# Structural Synthesis of the Trigger Mechanism in an Ancient Japanese Automaton "Ryomon Waterfall"

Zhi-Jie Zhang[1], Yu-Hsun Chen[1](✉), and Hong-Sen Yan[2]

[1] National Taiwan University of Science and Technology, Taipei, Taiwan
yhchen@mail.ntust.edu.tw

[2] National Cheng Kung University, Tainan, Taiwan
hsyan@mail.ncku.edu.tw

**Abstract.** Japanese automata, representing a significant facet of mechanical art development, have historical roots dating back to the 8th century. This paper focuses on the reconstruction design of the trigger mechanism in the automaton "Ryomon Waterfall" from the 18th-century compendium "Karakuri Zui." The automaton narrates a mythical tale of a carp transforming into a dragon and ascending to the sky. Despite historical significance, the internal mechanisms are not fully illustrated. A systematic design procedure is proposed, involving the synthesis of feasible mechanism structures and subsequent dimensional design. The process is applied to the trigger mechanism, and a prototype is constructed, showcasing the applicability of the method. The study contributes to the understanding and reconstruction of ancient automata, shedding light on Japan's mechanical craftsmanship during the 18th century.

**Keywords:** Ancient machines · Karakuri Zui · technology in Edo period · reconstruction design · history of machines and mechanisms

## 1 Introduction

The automata of Japan represent a crucial facet of the nation's mechanical artistry, primarily dedicated to entertainment and performance rather than utilitarian functions [1]. These automata, harnessing power from sources like flowing water, sand, gravity, or springs, trace their historical origins back to the 8th century. The Edo period (1603–1867) marked the distinctive development of Japanese automata dolls, showcasing unparalleled craftsmanship. Despite the loss of numerous physical prototypes, historical documents and mechanical design books persist, offering valuable insights into the evolution of craftsmanship across different epochs and holding significant historical relevance in mechanical development.

While modern scholars have delved into research on these automata [2–6], a comprehensive exploration has been lacking, impeding a thorough understanding of their mechanisms and precluding corrections of ambiguities in their designs. Consequently, a systematic reconstruction design method has been previously proposed to elucidate unclear


M. Ceccarelli and I. Aslan Seyhan (Eds.): HMM 2024, HMMS 47, pp. 243–254, 2024.
https://doi.org/10.1007/978-3-031-54876-5_17

aspects in illustrations and descriptions [1]. This design procedure categorizes ancient automata based on power sources and transmission types, addressing cases with incomplete drawings and descriptions. It outlines the device's functions in textual narratives, deduces its design requirements and constraints, and synthesizes feasible mechanism structures aligned with historical craftsmanship. In this paper, we exemplify this approach with the reconstruction of the Japanese automaton "Ryomon Waterfall" described in the ancient book "Karakuri Zui" (機巧図彙, The Compendium of Automata) by Hosokawa Yorinao (細川半藏, ?-1796). The exterior design is illustrated in Fig. 1. This automaton narrates a legendary tale wherein a carp ascending the Ryomon waterfall transforms into a dragon and ascends to the sky. Placing the carp beneath the waterfall prompts the fish to climb upward. Once the carp reaches the source of the waterfall, it disappears, and a dragon emerges. With the appearance of dark clouds, the dragon ascends to the sky, as depicted in the figure. Remarkably, the internal mechanisms remain skillfully concealed even when removing the carp.

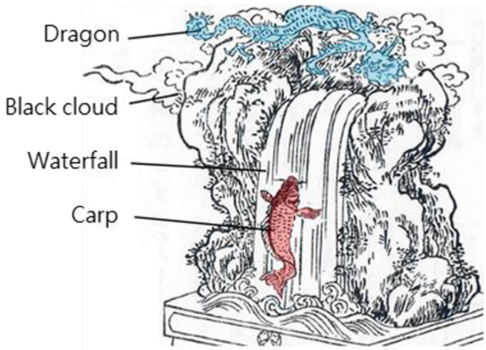



**Fig. 1.** External illustration of Ryomon Waterfall [1]

For the reconstruction of the Ryomon Waterfall device, the mechanical structure is analyzed concerning its power flow, and feasible mechanism structures for uncertain parts are generated using Yan's reconstruction procedure [7]. A 3D model is created using SolidWorks, and a prototype is constructed and experimented upon to verify the feasibility of the restoration design.

