Chapter 1 Introduction

This text explores ancient Chinese machines that have been lost to time, and proposes a methodology for systematic reconstruction to allow for their rebuilding. This chapter starts with the introduction of the study of ancient machines. It proceeds by describing the classifications of ancient Chinese machines and the process for their reconstruction design. It ends by explaining the application scope of the text.

1.1 Study of Ancient Machines

The human motivation to invent machines originated from livelihood requirements. Man-made machines have increased the production of goods, which in turn has affected lifestyle. Subsequently, social structures have upgraded due to the progressive development of machines. As a result, the invention and improvement of machines have facilitated the advancement of society.

In the long history of Chinese civilization, many ingenious machines were invented. Studies relating to the development of ancient machines have focused on people, events, objects, and causes [1–4]. Here, *people* refers to those who have contributed and affected inventions, designs, or leadership in the development of ancient machines; *events* refer to the social background, technology level, policy decision, and outcome influence in machine development; *objects* refer to the hardware, principles, and relevant literature of machines; and *causes* refer to rules, experiences, and lessons learned from the development of machines. All these four concepts are interrelated.

Studying the historical development of machines enables one to trace their paths and logics. It also leads one to understand past developmental patterns of mechanical technology. The reconstruction of ancient machines seeks to rebuild original machines by applying ancient mechanical principles, engineering, and craftsmanship. Through such an approach, the reconstructed machines can be used to demonstrate the level of mechanical technology of their times.

1.2 Classifications of Ancient Chinese Machines

Ancient China was outstanding in its mechanical technology. Numerous ingenious machines were invented before the 15th century. However, due to incomplete documentation and the loss of finished objects, most original ancient machines cannot be verified and many inventions were not passed down to later generations. For some designs, later generations could only regard these inventions as novelties, and even questioned them as being preposterous.

1.2.1 Classifications based on applications

Based on their applications, ancient Chinese machines can be classified into the following areas [5, 6]:

Labor-saving devices

Typical labor-saving devices were simple machines such as wedges, inclined planes, pulleys, levers (rods or links), wheels (pulley blocks), and their combinations.

Transmission elements

Typical transmission elements were wheels, bearings (cylinders, circular shafts), links, levers, cranks, gears, ratchets, cams, ropes, chains, screws and springs, and their combinations.

Water-drawing devices

Ancient water-drawing devices were the sharp-bottom pottery water container, shadoofs, buckets, pulley blocks, paddle blade devices, water siphons, water wheels, dragon-bone water lifts, scoop water wheels, cow-driven paddle blade machines, water-driven paddle blade machines, dragon tail machines, and others.

Agricultural devices

Ancient agricultural devices were pestle machines (tilt hammers, water-driven tilt hammers, spoon hammers, foot paddle-operated pestles, and connected pestles), grinding machines (mills, grinders, animal-driven multiple grinders, water-driven multiple grinders, and animal-driven cable grinders), crushers (stone crushers, roller crushers, and water wheelbarrows), windmills (winnowing fans), seeding machines (seed ploughs), and others.

Textile machines

Ancient textile machines were spinning machine (spinner), weaving machine, jacquard harness, and others.

Mining and metallurgy machines

Ancient mining and metallurgy machines were drills, jade polishers, the water-driven wind box, the dual-action piston wind box, and others.

