Doctoral Dissertation

Production Support Using Staging Methods to Encourage Collaborative Creation with Visual and Haptic Information

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Abstract

Unlike two-dimensional (2D) representations, such as pictures, three-dimensional (3D) objects can be uneven, and when they are viewed from certain directions, some parts cannot be seen. To grasp the full picture, it is necessary to look around the object, and the parts that cannot be seen must always be filled in by the imagination. The more complex the shape, the more imagination is required. For this reason, the creation of 3D objects, such as building blocks and LEGO, develops human creativity. However, individual creativity has its limits, and the creation of large or complex 3D objects requires the collaboration of multiple people. Co-creation makes it possible to share and combine ideas and information. In collaborative creation, creators cooperate to achieve a common goal, giving them a sense of accomplishment and unity in their production activities and a fulfilling creation experience.

Collaborators are essential to co-creation, and flexible collaboration, efficient work, and cooperation among creators are key elements. In addition, mutual understanding through information sharing and communication is essential to achieve common goals. Having confidence in the results of one's work and a sense of contribution are other important elements in gaining satisfaction and fulfillment through co-creation and are achieved through active participation in activities. Hence, co-creation is composed of various elements and forms the basis for creative outcomes. In production activities, in particular, the sharing of ideas and information creates value that cannot be achieved by individuals alone. Therefore, it is important to understand and share the overall picture of creation, the steps of production, and efficient methods as well as to work together to achieve the goal. However, levels of knowledge, experience, and skills related to production vary among individuals, leading to discrepancies in the information shared and uneven progress in production. For those who are unfamiliar with production activities, in particular, such difficulties can lead to a lack of motivation and sense of contribution, a mismatch in the pace of production, and creator isolation, which can hinder the fulfilling experience that co-creation can offer. Therefore, it is important to create an environment in which everyone recognizes a common goal and can collaborate while sharing a sense of accomplishment and enjoyment. To promote such an environment, it is necessary to support the process of collaborative creation.

To address this issue, this thesis proposes a method to promote collaborative creation that addresses three key elements of collaborative activities: 1) clarifying the final product image and deepening the understanding of common production

goals, 2) facilitating large-scale production to understand and share efficient production methods, and 3) promoting a sense of unity among makers to enhance a sense of unity and thus prevent isolation and lack of communication. Moreover, the thesis aims to realize the proposed methods by using augmented reality (AR) technology, which presents visual and tactile information to s and is the focus of attention in various research fields as an information medium. In AR, visual information through information projection can superimpose virtual content in the real world. In addition, haptic information using small actuators can instantly present clear sensations to users without interfering with their visual or auditory senses. Therefore, these technologies are used for play, education, sports support, tactile reproduction in virtual spaces, navigation, and other applications.

In Methods 1 and 2, we use spatial augmented reality (SAR) technology facilitated by projectors. SAR enables the highly integrated overlaying of virtual content onto the real world, allowing for the natural integration of the projected content and information sharing among multiple users. Therefore, SAR is well suited for presenting information for the collaborative creation of large-scale 3D objects. In Methods 1 and 2, we propose a method for visualizing production objects in real space using SAR to achieve large-scale production.

Method 1. Clarifying the final image of the production subject: Observing objects through touch enables a detailed grasp and an intuitive understanding of the shape and scale of the production subject. To facilitate these outcomes, we propose a real-time projection system using SAR to project distorted images with the aim of achieving natural interaction with the projected content. The proposed method presents lifelike images to users without the use of physical displays, such as smartphones or AR glasses. Constantly presenting stereoscopic images that are responsive to the user's viewpoint enables users to gain a prior understanding of the shape and scale of the 3D object.

Method 2. Facilitating the creation of large-scale 3D objects: Presenting clear production procedures and methods enables even those without knowledge of or skills in production activities to understand and share efficient production methods. To achieve this outcome, we use SAR to interactively visualize the production steps of the creation subject, providing creators with intuitive and accurate material placement locations. This approach allows creators to effectively collaborate on a single goal and produce large-scale 3D objects as tall as a person, which would be impossible for an individual to do.

Method 3. Enhancing unity among creators with a haptic presentation approach: We implement a haptic presentation system using pneumatic actuators to improve the sense of unity among creators. To achieve this, we develop a device that presents the production actions of others as haptic sensations on the creator's neck, enabling them to understand the actions of the collaborators. This approach allows creators to comprehend the production status of the collaborators, facilitating efficient collaboration in the production process.

The research on Method 1 revealed that the real-time deformation of distorted images improves the realism of the projected content and has the effect of making it possible to see and interact with the projected image as if it were a real object. This effect allows the natural movement of the production object, as if the user were observing a real body, and contributes to clarifying the image of the completed production goal necessary for collaborative creation.

The research on Method 2 demonstrated that presenting interactive production procedures through information projection enables accurate material placement, which eases large-scale production. Collaborative production activities in such large-scale projects contribute to the enjoyment, fun, and shared sense of accomplishment, fostering the necessary communication for collaborative creation. Moreover, the proposed method involves processing the production subject computationally and recreating it in the real world using common materials, such as balloons, plastic bottles, or cans. Therefore, it facilitates the creation of artistic expressions and innovative designs, generating creative value.

The research on Method 3 revealed that grasping the actions of others through haptic presentations makes the participants imagine the situation of others and improves the sense of unity. These outcomes have the effect of preventing creator isolation, as creators can match each other's pace of creation, and of promoting conversation. Such production activities enable the sharing of ideas and information necessary for collaborative creation and contribute to the building of cooperative relationships. The sharing the ideas or information facilitates creative processes, such as collaboration and the acquisition of inspiration.

These approaches focus on essential elements for co-creation in production activities. Understanding and sharing the image of the completed production object, production procedures, and efficient production methods, as well as achieving the

goal through cooperation, enable a sense of accomplishment and enjoyment of the production process to be shared. It is expected that working in this way will lead to the realization of fulfilling production activities.

Keywords: *Production Support, Projection Mapping, Haptic, collaborative creation, Augmented Reality*

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Chapter 1

Introduction

Production activities are the acts of shaping one's ideas. For example, "tsumiki" combines many blocks of different shapes to create three-dimensional (3D) objects. Many people, from children to adults, enjoy playing tsumiki, and the creators create their works of art through trial and error and by imagining the finished products. These 3D objects have not only shapes but also hidden parts that are not visible from the depth and position directions. Therefore, it is necessary to look around a 3D object of this type to grasp its full shape, and the invisible parts must always be filled in by the creator's imagination. The more complex the shape, the more the creator is required to use their imagination. For this reason, 3D production activities, such as tsumiki, have a role in intellectual education. The act of creation is self-expression and fosters creativity and imagination. One's creativity, expressed through the stacking of blocks, is expanded by one's imagination, and the repetition of the act of creation leads to the next new act of imagining. Imagination allows humans to engage in a wide range of expressive activities, from pretend play to artistic creation.

When others intervene in the production process, the production activity becomes co-creation. Creators communicate with each other to accomplish the production activity. Increased communication leads to the sharing of ideas and knowledge, providing an opportunity for producers to enhance each other's creativity and leading to more advanced production activities. However, as the levels of knowledge, experience, and skill in production vary from person to person, there are discrepancies in the information shared and variations in the progress of production. For those who are unfamiliar with the act of production, in particular, the difficulty of production activities can lead to a decrease in motivation and the sense of contribution to production. Moreover, creators can be isolated due to inconsistencies in the pace of production, making it impossible for them to have fulfilling production experiences through collaborative creation. These problems hinder the self-expression of creators and occur in various production activities. To facilitate production activities, it is necessary to understand and optimize the structure of the production object and visualize the production process. Therefore, several works have proposed methods to support production activities and facilitate the production of 3D objects by beginners without special skills or knowledge.

1.1 Production & Communication Support

Previous research has analyzed and optimized structures for complex and diverse types of 3D objects using computer graphics (CG) to support production activities. In their work on 3D models, Filoscia et al. [1] split a 3D model for 3D printing. This method optimizes the partitioning to reduce the support material used to support the output during the 3D printing process. Hao et al. [2] proposed a method to generate LEGO models from input user sketches by modeling the properties and connection mechanisms of LEGO blocks and using a system that analyzes the balance, stresses, and assemblability of the model. Nuvoli et al. [3] proposed a geometry processing pipeline for 4-axis CNC machining. The proposed system computes and splits the rotation axis of the input mesh to cut a complex shape from a single block. These three studies lead to the materialization of structures in the computer to the real world. People materialize their own desires through creation. The results of this research may contribute to self-expression through creative activities. Other works have proposed the structural analysis of 3D objects using wire structures [4, 5, 6], and researchers have also proposed assemblies that could be applied in the field of architecture [7, 8, 9]. Hsaio et al. [10] proposed a computational framework for automatically creating multi-view 3D wire sculptures, simplifying a task that would take an enormous amount of time to complete manually. Larsson et al. [11] proposed a system for designing woodworking joints for wooden frame structures called "Tsugite." The system allows interactive joint editing and the easy exploration of joints in complex structures, enabling even non-expert users to edit joints. In this way, recent works support creative activities using a variety of structures. Today, anyone can easily produce movies and music due to the advancement of technology. Therefore, in the near future, everyone will be able to easily engage in creative activities such as DIY and artmaking with substance.

Understanding the structure of the object is an important element in supporting creative activities. However, even if the structure of the object to be created is grasped, creative activity is not possible without an understanding of the creation procedure. Recently, augmented reality (AR) technology has become more accessible due to the advancement of information technology. For example, some smart devices have made it possible to superimpose virtual characters and geographic information onto real space. When the camera is held over the text, the translated text is superimposed over the original text. In this way, AR technology provides effective and intuitive information and interaction to the user. Previous studies have proposed interaction procedures for AR-based creative activities. In addition, AR technology allows users to directly create 3D objects without being restricted by their locations. Song et al. [12] added the value of story to the handicraft experience of origami for parents and children. By applying AR technology, the system the authors developed visualizes the origami process and presents animated storytelling. User studies suggest that the proposed system facilitates interaction between parents and children.

There are other ways to incorporate AR into creative activities besides smart devices and headsets. Several works have constructed spatial augmented reality (SAR) systems using information projection devices. Hattab et al. [13] projected guidance information onto the material for a rough engraving. When engraving, it is easy to cut the material roughly but difficult to cut it exactly. This problem is solved by projecting the cutting point. Flagg et al. [14] proposed a painting support system using projection mapping: when an artist is using actual brushes and colors to paint, the system projects guidance information, such as the position of the painting, the colors used, and the texture of the painting. This guidance enables beginners to create paintings using traditional methods and tools. As shown in these studies, AR can add information that does not exist in the real world and can present a variety of interaction procedures. To support creative activities, presenting information by AR is important.

These studies propose methods to facilitate production and support users' skills and knowledge related to production. However, in cooperative creation in which others intervene, creators are engaged in creation activities with the same goal in mind. Therefore, it is important for creators to read each other's situations and share information related to creation. Ganesh et al. [15] used a robot interface to investigate how physical interactions with others affect individuals' own motor behavior. The results of the study showed that the performance of both users was improved. Takeuchi et al. [16] investigated the effects of haptic sharing on players' emotions and behaviors through the public goods game. The results showed that haptic sharing amplified feelings of guilt and the inhibition of people's uncooperative behavior. Haptic Empathy [17] proposed a system in which people share their subjective emotions using simple vibrotactile feedback. Simple vibrational feedback may be an effective medium for expressing subjective emotions. As shown in these studies, users can share their feelings through physical interactions, and such interactions can enhance behavioral performance. Haptic feedback is especially effective as a method to transmit information instantly without restricting users' visual and auditory senses. The sharing of haptic feedback is important to improve the sense of unity among creators in production activities.

1.2 The Scope of this Thesis

This study aims to facilitate collaborative creation in production activities by using visual and haptic expressions enabled by AR technology, focusing on key elements essential for co-creation in the production process.

Collaborative creation is the process of working with others to achieve a common goal. WeBuild [18] proposes a system to solve the problem of the efficient coordination of work roles in a group for collaborative physical assembly and construction work. For efficient production, tasks are assigned so that each creator clearly understands their role. In addition, creators can receive real-time information on project progress and changes through their smart devices, a system that helps all creators work toward a common goal. Feedback from others is also provided, allowing for accurate information recognition and smooth communication. Crowdsourced Fabrication [19] proposes a crowdsourced fabrication system for large-scale production using digital technology. The proposed system uses smart devices and indoor location detection to present the production process to creators in real time, and as a demonstration experiment, many creators collaborated on a large-scale production. As a result, the system contributes to the efficiency of collaborative work and the ability of creators to participate in production activities regardless of their skills and levels. Other important elements of collaborative creation are discussed, including the importance of people's active participation in production activities and of different points of view and the sharing of interests [20, 21, 22, 23, 24].

As shown in these studies, co-creation requires having a common goal, information sharing, and a common understanding. For this purpose, smooth communication and a sense of unity among creators are important, and it is also important that creators who are not familiar with production can participate in production activities. If these elements are present in co-creation, creators can obtain a sense of accomplishment and satisfaction from production activities as well as confidence in the results of their work and a sense of contribution. Hence, co-creation consists of various elements and creates value that cannot be created by an individual through the sharing of ideas and information. Creators can also share the joy and pleasure of creation activities with each other and gain a fulfilling experience of creation activities. However, it is difficult for beginners who are unfamiliar with the act of production to grasp in advance the image of the completion of an unfinished production goal. It is also difficult to think about the production process, and relying on the system for this purpose leads to individual work. Such difficulties in production activities lead to a decrease in motivation and the sense of contribution to production as well as the isolation of creators due to inconsistencies in the pace of production. In such cases, a fulfilling production experience through collaborative creation cannot be achieved. To have a fulfilling production experience, it is important to understand and share the image of the finished product, the production process, and the efficient production method with others; otherwise, it may be difficult to achieve the goal of collaboration. In this thesis, we propose a method that addresses the elements which, as described above, are important for cooperative creation in production activities. Specifically, we focus on three of the elements that are important for collaborative creation: clarification of the image of the completed production object, understanding and sharing of efficient production procedures and methods, and a sense of unity with others. Then, we produce opportunities for collaborative creation by utilizing the effects of visual information through SAR using a projector and tactile information through pneumatic pressure. We aim to contribute to the clarification of the completed image of the production object and the understanding and sharing of the production procedure and method through production that addresses some of the elements that are important for collaborative creation in production activities.

In this study, we propose a method to promote collaborative creation through visual and tactile stimuli using AR technology. Since SAR can add information that does not exist in real space, it provides a new experience by displaying virtual content. For example, users can walk and communicate with their favorite characters by superimposing virtual characters in front of their own eyes. In general, AR is used for business, guidance, simulation, and education using smart devices and headsets. One of the advantages of AR applications is the interaction with content that does not exist in real space. AR interaction facilitates the user's understanding of the content. However, AR applications using smart devices are difficult to interact with naturally, as the hands are occupied and the touch panel is not always easy to operate. In addition, smart devices and headset displays create an obstacle between virtual content and the real world. These problems limit user actions, making it difficult to share information with multiple people simultaneously and gain a sense of "being there" for virtual content. If this obstacle is removed, it will be possible to present virtual content as if it exists in the real world and present information that encourages natural interactive behavior.

The first method presents stereoscopic images to the user. The projected image is changed according to the user's head position; thus, the user can always see the stereoscopic image and interact with the projected content through natural movements. It is difficult to grasp the shape and scale of a work that is not created by imagination alone. In addition, using AR with smart devices limits the user's movements. Touching and observing the object of creation allows for a detailed and intuitive understanding of its shape and scale. The ability to see and interact with the object in the same way as with a real object facilitates the understanding and sharing of the creator's production goals as prior knowledge of the production activity, contributing to the clarification of the image of the finished production goal that is necessary for collaborative creation. In addition, due to the projection characteristics of the projector, changes in the projected position of the image cause changes in the size of the projection. Therefore, it is difficult to project information for the creation of 3D structures. This problem becomes more pronounced the larger the scale of the 3D object. If this obstacle is removed, it will be possible to create 3D structures as large as a person's height, which will induce cooperative work and communication.

The second method uses SAR to achieve large-scale production. It adjusts the size of the projected image according to the projection position and presents the creator with intuitive and accurate material placement positions. This enables creators without sufficient production knowledge, experience, or skills to create 3D works through collaborative creation, generating creative value such as artistic expression and new designs.

On the other hand, in creative activities, creators create by perceiving objects and materials with their eyes. During these activities, creators communicate with each other by speaking and hearing. In other words, in creative activities, the creator's visual and auditory senses perceive information for the purpose of production. Presenting new visual or auditory information to the already engaged visual and auditory senses may hinder creative activities and communication. Therefore, haptic information is effective as an indirect presentation of information. However, the complexity and size of the system limit the creator's actions and prevent creative activities such as moving around freely, potentially hindering communication between creators. Therefore, the third method proposes a lightweight and simple system using pneumatic actuators to improve the sense of unity. This system enables the creator to understand the production status of collaborators and work efficiently through collaboration. The improved sense of unity enables the sharing of ideas and information necessary for collaborative creation and facilitates the creative process of collaboration and inspiration.

These methods focus on some of the key elements for collaborative creation in the above-mentioned production activities. They provide a sense of accomplishment and enjoyment for those who are unfamiliar with production activities and those who lack related skills and knowledge. In this way, even those who are unfamiliar with production activities and those who lack skills and knowledge can share the sense of accomplishment and enjoyment of production. These elements add value to cooperative creation and are expected to realize fulfilling production activities.

1.3 The Goal of this Thesis

The goal of this thesis was to encourage collaborative creation in production activities using AR. To achieve this goal, we have developed a system that directly and indirectly supports production activities in the real world. We aimed to use the developed system to clarify the completion image, simplify the production process, and improve the sense of unity among creators, which are important elements in collaborative creation.

As mentioned in Section 1.2, cooperative creation involves a variety of factors. In particular, this thesis focuses on clarifying the completion image of the production object so creators can understand the common production goal, achieving large-scale production – in which multiple producers cooperate in production activities – and improving the sense of unity to prevent a lack of communication among and the isolation of producers (see Figure 1.1). In cooperative creation, coordinated production activities are not possible without a clear common understanding of goals and directions. For those who are unfamiliar with production activities, in particular, the difficulty of undertaking such activities leads to a decrease in motivation for production. Therefore, it is important to understand the purpose and direction of production and to cooperate with others. In addition, communication is an important element in ensuring that all creators involved in collaborative creation have a fulfilling production experience. By communicating, multiple creators can collaborate and generate creative value that cannot be produced by an individual. Producing alone limits the generation of ideas, and the impossibility of sharing the joy and sense of accomplishment of production with others hinders a fulfilling production experience. Therefore, we focus on each element that is important for collaborative creation in production activities and propose three methods for producing such creation: presenting stereoscopic views, realizing large-scale production, and understanding the actions of others. The proposed methods aim to create opportunities for the creation of cooperatives by directly or indirectly supporting the elements that are important for producers to cooperate with each other in their production activities. Direct support includes an easy understanding of the structure and size of the object to be created, manipulation of the virtual model with natural movements, and support for the placement of materials for creation. For these supports, the approach goes beyond merely presenting information. By staging artistic expressions such as real-time transformation of distorted images and the projection of numbers with animations, as well as deformed expressions, it directly assists the act of production. Indirect support aims to improve a sense of unity by ensuring users understand each other's actions. In addition, we clarify the influence of these supports on the experience of creative activities. To understand actions, the approach does more than just present tactile sensations. It stages a sense of unity by converting each creator's production actions into tactile sensations, indirectly supporting collaborative production activities.

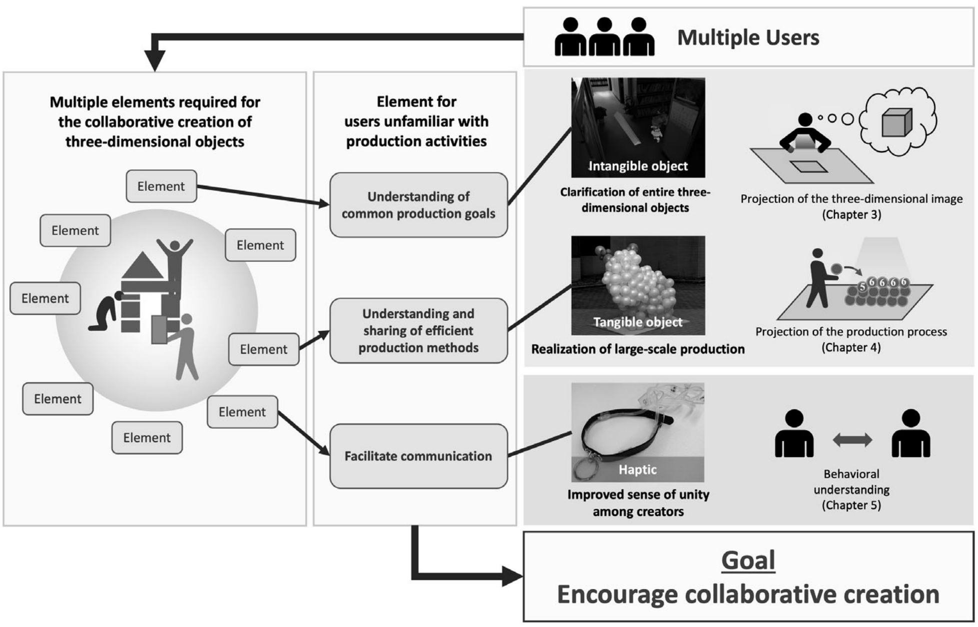


Fig. 1.1 A staging method for encouraging collaborative creation for three-dimensional object creation activities. Several elements are necessary to make collaborative creation fulfilling. Among these elements, this thesis proposes a method to facilitate production activities for those who are not familiar with production activities.

The principal research question concerns how to enhance the experience of creative activity. In response to this, we aim to provide production support that involves the creation of a sense of co-creation. The sense of co-creation treated in this study consists of the following three feelings: 1. knowing that others are creating the same target as oneself, 2. knowing that others understand one's creative behavior, and 3. in creative activities where such interaction exists, having the feeling that one was able to create the object due to the cooperation of all creators. To solve this question, it is necessary to provide a system in which multiple creators can actively cooperate. In particular, it is necessary to clarify the finished image of the production object. It is also necessary to provide a method for decomposing the production object into individual parts and enabling creators to complete them cooperatively to realize large-scale production. Furthermore, to facilitate collaborative creation, it is necessary to perform the act of production according to the situations of others through intrinsic motivation. To solve these problems, we use three sub-research questions.

1: How can the reality of virtual content be improved without the use of a physical screen?

This study proposes a method of presenting 3D images without using physical screens, such as smartphones or AR glasses, so creators can easily grasp the entire image of the object to be produced. Recently, it has been possible to superimpose virtual content on real space with the development of AR and virtual reality (VR) technologies. However, physical screens, such as smartphones and AR glasses, cannot realize natural movements to interact with virtual content or give a natural sense of reality. To solve this problem, we projected a distorted image that deforms according to the position of the user's head onto a real space, such as a desk or the floor. The system aims to improve the reality of virtual content by constantly presenting stereoscopic images to the user and realizing interactions with natural movements. To verify whether this improvement occurred, we developed a head-mounted 3D projection system. Users could feel the three-dimensionality and presence of the projected content by the distorted image deformed according to the position of the head. In addition, some users expressed affection for the projected objects. It was also suggested that the projected contents gave a sense of presence to the user.

2: How can changes in projection size due to changes in projection distance be prevented?

This study proposes a method to appropriately disassemble virtual objects to be created and reproduce the individual parts of the disassembled virtual model as entities. Recently, digital fabrication research using 3D printers and information projection technology has been drawing attention. However, when the 3D modeling becomes large-scale, structural understanding and the creation act become difficult due to the complexity and number of creation procedures. In addition, there is no guidance method for the placement of materials to facilitate large-scale creation. To solve these problems, we propose a layered projection mapping technique that adjusts the projection size to be constant according to the projection position established at each constant height. This system prevents the projection size from changing depending on the projection distance. Using this system, it is possible to create large 3D objects by leveraging SAR's visual representation. To verify this, we conducted a large-scale production experiment using balloons to create a virtual model of a hemisphere and a rabbit of about the same height as a person. In the hemisphere creation experiment, we conducted production experiments with and without the system. It was confirmed that the proposed system can produce hemispheres that are close to the target size and shape. In the rabbit creation experiment, users were able to create a balloon artwork approximately 150 cm high without any interruption in their creative activities.

3: How does the presence or absence of haptic feedback affect creators' sense of unity?

We propose a haptic presentation system using a pneumatic actuator, which is small and easy to produce. This system presents the creator's creation actions to the collaborator's neck as a haptic sensation. Physical stimulation of the skin is an effective way to attract the user's attention because it is a clear stimulus. However, existing methods limit the range of system use due to the complexity and size of devices, so it is difficult to present simple and clear haptic feedback that does not interfere with the user's movements. Large-scale creative activities require users to be able to take free and natural actions, such as the observation of virtual models, creation of parts, and assembly. For this reason, the chosen system should not restrict the user's actions. To solve this problem, we developed a small device using pneumatic actuators. This device presents information to the creator that enables the latter to grasp the directions and actions of others. For this verification, we conducted user guidance experiments using the developed device. The results showed that almost all users reached their destinations; thus, users knew the direction in which they felt pressure and the direction in which their goal was located. Applying this directional information to creative activities, we can present creators with haptic feedback on another person's creative action. The purpose is to improve the sense of unity among creators in creative activities.

As mentioned in section 1.2, previous works have used smart devices, computers, and frameworks for collaborative creation. Among the elements of collaborative creation discussed in these works, this thesis approaches three elements specifically for production activities. For production support, as mentioned in section 1.1, previous works have used computer simulations and AR headsets to present production procedures. These methods limit the sharing of information with each creator and make it difficult to realize smooth collaborative work. Therefore, this thesis aims to facilitate the sharing of information among creators and the realization of smooth collaborative production activities by using information projection and haptic presentation technologies. For each of the three elements, the proposed system stages the real-time transformation of distorted images, the projection of animated numbers, and the conversion of the act of creation into a haptic sensation. Staging provides the creators with an opportunity for collaborative creation of creative value. This paper outlines the foundational technologies for such collaborative creation.

1.4 Overview

The rest of this thesis is organized as follows.:

- In Chapter 2, we review case studies and research using visual and haptic stimuli for the following chapters (Chapters 3, 4, and 5) and present related research on each topic.

- Chapter 3 describes the head-mounted stereoscopic projection system we have developed and the method of presenting 3D images to the user. It also presents details of research on conventional projection mapping techniques and a discussion of future issues. In this chapter, we demonstrate the effect of the proposed system on the user and describe the results. To evaluate the usability of the proposed system, we conducted a user survey and evaluated users' impressions of the projected contents. As a result, we found that the interaction with the projected content gives the user the feeling that the content is present.

- Chapter 4 describes the layered projection mapping technique, which projects the appropriate size for each level of the hierarchy. It also describes an interaction procedure by disassembling a virtual model and visualizing cross-sections of the disassembled parts. In this study, we describe the contribution of the proposed system to large-scale fabrication and as a demonstration experiment. In the experiment, we created a hemisphere and a virtual character using balloons. As a result, we found that the proposed system can produce a hemisphere that is close to the pre-defined target size and the balloon art of a virtual character.

- Chapter 5 describes a pneumatic actuator-based direction guidance device with haptic feedback. We explain the mechanism of direct presentation and investigate the direction presentation pattern perceived by the user. In addition, this chapter presents the actual experiment conducted, which confirmed that the user was able to reach the destination using only the proposed device. Using this result, we discuss how haptic presentation affects creative activity.

- Finally, in Chapter 6, we summarize our research, conclude this thesis, and discuss future challenges.

Chapter 2
Related work

This chapter introduces the related work in this thesis. This thesis proposes an interactive system using projection mapping and haptic feedback as production support with AR technology. AR technology is one of the components of extended reality (XR), which includes VR and mixed reality. Therefore, we first present examples of applications and related research on interactive systems using XR technology. Next, we review related work on projection mapping (Chapters 3 and 4) and haptic feedback (Chapter 5). In addition, as this study focuses on co-creation and aims to realize collaborative work using digital technology, we present research on collaborative work.

2.1 Interactive Plays using AR Expression

The development of information technology has made it easy to obtain depth sensors, such as Microsoft Kinect® and LeapMotion, high-definition projectors, and high-performance personal computers (PCs). In addition, we can easily prepare the environment to produce interactive content because information sharing is becoming easier with the popularization of the Internet. The miniaturization of devices and availability of easy-to-start content production have contributed greatly to enhancing users' experiences of digital attractions. A digital attraction is a hands-on interactive work of art that provides people with an interactive play experience using visual expression, light, sound, and touch. Digital attractions, also known as media art or digital art, use information technology to provide users with surprising and emotional experiences that are not possible in daily life and contribute greatly to communication among experiencers, fostering imagination, stress reduction, and education. They also play a role in local development and disaster recovery, and many people enjoy entertainment using digital technology [25, 26, 27] (Figure 2.1). Furthermore, creative activities such as digital building blocks [28] and LEGO®BRICK DIGITAL ATTRACTION [29] contribute to interactive presentation and presence by visual expression, which stimulates users' curiosity and creativity (Figure 2.2). Although digital attractions mainly use projectors, other events use monitors, headsets, and toys for the experience (see Appendix A). These interactive games can be divided into two categories: augmented experiences and immersive experiences.

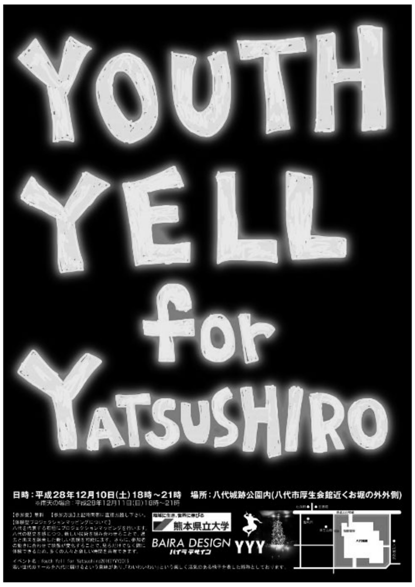


Fig. 2.1 Events for interactive attractions aimed at community development **[25]**.

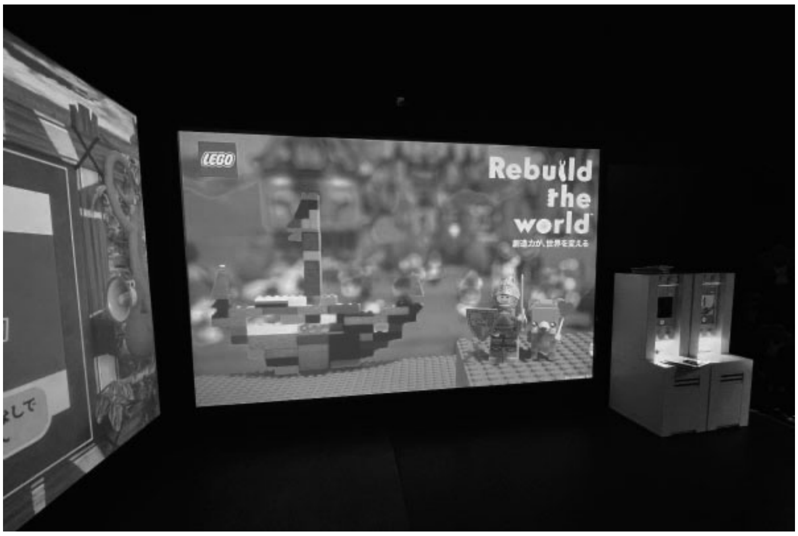


Fig. 2.2 LEGO®BRICK DIGITAL ATTRACTION **[29]**.

AUGMENTED EXPERIENCE AR technology enhances the user experience using projectors, smart displays, and physical objects. Mimi Action [30] creates a light effect using a projector and a cushion (Figure 2.3). When the user taps the cushion, light particles burst and collect on the cushion. Fantasy Diorama [31] is interactive content that visualizes fantasies through "playing with cars", namely, projecting vehicles and a city onto toy cars and their surroundings. When the cars are connected, images of trains are projected onto them. DIGITAL GOLDFISH SCOOPING [32], a goldfish scooping game that uses a smart device as a net, is one of many works that extend real space in this way. Flying Paint [33] is a drawing game using coloring images that scans the user's coloring-in images and projects them on the wall or displays. Miru Ensemble [34] visualizes a multi-person ensemble based on the motif of auditory expression: the user colors the wall surface by layering sounds together with other people on the spot. These works are extensions of creative activities. Other works are based on human body movements. toatope [35] is an interactive work of shadow play using hands. This work creates shadow creatures from hand shadow images when the user holds their hand over the table. The sizes and shapes of the shadow creatures vary depending on the person, and they move as if they were brought to life. Colored Shadow [36] is an experiential artwork that displays colored shadows of the experiencer and objects. The shadows move according to the movements of the experiencer. These works are extensions of the physicality of the body.

https://ponboks.com/works/action/

Fig. 2.3 mimi Action **[30]**

IMMERSIVE EXPERIENCE Immersive content provides users with an experience of the world that differs from the real world. Sports and balloon ride experiences using headsets [37, 38, 39] provide users with realistic experiences by using live action images. In addition, using a real hang glider and a wheelchair provides a more immersive experience for the user. Mario Kart Arcade Grand Prix VR [40] is a racing game using a headset (Figure 2.4). However, as the system also includes a hand-tracking mechanism that users can use to grab items with their own hands, it can realize an immersive experience without the use of a headset. Treasure Explorer [41] provides an immersive experience for many people by projecting images onto surrounding walls. In addition, the seats vibrate in response to the images, which increases the immersive nature of the experience. Survival From Z [42] provides an immersive experience by projecting images of the surroundings. An even more immersive experience can be achieved by wearing a vest that provides haptic feedback in sync with the video.

In this way, immersive works allow for experiences with a sense of presence and impressive. However, they require expensive equipment and large-scale systems. On the other hand, augmented works can construct a SAR system by simply preparing various sensors and projectors. In addition, systems utilizing SAR can present information to multiple people, enabling several individuals to experience the work simultaneously. Therefore, this thesis focuses on AR technology. We aim to support production activities such as building blocks, specifically, digital building blocks [28] and LEGO®BRICK DIGITAL ATTRACTION [29].

https://www.famitsu.com/news/201912/26189874.html

Fig. 2.4 Mario Kart Arcade Grand Prix VR **[40]**

2.2 Projection-Mapping

The evolution of video expression has brought tremendous benefits to projection mapping. Projection mapping (PM) is a technology that uses a projector to change the appearance of an object by projecting an image that matches the shape of the target object. The produced image follows the shape and tilt of the projected object. If the image is projected onto a flat surface, it tends to be distorted significantly. In other words, it is necessary to consider the distortion of the image in advance when creating images for projection mapping. Projection mapping is used for entertainment, sports, education, and other purposes and has been projected onto structures such as train stations, buildings, and vast floors (see Figure 2.5 [43, 44, 45, 46, 47, 48, 49]). MlioLight [50] blends multiple images and projects into different images only at the illuminated points. Projection mapping can project artificially generated shadows as well as colorful images. Jensen et al. developed a lamp that projects controllable ambient information [51]: the light is masked using an electrochromic display, and shadows are projected on walls and ceilings in two or more patterns that can change. This lamp helped to improve the immersive experience during the reading of children's books. Raudanjoki et al. examined whether human shadows projected as ambient information can be used to convey information [52]. The experimenter gathered users in a room where projections of realistic-looking human shadows were shown, observed their reactions, and found that users thought that the shadows were real shadows. In other words, the shadows were perceived as the natural scenery of the place. When a shadow moved, users paid attention to it. In other words, the transition of the shadow state helped users understand the meaning of the shadow and was perceived as an important clue that something was happening. Thus, shadows have a very close relationship with the real world, and projecting shadows can influence users' actions and feelings. In addition, Yong created an immersive installation work in which a life-size shadow figure was projected [53]. Tsubokura created an artwork that projects the shadow of a statue by pointing a tracker that resembles a flashlight at an empty pedestal [54] (Figure 2.6) and designed the device to be easily handled even by individuals who do not know how to operate special devices. In this way, PM can project a variety of information and be used for illusions and artworks.

