abstract Since the widespread introduction of laparoscopic cholecystectomy in late 1989, the minimally invasive surgery (MIS) has been rapidly developed and applied to many classes of traditional surgeries. Along with the germination of the first surgical robot in 1985, it was not until April 1991 that the first robotically-assisted MIS was clinically applied to patients in a minimally invasive prostate surgery. Therefore, this paper is devoted to reviewing the development of robotics from the perspective of kinematics in MIS during the past twenty years taking account of the kinematic structures of the manipulator design of the robots. An exclusively kinematic geometry, namely the "remote center-of-motion", for MIS is reviewed by which a classification of MIS robots is concluded.

Keywords Minimally invasive surgery, Surgical robot, Remote center-of-motion, Kinematics

Introduction

Minimally Invasive Surgery (MIS) is a type of surgery whereby the surgical operation is done through small incisions. It has been rapidly developed since the introduction of laparoscopic cholecystectomy in late 1989 [1]. The basic operation concept of MIS is to insert the surgical instruments, e.g., the laparoscope, endoscopic camera, etc., into patient's body through small incisions so that the surgical

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operations can be implemented inside the patient's body at the proximal end of the tools that are maneuvered by surgeon's hands outside patient's body. Compared to open surgery, MIS has many advantages such as reduced risk of infection, less pain, bleeding and scarring, shorter hospitalization, and reduced recovery time, etc. It hence gradually became popular and dramatically replaced many traditional surgical procedures in open surgeries. Currently, the MIS are widely used in the fields such as endoscopy, percutaneous surgery, laparoscopic surgery, keyhole surgery, and microsurgery, etc.

Along with the fine development of hands-on surgeries, the surgical robots have been introduced to assist surgeons performing various surgeries for the past two decades. Compared to the hands-on surgeries, the robotically assisted surgery is a more precise operation that minimizes any potential damages which may be incurred from the negligence of surgeon's hands. A rigorous definition of "surgical robot" provided by Davies [2] states that "the surgical robot would be a powered computer controlled manipulator with artificial sensing that can be reprogrammed to move and position tools to carry out a range of surgical task". Briefly speaking, the surgical robot is a robotic manipulator which is used to assist surgeons to perform the surgical operations. Historically, the first surgical robot appears to be introduced by Kwoh who in 1985 used a standard industrial robot PUMA 560 to hold a fixture next to the patient's head to locate a biopsy tool for neurosurgery [3]. Since then, many surgeries began to attempt surgical robots as the assistive devices in operation rooms.

While MIS was thriving since 1989 and surgical robots was introduced in 1985, the first robotically assisted MIS was performed in 1991 by a robotic system "Probot". The Probot was developed based on a laboratory study at Imperial College London, UK and was clinically applied to patients in April 1991 in a minimal invasive prostate surgery [2]. After this work, a large number of MIS robots were continuously revealed, including the renowned da Vinci surgical system which was proposed in 1999 by Intuitive Surgical Inc., USA. Thus following the rapid development in the past years, the robotically assisted MIS have been widely accepted by worldwide surgeons and patients nowadays.

Distinguished from industrial robots, safety is a crucial design issue for surgical robots. Particularly in MIS, a special surgical geometry is exclusively presented to which the MIS robot should adhere to guard safety. In an MIS, the surgical instrument, usually held by a robotic wrist, is moved with relatively large angular mobility about a single point or within a limited spatial volume. In laparoscopy, for example, the instrument pivots at the point at which they enter the patient's body. Such constraint enforces the surgical tool being manipulated with four degrees-of-freedom (DOF), including three rotational DOFs pivoted at a point and one translational DOF whose axis moves through this point. This design consideration has inspired researchers to design the MIS robots to articulate a mechanism that can mechanically decouple rotational and translational motions of tools at a point some distance from the mechanical structure of the robot. This mechanism is so-called the "remote center-of-motion (RCM)" mechanism [4]. The RCM mechanism thus plays a principal role in the kinematic design of MIS robots.

This paper is, therefore, devoted to the review of robotics for minimally invasive surgery taking account of the kinematic design of the robotic manipulators. First, the historical development of MIS robots is introduced. Then, the special surgical geometry of MIS is presented, followed by the derivation of the remote center-of-motion mechanisms. Finally, the kinematic structures of the developed MIS robots are analyzed based on the embedded remote center-of-motion mechanisms. It should be noted that while a surgical robotic system may involve a group of automation devices such as the control system, sensing system, imaging system, etc., the discussion addressed in this paper focuses mainly on kinematic structures of the robotic manipulators.

The History of Robotics for Minimally Invasive Surgery

In review of the development of robotic surgery, most MIS robots were exclusively dedicated to the specific operations in MIS, majorly to endoscopic and laparoscopic surgeries. Even though there were perhaps some unpublished trial works that had been attempted in the early vintage, the earliest feasible models of MIS robots may be found in 1991 as we track the historical records of the development in commercial products and laboratory studies for MIS.

The commercial products of MIS robots was attributed to a dominated position promotion of robotically assisted MIS. Historically, the Computer Motion Inc., a US medical robotics company, could be regarded as the pioneer in promoting robotically assisted MIS. Founded in 1990, Computer Motion developed the first commercial MIS robotic systems in 1992 and performed its clinical application in laparoscopic cholecystectomy in 1993. In addition to Computer Motion's development, the Intuitive Surgical Inc., which is also a world-leading organization in producing MIS robots, announced the well-known da Vinci surgical system in 1999. The birth of da Vinci surgical system presents a milestone in robotically assisted MIS and it makes the MIS robots being widely marketed to the hospitals around the world. It promotes the robotically-assisted MIS as a prevailing surgical fashion.

Apart from the development of commercial products, some other distinguished laboratory studies of robotically assisted MIS had been conducted even several years earlier than the origination of commercial MIS robots. As early as in 1987 Imperial College London's Probot was designed, its clinical test was completed in 1991. This work is worth to be noted that it should be documented as the earliest MIS robot which has successful clinical application. Followed by this work, several laboratory studies were substantially started in developing the robots for various MIS applications.

In what follows, the history of robotics for MIS is reviewed in details. Both of commercial products and laboratory studies are described in parallel. Some notable works and milestones are of interests.

AESOP

The first commercial MIS robot in the world appears to be the AESOP (Automated Endoscopic System for Optimal Positioning) [5] in Fig. 1. In 1990, Computer Motion Inc., an US medical robotics company, was established in California, and the AESOP was their first major product developed in 1992. The AESOP is an endoscopic robot system for holding cameras in MIS that improves the problems of fatigue and hand tremor in traditional hands-on surgery. Its first clinical operation was done for a laparoscopic cholecystectomy in August 1993. It became the first medical robot approved by the FDA (Food and Drug Administration, USA) one month later [6].

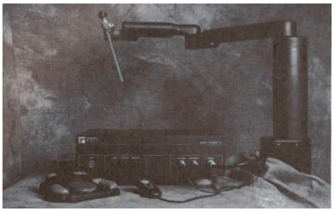
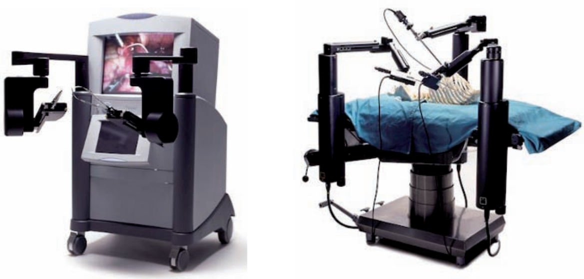


Fig. 1 The first commercial MIS robot: AESOP, 1992 [5]

Zeus

In 1995, Computer Motion began to investigate robotic solutions to other problems posed by laparoscopic surgery. They started to focus on the development of a master-slave robotic system for MIS. In 1998, by combining three modified AESOP arms into a whole, they announced the Zeus [7], which is a new telerobotic surgical system as shown in Fig. 2. Unlike AESOP, Zeus is a master-slave robot comprising of two parts, the master console and the slave robotic arms. The surgeon sits at the master console while manipulating the ergonomically designed controls. The surgeon's movements are translated and digitized by the computer system that allows controls of the slave robot arms even over distances of hundreds of miles. Three separate robot arms are attached to the operating table independently. One arm holds the camera and is essentially an AESOP. The other two hold surgical instruments that articulate near their tips with six DOFs [6].



a) Console b) Robot arms

Fig. 2 Zeus surgical system, Computer Motion Inc., 1998 [8]

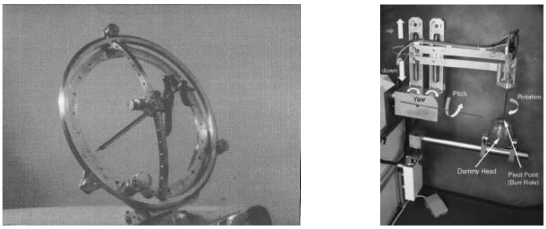
da Vinci
In parallel with Computer Motion's business, the Intuitive Surgical Inc. was founded in California in 1995. In January 1999, drawn from the researches of IBM and the Massachusetts Institute of Technology, Intuitive Surgical launched the da Vinci surgical system [9], Fig. 3. In 2000, it was cleared by the FDA for general laparoscopic surgery. Similar to Zeus, the da Vinci is also a master-slave robotic system in which the console part is provided for surgeon's manipulation and the slave part comprising of four robot arms is controlled to execute surgical operation. The four robotic arms are with two control strategies in which two are telemanipulated by surgeon and the other two are passive control by human assistants. In 2003, Intuitive Surgical merged with Computer Motion to form a global leader of robotically assisted MIS. Today, da Vinci surgical system has become the most widespread MIS robot around the world.

Notable Laboratory Studies
Along with the commercial products, there are some notable laboratory studies that are worth to mention in the history of robotics for MIS.

Before the germination of AESOP, some academic and industrial institutions had motivated their researches on robotically assisted MIS as early as in 1987, with Davies and his research group's "Probot" project on a preliminary feasibility study with manually powered robotic system on forty patients, Fig. 4a. It was not until April 1991 that an earlier generation of the Probot was powered under computer control with clinical application to five patients [10]. In addition to the Probot project, Davies el al. also proposed another MIS robot in 2000 specifically used for neurosurgery, Fig. 4b [11].