Printing machines
Ancient printing machines were the rotating composing frame, rotating book shelves, and others.
Military hardware
Ancient military hardware were flamethrowers, barrel-type guns, rockets, catapults, crossbows (sight of crossbow, Zhu-ge crossbow), and others.
Aviation devices
Ancient aviation inventions were kites, airborne crafts, bamboo dragonfly, parachutes, hot air balloons, double-layered wings, and others.
Water transportation
Ancient water transportation designs were ships with paddle wheels, foot-driven paddle-wheel ships, rowing vessels, vessels that use rushing water (paddle wheel) to travel, armored ships, and others.
Land transportation
Ancient land transportation designs were war vehicles, military chariots, road carriages, man-powered twin-wheel carriages, carriages with rollers, carts with sail, single-wheel carts, south-pointing chariots, hodometers, the wooden horse carriage, the wooden cow and gliding horse, and others.
Fluid machinery
Ancient fluid machinery included revolving fans, revolving lanterns, windmills, and others.
Astronomical instruments
Ancient astronomical instruments were devices for observing the movement of the sun, solar measuring devices made from stone, sundials, compasses, telescopes, simplified armillary spheres, burning clocks, clepsydras, armillary spheres, the water-driven armillary sphere, the water-driven astronomical clock tower, the sand timer, and others.
Other devices
There were also numerous other designs, such as the sharp-bottom pottery water container, the seismograph, the lathe, the bedsheet censer, foldable umbrellas, robots, and others.

1.2.2 Classifications based on historical archives

From a restoration viewpoint, ancient Chinese machines, based on their historical archives, can be divided into three types: documented and proven, undocumented but proven, and documented but unproven [7, 8]. Here, historical archives refer to ancient manuscripts, historical artifacts, archeological data, and existing physical evidence. Ancient manuscripts refer to words and images found in official and unofficial historical records;

historical artifacts include buildings, implements, and paintings; archeological data include images and language characters on archeological findings; and existing physical evidence includes excavated ancient machines and original historical materials. Because literature on and images of artifacts only show the outer appearance but not the internal structure and dimension of parts, they are considered documented but unproven. Therefore, “documented” refers to nonphysical historical materials, while “proven” refers to the actual object.

Type I: Documented and proven

These refer to actual ancient machines with historical documentation. Generally, they are ancient machines that were widely used, some of which are excavated ancient machines with relevant literary records from their times. For instances, the wooden carriage of the Eastern Zhou Dynasty (770–256 BC) excavated from the tomb of Guo Guo (虢國) in city Sanmenxia of province Henan, the old city of Zhenghan in city Xinzheng, and the Che Ma Pit of the tomb of Zhao Qing (趙卿) in city Taiyuan of province Shanxi. Another example is the bronze arrowhead excavated from the Terra Cotta Warrior Pit of the Qin Imperial Tomb in city Xian of province Shanxsi. Relevant descriptions of these devices can be found in the book Kao Gong Ji《考工記》[9] and later annotations such as Zheng Xuan Zhu《鄭玄注》during the Eastern Han Dynasty (AD 25–219). In addition, Figure 1.1 shows the bedsheet censer (被中香爐) of Ding Huan (丁緩) in the Eastern Han Dynasty around AD 180.

Some machines such as the water wheel, water-driven tilt hammer, dragon-bone water lift, winnowing fan, and weaving machine are so practical and fully developed that they are still being used today, and relevant descriptions can often be found in historical archives. Others include the bedsheet censer and old gears.

Type II: Undocumented but Proven

These refer to excavated ancient machines that have no relevant historical documentation, such as the copper horse chariot (銅車馬) from the Qin Imperial Tomb around 210 BC and the sharp-bottom pottery water container (尖底陶瓶) excavated from the Yangshao relic site around 4,000 BC, Figure 1.2. Another unusual example is ancient Chinese paddle locks, Figure 1.3 [10, 11].

Type III: Documented but Unproven

These refer to ancient machines that have historical records but no actual evidence of existence. These machines can be further classified into those with written descriptions and illustrations, with written descriptions but without illustrations, and without written descriptions but with illustrations.

