STRUCTURAL SYNTHESIS OF SOUTH POINTING CHARIOTS WITH A FIXED AXIS WHEEL SYSTEM

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ABSTRACT

South Pointing Chariot is one of the important mechanical inventions in ancient China. It achieves the purpose of fixing direction by applying mechanical devices with either the fixed axis wheel system or the differential gearing system. In this study, the historical background and records of South Pointing Chariots are introduced. The characteristics of existing designs of South Pointing Chariots with a fixed axis wheel system are analyzed. Representations to identify different axial directions of joints and characteristics of members are presented. A design methodology is proposed to synthesize all feasible design concepts of South Pointing Chariots with a fixed axis wheel system systematically. And, three examples are provided.

SYNTHÈSE STRUCTURALE DE CHARIOTS POINTANT LE SUD AVEC UN SYSTÈME DE ROUES D'AXE FIXE

RÉSUMÉ

Le chariot pointant le sud est l'une des plus importantes inventions mécaniques de la Chine ancienne. Il réussit à fixer une direction en appliquant des appareils mécaniques à un système de roues d'axe ou un système d'engrenage différentiel. Dans cette étude, on analyse le contexte et les cas historiques de chariots pointant le sud avec un système de roues d'axe fixe. Des représentations pour reconnaître différentes directions axiales de joints et les caractéristiques de membres sont illustrées. Une méthode de design est proposée pour synthétiser tous les concepts de design réalisables de chariots pointant le Sud avec un système de roues d'axe fixe de façon systématique. Trois exemples sont offerts.

INTRODUCTION

In ancient China, during 300 B.C. to 1500 A.D., there were various mechanical inventions in agriculture, textile machinery industry, astronomy, weaponry and vehicular engineering. However, these achievements are not familiar to the public majority due to the lack of the surviving objects and the literatures. South Pointing Chariot is a typical example. In early days, people often confused the Chariot with the compass, and they even believed that South Pointing Chariot was functioned by a magnet hidden inside. In fact, South Pointing Chariot should be called "fixed direction chariot" in the functional aspect, since it achieves the purpose of the fixing direction based on mechanism devices. So far, no relative ancient objects or archaeological relics are found, and no literature provides the interior mechanism in the ancient times clearly. As a result, the design of South Pointing Chariots is still an uncertain mystery.

In the 18th century, scholars began to pay attention to this topic and started to study the existence of South Pointing Chariots in ancient China. In 1732, Gaubil [1] and other scholars in Europe assumed that South Pointing Chariot was equal to the compass. In 1834, Klaproth [2] misunderstood and translated the "South Pointing Chariot" into "Char Magnetique". In 1908, Hirth [3] doubted the feasibility of controlling the output to fix the same direction by several gears. In 1909, Giles [4] translated two paragraphs of descriptions about South Pointing Chariot in Song-Shi (the book of Song dynasty) into English, but failed in manufacturing the model. In 1925, Moule [5] retranslated into a more exact version and successfully reconstructed Yan Su's South Pointing Chariot invited in Northern Song dynasty (960 – 1127 A.D.). In 1937, Wang [6] studied and organized the historical records in ancient China and reconstructed Yan Su's South Pointing Chariot. According to another hypothetical structure, in 1947, Lanchester [7] proposed a South Pointing Chariot with a differential mechanism. Thereafter, Needham [8], Lee [9] and Lu [10] summarized the studies of South Pointing Chariots and some scholars focused on designing different interior mechanisms [11-19].

In 1994, Lu [10] classified South Pointing Chariots into two systems: the fixed axis wheel system and the differential gearing system. South Pointing Chariots with a fixed axis wheel system are close to the descriptions of the historical records in Song Shi, and the degree of freedom is one. However, such designs are difficult to control. South Pointing Chariots with a differential gearing system provide better performance and accuracy, and the degrees of freedom are two. However, such designs or relative applications have not discovered in ancient China. The purpose of this paper is to present different representations and a design process for the structural synthesis of South Pointing Chariots with a fixed axis wheel system to meet required specifications and design requirements.

HISTORICAL BACKGROUND

It was said that both Huang-Di (2697-2599 BC) and Zhou-Gong (1122-1035 BC) invented South Pointing Chariots successfully in ancient China. However, they were not recorded in the official literatures and there were not enough evidences to support the argument.

South Pointing Chariots appeared in some official literatures during the period of the Three

Kingdoms (220-280 AD) to the Jin dynasty (1115-1234 AD). And, over 20 ancient books mentioned the chariots. The results show that South Pointing Chariots were solid invented successfully many times during the 3rd to the 13th centuries. Furthermore, there were two detailed records about the interior mechanism of South Pointing Chariots in Song-Shi [20], including the exterior shape, the dimensions, and the numbers of teeth. And, it is clear that South Pointing Chariot should firstly appear in the period of the Three Kingdoms (220-280 AD) [21].

In the beginning, South Pointing Chariot was used for military purpose. In the later period, it became a meaning to show the power and prestige of the emperor. Thus, the size of South Pointing Chariots became larger and larger gradually.

The development of South Pointing Chariots was not improved from any previous designs continuously. Various designs that appeared in different dynasties of ancient China should be invented independently. The objects were always destroyed or lost in the flames of wars during the change of dynasty. And, it was a pity that no records or real objects were found after Yuan dynasty (1206-1368 AD). As a result, we are not able to assure the structure of mechanisms of South Pointing Chariots in ancient China exactly.