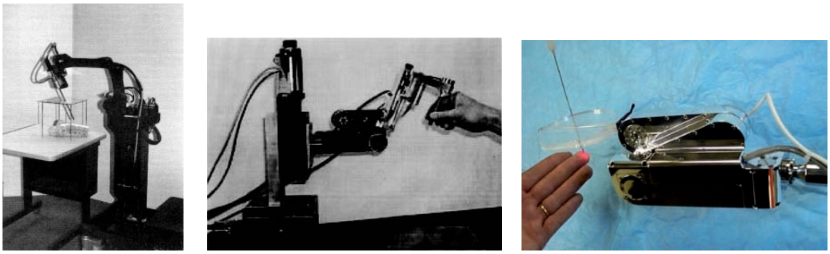
a) Console b) Robot arms

Fig. 3 Da Vinci surgical system, Intuitive Surgical Inc., 1999 [12]



a) Probot, 1991 b) Neurobot, 2000

Fig. 4 Two MIS robots developed by Imperial College London, UK [10,11]

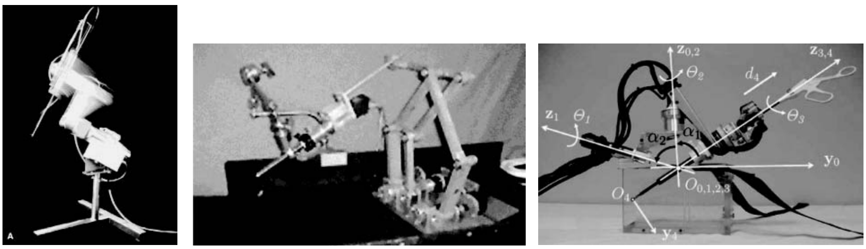


a) LARS, 1995 b) Steady-Hand, 1999 c) PAKY-RCM

Fig. 5 Three MIS robots developed by Johns Hopkins University/IBM, USA [13–15]

In parallel with Davies' efforts, Taylor who was working at IBM in USA was developing in collaboration with Johns Hopkins University a telerobotic assistant for laparoscopic surgery (LARS) [13] in Fig. 5a around 1995. Taylor then joined Johns Hopkins University as a professor in September 1995 and proposed another MIS robot as "Steady-Hand" in Fig. 5b for extending a human's ability to perform small-scale manipulation required by microsurgery [14]. In 1998, he and his colleague Stoianovici further designed the PAKY-RCM robot in Fig. 5c for percutaneous access surgery [15].

In addition to the pioneering works from England and America, the study of robotically assisted MIS at other areas started to surface several years later. In Germany, a project "ARTEMIS" for designing a robot for endoscopic surgery had been conducted since 1991 by Eberhard Karls University with collaboration from Karlsruhe Research Center, and the results were published in 1996 [16]. A master-slave robotic system Fig. 6a was designed with two robotic arms which hold two steerable laparoscopic instruments. In Japan, the University of Tokyo proposed a needle insertion manipulator for CT-and MR-guided stereotactic neurosurgery in 1998 [17] and a robotically-assisted laparoscopic surgery in 1999 [18] as in Fig. 6b. In France, a new robot namely "MC^2E" was devoted by the University of Paris in 2004 for the laparoscopic surgery [19] in which the manipulation force can be measured, Fig. 6c. In summary to the above results, Fig. 7 shows the chronology and the geographical distribution of some developed MIS robotic systems around the world.



a) b) c)

Fig. 6 Examples of MIS robots developed in Germany, Japan, and France. (**a**) ARTEMIS, Germany, 1996 [16]; (**b**) University of Tokyo, Japan, 1999 [18]; (**c**) MC^2E, France, 2004 [19]

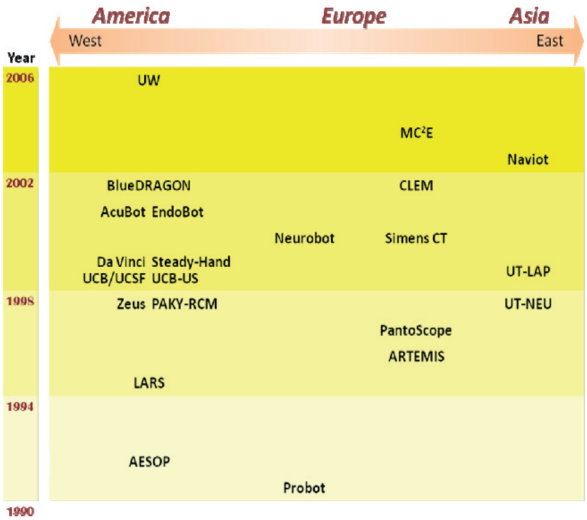


Fig. 7 Chronology and geographical distribution of sample MIS robotic systems[1]

Remote Center-of-Motion Mechanisms

Before discussing the kinematic structures of MIS robots, a special mechanism called the "remote center-of-motion mechanism" is worth to pay attention. In what follows, the DOFs of the surgical tools required by general MIS operations are discussed. It follows with the discussion of the remote center-of-motion mechanisms.

Surgical Tool DOFs

The most distinguished characteristic of an MIS operation is that the surgeon needs to maneuver the surgical tools working with large angular mobility about a single point or within a limited small spatial volume. In laparoscopic surgery, for example, a surgical instrument is inserted into patient's body through a small trocar inserted into the abdominal wall at which the instrument is pivoted at the trocar. This arrangement forms a "fulcrum effect" at patient's abdominal wall (or skin) that the instrument has only four DOFs (three rotations and depth of penetration) centered at the entry point. Only very constrained lateral motions are acceptable that they are almost ignored when considering the mobility of the surgical instruments for MIS. Figure 8 illustrates the active four DOFs in a laparoscopic surgery. As one can see, the three rotational DOFs, usually called the pan-till-spin motions or the roll-pitch-yaw motions used in kinematics, are centered at the trocar point; the only one translational DOF, dedicated to the insertion and retraction for the tool, moves through the point at which the rotations are pivoted.

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[1] Detailed information of the denoted robotic systems refers to Table 1.

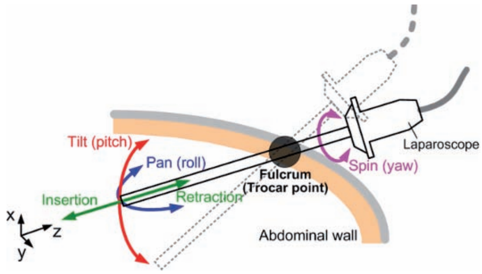


Fig. 8 Mobility of an MIS surgical tool—example in laparoscopic surgery

Remote Center-of-Motion (RCM)

The particular mobility required by the MIS surgical tools are of course an important factor in determining its manipulator design. This led the researchers to develop mechanisms that can naturally (mechanically) decouple rotational and translational motions of tools at a point some distance from the mechanical structure of the robot. To come up with this, the concept of *remote center-of-motion* (RCM) [4] was devised. The remote center-of-motion of a mechanism is geometrically a point at which one or more rotational motions are centered and these motions are under "remote-control" by the mechanism. The "remote-control" may be realized as that the controlled point is *not* located on the mechanism—it locates elsewhere outside the mechanism. With correspondence to the MIS operation, the RCM could be located at none other than somewhere on the surgical instrument, and, of course, will be coincident to the entry point of the tool. This design makes the possibility for MIS robots that the robot can work with large workspace outside patient's body but the holding instrument naturally keeps the pivoted motions when operating. It also simplifies the control of manipulators and automatically avoids the potential hazard both for the surgeon and patient caused by any control or coordination failure. For instance, Fig. 9 is an RCM robot for ultrasonography. One can image that no matter what the robotic arm is posturing, the ultrasound probe is always pivoted at the entry point on throat subject to the special arrangement of the RCM mechanism.

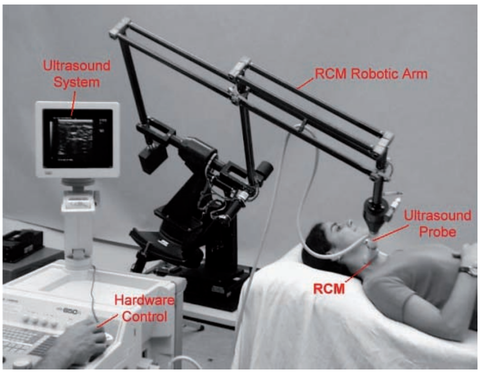


Fig. 9 The remote center-of-motion robot for ultrasonography [20]

Kinematic Structures of MIS Robots

From the viewpoint of kinematic structures, most MIS robots are constructed by two patterns. One is using a serial-type manipulator as the positioning arm and attaching an RCM mechanism to its end as a wrist, while the other is using a parallel-type manipulator that possesses the feature of RCM mechanisms. For the serial-type, the surgical tool is held by the robotic wrist whereby the RCM function can be achieved solely by the kinematic constraint of the RCM mechanism. For the parallel-type, the surgical tool is instrumented on the moving platform and the RCM function is achieved by either suitable control of platform legs or the kinematic constraint of the platform. From the review, almost all developed MIS robots are serial-type that require less working volume and have greater angular orientation and their RCM function could be separately designed form the robot coordination.

It should be reminded that for a general MIS operation the mobility of the surgical tool is required by three pivoted rotations plus one translation though sometimes they are not all needed by some specific MIS procedures. In most MIS robots, whether they are serial- or parallel-type, the manipulator generally provides only two pivoted rotations (till and pan) for the RCM. The other two DOFs (spin and depth of penetration) are in general achieved by the motors instrumented on the surgical tool itself.

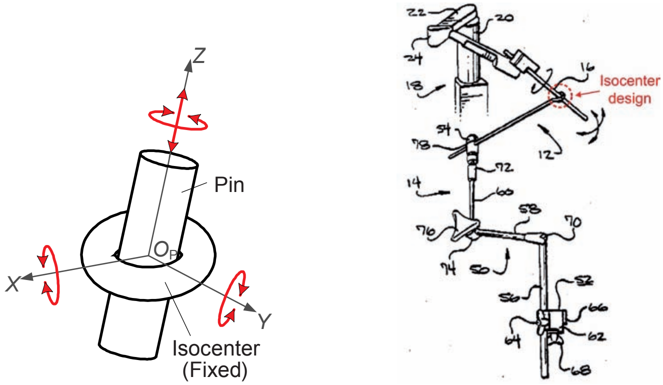
Based on the mechanism types, the RCM mechanisms used for MIS robots can be classified by eight types as isocenters, circular tracking arcs, parallelograms, synchronous belt transmission, spherical linkages, parallel manipulators, compliant mechanisms, and passive RCMs. Each type is introduced as follows.

Isocenters

The most intuitive and the easiest design for producing pivoted motions is the use of isocenters. Isocenter is conceptually composed of a circular ring for constraining an object which moves inside the ring. From the viewpoint of kinematics, the contact between the isocenter and the guided object can be regarded as a 4-DOF pin-in-ring joint as Fig. 10a. Figure 10b shows an example of isocenter-based RCM mechanism used in the robotic arms of the Zeus surgical system [7] (also see Fig. 2). Under the kinematic constraints from the guiding robotic arm and the isocenter, the Zeus' RCM mechanism has 3 DOFs, i.e., three rotations pivoted at its RCM point.