## 2 Design Procedure

A systematic design procedure for reconstructing ancient mechanisms with unknown structures is introduced, drawing inspiration from Yan's methodology [7, 8] and extended research [9–12]. This method is organized into four steps, aiming to synthesize all feasible configurations of mechanisms that align with designated requirements and constraints. The four steps are explained as follows:

I. In the initial step, the mechanism's design specifications are established based on insights from historical documents and contemporary research. These specifications include determining the viable types of links and joints, potential numbers of links and joints, and the degrees of freedom.
II. Subsequently, a generalized chain atlas is obtained, guided by the design specifications from the preceding step.
III. The third step involves generating all feasible specialized chains by assigning types of links and joints to the generalized chains, considering the established design requirements and constraints.
IV. Finally, an atlas of feasible designs is synthesized based on the specialized chains through a process of particularization.

Furthermore, the reconstruction process encompasses three additional phases: dimensional parameters design, computer-aided simulation, and prototype testing. One or more feasible designs are selected, and the dimensional parameters of the mechanism are synthesized to meet the motion requirements specified in the design specifications. The feasibility of the reconstructed designs is rigorously evaluated through 3D modeling and motion simulation. Ultimately, a prototype is constructed based on the simulation results, and the testing phase is documented. This comprehensive design procedure has been successfully applied in the reconstructions of the automata in previous publications. Importantly, its versatility extends to the reconstruction of other ancient mechanisms characterized by unknown or unclear mechanical structures.

## 3 Mechanical Analysis

In accordance with the description in the referenced book [1], the Ryumon Waterfall automaton can be dissected into five subsystems: the speed-controlling mechanism, carp-backflowing mechanism, trigger mechanism, dragon pop-up mechanism, and the black cloud mechanism, as illustrated in the power flow block diagram in Fig. 2. This automaton is propelled by a clockwork spring wound using a key, transmitted through a set of gear trains. Speed regulation is achieved using an escapement composed of a verge and a crowned wheel, as depicted in Fig. 3(a).

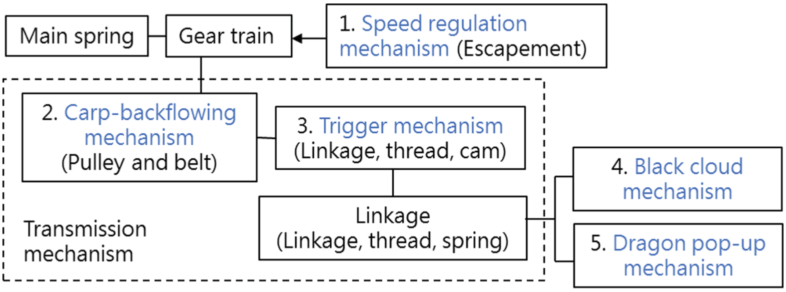
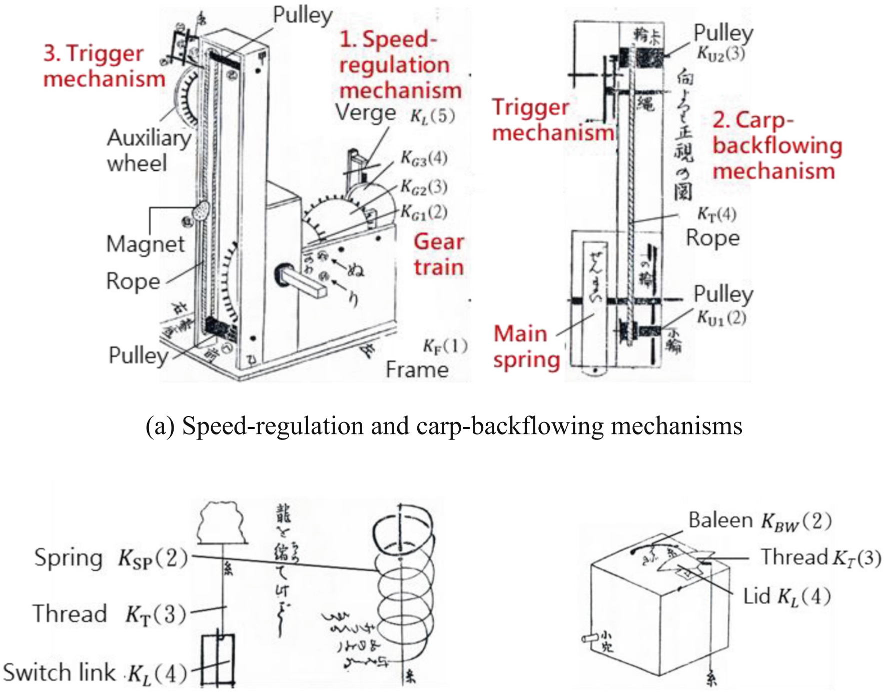