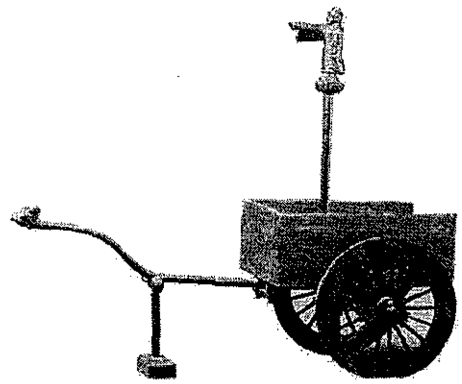
CHARACTERISTICS OF EXISTING DESIGNS

All existing designs of South Pointing Chariots can be decomposed into four sub-systems: two inputs, one transmission sub-system, one passive feedback mechanism, and one output [22]. And, the mechanical components include linkages [5-7, 11-19], gears [5-7, 11-19, 23], ropes and pulleys [5, 6, 19], and frictional wheels [19].

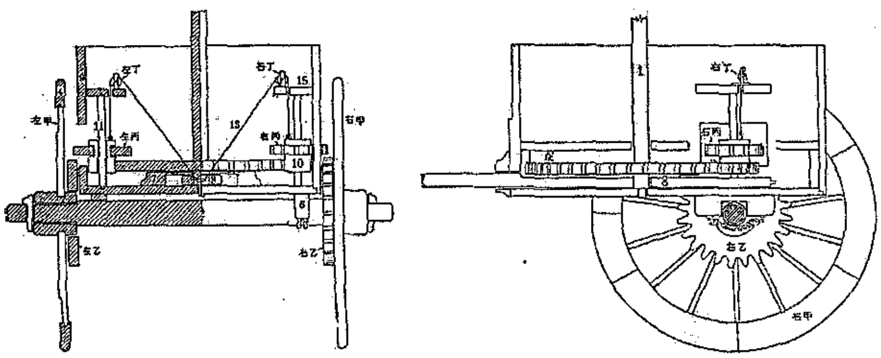
The numbers of existing designs of South Pointing Chariots with a fixed axis wheel system are fewer than those with a differential gearing system due to the reason that the latter are easily controlled and the inner constructions are more varied than the former. Hence, from literature research, only two feasible designs belong to the system with a fixed axis wheel [6, 23]. As a result, based on the topological structure analysis, the characteristics of South Pointing Chariots with a fixed axis wheel system are concluded as follows:

1. The topological structures are different between the phases of the straight motion and the turning motion.
2. The topological structures are symmetrical. We define the line from the output to the frame as the symmetrical axis since they are the common links in the operating process.
3. The degree of freedom is one. And, there is a link or a rope as the function of clutch when the chariot changes the direction.
4. The function of the pulleys is to change the direction of the ropes.

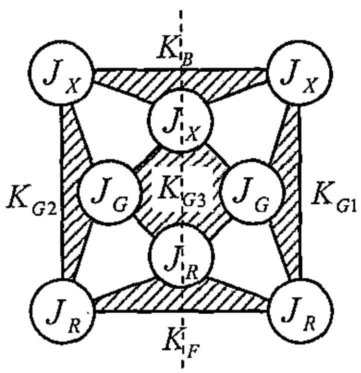
Figure 1 shows the design by Wang [6] and its corresponding topological structure in the form of a generalized chain based on the process of generalization [22]. In the phase of turning motion, a shaft pulls the rope to control the two gears up or down for connecting the output gear and the two wheels. Since only half of mechanism is affected in the turning motion, the generalized chain can be divided into two identified parts along the symmetrical axis as shown in Figure 2(a). And, for the sake of simplicity, the pulleys are ignored.



(a) Physical model



(b) Interior mechanism



(c) Corresponding generalized chain

Figure 1 Wang's design reconstructed from Yan Su's South Pointing Chariot [6]

However, some designs are based on the same generalized chain, but the inputs and the output are identified as the different members respectively. Furthermore, different models are also obtained by replacing different types of gears and designing different transmission sub-systems.

REPRESENTATION OF JOINTS AND MEMBERS

Here, we propose a novel representation to identify the joints and members of generalized chains. From the results of structural analysis, we conclude that the axial directions of revolute pairs in existing mechanisms are either horizontal or vertical to the ground. For non-revolute pairs, there are three connecting types: perpendicular, internal, and external. And, the representation of joints is as follows:

$$J_{\text{type of the joint}}^{\text{characteristic of the joint}}$$

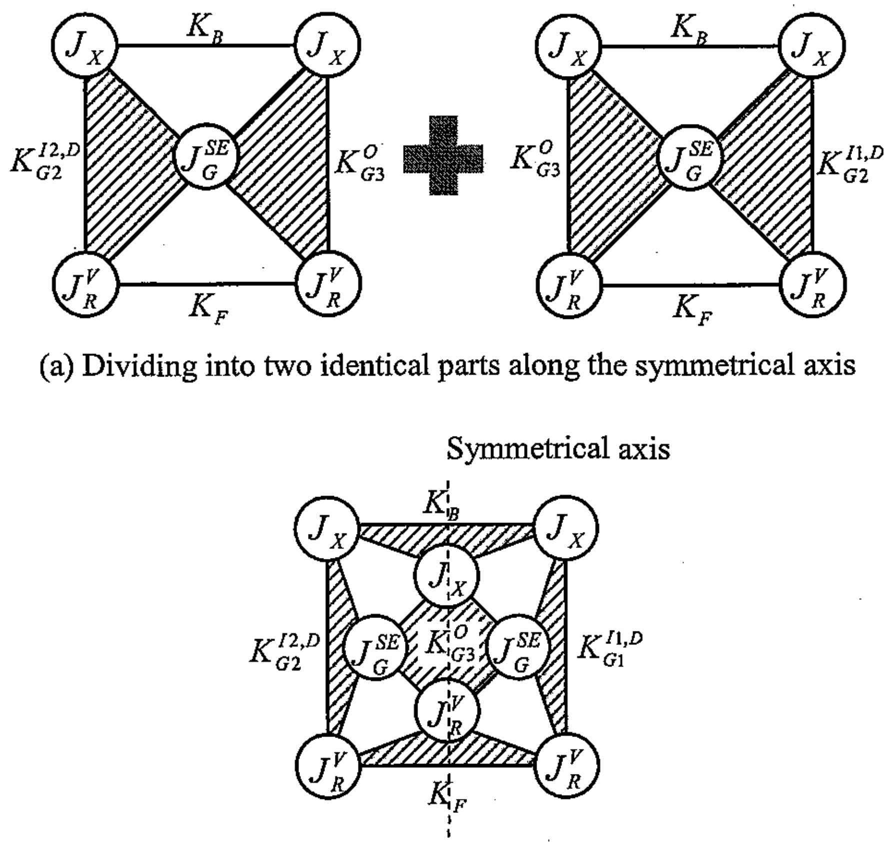
in which the subscript denotes the type of the joint and the superscript denotes the characteristic of the joint. For revolute pairs, there are two characteristics: vertical (*V*) or horizontal (*H*) to the ground. For non-revolute pairs, there are three types: the joint is incident to two members with perpendicular axial direction (*B*), the joint is incident to two members with parallel axial direction and external connection (*SE*) or internal connection (*SI*), respectively. For examples, the joint denoted as J_R^V represents that the axial direction of a revolute joint is vertical to the ground. And, J_G^B represents that the characteristic of a gear pair is incident to two gears whose axial directions are perpendicular to each other. The fixed pairs J_X do not need to identify any particular characteristic.