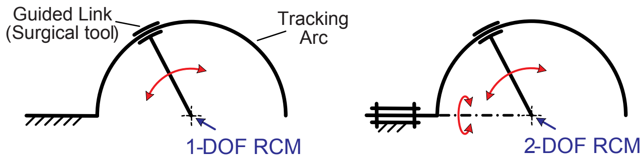
Circular Tracking Arcs

The structurally simplest way to produce RCM mechanisms is to use circular tracking arcs. The fundamental concept is to provide a circular track as the base and let a passive member sliding on it. Accordingly, a 1-DOF RCM can be found in the curvature center of the track. Figure 11a shows the concept of this design. Furthermore, if the tracking arc is pivoted to the base by a revolute joint whose axis passes through the RCM point, an additional rotational DOF will be added to the RCM point, Fig. 11b. The Probot (Fig. 4a) use this concept as its RCM mechanism. As shown in Fig. 12a, Probot uses a double circular tracking arcs mechanism to generate a 2-DOF RCM. The mechanism is connected by a slider that serves as the positioning arm for the system. Another example is the UT-NEU which was developed by University of Tokyo for neurosurgery, Fig. 12b. A 3-DOF positioning table is used as its positioning arm and a 2-DOF RCM circular tracking arc is adopted as the RCM mechanism. An additional translational motion for the surgical tool is provided by the motor which is instrumented on the holder of the surgical tool. It can be found that the generated rotations at the RCM point for this type of RCM mechanisms are decoupled, i.e., each rotation can be controlled independently.



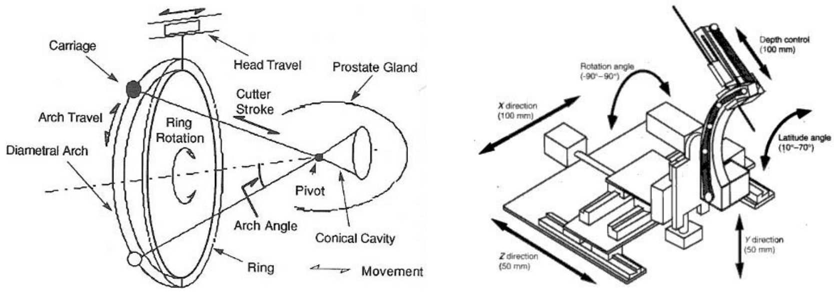
a) Fundamental concept of isocenters b) Isocenter design in Zeus [21]

Fig. 10 An MIS robot using isocenter RCM design



a) 1-DOF RCM b) 2-DOF RCM

Fig. 11 Fundamental concepts of RCM mechanisms using circular tracking arcs



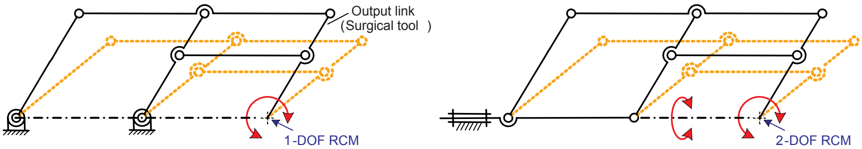
a) Probot b) UT-NEU

Fig. 12 Two MIS robots using circular tracking arc RCM designs [10,17]

Parallelograms

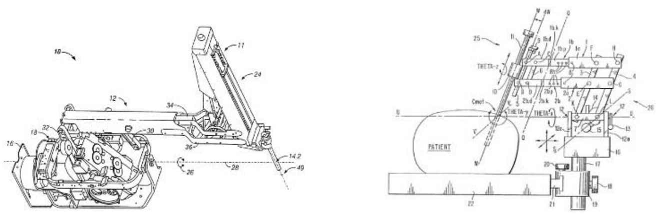
The most familiar RCM mechanism used by MIS robots appears to be the parallelogram-based design. Figure 13 shows the basic concepts of generating an RCM via the parallelograms. In Fig. 13a, based on the combination of two parallelograms, the RCM can be located at the point where two adjacent sides of the either parallelogram are intersected. Similar to the design concept of circular tracking arcs, when the driving parallelogram is pivoted to the base by a revolute joint whose axis passes through the RCM point, the mechanism will receive one additional rotational motion for its RCM point, Fig. 13b. By following this logic, more other parallelogram-based RCM mechanisms can be generated by assembling different parallelograms into together [22].

There are many robotically assisted surgical systems adopting the parallelogram-based design as their RCM mechanisms. For example, the da Vinci (Figs. 3 and 14a), LARS (Fig. 5a and 14b), UCB-US (Figs. 9 and 14c), BlueDRAGON (Fig. 14d), etc. These RCM robots have two rotational DOFs with orthogonal axes at an RCM point. Figure 15, however, is another design of parallelogram mechanisms used for generating the RCM with two non-orthogonal axes by means of two parallelograms.

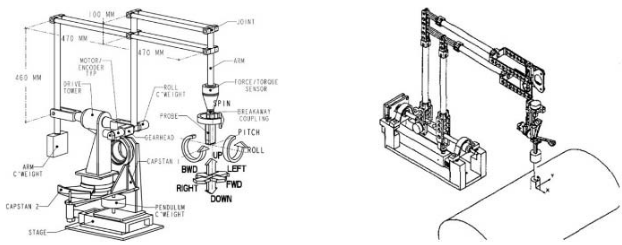


a) 1-DOF RCM b) 2-DOF RCM

Fig. 13 Fundamental concepts of parallelogram-based RCM mechanisms

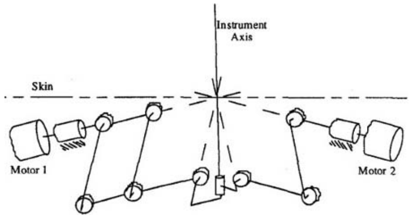


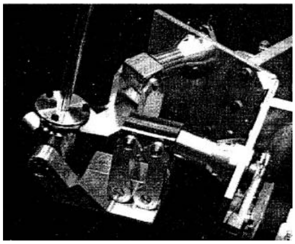
a) da Vinci's RCM mechanism b) LARS' RCM mechanism



c) UCB-US d) BlueDRAGON

Fig. 14 Four MIS robots using parallelogram-based RCM design [23,24,20,25]



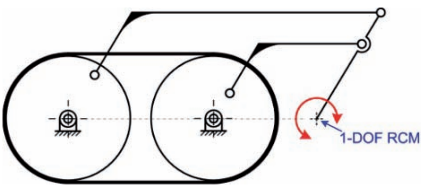


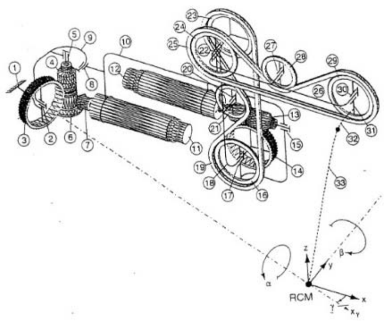
a) Kinematic structure b) Prototype

Fig. 15 PantoScope: The MIS robot using parallelogram-based design with non-orthogonal axes [26]

Synchronous Belt Transmission

One way to simulate the function of parallelograms is to use the synchronous belt transmission. Figure 16a, for example, shows an RCM mechanisms based on the combination of a parallelogram and a synchronous belt. Compared to Fig. 13a, the shown design replaces one parallelogram by a belt transmission such that it can remain the parallel-motion transmission. Furthermore, all parallelograms of a parallelogram-based RCM mechanism can be replaced by belt transmission but the RCM is reserved. Figure 16b, for instance, shows a surgical robot namely “PAKY-RCM” comprising of a 2-DOF RCM mechanism. It uses a double belt drive, without parallelogram linkage, associated the gear drives to simulate the function of a double parallelogram mechanism. A very special feature from this design is that, the RCM has adjustable, non-orthogonal pivot axes so that this module can facilitate various end-effector usages.





a) Fundamental concept b) PAKY-RCM robot [27]

Fig. 16 Synchronous-belt based RCM design: concept and a sampler MIS robot

Spherical Linkages

Spherical linkage is a spatial mechanism that enforces all its moving bodies rotating around a unique point which is permanently fixed in space. Some RCM mechanisms have been devised via spherical linkages. For example, Fig. 17 is a patented robotic arm with five-bar spherical linkage for endoscopy [28]. The five bars are all connected by revolute joints whose axes are intersected at a point where is the RCM point. This mechanism produces a three-dimensional rotation for the RCM. However, this 3-D rotation is resolved by the five-bar linkage into two single input controls. Either rotational direction in space cannot be controlled independently.

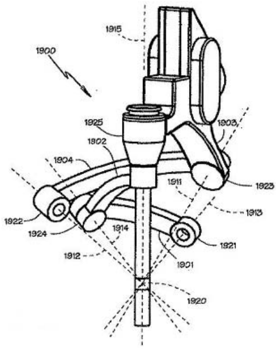
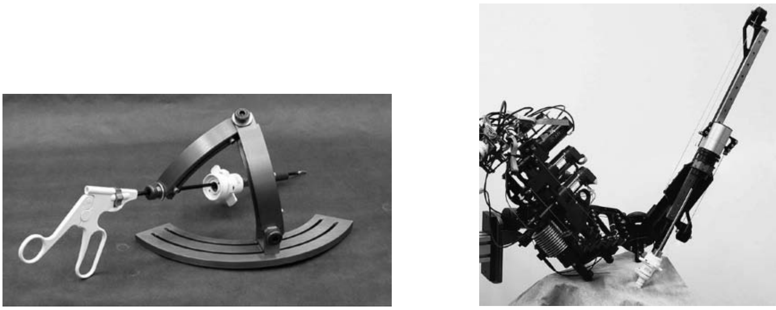


Fig. 17 A patented MIS robot using spherical linkage RCM design [28]

By combining the concepts of the spherical linkages and the circular tracking arcs, another RCM design was devised as Fig. 18. As shown in Fig. 18a, the basic structure of the RCM mechanism is to mount a two-revolute-joint (2R) spherical mechanism on a circular tracking arc so that the overall mechanism is equivalent to a 3R spherical linkage. It thus has three decoupled rotations at the RCM point. Figure 18b is its prototype MIS robot developed by the University of Washington, USA.