**Fig. 2.** Structural analysis and power flow

Moreover, while the detailed configuration of the gear train is not explicitly illustrated in Fig. 3(a), it is inferred to be a coaxial device with a large gear and a small gear, following the principles of gear transmission. The number of teeth on each gear is also not specified. The only information on gear ratio inferred from the literature is in Fig. 3(a), where the turning of gear $K_{G1}$ from "ぬ" to "り" leads to the carp rising from the lower pulley to the upper position. The shaft of the uppereach gear is also not specified. The shaft of the upper pulley connects to the trigger mechanism of the "auxiliary wheel" in the upper left of Fig. 3(a) and is transmitted by a "#" shaped component, controlling the triggering of the dragon pop-up and dark cloud mechanisms. The motion of the carp backflowing is achieved through the magnetic attraction of the rope driven by the pulleys, as shown in Fig. 3(a).

The dragon pop-up mechanism involves a pre-compressed spring wound in silk cloth, pulled by a wire to release the spring, causing the dragon to jump out, as shown in Fig. 3(b). Simultaneously, the effect of "black clouds appearing" is achieved by placing pine smoke in a box, covered with a lid. When the wire is pulled to open the lid, the black clouds are released. The wire triggering both the dragon and the black cloud mechanisms is the same, as illustrated in Fig. 3(c).

The trigger mechanism transmits power from the carp-backflowing mechanism and is used to initiate the subsequent two performance mechanisms—dragon and black cloud.




(a) Speed-regulation and carp-backflowing mechanisms

(b) Dragon pop-up mechaism

(c) Black cloud mechanism

**Fig. 3.** Internal structure [1]

The diagram of the trigger mechanism, as depicted in Fig. 4, comprises a fixed link (Link 1, $K_F$), an input link (Link 2, $K_I$), a cam (Link 3, $K_A$), and one or two triggering links (Link 4, $K_{L1}$, and Link 5, $K_{L2}$). Due to various unclear aspects in the drawing and description of the trigger mechanism, it is not possible to distinctly comprehend how the triggering links (Link 4, $K_{L1}$, and Link 5, $K_{L2}$) accomplish the forceful downward pull indicated in Fig. 4 to initiate the dragon and black cloud mechanisms. Therefore, feasible mechanism structures are generated in the next section using the design procedure presented in Sect. 2.

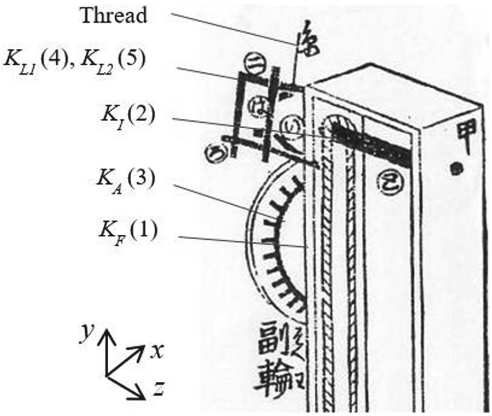



**Fig. 4.** Trigger mechanism [1]

## 4 Structural Synthesis of the Trigger Mechanism

As depicted in Fig. 4, a Cartesian coordinate system is defined, with the z-axis representing the axial direction of the cam (Link 3, $K_A$), and the x and y axes representing the horizontal and vertical directions of the original frame. Following the systematic design procedure outlined in Sect. 2, this section aims to synthesize feasible mechanism structures.

