Chapter 8 Walking Machines

Studies and publications on modern walking machines appeared only in the last 100 years. However, according to ancient Chinese records, walking machines, devices that mimic the horse or ox using mechanical legs, might have been created before the time of Christ, especially the Wooden Horse Carriage (木車馬) of Lu Ban (魯般) around 480 BC and the Wooden Ox and Gliding Horse (木牛流馬) of Zhu-ge Liang (諸葛亮) around 230 AC. These inventions were treated as novelties, and they can be found in literary records but without surviving hardware.

This chapter systematically reconstructs all feasible designs of Lu Ban's wooden horse carriage with mechanical legs that meet the scientific and technological standards of the subject's time period [1–6]. Historical background, literature and development of ancient Chinese walking machines are studied and discussed. Works involving restoration are also presented. Finally, two examples based on different design requirements and constraints are provided.

8.1 Lu Ban the Man

Lu Ban (魯般) (~507–444 BC), whose original family name was Gong-shu (公輸), was a master carpenter and inventor in the State of Lu during the Era of Spring and Autumn (770–481 BC). Although believed to be a native of Dunhuang in ancient China, there is no definite reference to his ancestral origin [7].

According to legend, Lu Ban was not fond of learning when he was young, but was enlightened when he studied under the scholar Zi Xia (子夏). Later, by coincidence, he received lessons from Bao Lao-dong (鮑老董), and learned fine wood-carving skills. Because the family of Lu Ban was engaged in handicrafts manufacturing, his major profession became carpentry, specializing in building houses and making furniture and other utilities.

Since the working tools and devices were primitive during his time, work had to be done manually. Each job was drudgery. But Lu Ban had a muscular physique; he was bright, and his works were refined. The houses he built were strong and durable, and the furniture he made was elegant. People near and far came to him for carpentry work, and he was kept busy all the time. However, even if business was good, if he could not produce on time, it would still be problematic. Lu Ban therefore began inventing and improving his tools, including the saw, planning tool, drill and shovel, carpenter's ink marker, carpenter's square, and hook and peg on the ink marker. Furthermore, Lu Ban's wife was also believed to be an inventor. She made an umbrella for Lu Ban to carry, enabling him to work outside under any weather condition.

Lu Ban was not only an excellent carpenter; he was also an outstanding inventor. He invented the bridge-tower which was a very tall contraption used to attack castles for the State of Chu. He also made a wooden kite to spy on enemy castles. He manufactured arms for Chu's warships, and invented a kind of hook and iron mast that enabled Chu's ships to maneuver efficiently upstream. But what fascinated people most were his designs for the wooden kite and the wooden horse carriage.

8.2 Literary Works Related to the Wooden Horse Carriage

The following are literary works about Lu Ban found in ancient Chinese historical records.

Wooden kite (木鳶)

1. Mo Zi · Chapter 5 · Article Lu Wen《墨子·第五卷魯問篇》[8]
   Lu Ban was bragging about how amazing his flying kite was, made from bamboo sticks, because it could fly in the sky for three days. Mo Zi reminded him that his flying kite was no match to the cart made by the artisan, because it could carry 50 dan (a unit of weight of dry measure for grain) with only a piece of wood three cun thick.『公輸子削竹木以爲鵲，成而飛之三日不下，公輸子自以爲至巧。子墨子謂公輸子曰，子之爲鵲也不如翟之爲車轄，須臾劉三寸之木，而任五十石之重。』
2. Huai Nan Zi · Chapter 11 · Article Qi Su Xun《淮南子·第十一卷齊俗訓》[9]
   Mo Zi told Lu Ban that his kite that could fly for three days in the sky could not be put to better use.『魯班墨子以木爲鳶而飛之三日，不集而不可使爲工也。』
3. Lun Heng · Chapter 8 · Article Ru Zeng《論衡·第八卷儒增篇》[10]

According to book Ru Shu, Lu Ban and Mo Zi built a wooden kite that could fly for three days. I believe this is possible, because if his wooden horse carriage could travel for three days, and he applied the same principle with the wooden kite, then the kite could fly for three days, too.『儒書稱魯班墨子之巧刻木爲鳶，飛之三日而不集。夫言其以木爲鳶飛之可也，言其三日不集增之也，夫刻木爲鳶以象鳶形安能飛而不集乎既能飛翔，妥能至於三日如審有機關一飛遂翔不可復下，則當言遂飛不當言三日。』

4. Lun Heng · Chapter 16, article Luan Long《論衡 · 第十六卷亂龍篇》[10]

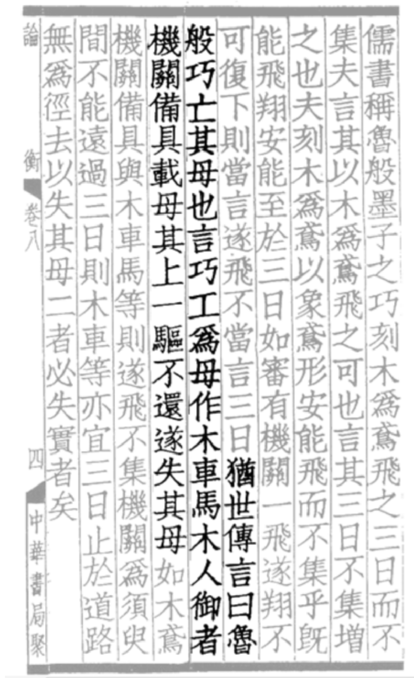
   Lu Ban and Mo Zi built the wooden kite which could fly for three days, it was an amazing creation."『魯班墨子刻木爲鳶飛之三日而不集，爲之巧也。』

Wooden horse carriage (木車馬)

The most realistic account of the wooden kite was in the book Ru Shu《儒書》[11]. Mo Zi (墨子) was born in 468 BC, 39 years later than Lu Ban. According to legend, Mo Zi was skilled in inventing tools. He spent 3 years building a wooden bird, but it could only stay in the sky for 1 day. Lu Ban bragged that his wooden bird could stay for 3 days, and that his work was superior to that of Mo Zi. Mo Zi later commented that the wooden bird of Lu Ban was no match for the wooden carts built by artisans, for these carts could carry 50 dan of heavy load with only a piece of wood three cun thick.

The book Mo Zi《墨子》[8] was jointly written by Mo Zi and his students. The discussion between Mo Zi and Lu Ban, as documented in Chapter 5 of the book, would therefore be realistic. In addition, there were also records of the wooden bird of Lu Ban in Chapter 11 of the book Han Zi Yu Ping《韓子迂評》[12], Chapter 11 of the book Huai Nan Zi《淮南子》[9], and Chapters 8 and 11 of the book Lun Heng《論衡》[10].

According to legend, Lu Ban was a filial son. He built a wooden horse carriage for his aged mother so that she would not tire herself when she went out. The carriage was designed to move without need of human control. It first appeared in the book Lun Heng by Wang Chong (王充, ~27–97 AC) in the Eastern Han Dynasty [10]. It states: "It is said that Lu Ban was mourning of the loss of this mother. He built a wooden horse carriage which was well equipped and needed no manual intervention. When his mother rode on it, it sped away never to return. If the mechanical principle used on the wooden kite was the same as that used in the wooden horse carriage, then it would fly in the sky. If the mechanism he installed on the carriage would not operate automatically for more than three days, then he would have found his mother along the three-day route.”『猶世傳言曰：「魯班巧，亡其母也。」言巧工爲母作木車馬，木人御者，機關備具，載母其上，一驅不還，遂失其母。如木鳶機關備具與木車馬等則遂飛不集，機關爲須臾間不能遠過三日，則木車等亦宜三日止於道路，無爲徑去以失其母。』(Figure 8.1)


儒書稱魯般墨子之巧刻木爲鳶飛之三日而不
集夫言其以木爲鳶飛之可也言其三日不集增
之也夫刻木爲鳶以象鳶形安能飛而不集乎既
能飛翔安能至於三日如審有機關一飛遂翔不
可復下則當言遂飛不當言三日猶世傳言曰魯
般巧亡其母也言巧工爲母作木車馬木人御者
機關備具載母其上一驅不還遂失其母如木鳶
機關備具與木車馬等則遂飛不集機關爲須臾
間不能遠過三日則木車等亦宜三日止於道路
無爲徑去以失其母二者必失實者矣

論衡 卷八 四 中華書局聚

Figure 8.1 Description of Lu Ban’s wooden horse carriage in Lun Heng《論衡》[10]

The work of Wang Chong was primarily a response to the book Ru Shu. There was a part in it that questioned the credibility of the claim that the flying contraption of Lu Ban could stay in the sky for 3 days. Wang Chong believed, however, that if the carriage of Lu Ban could move automatically without stopping, then if Lu Ban had applied the same mechanical principle for his kite, then it could also fly for 3 days without falling. Furthermore, if the wooden carriage could not move on its own, then when Lu Ban’s mother was riding in the carriage, the carriage should have stopped moving somewhere, enabling Lu Ban to find his mother along the 3-day carriage route. According to historical records, however, Lu Ban’s mother was never found.

Lu Ban lived in Dunhuang, a place full of mountainous slopes. This may also strongly imply that his carriage could move in the rugged mountainous terrain based on the principle of inertia and using the concept of balance of energy.

Literary works about the carriage were few, but there were many records of Lu Ban's wooden bird in history books. Therefore, based on the book Lun Heng by Wang Chong, the existence of the wooden horse carriage of Lu Ban could be proven indirectly. If the wooden bird had existed, then the carriage must have existed also because the design of the flying device should be more difficult than the ground carriage. In addition, if the carriage were operated by linkage mechanisms, it would not be a problem for a carpenter like Lu Ban. The most critical issues were the correct dimensions and assembly of the parts. To somebody like Lu Ban who had no modern technological background, the structure of the device would certainly be based on experiments done with rich engineering experiences. Therefore, the creation of the wooden horse carriage was possible.