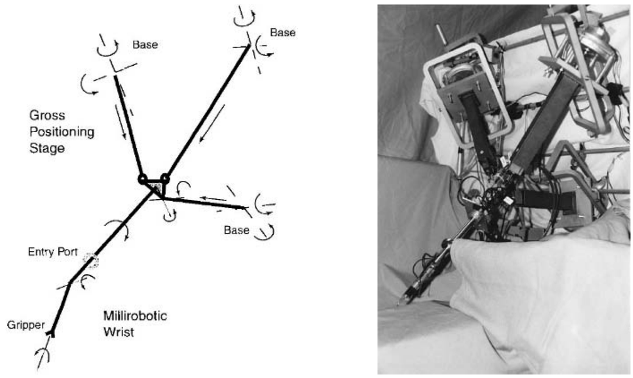
a) Kinematic structure of the RCM mechanism b) Prototype

Fig. 18 An MIS robot using the spherical linkage and circular tracking arc as its RCM mechanism [29]

Parallel Manipulators

In the previous RCM mechanism types, the RCM point is defined and mechanically locked by the kinematics of mechanisms. For the RCM mechanisms using parallel manipulators, the RCM point is achieved by the adequate control of the limb actuators on the manipulator. For example, Fig. 19 is a 3-limb (2-UPS limb

& 1-UPU limb) parallel manipulator for laparoscopy [30]. The pivoted RCM rotations are generated via the suitable control of the linear motors instrumented on the three limbs of the manipulator. Briefly, this approach has advantages of pivot flexibility, increased maneuverability, and overall versatility. For MIS application, however, the mechanical RCMs are suggested to be safer due to their reduced DOFs, decoupled motion, controller simplicity, and locked pivoted feature [4]. Besides, it should be noted that since the control variables of the manipulator in Fig. 19 are fewer than the required DOFs for making determinate motion of the manipulator, the manipulator remains some DOFs for *passive* control which will be discussed in Section "Passive RCMs".

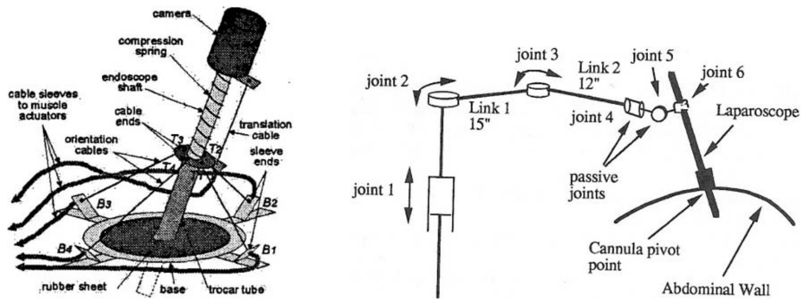


a) Kinematic structure b) Prototype

Fig. 19 An MIS robot using the parallel manipulator as its RCM mechanism [30]

Compliant Mechanisms

A new type of compliant, cable-driven RCM was recently reported for endoscopy manipulation [31], Fig. 20a. It has five driving cables in which four cables control the three-dimensional rotations of the tool and the other one adjusts the translational length of the endoscope. The resulting RCM has 4-DOF with three coupled rotations and one translation decoupled from these rotations.



a) Compliant RCM mechanism b) Passive RCM used by AESOP

Fig. 20 Compliant RCM and passive RCM mechanisms [31,5]

Passive RCMs

There is a special RCM type used in AESOP robots (see Fig. 1). Structurally, the AESOP robotic arm is composed of a seven-bar serial-type manipulator as shown in Fig. 20b. The surgical tool (the laparoscope) is held by the proximal joint. The last two revolute joints (joints 4 and 5) are passive with intersecting axes. The intersection of these axes is neither remote from the mechanism nor located at the laparoscopic entry port. Hence this manipulator is not a genuine RCM mechanism, but rather a passive RCM, which provides a safe way of pivoting the laparoscope in case of accidental patient motion [4].

In addition to above illustration, some other developed MIS robots are summarized in Table 1.

Table 1 A sampler of robotic systems for minimally invasive surgery

System	*Year*	*Manipulator structure*	*RCM DOF*	*RCM type*	*Refer-ences*
AcuBot	2001	Serial manipulator with end belt-parallelogram	2R (Decoupled)	Synchronous belt	[32]
AESOP	1992	7-bar serial manipulator	2R (Coupled)	Passive	[5]
ARTEMIS	1996	Serial manipulator with end parallelogram	2R (Decoupled)	Parallelogram	[16]
BlueDRAGON	2002	Parallelogram linkage mechanism	2R (Decoupled)	Parallelogram	[25]
CLEM	2002	4-cable-limb parallel manipulator	3R+1T (3R coupled, T decoup from 3R)	Compliant mechanism	[31]
da Vinci	1999	Serial manipulator with end parallelogram	2R (Decoupled)	Parallelogram	[9, 23]
EndoBot	2001	Gross instruments mounted on double circular arcs	2R (Decoupled)	Circular tracking arc	[33]
LARS	1995	Serial manipulator with end-parallelogram	2R (Decoupled)	Parallelogram	[13]
MC^2E	2004	3-bar spherical open-loop linkage	2R (Coupled)	Spherical linkage	[19]
Naviot	2003	Parallelogram linkage and serial manipulator	2R (Coupled)	Passive	[34]
Neurobot	2000	Adjustable parallelogram	2R+1T (Decoupled)	Parallelogram	[11]
PAKY-RCM	1998	Serial manipulator with end belt-parallelogram	2R (Decoupled)	Synchronous belt	[15]
PantoScope	1997	Double parallelogram linkage mechanism	2R (Coupled)	Parallelogram	[26]
Probot	1991	Slider robotic arm with double circular tracking arcs	2R (Decoupled)	Circular tracking arc	[10]
Siemens CT	2000	Serial manipulator with end parallelogram	2R (Decoupled)	Parallelogram	[35]
Steady-Hand	1999	Serial manipulator with end-belt drive	2R (Decoupled)	Synchronous belt	[14]
UBC-US	1999	Serial manipulator with parallelogram	2R (Decoupled)	Parallelogram	[20]
UCB/UCSF	1999	3-limb (2-UPS & 1-UPU) parallel manipulator	3R (Coupled)	Parallel manipulator	[30]
UT-LAP	1999	Parallelogram linkage and serial manipulator	2R (Coupled)	Passive	[18]
UT-NEU	1998	3-bar serial manipulator with end circular tracking arc	2R (Decoupled)	Circular tracking arc	[17]
UW	2006	Serial manipulator with 3-bar open-loop spherical linkage	2R (Coupled)	Spherical linkage	[29]
Zeus	1998	Serial manipulator with an isocenter	3R (Coupled)	Isocenter	[7, 21]

Conclusions

This paper reviewed the historical development and kinematic characteristics of robotic systems used for minimally invasive surgery. Although the first robotically-assisted MIS had its successful clinical application to patients no more than twenty years ago, the MIS robots were well-developed in the past few years and were widely accepted by surgeons and patients. The special kinematic geometry of remote center-of-motion characterizes the MIS robots being developed towards a special-purpose robot for medical application. Based on this review, eight categories of RCM mechanisms were identified. Having known the current success of the development of MIS robots, it is hoped that further innovative or improved ideas for the mechanism design of MIS robots, particularly for the kinematic design of RCM mechanisms, can be bred in the future.

References

1. Vierra M (1995) Minimally Invasive Surgery, Annual Review of Medicine, Vol. 46, pp. 147–158.
2. Davies B (2000) A Review of Robotics in Surgery, Proceedings of the Institution of Mechanical Engineers Part H-Journal of Engineering in Medicine, Vol. 214, No. 1, pp. 129–140.
3. Kwoh YS, Hou J, et al. (1988) A Robot with Improved Absolute Positioning Accuracy for CT Guided Stereotactic Brain Surgery, IEEE Transactions on Biomedical Engineering, Vol. 35, No. 2, pp. 153–160.
4. Taylor RH, Stoianovici D (2003) Medical Robotics in Computer-Integrated Surgery, IEEE Transactions on Robotics and Automation, Vol. 19, No. 5, pp. 765–781.
5. Sackier JM, Wang Y (1996) Robotically Assisted Laparoscopic Surgery: From Concept to Development, in Taylor RH, Lavallée S, et al., Eds, Computer-Integrated Surgery: Technology and Clinical Applications, Cambridge, Massachusetts, MIT Press, pp. 577–580.
6. Ewing DR, Pigazzi A, et al. (2004) Robots in the Operating Room—The History, Surgical Innovation, Vol. 11, No. 2, pp. 63–71.
7. Ghodoussi M, Butner SE, Wang Y (2002) Robotic Surgery—The Transatlantic Case, Proceedings of IEEE International Conference on Robotics and Automation, Washington, DC, 11–15 May, pp. 1882–1888.
8. TrueForce™, http://trueforce.com/Medical_Robotics/Medical_Robotics_Companies/zeus htm
9. Guthart GS, Salisbury JK, Jr. (2000) The Intuitive™ Telesurgery System: Overview and Application, Proceedings of IEEE International Conference on Robotics and Automation, San Francisco, California, 24–28 April, pp. 618–621.
10. Davies BL, Hibberd RD, et al. (1996) A Clinically Applied Robot for Prostatectomies, in Taylor RH, Lavallée S, et al., Eds, Computer-Integrated

Surgery: Technology and Clinical Applications, Cambridge, Massachusetts, MIT Press, pp. 593–601.
11. Davies B, Starkie S, et al. (2000) Neurobot: A Special-Purpose Robot for Neurosurgery, Proceedings of IEEE International Conference on Robotics and Automation, San Francisco, California, 24–28 April, pp. 4103–4108.
12. Intuitive Surgical Inc., http://www.intuitivesurgical.com/
13. Taylor RH, Funda J, et al. (1996) A Telerobotic Assistant for Laparoscopic Surgery, in Taylor RH, Lavallée S, et al., Eds, Computer-Integrated Surgery: Technology and Clinical Applications, Cambridge, Massachusetts, MIT Press, pp. 581–592.
14. Taylor R, Jensen P, et al. (1999) A Steady-Hand Robotic System for Microsurgical Augmentation, The International Journal of Robotics Research, Vol. 18, No. 12, pp. 1201–1210.
15. Stoianovici D, Whitcomb LL, et al. (1998) A Modular Surgical Robotic System for Image Guided Percutaneous Procedures, Proceedings of Medical Image Computing and Computer-Assisted Intervention – MICCAI'98, Cambridge, Massachusetts, 11–13 October, pp. 404–410.
16. Schurr MO, Buess G, et al. (2000) Robotics and Telemanipulation Technologies for Endoscopic Surgery: A Review of the ARTEMIS Project, Surgical Endoscopy, Vol. 14, No. 4, pp. 375–381.
17. Hata N, Masamune K, et al. (1998) Needle Insertion Manipulator for CT- and MR-Guided Stereotactic Neurosurgery, in Jolesz FA, Young IR, Eds, Interventional MR: Techniques and Clinical Experience, London, Martin Dunitz, pp. 99–106.
18. Kobayashi E, Masamune K, et al. (1999) A New Safe Laparoscopic Manipulator System with a Five-Bar Linkage Mechanism and an Optical Zoom, Computer Aided Surgery, Vol. 4, No. 4, pp. 182–192.
19. Zemiti N, Morel G, et al. (2007) Mechatronic Design of a New Robot for Force Control in Minimally Invasive Surgery, IEEE/ASME Transactions on Mechatronics, Vol. 12, No. 2, pp. 143–153.
20. Salcudean SE, Zhu WH, et al. (1999) A Robot System for Medical Ultrasound, The 9th International Symposium of Robotics Research (ISRR'99), Snowbird, Utah, 9–12 October, pp. 195–202.
21. Sanchez D, Black M, Hammond S (2002) A Pivot Point Arm for A Robotic System Used to Perform A Surgical Procedure, European Patent No. 1254642.
22. Pei X, Yu J, et al. (2007) Enumeration and Type Synthesis of One-DOF Remote-Center-of-Motion Mechanisms, Proceedings of 12th IFToMM World Congress, Besançon, France, 18–21 June.
23. Morley TA, Wallace DT (2005) Roll-Pitch-Roll Surgical Tool, US Patent No. 2005204851.
24. Taylor RH, Funda J, et al. (1994) Improved Remote Center-of-Motion Robot for Surgery, US Patent No. EP0595291.
25. Rosen J, Brown JD, et al. (2002) The BlueDRAGON – A System for Measuring the Kinematics and the Dynamics of Minimally Invasive Surgical Tools In-Vivo, Proceedings of IEEE International Conference on Robotics and Automation, Washington, DC, 11–15 May, pp. 1876–1881.