Figure 1.1 A bedsheet censer

Figure 1.2 A sharp-bottom pottery water container

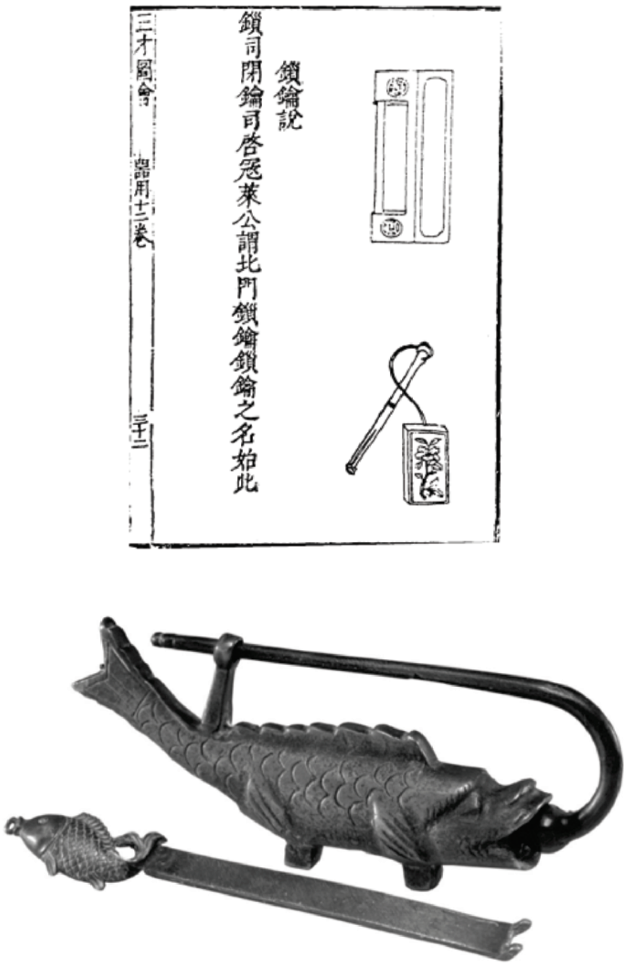

Figure 1.3 Ancient Chinese paddle locks [10, 11]

With written descriptions and illustrations
Some historical scientific literature contains written descriptions and pictorial illustrations of ancient machines. For instance, the book Wu Jing Zong Yao《武經總要》[12] during the Northern Song Dynasty (AD 960–1126) has pictorial illustrations of weapons for attacking and defending city walls, Figure 1.4. These weapons included bows, crossbows, and catapults. The book Xin Yi Xiang Fa Yao《新儀象法要》[13] also from the Northern Song Dynasty contains an illustration of an astronomical clock. The book Nong Shu《農書》[14] from the Yuan Dynasty (AD 1280–1368) has pictorial illustrations of agricultural implements such as seed ploughs and spades, as well as textile machines such as those for spinning and weaving. The book Tian Gong Kai Wu《天工開物》 [15] from the Ming Dynasty (AD 1368–1644) has pictorial illustrations of daily implements and manufacturing technology such as agricultural tools, weaving machines, metallurgies, and bows and crossbows. The article Nan Chuan Ji《南船紀》[16] from the Ming Dynasty has pictorial illustrations of all kinds of civilian and military vessels such as imperial boats, military patrol boats, and bridge boats. The publication Wu Bei Zhi《武備志》[17] also from the Ming Dynasty has pictorial illustrations of weapons for attacking and defending city walls, such as rifles and cannons, as well as weapons for sea and land combat, such as war vehicles and warships.

With written descriptions but without illustrations
There are many cases with written descriptions but without illustrations. Examples are Lu Ban's (魯班) wooden horse chariot during the Eastern Zhou Dynasty, Zhang Heng's (張衡) seismograph during the Eastern Han Dynasty, Zhu Ge-liang's (諸葛亮) wooden cow and gliding horse during the period of Three Kingdoms (AD 220–280), Zhang Si-xun's (張思訓) tai ping hun yi (太平渾儀) during the Northern Song Dynasty, Yan Su's (燕肅) south-pointing chariot during the Northern Song Dynasty, and Kuo Shou-jing's (郭守敬) Deng Lou at the Da Ming Hall during the Yuan Dynasty. Most of the relevant literature focuses on the form and description of functions but have simplistic or missing narration of their structure of mechanisms. Consequently, there are problems in restoration research that require more imagination.