The wooden horse carriage of Lu Ban was invented under such a condition; but the invention was treated as a novelty and quickly disappeared. No relevant information about his invention was recorded because the scholars during that time were ignorant of technological knowledge. Nevertheless, it is the earliest story of ancient Chinese walking machine.

Based on the records of the above-mentioned history books, the existence of the wooden horse carriage and the wooden bird should be valid. Seen from a modern technological perspective, if the account of Wang Chong was true, then the wooden horse carriage would be one of the major inventions of ancient China. Unfortunately, the invention was lost during the Eastern Han Dynasty (AD 25–220). Consequently, people are not able to see this magnificent work today.

In past history, very few scholars studied lost ancient Chinese walking machines. However, in recent decades, scholars who believe that the wooden horse carriage of Lu Ban was an enigmatic ancient invention have been reproducing the device. Around 1986, Wang Jian (王湔) of Urumqi in province Xinjiang of China, built a wooden horse carriage based on his ingenious experience and sense of practicality, Figure 8.2 [5, 6]. This design is composed of a walking mechanism with leg function and a trailer with balance function. The walking mechanism has four sets of eight-bar linkage with the same configurations.

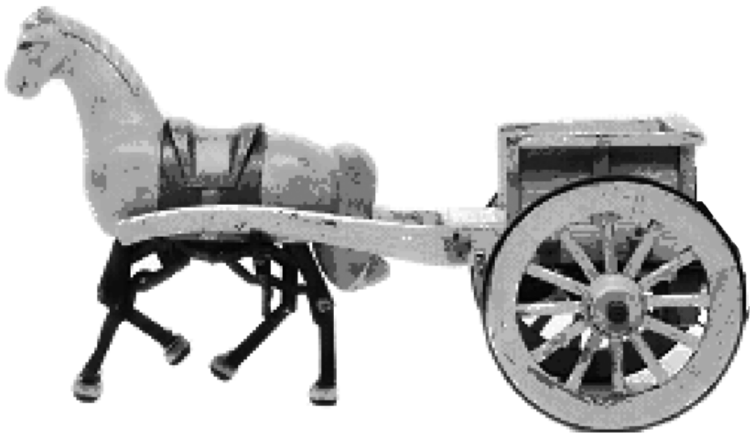


Figure 8.2 The wooden horse carriage by Wang Jian

8.3 Literary Works Related to the Wooden Ox and Gliding Horse

Another famous walking machine named wooden ox and gliding horse (木牛流馬) in ancient China was invented by Zhu-ge Liang (諸葛亮) in the Era of Three Kingdoms (AD 220–280).

The book History of the Three Kingdoms《三國志》by Chen Shou (陳壽) recorded that [13]: "In the ninth years, Zhu-ge Liang staged another war at mountain Qi, used the wooden ox to transport supplies. The army retreated when the supply was exhausted. The general of Wei, Zhang He, was killed in a battle by the army of Shu. In spring of the twelfth year, Liang led his army through the valley, using the wooden ox as transport. His army camped at Wu Zhang Yuan, opposing the army of King Si-ma Xuan in Wei Nan."『九年，亮復出祈山，以木牛運，糧盡退軍，與魏將張郃交戰，射殺郃。十二年春，亮率大眾由斜谷出，以木牛運，據武功五丈原，與司馬宣王對於渭南。』This narration clearly indicated that the cattle machine was created for food supplies in the rough terrain of mountainous regions. It first appeared in AD 209, and was a machine invented due to the necessities of war.

Since the legendary cattle machine of Zhu-ge Liang did not survive to the present and historical records on the subject are not comprehensive, scholars have different opinions about its existence. Several theories have been proposed in the past hundreds of years. Two major credible theories are: the device is a single-wheel barrow (Figure 8.3), and the device is a four-legged walking contraption.

Figure 8.3 A single-wheel barrow [14]

Many books and records supported the theory that the wooden ox and gliding horse was a four-legged walking machine. The earliest one was in the Biography of Zu Chong-zhi in the book Nan Qi Shu《南齊書·祖沖之傳》[15]. It stated that: "Zhu-ge Liang invented machines, namely the wooden ox and gliding horse, that were powered neither by the wind nor water, and the wooden ox and gliding horse carried loads without need of man's physical efforts."『以諸葛亮有木牛流馬，乃造一器，不因風水，失機自運，不勞人力。』The book further described that when left on a slope, the wooden ox and gliding horse moved down without human intervention.

Author Li Fang (李昉), in his Tai Ping Imperial Panorama《太平御覽》[16], further classified the wooden ox and gliding horse as "skilled invention" rather than "military gadget," adding support to the theory. The Instructions on Making Wooden Ox and Gliding Horse in book Zhu-ge Liang Collection《諸葛亮集·作木牛流馬法》[17] described the wooden ox and gliding horse as raising two shafts to walk four hooves forward, while a man moves six chi. Furthermore, there are many impartial historical narratives on the wooden ox and gliding horse, such as: Biography of Zhu-ge Liang《諸葛亮傳》[18], Yuan He Prefecture and County Policies 《元和郡縣志》 [19], Tale of the End of the Han Dynasty《漢末傳》[20], Other Tales of Pu Yuan《蒲元別傳》[21], Collective Analysis on the History of the Three Kingdoms《三國志集解》[22], Book of Shu 《蜀書》[23], History of the Political Units of Han Dynasty《漢郡國志》[24], Wei's Records of the Spring and Autumn Period《魏氏春秋》[25], and Inscriptions in the Zhu-ge Temple《諸葛武侯廟碑銘》[26]. Materials that are helpful in the reproduction of the cattle machine include: Zi Zhi Chronicle《資治通鑑》[27], Book of General References《通典》[28], Romance of the Three Kingdoms《三國演義》[29], and Instructions on Making Wooden Ox and Gliding Horse in book Zhu-ge Liang Collection [17].

Although literature did not specifically record the use of the wooden ox and gliding horse, the importance and contributions of the device to the Shu Kingdom in the Era of Three Kingdoms (AD 220–280) can be rationalized from their contents.

The book Zhu-ge Liang Collection – Instructions on Making Wooden Ox and Gliding Horse described this machine as "*being able to carry heavy loads but advances slowly, suitable for cumbersome tasks and not for light applications.*"『載多而行少，宜可大用，不可小使。』 This statement directly pointed out the main function of the device. There are two theories regarding its description [30, 31]:

1. The cattle machine was suited for military applications and not for transporting light cargoes. This theory assumes that the device was created for transport purposes during war. The production of such devices was not easy and high technology was involved. Thus, it seems impractical for this device to be used as a civilian transport.
2. The cattle machine could carry heavy loads, but it moved slowly. The conditions during that time, however, did not allow it to make many trips.

If the reference material is understood in its entirety, the second theory seems more rational.

After the wooden ox and gliding horse of Zhu-Ge Liang was lost to civilization, Zu Chong-zhi (祖沖之, AD 429–500) reproduced his version of the machine, but it too was lost.

Around 1986, Wang Jian of Urumqi in province Xinjiang in China, built his version of the wooden ox and gliding horse based on his ingenious experience and sense of practicality, Figure 8.4. This design is a 33-link, four-legged walking machine. The mechanisms on both sides of the device are symmetrical, and they are connected to a common crank that causes the links of the two sides to move in opposite directions. When the legs on one side of the machine move during the supporting stage, they initiate striding movement of the two legs on the other side. The four links of the front hooves correspond with the four links of the rear hooves; and they are connected to two equal-length long links. When the rear hoof moves, the momentum is passed through the long links, forcing the front hoof to move in step. The knee joint of the front leg is in front of the point where the hip joint touches the ground. When the front leg is raised, the joint protrudes forward. On the contrary, the knee joint of the rear leg is behind the point where the hip joint touches the ground. When the leg is raised, the knee joint protrudes backward. In this way, the movement of the machine closely approximates that of real cattle. And, the two legs on either side of the machine operate in a synchronous manner when it is moving.

8.4 Other Walking Machines

In the Song Dynasty (AD 960–1279), the interpretations regarding the wooden ox and gliding horse became diverse. However, it is noteworthy that the poem Yang Ma Ge (秧馬歌) by Su Shi (蘇軾) (AD 1037–1101) described a horse planting rice seedlings in the field. The reasonable conjecture should be that there is a horse-shaped mechanical device helping the job of a farmer. Furthermore, the works of Yuan Mei (袁枚) in the Qing Dynasty (AD 1644–1911) mentioned that Jiang Yong (江永, AD 1681–1762) could invent magical walking devices. For example, Chapter 107 in the Bei Zhuan Collection《碑傳集》said that: "Someone rode a wooden donkey that eats nothing and talks silence outside the city, and people took it as a weird thing. However, this amazed device was functioned mechanically based on Zhu-ge Liang's approach, not a weird thing."『行城外騎一木驢，不食不鳴，人以爲妖。笑曰：此武侯成法，不過用機耳，非妖也。』[5, 6]