26. Baumann R, Maeder W, et al. (1997) The PantoScope: A Spherical Remote-Center-of-Motion Parallel Manipulator for Force Reflection, Proceedings of IEEE International Conference on Robotics and Automation, Albuquerque, New Mexico, 20–25 April, pp. 718–723.
27. Stoianovici D, Whitcomb LL, et al. (2003) Remote Center of Motion Robotic System and Method, International Patent No. WO03067341.
28. Schena B (2007) Center Robotic Arm with Five-Bar Spherical Linkage for Endoscopic Camera, International Patent No. WO2007114975.
29. Lum MJH, Rosen J, et al. (2006) Optimization of a Spherical Mechanism for a Minimally Invasive Surgical Robot: Theoretical and Experimental Approaches, IEEE Transactions on Biomedical Engineering, Vol. 53, No. 7, pp. 1440–1445.
30. Çavuşoğlu MC, Tendick F, et al. (1999) A Laparoscopic Telesurgical Workstation, IEEE Transactions on Robotics and Automation, Vol. 15, No. 4, pp. 728–739.
31. Berkelman P, Cinquin P, et al. (2002) A Compact, Compliant Laparoscopic Endoscope Manipulator, Proceedings of IEEE International Conference on Robotics and Automation, Washington, DC, 11–15 May, pp. 1870–1875.
32. Stoianovici D, Cleary K, et al. (2003) AcuBot: A Robot for Radiological Interventions, IEEE Transactions on Robotics and Automation, Vol. 19, No. 5, pp. 927–930
33. Kang H, Wen JT (2001) Robotic Assistants Aid Surgeons During Minimally Invasive Procedures, IEEE Engineering in Medicine and Biology Magazine, Vol. 20, No. 1, pp. 94–104.
34. Yasunaga T, Hashizume M, et al. (2003) Remote-Controlled Laparoscope Manipulator System, Naviot™, for Endoscopic Surgery, CARS 2003 – Computer Assisted Radiology and Surgery: Proceedings of the 17th International Congress and Exhibition, Lemke HU, Inamura K, et al., Eds, London, United Kingdom, 25–28 June, pp. 678–683.
35. Loser MH, Navab N (2000) A New Robotic System for Visually Controlled Percutaneous Interventions under CT Fluoroscopy, Proceedings of Medical Image Computing and Computer-Assisted Intervention – MICCAI 2000, Delp SL, DiGoia AM, Jaramaz B, Eds, Pittsburgh, Pennsylvania, 11–14 October, pp. 887–896.

Multiple Bolts as Security Devices

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Abstract The purpose of this study is to introduce the use of multiple bolts as security or safety devices in our daily life. Firstly, the classification and advantages of mechanical locks were introduced. This was followed by the description of the definitions and the development of mortise locks. Then, the multiple bolts locks were decomposed into four sub-parts according to their different functions, including the latch bolt lock, the dead bolt lock, the dead-latch bolt lock, and the connecting mechanism. The four sub-parts were further analyzed with reference to their structural characteristics as well as design requirements and constraints. The use of multiple bolts in locks in ancient and modern times was then compared. It was found that although the technology in lock mechanism has improved with time, the basic design methods, however, have been used extensively in new and improved devices.

Keywords Dead bolt, Latch bolt, Mechanism design

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Introduction

Locks are devices to secure one's possessions. They have continually been developed in every country for centuries. Nowadays, locks are used in every family, sometimes even more popular than any consumer electronics. They are found on doors, vehicles, and containers etc. According to its shape, operation, and installation method, locks can be classified as mortise locks, rim locks, bored-in lock, combination locks and padlocks. Amongst them, mortise locks are known as the best developed.

Multiple bolts design for locks is commonly adopted with a long history, as recorded in many books and relics. After generations of improvement and evolution, the most important advancement is the significant improvement in security. An example of such locks is the contemporary multipoint locks. This type of design combines traditional features of a mortise lock with a rim lock by connecting the two locks with links. The design of multipoint mortise locks can be decomposed as two parts—the primary lock and the auxiliary lock, both of which are mortise locks.

Although lock manufacturing is a mature technology, there is no easy systematic strategy in designing new lock mechanism. This study also introduces the application of multiple bolts as a lock design.

Anatomy of Bolt Security

Mechanical locks are common devices in our daily lives. According to its shape, operation, and installation methods, they can be classified as mortise locks, rim locks, bored-in lock, combination locks, and padlocks. The mortise lock is named by the way the inlay of the lock body (a bolt), inserts into the strike plate. Similar to the typical Egyptian lock and the associated mechanism, the lock can consist of at least two parts, i.e. the staple or locking device and the bolt proper, which slide back and forth, securing a door to the door jamb. Traditionally, a typical lock may consist of a latch bolt and a dead bolt, the former of which is unlocked by a handle, whilst the latter by a key or a knob, as shown in Fig. 1.

According to the above discussion, a mortise lock uses a bolt as the barrier, which fits into a mortise for locking. To unlock, the bolt is separated from the mortise, as shown in Fig. 2a and b. Therefore, a mortise lock can be defined as "A lock with tenon and mortise. Its lock body must be embedded into the objective. The bolts consist of a latch bolt and a dead bolt, which can be unlocked by a handle and a key, respectively."

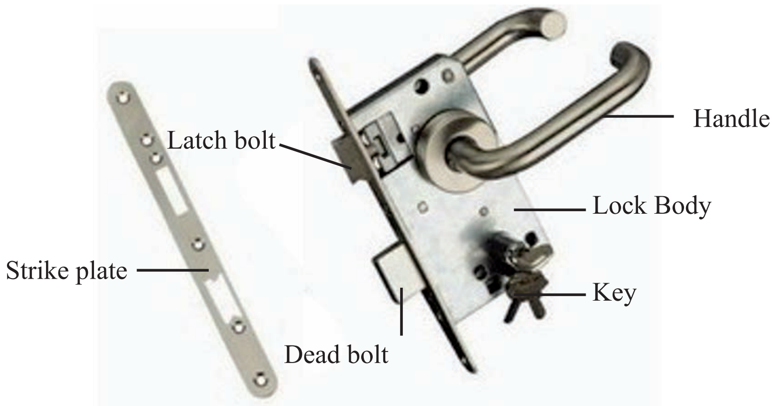
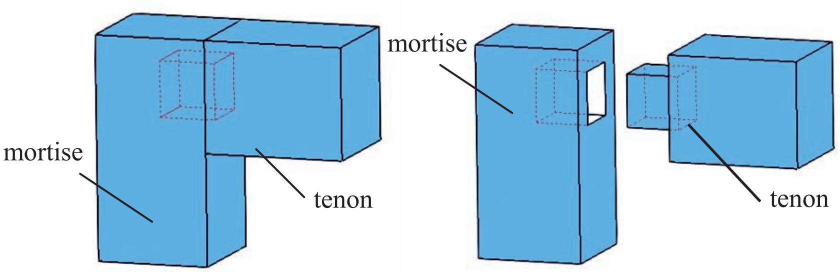


Fig. 1 A mortise lock



a) The tenon fits into the mortise b) The tenon separates from the mortise

Fig. 2 The mortise and the tenon

Use of Multiple Bolts in Ancient Time

Aside from the typical Egyptian lock which utilized a bolt as the barrier, there are also many ingenious applications of bolts in locks. The advantage of multiple bolts lies in the additional strength provided by the use of two or more bolts instead of simply one. Ordinary doors seldom afford examples of these multiple bolts; but they may be frequently seen in cabinets and desks, where two staples fixed to the lid fall into two holes in the lock, and are retained by two bolts. The most remarkable and complicated varieties, however, are those in which the bolts, instead of shooting parallel and nearly together, shoot in wholly different directions; one up, one down, one to the right, one to the left, and so on. These can usually be found on safes, strong boxes, and the doors of strong rooms containing valuable treasures.

The mechanism is such that the key acts upon all the bolts at once, through the intervention of levers and springs of various kinds. Figure 3 shows a very curious specimen of these multiple-bolt locks. It is copied from a great French work; and the ponderous chest to which it is attached is, having been told by Réaumur, “known at Paris by the name of the strong German coffer.” He further said, “Nothing is wanting in these coffers on the score of solidity. They are made entirely of iron; or if of wood, they are banded both within iron; and can only be broken open by very great violence.” The chest locks shown in Fig. 3 are almost as large as the top of the coffer, and was secured when closed with a great number of bolts, in this case twelve fastenings. His next remark on the subject was a sensible one: “Notwithstanding the large size of these locks, and all the apparatus with which they are provided, they correspond but ill with the solidity of the rest of the coffer. If we have given a representation of one, it is chiefly to show how little confidence one could have in such a locks, and what are its defects, in order that we may avoid them.” It is not difficult, by tracing the action of the several levers, to see how one movements of the key, in the centre of the lid, would act upon all the bolts. In the figure there are the four corner bolts; and six others are on the long sides, three on each; and two, on the short sides. Every bolt is provided with a spring. There is no staple or box to receive each bolt; but all shoot or snap beneath the raised edge running round the top of the box just within the exterior. The keyhole in the front of the box is a deception or mask; the real keyhole is in the middle of the lid concealed by a secret door opened by a spring. When the key has moved the great central bolt, this acts upon the other bolts as studs which act upon two of the bolts; and there are also staples confining the great bolt; there are also a few small levers which render a similar service to the side and end bolts. In addition, there are also other contrivances for limiting the movement of the latter, such as iron straps or bands by which the interior of the chest is strengthened. This example shows not so much a lock but more a series of spring latches [1].

