Reconstruction Designs of the Automata in the Ancient Korean Water Clock "Heumgyeonggaknu"

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Abstract. *Heumgyeonggaknu* (欽敬閣漏, Clock of Respectable Veneration Pavilion) is a Korean water clock made by Jang Yeong-Sil (蔣英實) in 1438. Based on astronomical observation, the functions of this water clock include time-keeping through a water wheel and telling the hours through many automata puppets set on the five floors of an artificial mountain. However, this device was not preserved. Although the external appearance and the functions are described in ancient literature, the internal structure is unknown. Based on the development of science and technology in ancient Korea, the historical records and the modern restoration designs of *Heumgyeonggaknu* are surveyed, and the works of timekeeping devices in Korea during the subject's time are discussed. In this study, a systematic design procedure is proposed for reconstructing the ancient mechanisms with unknown parts, and the automata set on the first floor of the *Heumgyeonggaknu* are taken as a design example. At first, the design specifications of the automata in the device are concluded from the review of historical documents. Then, based on the atlas of generalized chains, specialization is implemented according to design requirements and constraints. All feasible designs that meet the scientific theories and techniques of the subject's time period are synthesized. As a result, two feasible mechanisms are generated for the automata on the first floor. Then, dimensional parameters are designed to meet the required motion, and a computer-aid virtual models is built for simulation. Finally, a prototype of the reconstructed automata is made to verify the movement characteristics and the feasibility of the presented reconstructed designs.

Keywords: Ancient machines · Reconstruction design · History of machines and mechanisms

1 Introduction

The clock is a scientific instrument for measuring time, and the automaton is a mechanical device that is able to convert the input motion to a specific output action by means of a mechanism transmission for time-telling or performance purposes. Both of them are

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important manifestations of science and technology. The scientific principles applied such as the flow rate control of water, the application of buoyancy, and the design of mechanical components are indicators of the development level in the history of machinery. Moreover, they are also the proof of the exchange between the cultures.

For thousands of years, the ancients have used long-term astronomical observations and records to develop methods for predicting the position of astronomical stars and calculating calendars, which serve as an important reference for the activities of the farming society in various seasons. In ancient Korea, King Sejong (世宗, 1397–1450) of the Joseon Dynasty (1418–1450) assigned the engineer Jang Yeong-Sil (蔣英實, 1383–1450) to make the self-striking water clock. After traveling to China and studying the designs of these kinds of devices [1, 2], Jang set up two mechanical clocks in Korea, namely the *Borugaknu* (報漏閣漏, clock of annunciating clepsydra pavilion) in 1433 [3] and the *Heumgyeonggaknu* (欽敬閣漏, clock of respectable veneration pavilion) in 1438 [4], as Fig. 1 shows. Both of the two clocks are powered by constant-speed water flow for timekeeping, and there are mechanical puppets equipped to the two clocks to tell the time. However, the records of these two devices in the literature are very different. In the former device, a rolling ball system to drive all automata is described in detail. For the latter device, the appearance, functions, and motions of automata puppets are illustrated, but just a few words related to the internal mechanical structure are presented.

(a) (b)

Fig. 1. Jang Yeong-Sil's two water clocks: (a) a modern reconstruction of the time-telling automata of *Borugaknu* [5], (b) the appearance of *Heumgyeonggaknu* [2].

According to the descriptions of *Heumgyeonggaknu* [2], the mechanical structure can be arranged as Fig. 2. Three subsystems are included, namely power source, transmission mechanisms, and automata puppets. The power source is a wheel driven by water flow. The automata puppets subsystem can be separated into five layers to compose a mountain on the pavilion, as Fig. 1 shows. From bottom to top, on the first floor (W1), twelve Gods of the Zodiac (十二神) show up at the corresponding time (Rat God for 23 o'clock, Ox God for 1 o'clock, Tiger God for 3 o'clock, Rabbit God for 5 o'clock, Dragon God for 7 o'clock, Snake God for 9 o'clock, Horse God for 11 o'clock, Goat God for 13 o'clock, Monkey God for 15 o'clock, Rooster God for 17 o'clock, Dog God for 19 o'clock, and Pig God for 21 o'clock). At the same time, a cave behind the acting Zodiac God opens, and a fairy with an hour-displaying card steps out of the cave. On the second floor (W2), an official and three warriors standing on a stage. One warrior strikes the bell every double-hour, another warrior beats the drum at the five double-hours in the night (at 19, 21, 23, 1, and 3 o'clock), the other warrior sounds a gong every 24 min during the five hours in the night. The official turns to the warriors before they sound their instruments. On the third floor (W3), the Four Guardian Gods (四神, including Azure Dragon of the East, the Vermilion Bird of the South, the White Tiger of the West, and the Black Tortoise of the North) stand at the four corners and turn to a specific position according to the corresponding time. On the fourth floor (W4), four fairies rattle the bell at the relevant double-hour respectively. On the top floor (W5), an armillary sphere rotates along a circular ring to simulate the sunrise and sunset once a day passing over the mountain.