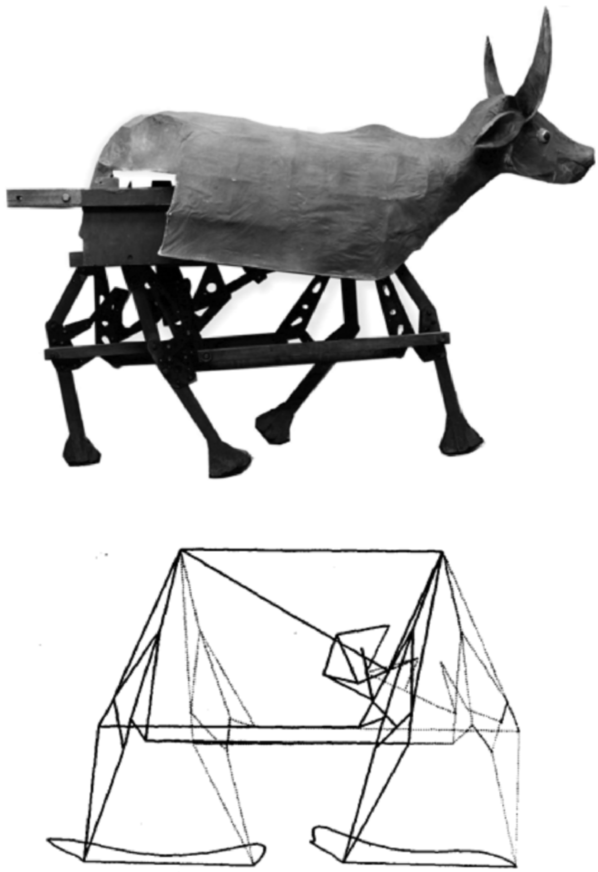


Figure 8.4 The wooden ox and gliding horse by Wang Jian

8.5 Reconstruction Design

Subject to limited historical records and technological constraints in ancient eras, the procedure for the reconstruction of design concepts of possible wooden horse carriages is shown in Figure 8.5. It consists of the following four steps:

Step 1. Design specifications

Since no original designs are available from historical archives, and based on exhaustive literature study, basic design specifications regarding the topological structure of the wooden horse carriage are defined as follow:

1. It is a quadruped walking machine that generates specific gait locomotion, and it mimics the motion of a real horse.
2. Each leg mechanism is a planar linkage with simple revolute joints and one degree of freedom.
3. A carriage is attached to the body of the wooden horse to provide the function of balance.

Step 2. Generalized kinematic chains
The second step is to obtain or identify the atlas of generalized kinematic chains with the required numbers of links and joints subject to defined design specifications (topological characteristics by applying the algorithm of number synthesis [32] or simply identified from Section 4.4.

Step 3. Specialized chains
The third step is to have the atlas of specialized chains with assigned types of links and joints subject to the concluded design requirements and constraints for each generalized kinematic chain obtained in Step 2.

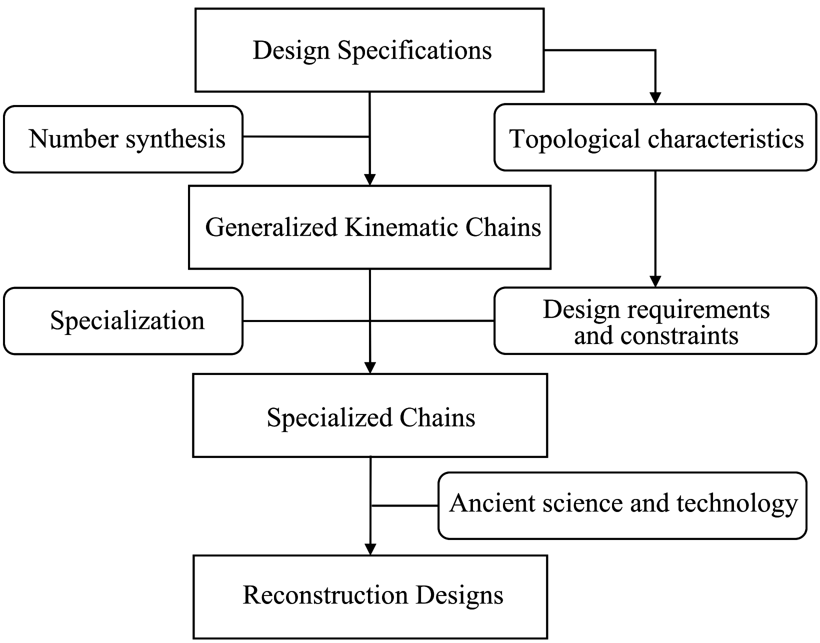


Figure 8.5 Process of reconstruction design

Step 4. Reconstruction designs

The last step is to obtain the atlas of reconstruction designs from the atlas of specialized chains according to the motion and function requirements of the ancient machinery, and by utilizing the mechanical evolution and variation theory to perform a mechanism equivalent transformation. Ancient science theories and technologies of the subject's time period are applied to find appropriate and feasible mechanisms that can be considered as the reconstruction designs.

8.6 Design Examples

Here, the target wooden horse carriage comprises a four-legged walking machine with identical leg mechanisms and a trailer. All feasible topological structures of the leg mechanisms of six-bar (Example 8.1) and eight-bar (Example 8.2) types are synthesized in the following two examples [1–4].

[Example 8.1]
Six-bar type wooden horse carriages.

For a planar six-bar leg mechanism with simple revolute joints and one degree of freedom, based on Equation (2.1) for the degrees of freedom $F_p = 1$, the number of members $N_L = 6$, and the number of degrees of constraint of a revolute joint $C_{pR} = 2$,

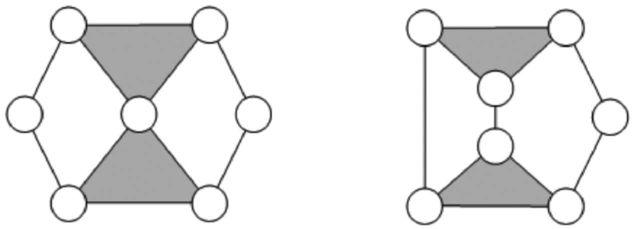
$$\begin{aligned} N_{JR} &= [3(N_L - 1) - F_p]/C_{pR} \\ &= [(3)(6 - 1) - 1]/2 \\ &= 14/2 \\ &= 7 \end{aligned}$$

the number of joints (N_{JR}) is seven.

Therefore, the leg mechanism of six-bar type wooden horse carriages should be a (6, 7) kinematic chain. And, there are two (6, 7) kinematic chains shown in Figure 4.22 and again in Figure 8.6.

Once the atlas of the kinematic chains is obtained, all possible specialized chains can be identified through the following substeps:

1. For each kinematic chain, identify the thigh link (member 3, K_{Lt}) and the shank link (member 4, K_{Ls}) that are adjacent to each other for all possible cases.
2. For each case obtained in substep 1, identify the ground link (member 1, K_F).
3. For each case obtained in substep 2, identify the crank (member 2, K_{Lc}).



(a) (b)

Figure 8.6 Atlas of (6, 7) kinematic chains (Example 8.1)

These substeps are carried out subject to the following design requirements and constraints:

1. It has a ground link (frame) as the body.
2. It has a crank.
3. The crank of the leg mechanism is adjacent to the body, and the fixed pivots of all the four cranks are coaxial.
4. It has a thigh link.
5. It has a shank link.
6. The crank, the thigh link, and the shank link must be distinct members.
7. The crank cannot be adjacent to the thigh link or the shank link.
8. The thigh link is adjacent to the body and the shank link.
9. The shank link cannot be adjacent to the body, but is adjacent to the thigh link. In addition, there is a foot point (coupler point) on the shank link to generate a path curve and to contact the ground.

In what follows, the kinematic chain shown in Figure 8.6(a) is chosen as an example for the process of specialization.

Thigh link (member 3, K_{Lt}) *and shank link* (member 4, K_{Ls})

Since there must be a thigh link which is adjacent to the shank link, four specialized chains with identified thigh link and shank link are available as shown in Figure 8.7.

Ground link (member 1, K_F)

Since there must be a link as the frame, the ground link can be identified based on the design requirements and constraints as follows:

1. For the case shown in Figure 8.7(a), the assignment of the ground link generates three results, Figure 8.8(a)–(c).
2. For the case shown in Figure 8.7(b), the assignment of the ground link generates two results, Figure 8.8(d) and (e).
3. For the case shown in Figure 8.7(c), the assignment of the ground link generates three results, Figure 8.8(f)–(h).

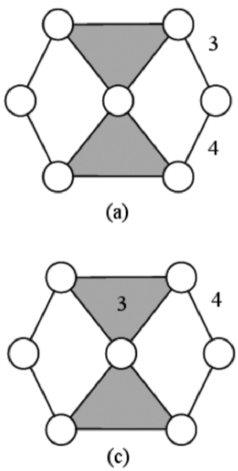


Figure 8.7 Specialized chains with identified thigh link and shank link (Example 8.1)

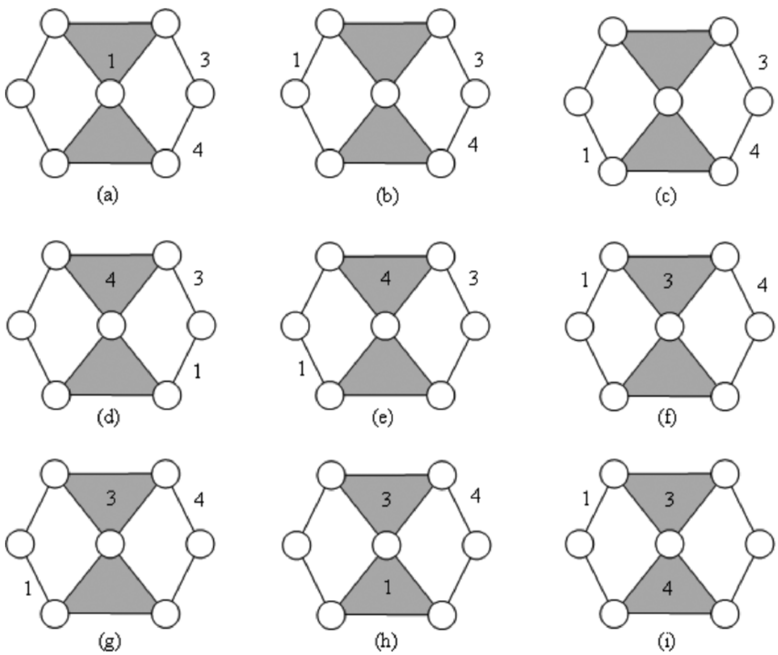


Figure 8.8 Specialized chains with identified thigh link, shank link, and ground link (Example 8.1)

4. For the case shown in Figure 8.7(d), the assignment of the ground link generates one nonisomorphic result, Figure 8.8(i).