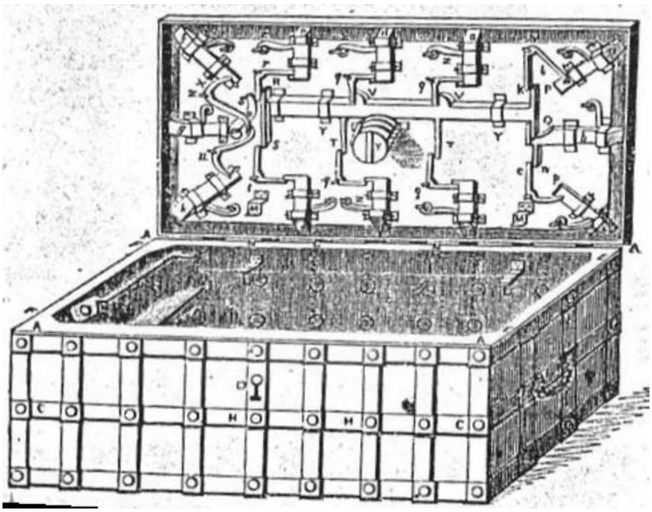


Fig. 3 An ancient chest with a multiple bolts design [1]

Conventional Multiple Bolt Security Devices

The application of bolts is quite popular, and the general type easily recognizable may be the mortise lock that can be embedded into the jamb or door body for security. The first commercialize mortise locks were possibly created in 1835 by Philos Blake and Eli Whitney Blake [2], with the objective of preventing unauthorized opening. A single bolt mortise lock is the most popular design in locking/unlocking doors and windows. The mortise latch lock [3] shown in Fig. 4, has a bolt in the form of a beveled latch with an auxiliary spring. While closing the door, the bevel is pushed by the wall to retract the latch, which in turn compresses the spring. When the pushing force is released, the latch springs back and fits into the strike plate on the wall. This is a simple design, but can be easily unlock when an intruder slides a thin card between the door and the frame to push back the latch.

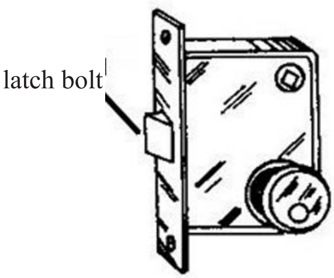


Fig. 4 Mortise latch bolt [3]

With increasing demand for security, the former mortise latch lock was improved to form the mortise deadbolt lock. As shown in Fig. 5 [3], the design has an added deadbolt button sitting along side the latch. The operation is similar to a latch lock. The only difference is that when the door is closed, the frame will push the deadbolt button to lodge the fillister onto the latch to keep it in place. In addition, the robustness of mortise locks is also enhanced to prevent intruders from using a pry bar to pry the lock out of the jamb.

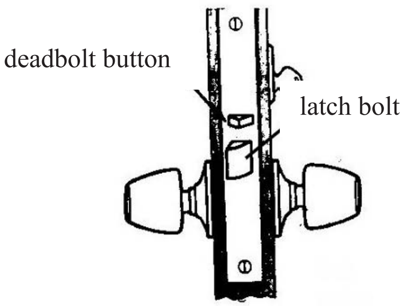


Fig. 5 Mortise deadbolt lock [3]

If an independent deadbolt is added to the mortise deadbolt lock, it turns into a mortise dual-bolt lock, as shown in Fig. 6 [3]. The design of the bolt is different from the way a deadbolt button lodges the latch. It has a stop arm inside the lock. During locking, the deadbolt stretches out of the lock body and the stop arm is triggered by the key to lodge the deadbolt. This type of lock provides double security as it has both a beveled latch as well as a rectangular deadbolt.

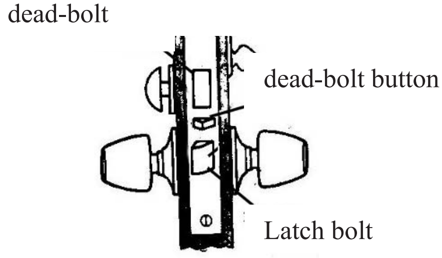


Fig. 6 Mortise double-latch lock [3]

Much literature on lock patent mentioned the idea of increasing the number of bolts to increase the robustness of mortise locks. The emergency door shown in Fig. 7 [4] has three bolts that can be opened by pushing a handle. Many emergency doors incorporate this design by adding a bolt on the top and the bottom of the door to provide additional security, while maintaining the ease of operation with a single push to the handle bar to open the door.

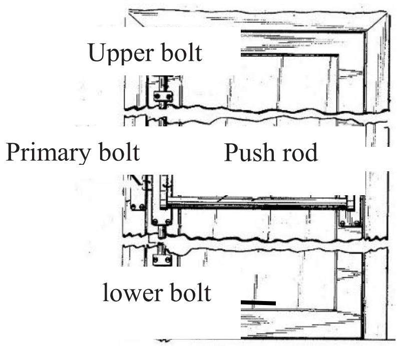


Fig. 7 Emergency door lock [4]

To enhance residential security, it is common practice to install an auxiliary lock on the door frame in addition to the primary lock (mortise lock or bored-in lock). The design is similar to the secure method provided by multipoint bolts. The auxiliary lock is installed on the frame, rather than being embedded in the door like a mortise lock. The installation of auxiliary locks can effectively improve security, but the procedure of unlocking becomes complex and inconvenient, and therefore less acceptable to users.

In 1895, Klein utilized the design of the interrelationship between multipoint bolts to combine the design of mortise locks and emergency doors. This design gives consideration to both the convenience and security of auxiliary locks. It cleverly utilizes a linkage to open the auxiliary lock when the primary lock is opened. As show in Fig. 8[5], this design solves the traditional inconvenience caused by the locking and unlocking operations of auxiliary locks. This design is further improved to form the multipoint mortise lock as shown in Fig. 9 [6,7], which is the target for the analysis and re-designing of this paper.

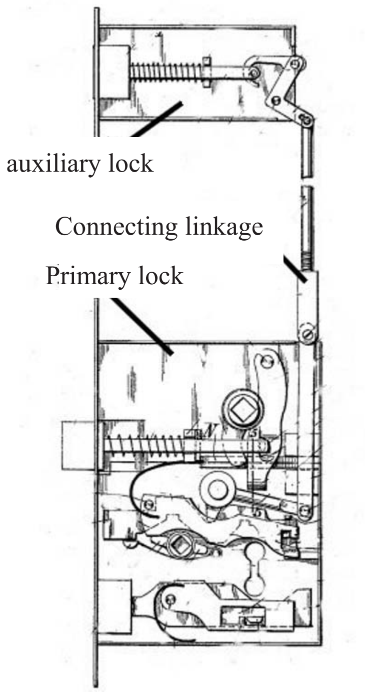


Fig. 8 Lock [5]

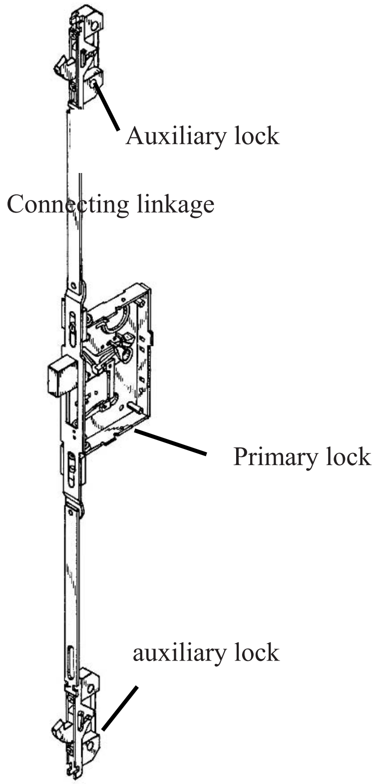


Fig. 9 Multipoint mortise lock [6]

A multipoint mortise lock consists of a primary lock and at least an auxiliary lock. A popular modern design is to replace the auxiliary lock as a mortise lock (mortise latch lock or a mortise deadbolt lock) embedded into the door. The movement direction of the bolt in the auxiliary lock is parallel to the bolt in the primary lock, and is triggered by a connecting linkage when the primary lock moves. When the primary lock is locked, the auxiliary lock cannot be opened. Moreover, the design of the transmitting linkage will prevent the primary lock from being unlocked from any operation in the auxiliary lock. On the contrary, if the primary lock can be correctly unlocked, the auxiliary lock will be unlocked automatically. The evolution of mortise locks has approached a mature stage from earlier mortise latch locks to the current multipoint mortise locks.

The Improvement of Modern Multiple Bolt Security

From the vast literature on lock patents, it can be surmised that in the mechanism of mortise locks, the number of links may lead to different designs, and the subordinate relationship of adjacent joints can also differ significantly. Because of space constraint, different designs of mortise lock will be required for specific applications. The new type of design proposed herein should fit in with the size limitation in accordance to the requirements of the consignor, as shown in Fig. 10. And the prototype of the new design, shown in Fig. 11, can also be manufactured by applying a systematic design procedure.

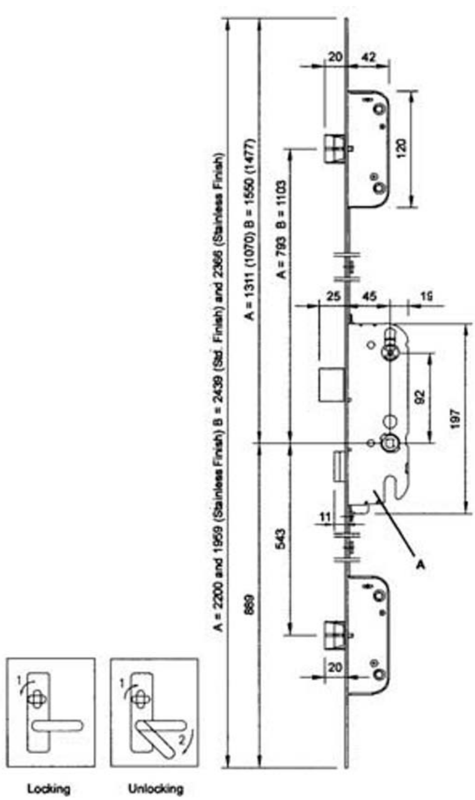


Fig. 10 Specification of a multipoint lock

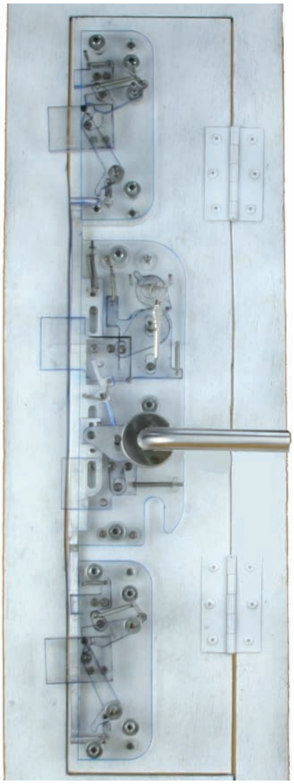


Fig. 11 The new design of a multiple bolt lock called the multipoint lock

This new type multipoint lock can only be opened by the operation of a key, and also met the requirement for use on a door in a specific area. This design also improves the usage of multiple bolt design lock only for chests. This lock is safe and easy to use, giving the user piece of mind from break-ins.