### 4.1 Design Specifications

Based on the structure analysis and descriptions provided, the design specifications are enumerated as follows:

1. This mechanism is a planar four-bar (Links 1–4) or five-bar (Links 1–5) mechanism.
2. The mechanism generates a powerful downward pulling motion through the rotation of the input link ($K_I$), causing the triggering links ($K_{L1}$ and $K_{L2}$) to move. Therefore, defining a degree of freedom as 1.
3. The fixed link ($K_F$) is a link with multiple joints.

4. The input link ($K_I$) is a binary link, adjacent to the fixed link ($K_F$) through a rotational joint ($J_{Rz}$).
5. The cam ($K_A$) is a ternary link, adjacent to the fixed link ($K_F$) and the input link ($K_I$) through rotational joints ($J_{Rz}$), and also adjacent to the input link ($K_I$) through a gear joint ($J_G$).
6. The triggering links ($K_{L1}$ and $K_{L2}$) must have one joint adjacent to the cam through a cam joint ($J_A$) and another joint adjacent to the fixed link ($K_F$) through an unknown joint.

### 4.2 Atlas of Generalized Chain

Based on the design specifications, assuming four or five links and one degree of freedom, the corresponding generalized chains are listed in Fig. 5.

### 4.3 Atlas of Specialized Chain

Subjected to the design specifications, the generalized chains undergo the specialization process. The necessary links and joints are assigned to each generalized chain to generate all feasible specialization chains. Compliance with the following design requirements and constraints yields 12 feasible specialized chains as shown in Fig. 5.

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 ($J_R$).

Cam (Link 3, $K_T$)

There must be a ternary link serving as the cam link ($K_A$), and it is adjacent to the fixed link ($K_F$) and input link ($K_I$) with a revolute joint ($J_{Rz}$) and gear joint ($J_G$).

Trigger link 1 and trigger link 2 (Link 4 and 5, $K_{L1}$ and $K_{L2}$)

There must be two separated links serving as the trigger links ($K_{L1}$ and $K_{L2}$), and it is adjacent to the cam ($K_{\mathrm{A}}$) and the fixed link ($K_F$) with a cam joint ($J_A$) and an uncertain joint, respectively.

Uncertain joint ($J_U$)

The trigger mechanism involves transforming the rotational motion of the input link into a powerful downward pulling motion. To fulfill the functional requirements in the literature, there are two possible configurations for the uncertain joint. One is a rotational joint ($J_{Rz}$) revolving around the z-axis, adjacent to the fixed link ($K_F$). The other slides along the y-direction ($J_{Py}$) with the fixed link.

Hence, eight feasible mechanism structures are generated through the design procedure, as illustrated in Fig. 6.

### 4.4 Atlas of Feasible Design

Feasible designs with the proposed mechanism structure are obtained through particularization. Eight mechanisms, as shown in Fig. 6, represent the culmination of the design procedure.