Although the passive feedback mechanism is the key in a South Pointing Chariot, the design of the inputs, the output, and the transmission sub-system also affect the final results. In fact, some existing designs have the same passive feedback mechanism but with different inputs, transmission sun-system, and output. To include this information in the topological structure, the representation of members is as follows:

$$K_{\text{type of the member}}^{\text{input/output and type of the transmission part}}$$

in which the subscript denotes the type of members and the superscript denotes the input/output and type of transmission sub-system. For examples, $K_G^{I1,G}$ represents that there is a gear as the input 1 and the transmission sub-system is composed of gears. And, $K_O^{I2,D}$ represents that there is a roller as the input 2 and it is connected to the wheel directly. Here, the member of belt/rope does not need to identify any particular characteristic.

Figure 2(b) shows the corresponding generalized chain of Wang's design based on the above mentioned representation of joints and members. The advantage of such a representation of members and joints is that the designer can transform all feasible designs into different generalized chains in the process of analysis and keep the information of the inputs, the output, and the transmission sub-system. And, such representations are also useful to synthesize all possible design concepts of South Pointing Chariots systematically.



(a) Dividing into two identical parts along the symmetrical axis

(b) Topological structure with particular identities

Figure 2 Analysis of Wang's design

STRUCTURAL SYNTHESIS

Here, we present an approach for the structure synthesis of South Pointing Chariots. By combining the creative mechanism design methodology [25] with the mechanical evolution, all feasible and appropriate designs that are consistent with the science theories and techniques of the subject time period can be systematically recreated. Before new literature and/or hardware evidences are found, this approach provides a novel direction and a unique tool for studying the lost machinery in ancient China. Figure 3 shows the design procedure for synthesizing the topological structure of South Pointing Chariots with a fixed axis wheel system. It consists of the following 5 steps:

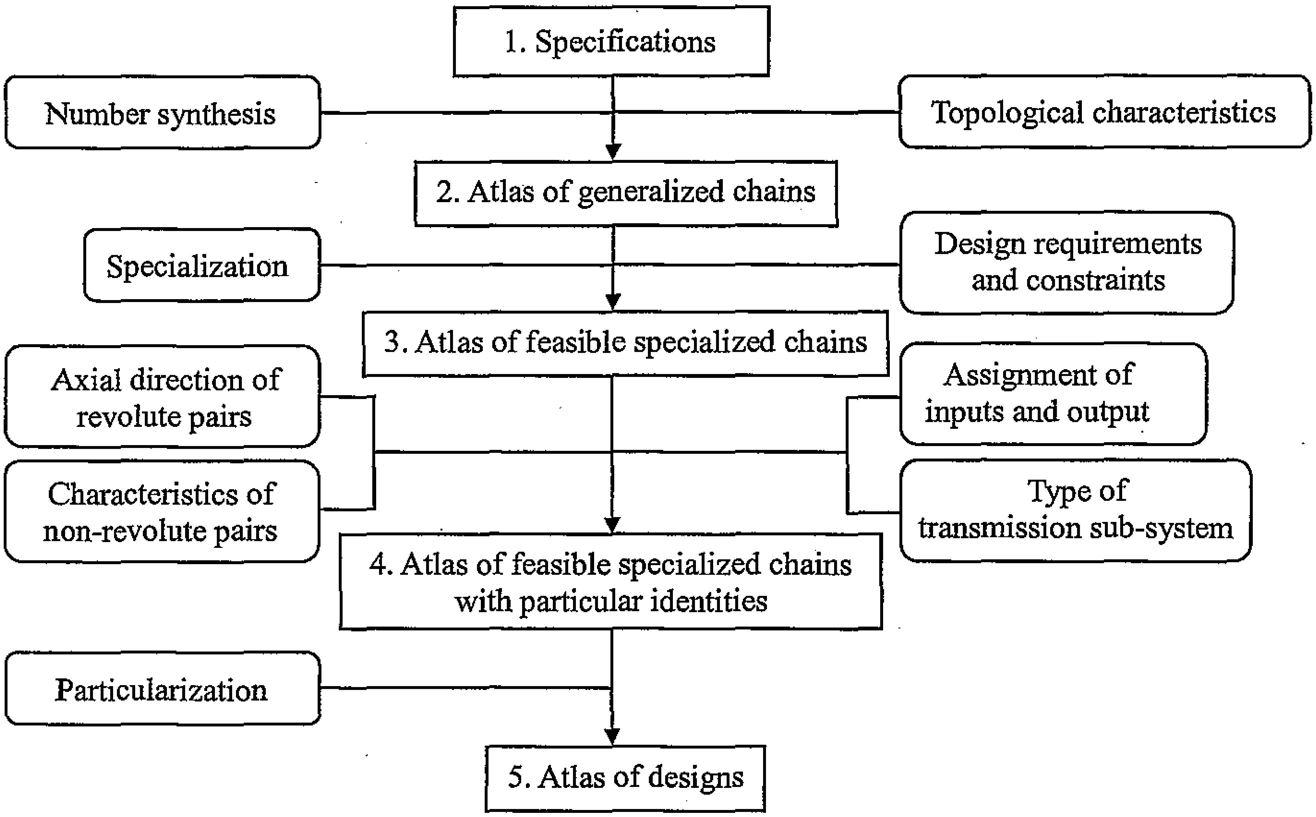


Figure 3 Steps of structural synthesis

Step 1. Specifications

After studying available literatures and analyzing existing designs, we recognize that the numbers of members in the passive feedback mechanism of the reconstruction designs are different. The mechanisms of South Pointing Chariots have various components in various dynasties based on the ancient science theories and technologies at that time. Due to the symmetry of South Pointing Chariots with a fixed axis wheel system, the first step of the design process is to define the design specifications of the half configuration, including the numbers and types of members and joints.

Step 2. Atlas of Generalized Chains

According to the process of generalization [22, 24, 25], the corresponding generalized chains of existing South Pointing Chariots can be obtained. And, the atlas of generalized chains with the required numbers of links and joints can be generated based on the algorithm of number synthesis or graph theory [25].

Step 3. Atlas of Feasible Specialized Chains

According to the development of mechanical components in the ancient China, ropes and pulleys were widely used before Qin Dynasty (221 - 206 BC), and the gear transmission was also applied to design astronomical and timing mechanical devices in Han Dynasty (202 BC - 219 AD). Through the process of specialization [24], specific types of members and joints are assigned to every generalized chain available in Step 2 to obtain the corresponding atlas of feasible specialized chains subject to design requirements and constraints.

Step 4. Atlas of Feasible Specialized Chains with Particular Identities

Here, the axial direction to each revolute pair and connection characteristic to each non-revolute pair are assigned first. The members of inputs/output are identified, and suitable types of the transmission sub-system are combined with the atlas of feasible specialized chains derived in step 3 to generate the atlas of feasible specialized chains with particular identities.

Step 5. Atlas of Designs

Finally, the two identical feasible specialized chains with particular identities are combined along the symmetrical axis to obtain the complete configuration. Then, according to the motion and function requirements of the mechanical devices, the corresponding schematic formats are particularized from the atlas of feasible specialized chains with particular identities to obtain the atlas of all designs.

DESIGN EXAMPLES

In what follows, we demonstrate the feasibility of the proposed design procedure shown in Figure 3 by three examples.

Example 1

In the process of mechanism design, engineers always accomplish the requirements of motion and function with fewer links. Since the half configuration of a South Pointing Chariot is composed of one input, one output and one frame, the number of links is three at least. Therefore, we synthesize the fixed axis wheel system South Pointing Chariots with three links as follows.

Step 1. Specifications

The type of members is open in this case. And, the design specifications are:

1. The number of links of the half passive feedback mechanism is three.
2. The degree of freedom is one no matter going straight or turning a corner.
3. The types of mechanical components are linkages, gears, and rollers.

Step 2. Atlas of Generalized Chains

For a planar mechanism with one degree of freedom (F_P=1) and three links (N_L=3), the number of joints is three (N_J=3; one joint with two degrees of freedom, and two joints with one degree of freedom). Figure 4 shows the atlas of generalized chains with three links and three joints.

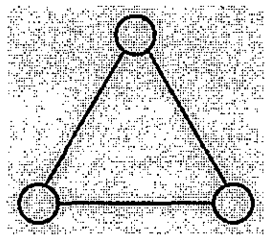


Figure 4 Feasible generalized chain (design example 1)

Step 3. Atlas of Feasible Specialized Chains

Once the atlas of generalized chains is obtained, all possible specialized chains can be identified according to the following steps:

1. For each generalized chain, identify the frame link for all possible cases.
2. For each case obtained in step 1, assign revolute pairs.
3. For each case obtained in step 2, assign non-revolute pairs.

The steps are carried out subject to the following design requirements and constraints:

Frame (K_F)

(1) One of the links in each generalized chain must be the frame.

Revolute Pair (J_R)

(1) Any joint incident to the frame must be a revolute pair.
(2) Every link must have at least one revolute pair except belts/ropes.
(3) There can be no loop formed exclusively by revolute pairs

Gear Pair (J_G)/Rolling Pair (J_O)

(1) A binary link cannot have two gear pairs or rolling pairs.
(2) A ternary link can only have two gear pairs or rolling pairs.
(3) There can be no three-bar loop formed exclusively by gear pairs.

After assigning all types of joints and members, we obtain two feasible specialized chains as shown in Figure 5.

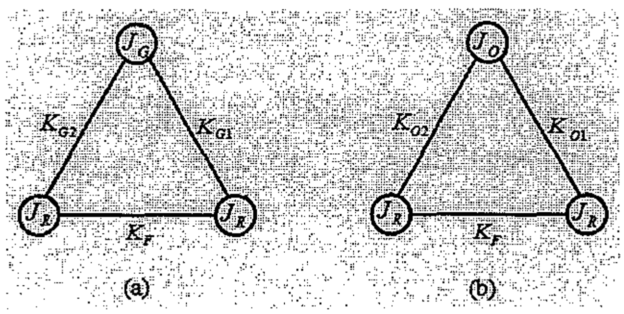


Figure 5 Feasible specialized chains (design example 1)

Step 4. Atlas of Feasible Specialized Chains with Particular Identities

In this step, the axial directions of revolute pairs and the characteristics of non-revolute pairs are identified first according to the following points:

1. Identify the superscript "V" or "H" to each revolute pair.
2. There must be at least one axial direction of revolute pair as the vertical direction.
3. The subscripts of non-revolute pairs are identified as "B" to represent the axial directions of the two adjacent members that are perpendicular to each other.
4. The subscript of non-revolute pairs is identified as "SI" or "SE" to represent the axial directions of the two adjacent members that are horizontal. Here, "I" or "E" indicates that the two gears (rollers) adjacent to a gear (rolling) pair can be internal or external.