Without written descriptions but with illustrations
There are also historical materials with illustrations and missing written records. Examples are the picture of the ladder with wheels on the bronze pan from the late Warring Period (480–222 BC) excavated from county Ji in province Henan. Restoration of this type is similar to the case that is

documented but unproven, but is more difficult because more thorough examination of the illustrated machine is needed.

Furthermore, Type III (documented but unproven) machines can also be divided into those that have convinced most scholars, such as the seismography of Zhang Heng in the Eastern Han Dynasty around AD 132 and the astronomical mechanical clock of Su Song (蘇頌) in the North Song Dynasty in AD 1088; and those that have not convinced most scholars, such as the south-pointing chariot of the Yellow Emperor around 2500 BC and the wooden cow and gliding horse of Zhu-ge Liang in the period of Three Kingdoms around AD 230.

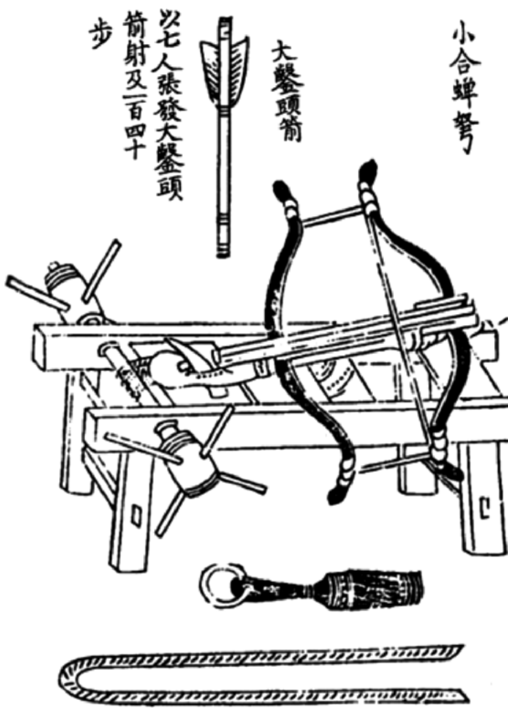

Figure 1.4 A crossbow in Wu Jing Zong Yao《武經總要》[12]

1.3 Reconstruction Design of Ancient Machines

The objective of reconstruction research is to rebuild ancient machines and to study their corresponding technology. For surviving ancient machines, the original designs are available for various studies. For lost (documented but unproven) ancient machines, since the actual machines or even pictorial illustrations are not available for verification, the reconstructed machines are often ambiguous and their correctness is difficult to prove. In general, the study of their ancient mechanical technology is even more difficult than their reconstruction.

Reconstruction research requires scientific factuality and historical objectivity in evaluating things. Only proven facts can be incorporated into the reconstruction design, and the unproven should be treated as variables. Therefore, the reconstructed design of ancient machines may not be singular, and diverse designs are normally unavoidable. Therefore, reconstructed designs can be treated as possible ancient machines belonging to the same period or as the evolutionary result of use of machines. For example, modern vehicle suspension systems are used to absorb road shocks from wheels hitting holes or bumps on the road. Figure 1.5(a)–(c) show three designs in 1980 for the rear suspension of motorcycles based on the concept of six-bar linkages by Honda (CR250R pro-link), Suzuki (RM250X full-floater), and Kawasaki (KX250 uni-trak), respectively [18]. These devices were designed for the same purpose, and the level of technology involved was similar. In fact, there can be variety in mechanical products having the same function; this was true in ancient times as well.