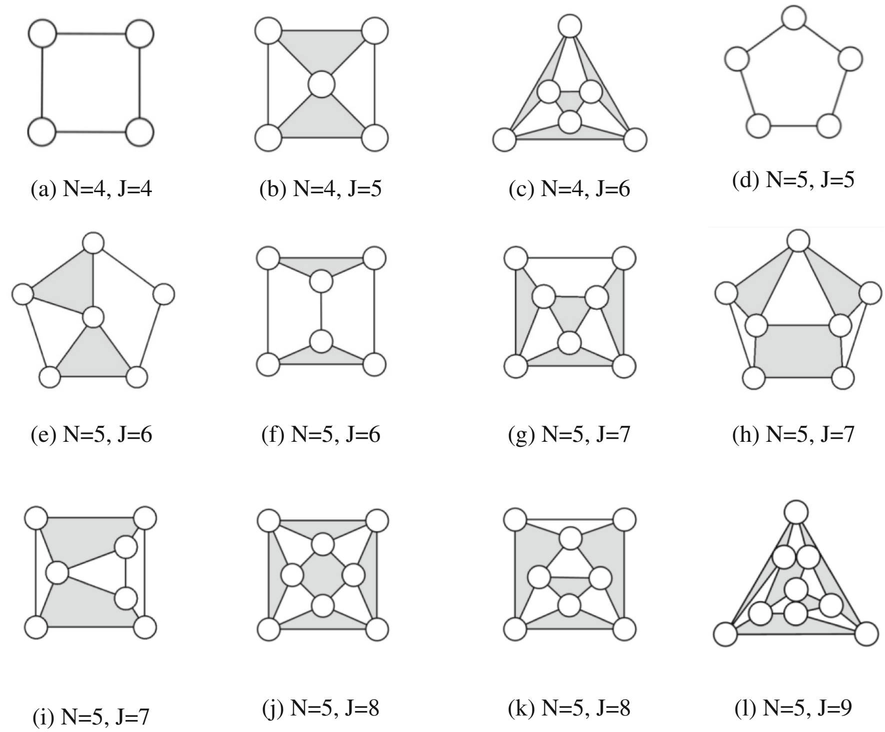



**Fig. 5.** Atlas of generalized chain with four and five links

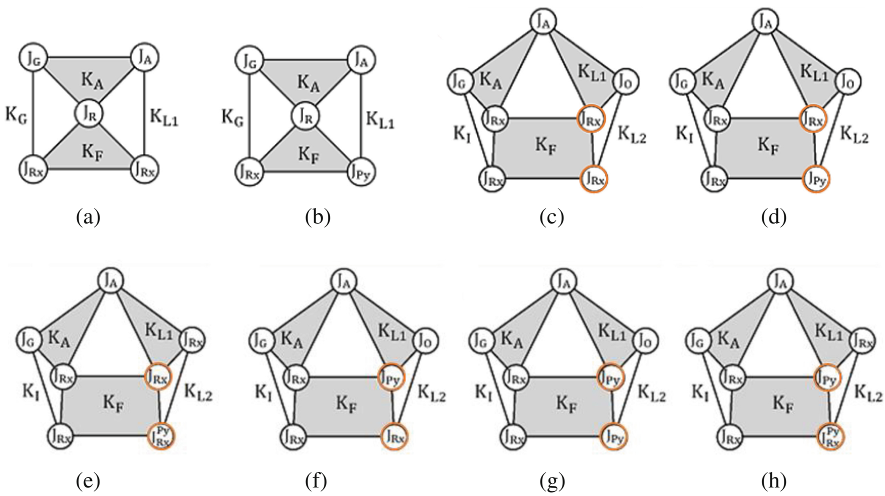



**Fig. 6.** Atlas of feasible specialized chain

## 5 Dimensional Design

While dimensional specifications for components are absent, relative dimension relationships from the book "Karakuri Zui" serve as a reference.