Different designs can be obtained by assigning different members as the two inputs and the output in the specialized chains. And, the inputs and the output are identified as follows:

Input

(1) The input link has to be adjacent to the frame.

Output

(1) The axial direction of the output link must be vertical to the ground.
(2) The output link must be adjacent to the frame.

Finally, the type of transmission sub-system in all the feasible specialized chains is considered. The transmission sub-system is adjacent to the two inputs and the passive feedback mechanism. Here, we choose the simplest solution – direct connection. As a result, we obtain six feasible half specialized chains with particular identities as shown in Figure 6.

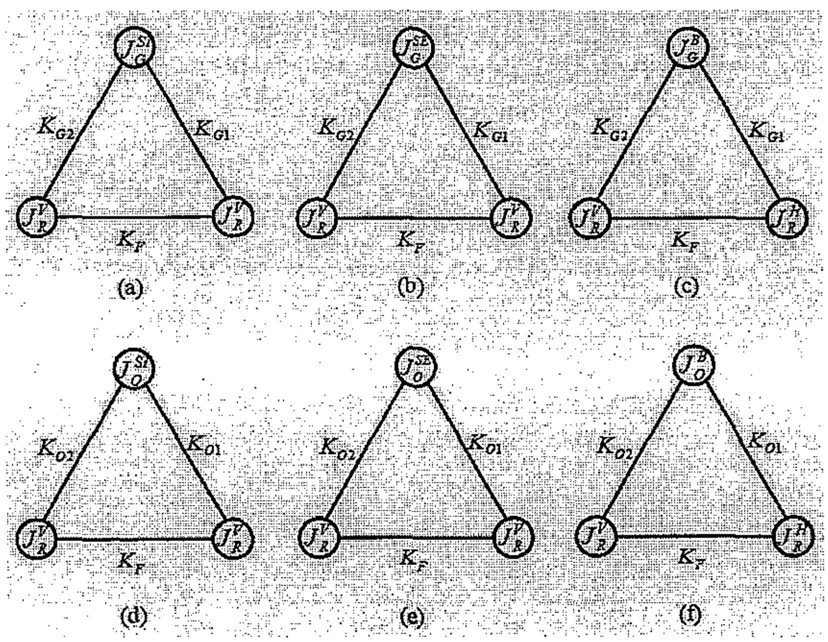


Figure 6 Atlas of feasible half specialized chains with particular identities (design example 1)

Step 5. Atlas of Designs

We combine the two identical feasible specialized chains with particular identities obtained in the above step, Figure 6, along the symmetrical axis to obtain the complete configurations of the designs as shown in Figure 7. Graphically, the process of particularization is the reverse process of generalization. However, we must notice that the rotational direction of the output should be opposite to the chariot when turning left or right. Figure 8 shows the atlas of designs through particularization, and we have six feasible design concepts of the fixed axis wheel system South Pointing Chariots with three links. The one in Figure 8(a) is designed by Bao Sihe [23].

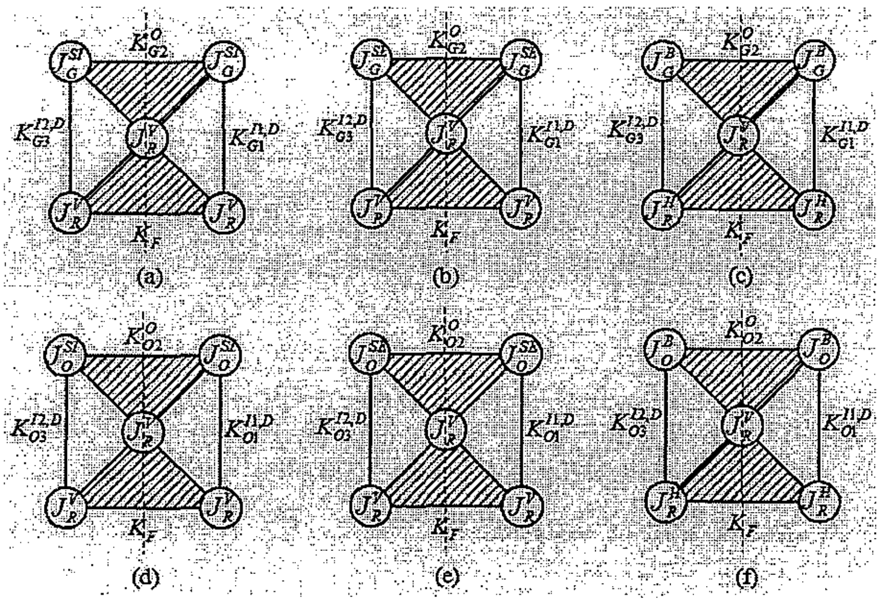


Figure 7 Atlas of feasible specialized chains with particular identities (design example 1)