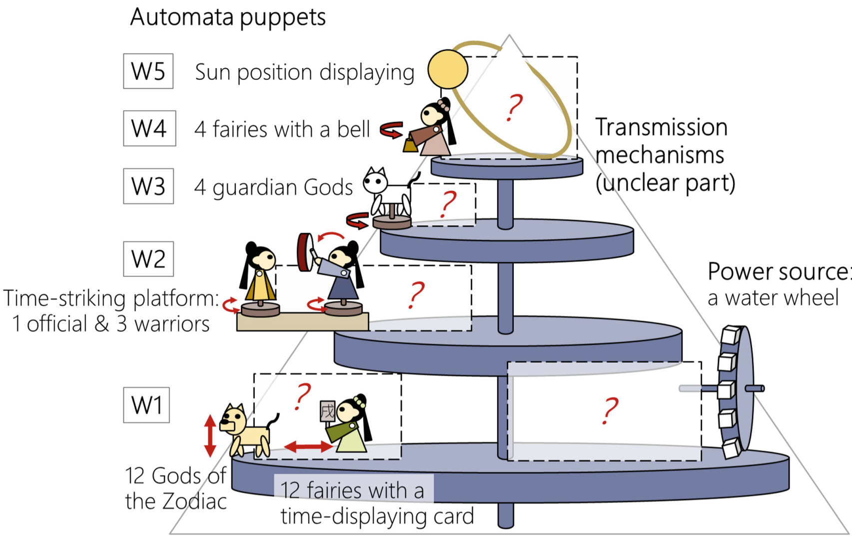


Fig. 2. Automata puppets and the unknown parts of *Heumgyeonggaknu.*

In this study, since the transmission mechanisms that drive the automata puppets are not clear in the description of *Heumgyeonggaknu* [4], a systematic design procedure is proposed to generate the feasible mechanism structures. Based on the ancient literature, the relevant design requirements and constraints are listed. By the concepts of specialization and particularization, the designs that meet the technical level of the project's time are synthesized. Finally, the feasible mechanism structures are generated, and the performance of the reconstructed mechanisms is verified through 3D modeling and simulation.

2 Design Procedure

A design procedure for reconstructing ancient mechanisms with unknown structures can be mainly divided into two parts, namely reconstructed mechanism design and reconstructed manufacturing. At the first part, the feasible structure of the lost/unknown mechanisms is synthesized through a systematic procedure [6, 7], and all feasible configurations of mechanisms that meet their design requirements and constraints with four steps. Firstly, the design specifications of the machine can be determined based on historical documents [3, 4] and modern research [1, 2, 5, 8–11], including the feasible type of links and joints, the possible number of links and joints, and the degrees of freedom. Secondly, according to the design specifications concluded in the previous step, the atlas of generalized chain is obtained. Thirdly, all feasible specialized chains are generated by assigning the types of links and joints to all generalized chains from the third step subject to the concluded design requirements and constraints. Finally, the atlas of feasible designs is synthesized according to the specialized chains through particularization. Then, one or several feasible designs are selected, and the dimensions parameters of the mechanism are synthesized to meet the motion requirement of design specifications.

At the second part, the feasible reconstructed mechanisms are verified through computer-aided modeling for simulation, and prototype testing. The kinematic characteristics such as the trajectory of the output link can be ensured in this stage. Based on the result of simulation, a prototype is made for testing. This design procedure has already been used in the reconstructions of the automata of blossoming flower clock [12, 13] and pagoda clock [14] in the Forbidden City, and a Chinese astronomical clock with a waterwheel steelyard clepsydra [15]. The procedure can also be applied to reconstruct the other ancient mechanisms with unknown/unclear mechanical structures.

3 Design Example

In this section, the mechanism of the automata puppets on the first floor (W1) of *Heumgyeonggaknu* is reconstructed as a design example. By going through the four steps of reconstruction design, the feasible mechanism structures can be generated in this section.