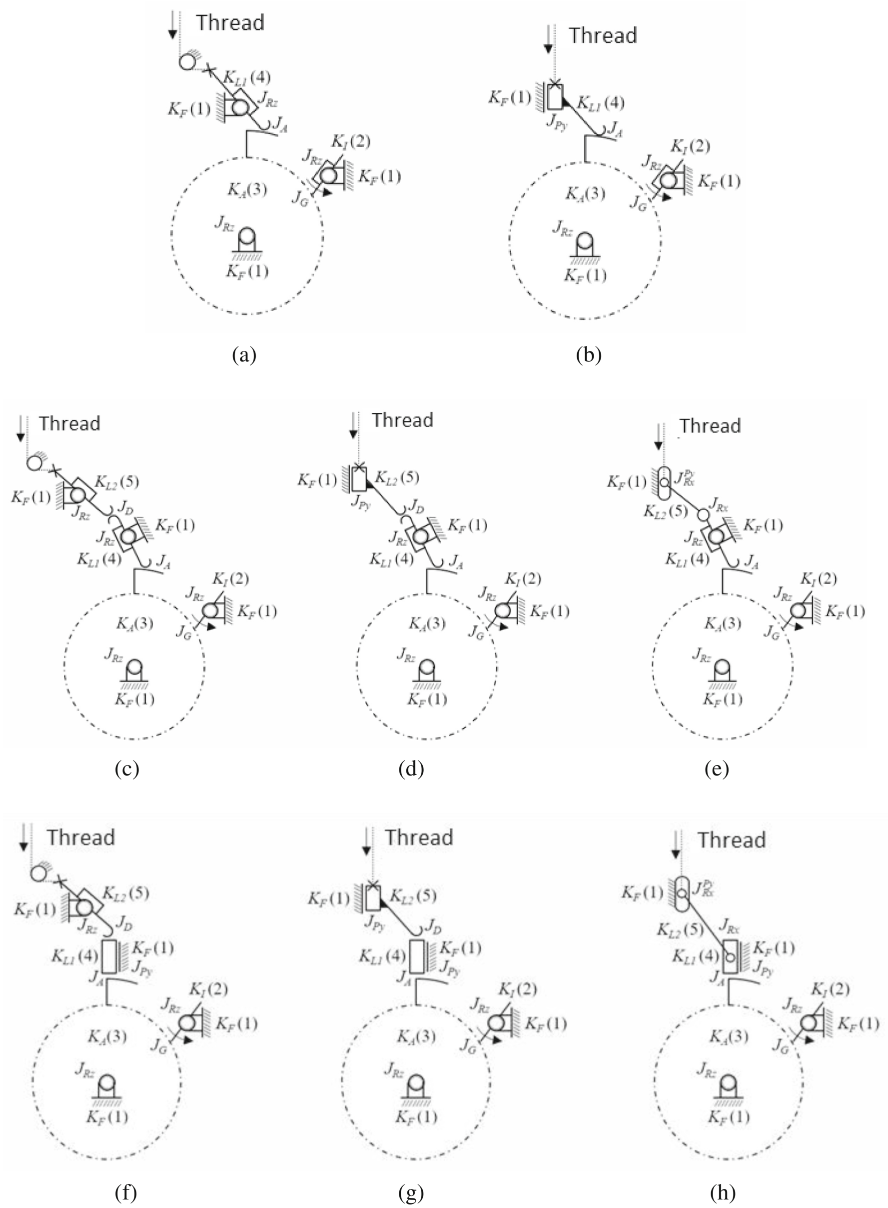


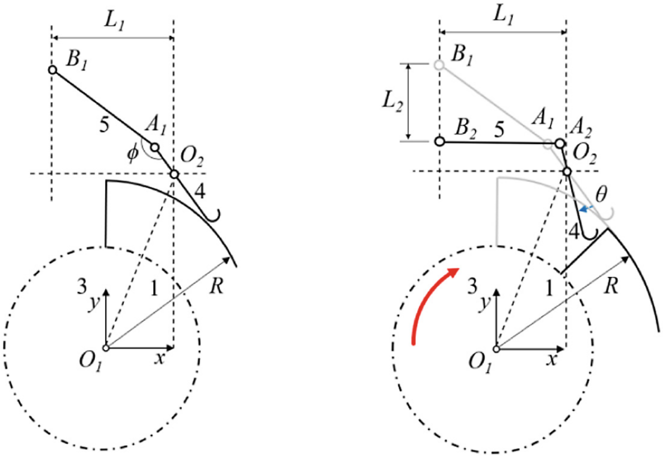

**Fig. 7.** Atlas of feasible mechanism

Figure 8 displays three types of cams used in various automata, including the Tea-serving Doll, Puppet with Drum and Whistle, and Cockfighting. The reconstruction design adopts one of the feasible mechanisms, illustrated in Fig. 7(e). The trigger mechanism's initial position is designed as in Fig. 9(a).