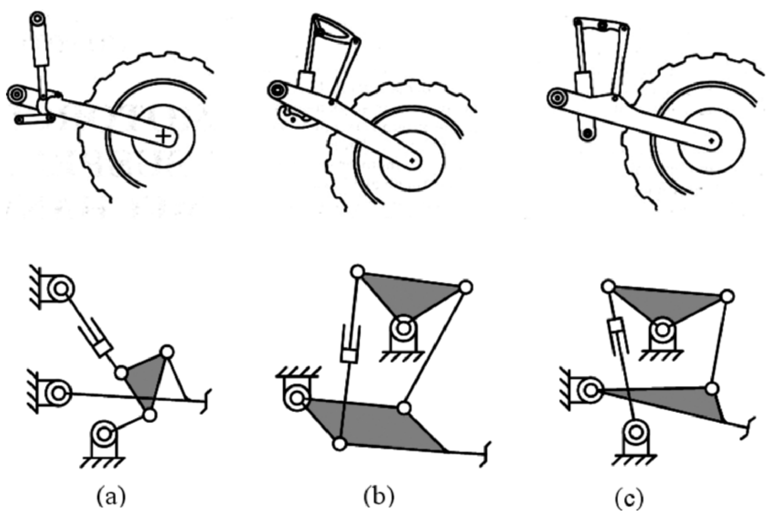

Figure 1.5 Diverse designs of motorcycle suspensions in 1980

The process for the reconstruction design of ancient machinery includes the study of historical archives, reconstruction analysis, and reconstruction synthesis, Figure 1.6 [8].

1.3.1 Study of historical archives

This step involves the study of historical archives to recognize the problem and then to identify ancient mechanical technology while using modern science and technology to define the problem for developing design specifications.

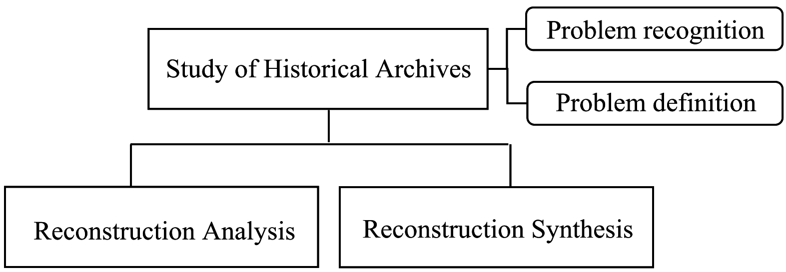

Figure 1.6 Process for reconstruction design of ancient machines

Problem recognition
Mining for information relevant to the history of ancient machines is an important foundational work, especially a thorough understanding of available archeological findings. Information to be collected should include the entire evolutionary path of the machines and existing relevant technology during that period. Attention should also be given to the names and terminologies of ancient machines. In ancient times, they may be different in different dynasties and places. For instance, the ancient Chinese water clock, named lou ke (漏刻), was referred to by different names in the past, such as qie hu (挈壺), lou (漏), tong lou (銅漏), lou hu (漏壺), ke lou (刻漏), and tong hu di lou (銅壺滴漏).

Verification, collation, and evaluation of historical archives are the first tasks toward problem recognition. Ancient literature, which accounts for the majority of historical archives, is generally simplified and may be inaccurate or exaggerated. Nevertheless, no past technological experiences and records should be ignored. For example, although there are many records on the chained-bucket mechanism in ancient literature, information on some key structures is vague, and available pictorial illustrations do not always show the structure of the chain. Since this type of machine has existed until now with very little change in its basic form, literary records and existing chained-bucket mechanisms can be used to explain its principle and structure of the design. The most credible archeological information is contained in historical artifacts. For example, drawings of sowing and weaving as well as ink paintings passed down through the ages are highly accurate reference materials. In addition, for machines that still exist today, such as water wheels and weaving machines, attention should be given to the differences between their current and ancient design and craftsmanship.

For this reason, it is necessary to refer to historical archives from various resources, as well as to correlate and verify such information in order to clarify basic issues in reconstruction research, such as principles, structures, materials, and manufacturing technology. Attention should also be given to the definition and evolution of terminologies of ancient machines. Furthermore, ancient machines in different stages and places should be collated, analyzed, and compared in order to understand their evolutionary paths.