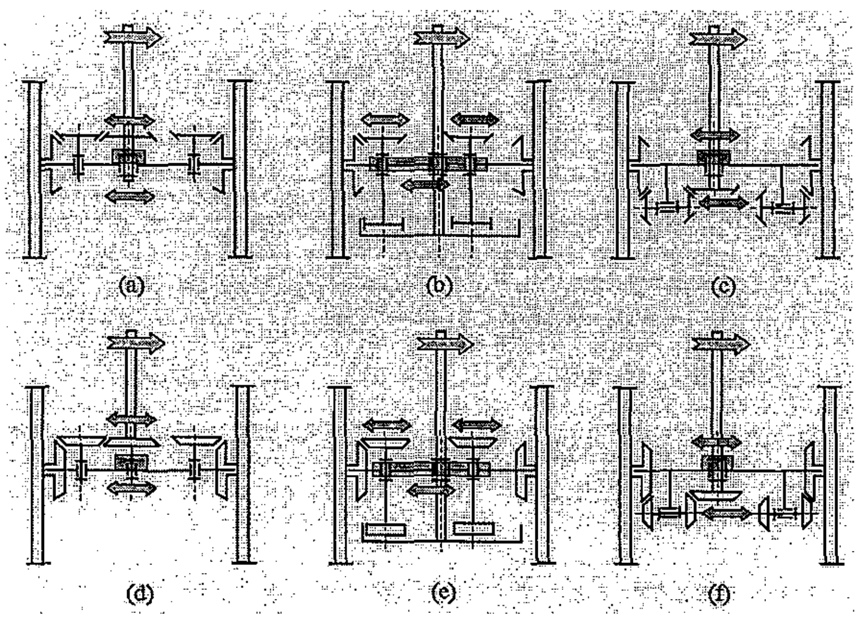


Figure 8 Atlas of designs (design example 1)

Example 2

According to the analysis of existing designs, there are at least three links in the half configuration of South Pointing Chariots. However, we can assume that the wheels are connected to the output link directly. In this case, we release one design specification: "There must be one link as the input" to synthesize the simplest designs. Therefore, the purpose of this example is to generate all possible designs of the fixed axis wheel South Pointing Chariots with two links.

Step 1. Specifications

The type of members is open in this case. And, the design specifications are:

1. The number of links of the passive feedback mechanism is two.
2. The degree of freedom is one.
3. The types of mechanical components are links, gears and frictional wheels.

Step 2. Atlas of Generalized Chains

For a planar mechanism with one degree of freedom (F_p=1) and two links (N_L=2), the number of joints is one (N_J=1; one joint with two degrees of freedom). Here, we present the generalized chains with a tree graph with two nodes (links) as shown in Figure 9.

Figure 9 Feasible generalized chain (design example 2)

Step 3. Atlas of Feasible Specialized Chains

For generating the feasible specialized chains, the two nodes (links) are assigned to the frame and the output link respectively due to the reasons that the input links are eliminated and one joint is assigned as the revolute pair. The output link can be a gear or a frictional wheel. Finally, we obtain two feasible specialized graphs (chains) as shown in Figure 10.

Figure 10 Feasible specialized chains (design example 2)

Step 4. Atlas of Feasible Specialized Chains with Particular Identities

There is only one choice to assign the horizontal axis to the revolute pair of the output. The transmission sub-system connects the two inputs and the passive feedback mechanism. Here we choose the simplest solution – direct connection. As a result, we have two feasible specialized graphs (chains) with particular identities are as shown in Figure 11.

Figure 11 Atlas of feasible specialized chains with particular identities (design example 2)

Step 5. Atlas of Designs

In this case, we do not need to combine the two identical feasible specialized chains with particular identities along the symmetrical axis, since the output is connected to the two wheels directly. Figure 12 shows the atlas of two feasible designs. They have the least numbers of links and they are the simplest mechanisms.

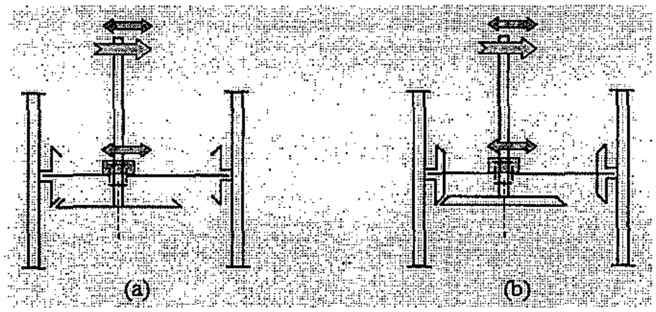


Figure 12 Atlas of designs (design example 2)

Example 3

In section 3, we analyzed Yan Su's South Pointing Chariot that was reconstructed by Wang. This Chariot contains ropes and pulleys for pulling the gears. In fact, in ancient China, the developments of laborsaving devices were much matured and full of various applications, especially the rope-and-pulley mechanisms. And, winches were widely used before the Qin dynasty (221 B.C.-206 B.C.). Besides, the friction wheels have the function of transmitting continuous rotational motion and the advantage of being simple in structure. Here, we synthesize the fixed axis wheel South Pointing Chariots with ropes, pulleys, gears, linkages, and friction wheels in this example.

Step 1. Specifications

The type of members is open in this case. And, the design specifications are:

1. The number of links of the passive feedback mechanism is four.
2. The degree of freedom is one.
3. The types of mechanical components are links, gears and frictional wheels.

Step 2. Atlas of Generalized Chains

The one rope and two fixed pairs are ignored since they do not function when the South Pointing Chariot moves straight ahead. First, for a planar mechanism with one degree of freedom (F_P=1) and four links (N_L=4, includes three members and one rope), the number of joints is five (N_J=5; one joint with two degrees of freedom, two joints with one degree of freedom, and two fixed joints). Therefore, the feasible generalized chain consists of four links and five joints as shown in Figure 13.

Step 3. Atlas of Feasible Specialized Chains

In this design example, we add one link as a rope. The process of specialization is the same with the design example 1. The relative design requirements and constraints of rope/belt and fixed pair are as follows:

Belt (Rope) (K_B)/Fixed Pair (J_X)

(1) The belt/rope must be a binary link.
(2) The belt/rope can not be adjacent to the frame.
(3) Any joint incident to the belt/rope must be a fixed pair.

Here, only the link which is not adjacent to the frame can be assigned to the rope and we obtain two results as shown in Figure 14.