In Fig. 9(a), the $O_1$ point of the fixed link (Link 1) is set as the coordinate origin (0, 0). To maintain contact with the cam surface without changing position, the outer contour R of the cam is a circle with a radius of 38 mm. The initial angle $\phi$ between Links 4 and 5 must be less than 180°. To fit the size of the fixed link, the horizontal distance $L_1$ between $O_2$ and $B_1$ is defined as 40 mm. Subsequently, the motion range of the mechanism is established, as displayed in Fig. 9(b). The motion range $\theta$ of Link 4 is defined as 25°. The maximum vertical distance $L_2$ from $B_1$ to $B_2$ is found to be 16.32 mm, and the coordinates of point $O_2$ of the fixed link (Link 1) are also established. The dimensional parameters for the cam and follower are presented in Table 1 and Fig. 10(a).

(a) (b) (c)

**Fig. 8.** The cam components recorded in the book "Karakuri Zui"

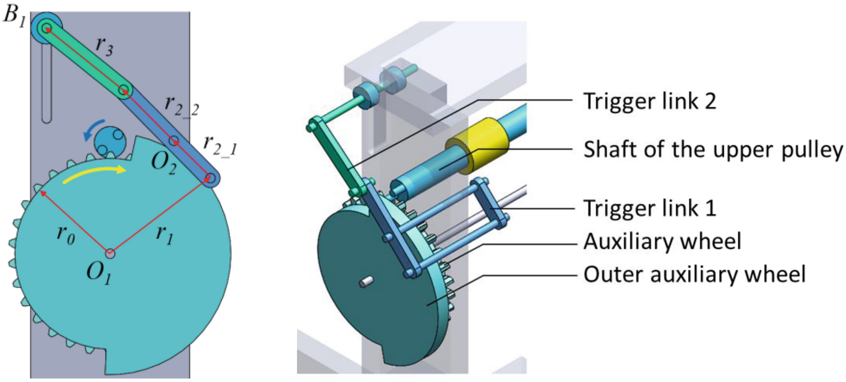



(a) Initial position (b) Motion range

**Fig. 9.** Dimensional design of the trigger mechanism

**Table 1.** Dimensional parameters

| Parameters | $r_0$ | $r_1$ | $r_{2\_1}$ | $r_{2\_2}$ | $r_3$ |
|---|---|---|---|---|---|
| Length(mm) | 30 | 38 | 12.5 | 15 | 30 |
| Points | $O_1$ | $O_2$ | $B_1$ (Initial position) | | |
| Position (mm) | (0,0) | (20,35.5) | (-20,77) | | |




(a) Dimensional parameters (b) Mechanism structure

**Fig. 10.** 3D model of the trigger mechanism

## 6 Reconstruction Manufacturing

A 3D model of the reconstructed trigger mechanism is proposed in Fig. 9(b), encompassing components that transmit power from the carp backflowing mechanism through the shaft to the upper pulley. The auxiliary wheel functions as a gear, and the outer one is the cam with a profile designed in the previous section. At the end of the upper pulley shaft is a pin gear connecting to the gear of the auxiliary wheel. The compound gear and cam rotate slowly, causing trigger link 2 to rotate and trigger link 1 with the "#" shape. This action pulls the thread connecting trigger link 1 and the mechanisms of the dragon and black cloud, sequentially activating these two mechanisms.

To assess the feasibility of the reconstructed trigger mechanism, a prototype is created with wood by laser cutting, as shown in Fig. 11(a). The described motion is tested by rotating the upper pulley shaft as the input. Figure 11(b) demonstrates the initial and final positions of trigger links 1 and 2 being driven, and the thread is pulled as expected.