There are two types of projection mapping: static projection mapping, in which the projected object does not move, and dynamic projection mapping, in which the projected object moves. The former projects various images onto a static object. The latter projects images in real time by either tracking objects that move and change shape in real time with a camera or moving the projector itself to project onto any location. Therefore, dynamic projection mapping enables expressions that were impossible with static projection mapping and is expected to be used in a variety of fields, including entertainment and education. In this thesis, we develop a system that presents an optical illusion to the user by projecting anamorphosis using dynamic projection mapping.

Anamorphosis is an image that is drawn using the perspective drawing method (Figure 2.7) and can only be seen as a figure when viewed from a single point of view. As shown in Figure 2.8 (a), when a largely distorted image is rotated by 90 degrees, it can be seen as a recognizable 3D image (Figure 2.8 (b)). Anamorphosis is used in many situations, for example, in museums, as a trick, or as art to prevent accidents (Figure 2.9).

https://www.kanazawa-it.ac.jp/kitnews/2017/20170308_pm-izuhara.html

Fig. 2.5 Projection mapping on the building.

Fig. 2.6 Invisible Sculpture.

https://www.johnlovett.com/perspective-drawing

Fig. 2.7 Figure drawn using perspective drawing method. As the object moves away from the viewer, its size decreases at a constant rate.

http://blog.blogpeople.net/2012/11/post_370.html

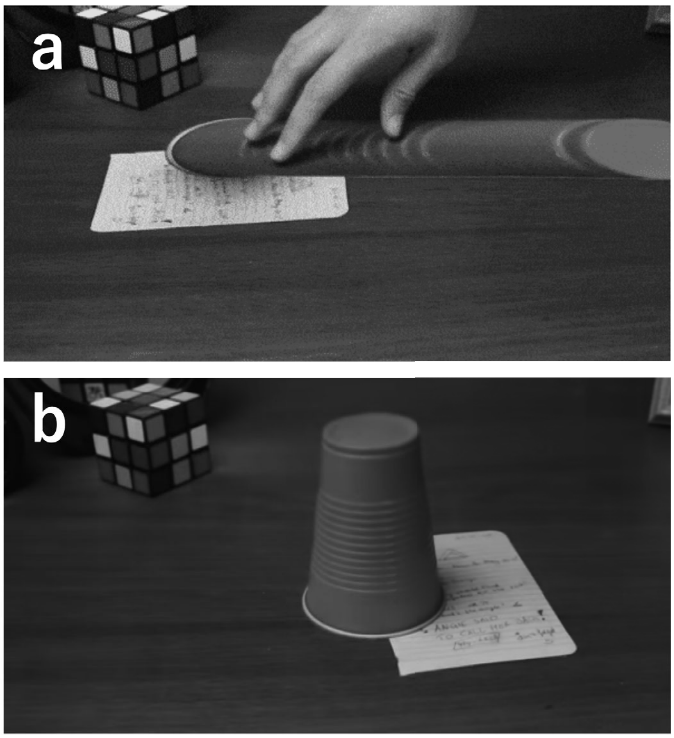


Fig. 2.8 Anamorphosis of a paper cup. When the deformed image (a) is rotated 90 degrees, it appears to be three-dimensional(b).

https://www.daska.jp/play/252

https://www.visir.is/g/2017170929734/vonast-til-ad-thrividdargangbraut-a-isafirdi-laekki-umferdarhrada

Fig. 2.9 Trick Art in Museums and Trick Art to Prevent Vehicle Accidents.

2.3 Haptic Feedback Technology

Haptic feedback is a technology that simulates the stimuli felt by the user's skin in the real world and makes the feedback experience richer when the user operates information devices. For example, the Taptic Engine in Apple's iPhone and the HD vibration in Nintendo Switch are technologies that realistically reproduce user operations and events displayed on the screen (Figure 2.10).

https://www.macrumors.com/2018/01/29/apple-immersion-enter-licensing-agreement/ https://www.youtube.com/watch?v=Jj4s

Taptic Engine HD vibration

Fig. 2.10 Haptic feedback integrated into daily life.
back integrated into daily life.

Haptic feedback technology has become an integral part of everyday life and is also used to enhance the immersive experience of VR and AR [55, 56, 57, 58, 59, 60, 61]. FingerX [56] (Figure 2.11) presents the shape of a virtual object to the user by extending and retracting extenders attached to each fingertip. For example, when grasping a thin stick, the proposed device can present the user with the sensation of grasping a thick stick or an uneven shape. GuideBand [57] (Figure 2.12) presents the user's arms with the sensation of being pulled in all directions and enhances the realistic sensation of being guided in a VR space. HeadBlaster [59] (Figure 2.13) presents a sustained sense of acceleration to the user using head-mounted air propulsion. Air can be injected laterally in a 360-degree direction and contributes significantly to the sense of presence and immersion of the content. Thus, the haptic presentation can be presented to the user through a variety of methods, such as wires and pneumatic pressure. In addition, haptic presentation technology contributes not only to the immersive experience in VR and AR but also to the reproduction of the haptic sensation in real space. MudPad [62] proposes a system that enables locally active haptic feedback on a multi-touch surface. Using ferrofluid and electromagnets, the system enables instantaneous movements. Cross-Field Haptics [63] proposes a new haptic rendering method using ferrofluid and an electrostatic field. This system reproduces the haptic sensation of projected textures by using the flexibility of ferrofluid and the resistance of electrostatic adsorption caused by an electric field. Other works include its use as a human augmentation [64], a drawing aid for users [65], and a haptic presentation method using lasers [66].

Fig. 2.11 FingerX: Rendering Haptic Shapes of Virtual Objects Augmented by Real Objects using Extendable and Withdrawable Supports on Fingers **[56]**.

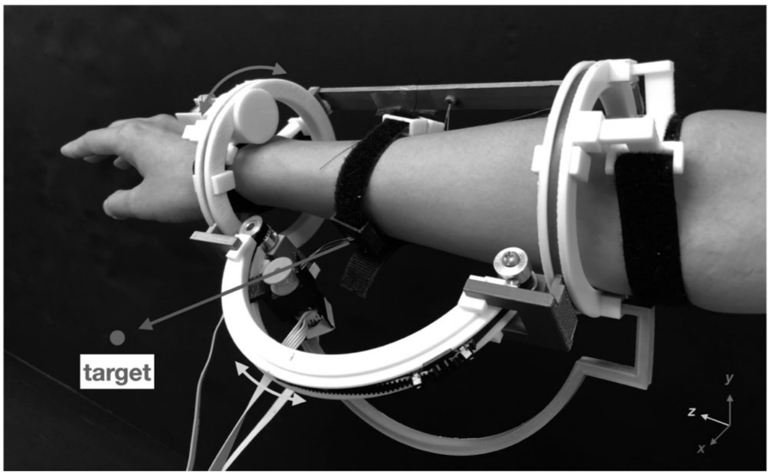


Fig. 2.12 GuideBand: Intuitive 3D Multilevel Force Guidance on a Wristband in Virtual Reality **[57]**.

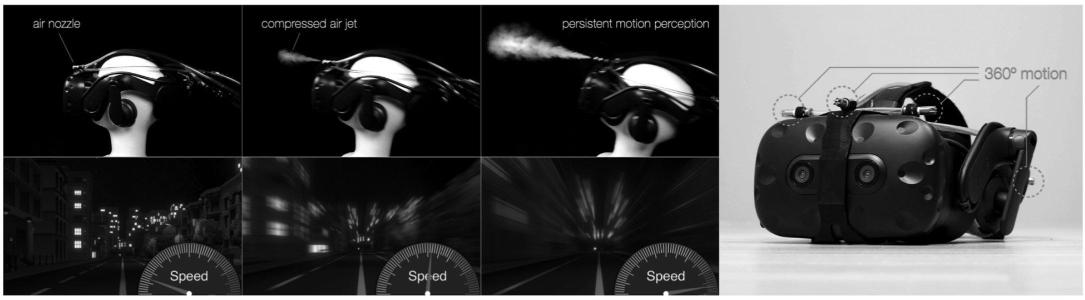


Fig. 2.13 HeadBlaster: A Wearable Approach to Simulating Motion Perception using Head-mounted Air Propulsion Jets **[59]**.

These systems are difficult for users to operate freely and naturally because of their complexity and the large size of the devices used. In this thesis, we use a pneumatic actuator to propose a haptic device that is compact enough to be used in daily life.

2.4 Collaboration Work

UMI3D [67] proposes a toolkit for collaborative work that simplifies the development of 3D user interfaces. Previous collaborative work with 3D applications was hampered by the fact that a working device is effective for some tasks but inadequate for others. Therefore, it is necessary to prepare multiple devices for each task. To solve this problem, this study proposed a tool that considers the context of the user's work. Thanyadit et al. proposed a system in which workers with different skills cooperate to perform a single task and improve the results [68]. In collaborative work in a virtual space, real-time information sharing contributes to work efficiency. However, real-time information sharing can be an obstacle to collaborative work when workers are in different locations or use different tools for their tasks. To solve this problem, this study developed a system that presents only information related to the current task, thus making it possible to prevent excessive information sharing among workers. Alina et al. described the design, implementation, and testing of Co-Creation Space (CCS), a digital tool for co-creation [69]. Media co-creation aims to support the artistic co-creation process but does not support the iterative community participation that is essential for artistic co-creation. Using CSS for artistic co-creation provided a tool for users to share ideas, discuss, receive feedback, and reflect on their work. Thus, CSS supported the complexity of the community co-creation process and the iterative community participation essential to artistic co-creation. These works are in the field of computer-supported cooperative work (CSCW), which realizes computer-assisted collaborative work. Miwa et al. proposed a system for co-creating physical expressions in remote areas [70] that presents the shadow of one user and particles reflecting their movements to a remote user. As a result, this system shared emotions with remote users through images and provided a stage for co-creating physical expressions. JackIn Head [71] proposed a system that transmits a user's first-person viewpoint to others using a 360-degree camera. In other words, it is possible to share the user's viewpoint with others. By obtaining the work viewpoint of a professional user, a beginner can learn a skill efficiently. Boiling Mind [72] proposed a system to improve the sense of unity between the audience and the performer. This system visualizes data acquired from the audience's heart rate and electrodermal activity (EDA) as a visual representation. The visualized images are shared with the performer as the mental state of the audience. This visual representation creates a "stage performance experience" between the performer and the audience. In this way, several works have proposed systems that connect with users and share their representations and actions. In this thesis, we focus on the collaborative activity of creative activity in a real space using visual and haptic presentation with AR technology.

The works mentioned in this chapter have proposed assistive technologies for collaborative work that facilitate the selection of appropriate tools, the presentation of information, efficient learning, and a sense of unity. As described in Section 1.2, the efficiency of collaborative work and the ability to perform activities regardless of a creator's skills or skill level facilitate collaborative work. The recognition of a common goal allows creators to cooperate with collaborators to achieve their goals. In this thesis, we aim to facilitate collaboration in real-world production activities by using AR technology for visual and haptic representation. We focus on clarifying the image of the completed work, understanding and sharing efficient production methods, and improving the sense of unity among creators. The goal is to create a place where participants can work together, recognize a common goal, and share a sense of accomplishment and enjoyment.

Chapter 3
Anamorphosis projection using a head-mounted device

In this chapter, we propose a real-time anamorphosis projection system that enables users to always see three-dimensional images using a projector and a tracker attached to the user's head (Figure 3.1). This system projects the anamorphosis of CG objects and CG characters onto a desk set up in real space as a projection surface. In addition, we evaluate the enjoyment of interaction, the three-dimensionality, and presence of the projected images, and the level of satisfaction with the system through interaction with static CG objects and dynamic CG characters projected using LeapMotion.

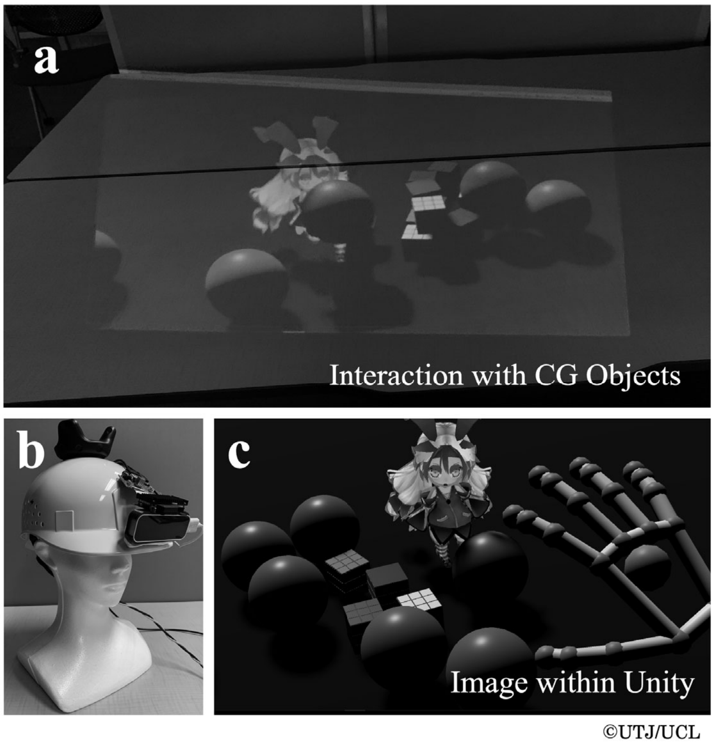


Fig. 3.1 Head-mounted real-time anamorphosis projection system**.** (a) Project a three-dimensional image in the real world with motion parallax and interact with virtual objects. (b) Using a head-mounted device, (c) projecting a simulated scene within a computer.

Using this system, the projection image distortion changes according to the user's head movement, and the three-dimensional image can always be presented from the user's point of view. In addition, by viewing the projected images directly without a physical screen, the user can interact more naturally with CG objects in harmony with the real space than with a display. Furthermore, CG objects can be presented to the user in a natural superimposition of the real space, without using a display, and free from the limitations of the screen area. In particular, the user interacts with static CG objects before interacting with CG characters to familiarize the user with the operation of the equipment used in the interaction.

In the next section, we describe the background and purpose of the research and the structure of this chapter.

3.1 Background

Recently technological advances have brought about a significant evolution in visual expression, and products using holograms have been developed and researched in the fields of computer graphics and computer interaction. For example, Gatebox® is a product that displays CG characters inside a capsule-like device based on the concept of "living with characters," and is now available nationwide (Figure 3.2). The user can interact with a CG character and can engage in conversation, chat via the communication application LINE, operate home appliances, and receive information notifications using GateBox®. In addition, CG characters can change their conversation and behavior the more the user talks with CG characters. Furthermore, GateBox can display animated characters such as Re: ZERO -Starting Life in Another World©, Spooky Kitaro©, and original characters created by the user. It can provide an experience that can be viewed and enjoyed as a digital figure. In this way, Gatebox® can be said a pioneer in attempting to integrate CG characters into real space. However, users cannot always experience the sensation of being near the CG characters because they are only displayed in the product. In addition, Head Mounted Display (HMD) and AR glasses have been developed, and research has been conducted to superimpose CG objects in real space to a high level. Holyski et al. realized a representation of CG objects as if they existed in real space by using SLAM [73]. For example, it is possible to express that the virtual object hides behind the real object. This is achieved by reconstruction of the estimated depth edge from a video and a sparse SLAM reconstruction as input.

Fig. 3.2 Gatebox

VR and AR have developed in many fields using various devices, such as not only interaction with CG but also taste change [74] and collaboration with the haptic [75]. In addition, advanced virtual content can be easily realized with smartphones, such as Apple's ARKIT 6 [76] and people occlusion, a method of representing CG objects as being occluded by humans. In this way, AR and VR are familiar technologies to us and are expected to bring great benefits to our daily lives in the future. For research on Mixed Reality (MR), Lang et al. proposed a system that corrects and displays a virtual agent in an appropriate position based on RGB-D data acquired with HoloLens [77]. However, in both cases, the user's immersive experience is hindered by the presence of a physical display between the image and the user. For example, when viewing an object, the farther away the object is viewed more blurred, and the closer the object is the clearer. However, virtual objects on a display are always clearly visible, regardless of where they are placed. In addition, the display area of CG objects is limited by the size of the display, so the contents of the display are perceived as being displayed in a different space from the real space. This makes the presence of the CG object feel diminished.

3.1.1 **Purpose of this research**

We propose a method to present CG characters as if they exist in the real world and to provide users with natural interaction with CG characters without the use of displays. The proposed system projects a lively CG character, which always exists in the user's vicinity and acts together with the user, as an illusionary three-dimensional image onto a desk or the floor using a small projector. This system creates a sense of reality by allowing the user and the CG characters to play catch with each other and by allowing the CG characters to walk freely around the user. In addition, the user can experience the sensation of "being there" by not using AR devices such as smartphones or see-through AR glasses.

3.1.2 **Organization of this chapter**

This chapter consists of six sections, and the structure and contents of each section are described below.

In Section 3.1, we describe the background and objectives of the study and in Section 3.2, we introduce related works on projection mapping, stereoscopic projection, and visual illusions, and clarify the position of this study. Section 3.3 describes the proposed device and method as an overview. Section 3.4 presents the implementation of the system, and Section 3.5 shows the user study and its evaluation. Section 3.6 summarizes this research and discusses limitations and future work.

3.2 Related Works

In this section, we introduce research on projection mapping, stereoscopic projection systems, and optical illusions as related research to this research.

3.2.1 Projection-Mapping

As mentioned in Section 2.2, there are two types of projection mapping: dynamic projection mapping, and static projection mapping. Miyashita et al. proposed a dynamic projection mapping system that does not require markers and does not limit the shape of the projection target but instead applies a texture to the tracked object [78] (Figure 3.3). The system measures surface normals in the infrared range in real time and projects material shading in screen space with a new fast texturing algorithm. The system can project onto people, liquids, and clay because it is markerless and model-less. They also developed the "Midas Touch Effect", which can gradually rewrite the material of objects that are touched, such as overwriting the surface of an apple with a metallic material.

Fig. 3.3 Midas projection: markerless and modeled dynamic projection mapping for material representation [78].

Illuminating Cray [60] is also a dynamic projection mapping system that utilizes the cray. By capturing the unevenness of the cray's landscape using a laser scanner, the system projects visual expressions based on the landscape's height. This system can simulate various information such as altitude, contour lines, slope angle, water flow and erosion, and sunlight and shadow. Other research includes Makeup Lamps [79], which projects shadows, lights, clowns, and other textures onto a human face to dynamically add facial expressions and make-up. Several other works on dynamic projection mapping have also been conducted [80, 81, 82, 83, 84, 85]. However, the projectors in these works are fixed and only project in a fixed direction. To project over a wider area, it is necessary to use multiple projectors. HeadLight [86] projects CG objects using a projector attached to the user's head, rendering a 3D virtual space that matches the physical environment. The projected content changes in response to the user's movements and a fisheye lens are used to expand the projected area. This makes it possible to present immersive images to the user. However, there is no interaction with CG objects, and the projected images have not been evaluated.

3.2.2 three-dimensional projection

There is research on presenting stereoscopic images to users using depth sensors and special displays. Takasaki and Mizuno proposed a system that enables direct interaction by hand while projecting stereoscopic images by motion parallax onto a special display [87]. To present the user with a three-dimensional view of the virtual model, this system reflects the image using a micromirror array plate. The reflected virtual model is deformed according to the position of the user's head, so the user can always see the three-dimensional virtual model. The interaction is based on LeapMotion, which allows the user to manipulate the CG object by grabbing, moving, and deforming it, as well as drawing lines and observing the object from multiple viewpoints. However, the projected content is only shown on the display in front of the user's eyes, limiting the range of projection and movement of the user.

OptiSpace [88] is an environment-independent interactive 3D projection mapping system. It projects 3D images to the user's viewpoint by tracking the user's point of view with a depth camera and simulating a virtual projection scene. It is possible to project images onto a wide area of a room by using two depth sensors and three projectors. In addition, the system transforms the projected images according to the tilt of desks, chairs, and walls, and takes into account the visibility and illumination of the desks and walls. Furthermore, by clustering the user's viewpoint position, the visibility of the projected content is improved. However, the system only projects in one direction and does not support projection to the entire room. In addition, usability evaluation of the projected contents and the system has not been conducted.

Hrvoje et al. developed the Mano a Mano system that allows two users facing each other to simultaneously view a single CG object by projecting a single virtual object in different ways [89]. The projected CG object can be viewed in three dimensions and can be interacted with the user's hand. The devices used are a projector and three Kinects, two of which are installed on the ceiling above the heads of both participants and the other between two devices. First, using RoomAlive [90], the system recognizes the shape of the room and the arrangement of the furniture and generates 3D objects. Next, using MirageTable [91], the user's head is tracked so that the user can view the 3D image. By combining these two systems, users can play catch with each other or throw balls at each other. However, they cannot move from where they are standing and can only interact with each other to a limited extent. The Mano a Mano system is complex because it requires three PCs to manage the three devices and a host PC to organize them.

Before constructing the real-time anamorphosis projection system, we constructed the RoomAlive [90] system as a part of preliminary studies. Room Alive is a system that projects automatically corrected images as virtual scenes from a projector by recognizing the floor, walls, and furniture in a room using Kinect. Any room can be transformed into an immersive AR entertainment experience (Figure 3.4). The system can be used to touch, step on, cover, and manipulate projected content, and present content that utilizes these features. The system is officially distributed as open source by Microsoft. To perform spatial alignment, a striped zebra pattern projected onto the surface is captured by Kinect. The projected surface is not necessarily flat, and the patterns may be distorted by the floor or furniture. The distortion is used to determine the shape of the projected surface and output a 3D model of the room shape in the virtual space. By projecting the output 3D model into real space, the user can view content without image distortion.

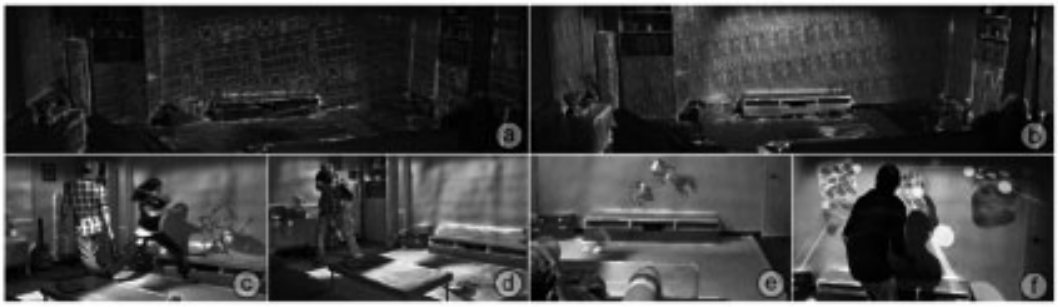


Fig. 3.4 RoomAlive: Magical Experiences Enabled by Scalable Adaptive Projector Camera Units [90].

We verified whether the Room Alive system can be utilized in this research. We recognized a corner of the room using Kinect and placed the generated 3D models in Unity (Figure 3.5). Then, the 3D models prepared as samples were placed in Unity and projected by a projector in the same room that recognized. However, RoomAlive cannot generate virtual scenes in real-time. Therefore, when projecting to a different space, it is necessary to capture the room once again and recreate the 3D model. This prevents real-time interaction with virtual objects. Therefore, this study uses a different method.

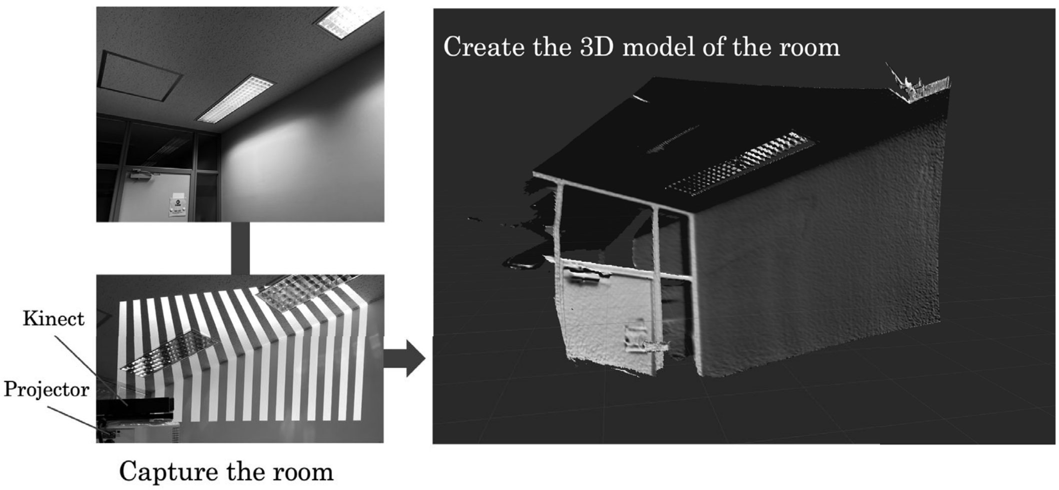


Fig. 3.5 The construction of a stereoscopic projection demo using the RoomAlive.

3.2.3 **Anamorphosis**

Researchers have been studying the projection and display of distorted images, textures, and shadows to make the projected content appear three-dimensional. Paola et al. proposed a system that can easily perform anamorphosis projection using a procedural algorithm with Grasshopper [92]. They demonstrated the usefulness of the system by allowing the user to see a normal image by looking at a distorted image from a certain viewpoint. Previous anamorphosis applications have been reproduced on simple surfaces such as flat surfaces, small cones, or cylinders. However, when applied to complex shapes, many complicated and tedious steps must be taken. During the creation of the image to be projected, it is necessary to interactively perform the steps to generate an image that conforms to the complex surface. Paola et al. achieved it using Grasshopper.

Lindlbauer et al. proposed a system to change the appearance of a real object by displaying images around it [93]. Although it is possible to change the appearance of a real object using projection mapping, it is difficult to project onto a highly reflective surface or transparent material. Therefore, by using a tabletop display to show images around a real object, the perceived information of the real object, such as size, color, and shape, can be changed regardless of the texture of the object (Figure 3.6a). In addition, the system tracks the user's head and projects an image that corrects the perspective according to the user's position as an optical illusion, thus presenting a three-dimensional effect to the user (Figure 3.6b). As an example of changing the perceptual information, by displaying a cube on the bottom of a cup, it appears as if the cup is on the cube. Also, by displaying a texture at the back of the bottle from the user's point of view, it can be expressed as if the color of the bottle's contents has changed.

Araújo introduces the construction of anamorphosis [94] and the concept of anamorphosis across several fields, including education and virtual reality [95]. Reference [94] introduces the perspective machine (Figure 3.7) which is a device used to draw pictures using perspective for the construction of planar anamorphosis. Reference [95] describes the definition of the anamorphosis perspective and the state of education on digital art and industrial design.

Our system constructs a system that projects an anamorphosis (distorted image picture) as described above and always presents a three-dimensional image to the user.

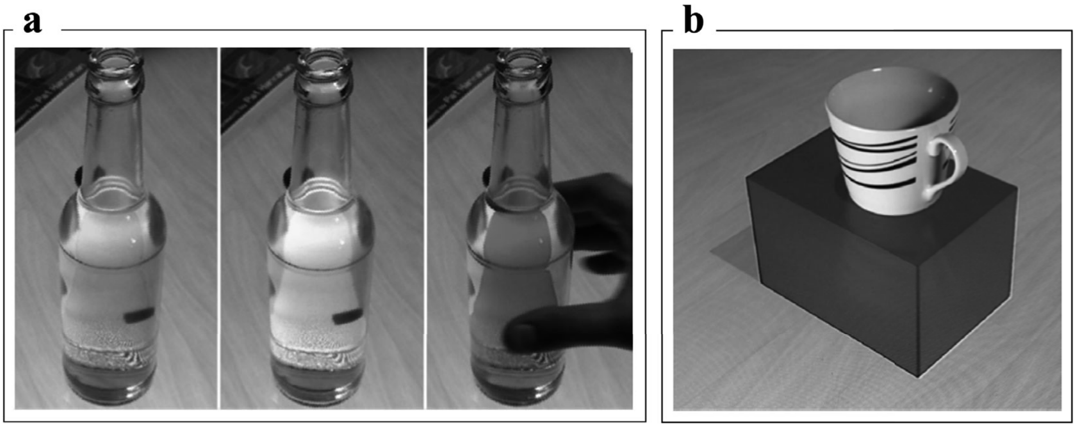


Fig. 3.6 Changing the Appearance of Real-World Objects by Modifying Their Surroundings [93]. By displaying colors on transparent bottles, the system encourages users to drink water. (a). By tracking the user's head, the system can display images as if the cup were on a box (b).

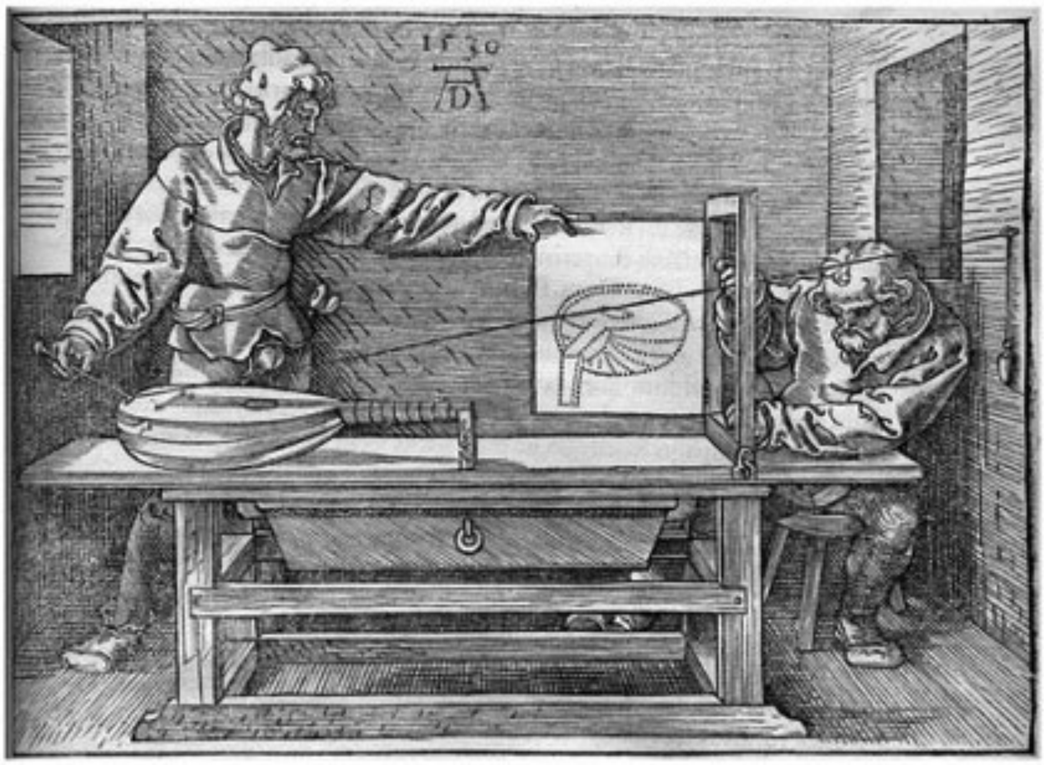


Fig. 3.7 Perspective machine by Albrecht Dürer

3.3 System Overview

We propose a system that always presents three-dimensional images to the user by attaching a tracker and a projector to the user's head. The projection surface consists of two rows of long tables, and the user can move freely around the tables. In addition, the system can display images that always appear three-dimensional from the user's perspective by projecting distorted images that are generated in response to the user's head movements. The system flow is as follows. First, align the virtual space with the real space and generate a mesh of the same size as the desk in the real space to be used as a projection surface in the virtual space. Next, the coordinates of a tracker attached to the user's head are synchronized with the coordinates of a virtual camera positioned in the virtual space, and CG objects or CG characters observed by the virtual camera are projected by a projector attached to the user's head. Finally, the user interacts with the projected content using their own hands (Figure 3.8).

To align the real space for interaction and the virtual space in which the system operates, we use HTC Vive and SteamVR. The scale of the real space and the space in Unity can be matched by reflecting the alignment data in Unity using SteamVR. In addition, a virtual desk mesh is generated in the aligned space using the coordinates of the desk in real space obtained with the Vive controller. The interaction between the CG object and the CG character uses the user's own hands which are recognized by LeapMotion. For example, the user can push or pinch a CG object with their hand, manipulate to walk a CG character by the user’s head movement, or play catch with a CG character. Using the proposed method, we aim to provide the three-dimensionality of CG objects and CG characters to the user by projecting an anamorphosis that is constantly deformed by the user's movements.

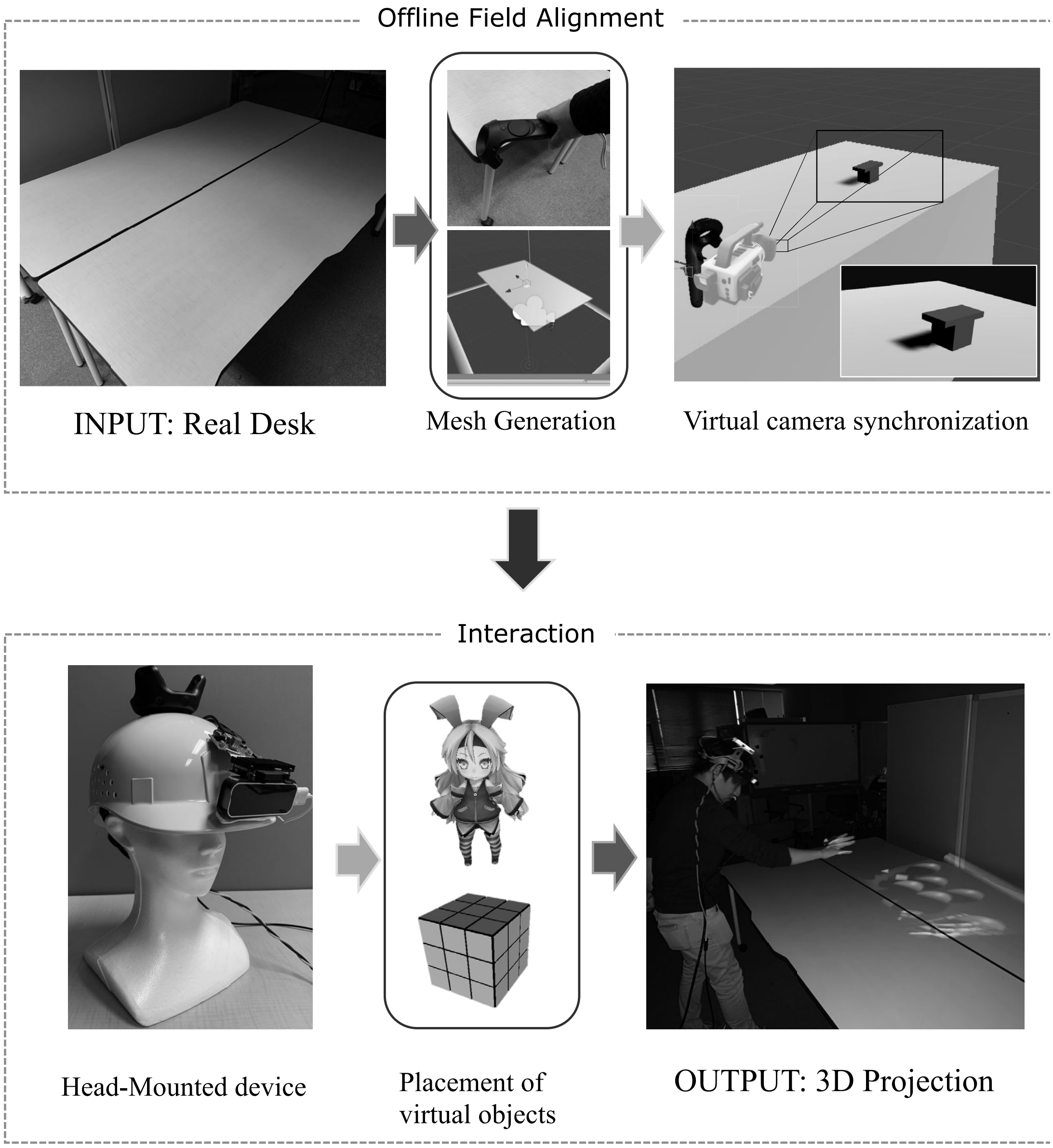


Fig. 3.8 Workflow of proposed system.