I. Design specifications

In the ancient literature [4], the descriptions about the first floor (W1 in Fig. 2) are as follows:

> "*At the flat ground on the first floor, the twelve gods are hided in their respective positions. ... When the ox-hour (1 o'ckock in the midnight) comes, the hole behind the ox opens, a fairy also walks outside of the hole, and the ox rises.*"

「又其下平地之上, 十二神各伏其位。...丑時至則牛後之穴自開, 玉女亦出, 牛亦起。」

According to the structural analysis in the first section and the descriptions above, the design specifications can be arranged:

1. There must be one input link (connected to the power source), two output links (one for the ox and the other one for the fairy), one fixed link (the frame), and at least one connecting link included. Therefore, this is a mechanism with at least five links.
2. Since the power source of the whole device is a water wheel, the only input of the mechanism is a rotating motion. Therefore, this is a mechanism with one degree of freedom.
3. The two output links make the ox rise/return and the fairy walk forward/backward. Both of the output motions can be analyzed as reciprocated motion.
4. With the consideration of the technical level and referring to the previous work *Borugaknu* of the inventor Jian Yeong-Sil, the type of the links can be considered as a set of linkage.

II. Atlas of generalized chain

As the design specification listed, the number of links is assumed as five, and the degree of freedom is one. For a mechanism with five links, the number of joints obtained is 6, including one joint with 2 DoF and five joints with 1 DoF. The corresponding generalized chains are listed in Fig. 3.

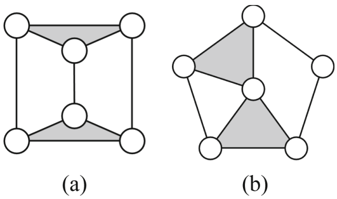


Fig. 3. Atlas of generalized chain with five links and six joints.

III. Atlas of specialized chain

According to design specifications, the obtained generalized chains are subjected to the specialized process, and the required links and joints are assigned to each generalized chain in order to generate all feasible specialization chains. To perform this step, the following design requirements and constraints are complied with as follows.

Fixed Link (Link 1, K_F)
There must be a multiple link serving as a fixed link (K_F).
Input link (Link 2, K_I)
There must be a binary link serving as the input link (K_I), and it is adjacent to the fixed link (K_F) with a revolute joint (J_R).
Transmission link (Link 3, K_T)
There must be a binary link serving as the transmission link (K_T), and it is adjacent to the input link (K_I) with a revolute joint (J_R).

Output link 1 (Link 4, K_{O1})
There must be a multiple link serving as the output link 1 (K_{O1}), and it is adjacent to the fixed link (K_F) with a revolute joint (J_R) or a sliding joint (J_P).
Output Link 2 (Link 5, K_{O2})
There must be a binary link serving as the output link 2 (K_{O2}). It is adjacent to the fixed link (K_F) with a revolute joint (J_R). Moreover, it is adjacent to the output link 1 (K_{O1}) with a cam joint (J_A).

By assigning all of the links and joints, for the generalized chain shown Fig. 3(a), there is not a loop that includes one multiple link and two connected binary links, so the first three links (K_F, K_I, and K_T) cannot be assigned in this case. Therefore, for the generalized chain shown in Fig. 3(b), two feasible specialized chains are generated as Fig. 4 shows.

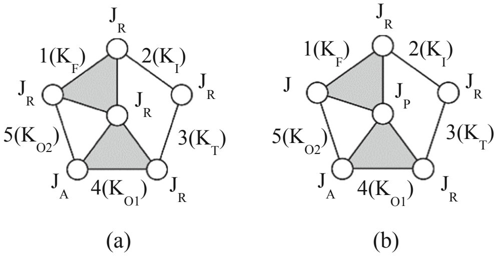


Fig. 4. Atlas of feasible specialized chain.

IV. Atlas of feasible design

The feasible designs with the proposed mechanism structure can be obtained through the step of particularization. The automata puppets such as the rooster god (one of the twelve gods) and one of the fairies with a time-displaying card are attached to the output links respectively, as the two mechanisms shown in Fig. 5.

