Graduate School of Creative Science and Engineering
Waseda University

博 士 論 文 概 要
Doctoral Thesis Synopsis

論 文 題 目
Thesis Theme

Computational Mechanical Design Method for Achieving Both Aesthetics and Functionality

審美性と機能性を両立させる計算的機構設計手法の提案

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The word "robot" is used in two senses: one for industry to do work on behalf of humans, and one for exploration to mimic the way living things are. When designing a robot to mimic living things, it is important to balance the functionality of the robot to perform its intended function with the aesthetics of the design that makes it easy for people to accept the robot. The act of designing a machine that has both functionality and aesthetics has been done even before the word "robot" was introduced, such as automata and Karakuri Dolls. After the development of electronics, it is still important to achieve both functionality and aesthetics, as exemplified by animatronics and humanoids.

However, it is difficult and time-consuming to design a machine that has both functionality and aesthetics, even with the current design support technology. This is because each component must be designed for a highly aesthetic machine, taking geometric, physical and material mechanical constraints into account during the design process. In addition, due to the difficulty of the design, a huge amount of time is required to search for a solution through trial and error.

In order to clarify the causes of this difficulty, this paper formulates the task of designing a machine that is both functional and aesthetic in the context of numerical optimization. This design process consists of four phases. First, the design-related parameters are defined in terms of a vector. Secondly, the objective function for functionality is defined. This objective function on functionality indicates that it operates normally when its value is zero. Third, we have an objective function for aesthetics. Finally, the minimum (optimal) value of the aesthetic objective function is found under the constraint that the objective function of functionality is zero. When the above four steps are successfully carried out, the design of the machine with both functionality and aesthetics is completed.

There are three problems in the above design work that make it difficult and time-consuming to complete. First, when the designer sets the design parameters, he cannot guarantee the existence of the solution in the parameter space. This is because it is difficult for the designer to predict which design parameters to choose in order to arrive at an appropriate solution. The problem is made worse by the fact that the problem of setting parameters is partly dependent on the designer's experience. Secondly, some fine tuning of the mechanism will be required after manufacturing. This is because the objective function for functionality set by the designer does not always match the actual performance of the mechanism. Thirdly, it is difficult to treat the search for highly aesthetic solutions as a numerical optimization problem while satisfying the constraints of the objective function of functionality. This is because the objective function for aesthetics is a subjective evaluation by the designer and cannot be set explicitly.

On the other hand, in recent years, with the spread of additive manufacturing technologies such as 3D printer, researches to achieve the desired function of designers including artists by directly outputting the geometrical shape obtained by optimization calculations in the virtual space to the real space have become popular. However, the method of designing a machine while taking aesthetics into account has not been dealt with effectively.

Therefore, this paper proposes three concepts to solve three main problems that have caused difficulties in the design process of a machine that is both functional and aesthetic, and introduces a concrete implementation. To address the first problem of selecting design parameters, a concept called "Constructability" is proposed, which allows a designer to move seamlessly from hand-drawn sketches to mechanism optimization. To deal with the second problem of fine tuning after manufacture, we propose the concept of "Programmability", which allows us to adjust the function of the entire machine by replacing only certain parts of the machine. For the third problem, which is difficult to explore aesthetics while satisfying the constraints of the objective function, we propose "Explorability", a search interface that allows the designer to interactively adjust parameters while satisfying the constraints of functionality.

In Chapter 2, we develop and propose a system to realize the concept of "Constructability", which allows a designer to seamlessly transition from hand-drawn sketches to the optimization of a mechanism by dealing with counterweights. In this system, the shape of the counterweight and the linkage mechanism are generated by the designer who draws a picture and specifies the joints. After the designer enters the picture through the interface, the picture is transformed into a polygonal shape. In addition, the designer draws a line on the polygons to specify the joint positions, which are then divided and generated into multiple links and joints. In addition, if the designer selects the link that corresponds to the root, the link mechanism is defined as information in a hierarchical structure. After setting the counterweight as a parameter, the objective function to adjust the position of the center of gravity around the joint is set considering the information of the hierarchical structure. The solution can be found using CMA-ES. The final mechanism is manufactured and assembled using a 3D printer and CNC. As a result, we have successfully manufactured several mechanisms that are stable and return to the original posture based on the geometry and joint structure freely specified by the designer.

In Chapter 3, we develop and propose a system to realize “Explorability”, a search interface that allows the designer to interactively adjust parameters while satisfying the constraints of functionality. We identify how many, where, and how much elasticity a spring should have to be attached to a complex linkage mechanism in order to establish a self-weight compensation mechanism. In addition, we propose a method of Null-Space Exploration, which allows the designer to interactively adjust the parameters of the self-weight compensation mechanism while keeping the mechanism as a constraint. First, the linkage mechanism is added to a collection of links and joints, and the parameters of the springs are defined. After specifying and calculating the link's range of motion, the potential energy (the sum of potential energy and elastic energy) of the entire link mechanism is calculated to determine how much it is distributed within the range of motion. By including the dispersion of the potential energy in the objective function of the optimization, the potential energy of the entire mechanism does not fluctuate within the range of motion, that is, the potential energy of the entire mechanism moves toward the state of the self-weight compensation mechanism. In addition, a GUI slider is presented on the screen that allows various parameters to be manipulated to adjust the designer's preference with the dead weight compensation mechanism as a constraint. When the designer specifies the direction of the parameter to be moved by the slider, the slider selects the one that is as close as possible to the direction the designer wants to go in the space composed of eigenvectors corresponding to the eigenvalue of the Hesse matrix of the objective function that is zero. By doing this on the interface, which is updated at 60 fps, we can pursue the aesthetics of the designer while keeping the value of the objective function at zero. As a result, it was confirmed that we were able to design the system in accordance with the designer's aesthetics by using this method. In addition, it was confirmed that the number of springs to achieve the self-weight compensation mechanism and their connection relationships, which had been difficult to find, could be identified. In addition, some new self-weight compensating mechanisms were found by using this method, which had been difficult to find before.