Therefore, nine specialized chains with identified thigh link, shank link, and ground link are available, as shown in Figure 8.8.

Crank (member 2, K_{Lc})

Since there must be a crank that is adjacent to the ground link and that cannot be adjacent to the thigh link or the shank link, the crank can be identified as follows:

1. For the case shown in Figure 8.8(a), the assignment of the crank generates two results, Figure 8.9(a_1) and (a_2).
2. For the case shown in Figure 8.8(b), the assignment of the crank generates two results, Figure 8.9(a_3) and (a_4).
3. For the case shown in Figure 8.8(c), the assignment of the crank generates two results, Figure 8.9(a_5) and (a_6).
4. For the case shown in Figure 8.8(d), the assignment of the crank generates one result, Figure 8.9(a_7).
5. For the case shown in Figure 8.89(e), the assignment of the crank generates two results, Figure 8.9(a_8) and (a_9).
6. For the case shown in Figure 8.8(f), the assignment of the crank generates one result, Figure 8.9(a_{10}).
7. For the case shown in Figure 8.8(g), the assignment of the crank generates two results, Figure 8.9(a_{11}) and (a_{12}).
8. For the case shown in Figure 8.8(h), the assignment of the crank generates two results, Figure 8.9(a_{13}) and (a_{14}).
9. For the case shown in Figure 8.8(i), the assignment of the crank generates one result, Figure 8.9(a_{15}).

Therefore, 15 specialized chains with identified thigh link, shank link, ground link, and crank are available, as shown in Figure 8.9(a_1)–(a_{15}).

By following the same process of specialization for the kinematic chain shown in Figure 8.6(b), 17 specialized chains with identified thigh link, shank link, ground link, and crank are available, as shown in Figure 8.9(b_1)–(b_{17}). In summary, there are a total of 32 feasible specialized chains available as the leg mechanism for six-bar type wooden horse carriages as shown in Figure 8.9(a_1)–(b_{17}).

Figure 8.10(a_1)–(b_{17}) show the corresponding schematic formats of the leg mechanisms, providing the atlas of all possible designs. Figure 8.11 shows a physical model of a six-bar type wooden horse carriage based on the concept from Figure 8.10(b_4) [3].

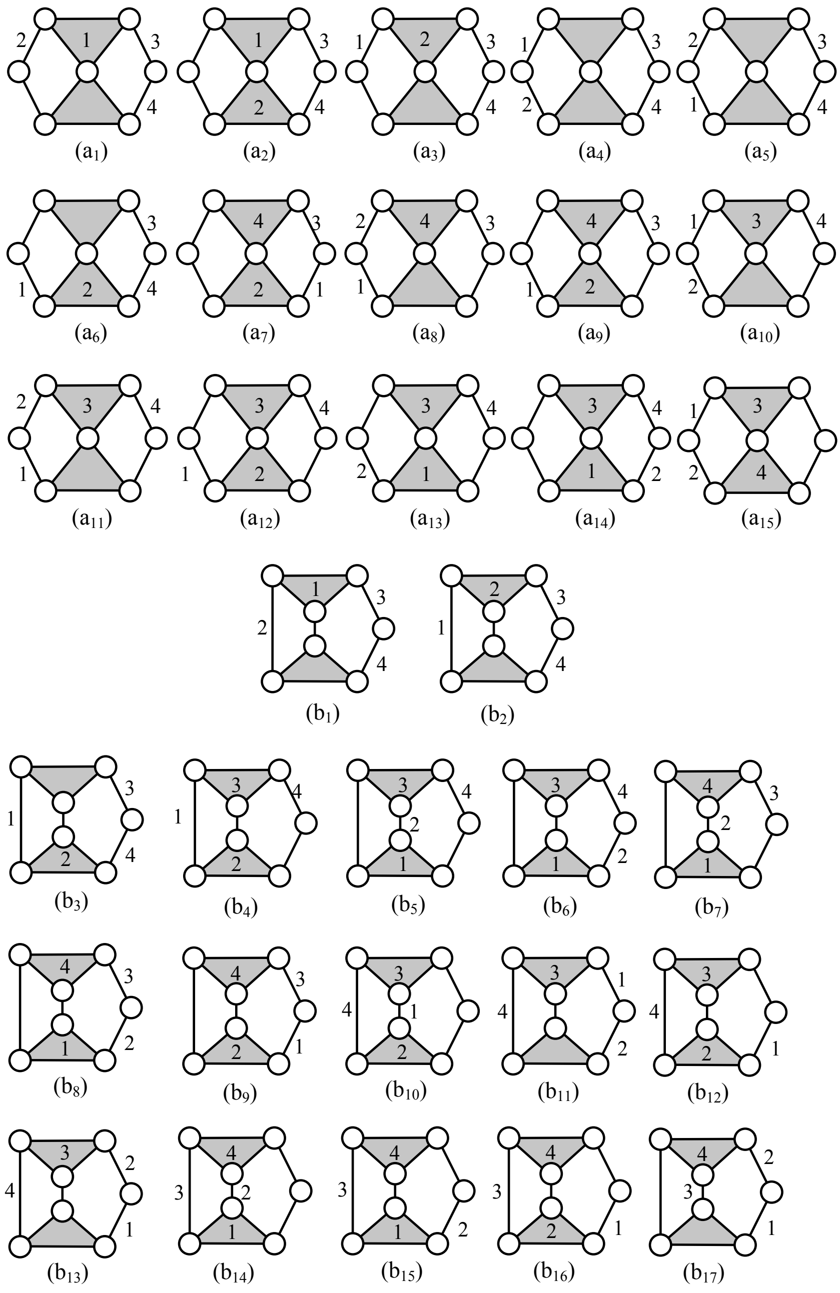


Figure 8.9 Specialized chains with identified thigh link, shank link, ground link, and crank (Example 8.1)

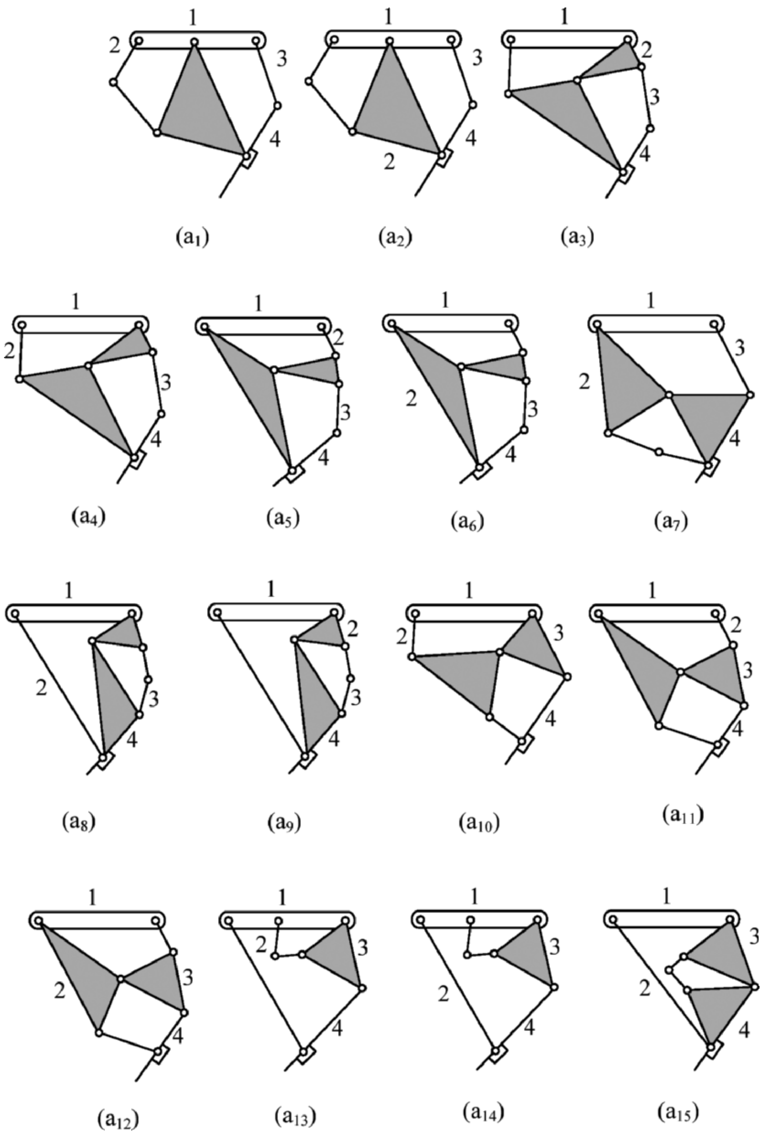


Figure 8.10 Atlas of leg mechanisms for six-bar type wooden horse carriages (Example 8.1)