3.3.1 **Room Scaling by HTC Vive**

The real and virtual spaces can be aligned using HTC Vive and SteamVR released by HTC. As shown in Figure 3.9, an interactive area is generated by setting a blue grid of virtual walls (chaperone boundaries) that serves as a room-scale area using the Vive controller. We used a headset and a Vive controller for spatial measurement. By determining the orientation of the headset, the height of the Vive controller, and the range of alignment, the real and virtual spaces can be accurately aligned. In addition, by using the system together with Unity, it is possible to create VR content by oneself. Room scaling with HTC Vive can align the space, but it cannot capture the real space. It is also not possible to align CG objects in the virtual space with objects in the real space. However, by matching the coordinate of the Vive controller with the coordinate of the object in the virtual space, it is possible to align the position of the object in the real and virtual space. In this way, real and virtual spaces and real and virtual objects can be sized and aligned by utilizing the room scaling functionality of HTC Vive. The mechanism is described in detail in section 3.4.

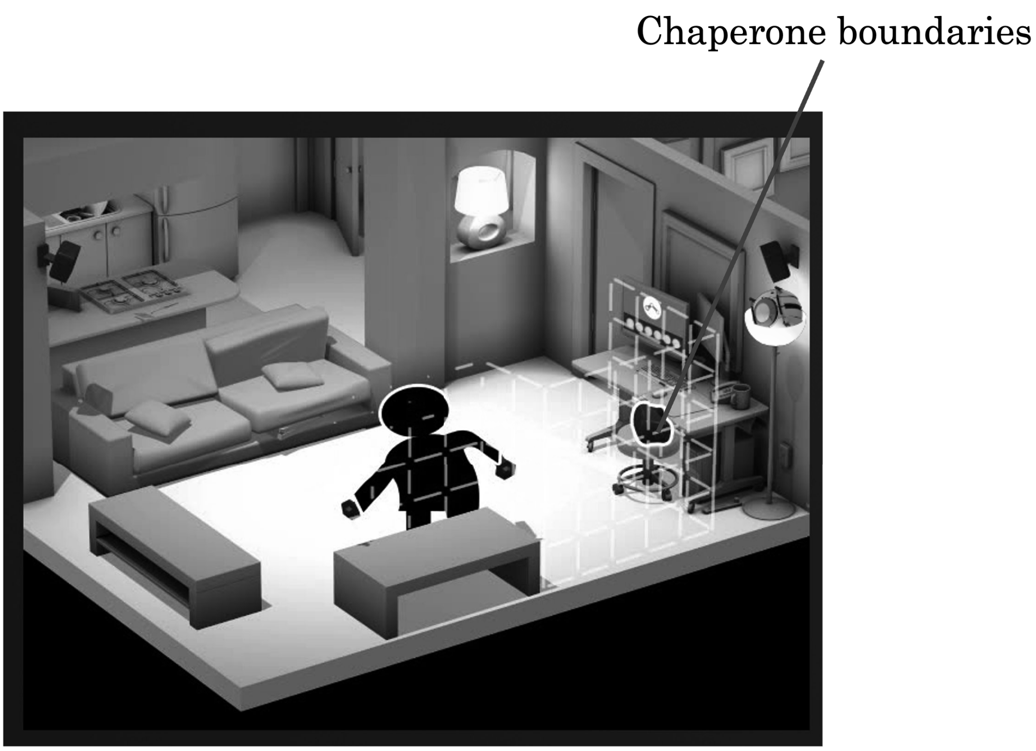


Fig. 3.9 Setting the chaperone boundaries by SteamVR.

3.3.2 **Technical Design**

In this study, we use a Vive controller and a Vive tracker. The Vive controller is used to align the virtual space with the real space and to generate a mesh that serves as a virtual desk. The Vive tracker is used by tracking the user's head. CG contents captured by the virtual camera can be projected by synchronizing the coordinates that the user's head coordinates acquired by the head-tracking tracker and virtual camera coordinates placed in Unity. In this process, the projected image is blurred due to positional fluctuations of the virtual camera caused by sensor noise and minute movements of the user. To solve this problem, we used Lerp damping to achieve smooth camera movement without blurring and improved the visibility of the projected image.

Lerp (Linear Interpolation) is a function that interpolates numerical values between two points in an approximate manner and allows smooth movement of the two points. Lerp can be expressed by

$$y = y0 + (y1 - y0)\frac{x - x0}{x1 - x1}$$

3.3.3 **Setting the Virtual Camera**

To project images that can be viewed three-dimensionally without distortion from the user's perspective, the focal length and viewing angle of the virtual camera must be set to match the user's viewing angle and focal length. We used the Physical Camera in the virtual camera settings placed in Unity, and set the sensor size to 35 mm and the focal length to 50 mm. The focal length of 50mm is the closest focal length to the human eye [96] (see Figure 3.10), and the viewing angle was set to 26.99 degrees.

Two points described in section 3.2.2 are replaced with the initial positions of the virtual camera and tracker after the move. This way, when the Vive tracker moves in the real world, the virtual camera in Unity moves along the same trajectory to follow. Then, the speed of movement of the virtual camera decreases as the distance between the virtual camera and the Vive tracker becomes shorter. In other words, the virtual camera hardly moves at all with small positional fluctuations of the head tracker due to sensor noise or minute movements of the user. Therefore, the blurring of the virtual camera is minimized and the projected image is not blurred.

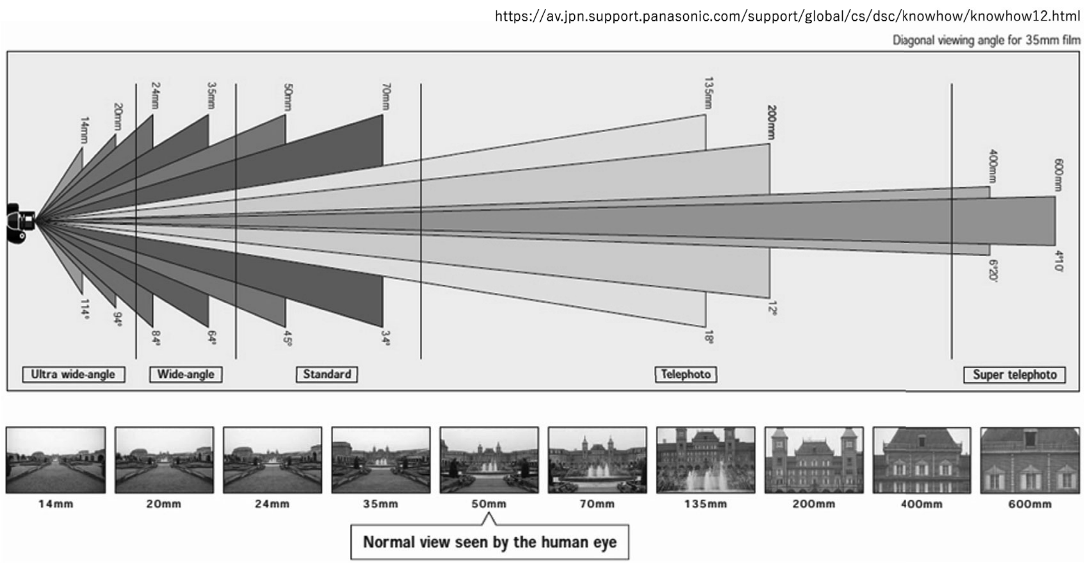


Fig. 3.10 Camera focal length and their respective visibility. The standard human focal length is 50mm.

3.4 System Implementation

For the interaction, we use LeapMotion, and the images are projected onto desks about 70.0 cm high and placed in front of the user. The projection size is about 75.0 cm (depth) and 90.0 cm (width). We used a desktop PC (Intel i7-8700 CPU 3.20GHz, 32GB RAM, GeForce GTX 1070 8GB), a laser projector (KSY Pico Projector HD301D1), LeapMotion and HTC Vive tracker, and a mobile battery to power the projector. The projector and LeapMotion are wired to a desktop PC, so the user's range of movement depends on the length of the cable used for the connection. On the other hand, the laser projector has a high resolution regardless of the projection distance. The data acquired from LeapMotion and the tracker were processed using Unity to control the contents. The system configuration is shown in Figure 3.11.

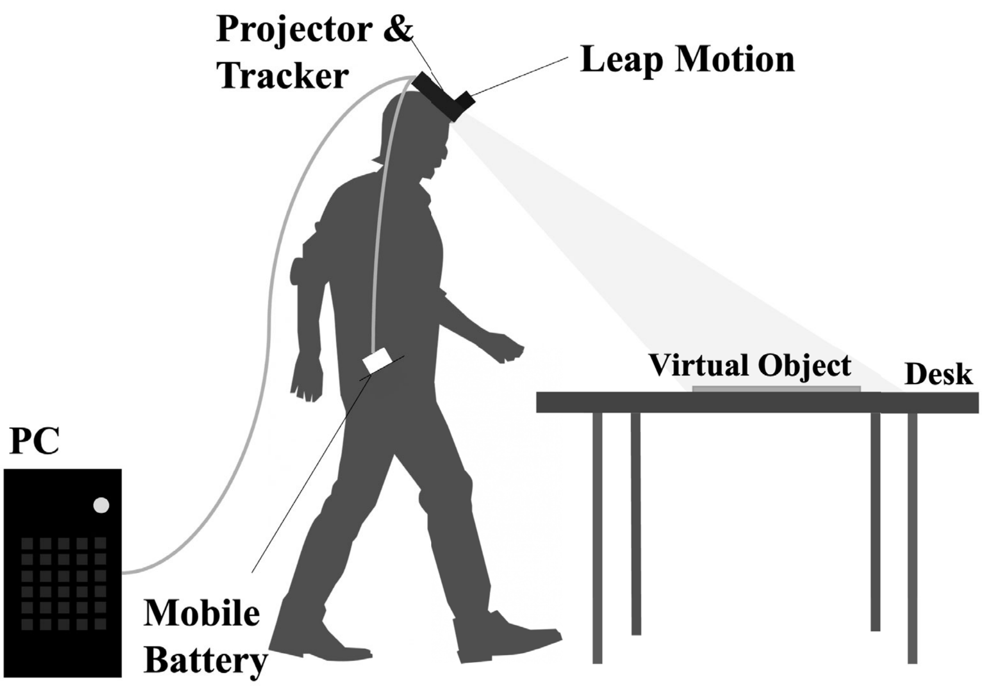


Fig. 3.11 System configuration

3.4.1 Room scaling and projection plane alignment

The available room space is approximately 3.0m x 4.0m, and a virtual field of 2.0m x 3.0m was formed within this area. To align the real and virtual spaces, we use the room scaling function of SteamVR. We set the orientation of the virtual space, the height of the base of the virtual space, and the range of the user's activity using SteamVR. This process completes the alignment of the real and virtual spaces.

To align the size and position of the desk as the projection surface and the virtual desk in the virtual space, we use a Vive controller for spatial measurement. First, place the desk as the projection surface in the room scaled real space. Next, obtain the coordinates of the four corners of the desk by holding the Vive controller over the four corners of the desk (Figure 3.12). By processing each of the four coordinates obtained as a vertex of the virtual desk, a virtual mesh with the same size and position as the desk in real space can be generated in the virtual space. In addition, add a collision detection function at the same time as the mesh is generated. Thus, the CG character no longer slips through the generated mesh and can walk around freely. To use the CG object in the interaction, we set the position of its appearance. The appearance position is automatically placed at about 30 cm toward the center from the coordinates of the second desk corner out of the four desk corners to be measured to facilitate user's interaction (Figure 3.13). By fixing and shifting the appearance position of the virtual object away from the center, the interacting user will go to that position each time the virtual object appears. This gives the user a wider view of the interaction space and it provides an opportunity to enjoy the three-dimensional effect of the projected contents more. The red cube in Figure 3.13 indicates the appearance position of the CG object. In addition, to add fun to user interaction, we elevated the appearance position of the virtual object and added the effect of the virtual object falling. The red cube is not visible to the user during actual interaction. These steps enable the placement of virtual desks and CG objects in the room-scaled virtual space at the same positions as the desks in the real space. Users can also interact with the virtual objects on the desks placed in the real space.

Fig. 3.12 Obtain coordinates of the play area using a Vive controller.

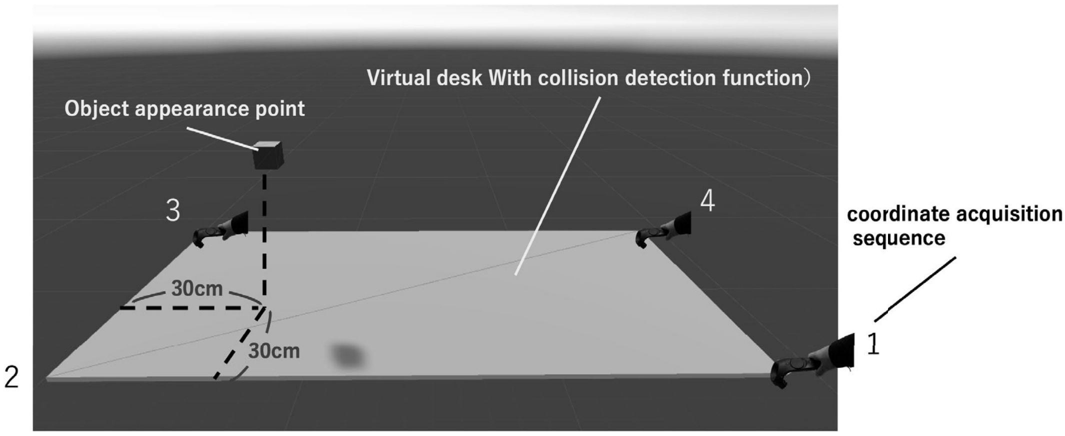


Fig. 3.13 Object appearance point, virtual desk and coordinate acquisition order.

3.4.2 **Head-Mounted Device**

We created a head-mounted device consisting of a projector and a tracker (Figure 3.14). It is attached to a work helmet and the tracker was screwed to the top of the head. We also created a holder for the LeapMotion to be attached to the head strap using a 3D printer. We disassembled the small projector and placed the disassembled projector lamp on the top of the LeapMotion attached to the helmet and installed the circuit board on the helmet. The small projector is powered by a mobile battery. The total weight of the head-mounted device is about 393 g. In this study, we used a plastic helmet weighing 172.4 g to attach some equipment. It is possible to reduce the weight of the helmet, depending on its shape and material.

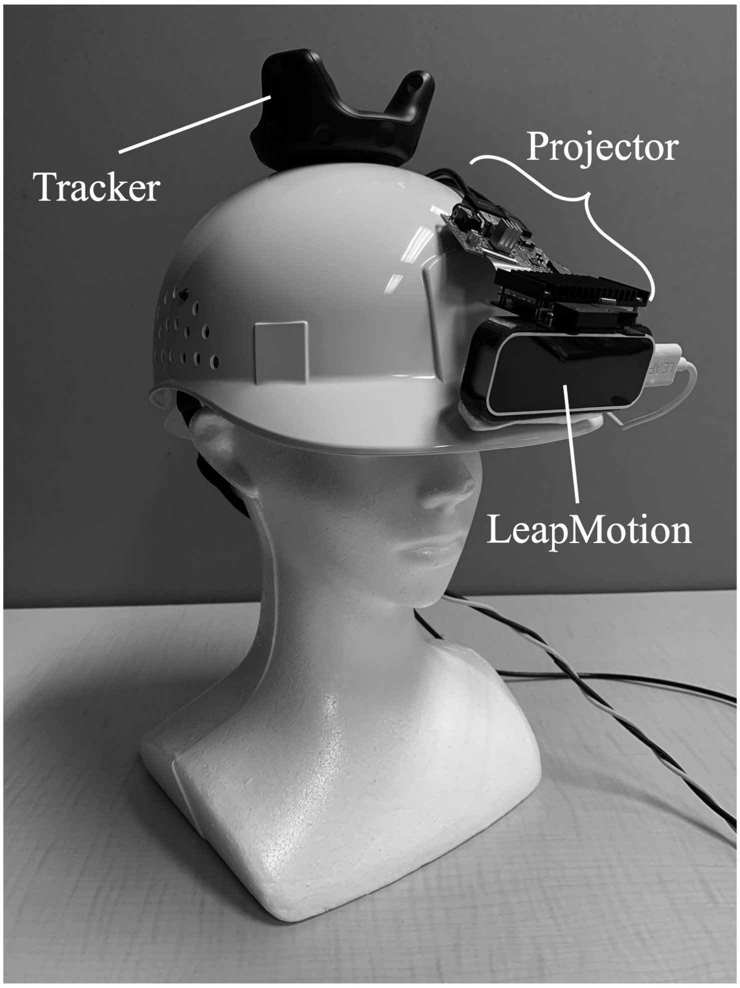


Fig. 3.14 Head-mounted device.

The tracker installed in the helmet can acquire images in the virtual space in the same direction as the user's gaze (Figure 3.15a). This is achieved by synchronizing the position and rotation information of the user's head in real-time with that of the virtual camera in Unity (Figure 3.15b).

When the user tilts the head, the tracker, and the projector above the user's head tilt at the same time. When the tracker tilts, the virtual camera synchronized with the tracker also tilts and obtains a tilted image. If this image is projected, it will be displayed at an unintended angle. However, due to the projector on the user's head also being tilted by the same amount, the projected image is not tilted. In other words, the tilt of the image is compensated for by the tilt of the projector. For example, when the projector is parallel to the floor (Figure 3.16a) and when the projector is tilted approximately 45 degrees to the right (Figure 3.16b), the projected image is not tilted.

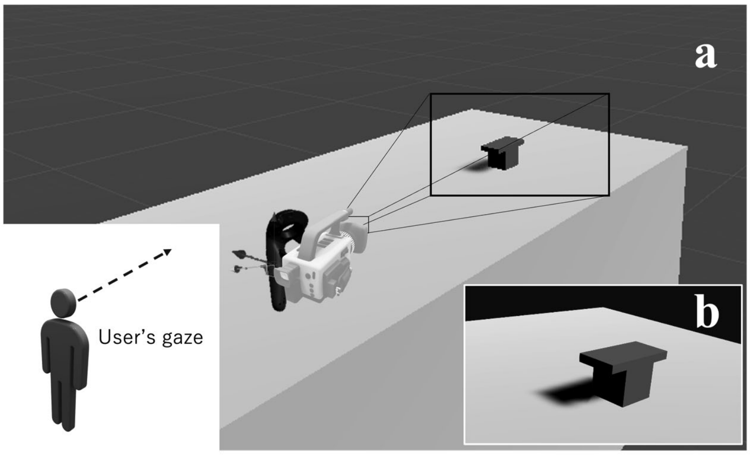
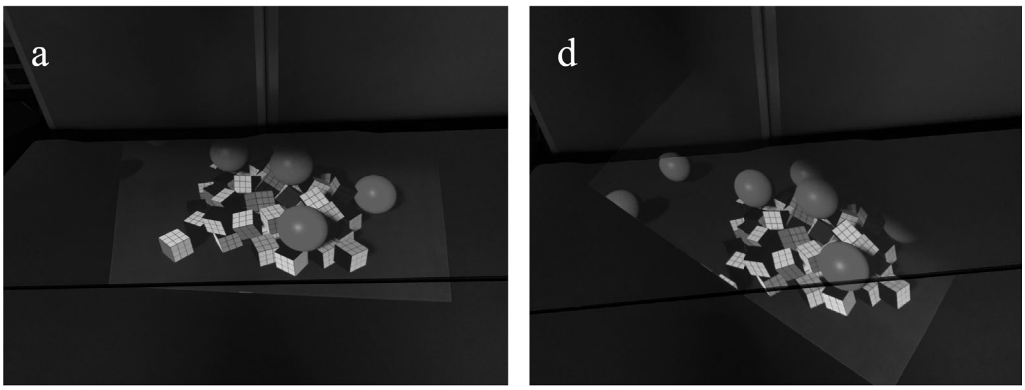


Fig. 3.15 Synchronization of virtual camera and tracker coordinates.



(a) When the projector is parallel to the floor (b). When the projector is tilted about 45 degrees to the right.

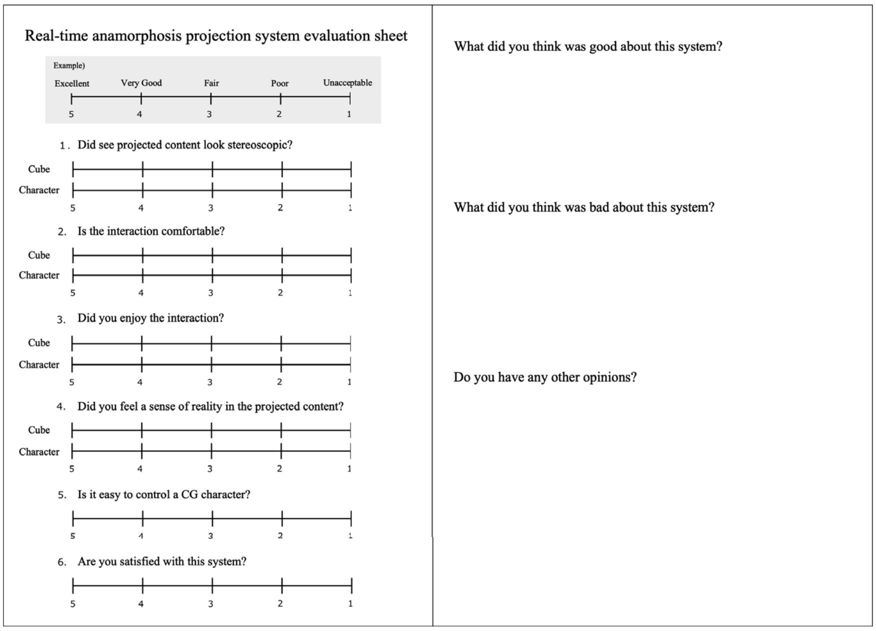
Fig. 3.16 View of the projected content when the projector is tilted.

3.5 System Evaluation

We conducted the user test to evaluate the three-dimensionality and reality of the projected contents and the usability of the system. There were seven subjects, all male, two in their 30s, and five 20s. The method of the evaluation experiment consisted of the following interactions for each subject: grabbing, pushing, and throwing CG objects, touching CG characters, manipulating CG characters, and playing catch with them. After the experiment, we conducted a questionnaire survey. Figure 3.17 shows the questionnaire form. The questionnaire was converted to PDF and saved in the "GoodNote 5" app on an iPad Pro (12.9-inch, 2017). After the experiment, the subjects answered the PDF questionnaire directly.
The questionnaire included items to evaluate the following:

- The questionnaire includes items to evaluate the three-dimensionality of the projection using the proposed system
- The comfort of interaction using the constructed device
- The enjoyment of manipulating CG objects and interacting with CG characters
- The usability of the system.

Each item is evaluated using a 5-point Likert scale. The evaluation items 1 to 4 in Figure 3.17 are for CG objects and CG characters.


Real-time anamorphosis projection system evaluation sheet

Example)
Excellent 5 — Very Good 4 — Fair 3 — Poor 2 — Unacceptable 1

1. Did see projected content look stereoscopic?
Cube 5 4 3 2 1
Character 5 4 3 2 1

2. Is the interaction comfortable?
Cube 5 4 3 2 1
Character 5 4 3 2 1

3. Did you enjoy the interaction?
Cube 5 4 3 2 1
Character 5 4 3 2 1

4. Did you feel a sense of reality in the projected content?
Cube 5 4 3 2 1
Character 5 4 3 2 1

5. Is it easy to control a CG character?
5 4 3 2 1

6. Are you satisfied with this system?
5 4 3 2 1

What did you think was good about this system?

What did you think was bad about this system?

Do you have any other opinions?

Fig. 3.17 The questionnaire

In addition, we included three free comment fields to obtain feedback on items other than the five-level evaluation items. The items are the following:

・What did you think was good about this system?
・What did you think was bad about this system?
・Do you have any other opinions?

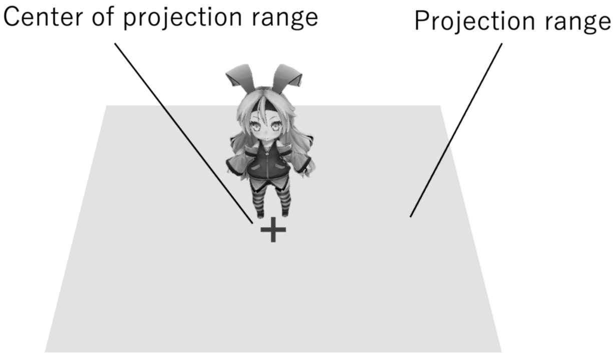
3.5.1 Experiment procedure

The CG objects were a 5-cm cube and a 12-cm-diameter red sphere. In the interaction with the CG object, the subject performs pushing, pulling, and grasping actions on two virtual objects with their own hands and observes them. In the interaction with the CG character, the subject throws a virtual ball toward the projection surface, and the CG character is asked to chase the ball and throw it back. The following is a description of the interaction procedure with the CG object. First, after completing the generation of the virtual desk, the experimenter presses the "L key" on the keyboard and places a CG object at a pre-defined point. Next, the subject wears a head-mounted device and has LeapMotion recognize their own hands. To enable the user to play catch with the CG character at any time, the user can appear a sphere object by pinching the index finger and thumb of the left hand. It is also possible to make a red sphere appear by pressing the "R key," and a cube can be made to appear by pressing the "B key". Finally, users can use their right hand to touch, grab, and throw the projected CG object. Users can use both hands for interaction, and the left hand has a function to make the red sphere of the CG object appear.

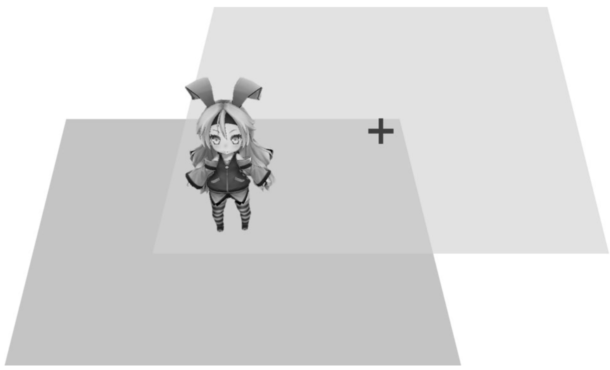
As a procedure for interacting with the CG character, after interacting with the CG object, press the "I key" to make the CG character "Unity-chan" appear. Next, referring to previous research [97], the user manipulates the CG character with head movements. The procedure for manipulating a CG character is as follows:

・Set the initial position of the CG character at the center of the projection range (Figure 3.18a).
・Synchronize the CG character's position with the real-world position. The CG character will then continue to appear in the same position in the real world even if the projector is moved.
・If the CG character moves beyond a certain distance from the center of the projection range (Figure 3.18b), the CG character moves toward the center of the projection range (Figure 3.18c).

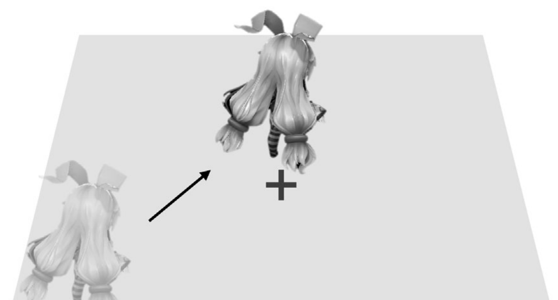
The CG character to be projected is a two-headed character of approximately 30 cm in height, considering the projection range of the projector and visibility. The interaction between the CG object and the CG character is shown in Figure 3.19.



(a) Initial position of the CG character.



(b) Movement of the projection area.



(c) Gaze and move to the center area of the CG character.

Fig. 3.18 How to move the CG character.

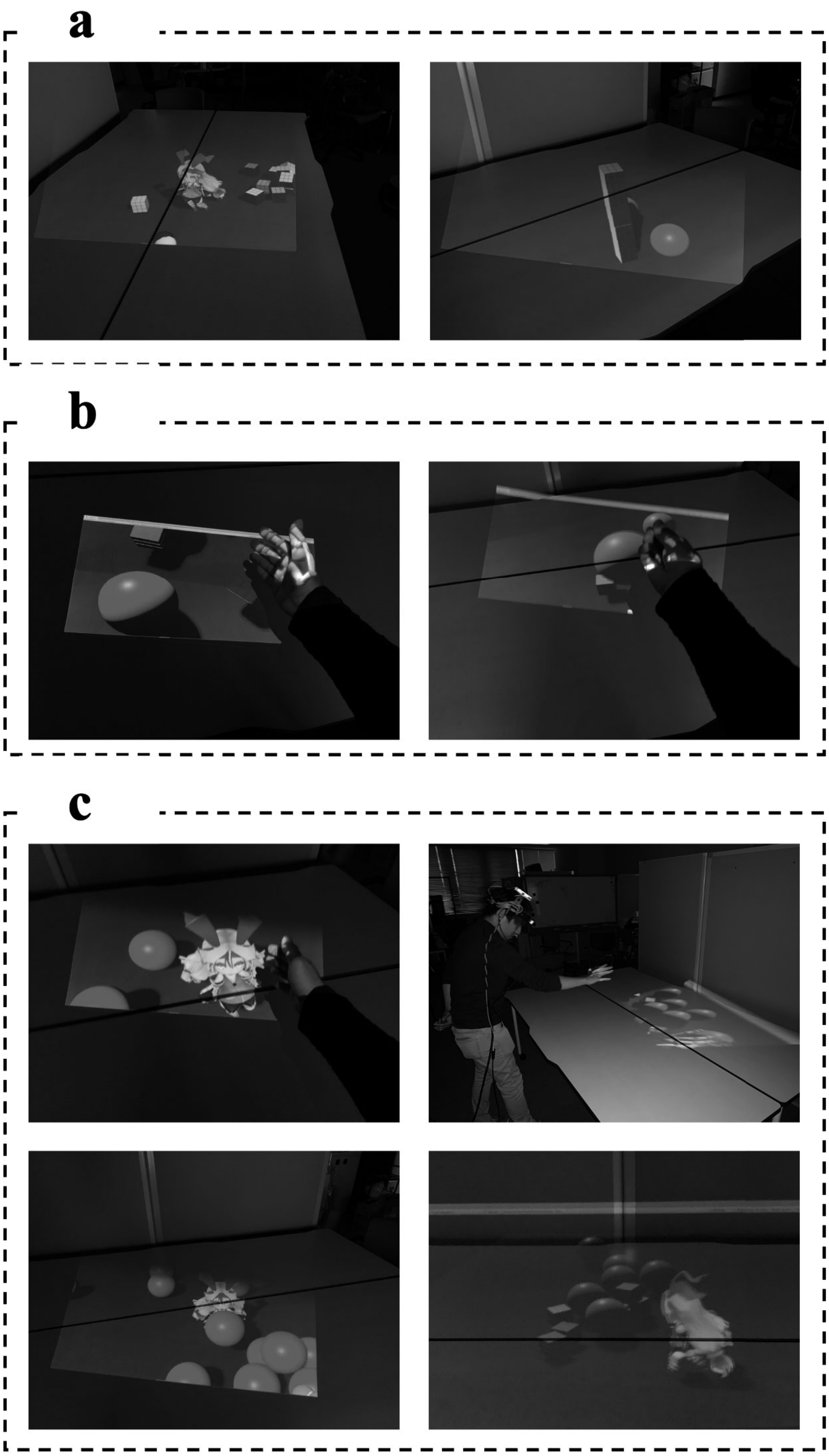


Fig. 3.19 The interaction of the CG object and the CG character. The user enjoys three-dimensional images (a), touches CG objects (b), and plays catch with CG characters (c).

3.5.2 **Selection of Survey Items**

We selected the items in the questionnaire to evaluate the subjective evaluation of the interaction with the content.

- Item 1, "Did see projected content look stereoscopic?" asked whether the distorted images were deformed in real-time and whether the images always looked three-dimensional from any angle.
- Item 2, "Is the interaction comfortable?" asks whether the subject was able to interact with the content without discomfort, and whether the interaction using the designed head-mounted device was smooth.
- Item 3, "Did you enjoy the interaction?" asked about the enjoyment of directly touching and manipulating the projected content, as well as interacting with characters that do not exist as entities.
- Item 4, "Did you feel a sense of reality in the projected content?" asked whether the user had a sense that the CG object or CG character was present in the scene through interaction with the content, rather than merely seeing the image in three dimensions.
- Item 5, "Is it easy to control a CG character?" asked about the operability of the CG characters that move according to the head movements.
- The last item, "Are you satisfied with this system?" is an overall evaluation of the ease of use and understanding of the system, and whether the interaction was enjoyable.

We used a five-point Likert scale for the answers. For example, for item 6, "Are you satisfied with this system?" the answer choices are "Excellent," "Very Good," "Fair," "Poor," and "Unacceptable.

3.5.3 **Result**

Figure 3.20 shows the results of the questionnaire evaluation. Items 1 through 6 in the figure correspond to the evaluation items described in section 3.5.2. In addition, Table 3.1 shows the average evaluation values for each item of the CG contents. In the table3.1, O_{ave} represents the average evaluation of virtual objects and C_{ave} represents the average evaluation of CG characters. I_{ave} is the average value of the item evaluations calculated for each content.

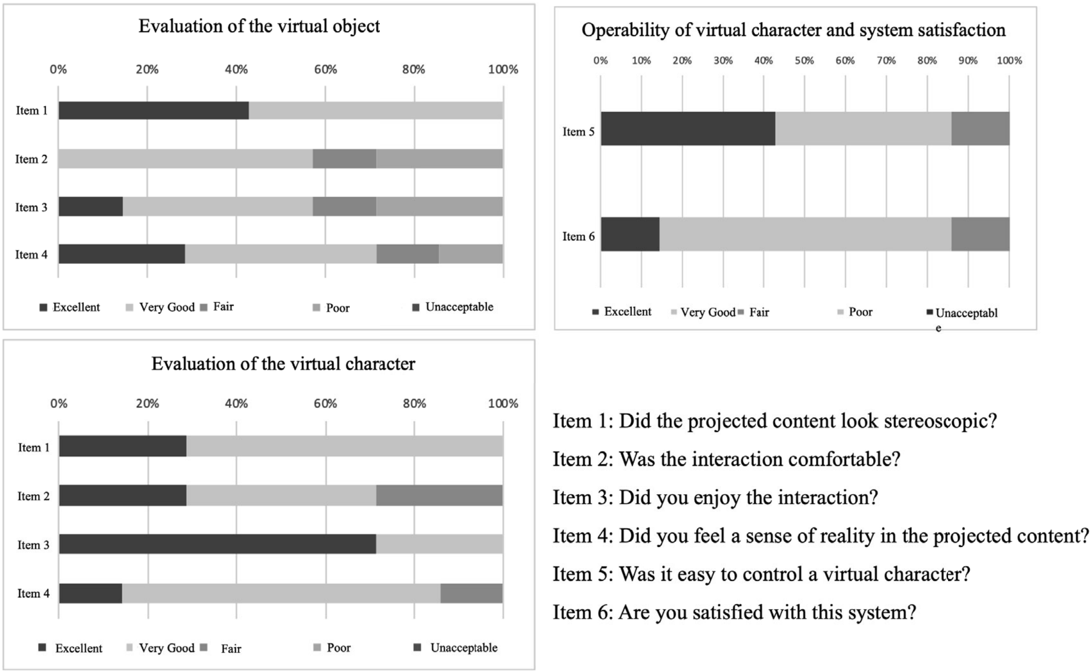


Fig. 3.20 Evaluation results of the proposed system and evaluation items in the questionnaire.

Table 3.1 Average ratings for CG objects and CG characters.