Problem definition

Normally each past era had its own terminologies regarding engineering technology and craftsmanship. Therefore, people today might not be able to comprehend past descriptions and jargons. For this reason, it is necessary to fully understand the evolution of ancient terminologies and jargons, as well as the design, construction, technology, and craftsmanship of ancient machines. Furthermore, it is necessary to redefine ancient machines based on modern science and technology to provide a fresh and clear base for reconstruction research, especially for lost ancient machines.

After fully understanding the problem through the study of historical archives, the problem must be defined precisely so as to elicit thoughts on problem solving. Problem definition includes the development of design specifications with requirements and constraints. The purpose of specifications is to guide reconstruction design to specific domains, including special features and technical requirements such as ancient technology and craftsmanship, in order to find ways for resolving the problem.

1.3.2 Reconstruction analysis

Reconstruction design includes reconstruction synthesis and reconstruction analysis. For ancient machines that are documented and proven, as well as those that are undocumented but proven, the task of reconstruction design is mainly analysis. For lost ancient machines that are documented but unproven, the task of reconstruction design is mainly synthesis.

The purpose of reconstruction analysis is to study, test, and verify proven subjects based on modern engineering technology. For example, analytical methods such as technical testing, engineering drafting, statistical analysis, simulation verification, and scientific deductions were extensively applied to research on weapons used in ancient battles, such as bronze chariots (Figure 1.7), bows and arrows that were excavated from the burial site of the Qin Emperor [19]. Modern equipment was used to carry out accurate tests regarding the geometric parameters of the components of bronze chariots and battle weapons. The surface processing techniques used in ancient artifacts were carefully observed and analyzed to collect volumes of important raw data, which were then used for mechanical drawings. Statistical regressive analysis and numerical computing technology were used to analyze the data collected, while manufacturing simulation and experimental approaches were applied to typical components in the artifacts for comparison and verification.

Figure 1.7 A bronze chariot from the burial site of the Qin Emperor [19]

For instance, among existing artifacts is an armillary sphere from the Ming Dynasty, Figure 1.8. In 1987, the Purple Mountain Observatory and Nanjing Museum carried out reconstruction analysis on this armillary sphere [20]. Since manufacturing techniques are closely related to the metallographic structures, implements can have different metallographic structures when different manufacturing methods are used on alloys with the same composition. For this reason, 24 samples from the broken parts of the yin wei ring (陰緯環) and yang jing ring (陽經環) of the liu he yi (六合儀), the equatorial ring and tien chang ring (天常環) of the san chen yi (三辰儀), nan ji zhou zuo (南極軸座), ao yun zhu (鼇雲柱), and long zhu (龍柱) were taken for analysis. A scanning electron microscope (SEM) was used for metallographic structure verification and spectrum analysis. Based on the uniqueness of the different structures, alloy composition, and the assembled components, the performance and craftsmanship of the material of the armillary sphere were analyzed to gain an understanding of the manufacturing techniques of traditional Chinese bronze apparatuses. At the same time, measurements, tests, and verification of the structure and dimensions were performed, particularly on the shape of the components, joint techniques between the rings, and fracture design, all of which were very important in the assembly procedures. The analytical results are very helpful in the reconstruction research for various armillary spheres which were lost through the ages, such as the water-driven astronomical clock tower by Su Song in the Northern Song Dynasty.

Figure 1.8 Armillary sphere in the Purple Mountain Observatory of Nanjing

Therefore, results of reconstruction analysis are important historical information. They provide a reliable basis to identify and reestablish ancient technology and craftsmanship of a particular time period. Furthermore, they also provide invaluable reference information for the reconstruction synthesis of lost machines in the same period.

1.3.3 Reconstruction synthesis

The objective of reconstruction synthesis is to regenerate ancient machines that are consistent with historical records and the levels of ancient technology and craftsmanship subject to the developed design specifications.

