AN APPROACH FOR THE RECONSTTUCTION 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, 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

Fig. 1 shows the procedure of reconstruction synthesis [4]. It includes the following four steps:

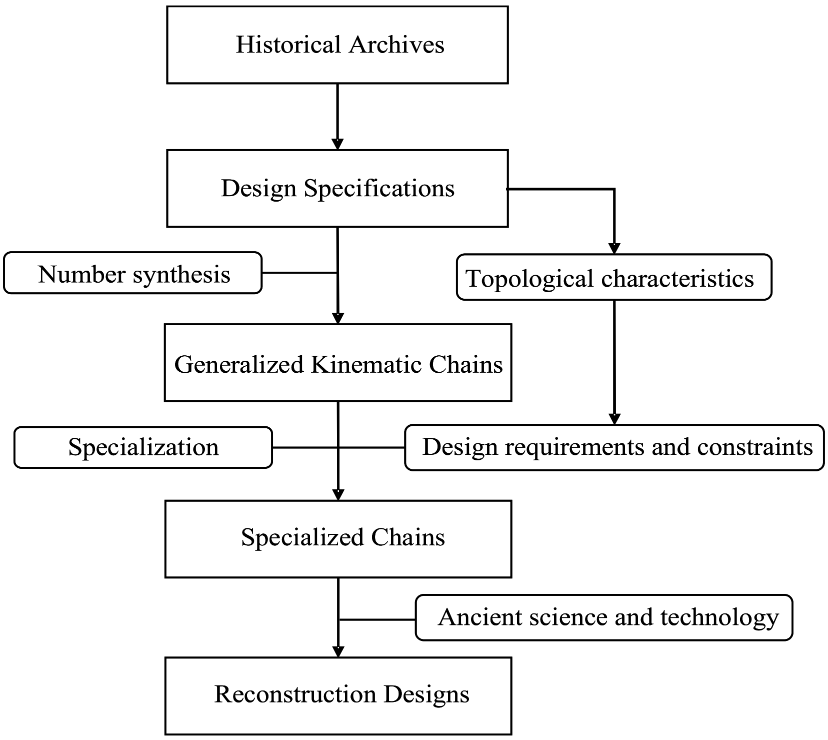


Fig. 1. Procedure of the reconstruction synthesis [4]

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 [4, 7-8]

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. 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:

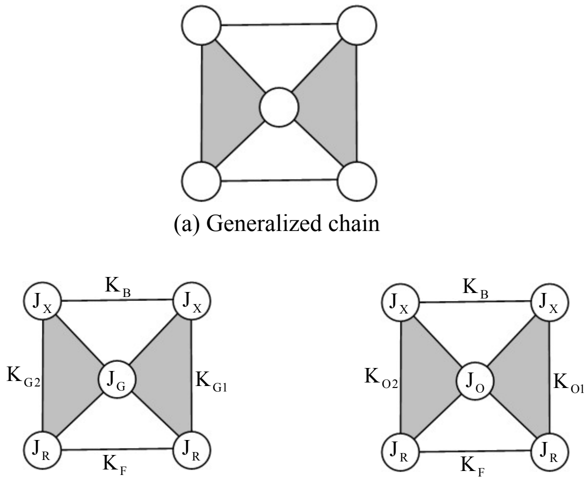
1. The number of links o is four.
2. The degree of freedom is one.
3. The mechanical components are links, gears and frictional wheels.

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. 2(a).

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. 2(b).



(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. Fig. 3 shows the corresponding design concepts from the atlas of specialized chains, in which Fig. 3(e) is Wang's design. And, Fig. 4 shows a physical reconstruction design of differential type south pointing chariots [7].

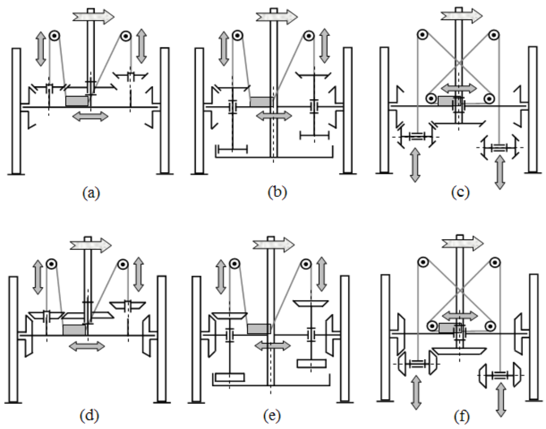


Fig. 3. Synthesized mechanisms of south pointing chariots

Fig. 4. A reconstruction design of differential type south pointing chariot [7]

Zhang Heng's Seismoscope [4, 11-12]

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). 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.