Items	1	2	3	4	I_{ave}
O_{ave}	4.34	3.29	3.43	3.86	3.73
C_{ave}	4.29	4.00	4.71	4.00	4.25

Evaluation of virtual object For item 1, "Did see projected content look stereoscopic?" three subjects answered "Excellent" and four subjects answered "Very Good," that is, all the subjects answered, "It looked three-dimensional". This is considered to be because the anamorphosis was accurately deformed by the head movement and presented as motion parallax to the subjects.

Regarding item 2, "Is the interaction comfortable?" four subjects answered, "Very Good", one subject answered "Fair", and two subjects answered "Poor", indicating that they were comfortable with the interaction with the projected content. Positive responses were due to the ease with which the system can be operated with a small number of movements, as well as familiarity with the LeapMotion operation. Negative responses could be due to unfamiliarity with LeapMotion operations or malfunctions caused by system malfunctions.

For item 3, "Did you enjoy the interaction?", one subject answered "Excellent", three subjects answered, "Very Good", one subject answered "Fair", and two subjects answered "Poor". Positive responses were probably because they were able to interact as they expected. From the result of item 1, it can be inferred that the subjects felt as if they were interacting with an object that existed in the interaction area. Negative responses were presumably because the subjects could not grasp the objects well due to a lack of distance, or because they could not touch the objects.

Regarding item 4, "Did you feel a sense of reality in the projected content?" two subjects answered "Excellent", three subjects answered, "Very Good", one subject answered "Fair", and one subject answered "Poor". Positive responses indicate that the interaction between the subject and the virtual content contributes to a more realistic impression, in addition to the three-dimensional appearance of the projected content. Negative responses indicate that the projection area was too narrow because the subject was too close to the projection surface, so the displayed content was interrupted or LeapMotion malfunctioned.

Evaluation of virtual character Regarding item 1, "Did see projected content look stereoscopic?", two subjects answered "Excellent, and five subjects answered "Very Good", that is, all subjects answered, "It looked stereoscopic". This is thought to be because the subject was able to accurately deform the anamorphosis due to head movement and present it as motion parallax, as was the case with the CG object evaluation.

Regarding item 2, "Is the interaction comfortable?", two subjects answered "Excellent", three subjects answered "Very Good", and two subjects answered "Fair. This is considered to be due to the ease of manipulating the CG character by head movements and the ease of catching the ball thrown by the CG character because it came toward the subject in a straight line rather than a parabolic line.

Regarding item 3, "Did you enjoy the interaction?", five subjects answered "Excellent", and two subjects answered "Very Good", in other words, all subjects answered, " I enjoyed the interaction".

Regarding item 4, "Did you feel as if the projected content was real?", one subject answered "Excellent", five subjects answered "Very Good", and one subject answered "Fair". As with the evaluation of the CG object, subjects were able to interact as they wished, and subjects felt as if they were interacting with an object that existed on the spot, as indicated by the high evaluation of items 1 and 3. In addition, it is assumed that the projected content appears three-dimensional and the interaction between the subject and the content contributes to the enhancement of the sense of reality.

In the comfort, enjoyment, and reality evaluation items, the subjects evaluated the CG objects negatively, but positively for the CG characters. This may be because the dynamic CG characters moving around and playing catch gave subjects a lively impression and made them feel as if the CG characters were alive.

Satisfaction with CG character operability and system Regarding item 5, " Is it easy to control a CG character?" three subjects answered "Excellent", three subjects answered "Very Good", and one subject answered "Fair". This system is simple in that the character moves in the direction in which the subject's head is turned. In addition, the speed of the CG character's movement is varied according to the distance from the center of the projection range, so that the subject does not lose sight of the CG character even if the subject suddenly changes the projection direction. These are thought to be the reasons for the high evaluation.

Regarding item 6, " Are you satisfied with this system", one subject answered "Excellent", five subjects answered "Very Good", and one subject answered "Fair". This result is due to the high evaluation of the three-dimensionality, comfort, enjoyment, and realism as described above.

3.5.4 Summary of survey

From the evaluation results, we confirmed that the three-dimensional feeling of the projected content, the enjoyment of interaction, and usability were highly evaluated. For Item 1, all subjects answered that the projected content had a three-dimensional feeling in the evaluation of both CG objects and CG characters. In addition, subjects felt highly evaluated the comfort and enjoyment of the interaction and the realism of the projected contents of the CG characters. The usability of the CG characters and the satisfaction with this system were also highly evaluated. It was confirmed that the usability of this illusion projection system is high for subjects.

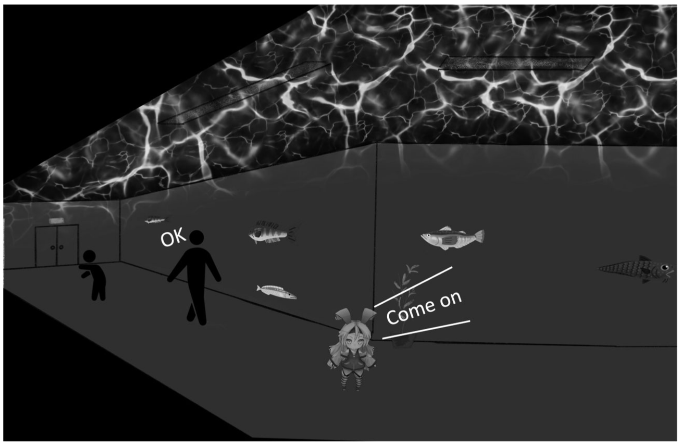
On the other hand, some subjects gave low ratings to the comfort, enjoyment, and realism of the interaction with the CG objects. When the subjects tried to grasp the CG object, they did not understand the distance and had difficulty in grasping the CG object. This may be related to the low evaluation of comfort and enjoyment. In addition, there were low-rated responses for the item of reality despite the high evaluation of the three-dimensionality. This suggests that three-dimensionality does not always contribute to the sense of reality. This may be because the human eye is binocular, making it difficult to recognize the distance and size of CG objects from images projected on a flat surface. However, the only item that received a low score for reality was static CG objects, and there were no low scores for the CG character reality item. This suggests that the CG character moving around the user contributes to the improvement of the sense of reality. To improve the sense of reality, it is necessary to set materials that reflect the shading of CG objects and the illumination and color tones of the real space.

Subjects were able to grasp the dynamic CG objects thrown by the CG characters without failure more often than the static CG objects. Subjects may have been able to understand the distance to the CG object because of the dynamic nature of the interaction. This may have contributed to the enjoyment of the interaction with the CG characters.

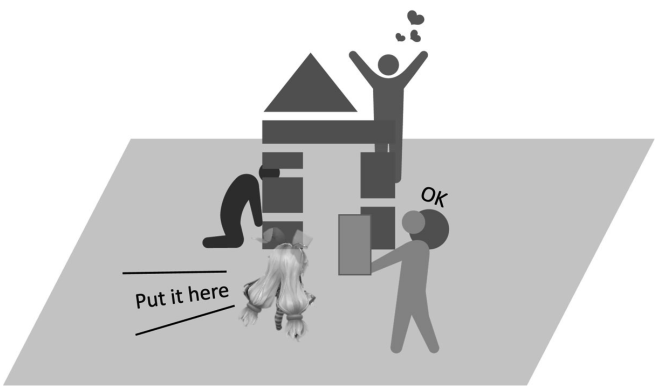
Table 3.1 also shows that users rated interaction with CG characters higher than interaction with CG objects. This suggests that dynamic content can provide users with the enjoyment of interaction and improve their sense of immersion and satisfaction.

3.5.5 Application

Proposed method can expect to provide new entertainment such as a guide in a museum (Figure 3.21a) or a creative activity (Figure 3.21b). In addition, applying this system to location-based AR games such as Pokémon™ GO can provide the sensation of actually playing an adventure with a character, and can enhance the entertainment value of the game. The system can also be used for educational purposes, for example, by projecting images on educational toys or interactive educational materials, thereby increasing interest and promoting understanding. In addition, from Matsumoto et al.'s [98] research using doll-type toys and Yonezawa and Ueda's [99] research on a loneliness-relieving robot, it is possible to apply this technology to the field of therapy, such as relieving loneliness and stress and healing, by projecting virtual characters or animals and interacting with them.



(a) Guides at the museum



(b) Creation support

Fig. 3.21 Examples of proposed method.

3.6 Summary and Discussion

We developed a real-time anamorphosis projection system that aims to harmonize real space and CG characters. We synchronize a virtual camera placed in a virtual space with a CG object that reflects the position of a tracker in real space. Then, the images reflected by the virtual camera are projected from a projector in real space to realize real-time stereoscopic projection. In addition, we used Lerp damping to solve the blurring of the projected image caused by sensor noise and positional fluctuations of the tracker due to minute user movements. Furthermore, we realized the alignment of the position and size of the real desk used as the projection surface and the virtual desk placed in the virtual space using a Vive controller for spatial measurement. In the user study, we asked seven subjects to experiment and conducted a questionnaire survey using a five-point scale. The evaluation results showed that many subjects gave a high evaluation of the system. We were able to confirm the usability of the system, the fun of interaction, and the three-dimensionality of the projected contents. In addition, we found that the subjects loved the CG characters by petting them and saying they were "cute" during the interaction with them. This suggests that the projected content and interactions are relaxing to the user. These results confirm the usefulness of interaction with CG objects and CG characters using a simple real-time anamorphosis projection system. It is also suggested that dynamic CG characters are effective in relieving users' stress and loneliness.

This study focuses on the clarification of the finished image of the production object as an important element for cooperative creation in production activities. By staging virtual content as distorted images that are transformed in real-time, the system aims to enhance the sense of realism of the virtual content. In other words, we attempted to facilitate insight by increasing the sense of reality. Thus, the proposed method is a staging method for insight. We confirmed that catching a ball with a virtual character and grasping a virtual object are realized through natural interaction. This allows creators to observe virtual content as if they were holding a real object in their hands. The prior observation of the production target and the understanding of the finished image will facilitate smooth collaborative creation. In addition, the sharing of information, ideas and interpretations obtained through observation fosters the creativity of creators. In this way, the proposed method adds the seasoning of presence to the production process. This seasoning leads to the clarification of the finished image. Clarification of the finished image contributes to collaborative creation in production activities.

3.6.1 **Limitations**

The system has three limitations. The first limitation is the projection range of the projector. The projected image expands as the projector gets further away from the projection surface and shrinks as the user gets closer (Figure 3.22). If the projector attached to the user's head and the projection surface are far apart, the projected area becomes wider and the image display area becomes larger. However, when the projector and the projection surface are closer, the projected area becomes narrower, and the image display area becomes smaller. If the display area is small, visibility becomes poor, and it affects the satisfaction of user's experience. This limitation can be solved by using a fisheye lens at the projector's projection port. The fisheye lens distorts the projected image to expand the projected area. Although this distortion causes image corruption, by modeling the distortion and performing inverse correction, the corruption of the enlarged projected image can be corrected.

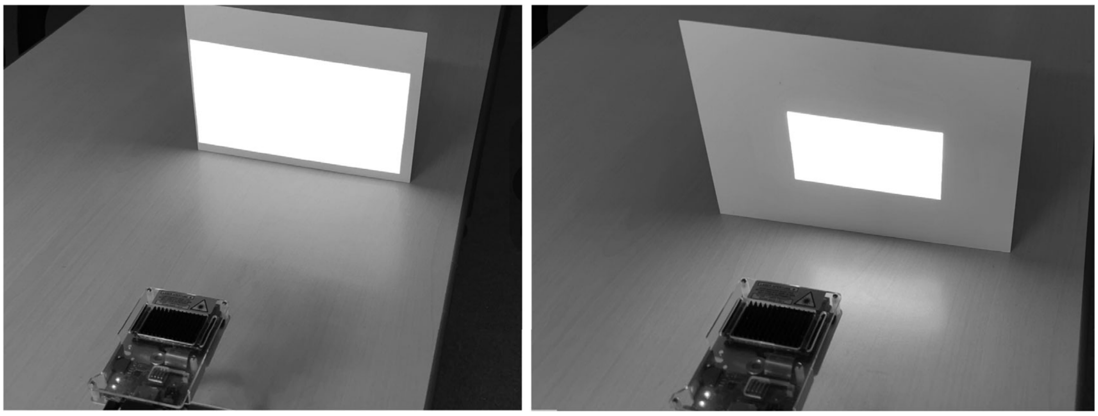


Fig. 3.22 Projection range changes according to the projection distance. If the projection distance is about 30 cm (Left), the projected size is about 24 cm (width) and 12.5 cm (height). When the projection distance is about 15 cm (Right), the projection size is reduced to about 12 cm (width) and 7 cm (height).

The second limitation is that projection and movement can only take place within a defined space. In this system, users can freely move and interact within the 2.0m x 3.0m area created by room scaling. However, the range of interaction is limited that images cannot be projected outside of the configured virtual space, and the head-mounted device and PC are wired together. To solve this limitation, a method that captures the space in real-time performs 3D reconstruction, and generates a spatial mesh can be considered, and a wireless connection between the PC and the system can be considered. This can be done by referring to methods such as CNN-SLAM [100]. However, there are concerns about the high processing load and delay of the wireless transmission of video.

The third limitation is that the projection size changes depending on the distance to the projection surface. For example, when projecting on surfaces with different depths, the projected image closer to the projector becomes smaller, and farther from the projector becomes larger (Figure 3.23).

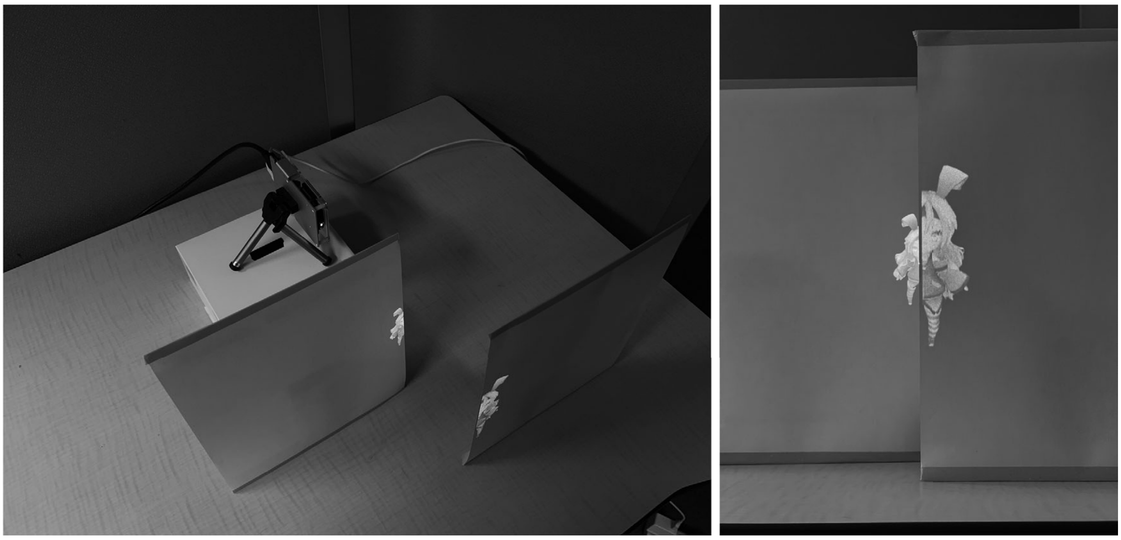


Fig. 3.23 When projecting images onto surfaces of different depths (Left), the sizes of each projection are different (Right).

3.6.2 Future Works

We confirmed the usefulness of the proposed system from user studies and evaluations. However, there are some issues in operability, realism, and user study. To increase user satisfaction, it is necessary to further improve the proposed method.

Improved Operability The system developed in this study uses the recognized hands to perform operations. Therefore, users who were not familiar with LeapMotion took some time to have LeapMotion recognize their hands. This may be related to the user's familiarity with the operation and the speed of understanding the device, as discussed in section 3.5.3. We believe that the system and the head-mounted device need to be improved and the usability of the system needs to be enhanced. For example, it is necessary to have a mechanism in which a CG object appears by touching a virtual button projected on a part of the body, as in LumiWatch [101], instead of by pinching a finger of the left hand to make a CG object appear. By projecting virtual buttons onto a part of the body, the user is no longer pinching. This improvement makes user operation more reliable and prevents user error from degrading the quality of the experience.

Improved Presence This study aims to achieve a natural harmony between real space and CG characters and to present a sense of reality to the user. To present a sense of reality, we use only visual information, such as the projection of a deforming distorted image. However, we believe that auditory information, such as the sound of CG characters' footsteps and the sound of a catch ball, can be used to further improve the realism of CG characters. In addition, the sound of events outside the projected area, such as the sound of falling CG objects, can also be played back to enhance the immersive experience.

More Detailed User Study The questions in this study were divided into broad categories and did not collect objective data such as the duration of the experiment or the number of successful catches. By subdividing the questions into smaller items and providing more specific questions, it is possible to obtain a more accurate evaluation of the comfort and satisfaction of the system from the users. In addition, it is possible to consider whether the three-dimensional and realistic senses are being presented to the user by collecting objective data.

Chapter 4
Layered Projection Mapping for Large-Scale Digital Fabrication of Balloon Art

In this chapter, we propose a production support system that uses a projector and a depth sensor to maintain a constant projection size, even if the projection distance changes. In addition, this thesis aims to create opportunities for co-creation to improve the sense of unity among users. Therefore, we focus on large-scale creation as an opportunity for users to cooperate with each other in creative activities. As an example of this system, we created an six-foot tall artwork. The proposed method consists of three steps. First, the system divides the 3D model into meshes using an approximate pyramid decomposition method (Figure 4.1a). Next, we further divide the divided parts into equally spaced layers and conduct calibration with real space for each layer (Figure 4.1b). Finally, we project the depth difference between the creation space and the divided creation part as a number (Figure 4.1c).

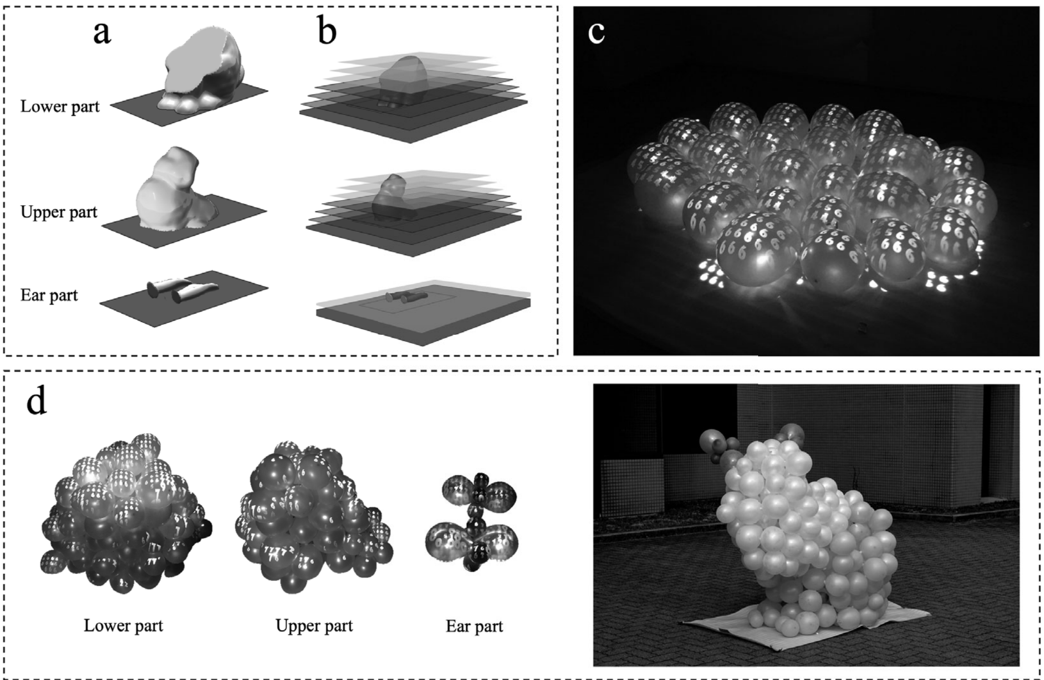


Fig. 4.1 Creation support system for larger-scale creation.

Previous works have used color gradients for the projection of the layers. This study used black-and-white numbers as the projected image, considering the texture and shape of the balloon. In addition, we applied a video effect to the projected numbers to increase the fun of the projection. Users were able to create large-scale balloon art using various colors and sizes of balloons in an enjoyable and cooperative (Figure 4.1d). In the next section, we describe the background and purpose of this research and the structure of this chapter.

4.1 Background

The appearance of inexpensive, sophisticated modeling tools and the low cost of 3D printers have made it easier for people to experience digital fabrication. There are also digital fabrication workshops, such as LITALICO Wonder [102]. These factors have made digital fabrication more accessible (Figure 4.2). Recently, studies on various digital fabrication technologies have been thriving in the fields of computer graphics and human–computer interaction. For example, Chengkai et al. proposes a modeling technique using a multi-axis bot arm [103] (Figure 4.3), a system that allows users to freely design shapes with beads [104] (Figure 4.4), and a glider design support system based on aerodynamic pre-calculations [105]. However, all of these studies are intended for small-scale digital fabrication.

https://wonder.litalico.jp/news/column2107-5/

Fig. 4.2 Example of digital fabrication **[102]**.

Fig. 4.3 Support-Free Volume Printing by Multi-Axis Motion **[103]**

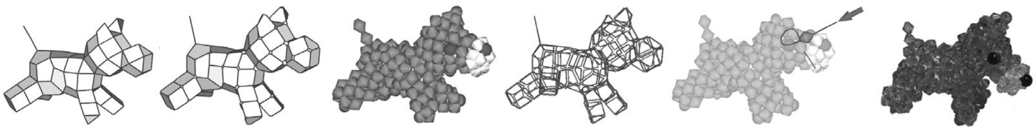


Fig. 4.4 Beady: Interactive Beadwork Design and Construction **[104]**

A case study of large-scale fabrication involved the use of a 3D printer to construct a house [106]. By utilizing specially formulated cement, the material was built up layer by layer, similar to a standard 3D printer. While this technique allows houses to be constructed at a lower cost than usual, it is not accessible to the public. There are also instances of stacked-type large-scale art production using familiar materials. As part of a public project, a large-scale tower was created by stacking plastic bottles [107]. The tower was illuminated with light projections to create a Christmas display. Takahashi et al. [108] proposed a support system for large-scale can art production that considers color schemes and the stability of placement based on physical laws. There are several examples of large-scale creative projects, but it is difficult to fully grasp the entire scope of large-scale works. In addition, due to the use of many components, it is necessary to thoroughly consider production procedures that take the physical properties of these materials into account. These factors make large-scale creation difficult. In this study, we focused on information projection technology that can share information with many people at once to support large-scale creation. Information projection presents interaction procedures for large-scale creation to users. Projection mapping technology is used in a variety of fields, such as art, games, education, and support, and is widely used throughout the world. However, these systems have fixed projectors and projection targets, and projection distance and angle are predetermined in most cases. In other words, a shift in the position of either the projector or the target can cause a breakdown in the image. To solve this problem, Miyashita et al. proposed a dynamic projection mapping system in which the projected image follows the movement of the projection target [78]. Our research aims to develop a support system for digital fabrication using projection mapping technology. To support digital fabrication using projection mapping, it is necessary to use a projector–camera system. These systems require the calibration of both the camera and the projector. In addition, they often use a depth camera to infer 3D information about an object. Previous works calibrated the system only once before modeling [109, 110]. However, when the object is large, the infrared illumination range of the depth camera and the projection range of the projector shrink as projection distance decreases. Therefore, there is a difference between the scale of the object model and the range of the depth map. This means that it is not possible to produce the object at the appropriate size. To solve this problem, Yoshida et al. proposed a system for creating large pavilions using a projector–camera system [111]. However, physical markers were needed for the calibration of the workspace.

4.1.1 Purpose of this research

We propose a layered projection mapping technique that projects images at appropriate sizes based on height (Figure 4.5). In addition, we created balloon art as a demonstration experiment. By using layered projection mapping, it is possible to provide users with a production procedure. In addition, the size of the projected image is not dependent on projection distance. The objective of this research is to propose a method that allows multiple users to easily create artwork that reaches the height of a person using a variety of materials. The proposed method presents a procedure for creating a 3D model by acquiring a depth map of the workspace and the 3D model to be created (Figure 4.5(a)) using a depth sensor. First, we divided the 3D model into multiple parts (Figure 4.5(b)) and then further divided these parts into multiple layers (Figure 4.5(c)). Next, we generated a depth map of the parts divided into multiple layers (Figure 4.5(d)) and calibrated each layer to project the layer image at an appropriate size in each layer. In addition, we project white numbers with animation to prevent from being affected by the texture and shape of the projected object (Figure 4.5(e)). The user arranges the balloons according to the projected numbers and assembles the parts (Figure 4.5(f)). By combining them, the balloon art is completed (Figure 4.5(g)). Anyone can easily use the proposed method for entertainment on a large scale. In addition, we expect to improve cooperation through collaborative work and reduce stress among users. In this study, we demonstrate the usefulness of the proposed method by creating large-scale balloon art. Balloon art is a popular form of entertainment for both children and adults, and it is inexpensive and safe for everyone. However, the creation of large-scale balloon art requires creators to imagine the final design. In addition, users must decide on complex placement procedures. Thus, support for large-scale balloon art production is essential.

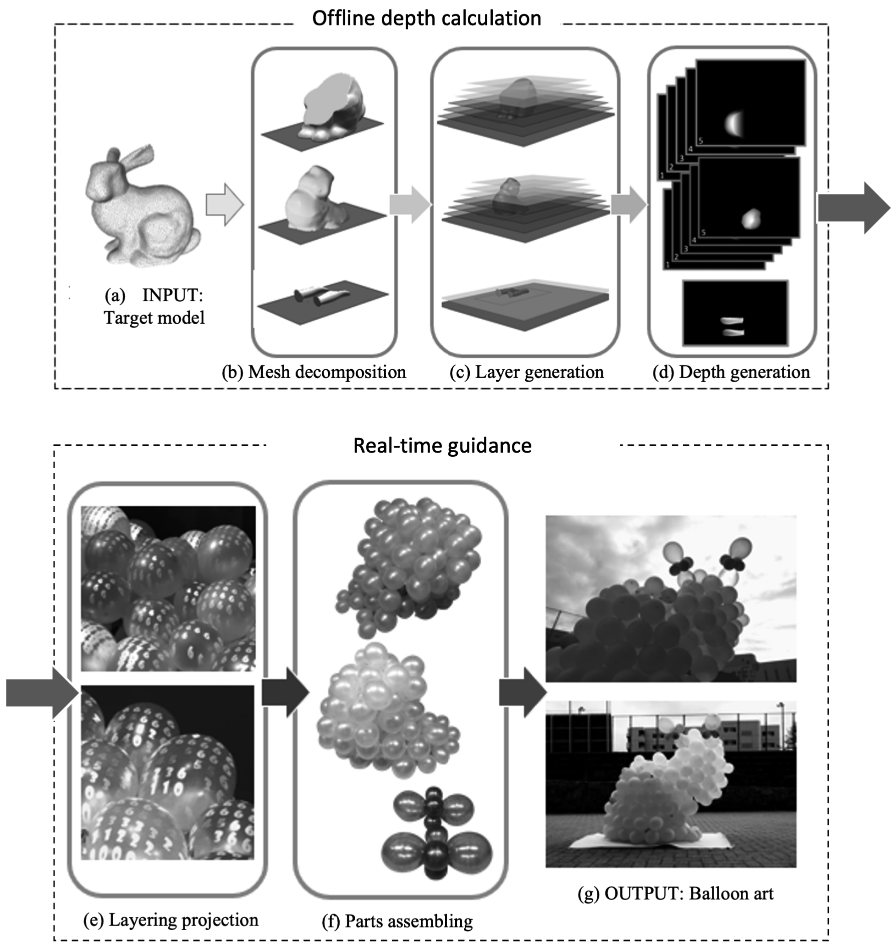


Fig. 4.5 Framework of the proposed system.

4.1.2 Organization of this research

This chapter consists of six sections, and the structure and contents of each section are described below.

In Section 4.1, we describe the background and objectives of the study. In Section 4.2, we introduce related works on projection mapping and digital fabrication and clarify the position of this study. Section 4.3 presents the proposed method as an overview of the system. Section 4.4 presents the implementation of the system, and Section 4.5 evaluates the use of the system in experiments. Section 4.6 summarizes this research, its limitations, and future issues.

4.2 Related Works

This section introduces research on interactions using projection mapping and digital fabrication. As mentioned in Section 4.1, projection mapping supports human actions. There are also studies that support people's creative activities.

4.2.1 Interaction With Projection Mapping

There are two types of projection mapping: static projection mapping, in which the projector and projection target are fixed, and dynamic projection mapping, in which the image follows the movement of the projection target. For interactive assistance, dynamic projection mapping is preferred because the content and extent of the projection change in response to human actions. PapARt [112] uses projection mapping to assist users in drawing (Figure 4.6). By projecting a 3D scene on paper, users can benefit from simplified and faster drawing while drawing directly on the paper. Users can also interact with the displayed content by tapping directly on the paper or by moving the paper. This system facilitates artistic and creative activities. Joshi et al. proposed a system that changes the projected content based on the user's object of interest and behavior [113]. By attaching a depth sensor and a projector to the user's chair, the system constructs a portable SAR system without any burden on the user. The system can also project onto objects such as floors, walls, plants, and shelves. Users can use this system for work activities, such as setting reminders and holding online meetings, and relaxation, such as doing mindfulness exercises and watching movies. Jens et al. developed KirigamiTable [114] (Figure4.7), a deformable tabletop display using a projector. Users can choose whether to show the table as a whole or individually by bending the central part of the table. By using two types of bends, it is possible to have variations such as individual and team viewing of contents and changes in the number of people viewing the contents. The developed system combines the deformation of the table shape with digital content and proposes a new interaction method that includes shape-first and content-first interactions, cooperative gestures, and physical and digital previews of the shape changes. Sano et al. developed a ball game augmentation system to bridge the gap between the levels of ball game players [47]. The system focused on soccer as an example of a ball game and visualizes the trajectory and velocity of the ball with a projector. The proposed system used 22 motion capture cameras and four projectors in a large immersive virtual environment 7.7 m high, 25 m wide, and 15 m long. The motion tracking of the ball and the user was achieved using an infrared reflective material. Dynamic projection mapping can also significantly contribute to assisting users in large environments.

Fig. 4.6 PapARt: Interactive 3D graphics and multi-touch augmented paper for artistic creation **[112]**.

Fig. 4.7 KirigamiTable: Designing for Proxemic Transitions with a Shape-Changing Tabletop **[114]**. The table performs the following transformations - four-fold (A), flat-fold (B) and two-fold (C)

4.2.2 **Digital Fabrication**

Recently, it has become easy to create three-dimensional models and toys. Among these, there are studies to develop design systems that are easier for users to use and to pursue new methods of digital fabrication. Prevost et al. proposed a system that can output well-balanced 3D models by reconfiguring the center of gravity of these models [115] (Figure 4.8). Using this system, it is possible to easily create 3D models that are full of dynamism and have proper balance. Rivers et al. proposed a system that projects color gradations onto a sculpture object to enable anyone to easily create beautiful sculptures [109]. However, the calibration of the workspace, sculpture object, and projected image is performed only once and is not applicable to large-scale sculptures. In addition, color gradations projected onto colorful materials, such as balloons, would be less visible because of the mixing of colors. Others include RoMA [116] and toy production [117]. However, they assume small-scale production.

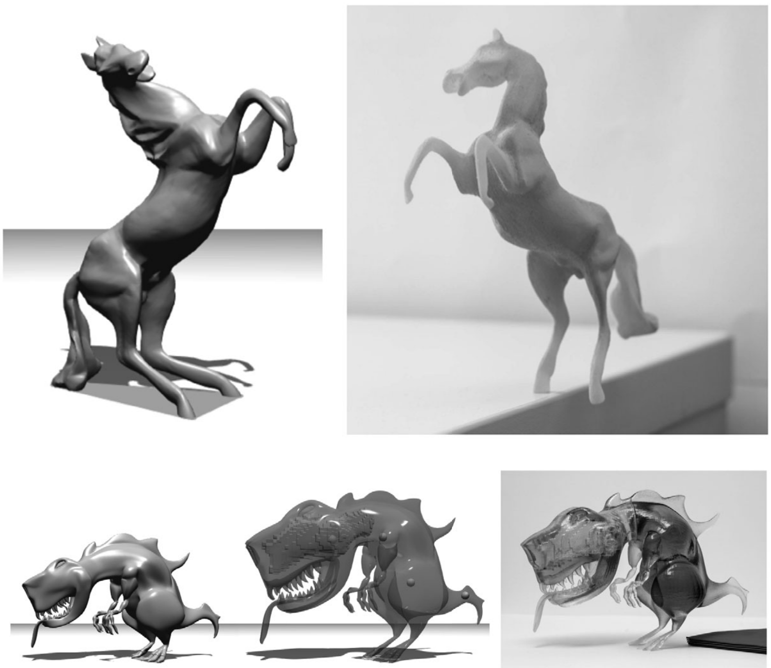


Fig. 4.8 Make It Stand: Balancing Shapes for 3D Fabrication **[115]**.

There are examples of large-scale digital fabrication, such as the creation of large-scale balloon art [118]. However, there have been insufficient investigations or discussions about layered calibration and depth calculation. Yoshida et al. proposed a 3D stacking technique for architecture by projecting the depth information of segmented 3D models and working with handheld tools [111]. However, as described in Section 4.1, calibration needs a physical marker. In addition, the position and size of the projected image and the object vary as the height of the object increases. Therefore, it is necessary to divide the target shape and move the base of the object. Other examples include Crowdsourced Fabrication [19], which utilizes smartwatches, and Trussformer [119], which creates robotic arms by connecting plastic bottles. Lau et al. proposed a system [120] that generates the necessary connectors and components to construct physical objects, such as furniture, from input 3D models. The system analyzes the 3D models and generates assembly instructions for building actual objects. In addition, Swaminathan et al. [121] proposed a room-scale fabrication technique using pneumatic structures. They designed interactive and deployable structures, manufacturing portable tables, and domes as applications. Another approach that enables large-scale creation involves printing methods utilizing ground-moving robots [122] and drones [123]. Furthermore, a different approach uses a handheld 3D printing system [124]. Utilizing a handheld plastic extruder, wireframe models were constructed in physical space with a sketch-like sensation. Our proposed method projects the object placement procedure in real space as an interactive visual image. Therefore, the user does not need to think about the complicated placement procedure of balloons. Users can efficiently create a balloon in a cooperative manner by following the projected guide.

4.3 System Overview

As described in Section 4.2, previous studies have examined interaction and digital fabrication using projection mapping. However, these systems have the limitation that the projection size changes with the projection direction of the projector. Therefore, it is difficult to use projection mapping for large-scale fabrication. In this study, we propose a system to support large-scale balloon art production using layered projection mapping. The framework of the proposed system is a process involving 1) the division of the 3D model and generation of a depth map and 2) interactive projection mapping in the real space during the work. In the previous step, we established a virtual space that matches the real space and divided the 3D model into several parts. The divided parts were further divided into multiple layers to generate a depth map. In the later step, we adopted a method of projecting information on the production procedure in real space using AR. In other words, information on the production procedure was generated using the difference between the depth information of the production object and the 3D model in the virtual space. By using the proposed system, it is possible to create three-dimensional objects. In addition, we added the interactive visual expression function to encourage users to accurately place materials.

4.3.1 System Setting

We used a laser projector (LG HF80JG, 2000 lumen) and a depth sensor (Microsoft Kinect V2, 512 × 424 resolution) to construct the working environment. To match the scale of the room in which the experiment was conducted, we set the projector at a height of approximately 2.5 m above the floor and positioned the depth sensor adjacent to the projector. We inflated balloons using a dual-nozzle electric air pump (AGPtek). Then, we attached the balloons to each other using Velcro tape. Figure 4.9 shows the system configuration. In addition, the size of the work area was determined by the height constraints of the experimental room. Therefore, depending on the size of the experimental room, we can set up a larger work area.