Reconstruction synthesis is not new in our time but has been practiced in long-past eras with respect to even more ancient times. Most such efforts were based on verification and collation of historical manuscripts and available artifacts, and also based on a designer’s knowledge, experiences, and judgments. But, 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 methodologies were developed for the structural synthesis of mechanical devices. These recent engineering approaches can be divided into four types. The first is a design method based on the structure of mechanisms [21, 22]. The second is a design method based on the concept of modularization [23]. The third is a design method based on evolutionary perspective [24]. The fourth is a design method based on available database and experience [25, 26]. Each method has its advantages and disadvantages, as well as scope and domain of applications. Furthermore, they can be applied interchangeably.

Taking the reconstruction synthesis of ancient timer devices for instance, the fourth method, such as the use of Theory of Inventive Problems Solving (TRIZ), can first be used to identify possible methods for sundials, water-driven clocks, sand-driven clocks, incense time-telling, astronomical clocks, and mechanical clocks. Then the second method, which uses modular concepts, can be used on astronomical clocks to enumerate a list of system modules. Thereafter, the first method can be applied on each system module for the configuration synthesis of mechanisms. Whenever necessary, the mechanical evolution method, which is the third method, can be used to simulate design evolutions and identify all designs that are consistent with ancient mechanical principles and craftsmanship.

Taking the reconstruction synthesis of the escapement regulator of Su Song's water-driven astronomical clock tower during the Northern Song Dynasty as another example, by incorporating the creative mechanism design methodology (the first method) and the concept of mechanical evolution and variation (the third method), and based on available primitive design of the water wheel steelyard-clepsydra device, all possible design concepts that are consistent with ancient machine technology and craftsmanship are synthesized [27]. Figure 1.9 shows one of the reconstructed designs of the water wheel steelyard-clepsydra device.

In summary, the first step of reconstruction research of ancient machines is to study historical archives and apply modern engineering science and technology to redefine ancient machines and to develop design specifications. The objective is to transform the problem of reconstruction design of ancient machines into modern mechanical design, and to apply modern engineering design approaches to solve the problem. Reconstruction analysis provides important historical information for further research regarding the proven subjects. And, reconstruction synthesis generates all possible design configurations of the lost machines.

Figure 1.9 One possible reconstruction design of Su Song’s water wheel steelyard-clepsydra device

1.4 Scope of the Text

The purpose of the reconstruction of ancient machines is to reproduce original machines based on principles, engineering, and craftsmanship available during that time. The reconstruction design of lost ancient machines is to regenerate possible ancient machines by applying modern design methods to ancient theories and technological level of their time period.

The book Kao Gong Ji《考工記》states: “A device is an accumulation of the efforts of many.”『一器於工聚焉者。』[9]. Therefore, in order to explain the actual process of historical development of machines, the models of ancient machines in various dynasties should be reconstructed. The requirements for the reconstruction of ancient machines are stringent. There is a high degree of difficulty in the reconstruction of documented but unproven ancient machines because it involves creating something from nothing, and because relevant historical archives are either incomplete, oversimplified, or exaggerated. As a result, reconstruction work for these machines focuses on reconstruction research, particularly reconstruction design. This would produce designs that are consistent with the technologies and craftsmanship existing during the times of such machines, and at the same time account for the diversity of the ancient designs.

The objective of this text is to offer an innovative approach in the field of mechanical historiography for the reconstruction design of lost machines. However, this work will not deal with the credibility of historical literary works. It supposes that the lost ancient machines existed, such as Lu Ban's wooden horse chariot during the Eastern Zhou Dynasty, and tries to present the feasibility of the lost designs.

The reconstruction of ancient machines is the key that links the ancient history and modern history of machines. With today's ever-developing technology and requirements for better and newer products, if one can reflect on the achievements of the past, one might be able to draw knowledge from the past to produce concrete models. Perhaps, one might even be able to generate new ideas from understanding the past.

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