(a) Mechanism structure (b) Initial and final position

**Fig. 11.** Prototype testing

## 7 Conclusions

The automata documented in "Karakuri Zui" offer a valuable glimpse into Japan's technological development during the 18th century. While most internal mechanical structures are clearly illustrated, some details are ambiguous. This study focuses on the Ryomen Waterfall automaton, an example with six subsystems depicting the ancient legend of a carp flowing upward in a waterfall. A systematic design procedure with four steps is proposed to synthesize the uncertain trigger mechanism. Design specifications are established, and eight feasible mechanism structures are generated. Although the outer shape and profile of the cam cannot be precisely replicated to match the ancient design, the type of cam is determined based on records of other automata with cam components. Moreover, through dimensional design, the motion of the reconstructed mechanism is validated to align with descriptions in the ancient book "Karakuri Zui." A 3D model is created in the SolidWorks environment, and a prototype is built to certify the feasibility of the presented mechanism design. The proposed design procedure has been verified and can be applied to complete the reconstruction designs for other automata with uncertain mechanisms, such as other mechanisms in the Ryomen Waterfall automaton, or even for other Karakuri automata with unclear parts in their records.

**Acknowledgments.** The authors are grateful to the Ministry of Science and Technology (Taipei, Taiwan) under Grant MOST 108-2221-E-006-177-MY2 for the support of this work.

## References

1. Kazuo, M.: Japanese Automata- Karakuri Zui: An Eighteenth Century Japanese Manual of Automatic Mechanical Devices, self-published book, Kyoto (2012)

2. Itagaki, E., Teranishi, I.: Studies in Relations to Karakuri-dolls (Mechanical Dolls) and of Cannons Described in Benkiti Ohno's Famous Notebook "Ittousi Kyuroku Seiyaku." J. Japan Sea Res. **47**, 49–69 (2016)
3. Kawamoto, N.: Technology transfer from Clock to Karakuri Ningyo (Mechanical Doll) Mainly study about units of escapements and governors. J. Horol. Inst. Japan **57**(208), 1–12 (2013)
4. Matsunaga, Y., Satsukawa, H.: Development of Karakuri somersault doll as a teaching material for technology and home economics classes in junior high school. Bull. Faculty Educ. Shizuoka Univ. **45**, 141–152 (2014)
5. Asai, S., Tsutsumi, I., Otsuka, H.: Trial manufacture on the mechanism arts TOUKEI in the Edo Era and its technological educational effects. Bull. Facul. Educ. Ibaraki Univ. Educ. Sci. **45**, 121–126 (1995)
6. Tamaya, S.: What's KARAKURI? KARAKURI NAGOYA, Tradition to the modern robot. J. Inst. Electric. Install. Eng. Japan **33**(1), 57–63 (2013)
7. Yan, H.S.: Reconstruction Designs of Lost Ancient Chinese Machinery. Springer, Dordrecht (2007)
8. Yan, H.S.: Creative Design of Mechanical Devices. Springer, Singapore (1998)
9. Hsiao, K.H., Chen, Y.H., Yan, H.S.: Structural synthesis of ancient Chinese foot-operated silk-reeling mechanism. Front. Mech. Eng. China **5**(3), 279–288 (2010)
10. Chen, Y.H., Yan, H.S.: Reconstruction of unknown automata designs of Blossoming Flower Clock in Forbidden City. Proc. Inst. Mech. Eng. C J. Mech. Eng. Sci. **7**, 1354–1368 (2016)
11. Chen, Y.H., Ceccarelli, M., Yan, H.-S.: Reconstruction and analysis of Zhan's sand clock in the 14th century. In: Zhang, B., Ceccarelli, M. (eds.) Explorations in the History and Heritage of Machines and Mechanisms. HMMS, vol. 37, pp. 123–133. Springer, Cham (2019). https://doi.org/10.1007/978-3-030-03538-9_11
12. Chiu, Y.-C., Chen, Y.-H., Yan, H.-S.: Reconstruction designs of the automata in the ancient korean water clock "Heumgyeonggaknu." In: Ceccarelli, M., López-García, R. (eds.) Explorations in the History and Heritage of Machines and Mechanisms: 7th International Symposium on History of Machines and Mechanisms (HMM), pp. 97–105. Springer International Publishing, Cham (2022). https://doi.org/10.1007/978-3-030-98499-1_9