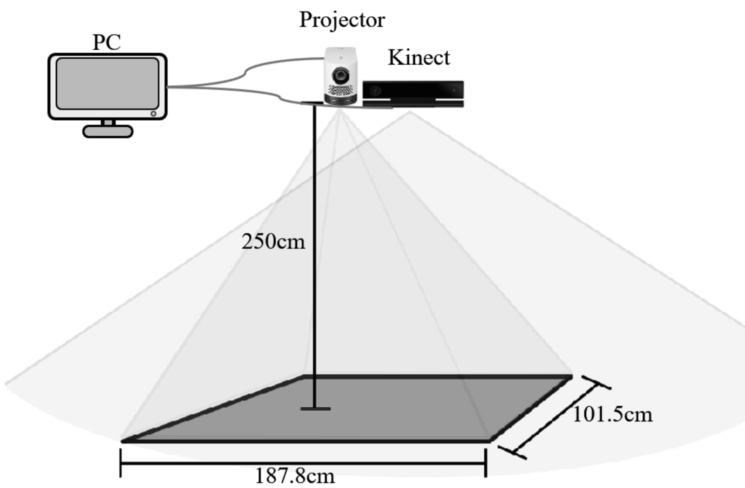


Fig. 4.9 Experiment environment.

4.3.2 Layer Calibration

The projection range of the projector and the infrared radiation range of the depth sensor expand as the equipment moves away from the projection surface. Therefore, the projected image and the acquired depth map become smaller as the working position increases. To maintain consistent sizes, we divided the depth map of the 3D model into six layers and calibrated it for each layer. The spacing between each layer was set to 15.0 cm to match the maximum height of the divided parts (approximately 90.0 cm). Calibration consists of three steps. First, we constructed a virtual workspace in the system. Next, we determined the ratio between the projected image area and the infrared irradiation area. We calculated the ratio of the area and position of the projected image area and the infrared irradiation area by dividing the infrared irradiation range of the depth sensor by the area of the projected image with the resolution of the depth sensor (512 × 424 pixel). By applying the calculated ratio to the projected images at each layer, it maintained a consistent projected image area, even when the infrared irradiation area became smaller. Finally, we calibrated the projection size of each layer. We set up a virtual rectangular object and projected its appearance into real space (Figure 4.10). In the real space, we adjusted the size of the whiteboard with a 50 cm square drawn on it and the cross-section of the installed rectangular object to match in each layer. In addition, we calibrated the position of the projected image by aligning the upper and left edges of the projected image area with the upper and left edges of the infrared illumination area of the depth sensor.

4.3.3 The Need for Layer Calibration

When constructing a virtual workspace, we set a virtual depth sensor and the projection range of the projector in the system just as we placed them in real space. However, the projection direction, angle, and range of each device installed in the real space were not identical. Additionally, the virtual depth sensor and projector set up in the computer did not match. To match the projection direction, angle, and range of each device in virtual space and real space, it was necessary to devise a new algorithm. In addition, we constructed an environment in which the workspace in the computer and the real space always matched by calculating the depth in real time. However, it was impossible to accurately recognize the real space due to the limitations of the resolution of the depth sensor and noise. Therefore, layer calibration was necessary. By establishing layers at regular intervals and aligning them one layer at a time, we were able to match the workspace in the computer with that in real space.

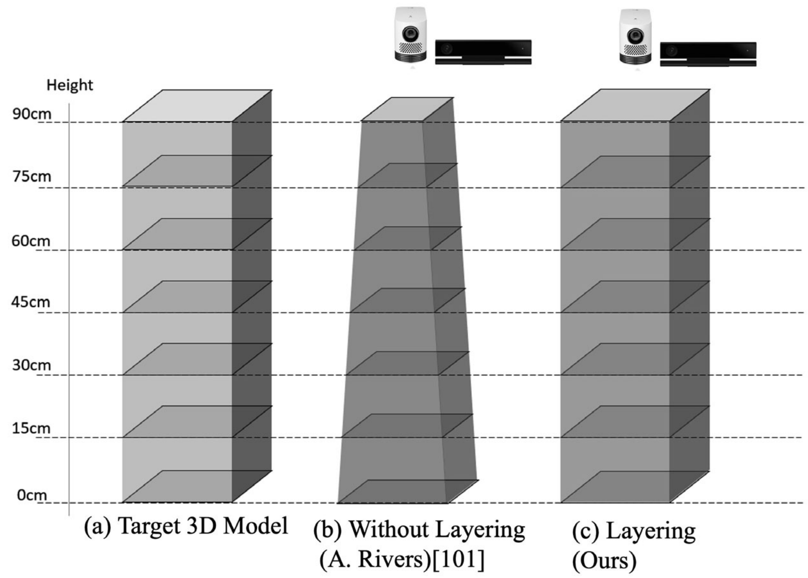


Fig. 4.10 The comparison of target 3D model. The model on the left shows a 50cm square target 3D model (a), and the shapes in the center and on the right represent the projected shapes of a target 3D model using existing methods and the proposed method. When projecting a target model using existing methods, the projected model becomes smaller as the height of the model increases (b). With our method, the size of the projected target model remains constant (c).

4.3.4 **Depth Calculation**

We placed the 3D model in the area in which the projected image and the depth sensor overlap in the computer to calculate the depth map. In addition, we used the ray–triangle intersection algorithm [125] to match the infrared irradiation range of the depth sensor with the virtual workspace in the computer. Figure 4.11 shows the calculation results. The vertical black lines indicate rays, and the red dots indicate intersections with the target mesh. In this method, we used 512 × 424 rays corresponding to the resolution of the depth map. The calculation of the 3D model was performed on a desktop PC (Intel i7-4790 CPU 3.60 GHz, 32 GB RAM) using MATLAB in parallel and took about 35 seconds.

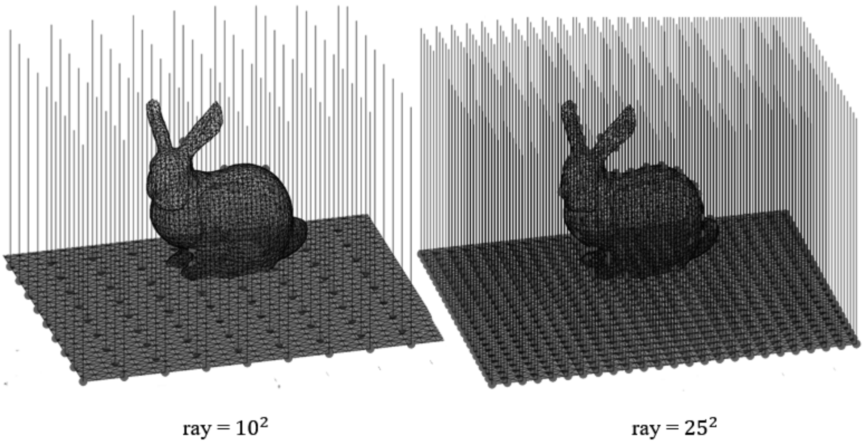


Fig. 4.11 Ray-tracing approach for depth map calculation

4.3.5 **Mesh Division**

In the process of completing the parts according to the projected production procedure, we adopted a process similar to the lamination method [111] of 3D printing technology. The actual workspace was a pyramid-shaped space within the projection range. In this study, we adopted the approximate pyramid decomposition method [126] to divide the 3D model (Stanford Bunny) into four parts: upper body, lower body, left ear, and right ear (Figure 4.12). The algorithm does not guarantee optimal pyramid decomposition for all shapes. In particular, it may not be able to achieve optimal decomposition for complex shapes or those with many holes. For example, as shown in Figure 4.13, there is a possibility that the decomposition will be far from optimal. Therefore, it may be necessary to manually pre-decompose the creation part when creating more complex shapes in the future. However, the 3D model used in this method was not complex; thus, it could be decomposed appropriately. In addition, the proposal of this method solved the issues of limited projection range and the generation of shadows due to the protruding parts of the components.

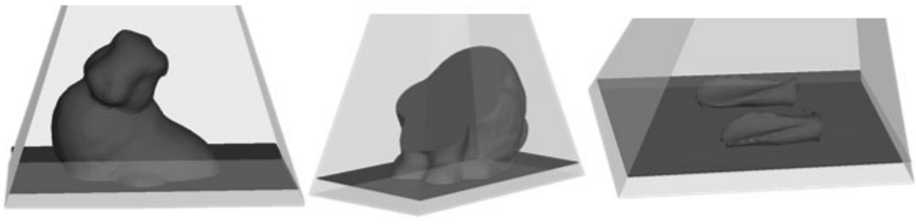


Fig. 4.12 Four decomposed models from the target model

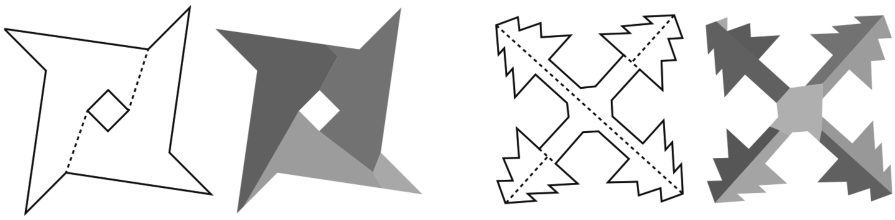


Fig. 4.13 Example of decomposition of a 3D model using existing method **[126]**. When decomposing a complex-shaped 3D model, the resulting decomposition (in color) may be far from the optimal decomposition (uncolored).

4.3.6 Depth Difference Calculation

First, we obtained the depth difference of the workspace with nothing on it to eliminate the effects of uneven floor surfaces (Figure 4.14(a)). Next, by subtracting this depth map from the depth difference obtained in real time, we obtained a corrected depth difference (Figure 4.14 (b)). In addition, the depth difference between the corrected depth difference during production and the generated 3D model was calculated (Figure 4.14(c)) and projected in the form of numbers (Figure 4.14(d), partially enlarged). The two-color bars on the left side of Figure 6 show the depth difference between the unevenness of the workspace and the depth difference between the generated 3D model and the floor surface.

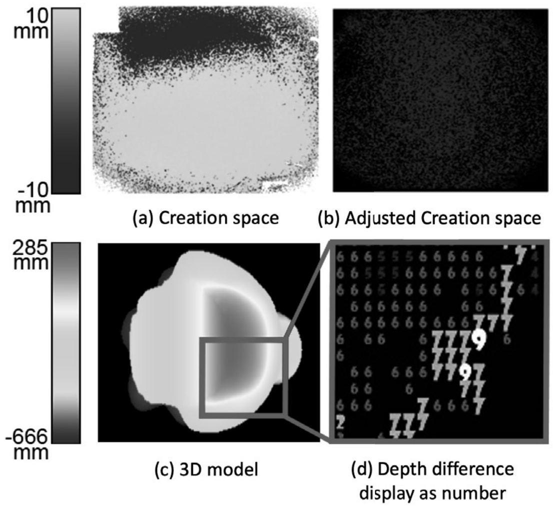


Fig. 4.14 Calculation results of depth differences

4.3.7 Projection of Numbers by Depth Difference

To verify the effective visualization of depth differences, we conducted a projection test of color gradients and numbers (Figure 4.15(a)). We performed edge detection using the Canny method to confirm the visibility of color gradients and numbers.

We confirmed that the visibility of monochrome numbers was better than that of the color gradients used in existing studies. It was also confirmed that the color gradient and the numbers were not affected by the color of the balloon when they were projected onto the balloon. Edge detection in the color gradient projection detected the rounded shape of the balloon. On the other hand, edge detection in the projection of numbers detected only the shape of the numbers. That is, it was possible to see only the pure numbers. For this reason, we decided to project monochrome numbers. For details of the specific evaluation, refer to Section 4.4.2. This method uses numbers arranged in a grid to indicate the difference in depth of the projected object and to project the range of the object's placement. The system projects a number from 0 to 9, depending on the height of the placement (Figure 4.14(d)). The projected number range is 0 to 5 if the object height is lower than the target height, 6 if appropriate, and 7 to 9 if the height is higher. This method produces parts by stacking materials from the bottom, and the height of the placed material is the tallest height in every stacking. Therefore, it is possible to place the next materials at a lower height than the target height but never to place materials higher than the height of the placed materials. To accommodate this, we set a broad range of lower numerical values. The projected number changed in real time according to the depth difference. The user can check the placement range and height of the objects by referring to this guide information. Then, the user could manually increase or decrease the number of objects or change their size. If the user placed an object in a position that was far outside the installation area, the system played an animation of the numbers shaking. This is because users intuitively understand large deviations. By shaking the three numbers 0, 1, and 9 (Figure 4.15 (b)), which are far from the appropriate number 6, we tried to motivate the user to place the object in the correct position.

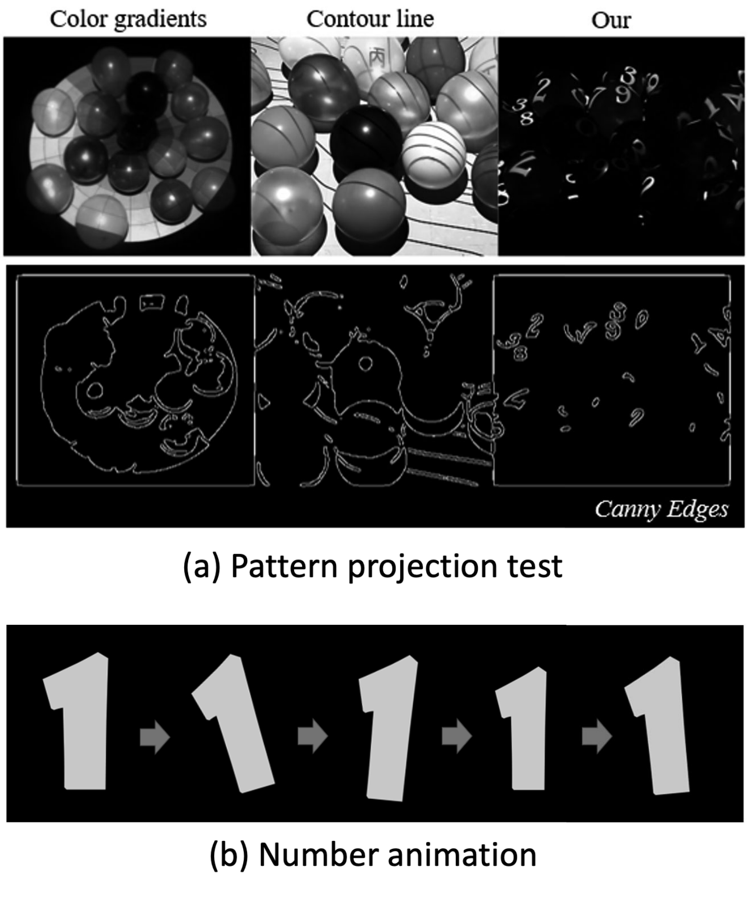


Fig. 4.15 Projection of numbers based on depth difference.

4.4 System Utilization and Experimental Result

To confirm the effectiveness of the proposed system, we compared it with existing research. In addition, we created balloon art as an example of the application of the proposed system.

4.4.1 Balloon Art Production Procedure

In this study, we conducted balloon art production [118] as an example of large-scale fabrication support. The production target was the "stand-up bunny," and the target height was set to 150 cm in consideration of the projection range limitation and ease of work.

Figure 4.16 shows the process of creating balloon art. First, the user selects a balloon of their favorite color and inflates it using an air pump. Next, the user places the balloons according to the projected numbers on the workspace and fixes them with Velcro tape. After the first layer of balloons is placed, the user removes them from the workspace and creates the parts for the next layer. This process was repeated as many times as necessary. Velcro tape was used to fix the completed parts to each other.

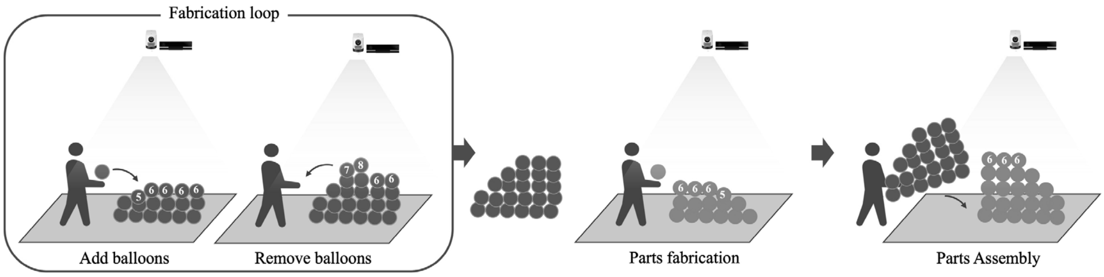


Fig. 4.16 Fabrication process in balloon art.

4.4.2 Comparison of Systems with Previous Studies

To confirm the usefulness of the proposed method, we used three methods to create a hemisphere consisting of three layers using balloons (Figure 4.17). Due to the limitations of the projection area, we aimed to create a hemisphere with a maximum radius of 40 cm. On the other hand, the diameter of the balloon was set to 15 cm. Therefore, the created hemisphere is a pseudo hemisphere with a 40-cm radius circle at its base with a height of 45 cm. The first method involved using color gradations without dividing the three-dimensional model [109]. The second method involved a three-dimensional model divided into three layers and color gradients. In this method, the divided 3D model is projected onto each layer. The height of each layer was set to 15 cm. The third method employed the same method as the proposed method in this study. Here, the 3D model was divided into three layers, and white numbers were projected onto the workspace. As shown in Table 4.1, we recorded the number of balloons used, the length of Velcro tape used, and the working time. The balloon was made of elastic material; thus, the shape of the balloon changed to some extent.

Fig. 4.17 The results of the hemisphere fabrication with three approaches. Without the layering method project the color onto the entire balloon; with the layering method project the color and numbers only onto the top balloon.

Table 4.1 Usages of balloons, Velcro tapes and time costs for each approach.

	Number of Balloon	*Velcro Tape (cm)*	*Time (min)*
Color Gradients	37	99	25
Color gradients & Layering	48	127.5	30
Shaking numbers & Layering (Ours)	61	145	35

We created three hemispheres, aiming at the value of the black semicircle in the figure, which was set to 40 cm in height. After we fabricated each hemisphere, we measured the diameter of its base and its height. Figure 4.18 shows the measured values of the balloon art produced. The green, blue, and red graphs represent the first, second, and third methods, respectively. The third method was the closest to the target. On the other hand, both the first and second methods produced errors in the height of the hemisphere, giving heights about 10 cm higher than the set height. This may be due to the smooth color change of the gradient not providing a clear guide regarding the height at which the balloon should be placed. Therefore, the user was not able to place the balloon at the appropriate height.

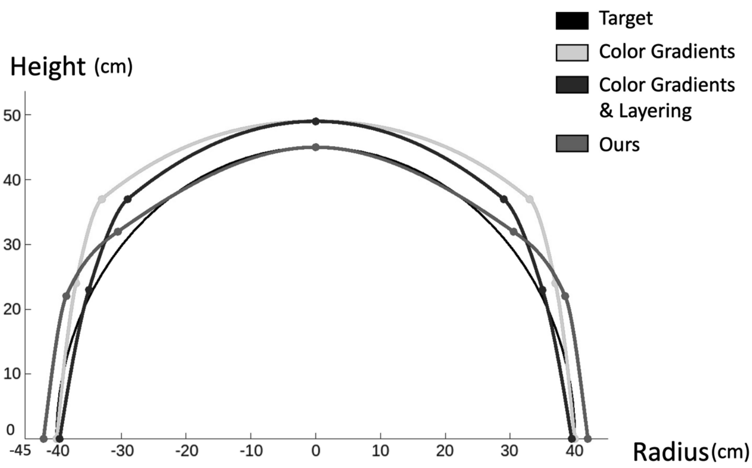


Fig. 4.18 Comparison of fabricated hemispheres with three approaches.

4.4.3 Balloon Art Creation

We conducted an experiment using the proposed method on three male subjects. The subjects created balloon art in about 3.5 hours using 245 balloons and 8.5 m of Velcro tape. We confirmed that the monochrome numeral projection method improved visibility and matched the shape and texture of the projected object better than the previous method (Figure 4.15(a)). In addition, users responded to the animation of the numerals and worked more lively. This confirms that animation not only serves as a motivator but also has the potential to reduce boredom and add enjoyment to the work. Figure 4.19 shows the results of the balloon art production.

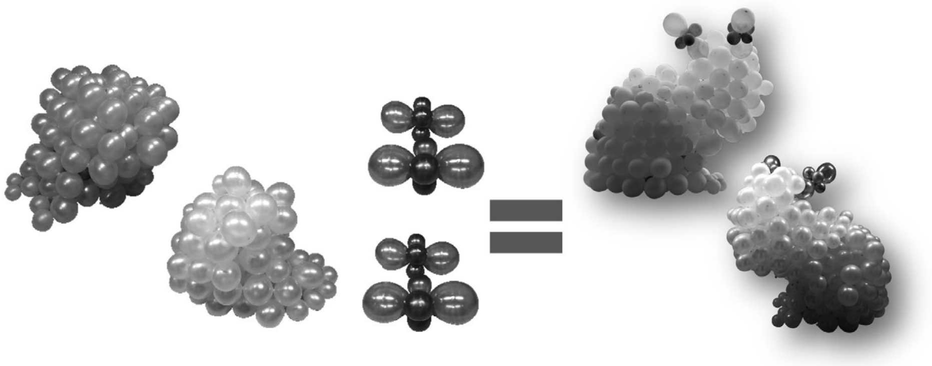


Fig. 4.19 Fabrication result of the large-scale balloon art using the proposed approach.

4.5 Summary and Discussion

In this study, we propose a method to simplify large-scale digital fabrication: a layered projection mapping technique that divides the models by layer and calibrates each layer with real space. In addition, it is suggested that the projection of the monochrome animated numbers with animation is highly visible and motivates users to act and improve the entertainment value. As an example of this application, we demonstrate the creation of a large-scale balloon art piece. We expect that using a Graphics Processing Unit will further shorten the time required for the depth calculation. Although we have successfully created balloon art using the proposed system, we have not clarified its usability. It is necessary to conduct a user study to objectively evaluate the system. These survey items would ideally include the clarity of the projected information, the ease of use of the system, and whether the user would like to continue to use the system for balloon art production in the future. In this study, we only created the Stanford Bunny. We would like to overcome the challenge of creating complex objects and determine the usefulness of the proposed method, along with further issues. Additionally, we would like to improve this system through discussions with balloon art creators.

This study focuses on understanding and sharing efficient production methods as an important element for collaborative creation in production activities to simplify the production process. By staging production procedures as numbers with added animations, the system aims to facilitate intuitive material placement for creators. In other words, we attempted to facilitate the understanding of component placement by presenting interactive placement information. Thus, the proposed method is a staging method for easy production. We confirmed that accurate component material placement was made possible by layering the projection space and interactive projection of the production process. In other words, the projection of the production process facilitates complex and large-scale production, and even those who are unfamiliar with production activities can easily perform them. In addition, SAR is able to present production processes to multiple people. This allows all creator to intuitively understand the production process, which facilitates smooth collaboration. In addition, it is expected that ideas and information will be shared by facilitating communication through collaborative creation. In this way, the proposed method adds the seasoning of ease of perception to the act of production. This seasoning leads to an understanding and sharing of efficient production methods. Understanding and sharing efficient production methods contribute to collaborative creation in production activities.

4.6 Limitation and Future Work

We describe future work based on the proposed method and the findings of the experiments.

Shape prediction by physical simulation We confirmed a case in which numbers were not projected where they should have been projected. It is thought that the shaking and weight of the stacked balloons caused the projected numbers to shift from the balloons during production. However, the target depth data remained the same. The visibility of the projected numbers was clear, and the balloon was fixed with Velcro tape, so it did not shift significantly. Therefore, the user was able to assemble the balloon without any problems. Using physics simulation, it is possible to predict the collapse of the balloon due to its own weight. For example, the system recognizes placed balloons and projects the predicted target shape in real time. In this way, the user can check how the balloon to be placed will affect adjacent balloons while creating the balloon art. It is also possible to use the prediction information to project a shape that is smaller than the correct shape. In this way, the exact shape can be formed through the extrusion of the balloons and through the collapse due to their own weight.

Alignment of Height and Projected Position of Each Layer The proposed method is based on the visual confirmation of the height and projected position of each layer, and adjustment is conducted by manual measurement. This process is cumbersome and does not allow for precise measurements. This could lead to variations in the adjusted values, depending on the user. To solve this problem, it is necessary to simplify and automate the alignment process by recognizing markers or feature points.

Application to More Large-Scale and Complex Shapes The proposed method uses a single projector and depth sensor to decompose layers vertically within a confined space. Using multiple devices enables the expansion of the workspace and allows for layer decomposition from different directions. This enables more large-scale creative activities and the creation of 3D models with complex shapes. In addition, changing the balloon size according to the part to be created allows for a more detailed and efficient creation of complex shapes. For example, it is possible to construct the central part of an object with a large balloon while employing a smaller balloon for the part visible to the user. This enables a reduction in work time and work processes. In addition, the use of robust materials such as bricks or plastic bottles [127] reduces measurement errors, as they do not deform as much as softer materials.

Chapter 5 NaviChoker: Augmenting Pressure Sensation via Pneumatic Actuator

In this study, we develop a choker-type device that automatically presents pressure around the neck according to the situation (Figure 5.1). We aim to develop a tactile sensation presentation device that can be automatically controlled. The device to be developed supplies air from an air pressure source to multiple pneumatic actuators attached to the proposed device using silicon tubes. By operating the solenoid valves, it is possible to operate each pneumatic actuator at arbitrary timing, enabling instantaneous pressure presentation and continuous pressure presentation for a certain period. We confirm whether the proposed device can provide the desired directional presentation and indicate the usability of the proposed device. For this purpose, we use a syringe to deliver air and blocking the silicone tube by hand to control the air path.

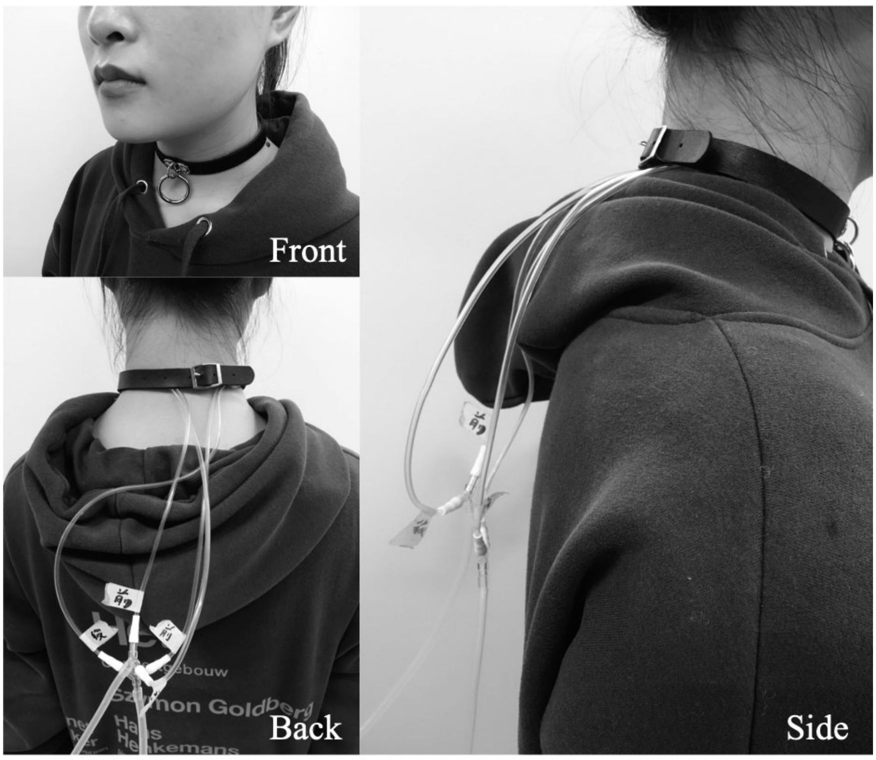


Fig. 5.1 NaviChoker using pneumatic actuators.

By using this device, the user can sense the position of pressure around the user's neck and recognize the direction of walking and the presence of objects. The actuators are capable of independent motion, so it is possible to present a few pressure patterns to the user. In addition, the proposed device is attached to commercially available fashion items such as chokers and turtleneck clothing. Thus, it looks natural, and others do not notice that the user is wearing the device. The system's mechanism and appearance are also simple, so users can wear the proposed device without hesitation. Before user study using the proposed device, we conduct a preliminary study. Here, we explore haptic patterns that present appropriate orientations. In the next chapter, we describe the background and purpose of our research and the structure of this chapter.

5.1 Background

Interaction and sensing using various stimuli in virtual worlds play an important role in virtual and augmented reality applications. Haptic interaction can be applied in many scenarios within the field of human-computer interaction (HCI) [128, 129]. In particular, the senses of force and touch can present a variety of stimuli such as temperature, pressure, vibration, and electricity, and have been developed in many fields [130, 131, 132, 133]. Thus, technologies that augment the user's experience with all kinds of tactile feedback can bring tremendous benefits to entertainment, education, and our daily lives.

There has been researching on devices that present force and tactile sensations to support people's actions and lifestyles. Sasaki et al. have developed the LevioPole, a tactile device with a total of eight propellers attached to each end of a rod that can translate and rotate in the air [134] (Figure 5.2). This device can provide the user with tactile sensations ranging from smooth (like a liquid) to rigid (like a rigid body) by generating propulsive force with each propeller and controlling the speed and direction of the rotation. An application of the LevioPole is to provide the user with walking directions. However, the device itself is too large to be used in confined spaces such as roads and buildings. In addition, the device requires the user to hold it with both hands, so the user cannot use their hands when necessary, making the device impractical.

Fig. 5.2 LevioPole: Mid-air Haptic Interactions using Multirotor **[134]**

Delazio et al. proposed the Force Jacket, which presents various pressures to the user by using pneumatic actuators inside the jacket [135] (Figure 5.3). By inflating airbags inside the jacket, the user can feel the impact of being hit by a ball or the sensation of being bewitched by a snake. However, this device uses a large air compressor to feed air to the actuators. Therefore, it can only be used in a limited space, such as inside a room.

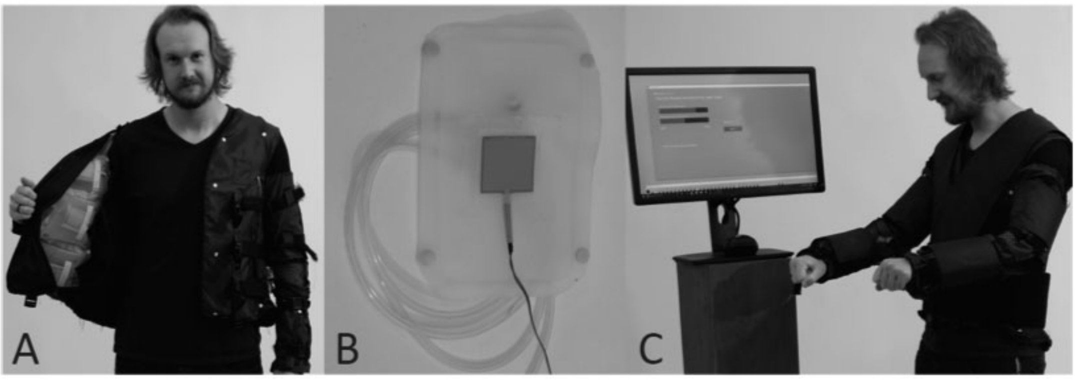


Fig. 5.3 Force Jacket: Pneumatically-Actuated Jacket for Embodied Haptic Experiences **[135]**

5.1.1 Purpose of this research

Based on the background, this research aims to fabricate a choker using pneumatic actuators. Four actuators made of polyethylene are attached to the inside of the choker and inflated to provide tactile sensations to the user's neck. We aim to develop a compact device using a small pump, such as a Micropump. The proposed device can be used anywhere because it does not require a large air compressor. In addition, by attaching multiple pneumatic actuators, it is possible to present haptic sensations around the user's entire neck. By presenting pressure using this system, the user can focus their attention on a given direction. The system can also provide variations in the way the actuators inflate and the order in which they inflate, making it possible to apply the system to a variety of situations. In addition, users can wear the proposed device without burden because the designed actuator is attached to a lightweight material, such as a commercially available choker.

5.1.2 Organization of this research

This chapter consists of five sections, and the structure and contents of each section are described below.

In Section 5.1, we describe the background and objectives of the study and in Section 5.2, we introduce related works on haptic feedback and clarify the position of this study. Section 5.3 shows the proposed device and method, and preliminary study. Section 5.4 presents the evaluation experiment of the system, and Section 5.5 summarize this study, limitations, and future work.

5.2 Related Works

This section describes related research on wearable devices and pneumatic actuator. Wearable devices use air, heat, vibration, and tangible interfaces. They are used in many ways, such as human augmentation and immersive VR applications. Pneumatic actuators are also suitable for wearable devices because they can be designed lightweight. Therefore, pneumatic actuators can also be used for human augmentation, immersive VR applications, and toys.

5.2.1 Wearable Device to support user movements

Xie et al. developed a physical tail capable of supporting the user's weight [136] (Figure 5.4). This device supports the user's sitting action, while also assisting in emotional expression through the movement of a tail. In addition, xClothes utilizes a stretchable structure to extend the sensation of human body temperature [137] (see Figure 5.5). An open/close hole structure is attached to the clothing worn by the user and can be switched open and closed using servo motors and wires. This structure enhances ventilation by controlling the holes as the user's body temperature increases. In other words, it can support the user's comfortable exercise by regulating body temperature. However, these devices have many moving parts and are complex. This can reduce robustness and inhibit user movement.

Fig. 5.4 Augmenting human with a tail **[136]**

Fig. 5.5 xClothes: Augmenting human thermoregulation using shape changing clothes **[137]**

Jeong et al. have improved communication by attaching Peltier device-based thermal stimulation devices to the wrist and back of the neck [138]. Yamazaki et al. proposed a neck-mounted haptic device capable of dynamically modulating the amplitude, phase, and frequency of vibration [139]. The device's haptic stimulation enables the user to perceive invisible images. These can be used to enhance the immersion of VR applications or for navigation purposes. However, in the former case, this device must be placed in close contact with the back of the wrist or neck to provide thermal stimulation. This may cause discomfort to the user due to the sensation of pressure. In the latter case, there are no specific applications for VR, and it is not used for guiding to destinations that involve walking.

5.2.2 **Studies using pneumatics**

In this study, we proposed a haptic presentation device using pneumatic pressure. For research using pneumatic pressure, Niiyama et al. proposed the Sticky Actuator, which creates multiple pneumatic actuators from inexpensive sheets of plastic to reproduce movements such as rotation and deflection [140] (see Figure 5.6). The system automatically creates free-form actuators such as square, circular, and ribbon-shaped actuators. The pneumatic actuators created are applied to the movements of robot arms and legs and the flapping of origami cranes. However, it does not consider functionality as a tactile presentation device for humans.