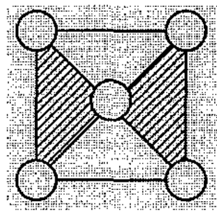


Figure 13 Feasible generalized chain (design example 3)

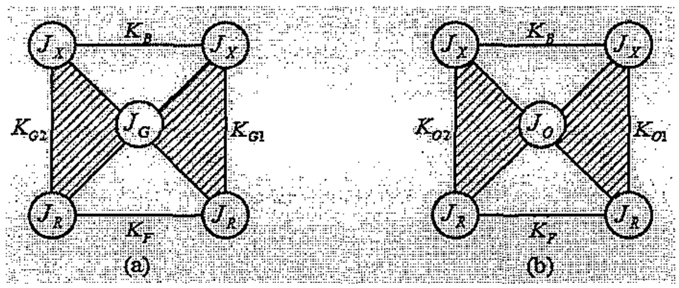


Figure 14 Feasible specialized chains (design example 3)

Step 4. Atlas of Feasible Specialized Chains with Particular Identities

Following the same representation, we assign the characteristics of all members and joints in this step except the rope and the fixed pairs. Then, we also choose the simplest solution – direct connection. As a result, we obtain six feasible specialized chains with particular identities are as shown in Figure 15.

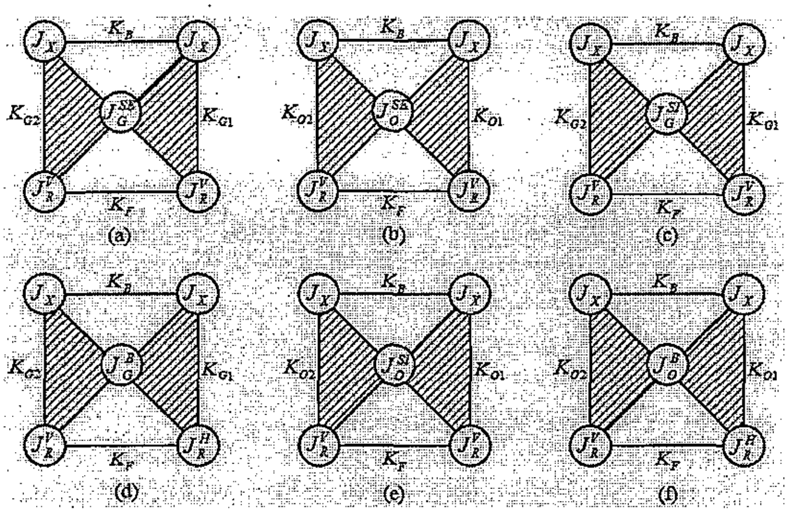


Figure 15 Atlas of feasible half specialized chains with particular identities (design example 3)

Step 5. Atlas of Designs

We combine the same two feasible specialized chains with particular identities obtained in the above step along the symmetrical axis to obtain the complete configurations of the designs as shown in Figure 16. We must notice that the rotational direction of the output should be opposite to the chariot is in the turning motion. Finally, we obtain six feasible designs through the particularization process as shown in Figure 17 in which Figure 17(a) is Wang's design [6].

The proposed methodology of this study is to synthesize all possible design concepts subject to design requirements and constraints. Figure 18 shows the corresponding 3D virtual models of above three design examples by Solidworks.

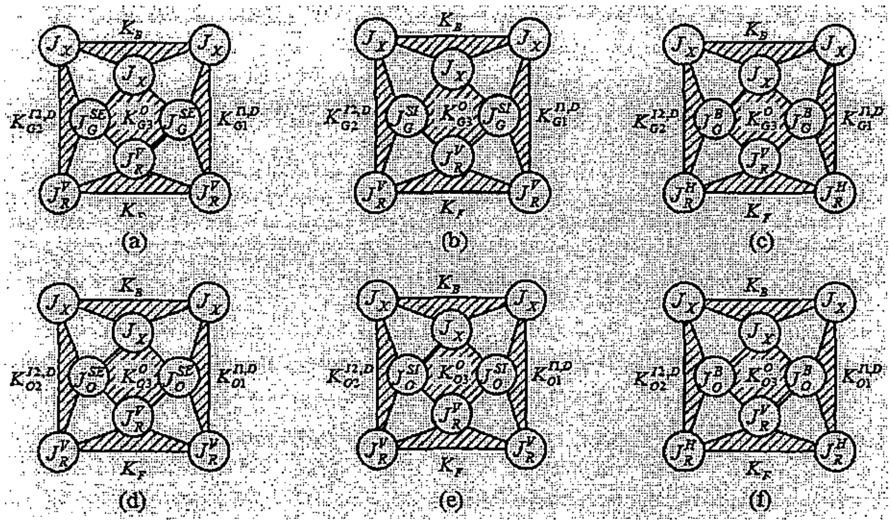


Figure 16 Atlas of feasible specialized chains with particular identities (design example 3)