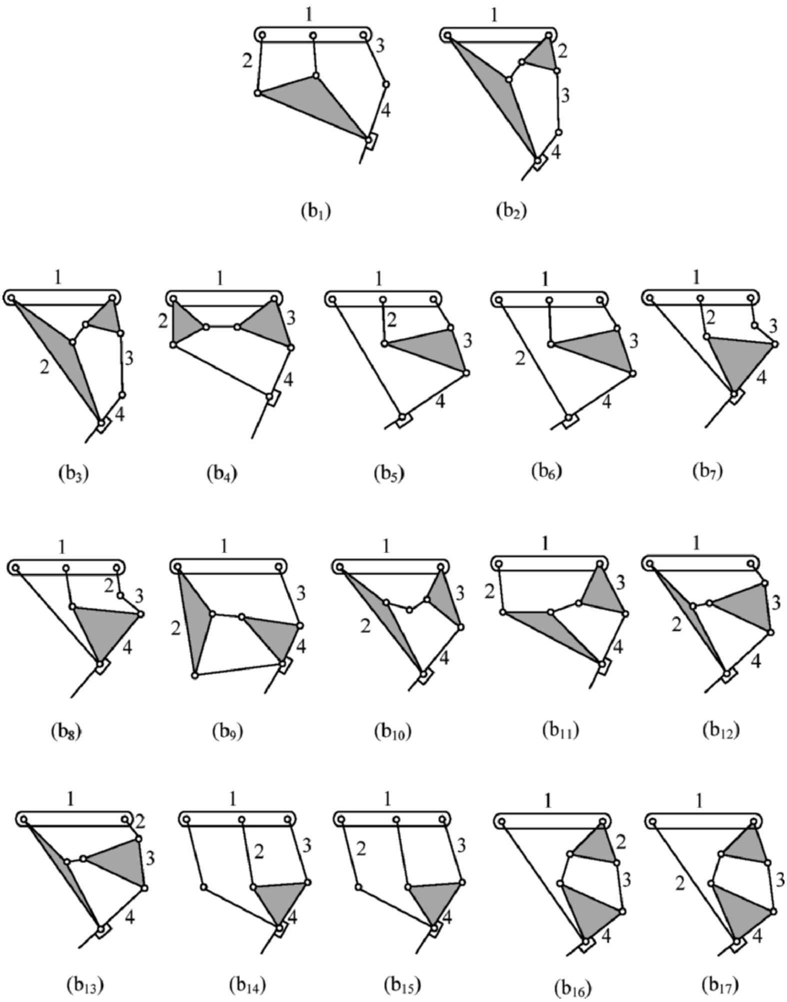


Figure 8.10 (*Continued*)

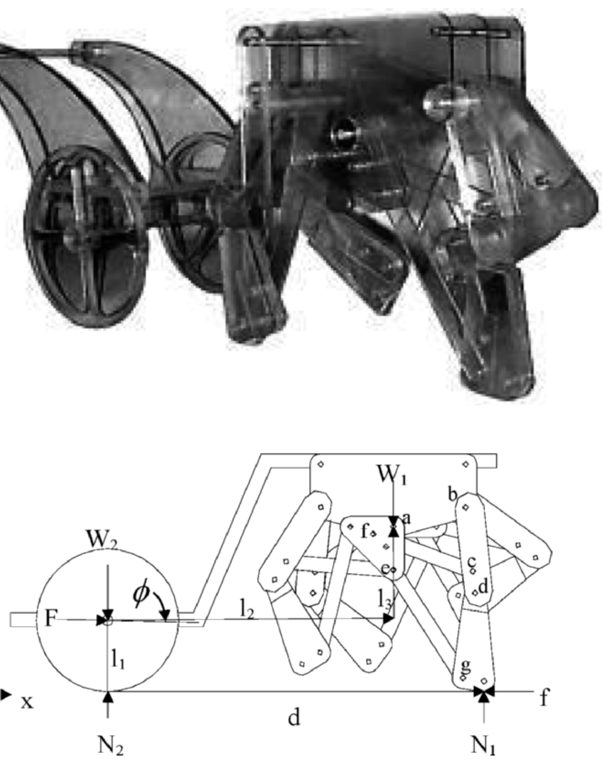


Figure 8.11 Physical model of a six-bar type wooden horse carriage (Example 8.1) [3]

[Example 8.2]
Eight-bar type wooden horse carriages.

For a planar eight-bar leg mechanism with simple revolute joints and one degree of freedom, based on Equation (2.1) for the number of degrees of freedom F_p = 1, the number of members N_L = 8, and the number of degrees of constraint of a revolute joint C_{pR} = 2,

$$\begin{aligned} N_{JR} &= [3(N_L - 1) - F_p]/C_{pR} \\ &= [(3)(8 - 1) - 1]/2 \\ &= 20/2 \\ &= 10 \end{aligned}$$

the number of joints (N_{JR}) is ten. Therefore, the leg mechanism of eight-bar type wooden horse carriages should be an (8, 10) kinematic chain. And, there are 16 (8, 10) kinematic chains as shown in Figure 4.23 and again here in Figure 8.12.

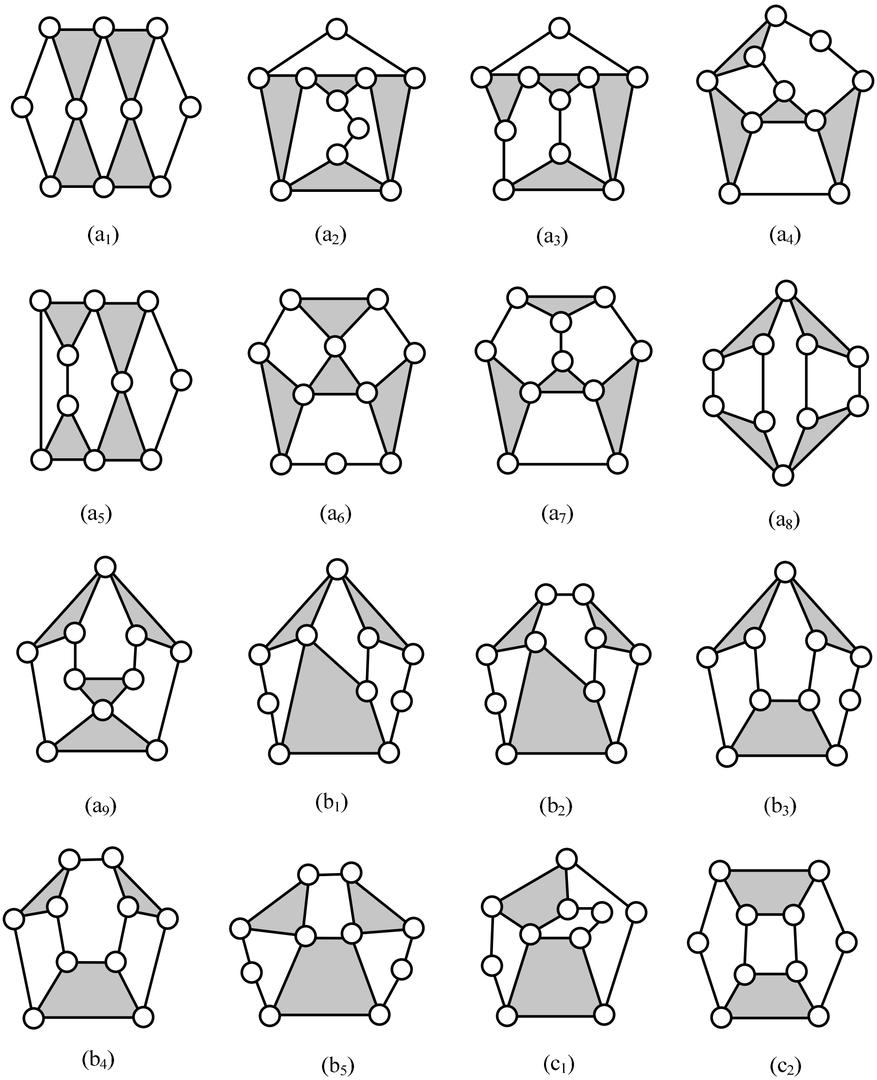


Figure 8.12 Atlas of (8, 10) kinematic chains (Example 8.2)

Once the atlas of the kinematic chains is obtained, all possible specialized chains can be identified through the following substeps:

1. For each kinematic chain, identify the ground link (member 1, K_F) for all possible cases.
2. For each case obtained in substep 1, identify the thigh link (K_{Lt}).
3. For each case obtained in substep 2, identify the shank link (K_{Ls}).
4. For each case obtained in substep 3, identify the crank (K_{Lc}).

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

1. It has a ground link as the body, and the ground link is a multiple link.
2. It has a crank, and the crank is a binary link.
3. The crank of the leg mechanism is adjacent to the body, and the fixed pivots of all the four cranks are coaxial.
4. It has a thigh link.
5. It has a shank link.
6. The crank, the thigh link, and the shank link must be distinct members.
7. The crank cannot be adjacent to the thigh link or the shank link.
8. The thigh link is adjacent to the body and the shank link.
9. The shank link cannot be adjacent to the body, but is adjacent to the thigh link. There is also a foot point (coupler point) on the shank link to generate a path curve and to contact the ground.

In what follows, the kinematic chain shown in Figure 8.12(a) is chosen as an example for the process of specialization.

Ground link (K_F)

Since there must be a multiple link as the ground link, and due to the symmetry of links, anyone of the four ternary links in Figure 8.12(a) can be identified as the ground link.

Thigh link (K_{Lt})

Since there must be a thigh link and the thigh link must be adjacent to the ground link, those three links adjacent to the ground link can be assigned as the thigh, Figure 8.13(a)–(c).

Shank link (K_{Ls})

Since there must be a shank link and the shank link must be adjacent to the thigh link, the shank link can be identified as follows:

1. For the case shown in Figure 8.13(a), the assignment of the shank link generates two results, Figure 8.14(a) and (b).
2. For the case shown in Figure 8.13(b), the assignment of the shank link generates two results, Figure 8.14(c) and (d).
3. For the case shown in Figure 8.13(c), the assignment of the shank link generates one result, Figure 8.14(e).

Therefore, five specialized chains with identified ground link, thigh link, and shank link are available as shown in Figure 8.14(a)–(e).