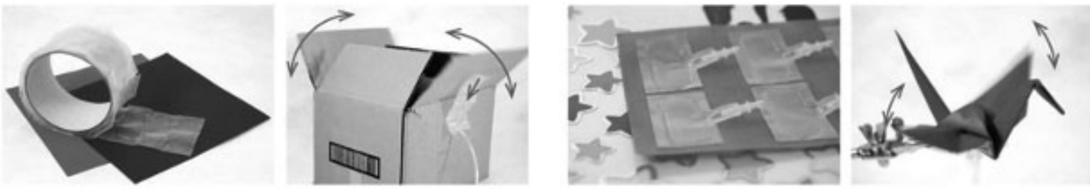


Fig. 5.6 Sticky Actuator: Free-Form Planar Actuators for Animated Objects **[140]**

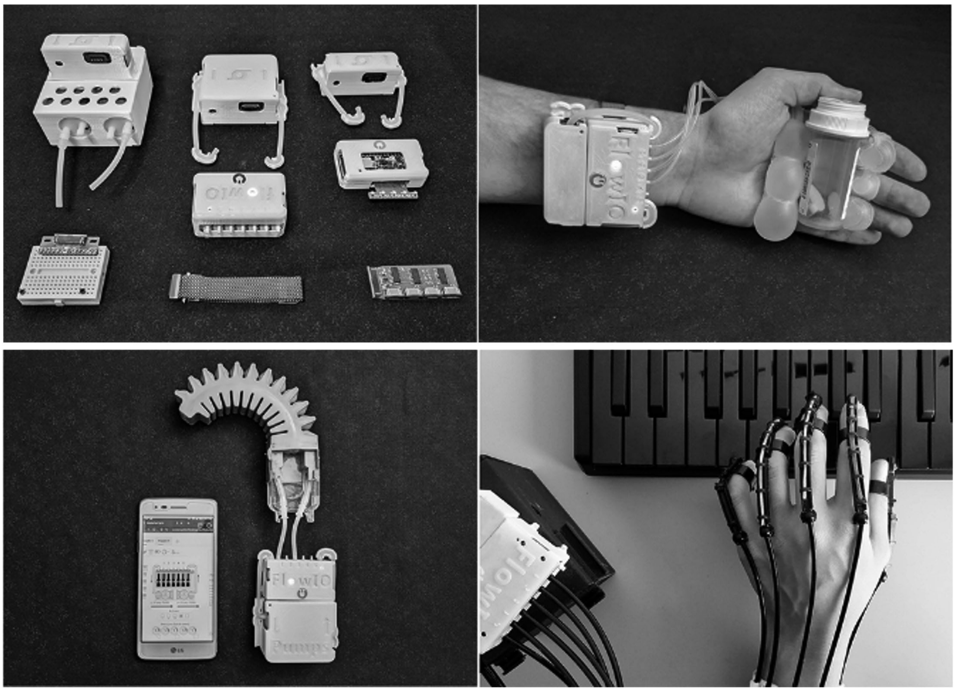


Fig. 5.7 FlowIO Development Platform – the Pneumatic "Raspberry Pi" for Soft Robotics **[143]**

Sonar et al. designed a wearable skin-like interface using small pneumatic actuators [141]. This can reproduce the roughness, shape, and size of an object. The system works by using a camera to read a soft pneumatic actuator (SPA)-skin and marker attached to the user's finger. When the user's finger approaches any shaped object, the system presents pressure on the user's finger as if to simulate the shape. PneuMod [142] is a pneumatic and thermal tactile presentation device. By using Peltier elements and pneumatically actuated silicon bubbles, it can render thermal pneumatic fade-back through shape, location, pattern, and motion effects. In addition, it can control temperature and bubble expansion r. ate, and degree of expansion.

The device can be attached to the user's socks or arm covers. However, these devices cannot be used as wearable devices because of the large amount of equipment used and the complexity of the device structure. FlowIO [143] is a compact pneumatic development platform (see Figure 5.7). The built-in micro-pump and main module are suitable for wearable devices and allow flexible development. However, it uses a DC pump for the pump module. It cannot be used for instantaneous haptic presentation

5.2.3 Pneumatic pressure presentation device for the neck

Based on the related research, we develop a device that presents pressure around the entire circumference of the neck using a pneumatic actuator. This device does not require a choker to be tightly fitted around the neck for clear haptic feedback. Therefore, it can provide even pressure around the entire neck without causing discomfort or a feeling of constriction to the user. In addition, by presenting haptic sensations on the neck using a choker-type device, the same directional information can consistently be presented to the user at the center. For example, when bending or twisting an arm fitted with a haptic feedback device, a discrepancy arises between the intended direction and the direction presented by the device [144]. Another problem is the possibility of interfering with the task at hand. However, haptic presentation to the neck does not interfere with daily life. It can also always provide appropriate directional information. In addition, the soft material of pneumatic actuators eliminates the risk such as injury or discomfort. In this study, we focused on presenting the direction and conducted evaluation experiments to verify the usefulness of the prototype.

5.3 Device Production

The proposed device presents haptic sensations around the entire circumference of the user's neck using actuators attached to the inside of the choker. For example, the inflated actuator on the left side can present pressure on the left side of the user's neck. Thus, the choker can direct the user's attention in eight directions. The actuators can operate individually, or one actuator can operate continuously. The proposed system can present a variety of haptic sensation patterns to the user.

The advantage of using pneumatics is that the actuators can provide clear pressure feedback to the user even when not tightly adhered to the skin. Some studies provide haptic stimuli to users using thermal stimuli [145] and studies that reproduce the weight of objects felt by users in a virtual space using electrical stimuli [146] as haptic presentations that do not use pneumatic pressure. These require the device or sensor to be in close contact with the skin. This can cause pressure and discomfort to the user. However, since pneumatic actuators increase in volume when air is pumped in, they do not need to be tightly adhered to the skin. Therefore, they can present haptic stimulation to the user without being affected by the contact condition of the actuator.

5.3.1 Pneumatic Actuator

Figure 5.8 shows the pneumatic actuator used in this system. Air is supplied to the actuator, and when it inflates, the user feels a tactile sensation. The actuator is made of 0.08 mm thick polyethylene film cut into 2.0 x 1.5 cm rectangles, and a silicon tube is used to send air to the actuator. In this study, we used silicon tubes with an outer diameter of 3.0 mm and an inner diameter of 2.0 mm and those with an outer diameter of 6.0 mm and an inner diameter of 4.0 mm because of the shapes of the syringe, silicon tubes, and the connector connecting the two tubes. To seal the film, we used a soldering iron [140]. Figure 5.9 shows the procedure for making a pneumatic actuator. First, draw a rectangular shape of 2.0 x 1.5 cm on a polyethylene film. Then, the cookie sheet is placed on a polyethylene film. Finally, trace the figure on the cookie sheet using a soldering iron. This procedure completes the pneumatic actuator.

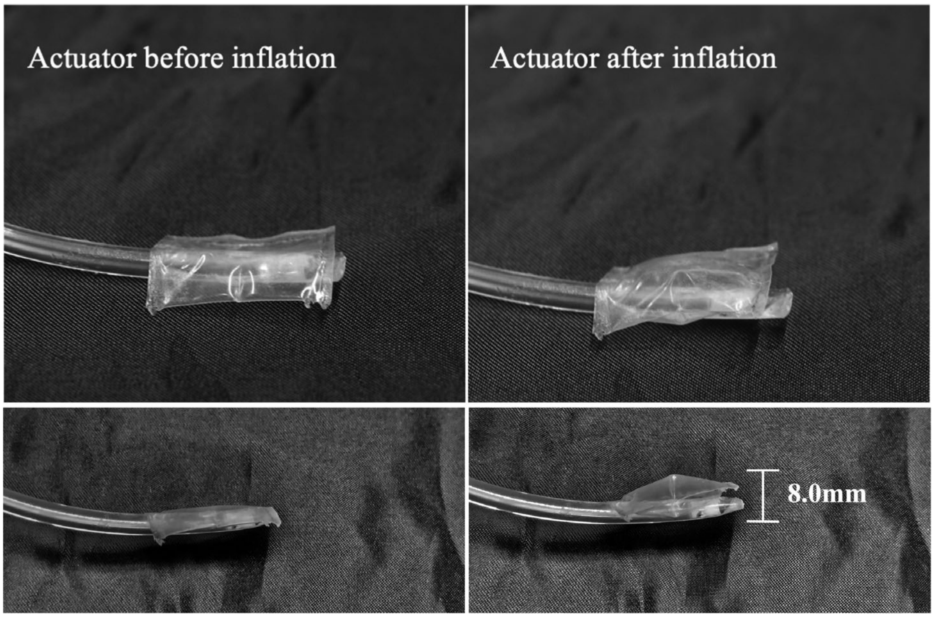


Fig. 5.8 Fabricated pneumatic actuator.

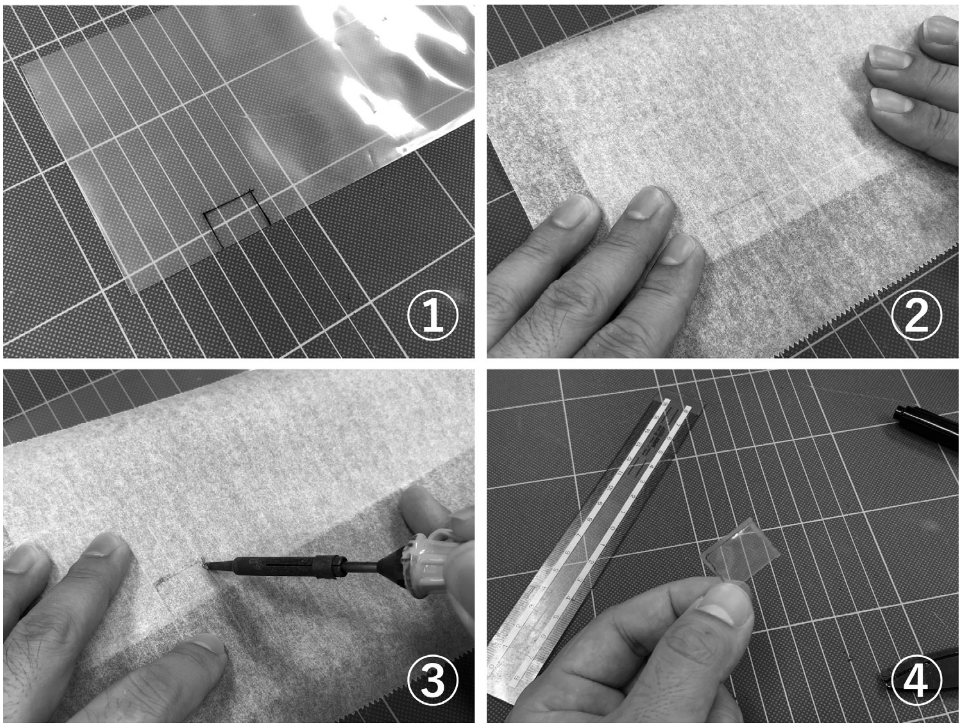


Fig. 5.9 Fabrication procedure for pneumatic actuators.

After bending the end of the tube to prevent air leakage, a 1.0 mm square hole is drilled in the side of the tube. Similarly, a 1.0 mm square hole is drilled in the center of one side of the actuator and both holes are glued together with Aron Alpha for plastic (Figure 5.10).

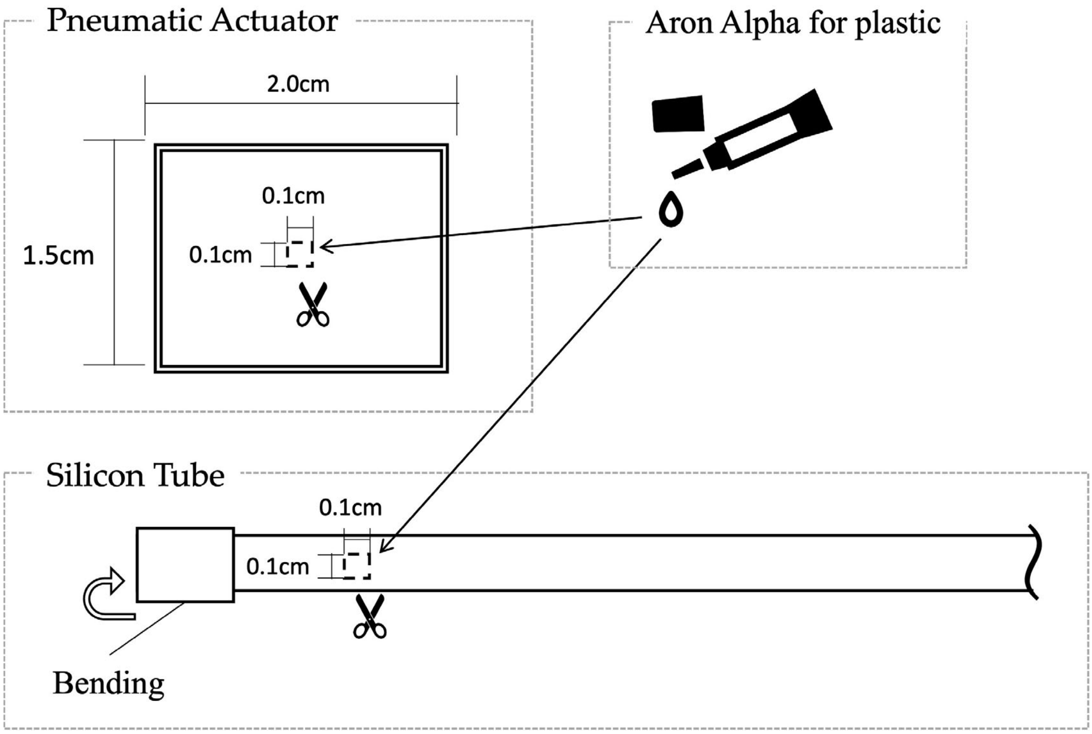
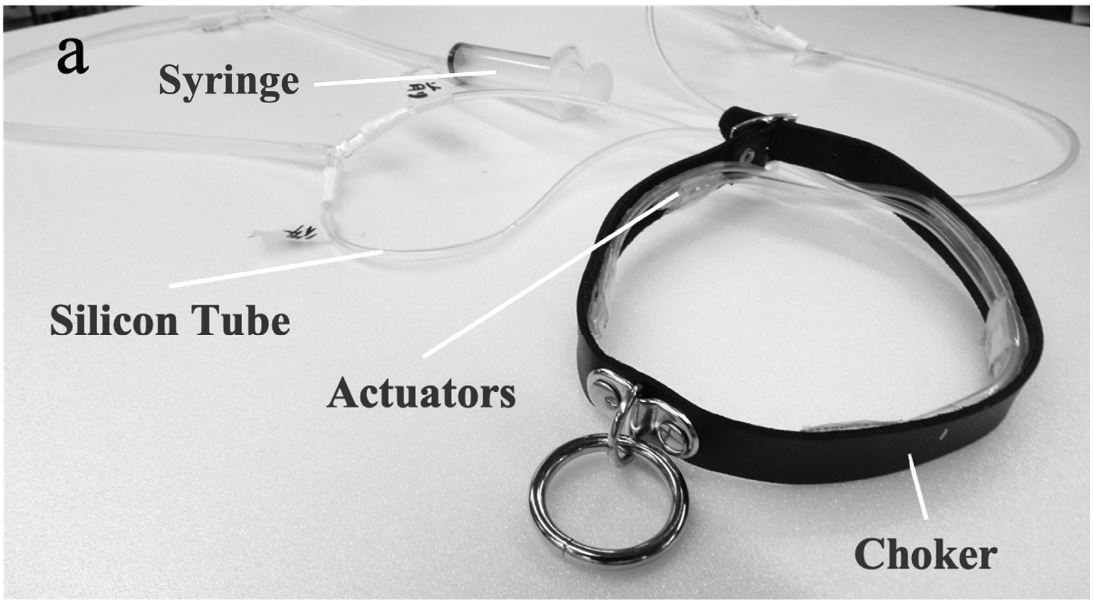


Fig. 5.10 Bending of silicon tubing and gluing to pneumatic actuators.

5.3.2 Prototype Production

Figure 5.11a shows a prototype of NaviChoker fabricated using pneumatic actuators. The operation patterns of four actuators, mounted at equal intervals around the user's neck, enable haptic presentation in eight directions. For example, it assumes that the user can focus attention forward when the front two actuators are activated, and forward diagonally to the left when one of the actuators on the forward diagonal left side is activated. To improve the wearing comfort and stability of the actuators, we covered the actuators with a soft cloth (Figure 5.11b).

NaviChoker is envisioned to operate each actuator automatically through electronic devices in the future. However, this study aims to confirm the feeling of the actuators, so the actuators are operated manually using a syringe. We leave the automation of the operation for future work.



(a) Prototype of NaviChoker.

(b) a cloth cover attached inside the device.

Fig. 5.11 Overall view of NaviChoker.

5.3.3 Preliminary Study

Before conducting a user study, we conducted a preliminary study to confirm the relationship between the direction of pressure presentation and the actual direction of a stimulus perceived by the user. There were seven subjects, six males and one female, in their 20s to 30s. It is possible that users perceive different stimulus directions depending on the number of actuators and the locations where the actuators are placed. Therefore, we verified the relationship between the direction of pressure presentation and the direction of stimulation perceived by the user. Specifically, we presented 15 different pressure patterns (Figure 5.12) to users and asked them to answer from which direction they felt the pressure was presented. Based on the results of the responses, the appropriate combination of actuator motions for each of the eight directions was confirmed.

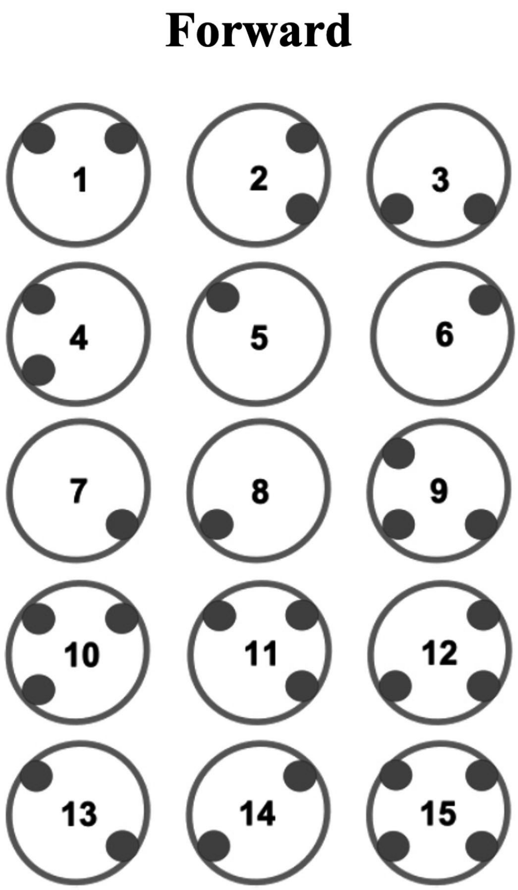


Fig. 5.12 All patterns of pressure presentation used in preliminary experiments.

As a result of the preliminary study, we set up the pressure presentation method used in the user study as shown in Figure 5.13 to present the eight directions to the user.

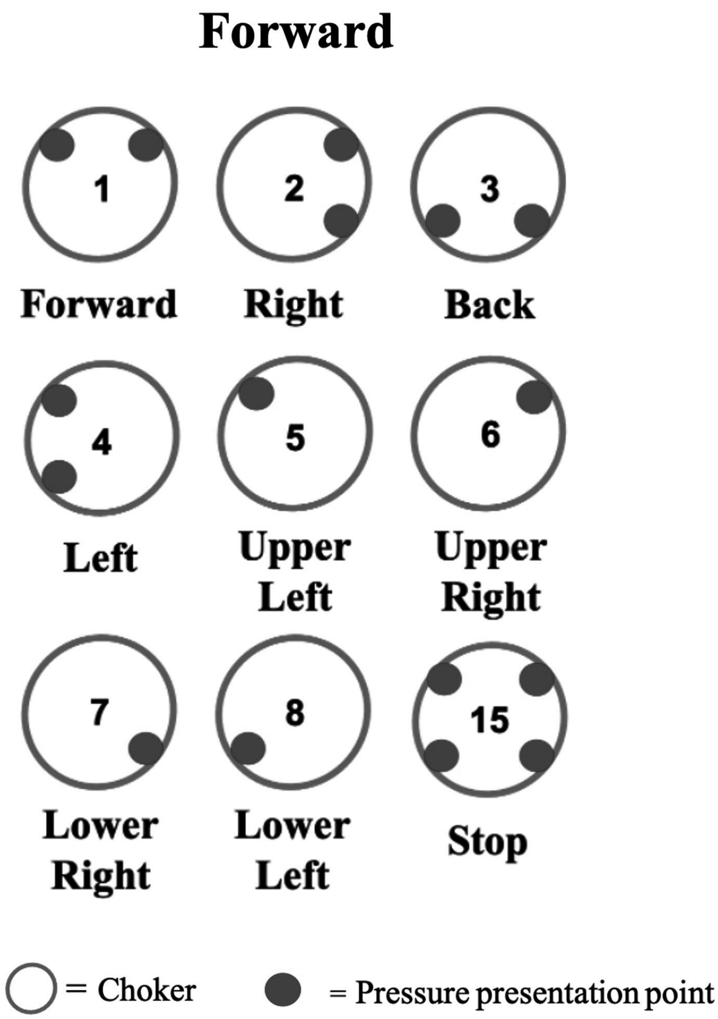


Fig. 5.13 Pressure pattern by presentation direction used in the experiment.

5.4 User Study 1: Walking direction indication

To confirm the wearability of the proposed system and the clarity of haptic and directional cues, we conducted a verification using a prototype. For this purpose, we conducted an experiment in which the user wears the device and moves to a destination using only pressure presentation (Figure 5.14). The user moves in the desired direction each time they come to a turn, feeling a pressure presentation (Figure 5.15). The pressure was presented to the user twice for directional presentation.

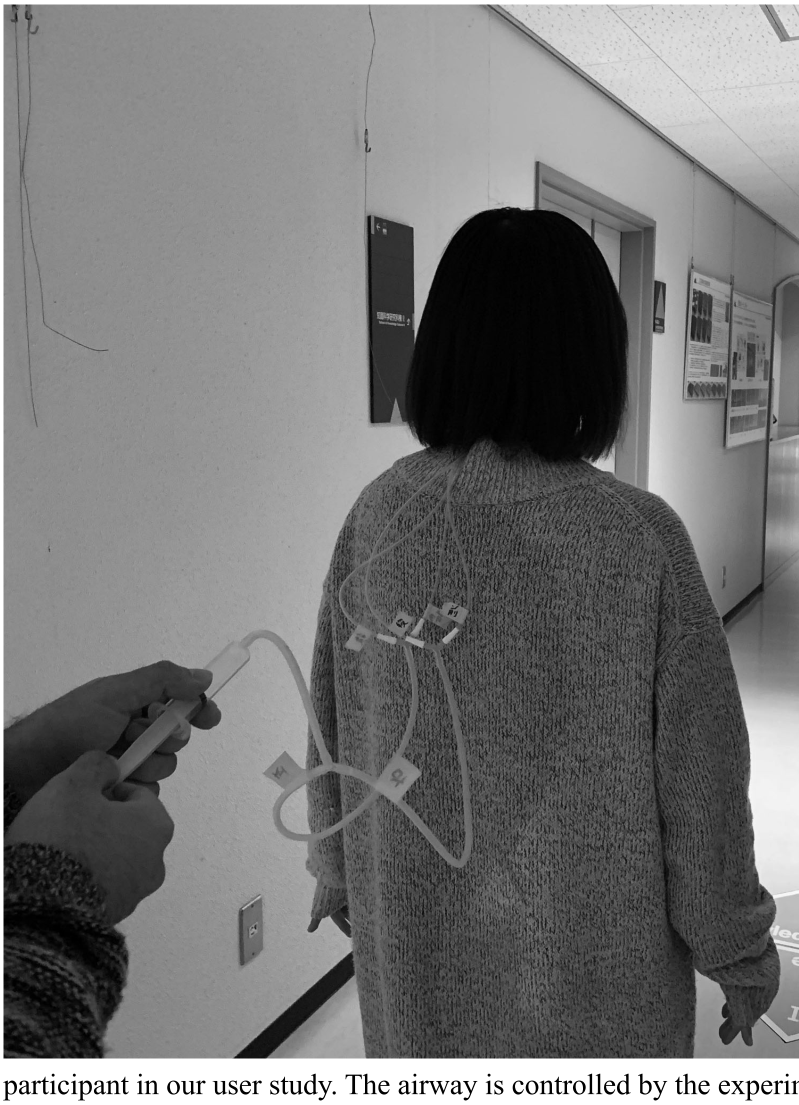


Fig. 5.14 A participant in our user study. The airway is controlled by the experimenter manually bending a silicon tube.

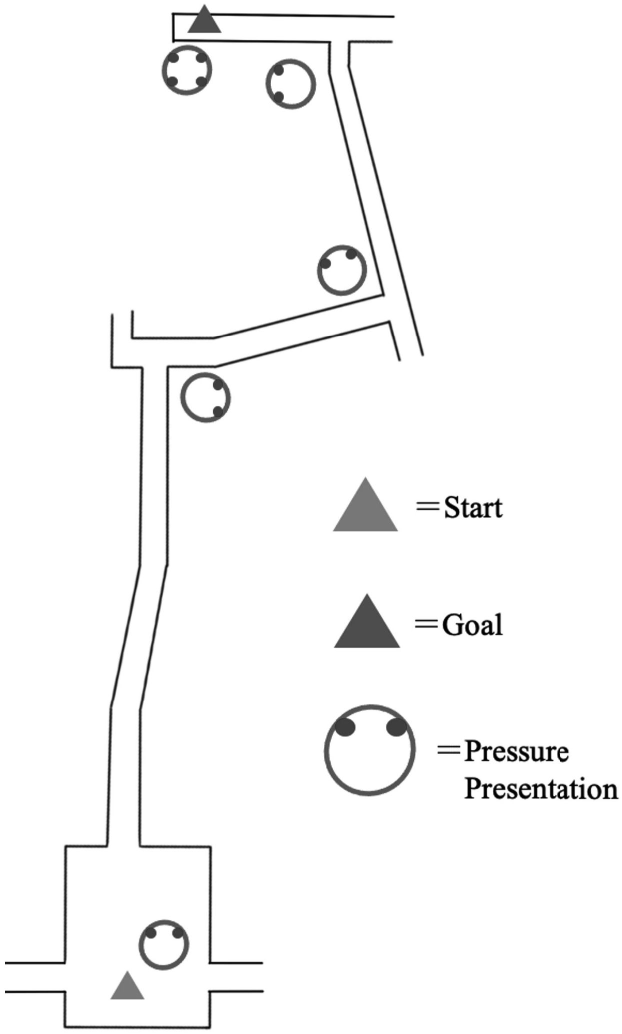


Fig. 5.15 Walking route and pressure presentation locations in the user study.

5.4.1 Walking Test

In the user study, we conducted an evaluation experiment of the proposed system on nine subjects. Seven of the subjects were male and two were female, and their ages ranged from 20 to 30 years old. The evaluation experiment consisted of a walking experiment using NaviChoker and a questionnaire survey. We used the Wizard of Oz method for the walking experiment [147], in which the actuators are operated manually. When the user approaches a predetermined turn while walking, the experimenter activates the pneumatic actuator using a syringe to provide the user with a direction to go. The user is not informed of the destination, and the user walks by relying solely on the pressure presentation from NaviChoker by using noise-canceling earphones to block out external sounds. In the user study, we presented pressure signals signifying the start and end of walking as well as the direction of walking. The pressure for the start of walking is to present the pressure in the target direction immediately after the start of the experiment, and the pressure for the end of walking is to present the pressure of No. 15 in Figure 5.13 around the destination. After the user study, we conducted a questionnaire survey on the following items to confirm the usability, fit, and pressure presentation of the system. We used a 5-point Likert scale (5: Strong agree to 1: Strong disagree) for each item.

1. Did you clearly feel the pressure presented by the actuator?
2. Did you clearly feel the differences between directional presentations?
3. Do you feel any discomfort due to the pressure presentations?

5.4.2 Result of Walking Test

As a result, eight of the nine users could reach the target location only by NaviChoker's pressure presentation. In addition, users also do not know the direction from the starting point to the destination. Therefore, at the starting point, some users were facing in a different direction from the goal point. However, all users were able to start moving in the destination direction with the pressure presentation at the start of the guidance. In addition, the user could recognize the cues for the end of walking, and the entire experiment could be performed from start to finish with only the presentation of pressure. This suggests that the use of a pneumatic actuator to present pressure around the neck could be useful as a navigation system. Navigation using screen displays and voice guidance on mobile devices has problems such as encouraging people to walk around and making it difficult to use in noisy environments. However, in the user study, users could be guided only by pressure, so it is suggested that these problems can also be solved. On the other hand, one subject failed to reach the destination. This is because the subject recognized backward pressure as the presentation of pressure at the end of the walk. Thus, the position and intensity of the pressure felt by different subjects may differ. Therefore, it is necessary to improve the actuators so that more participants can equally perceive the location of pressure presentation. Specifically, this involves investigating and analyzing the appropriate pressure intensity and presentation location for each user.

5.4.3 **Result of the Questioner Survey**

Figure 5.16 shows the results of the questionnaire survey. The evaluation criteria include whether the direction difference was understood, whether the pressure was clear, and the wearability of the device. As a result of the evaluation, it was confirmed that the items related to the presentation of pressure were highly rated. In particular, all subjects responded that they "felt pressure" when pressure was presented by the pneumatic actuators. Many subjects also felt a difference in the direction of the presentation. One respondent stated that they did not see much of a difference. The reason for this can be attributed to the fact that the device was not properly fitted due to the slimness of the participants' necks. In addition, there is a possibility that the haptic feedback was being presented in areas where it was difficult for participants to perceive the stimulation. This issue may be resolved by inflating the actuators to a larger size. Therefore, the device needs to be improved. As for the discomfort of wearing the device, only four subjects rated the device as "not uncomfortable," confirming that more than half of the users were not satisfied with the wearing feeling of the device. The reasons for this may include the fact that some users do not feel comfortable wearing something around their necks, the actuator edge irritates the user's neck, and the silicone tube connected to the actuator may prevent them from feeling comfortable wearing the device. As a solution, it is necessary to place a more soft cloth between the neck and the device, smoothing the ends of the actuator to avoid pain and using a thinner silicone tube to reduce the presence of the mechanism on the user.

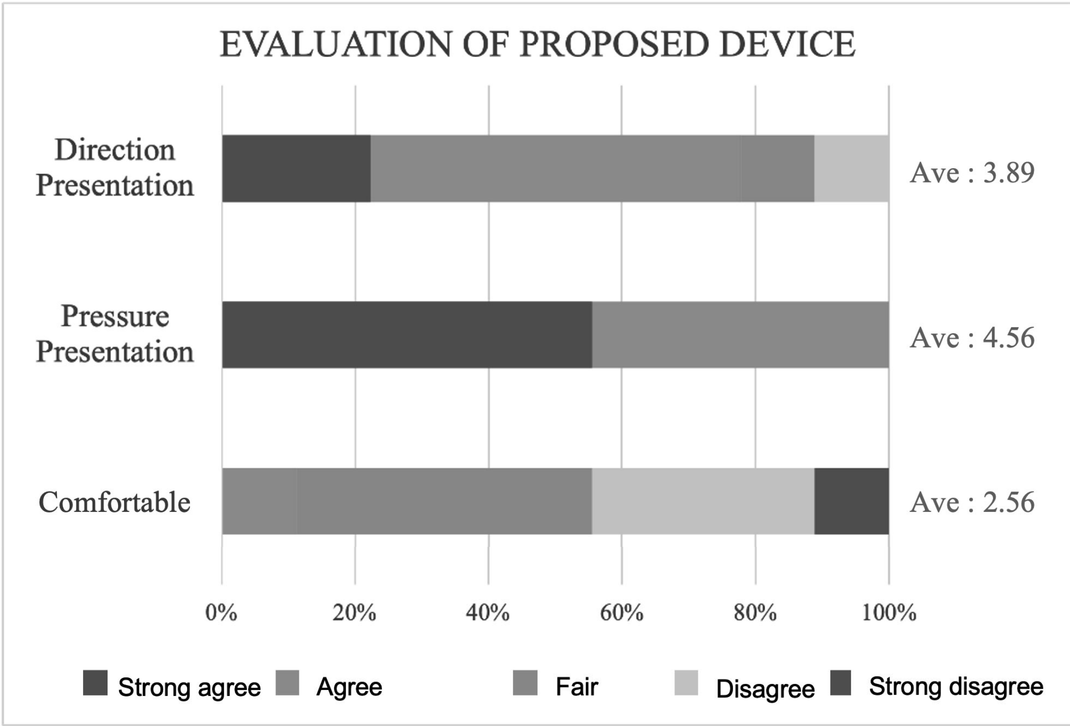


Fig. 5.16 Evaluation results of our user study.

5.4.4 Pressure test using differently shaped actuators

The shape of the pneumatic actuator used in this study is a rectangle of 2.0 cm x 3.0 cm. To verify the difference in the user's perception of pressure based on the different shapes of the actuators, we conducted an experiment using four different shapes of pneumatic actuators. In addition, to reduce the thickness of the actuator when the actuator inflates, the tube attachment was modified (Figure 5.17). The area of the actuator for each shape was standardized at approximately 4.0 cm^2. Subjects consisted of eight people, four males, and four females, in the age range of the 20s to 30s. The experimental procedure consisted of presenting each user with pressure using four different shapes. We presented 8 patterns of pressure for each shape (Figure 5.13) and asked the users to answer which actuator worked and which shape they felt the pressure. One score is given for each correct answer to a pattern. In other words, the number of correct answers was scored out of 8 points for each shape.

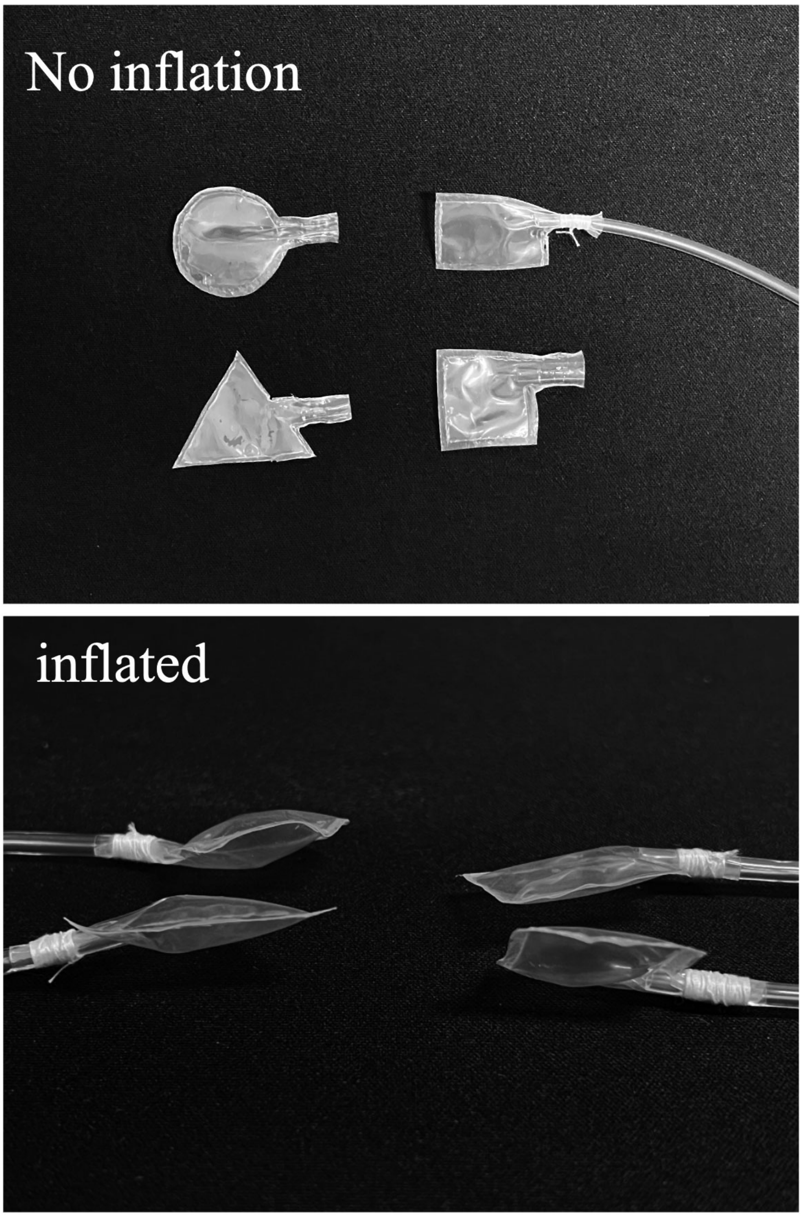


Fig. 5.17 Four shapes used in pressure presentation experiments.
Each shape has a tube to pass through.