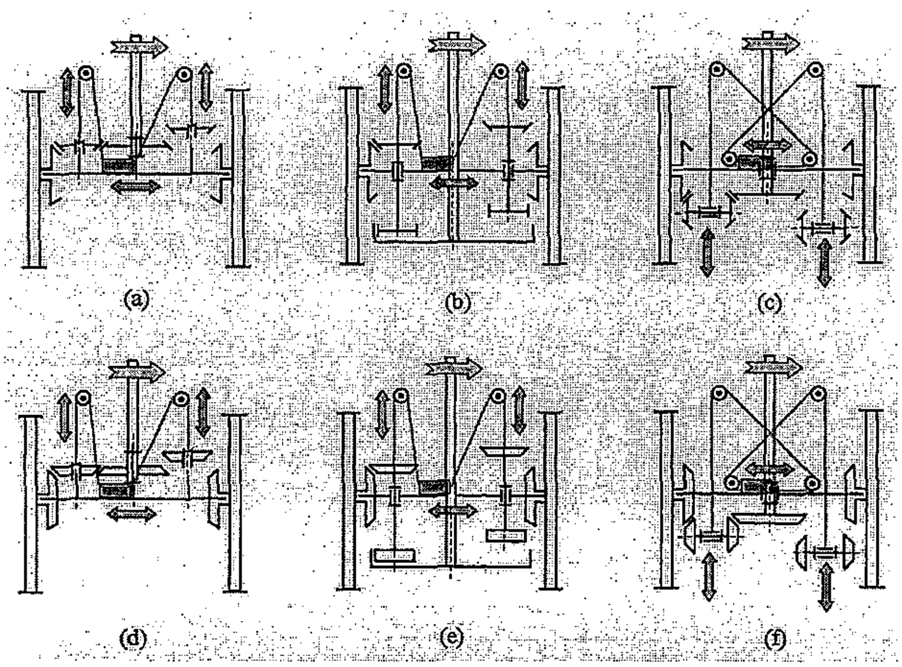
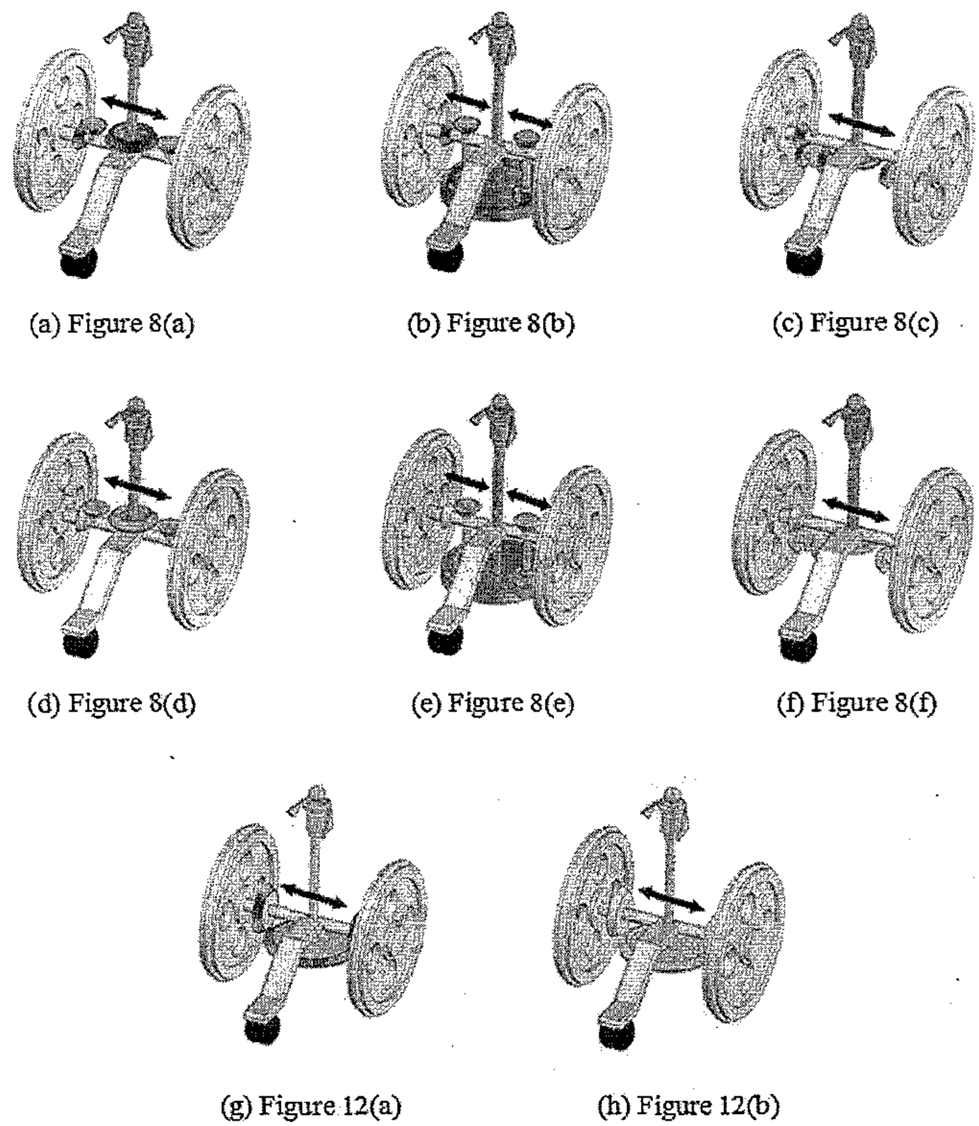


Figure 17 Atlas of designs (design example 3)



(a) Figure 8(a) (b) Figure 8(b) (c) Figure 8(c)

(d) Figure 8(d) (e) Figure 8(e) (f) Figure 8(f)

(g) Figure 12(a) (h) Figure 12(b)

Figure 18 3D virtual models of synthesized results of design examples

CONCLUSIONS

The most difficult task in the reconstruction research on ancient machinery is to create the reconstruction designs. According to the historical literatures of South Pointing Chariots in ancient China, the interior mechanisms are still mysteries. Consequently, this study provides a different view for the structural synthesis of the lost ancient machinery systematically.

In summary, novel representations for members and joints are proposed. This not only shows different designs with the same topological structures in the analysis process, but also indicates the four sub-systems of South Pointing Chariots. The design requirements and constraints of South Pointing Chariots are defined according to the topological structure analysis of the existing designs. A systematic approach is presented for synthesizing all possible design concepts of South Pointing Chariots with a fixed axis wheel system that are consistent with available mechanical members of the subject time period. Finally, three design examples are provided to design South Pointing Chariots based on the required design specifications. At present, the results of the design example 2 are the simplest designs of South Pointing Chariots with a fixed axis wheel system.

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