Su Song’s Escapement Regulator [4, 15-16]

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 [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.

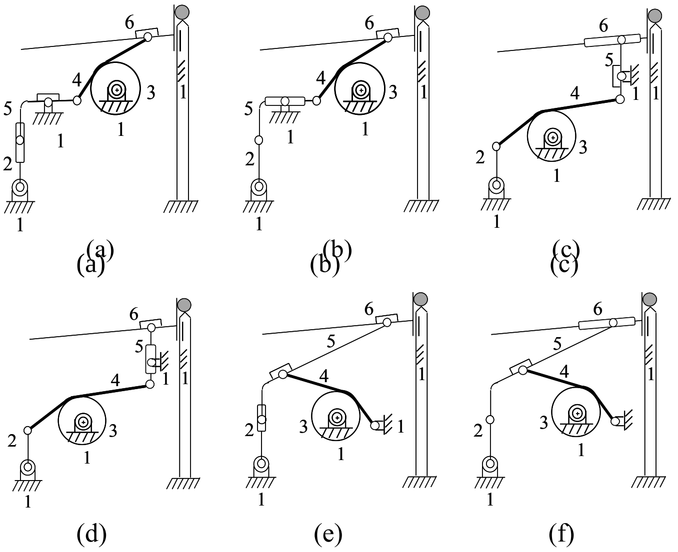


Fig. 6. Synthesized interior mechanisms Zhang Heng’s seismoscope

(d) (e) (f)

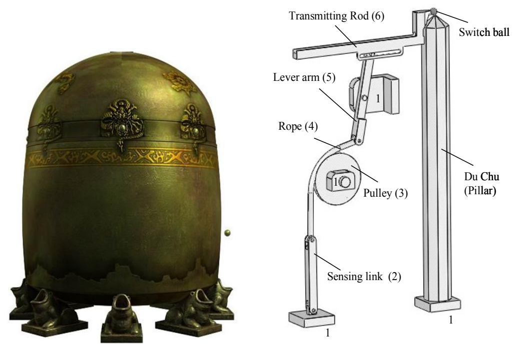


Fig. 7. A reconstruction design of Zhang Heng’s seismoscope [4]

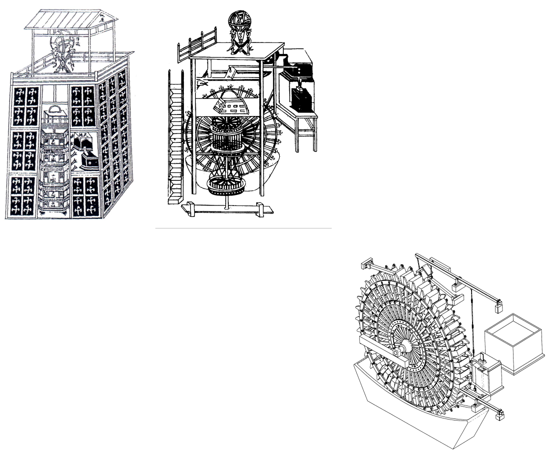


Fig. 8. Su Song's clock tower and escapement regulator [17]

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，正中為關軸於平水壺南北橫桄上，為兩頰以貫其軸，常使運動。首為格叉，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.

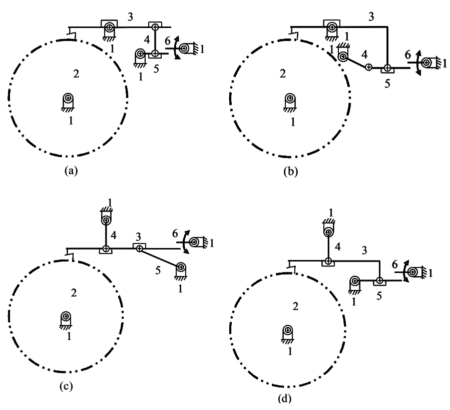


Fig. 9. Four feasible designs of the waterwheel steelyard-clepsydra device

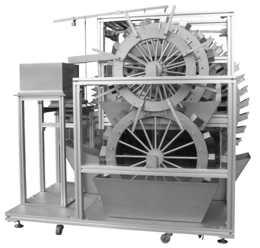


Fig. 10. A reconstruction design of Su Song's waterwheel steelyard-clepsydra device [4]

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.

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