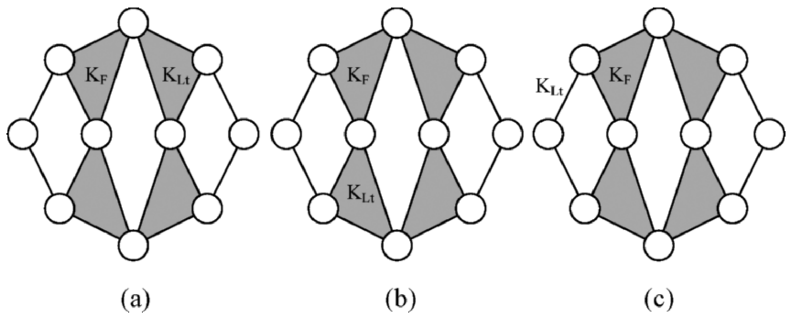


Figure 8.13 Specialized chains with identified ground link and thigh link (Example 8.2)

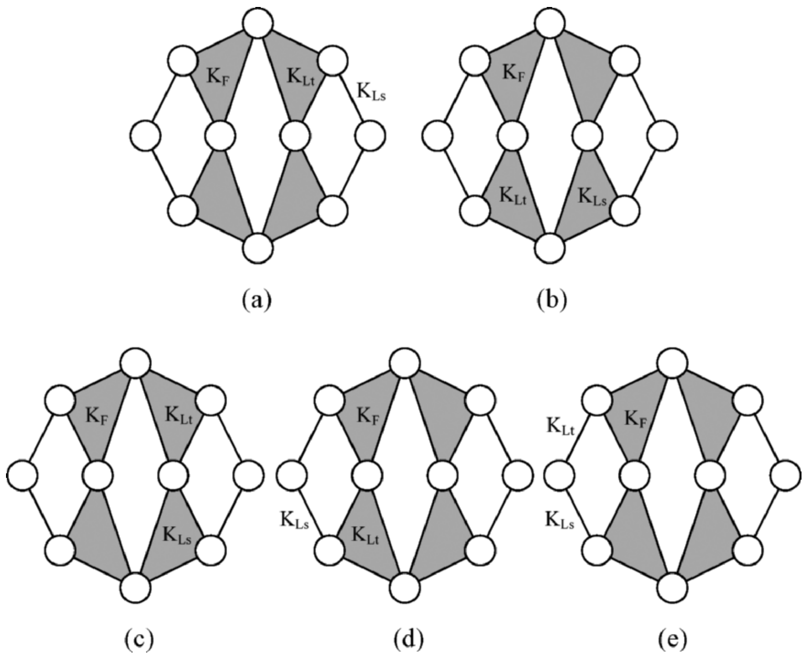


Figure 8.14 Specialized chains with identified ground link, thigh link, and shank link (Example 8.2)

Crank (K_F)
Since there must be a binary link as the crank that is adjacent to the ground link, but that cannot be adjacent to the thigh link or the shank link, the crank can be identified as follows:

1. For the case shown in Figure 8.14(a), the assignment of the crank generates one result, Figure 8.15(a).
2. For the case shown in Figure 8.14(b), the assignment of the crank generates one result, Figure 8.15(b).
3. For the case shown in Figure 8.14(c), the assignment of the crank generates one result, Figure 8.15(c).
4. For the case shown in Figure 8.14(d), since the binary link adjacent to the ground link is also adjacent to the shank link, no result can be generated.
5. For the case shown in Figure 8.14(e), since the binary link adjacent to the ground link is already assigned as the thigh link, no binary link is available to be assigned as the crank and no result can be generated.

Therefore, three specialized chains with identified ground link, thigh link, shank link, and crank are available, as shown in Figure 8.15.

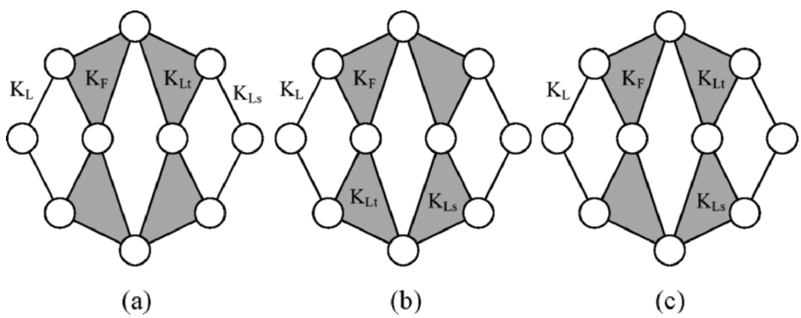


Figure 8.15 Specialized chains with identified thigh link, shank link, ground link, and crank (Example 8.2)

By following the same process of specialization for the kinematic chains shown in Figure 8.12(b)–(p), 114 specialized chains with identified thigh link, shank link, ground link, and crank are available. In summary, there are a total of 117 feasible specialized chains available as the leg mechanism for eight-bar type wooden horse carriages as shown in Figure 8.16(a_1)–(p_3).

Figure 8.17 shows some of the corresponding schematic format of the leg mechanisms. It is interesting to note that the mechanism shown in Figure 8.17(b) is the leg mechanism of the wooden horse carriage by Wang Jian as shown in Figure 8.2.

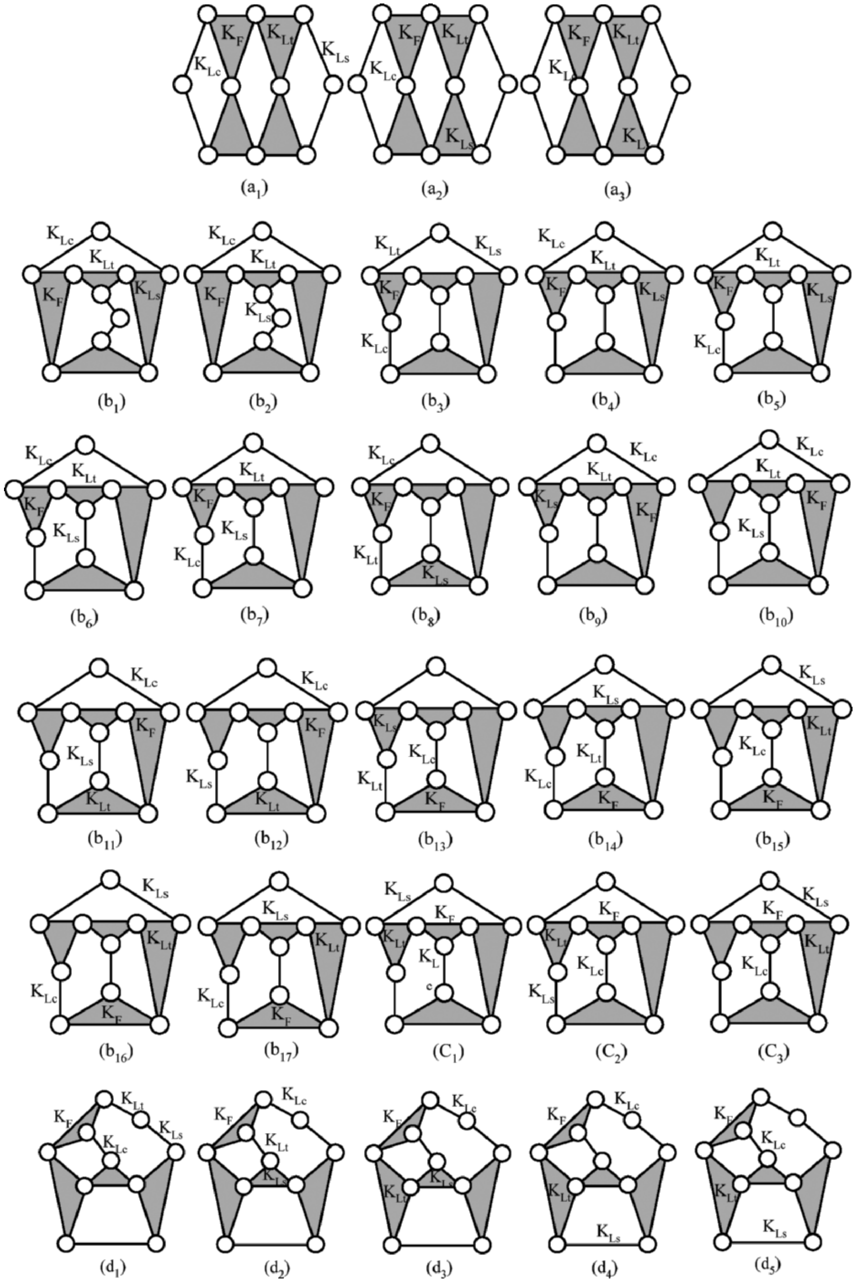


Figure 8.16 Atlas of specialized chains with identified thigh link, shank link, ground link, and crank (Example 8.2)