Table 5.1 shows the results of the survey of the number of correct answers as to which actuators worked, and Figure 5.18 shows a graphical representation of the number of correct answers. In Table 5.1, F_{Ave} is the average of the evaluated values of female respondents, M_{Ave} is for male respondents, and A_{Ave} is the average of the evaluated values of all respondents. In addition, we calculated statistical test values using Wilcoxon's rank-sum test to see if there was a significant difference between the two shapes that showed a large difference in the number of justifications for this system, or if there was a significant difference in the number of justifications for actuators that worked due to differences in shape regardless of gender or age (Table 5.2, 5.3). Table 5.2 is a table of the number of correct actuators that worked, where C_{Ave} is the average number of correct actuators for the circular actuators and R_{Ave} is the average number of correct actuators for the rectangular actuators. Table 5.3 shows the differences between the genders. In Tables 5.2 and 5.3, z and P are the test statistic and p-value. The significance level is set at $\alpha=0.05$. In the number of correct actuators that worked in Table 5.2, the difference in averages was small, and there was no significant difference between each shape in p-values. This suggests that there is no difference in the feeling of pressure due to differences in actuator shape. This may be because the size of the actuator was small, to begin with, and it is possible that there was not much difference in the degree of inflation. In addition, there was no significant difference in the average value and p-value between genders. This suggests that there is no difference in pressure perception between genders.

The shape that most clearly showed pressure was a circle, selected by 6 users. No user selected a rectangular shape, and this result was consistent with that of the number of correct answers. Despite the non-significant difference in the number of correct actuators that worked for the different shapes, most users answered that the circular shape presented the clearest pressure. This means that even if the shape that can present the most pressure to the user is used, it does not necessarily improve the accuracy of the direction presentation. This means that accurate direction presentation is not necessarily improved by using the shape that can present the most pressure to the user. Future improvements to the actuator could include adjusting the degree and speed of inflation rather than changing the shape of the actuator. This may enable the pressure to be presented clearly to the user. In addition, we were able to guide almost all users to their destinations in the user study. Therefore, it is considered that the current system guarantees the accuracy of direction indication to some extent. If there is no difference in the accuracy of direction indication depending on the shape of the actuator, users can enjoy designing chokers based on the shape of the actuator. In other words, we believe that the proposed system can guarantee designability as a fashion item.

Table 5.1 Results of a survey of the correct number of which actuators did operate.
The scores are recorded on an 8-point scale.

Shape＼User	A	B	C	D	E	F	G	H	M_{total}	F_{total}	Total	M_{ave}	F_{ave}	A_{ave}
Circular	5	8	7	7	6	6	6	6	27	24	51	6.750	6.000	6.375
Triangle	7	7	6	5	6	6	8	3	25	23	48	6.250	5.750	6.000
Square	6	5	6	8	6	4	8	7	25	25	50	6.250	6.250	6.250
Rectangle	5	2	7	6	5	4	8	4	20	21	41	5.000	5.250	5.125
Total	23	22	26	26	23	20	30	20	97	93	190			

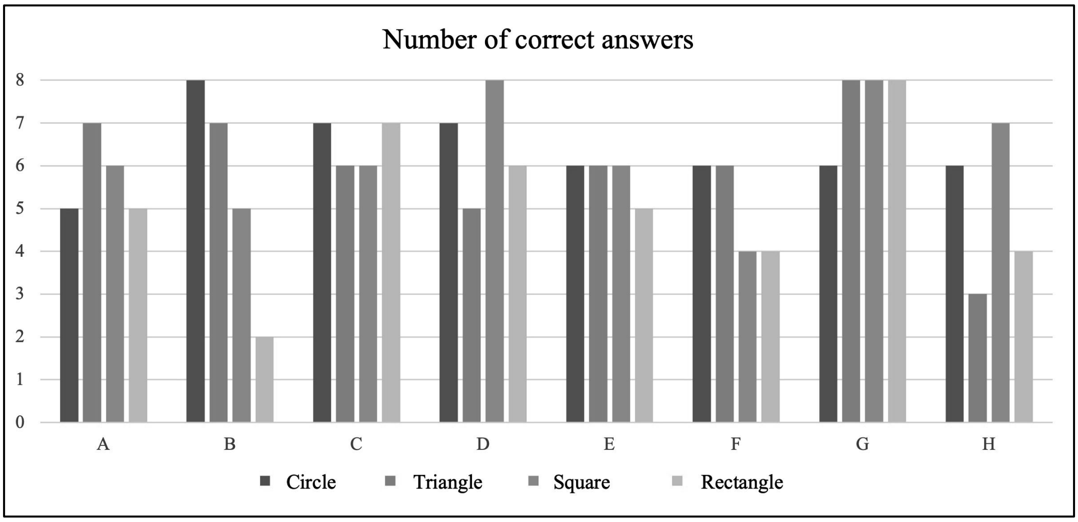


Fig. 5.18 Graph the number of legitimate users.

Table 5.2 Investigate whether there is a significant difference between the two shapes that had a large difference in the number of correct.

C Ave	6.375
R Ave	5.125
z	1.556
P	0.119

Table 5.3 Investigate whether there are significant differences between men and women.

Shape	Circular	Triangle	Square	Rectangle
F Ave	6.000	5.750	6.250	5.250
M Ave	6.750	6.250	6.250	5.000
A Ave	6.375	6.000	6.250	5.125
z	1.239	0.298	0.149	0.146
P	0.215	0.766	0.882	0.884

5.5 User Study 2: Haptic and Collaboration

We verified the effectiveness of the haptic and directional presentations of the proposed system for creative activities. We conducted creation experiments with two users, who each created an object while wearing the device and shared their somatosensory perception (Figure 5.19). These experiments involved the creation and assembly of parts with LEGO blocks (Figure 5.20). The users performed the simple tasks of creating and assembling parts in their own booths. The users created and assembled the parts according to the illustrated instruction manual. Then, the users assembled the completed parts in the assembly space. While repeating this process, the users collaboratively created an object. In addition, we divided four types of information about the user's assembly and part-making actions into somatosensory information. The proposed device presented these four pieces of information as haptic feedback around the user's neck. To confirm the effectiveness of haptic feedback, we conducted a comparison experiment with and without haptic feedback.

Fig. 5.19 Experiments in creative activities using blocks. The experimental environment consists of three desks. Users create parts on the desks at the ends and assemble them on the center desk.

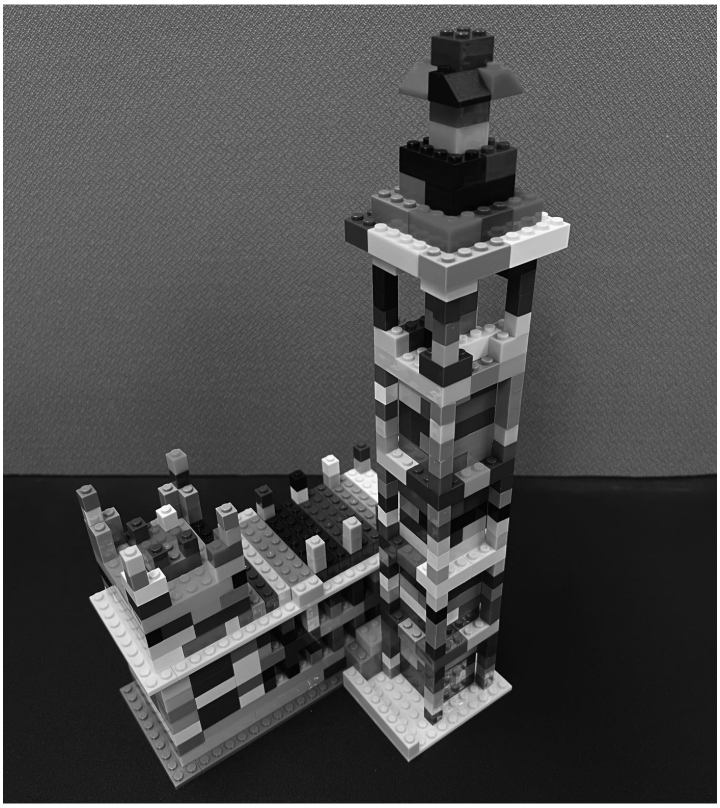


Fig. 5.20 Creation of objects with blocks.

Experimental Environment Figure 5.21 shows the experimental environment. We set up a Parts Assembly Space (PAS) in the center of the workspace and two Parts Creation Spaces (PCSs) flanking the PAS. The PAS functioned as a collaborative workspace. In each PCS, there were boxes of LEGO bricks for making parts, roughly equal in number according to the shape of the parts. The user created parts using the PCS as their own booth. In addition, we set up a spot for users to place their finished parts (right) and their unfinished parts (left) at both ends of the PCS. The distance between the PAS and the PCS was about 1.9 m. This was to ensure that the users needed to turn their bodies toward the PAS when placing a part on the PAS. By opening some distance between the PAS and the PCS, it takes approximately three steps to get to the PAS. In the creative activity experiment, we used the Wizard of Oz method for haptic presentation, as in the walking direction presentation experiment (Section 5.4.1). We placed a partition between the experimenter operating the actuator and the subjects to prevent them from seeing the experimenter. In addition, we suspended the silicon tube from the ceiling to prevent it from obstructing the users' actions (Figure 5.22).

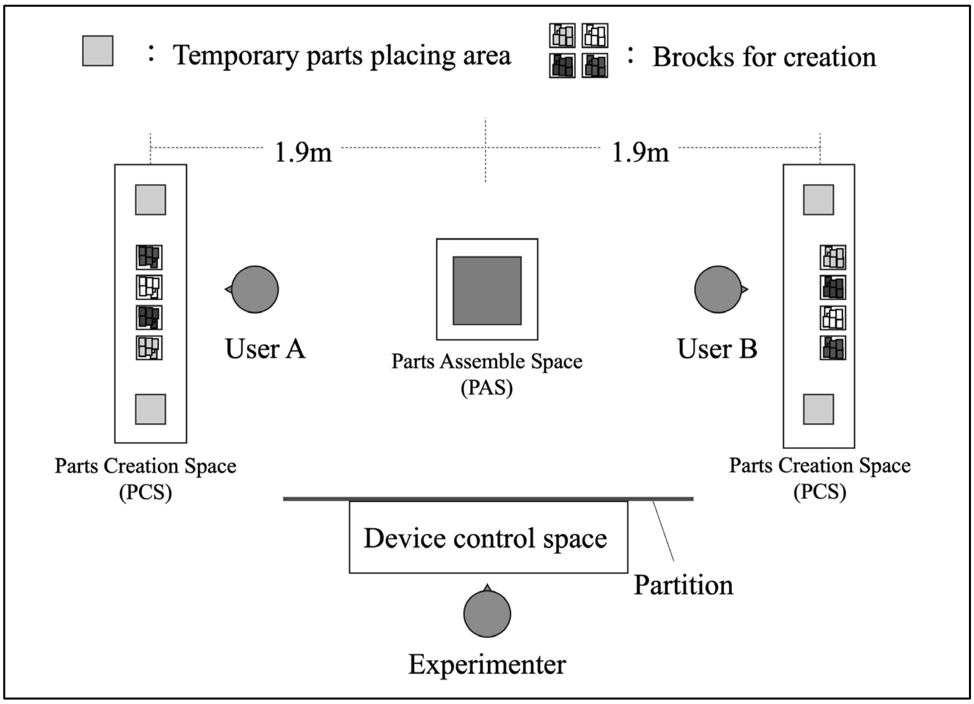


Fig. 5.21 Study environment.

Fig. 5.22 Silicon tubes suspended from the ceiling.

Target Object We chose “Big Ben,” a clock tower in London, the capital of the United Kingdom, as the creation target (Figure 5.23). This is because we thought that the distinctive parts and the differences in the elevation of the buildings would facilitate the creation of parts and the imagining of the completed building. To create the production target with LEGO bricks, we simulated it using CAD software (Figure 5.24). The device we used was an iPad Pro (Early 2021), and the software used for simulation was Shapr3D [148]. We simulated a virtual model with a height of 36.0 cm, a width of 19.2 cm, and a depth of 16.0 cm as the production object. Using the simulated object, we created an instruction manual (Figure 5.25). Figure 5.25(a) shows the procedure for part production, and Figure 5.25(b) shows the procedure for part assembly.

https://www.britannica.com/summary/Big-Ben-clock-London

Fig. 5.23 The building that became the motif of the target object in creative activity.

Fig. 5.24 Shapr3D **[148]**.

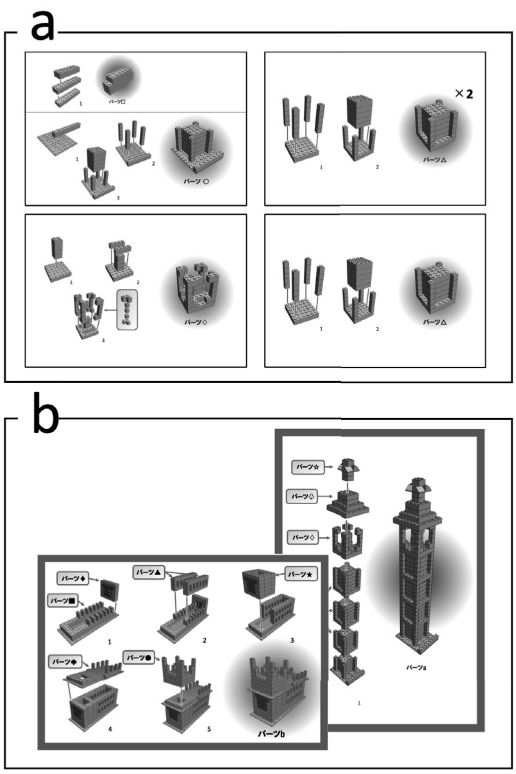


Fig. 5.25 Part of the instruction manual produced. The instruction manual shows how to make parts (a) and assemble parts (b). All the improved instructions are listed in Appendix B.

5.5.1 Preliminary Study in Creative Activity Experiment

Before conducting a creative activity experiment using haptic stimulation, we conducted a preliminary study with two users. The purpose of the preliminary study was to confirm the experimental procedure, the difficulty of the creations, the adequacy of the assembly instructions, and the effectiveness of the haptic presentation. The subjects were two males, both in their 20s. We conducted the experiment twice, the first time without haptic presentation, and the second time with haptic presentation. We assigned the following meanings to the four directions used in the haptic presentation.

Front: Walking motion of the partner toward the PCS
Back: Walking motion of the partner toward the PAS
Left: Work action of partner's left hand (placing a part, assembling a part)
Right: Work action of partner's right hand (placing a part, assembling a part)

For example, when the subject places the completed part on the desk with the left hand, the action of "placing" stimulates the left side of the other user's neck as a haptic sensation. When the subject walks to the PAS and places the completed part on the desk with their right hand, the "walk" and "place" actions stimulate the back and right sides of the other subject's neck. The meaning of the directional information was given to the subjects in advance. Therefore, one subject can discern the other's behavior based on the haptic information.

In the experimental procedure, users first created without haptic feedback. The users created parts in their own PCS while referring to the instruction manual distributed in advance. After creating the parts, the users went to the PAS and assembled the parts in their own time. This process is repeated to complete the creative activity. After the first creative activity, we conducted a questionnaire survey and started the second creative activity. The second creative activity employed haptic feedback. We also conducted a questionnaire survey after the second experiment.

The experimenter allocated the parts to be created by each user in advance. This was done to minimize the difference in the amount of work required to create parts for each user. This means that the burden of creating parts was equalized as much as possible. Specifically, when counting the protrusion of a LEGO block as one square, we assigned user A to create a total of 1206 squares and user B to create a total of 1118 squares. After the first study, we conducted a questionnaire survey to confirm the sense of unity between users, the degree of difficulty in creating parts, and the enjoyment of the activity. We used a 5-point Likert scale (5: Strong agree to 1: Strong disagree) for each item. After answering the questionnaire, the users exchanged instruction manuals with each other, and a second study was conducted. After the second study, we conducted the same questionnaire survey as in the first study. We used the following items in the survey.

1. Do you think you were able to communicate with each other through conversation, eye contact, etc.?
2. Did you imagine the partner's actions such as making or assembling parts?
3. Did you understand the partner's actions such as making or assembling parts?
4. Did you make any efforts to improve the efficiency of parts production, such as producing parts with a small number of parts or working quickly?
5. Did you get any satisfaction from the partner?
6. Did you have any complaints against the partner?
7. How difficult was it to create the parts?
8. How difficult was it to assemble the parts?
9. How difficult was the creative activity throughout the entire process?
10. Did you enjoy the creative activity?

In addition, we surveyed the following items in addition to the users who rated 5 or 4 in items 5 and 6. Responses are free text.

5-1. What did you find satisfying about the partner?
6-1. What did you find frustrating about the partner?

Subjects are allowed to talk to each other during the study. In addition, subjects' declaration of completion is the end of the experiment.

5.5.2 **Result**

As a result, the subjects were able to produce the target as described in the instruction manual. In addition, there was no behavior such as disassembling the created parts or spending a long time worrying about the creation of the parts. Therefore, it was confirmed that the subjects were able to produce the target using the instruction manual. The first study (without haptic stimulation) took 33 minutes and 52 seconds, while the second study (with haptic stimulation) took 21 minutes and 33 seconds. The difference between them was 12 minutes and 19 seconds. At the beginning of the second study, the subjects exchanged instruction manuals, so both subjects made different parts than in the first study. It is possible that the reduction in production time is due to getting used to the production procedure and a sense of competition due to an understanding of the partner's behavior.

On the other hand, subjects did not converse in either session until near the end of the study. This may have been due to the lack of opportunities for communication in the experimental procedure. For example, it is possible to assemble predetermined production parts using only the parts provided in their own booths. Therefore, there is no need to hand over materials. In addition, they placed the parts in the assembly space when the parts were completed. The users did not assemble in the PAS until all parts were completed, and no conversation occurred. In addition, in both sessions, one user completed all the parts early. This rushed the production of the partner. It is not the purpose of this study to improve the experimental procedure. However, the presence or absence of communication may change the meaning of haptic perception. With communication, the haptic impression received by the users may change from a sense of competition to a sense of co-creation.

5.5.3 **Feedback**

Table 5.4 shows the results of the user questionnaires for each session and the amount of change in user evaluations from Session 1 to Session 2. As a result, the users could not obtain the highest evaluation except for item 10 in Session 1. In particular, items 1, 2, and 3, which involve imagining the other person's actions, did not receive the highest ratings. Subjects were not wearing the noise-canceling earphones used in the walking experiment. We conducted the experiment in an environment in which the subjects could hear the surrounding environmental sounds. This suggests that the subjects did not imagine the actions of the partner by the sound of their movements. In Session 2, the same items were evaluated more highly. That is, haptic presentation triggered the subjects to imagine the partner's actions. In both sessions, there was no change in the evaluation of item 10. It is possible that haptic presentation does not affect the enjoyment of the creative activity. After administering the second questionnaire, we asked the subjects for their impressions of the preliminary study. Both subjects stated that the haptic presentation enabled them to grasp the progress of their partner's work. However, they did not consider the meaning of the haptic sensation. In addition, one of the subjects felt a sense of competition through the haptic sensation. This subject was slower than their counterparts in completing the parts in both sessions. In addition, as described above, there was no opportunity for them to communicate with each other. Therefore, it is possible that the subject perceived the haptic presentation as a competition due to the subject's impatience. As for other feedback, subjects wanted a haptic sense of knowing which partner was making which parts and what their partner was doing in the assembly space. By understanding the parts that a user's partner is creating, it is possible for the user to understand the pace of their own work. Moreover, by understanding the work in the PAS, it is possible to understand whether the partner is producing or assembling the parts. The subjects described their impressions of the device. The subjects found the haptic sensation of the pneumatic actuator difficult to understand, and it was not easy to understand the meaning of the haptic sensation. In particular, they found it difficult to feel the two frontal haptic sensations. As described above, the subjects did not consider the meaning of the haptic sensation. This may be due to the difficulty in feeling the haptic sensation. Based on these opinions, it is necessary to improve the experimental procedure, reexamine the meaning of the haptic sensation, and improve the haptic presentation device. The number of subjects evaluated was two. For the user study, improvements to the system and an increase in the number of participants are likely to change these evaluations.

Table 5.4 Results of Questionnaire Surveys at Each Session.

without Haptic				with Haptic				
session1	A	B	Average	session2	A	B	Average	Average different
Item 1	2	2	2.0	Item 1	3	3	3.0	1.0
Item 2	1	1	1.0	Item 2	5	3	4.0	3.0
Item 3	1	1	1.0	Item 3	5	4	4.5	3.5
Item 4	3	4	3.5	Item 4	4	4	4.0	0.5
Item 5	4	3	3.5	Item 5	4	3	3.5	0.0
Item 6	1	1	1.0	Item 6	1	2	1.5	0.5
Item 7	3	3	3.0	Item 7	4	3	3.5	0.5
Item 8	3	4	3.5	Item 8	4	3	3.5	0.0
Item 9	3	3	3.0	Item 9	4	3	3.5	0.5
Item 10	5	4	4.5	Item 10	5	4	4.5	0.0

5.5.4 Improvements in Experimental Procedures and Devices

Based on the feedback from the preliminary study, we improved the experimental procedure and the proposed device. In the preliminary study, there was no procedure for users to communicate with each other. The activation of communication may make the impression of haptic presentation more positive. We created procedures for users to communicate with each other during the experiment. For example, one procedure allowed users to pass parts to each other during the experiment. To enable this, we designed a procedure in which the subject decides in advance which parts to create. In the preliminary study, we divided the production parts to make the number of squares as even as possible. We then divided the production parts into 16 pieces to make the number of parts to be produced equal in the user study. In addition, we marked half of them in red and the other half in blue. The user selects the parts to create eight parts each, divided into four red and four blue parts. By deciding which parts each user will produce, it is possible that the blocks prepared in advance will be insufficient for production. In such a case, it is necessary for users to pass blocks on to each other. In addition, if a user finishes their own work early, they can help their partner accomplish their work. In this case, the partner receives an instruction manual from the user. We believe that such a procedure will encourage communication between users.

In the preliminary study, users did not care about the meaning of the directional information. This may be because the meaning of the directional information was difficult to understand or because the size of the device and the position of the pneumatic actuators did not match. In addition, users wanted information on the progress of their partner's part production, which parts were being produced, and whether they were working in the PAS. To address this, we improved the device (Figure 5.26). By dividing the device into left and right sections, it can fit the user's neck. Additionally, by placing a silicone tube under the device, the pneumatic actuator contacts the front and back of the user's neck evenly. We also changed the meaning of the four directional information as follows.

Front: Movement when the partner is making a part that can combine with the user's creation part
Back: Movement when the partner is making a part in the PAS
Left: Movement when the partner is making the first half of the eight parts
Right: Movement when the partner is making the second half of the eight parts

This kind of semantics allows the user to grasp the progress of their partner and provides an opportunity to communicate about the assembly of the parts. However, during creative activities, constantly being presented with haptic feedback may become bothersome. Moreover, it can be difficult to discern whether a partner is continuously working on one part or has moved on to another. Therefore, we decided to provide haptic feedback to users three times for each part creation. After three bouts of the same haptic feedback, the next haptic feedback indicates that the partner has moved on to a different part.

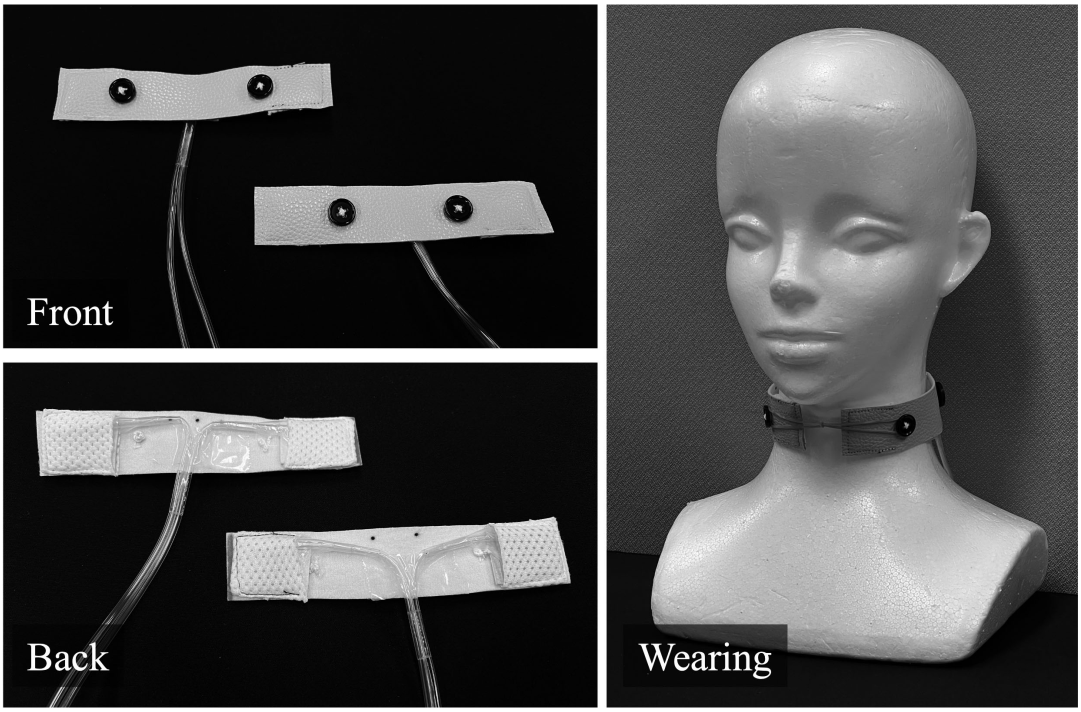


Fig. 5.26 Improved proposed device. The splitting of the device into left and right halves improves the fitting. In addition, we added a pocket on the inside of the device to hold the actuator. This prevents the user from feeling the stiffness characteristic of the film.

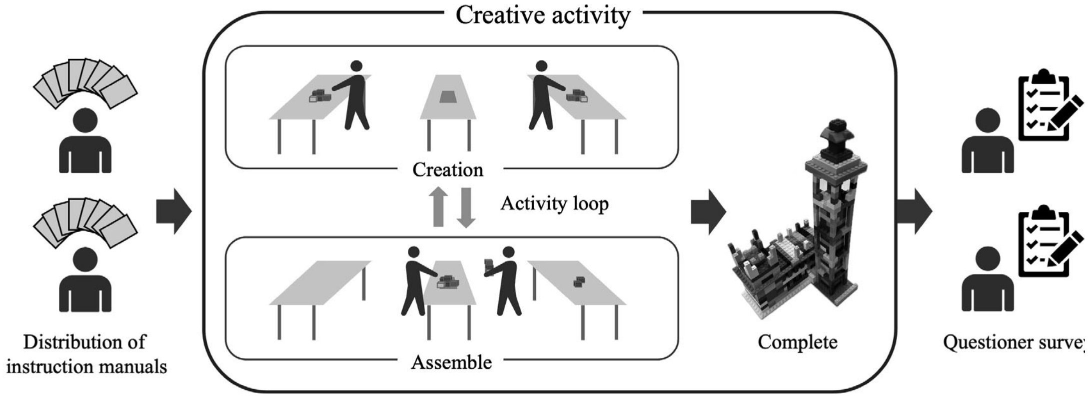


Fig. 5.27 Experimental procedure. We conducted the experiment twice, with and without haptic sensation.

5.5.5 User Study

After improving the experimental procedure and device, we conducted a user study with eight subjects (six males and two females) to compare the proposed system with and without the haptic stimulate. Figure 5.27 shows the experimental procedure. The subjects were in their 20s and 30s. The experimental method was the same as in the preliminary study. Before the experiment, two users selected an instruction manual for the parts to be created. After each session, we conducted a questionnaire survey to evaluate satisfaction with the proposed system and the sense of unity in the creative activity. After both sessions, we conducted a questionnaire survey to compare the evaluation with and without haptic presentation throughout the entire session. We used a 5-point Likert scale (5: Strong agree to 1: Strong disagree) for each item. The survey items are as follows.

1. Did you think you were able to communicate through creative activities?
2. Did you imagine the partner's actions such as making or assembling parts?
3. Did you grasp the partner's actions such as making or assembling parts?
4. Did you imagine which parts the partner is creating?
5. Did you grasp which parts the partner is creating?
6. Did you make any efforts to improve the efficiency of parts production, such as producing parts with a small number of parts or working quickly?
7. Did you imagine the progress of your partner's work during the creative activity?
8. Did you compare your own progress with your partner's during the creative activity?

9. Did you grasp the progress of the partner's creation?
10. Did you get any satisfaction from the partner?
11. Did you have any complaints against the partner?
12. How difficult was it to create the parts?
13. How difficult was it to assemble the parts?
14. How difficult was the creative activity in session 1 (session 2)?
15. Did you enjoy the creative activity?

In addition, we surveyed the following items in addition to the users who rated 5 or 4 in items 5 and 6. Responses are free text.

1-1. What did you feel you were able to communicate?
10-1. What did you find satisfying about the partner?
11-1. What did you find frustrating about the partner?

When conducting the two experiments with and without the system, we divided the subjects into two groups: with haptic (WH) first group and without haptic (WoH) first group (Figure 5.28). This is because if the experience from the first experiment affects the second experiment, it is difficult to determine whether the evaluation results are due to the system or if they are caused by work experience. By dividing subjects into two groups, we can better discuss the usefulness of haptic presentation for creative activities. For example, we can discuss whether the effect of haptic presentation is temporary or lasting.

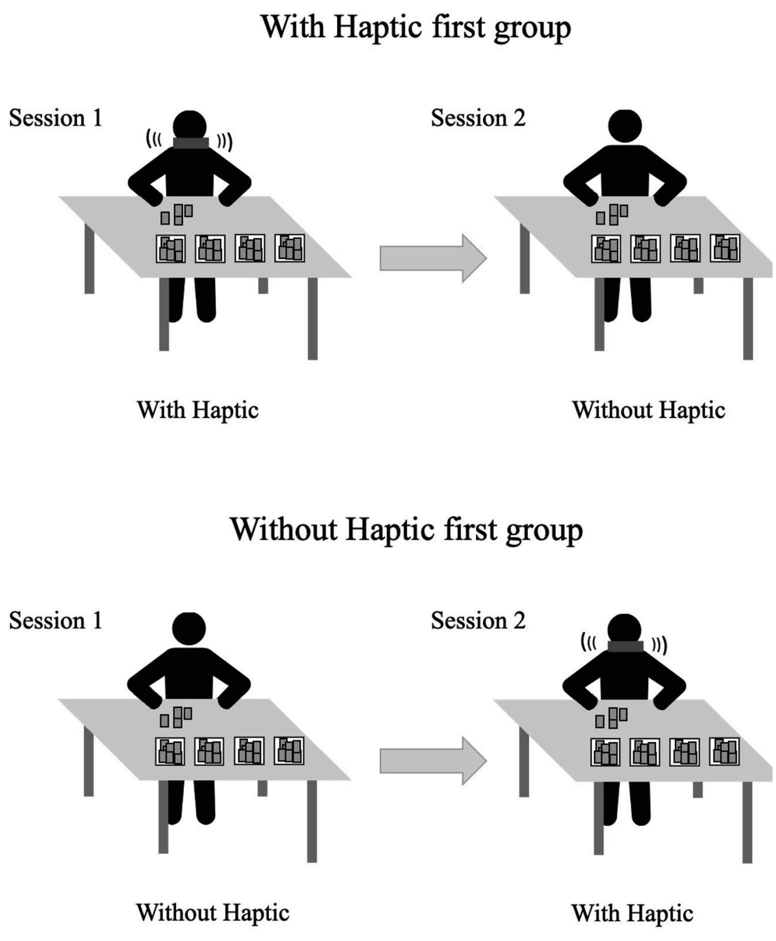


Fig. 5.28 Order of experiments.

5.5.6 **Result of the Creation Experiment**

As a result of user study, three pairs created the object as described in the manual. One of the remaining pairs did not complete one part of the object. When asked about this after the experiment, this pair forgot to create the unfinished part. However, the other parts were produced correctly.

We conducted a haptic presentation experiment just before the start of the user study. We randomly presented the user with the front-back and left-right directions and asked which direction the user's haptic sense indicated. All users clearly perceived the haptic sensation and understood its direction. This clear haptic presentation generated communication between the users. For example, the forward haptic sensation generates communication to assemble the parts. Additionally, by allowing users to select the parts to be created, the users were able to hand over the blocks to their partners. This suggests that the users worked in cooperation with each other. On the other hand, users in all groups did not help their partners create the parts. To help their partner, a user must hand the instruction manual to them, and this action may be too cumbersome for the partner. Therefore, it may be necessary to devise a way to make it easier to hand over the instruction manual. Users who finished making parts quickly assembled and modified parts in the PAS.

5.5.7 **Result of the Questioner Survey**

Based on the results of the questionnaire survey, we analyzed the effects of the presence and absence of haptic presentation on creative activities. First, we analyzed the differences in ratings throughout the experiment. Next, we analyzed the difference between the evaluation of the haptic presentation in both sessions. Finally, we analyzed the differences in the evaluations between the WH first group and the WoH first group. In the analysis, to confirm the significant difference between the WH first and WoH first groups, and because the proposed system targets many users of all ages and genders, we employed Wilcoxon's rank-sum test. WH_{ave} in each table is the average of the evaluation values of each item in the WH first group, WoH_{ave} is the average of the evaluation values of each item in the WoH first group, and A_{ave} is the average of the evaluation values of all users. The variables z and P are the test statistic and the p-value, respectively. The significance level is set at α=0.05. The bold lines in the table show the larger values comparing WH_{ave} and WoH_{ave}, and the underlines show the values for which the p-value was below the significance level. Table 5.5 shows a tabulation of the questionnaire results.

Table 5.5 Questionnaire results.

		WH First Group					WoH First Group				
		GroupA		GroupB			GroupC		GroupD		
		With Haptic (WH)					*Without Haptic (WoH)*				
	Item ╲ User	A-1	A-2	B-1	B-2	Average	C-1	C-2	D-1	D-2	Average
Session 1	1	4	4	4	5	4.2500	2	4	2	2	2.5000
	2	4	4	4	4	4.0000	2	1	2	2	1.7500
	3	4	4	3	5	4.0000	2	2	2	1	1.7500
	4	2	2	5	5	3.5000	1	1	2	1	1.2500
	5	5	4	4	4	4.2500	2	1	2	1	1.5000
	6	4	4	5	4	4.2500	1	3	2	3	2.2500
	7	2	5	4	5	4.0000	3	1	2	2	2.0000
	8	2	5	3	4	3.5000	2	4	3	2	2.7500
	9	4	5	4	4	4.2500	2	4	1	1	2.0000
	10	4	4	3	4	3.7500	2	3	2	3	2.5000
	11	1	1	1	2	1.2500	1	3	1	2	1.7500
	12	5	4	3	4	4.0000	3	2	2	4	2.7500
	13	3	4	2	4	3.2500	3	2	2	4	2.7500
	14	3	4	3	4	3.5000	3	2	1	4	2.5000
	15	4	5	3	5	4.2500	3	2	3	3	2.7500
						3.7333					**2.1833**
		Without Haptic (WoH)					*With Haptic (WH)*				
	Item ╲ User	A-1	A-2	B-1	B-2	Average	C-1	C-2	D-1	D-2	Average
Session 2	1	5	3	3	3	3.500	4	2	5	4	3.750
	2	2	1	2	4	2.250	5	2	5	5	4.250
	3	4	2	3	3	3.000	4	2	5	5	4.000
	4	2	2	1	3	2.000	3	3	4	2	3.000
	5	4	4	3	3	3.500	2	1	4	2	2.250
	6	1	2	4	5	3.000	3	5	5	4	4.250
	7	2	4	4	3	3.250	5	2	4	5	4.000
	8	1	4	4	3	3.000	5	1	4	5	3.750
	9	4	4	4	4	4.000	5	2	4	4	3.750
	10	5	4	3	4	4.000	5	3	4	3	3.750
	11	1	1	1	1	1.000	1	3	1	1	1.500
	12	4	4	3	4	3.750	3	3	2	3	2.750
	13	5	4	4	4	4.250	3	2	2	5	3.000
	14	5	4	3	4	4.000	4	4	2	5	3.750
	15	5	5	2	5	4.250	3	4	5	4	4.000
						3.250					**3.450**

Overall differences between the WH first and WoH first groups Table 5.6 shows the results of the survey. The table shows overall higher evaluations for the trials with haptic presentation. In addition, the evaluation value of WH_{ave} is much higher than that of WoH_{ave} in the items of unity, efficiency, and progress. Moreover, there is a significant difference between the p-values of the WH first and WoH first groups. On the other hand, the evaluation of item 13, which investigated the degree of difficulty, was higher for the WoH first group. This may be due to the haptic presentation at the back influencing the timing of the user's parts assembly. However, the difference was not significant. In the future, it is necessary to increase the number of samples used for evaluation and conduct more accurate analysis.