Conclusions

According to the shape, operation, and installation method, mechanical locks can be classified as mortise locks, rim locks, bored-in lock, combination locks, and padlocks. This paper analyzed the structure of a multipoint mortise lock, which was decomposed into four sub-parts by the different functions, including the latch bolt lock, the dead bolt lock, the dead-latch bolt lock, and the connecting mechanism.

And from this study, the design of a mortise lock has been analysed and further understood, which provided the basis for summarizing the movement property of multiple-bolt locks, such as a multipoint mortise lock.

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References

1. Hopkins A (1928) The Lure of the Lock, The General Society of Mechanics and Tradesmen, New York, p. 14.
2. Kane JN (1964) Famous first facts: a record of first happenings, discoveries and inventions in the United States, H. W. Wilson, New York.
3. Hu JJ (1991) Lock, Publisher of hsu's foundation, Taipei, Taiwan.
4. Vanderburgh GW (1974) Exit Device, U.S. Patent No. 3,819,213.
5. Klein B (1895) Lock, U.S. Patent No. 536,957.
6. Eller DC, Fleury BA, Leiper DS, Simmer TC (2001) Multipoint Mortise Lock, U.S. Patent No. 6,282,929 B1.
7. Resch JV, Renz W, Gründler D, Dieners U (2001) Lock, in Particular Mortise Lock for an Exterior Door, U.S. Patent No. 6,226,981 B1.

Technology Transfer of Educational Machine Mechanism Models

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Abstract Machine mechanism models, which were imported from Germany in 1903, are preserved in Japan at Kyoto University. A German company, GUSTAV VOIGT Company, used to produce and export these models around the globe, and many of them are preserved in the United States at Cornell University. Recently, it became clear that similar machine mechanism models, which were produced by SHIMDZU Corporation in 1913, are preserved at three Taiwanese universities (NCKU, NTUT, and NTU). Hence, this is an example of the technology transfer, that is, the (Germany)→ [Japan, (U.S.A.)] →(Taiwan). In this case, it is believed that the models sold from Japan to the Taiwanese universities were not only copies, but also included original ideas of SHIMADZU Corporation.

Keywords Educational machine mechanism models, Reuleaux models, Technology transfer, Taiwan, SHIMDZU Corporation, GUSTAV VOIGT Company

Preface

The authors have investigated educational machine mechanism models, which were imported from Germany and preserved at Kyoto University (founded in 1897), as well as produced three-dimensional animations of them on the website of the Kyoto University Museum beginning in 1999. Via communication with a Taiwanese researcher who saw the Internet in the early part of 2007, it became clear that similar machine mechanism models are preserved at Taiwanese universities and that most of them were exported from Japan prior to World War II.

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In this research, the models preserved in Taiwan are introduced and compared to the models preserved at Kyoto University. In addition, the technology transfer of the machine mechanism models is examined.

Machine Mechanism Models Preserved at Kyoto University

Because the authors have already published information about the models preserved at Kyoto University [1–7], a brief explanation should suffice. The purchase slip from 1903, which has been preserved, clearly indicates that 19 products (although the origin of one is still in doubt) made by the German GUSTAV VOIGT Company are among the machine mechanism models preserved at Kyoto University. Figure 1 shows the display of the mechanical models exhibition at the Kyoto University Museum.

Fig. 1 Display of the mechanical models exhibition at the Kyoto University Museum [8]

The "GUSTAV VOIGT" factory, which manufactured and exported educational machine mechanism models to Kyoto University in the Meiji Era, existed in downtown Berlin, and appears in the address book, "Germany Precise Machine and Optical Equipment Factories", suggesting that the factory was small but famous. Although the name changed slightly, the factory was managed by the Voigt family from 1879 to 1933 [5]. The educational models were devised for students to understand easily basic mechanical mechanisms, and are still useful today. The models must have played an important role in mechanical engineering education during the early phase of Japanese industrialization. Figure 2 shows a GUSTAV VOIGT Company's label attached to a model, while Fig. 3 shows the original location of the company. (At the time of the photograph, the factory had been replaced by a parking lot.)

Fig. 2 GUSTAV VOIGT Company's label

Fig. 3 Original location of the company [9]

GUSTAV VOIGT Company manufactured numerous models, which were sold around the globe. Cornell University (USA) has preserved around 220 of these within the catalogue as Reuleaux models, including those preserved in Kyoto University. Figure 4 shows the exhibition of the mechanism models at Cornell University.

Fig. 4 Exhibition of the mechanism models at Cornell University [10]

Machine Mechanism Models Preserved in Taiwan

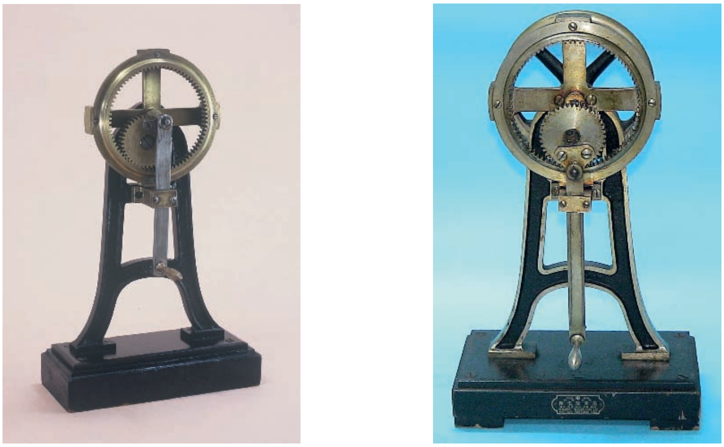
Most of the machine mechanism models preserved in Taiwan were made by SHIMADZU Corporation in 1913. At this point in history, Taiwan had fallen under the rule of Japan, and it is thought that various technologies were brought into Taiwan, including the machine mechanism models. In other words, around the time Kyoto University imported machine mechanism models from Germany, SHIMADZU Corporation obtained the information about the models, immediately replicated them, and it seems, then sold them as the products of SHIMADZU Corporation. These products were exported into Taiwan 10 years later. Hence, this is an example of the flow of technology transfer (Germany→Japan, U.S.A.→ Taiwan).

The machine mechanism models in Taiwan are preserved at NCKU (National Cheng Kung University), NTUT (National Taipei University of Technology), and NTU (National Taiwan University). Most of these models were made by SHIMADZU Corporation. Figure 5 shows the exhibition of the models at NTUT. The models are introduced on the websites of NCKU in Chinese and in English [11]. Professor Hong-Sen Yan of NCKU, former President of Da Yeh University, is a collector and researcher of ancient locks, and part of his collection is exhibited and preserved in a clean exhibition room. It is thought that his collection of ancient locks and its examination will be useful when he rearranges and investigates the machine mechanism models. In addition, Professor Hong-Sen Yan's article about machine mechanism models refers to the authors' article [12].

Fig. 5 Exhibition of machine mechanism models at NTUT [13]

Similarity of the Models

The left side of Fig. 6 shows a model from GUSTAV VOIGT Company preserved at Kyoto University, while the right side shows a model from SHIMADZU Corporation preserved at NTU. These models show a conversion mechanism of linear motion and rotary motion, which is illustrated in Fig. 7.



Made by GUSTAV VOIGT Company   Made by SHIMADZU Corporation [11]

Fig. 6 Comparison of the conversion mechanism of the linear motion/rotary motion using a planetary gear

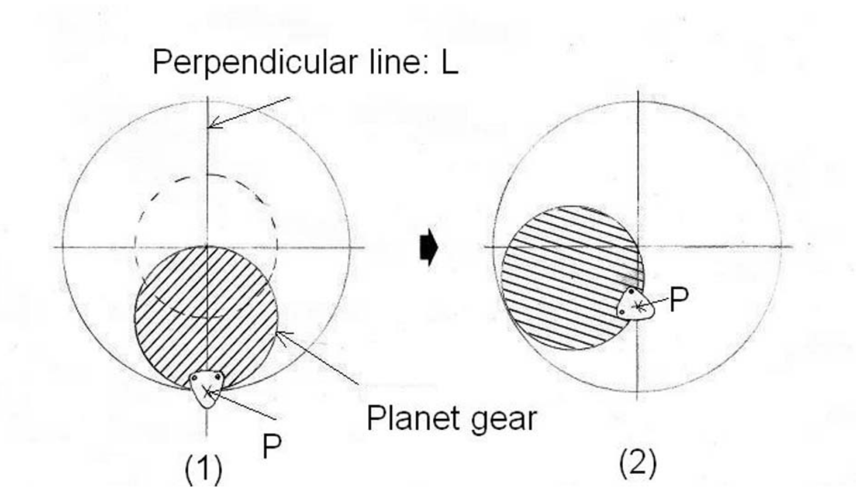


Fig. 7 Illustration of the conversion mechanism of the linear motion/rotary motion using a planetary gear

In Fig. 7, the diameter of the internal gear with outward facing teeth is twice the diameter of the external gear with inward facing teeth. The external gear moves by intermeshing with the teeth of the internal gear which is fixed.

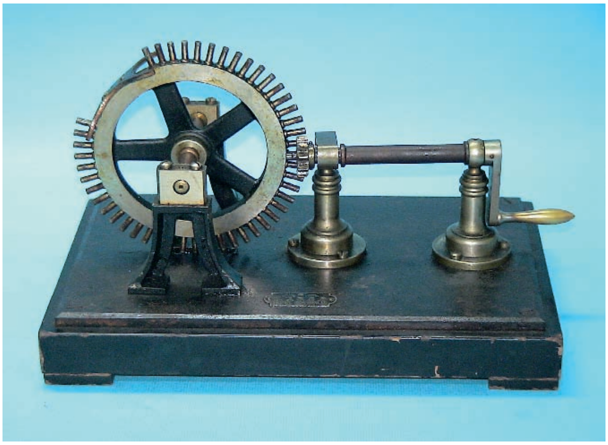
Assuming that the point of contact between the planetary gear and the internal gear is point P, the center of the internal gear, the planetary gear, and point P are all on line L [Fig. 7 (1)]. Then, point P continues to move perpendicularly along line L regardless if the center of the planetary gear intermeshes clockwise or counter-clockwise [Fig. 7 (2)]. In other words, point P on the circumference moves in a linear motion despite the center of the planetary gear moving in a rotary motion. Therefore, this mechanism can be used to convert rotary motion into linear motion.