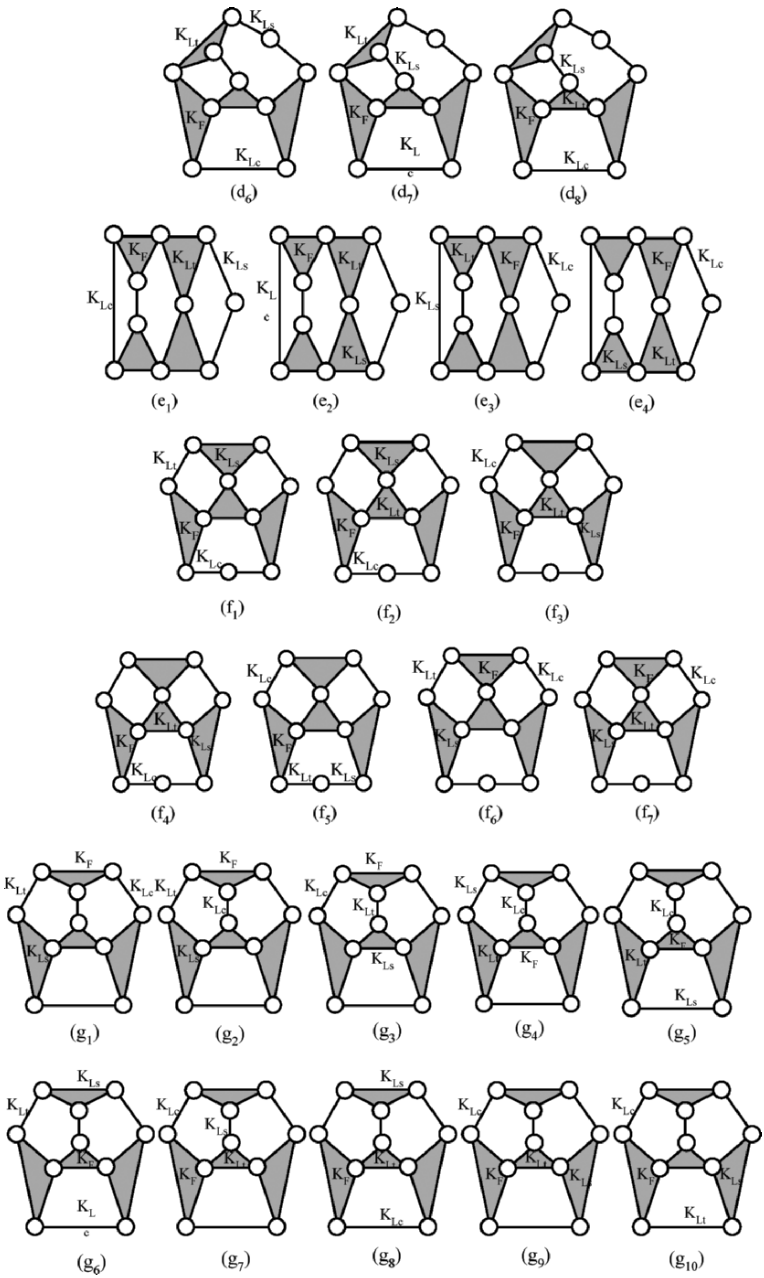


Figure 8.16 (*Continued*)

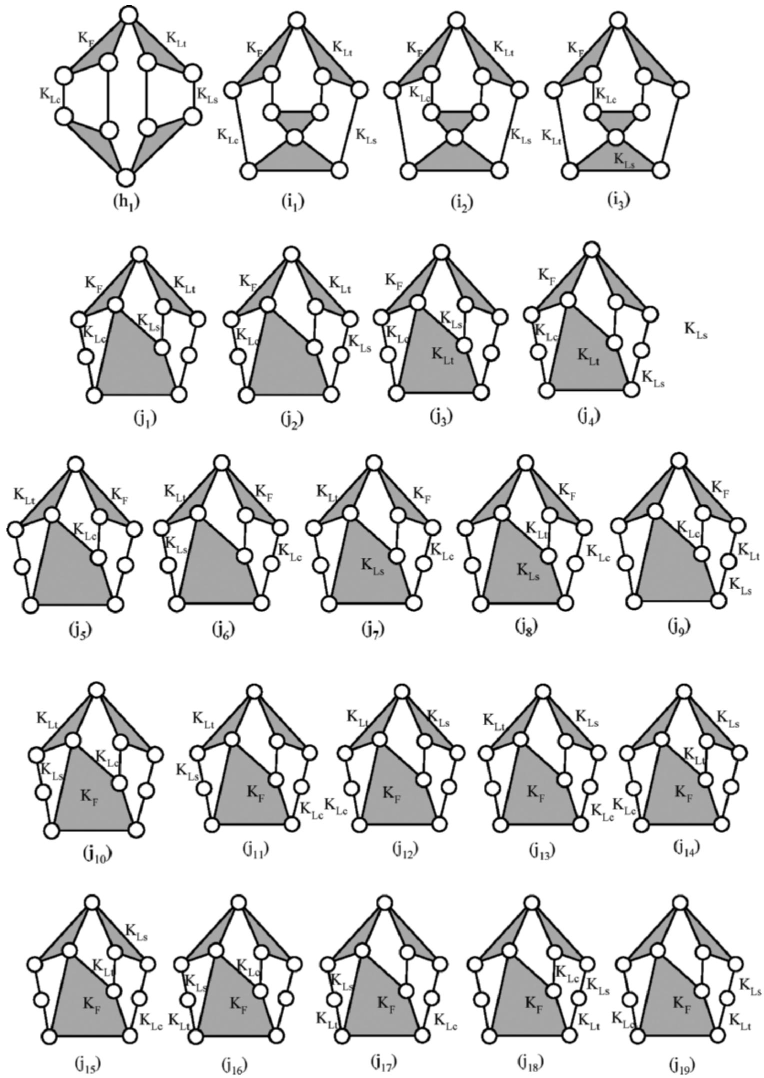


Figure 8.16 (*Continued*)

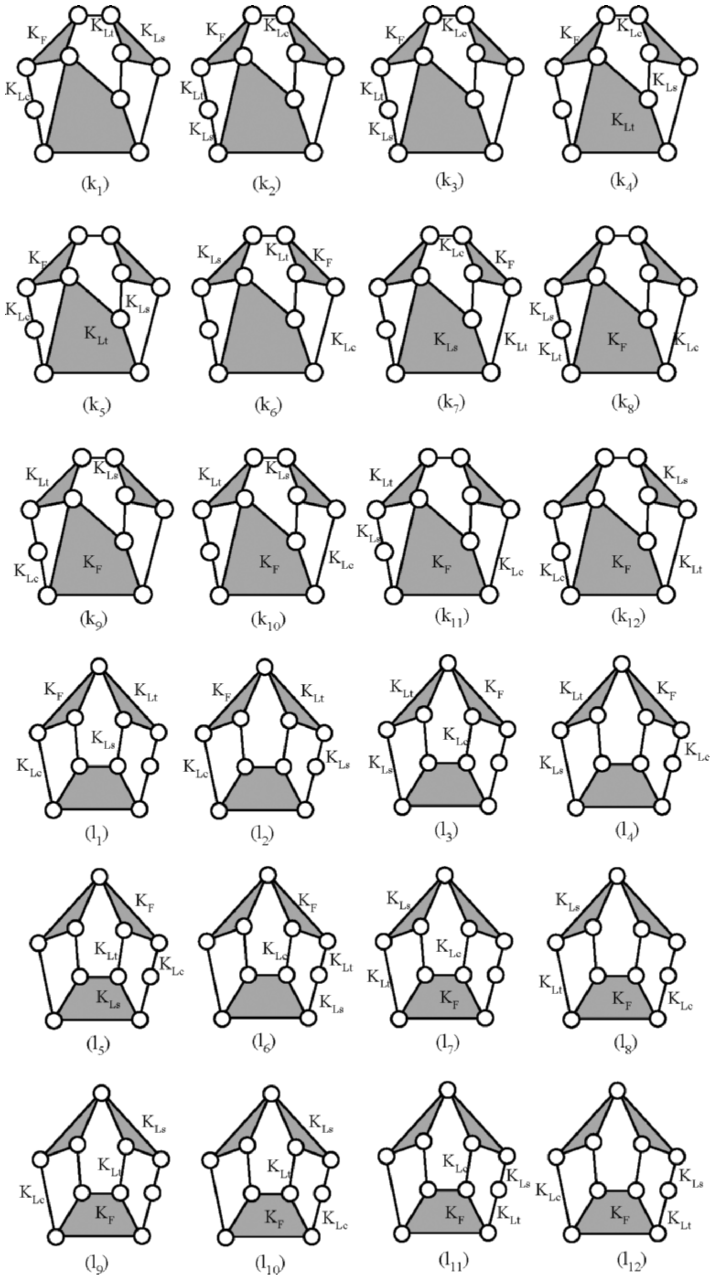


Figure 8.16 (*Continued*)

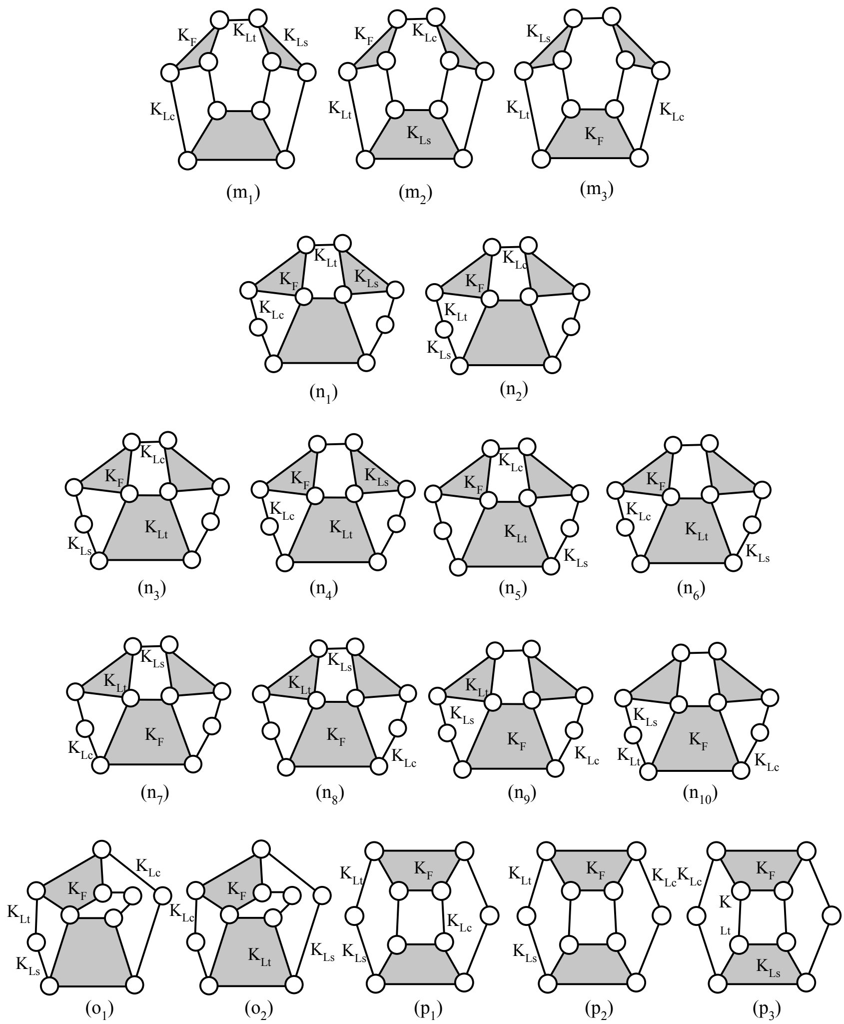


Figure 8.16 (*Continued*)