In Chapter 4, we develop and propose a system to realize the concept of "Programmability", in which the function of the entire machine can be adjusted by replacing only specific parts of the machine, using a cam mechanism as the subject matter. The system converts the three-dimensional trajectory specified by the designer into a cam disk shape that can be tracked by the movement of the cam mechanism and linkage mechanism. In other words, it is possible to produce a programmable automaton that can draw programmable character changes. The programmable automata consists of a set of links and joints and a cam mechanism. A cam mechanism consists of two parts, a cam disk and a cam follower, and is characterized by the fact that the periodic motion of the cam follower, which moves in contact with it, can be programmed by changing the shape of the cam disk. Three cam mechanisms are arranged in parallel in the automata, and are connected to the three cam followers through a link mechanism that can be converted to a three-dimensional motion of the automata's arms. The designer inputs the three-dimensional trajectory that the automata should follow via the GUI's handwriting interface. The geometries of the three cam discs were determined by continuously calculating the angles that the cam followers should be at, using a joint that specifies the constraint on the positional relationship of the links as a cost function. The calculated results are manufactured by a 3D printer and assembled as an automaton. As a result, we have successfully manufactured an automaton that can follow any trajectory specified by the designer in real space. Furthermore, by replacing only the cam discs, we were able to see how the behavior was changed to track the trajectory specified separately by the designer.

The problems of parameter setting, fine adjustment after manufacturing, and difficulty in finding aesthetic properties were mitigated through the development of a design support method using the optimization technique, which took three approaches: Constructability, Explorability, and Programmability. Research on technologies to support the design of aesthetically pleasing machines while ensuring functionality is new and there are still many issues that need to be solved. The results obtained from this study suggest that they can contribute as a steppingstone to solving those problems.

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(List of research achievements for application of doctorate (Dr. of Engineering), Waseda University)

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○	[1] T. Takahashi, J. Zehnder, H. G. Okuno, S. Sugano, S. Coros, B. Thomaszewski: Computational Design of Statically Balanced Planar Spring Mechanisms. 2019 IEEE Robotics And Automation Letters (RA-L), pp. 4438 – 4444. Vol.4, Issue 4, 2019.
	[2] S. Suzuki, T. Takahashi, H. G. Okuno: Development of a Robotic Pet Using Sound Source Localization with the HARK Robot Audition System, Journal of Robotics and Mechatronics Vol.29 No.1, 2017
国際学会（査読あり）	
○	[3] T. Takahashi, H. G. Okuno, S. Sugano, S. Coros, B. Thomaszewski: Computational Design of Balanced Open Link Planar Mechanisms with Counterweights from User Sketches. 2020 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS) (Oral Presentation with Review)
○	[4] T. Takahashi, J. Zehnder, H. G. Okuno, S. Sugano, S. Coros, B. Thomaszewski: Computational Design of Statically Balanced Planar Spring Mechanisms. 2019 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS), 450-455. 2017 (Oral Presentation with Review)
○	[5] T. Takahashi, H. G. Okuno: Design and Implementation of Programmable Drawing Automata based on Cam Mechanisms for Representing Spatial Trajectory. 2018 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS), 450-455. 2017 (Oral Presentation with Review)
○	[6] T. Takahashi, T. Soma, Y. Miwa, N. Hiroko: Design of hand contact improvisation interface supporting co-creative embodied expression, Human-Computer Interaction International 2017 (HCII2017), HIMI 2017, Part II, LNCS 10273, pp. 631-639, 2017.7 (Oral Presentation with Review)
○	[7] T. Takahashi, R. Hayashi, Y. Miwa, N. Hiroko: Co-creative Expression Interface：Aiming to Support Embodied Communication for Developmentally Disabled Children, Human-Computer Interaction International 2016 (HCII2016), HIMI 2016, Part II, LNCS 9735, pp.346-356, 2016.7 (Oral Presentation with Review)
	[8] Y. Kajita, T. Takahashi, Y. Miwa, S. Itai: Designing the Embodied Shadow Media Using Virtual Three-Dimensional Space, Human-Computer Interaction International 2015 (HCII2015), HIMI 2015, Part II, LNCS 9173, pp.610-621, 2015.8 (Oral Presentation with Review)

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国内学会（査読なし）	[9] Takuto TAKAHASHI, Masanori TSURUTA, Yoshiyuki MIWA, Hiroko NISHI: Measurement co-creative bodily expressions by hand contact interfaces, LIFE2016, 2016.9 (Oral Presentation without Review) [10] TAKAHASHI Takuto, KAJITA Yusuke, ITAI Shiroh, MIWA Yoshiyuki, NISHI Hiroko: Design of Bodily Expression Media by Integration of Skeleton Information and Shadow, SI2015, 2015.9 (Oral Presentation without Review) [11] Takuto TAKAHASHI, Masanori TSURUTA, Yoshiyuki MIWA, Hiroko NISHI: Measurement co-creative bodily expressions by hand contact interfaces, HI2015, 2015.9 (Oral Presentation without Review)