The models in Fig. 6 are very similar. Not only the dynamic parts, the static parts which do not have mechanical functions are also similar. For example, the design of the gear's supporting part is identical. In addition, other models are similar. Hence, it is speculated that SHIMADZU Corporation reproduced GUSTAV VOIGT Company's model (either under a licensing agreement or illegally). At least, it is recognized that in those days SHIMADZU Corporation had the technology to machine metal into the same pattern as the original piece, regardless of the complexity.

Figure 8 shows two pin gear mechanism models; one made by GUSTAV VOIGT Company (preserved at Kyoto University) and the other by SHIMADZU Corporation (preserved at NCKU). The pin gear models' mechanisms are that the pin gear continues to rotate in the same direction when the handle of driving shaft is rotated in the same direction, but when a pin is not present, the pin gear's rotating direction changes. However, the handle of the driving shaft for the model made by GUSTAV VOIGT Company is missing.

When both models are compared, they look virtually identical, except for the missing part. However, the driving shaft of the SHIMADZU Corporation's model has an equal diameter, whereas the driving shaft of the GUSTAV VOIGT Company's model is cone-shaped. Although the author is unaware of the exact reason, it is thought that SHIMADZU Corporation changed the shape of the axis according to SHIMADZU Corporation's own judgment because there is not a mechanical reason for the driving shaft to have a cone-shaped axis.

Made by GUSTAV VOIGT Company



Made by SHIMADZU Corporation [11]

Fig. 8 Pin gear mechanism models

Figure 9 shows a toggle mechanism model preserved at NTUT. It is unverified, which company made this model. In the catalog (preserved at Cornell University) of GUSTAV VOIGT Company, the author could not find this exact model. Thus, it is believed that SHIMADZU Corporation or a Taiwanese company made the original model by taking a hint from the models of GUSTAV VOIGT Company.

Fig. 9 Toggle mechanism model

Taiwanese Trade Between 1896 and 1920

In this chapter technology transfer is examined in the context of change in the imports and exports in Taiwan between 1896 and 1920.

Figure 10 shows the total value of exports and imports during a twenty-five year period from 1896 to 1920. Figure 11 shows the total value of "machinery, clocks, watches, scientific instruments, fire arms, vehicles, and vessels" imported into Taiwan, while Fig. 12 shows the total value of the same items exported from Taiwan. The author made these graphs based on data from the Taiwan governor-general's office editing document [14]. Two wars occurred during this time, the Russo-Japanese War in 1904, and World War I began in 1914.

Although the total amount of both imports and exports increased with World War I, imports of technological goods decreased, while exports of these goods dramatically increased. The Japanese Meiji Government adopted a policy of promoting industry, which emphasized the importance of mechanical technology.

Under this policy, Japan took a lot of modern technology from the U.S. and Europe. Consequently, Japan and Taiwan's level of technological education increased along with the practical production of such technology. From this, Japan and Taiwan were able to capitalize on the increased demand that arose around World War I.

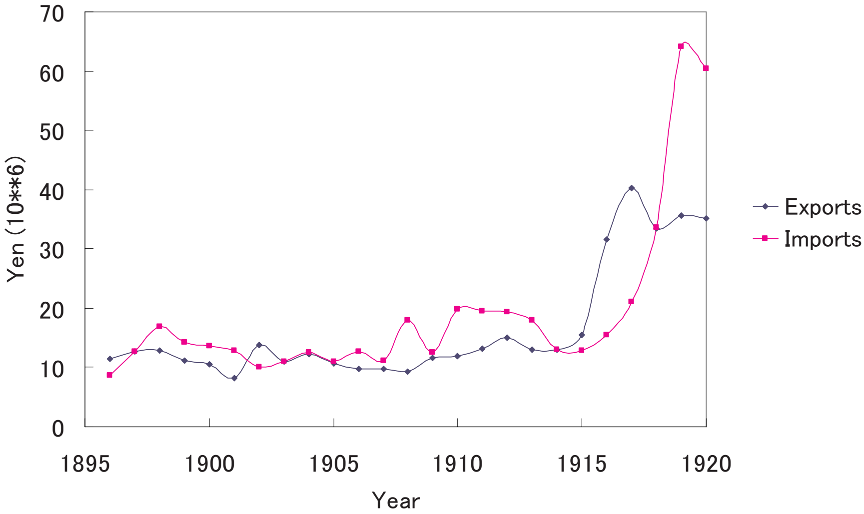


Fig. 10 Total value of exports and imports

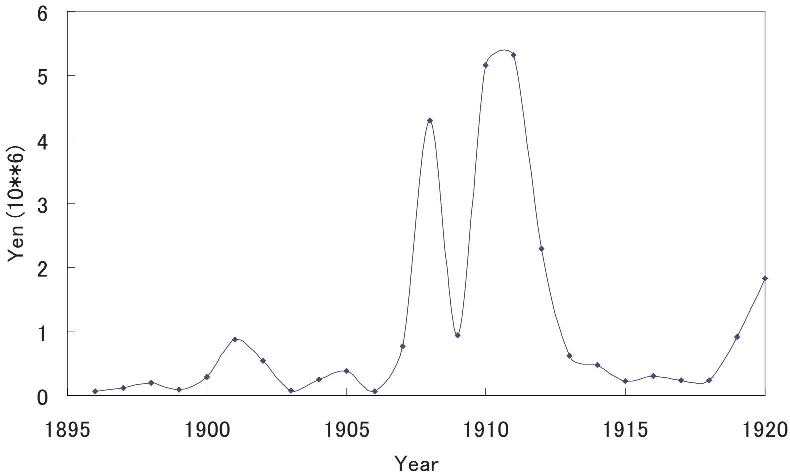


Fig. 11 Imported commodities (Machinery, clocks, watches, scientific instruments, fire arms, vehicles, and vessels)

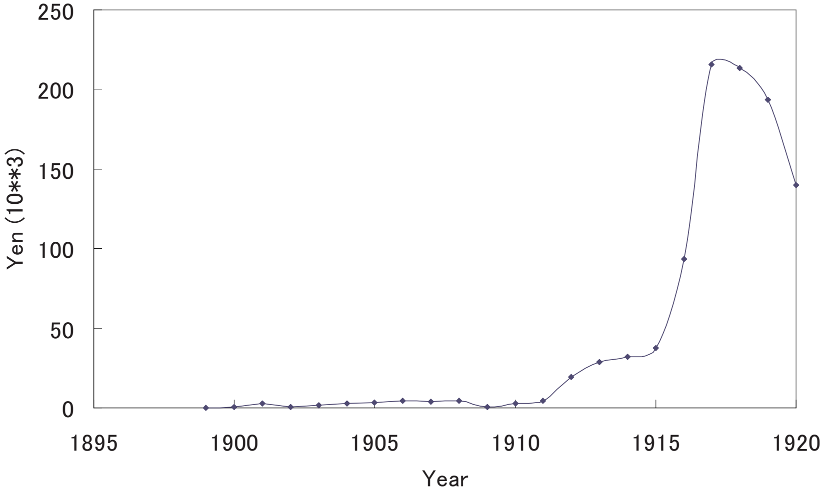


Fig. 12 Exported commodities (Machinery, clocks, watches, scientific instruments, fire arms, vehicles, and vessels)

Technology Transfer of the Machine Mechanism Models

It has become apparent through the Internet that many machine mechanism models (some of which are preserved at Kyoto University) made by GUSTAV VOIGT Company are preserved at Cornell University, while similar models (made by SHIMADZU Corporation) are preserved in Taiwan. Hence, the flow of the technology transfer is demonstrated as the same types of models, which were purchased at different times in various countries, are found. Therefore, a cooperative study as well as an international conference between organizations preserving the models has been initiated. Further research results about the technology transfer are expected.

Summary

It is clear that educational machine mechanism models, which were made by SHIMADZU Corporation, are preserved at Taiwanese universities. The models were made and sold ten years after Kyoto University imported them from Germany. Author's observations of these models indicate the following:

(1) Back at that time, Japan was already at a high technical level, and possessed the ability to completely copy a product, even complicated metal model.
(2) In addition to simply copy products, original devices using the ideas of the original machine mechanism were made.

(3) The flow of technology transfer is apparent in the fact that three counties have preserved the same type of models, which were purchased at different times.

References

1. Sohei Shiroshita, Hiromitsu Kumamoto, Osamu Nishihara (1999) Computer graphic animations and internet publications of Meiji Era educational machine mechanism models imported by the University, 1999 JSME TECHNOLOGY AND SOCIETY DIVISION Annual Meeting, pp. 81–82. (In Japanese)
2. Sohei Shiroshita, Hiromitsu Kumamoto, Osamu Nishihara (2000) Educational Machine Mechanism Models Imported by the University in the Meiji Era - Computer Graphic Animations and Internet Publication, J. Soc. Mat. Sci., Japan, Vol. 49, No. 1, pp. 130–131. (In Japanese)
3. Sohei Shiroshita (2000) Meiji Era Educational Machine Mechanism Models Imported from Germany by Kyoto University, 2000 JSME TECHNOLOGY AND SOCIETY DIVISION Annual Meeting, pp. 61–62. (In Japanese)
4. Sohei Shiroshita, Hiromitsu Kumamoto, Osamu Nishihara(2001) Constructing A Virtual Museum Of Machine Mechanism Models Imported From Germany During Japanese Westernization For Higher Education: 3D Animations Based On Kinematics And Dynamics, Di Jing, Museums and the Web 2001 Proceedings (CD-ROM).
5. Sohei Shiroshita (2001) Meiji Era Educational Machine Mechanism Models Imported from Germany, 2001 JSME Annual Meeting, pp. 407–408 (In Japanese).
6. Sohei Shiroshita (2002) The Models of Mechanisms Imported by Kyoto University in Meiji Era and Reuleaux Collection, 2002 JSME Annual Meeting, pp. 373–374. (In Japanese)
7. Sohei Shiroshita, Hiromitsu Kumamoto (2002) A Technology Transfer Using the Models - Mechanical Models that Kyoto University Purchased in Meiji Era, The 1st International Conference on Business and Technology Transfer (ISSN 1347-8834), pp. 195–200.
8. [Photo.] Author (2006).
9. [Photo.] Andreas Kueppers (2001).
10. [Photo.] Author (2002).
11. Nationnal Cheng Kong University, Digital Museum “Taiwan’s Antique Mechanism Teaching Models”, http://www.acmf.org.tw/model/
12. Hong-Sen Yan, Hsing-Hui Huang and Chin-Hsing Kuo (2007), Historic Mechanism Teaching Models in Taiwan, the 12th IFToMM World Congress (Besancon, France).
13. [Photo.] Author (2007).
14. THE GOVERNMENT OF TAIWN edit (1922), Return of The Trade of TAIWAN (FORMOSA) for the Twenty five years from 1896 to 1920 Inclusive, p. 1, p. 42, and p. 45.

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