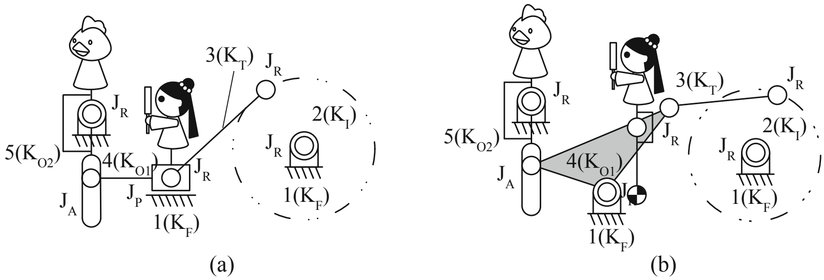


Fig. 5. Atlas of feasible mechanism.

4 Computer-Aided Modeling and Prototype Testing

Based on the feasible mechanism structures synthesized in Sect. 3, the reconstruction manufacturing is made through computer-aided modeling and prototype testing. A 3D model is built by the software SolidWorks, as Fig. 6 shows, in accordance with the mechanism shown in Fig. 6(b) and the results of dimensional parameters design to meet the motion requirements. Besides, a corresponding wooden prototype is made to verify the motion. Figure 7(a) shows the initial position of this automaton, the puppet of the twelve gods is hidden below the stage, and the fairy stays inside the cave. With the input link rotates in a half-circle, the output links arrive at their performance positions. As Fig. 7(b) shows, the puppet of the twelve gods rises to show up, and the fairy walks out of the cave to tell the time with the displaying card. Then, with the input link completing a full-circle rotation, the two puppets return to their initial position. As the result, the motion of the automata is able to meet the descriptions recorded in the ancient literature [4], therefore the feasibility of the proposed design procedure and reconstructed designs are evaluated.

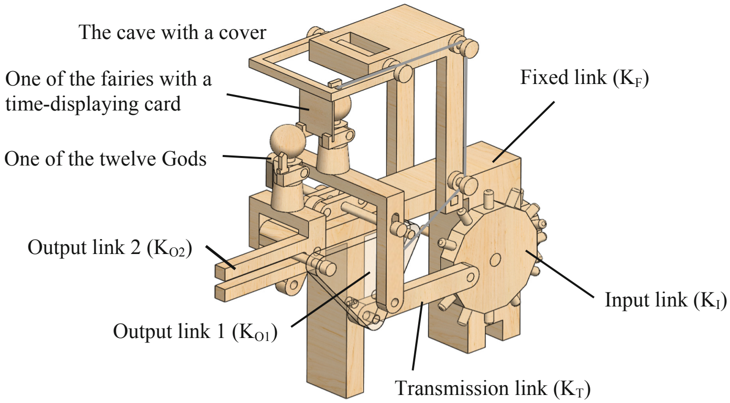
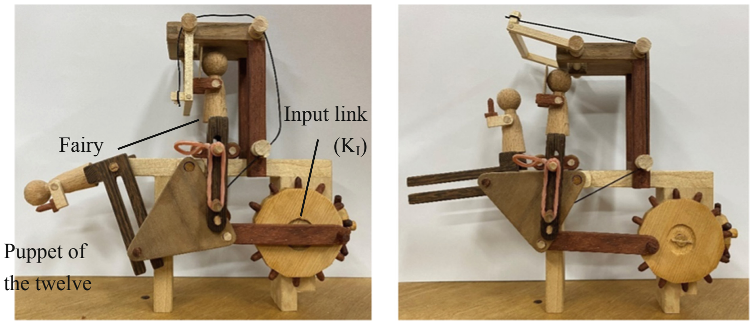


Fig. 6. A 3D model of the automata



(a) (b)

Fig. 7. Prototype testing: (a) initial position, (b) performance position.

5 Conclusions

Heumgyeonggaknu is a water clock made in Korea during the 15th century. With five sets of automata puppets equipped on the five floors of the water clock for time telling, the appearance and motions for performance are clearly recorded in the ancient literature. However, the internal mechanical structure was neither documented nor preserved. In this study, a systematic design procedure to reconstruct the ancient automata with unknown structures is presented. The automaton on the first floor of the *Heumgyeonggaknu* is taken as a design example. By applying the four steps for synthesizing the mechanism structure, the design specifications are concluded, and two feasible mechanisms with five links are synthesized. Moreover, the results are evaluated through computer-aid modeling and prototype testing. A 3D model has been elaborated in SolidWorks environment for motion simulation for performance characteristics and design developments. Finally, a prototype is shown with preliminary results within a project for future developments. The design procedure is verified and it can be applied to complete the reconstruction design for the whole device of *Heumgyeonggaknu.*

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