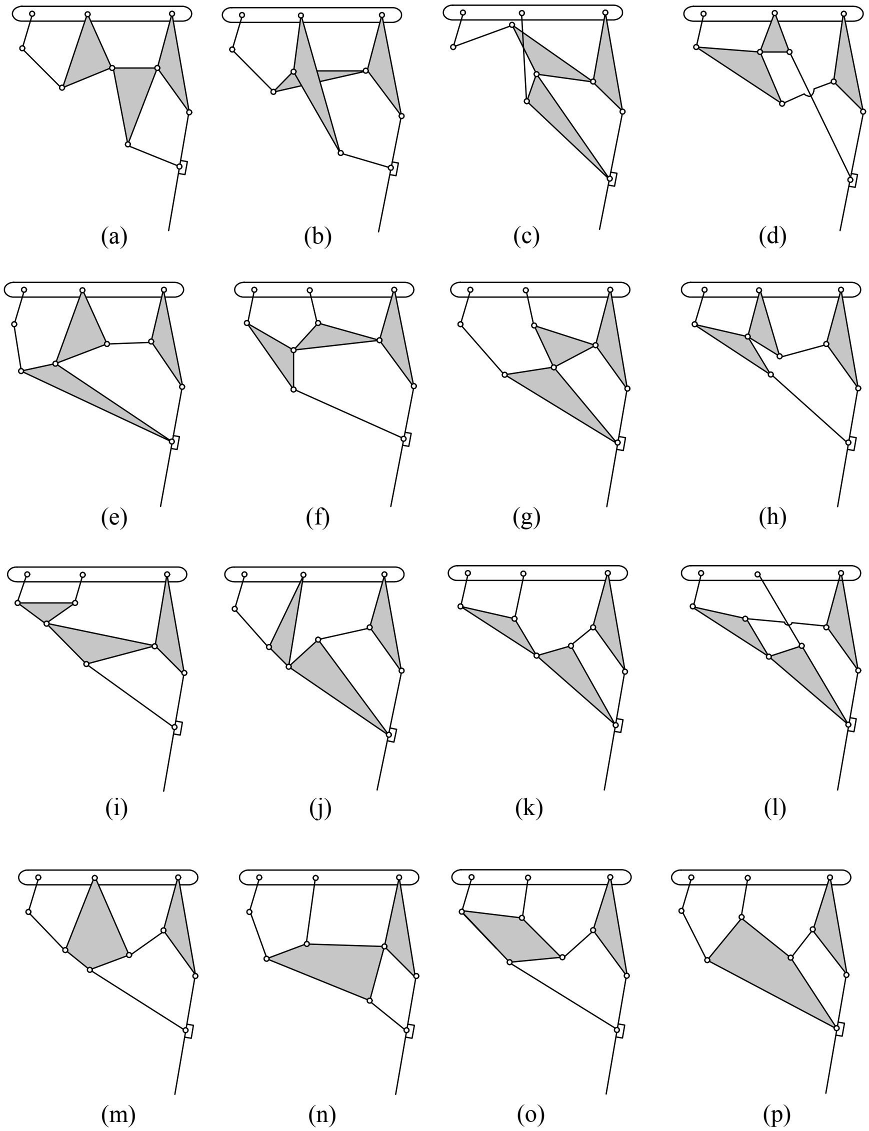


Figure 8.17 Some leg mechanisms for eight-bar type wooden horse carriages (Example 8.2)

Figure 8.18 shows a physical model developed at National Cheng Kung University (NCKU), Tainan, TAIWAN in 1996 [1]. This carriage is pushed to move forward and pulled to move backward. It requires only a small force to push or pull to walk up a reasonable slope. When left on a slope, it moves down without human intervention due to gravity. This might prove that such an invention may be feasible as indicated in the book Lun Heng by Wang Chong (AD ~27–97) in the Eastern Han Dynasty (AD 25–220), the earliest historical record of this legendary design.

8.7 Remarks

Lu Ban's wooden horse carriage is one of lost ancient Chinese machines with written descriptions but without illustrations and existing actual evidence. Restoration of this type is more difficult, and more imagination is required.

Evolutionists see history in terms of steady progress through the ages. The life cycle of a mechanical device is usually long, and its function is normally improved gradually with the development of society. The design of a mechanical device basically relied on the continuity of experience, and its development should be a continuous and smooth process. Therefore, if Lu Ban's wooden horse carriage in the Era of Spring and Autumn (770–481 BC) was real, Zhu-ge Liang's wooden ox and gliding horse invented in the Era of the Three Kingdoms (AD 220–280), 600–700 years later, could have been the eventual improvement of the original wooden horse carriage. Furthermore, 700–800 years later the mechanical horse for possible rice seedlings in the Song Dynasty (960–1279) could have been a heritage resulting from an artisan's family who had produced walking machines for generations. And, Jiang Yong of the Qing Dynasty (1644–1911) could also have been a member of the artisan's family.

Due to incomplete documentation and the loss of finished objects, the original structures of the walking machines, such as the wooden horse carriage of Lu Ban and the wooden ox and gliding horse of Zhu-ge Liang, have been a mystery through many eras. However, before new literature and/or hardware evidence are found, the proposed systematic approach for the generation of all possible topological structures of mechanisms subject to design requirements and constraints as described in Chapter 4 and Section 8.5 should be a novel direction and useful tool for assisting the study of lost ancient machinery. Thus, this chapter has sought in this spirit to trace the historical development of ancient Chinese walking machines.

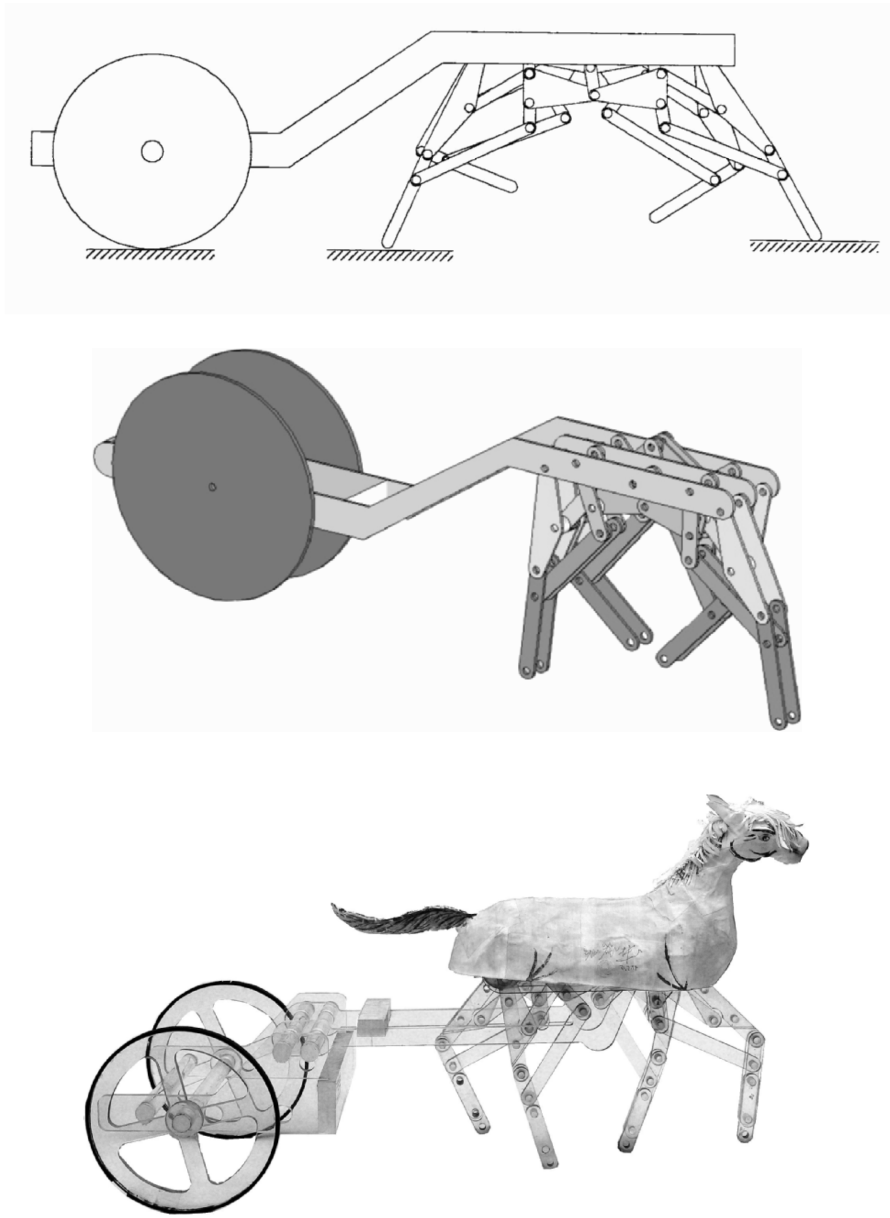


Figure 8.18 NCKU's eight-bar-type wooden horse carriage [1]

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