Table 5.6 Comparison of WH or WoH in each item.

Item	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
WH ave	**4.0000**	**4.1250**	**4.0000**	**3.2500**	**3.2500**	**4.2500**	**4.0000**	**3.6250**	**4.0000**	**3.7500**	1.3750	**3.3750**	3.1250	**3.6250**	**4.1250**
WoH ave	3.0000	2.0000	2.3750	1.6250	2.5000	2.6250	2.6250	2.8750	3.0000	3.2500	1.3750	3.2500	**3.5000**	3.2500	3.5000
A ave	3.5000	3.0625	3.1875	2.4375	2.8750	3.4375	3.3125	3.2500	3.5000	3.5000	1.3750	3.3125	3.3125	3.4375	3.8125
z	1.8593	2.9146	2.5400	2.5641	1.2002	2.3202	2.0584	1.2382	1.6944	1.1107	0.0000	0.1112	0.7149	0.5535	1.0449
P	0.0630	0.0036	0.0111	0.0103	0.2301	0.0203	0.0395	0.2157	0.0902	0.2667	1.0000	0.9114	0.4747	0.5799	0.2961

Difference between Session 1 and Session 2 Table 5.7 shows the results of the survey. Each table compares WH and WoH. Table 5.7(a) compares the ratings in Session 1 for each item, Table 5.7(b) compares the ratings in Session 2 for each item, and Table 5.7(c) compares the ratings in both sessions. Users also experimented with the WH and WoH. That is, the WH users in Table 5.7(a) and the WoH users in Table 5.7(b) are the same. Table 5.7(a) shows that WH was rated higher overall. This is similar to the results presented in in Table 5.6, and there are significant differences in many of the items. In particular, there is a significant difference in all the items concerning the sense of unity. This suggests that haptic presentation contributes to the improvement of the sense of unity in creative activities. However, Table 5.7(b) shows no significant difference in most of the items. Only item 12, which concerns difficulty, showed a significant difference. Comparing Tables 5.7(a) and 5.7(b), we can see that the overall evaluation of WoH in Session 2 is higher than that of WoH in Session 1. This may be due to WoH users in Session 2 gaining work experience from Session 1, and thus understanding the creation process and communication methods. We also observed that users' ratings of items 5, 9, 10, 12, 13, 14, and 15 for WoH in Session 2 were higher than their ratings for WoH in Session 1. It is possible that the impression of the creative activity by the haptic presentation in Session 1 influenced the creative activity in Session 2. However, there was no significant difference in the evaluation of these items between WH and WoH. Therefore, it is necessary to increase the number of samples for more accurate analysis. Table 5.7(c) shows that WH is highly evaluated in each session. In addition, there was a significant difference in the evaluation of WH and WoH in Session 1. This suggests that the users in Session 1 did not have working experience and that the haptic information contributed to their work. On the other hand, users using haptic feedback in Session 1 lowered their evaluation in Session 2. Users without haptic feedback in Session 1 improved their evaluation in Session 2, where haptic feedback was used. This suggests that the haptic presentation function contributes significantly to the high evaluation of creative activities.

Table 5.7 Comparison of WH or WoH in each item between two sessions.

(a) Session 1

Item	1	2	3	4	5	6	7
WH ave	**4.2500**	**4.0000**	**4.0000**	**3.5000**	**4.2500**	**4.2500**	**4.0000**
WoH ave	2.5000	1.7500	1.7500	1.2500	1.5000	2.2500	2.0000
A ave	3.3750	2.8750	2.8750	2.3750	2.8750	3.2500	3.0000
z	2.0555	2.5298	2.3814	2.1385	2.3966	2.3814	1.7860
P	0.0398	0.0114	0.0172	0.0325	0.0165	0.0172	0.0741

Item	8	9	10	11	12	13	14	15
WH ave	**3.5000**	**4.2500**	**3.7500**	1.2500	**4.0000**	**3.2500**	**3.5000**	**4.2500**
WoH ave	2.7500	2.0000	2.5000	**1.7500**	2.7500	2.7500	2.5000	2.7500
A ave	3.1250	3.1250	3.1250	1.5000	3.3750	3.0000	3.0000	3.5000
z	0.8987	2.0128	2.1385	0.8333	1.6476	0.7638	1.2140	2.0128
P	0.3688	0.0441	0.0325	0.4047	0.0994	0.4450	0.2248	0.0441

(b) Session 2

Item	1	2	3	4	5	6	7
WH ave	**3.7500**	**4.2500**	**4.0000**	**3.0000**	2.2500	**4.2500**	**4.0000**
WoH ave	3.5000	2.2500	3.0000	2.0000	**3.5000**	3.0000	3.2500
A ave	3.6250	3.2500	3.5000	2.5000	2.8750	3.6250	3.6250
z	0.4494	1.8209	1.1832	1.5174	1.4979	1.0418	1.0485
P	0.6532	0.0686	0.2367	0.1292	0.1342	0.2975	0.2944

Item	8	9	10	11	12	13	14	15
WH ave	**3.7500**	3.7500	3.7500	**1.5000**	2.7500	3.0000	3.7500	4.0000
WoH ave	3.0000	**4.0000**	**4.0000**	1.0000	**3.7500**	**4.2500**	**4.0000**	**4.2500**
A ave	3.3750	3.8750	3.8750	1.2500	3.2500	3.6250	3.8750	4.1250
z	1.0485	0.0000	0.4583	1.0000	2.0555	1.3481	0.1548	0.7742
P	0.2944	1.0000	0.6468	0.3173	0.0398	0.1776	0.8770	0.4388

(c) Both session

	Session 1	*Session 2*
WH ave	**3.73330**	**3.45000**
WoH ave	2.18330	3.25000
A ave	3.34583	3.35000
z	4.08949	0.54544
P	0.00004	0.58545

Difference between WH first group and WoH first group Table 5.8 shows the results of the survey. Se.1 and Se.2 in Table 5.8 indicate Session 1 and Session 2, respectively. Each table compares WH and WoH. Table 5.8(a) compares the ratings in the WH first group for each item, Table 5.8(b) compares the ratings in the WoH first group for each item, and Table 5.8(c) compares the ratings in both groups for each item. From Table 5.8(a), the evaluation of WH was generally high. Significant differences were found only in item 2, which relates to the sense of togetherness. This suggests that haptic presentation is effective as a means of imagining the partner's behavior. On the other hand, the WH first group was rated higher in Table 5.8(b), with significant differences in several items. The items in which significant differences from the WoH first group occurred were those related to the sense of unity, efficiency, and satisfaction. As described above, this indicates that haptic presentation contributes to users' creative activity. In addition, Table 5.8(c) shows that the WoH ratings for the WoH first group are lower than those of the WH first group. This suggests that the haptic presentation influenced the creative activity in Session 2. The difference between WH and WoH was larger in the WoH first group than in the WH first group, and there was a significant difference. In other words, users who did not use haptics significantly improved their evaluation of creative activities after using haptic feedback. This also suggests that haptic presentation contributes to the creative activity.

Table 5.8 Comparison of WH or WoH in each item between two groups.

(a) WH first

Item	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Se.1 WH ave	**4.2500**	**4.0000**	**4.0000**	**3.5000**	**4.2500**	**4.2500**	**4.0000**	**3.5000**	**4.2500**	3.7500	**1.2500**	**4.0000**	3.2500	3.5000	4.2500
Se.2 WoH ave	3.5000	2.2500	3.0000	2.0000	3.5000	3.0000	3.2500	3.0000	4.0000	**4.0000**	1.0000	3.7500	**4.2500**	**4.0000**	4.2500
A ave	3.8750	3.1250	3.5000	2.7500	3.8750	3.6250	3.6250	3.2500	4.1250	3.8750	1.1250	3.8750	3.7500	3.7500	4.2500
z	1.3748	2.0000	1.5174	1.2386	1.6667	0.9290	1.0485	0.4465	1.0000	0.5000	1.0000	0.5000	1.6536	0.9487	0.3307
P	0.1692	0.0455	0.1292	0.2155	0.0956	0.3529	0.2944	0.6552	0.3173	0.6171	0.3173	0.6171	0.0982	0.3428	0.7409

(b) WoH first

Item	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Se.1 WoH ave	2.5000	1.7500	1.7500	1.2500	1.5000	2.2500	2.0000	2.7500	2.0000	2.5000	**1.7500**	2.7500	2.7500	2.5000	2.7500
Se.2 WH ave	**3.7500**	**4.2500**	**4.0000**	**3.0000**	**2.2500**	**4.2500**	**4.0000**	**3.7500**	**3.7500**	**3.7500**	1.5000	2.7500	**3.0000**	**3.7500**	**4.0000**
A ave	3.1250	3.0000	2.8750	2.1250	1.8750	3.2500	3.0000	3.2500	2.8750	3.1250	1.6250	2.7500	2.8750	3.1250	3.3750
z	1.4230	2.0555	2.0128	2.2468	0.9487	2.0837	1.7860	1.0289	1.6476	1.8580	0.5000	0.1581	0.1548	1.3395	2.0128
P	0.1547	0.0398	0.0441	0.0247	0.3428	0.0372	0.0741	0.3035	0.0994	0.0632	0.6171	0.8744	0.8770	0.1804	0.0441

(c) Both group

	WH first	*WoH first*
Se.1 ave	**3.7333**	2.1833
Se.2 ave	3.2500	**3.4500**
A ave	3.4917	2.8167
z	1.8748	3.7361
P	0.0608	0.0002

Questionnaire survey after the user study After the two experiments, we surveyed the subjects' impressions of WH or WoH. Items 16–19 investigate whether the subjects liked WH or WoH better for each question. In item 20, we asked if they would like to use the haptic presentation function in the future. Figure 5.29 shows a graph of the survey results. The findings reveal that many users prefer the use of haptic presentation in terms of the sense of unity and attractiveness. On the other hand, users felt that they could work at their own pace without the haptic presentation. In addition, there was no significant bias in their particularity in creating parts or in their enjoyment of the creative activity.

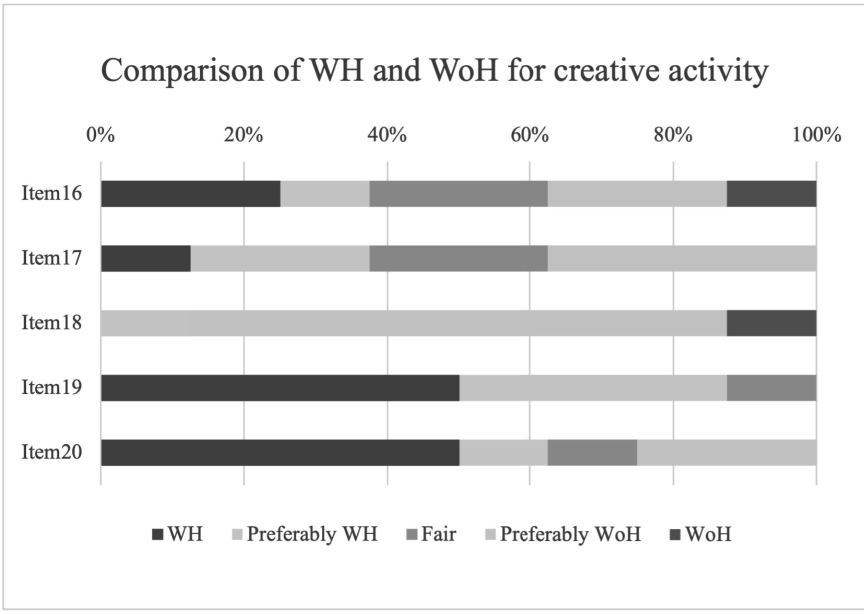


Fig. 5.29 Evaluation result of user study after all experiment.

5.5.8 Discussion

The comparison of WH and WoH evaluations revealed that WH was generally rated higher. Additionally, we found significant differences in some of the items. Thus, it was confirmed that haptic presentation was effective mainly for items related to the sense of unity, regardless of the sequence of WH or WoH.

Difference between Session 1 and Session 2 We found a significant difference in Session 1 and a smaller difference in Session 2 (Table 5.7(c)). In addition, we confirmed that the haptic presentation in the first task did not improve the evaluation in the second task. It was also confirmed that the absence of haptic presentation in the first task significantly improved the evaluation in the second task. This suggests that users are greatly influenced by haptic presentation when they have no prior knowledge of the task. On the other hand, we confirmed that user evaluation without haptic presentation was higher in Session 2 than in Session 1. This may be due to prior knowledge of the users' experience with haptic presentation in Session 1 influencing the work in Session 2. However, when comparing users who used haptic presentation in each session, the evaluation of Session 2 was lower than that of Session 1.

Difference between WH first and WoH first In the comparison of the difference between WH or WoH between the WH first and WoH first groups, the WH first difference was small, whereas the WoH first difference was large enough to be significant. In other words, haptic presentation may be more effective than work experience in improving evaluation. In addition, the WH first group evaluated higher in general. It is suggested that the use of haptic presentation when working for the first time influences creative activity more. As shown in Table 5.9, there was no significant difference between the sessions in the evaluation using haptic presentation. However, the evaluation without haptic presentation was higher in Session 2, and there was also a significant difference. In other words, users' evaluations without haptic feedback in the WH first group were significantly higher than those of users without haptic feedback in the WoH first group. If there is no difference between users' evaluations without haptic presentation in the two groups, it is considered that the effect of haptic presentation in the WH first group does not affect the subsequent work. However, there was a significant difference in the evaluation between sessions without haptic presentation, with a higher evaluation in Session 2. This suggests that the effect of haptic presentation in Session 1 influences the task in

Session 2. In other words, the effect of haptic presentation is continuous.

Table 5.9 Comparison of WH or WoH in both sessions.

	WH	*WoH*
Se.1 ave	**3.7333**	2.1833
Se.2 ave	3.4500	**3.2500**
A ave	3.5917	2.7167
z	1.3081	3.3721
P	0.1908	<u>0.0007</u>

Evaluation by questionnaire survey From the results of items 19 and 20 of the questionnaire survey, we found that users felt a greater sense of unity with their partner when they used the haptic presentation. This may be due to users grasping the meaning of the directional information in the four directions and understanding their partner's actions. On the other hand, many users felt that they could work at their own pace without the haptic presentation. As shown in the evaluation of item 19, when the user understands the actions of their partner, they may adjust the pace of their own creation to match that of their partner. This is an important point in collaborative work, and it is thought that simple tasks change into co-creation. For the items of particularity and enjoyment, there was no significant bias. This suggests that haptic presentation does not directly affect these items. Haptic presentation provides indirect support. It is thought that a user's enjoyment of the creative activity and the particularity of their own creation depend on the amount of communication with their partner and how much interest the user has in the creative activity.

From these discussions, it is evident that the haptic feedback from the proposed device significantly contributes to the sense of unity among users. Furthermore, the haptic feedback is highly effective, and its impact persists in subsequent tasks that do not use haptic feedback. Thus, haptic feedback initiates communication and fosters opportunities for collaborative creation.

5.6 Summary

In this study, we proposed and fabricated a prototype of NaviChoker, an all-surrounding pressure presentation system that utilizes pneumatic actuators. In addition, by conducting a user study focusing on the presentation of walking direction, we confirmed the difference in users' perceptions of the pneumatic actuator and the usefulness of the actuator. In particular, users could perceive the pressure clearly, suggesting that the actuator was sufficiently useful as a device for presenting the direction of walking. At the same time, we expect that the device can be made to provide more diverse tactile presentations by modifying the device. For example, by increasing the number of actuators, it is possible to present sequential haptic sensations to the user's neck. Additionally, by sharpening the contact area between the actuators and the user's neck, we believe that a clearer tactile presentation can be achieved. More than half of the subjects were not satisfied with the wearing comfort of the device; thus, future works can investigate how to address this.

The proposed device can be used for navigation, notification, alarm, and entertainment. For example, for the notification function, it is possible to change the intensity and pattern of the haptic presentation depending on the application and the sender of the message. In addition, by applying various combinations of actuator motions, haptic presentations such as Morse code can be expected to be used as communication tools.

We conducted a creative activity experiment as an application of NaviChoker. This experiment aimed to improve the sense of unity in creative activities through the sharing of somatosensory perception by haptic presentation. Through this experiment, we showed that users were able to imagine the actions of their partners in the creative activity and that they tried to act according to their respective partner's actions by the haptic presentation. We also confirmed that haptic presentation activated communication. These results indicate that haptic presentation using the proposed device contributes to the sense of unity in the creative activity. In addition, the improved device provided a clearer haptic sensation for all users. This will be a useful reference for future device design. The purpose of NaviChoker was originally to provide directional information. However, through experiments in creative activities, we confirmed that the NaviChoker can also present information in the form of symbols. That is, the proposed device enables both directional presentation and information presentation. Users can use NaviChoker in a wide range of situations because they can change the meaning of the haptic sensation depending on the context.

This study focused on improving the sense of unity to prevent a lack of communication and isolation of the creator. This sense of unity also serves as an important element for cooperative creation in production activities. By staging a sense of unity through haptic sensations generated by pneumatic pressure based on the collaborators' production actions, the system aims to facilitate the understanding of the collaborators' situations. In other words, we attempted to facilitate smooth information sharing by understanding the production status. Thus, the proposed method is a staging method for sharing the production status through haptic sensation. We confirmed that the haptic presentation of the production activity enabled the creator to understand the production status of their partner. In addition, by understanding the partner's production status, the user was able to adjust their own production pace and plan opportunities to assemble parts. In other words, grasping their partners' production status enabled the participants to establish cooperative relationships in the production activity. In this way, the proposed method adds seasoning of unity to the act of production. This seasoning leads to an understanding of the production status of the collaborators. In other words, haptic presentation enables production activities that allow for the visualization of a collaborator's situation and facilitate communication. Facilitating communication creates opportunities to share ideas and information. Understanding the status of collaborators' work adds a creative process of collaboration and inspiration to a simple task.

5.7 Future Works

We describe the challenges we found through two types of experiments using NaviChoker. In future work, we can consider the automation of the actuator, linkage with external sensors, improvement of the device, and an increase in the number of test subjects.

Automated operation In future work, it is necessary to automate the operation of the pneumatic actuators. In this study, the actuators were operated manually using the Wizard of Oz method, so it was not possible to quickly change the directional presentation. If the actuators could be freely controlled by automation, it would be possible to finely control the strength, speed, and frequency of actuator inflation. In addition, by increasing the number of actuators, it is possible to consider complex and varied motion patterns and analyze the direction of the pressure felt by the user and what the user perceives the presented pressure to mean. This leads to the creation of new pressure presentations with continuous motion. In addition, it is necessary to design a compact pneumatic circuit to attach an automated pneumatic actuator to a commercially available choker (e.g., Bubble [149]). For example, by using a micropump, a small solenoid valve, and a microcontroller, we can create a device about the size of a palm. The weight reduction and miniaturization of the device are expected to reduce the burden on the user. For this purpose, we aim to develop a device that is smaller and lighter than FlowIO [143] (e.g., dimensions of 50 × 80 × 30)mm and weight of 150.0 g or less, including the main module) for future work.

Linkage with external sensors To utilize the proposed device for various purposes, it is necessary to have equipment suited to each specific application. For example, to understand a user's progress in creative activities, it is essential to use sensors that detect changes in weight when parts are placed on a desk or in response to the pressure of fingers. This can be achieved by using pressure sensors to detect the user's actions. Other situations involving interaction with people and objects also require external sensors. For example, GPS and orientation sensors are necessary for navigation to a destination. A camera and infrared sensor, among other components, are needed to recognize obstacles or maintain social distance. Therefore, we would like to investigate and develop a link between the proposed device and external sensors in the future.

Device Improvements The shape of the actuator used in this study looks like two rectangular pieces of plastic film stacked on top of each other. Therefore, the actuator bulges out from the center. Variations in the haptic sensation perceived by the user can be tuned by designing an actuator to inflate in different ways. For example, we can design the actuator such that the center of the actuator is raised or only the area surrounding the center is raised. Therefore, it is necessary to investigate the differences in haptic perception by users due to the difference in inflation for a clearer and more diverse haptic presentation. In addition, we believe that the improvement of actuators and devices based on the investigation results may lead to an improvement in the wearing comfort of the devices.

Increase in the number of subjects In the creative activity experiment, it was confirmed that the haptic presentation contributed to the sense of unity among users. However, the number of subjects was small, and for some survey items, the test value was zero or the p-value was 1.0. These are rare occurrences and can be attributed to the small sample size. As shown in Tables 5.6(c), 5.7(c), and 5.8, the p-values are small in the evaluation of the difference between WH and WoH and in the evaluation of each WoH session. Therefore, we believe that the trend of evaluation can be confirmed to some extent. However, for more accurate analysis and discussion, it is necessary to conduct analyses using a larger number of subjects in the future.

Chapter 6
Conclusion and Future Work

This chapter concludes each of the studies conducted under this research theme and discusses future issues. The first section summarizes this research, and the second section discusses the contributions of this research to the production activity and knowledge science. In the final section, we present suggestions for future work.

6.1 Summary

The main objective of this thesis is to propose staging methods that encourages collaborative creation using visual and haptic stimuli. In particular, as seasoning for the act of production, we used real-time deformation of distorted images, the projection of animated figures, and the presentation of the act of production through haptic sensation. These seasonings provide effects such as clarification of the finished image of the production object, understanding and sharing of efficient production methods, and understanding of the production status of the collaborators. These three methods aim to present information that enables creators to easily grasp the production target, intuitively interact with it, and understand the actions of partners.

6.1.1 Information presentation by projection mapping

The first method aims to achieve a more natural behavior interaction with virtual contents. In this study, we propose a head-mounted three-dimensional image projection system that presents 3D images to users without using any physical displays, such as smartphones or AR glasses. By projecting anamorphosis that deforms according to the position of the user's head, the system constantly presents 3D images to the user and improves the visual presence of the virtual contents. The head-mounted device is helmet-shaped and weighs approximately 550g. In addition, a depth sensor attached to the device recognizes users' hand movements. As a result, users were able to feel the three-dimensionality and presence of the projected contents. In addition, users could grab and stack the projected contents with natural movements.

The second approach aims to realize parts creation support using interactive information. In this study, we propose a method that appropriately decomposes the virtual objects to be created and reproduces individual parts of the decomposed virtual model as entities. The proposed method enables large-scale creative activities that are difficult to achieve with 3D printers and existing information projection technology. Specifically, the proposed method projects guidance information that enables easy understanding of the placement of materials in the creation process. To realize this system, we propose a layered projection mapping technique. The proposed system divides meshes using the approximate pyramid decomposition method and projects cross-sections of the decomposed parts as numbers. This makes it possible for ordinary creators without specialized skills to easily create large-scale models. Using the proposed system, we conducted experiments to create a virtual model of a hemisphere and a rabbit made of balloons. In the hemisphere production experiment, we conducted production activities with and without the system. Using the proposed system, it was confirmed that it was possible to create a hemisphere that was closer to the pre-defined target size and shape. In the experiment of creating a virtual model of a rabbit, it was possible to create a balloon art of approximately 150 cm in height without any interruption to creative activities.

The above studies are information presentations for "objects." The first method has intangibles, and the second approach has tangible information. Therefore, the former does not require a specific projection object, while the latter targets materials used in production. For interaction with free movement, there should be no limited information projection that interferes with free movement. To support the act of creating parts using materials, it is important to project information directly onto the materials and present interaction procedures. That is, we positioned the first method as a presentation of information to provide guidance on the production target to be created and to promote the understanding of its finished image. Additionally, we positioned the second method as the presentation of information to promote the understanding of how to actually create the parts. In this way, the two approaches added a seasoning to the visual information to facilitate production process.

6.1.2 Presenting haptic stimulus location by haptic presentation

The third approach aims to present the direction of an object's presence to the user. To present the direction of presence using haptic feedback, we propose a haptic presentation system that uses a small pneumatic actuator to present the direction to users' necks. Physical stimulation of the skin is an effective means of presenting a sense of presence to the user due to its clarity. Therefore, haptic presentation technology can be used in various ways, such as reproducing the sense of touch of virtual objects and guiding the users' actions. To solve the problems of existing methods, such as the complexity and large size of devices, we developed a choker-type device that uses a small and easy-to-produce pneumatic actuator and can be used in daily life. Using the proposed device, we conducted an experiment on co-creative activities to determine whether creators could comprehend their partner's actions. Creators depend on haptic feedback from pneumatic actuators, operated individually, to understand their partner's movements and progress. As a result, creators were able to grasp their partner's movements and the progress of their creation, allowing them to adjust the pace of their own creation and engage in communication. In this way, the proposed method added seasoning to the haptic information to enhance the sense of unity among creators. Another application of the proposed is navigational purposes. Users can discern their walking direction via haptic feedback from pneumatic actuators operated individually. The proposed device enables users to sense the presence and direction of other users or objects. By providing both directional and partners' action information, it offers versatile applications depending on the situation.

6.2 Contributions

It is expected that the results obtained from this study will contribute to creative activity and knowledge science. This section discusses these contributions.

6.2.1 Creative Activity

Co-creation is an activity that fosters the creativity and intelligence of creators and provides a platform to communicate with others. As described in Chapter 2, an increasing number of events are providing opportunities to experience creative activities using digital technology. In addition, creative experiences are being delivered through familiar devices, such as smartphones. Moreover, collaborative creation allows ideas and information to be shared and combined. Therefore, collaborative creation, in which creators work together to achieve a common goal, gives them a sense of accomplishment and unity in their creative activities and brings about a fulfilling creative experience. Thus, when creators cooperate with each other in production activities, they can promote communication, reduce stress, and share a sense of accomplishment. However, the level of knowledge, experience, and skill in creation varies from person to person, which can lead to discrepancies in the information shared and variations in the progress of the creation process. This makes it impossible to have a fulfilling production experience through collaborative creation.

In this thesis, we propose three methods of presenting information to support production. These methods support important elements of collaborative activities among creators by providing a direction that encourages collaboration. For example, the study of anamorphosis image projection provides a way of interacting with virtual objects in natural motion by projecting realistic images. It revealed that real-time deformation of the anamorphosis image improves the realism of the projected contents. This makes it possible to see and interact with the projected contents in the same way as a real object. This effect makes it possible to observe the real object as if holding it in one's hand and contributes to clarifying the image of the finished production target, which is necessary for collaborative creation. This induces knowledge sharing among creators. The study of layered information projection simplifies the production process by projecting information directly onto the material. It revealed that the interactive presentation of the production process by information projection enables accurate placement of materials. The proposed method can be reproduced in the real world using common materials, such as balloons, plastic bottles, and cans, by processing the object in the computer. This generates creative value in the form of artistic expression and new designs and induces collaboration among creators. The study of haptic presentation allows creators to understand the actions of collaborators from four directions. This provides an opportunity for creators to work while being aware of each other. Through production experiments, it became clear that understanding the actions of others through haptic presentation improves the sense of unity by allowing creators to imagine the situation of collaborators. This results in the prevention of creators' isolation and encourages conversation by matching the pace of production. It also enables the sharing of ideas and information necessary for collaborative creation and contributes to the establishment of cooperative relationships. This encourages communication among creators.

These methods focus on some of the key elements for collaborative creation in production activities. They do not restrict the creators' actions, nor do they use extensive systems. They also provide a way of understanding and sharing the image of the finished product, the production process, and the efficient production method, and guide goal achievement through collaboration. Experiments to confirm these results showed that the system performed well. Therefore, it is expected that the creation of opportunities for cooperative creation using visual and haptic stimuli enables the sharing of a sense of accomplishment and enjoyment of production and the realization of fulfilling production activities.

6.2.2 Knowledge Science

The method used in this thesis presents information for creative activity support. The user recognizes the presented information. Then, they understand their impressions and actions toward the object to be created and others through interpretation and imagination. Therefore, the production support information used in this thesis can create new interactions and communications.

In the study of anamorphosis projection, the real-time deformation of the projected image adds the value of a three-dimensional effect to the flat projection image. Users were able to interact with the projected contents with natural movements and obtained a sense of its reality. In production activities, the complexity of an object's shape and its large size can make it difficult to grasp the finished image of the object in advance. If it is difficult to grasp the image of the finished product in advance, it is also difficult to grasp the structure of the object and to devise a production process. This may lead to a decrease in motivation for those who are unfamiliar with production activities. The proposed method for creating a three-dimensional effect allows the user to see the projected contents as if it were a real object. Thus, the creator can observe the contents of the projection as if holding a real object and can understand and interpret the contents while acquiring information about the production object. In this way, creators gain insights into the production subject, and the understanding and interpretations become knowledge. This knowledge leads to a preliminary understanding of the finished image of the object to be created. Through observation, the creator understands the characteristics and structure of the object and is able to devise the design and process of production. This contributes to knowledge creation.

The study of layered projection mapping gives value to objects as a medium for presenting information at each layer. This allows the user to obtain visual information directly from the object. The system presented the production process to users by dividing the model to be created into sections and visualizing the sections of the divided model as numbers. The projected numbers change according to the height of the balloon, and an animation is played. The user places the balloon in the correct position based on the numbers projected on the balloon. In this way, the real-time recognition of the balloon's position and height and the presentation of the production process motivate the user to place the balloons correctly. In other words, the user searches for the correct position to place the balloon. By searching, the user's ambiguous production process and balloon placement positions become accurate. In this way, the user understands how to create a three-dimensional object by understanding the production process. This leads to creative values, such as artistic expression and new designs.

In the haptic presentation study, we developed a device that presents a sense of touch to the user. Sharing users' production actions as tactile sensations improved the sense of unity between users. By inducing a pressure sensation by inflating four pneumatic actuators on the user's neck, the user was able to recognize eight directions: forward, backward, left, right, and diagonal directions. We confirmed the usefulness of the proposed device in a walking experiment. In the creative activity experiment, we presented haptic sensations from four directions to the user to share the collaborator's creative act. This enabled the user to understand the status of the collaborator's creation. We also found that understanding the situation led to adjustments in the pace of the creator's production and to conversation. In other words, by communicating the act of creation through the haptic senses, the creator can conduct production activities while imagining the situation of partners. This enables the sharing of ideas and information, contributes to the building of cooperative relationships, and facilitates the creative process of collaboration and inspiration. The use of information and ideas obtained through sharing for common goals leads to the co-creation of knowledge.

In this way, the knowledge gained through the experience of projection and haptic presentation induces active user behavior and communication. This leads users to utilize their knowledge in creative activities and share it with others. The repetition of such actions creates new knowledge and enables the substantiation of new ideas. Facilitating collaborative creation is an important research approach for human communication. It is expected that the outcomes of these studies will contribute to knowledge science.

6.3 General Conclusions and Future Work

In this thesis, we propose a support method for elements that are important for multiple cooperative creations. In particular, we focused on clarifying the finished image of the production object to understand the common production goal, realizing large-scale production to recognize and share efficient production methods and improving the sense of unity to prevent lack of communication and isolation of creators. To achieve this, we aimed to present users with production support information using projection mapping and pneumatic actuators for visual and haptic stimulation.

The approach and outcomes introduced in this paper represent the early stages of a long-term research project. The next step is to enable more people to engage in collaborative production activities smoothly. To this end, we need to delve deeper into the elements of collaborative creation and consider appropriate support methods that align with the skills and experience involved in production activities.

Creation support through intuitive interactions We propose a system that projects distorted images that deform according to the user's head movements and enables virtual contents to be overlayed more naturally in the real world. By constantly presenting stereoscopic images according to the creator's viewpoint, the creator is able to grasp the shape and scale of the object to be created in advance. In addition, we propose a method to support the creation of parts using interactive information and presented the process of creating parts to users. The results of this research make it possible for even those unfamiliar with production activities to easily engage in them. The approach and results reported here are the first phases of a long-term research project. At this stage, there are very few examples of applications and some limitations in interaction. The goal of the next phase is to produce a system with several applications and interactions and study further possibilities of the proposed system. For example, in a study concerning the projection of distorted images, it is possible for multiple people to view 3D images simultaneously by creating a device using Polymer Dispersed Liquid Crystal (PDLC) film [150]. This film becomes transparent or opaque with the switching on or off of an electric current. This is achieved by operating the PDLC film at the same interval as the refresh rate of the distorted image presented to the user (Figure 6.1). Device improvement makes it possible to present images according to their skills, experience, and role in the production activity.

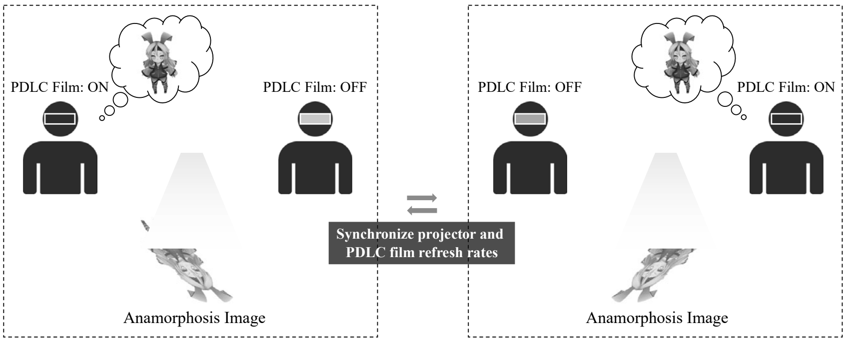


Fig. 6.1 Display of an anamorphsis image for multiple people.

Improved sense of togetherness through shared somatic sensation We propose a haptic presentation system using air pressure, which can present a total of eight directions to the user: forward, backward, left, right, and in diagonal directions. Future works include the possibility of automating the device. We expect that the proposed device can be used for navigation in noisy environments and can serve as a notification function for information terminals. In addition, we found that the creative activity experiment improved the sense of collaboration. This is expected to become a new way of communication. This study is still in the preliminary stage, and experiments on the strength of the haptic sensation and the method of presentation from the perspective of the user's skin sensation are still needed.

In the future, we will improve the three proposed systems to discuss more deeply the production of opportunities for collaborative creation. For the SAR method, we will reconsider the information projection equipment used and the method of projection. In addition, we will develop a method to present the presence of virtual content and effective production procedures to users. For the haptic presentation method, we will reconsider the haptic presentation points and presentation methods. Reconsideration of points and presentation methods is for further utilization of haptic presentation and more effective patterns of haptic presentation. In the study of anamorphosis image projection, a depth sensor and small projector are connected to the computer by a long cable. In the haptic presentation research, a long silicone tube is connected to the air pressure source. Although the long cables did not restrict users' actions, they may hinder users' actions in actual production activities. Therefore, it is necessary to make the devices wireless. In this way, future challenges will include improving systems and devices, further exploring the elements necessary for collaborative creation, and considering appropriate support methods tailored to the skills and experience in production activities.

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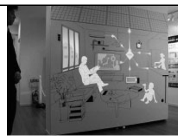
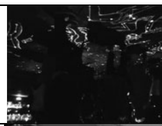
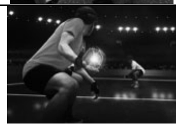
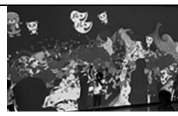
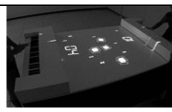
Appendix A
List of Digital Attractions (Chapter2)

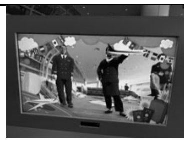
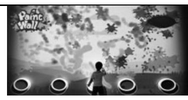
Examples of digital attractions are shown in Table A.1.

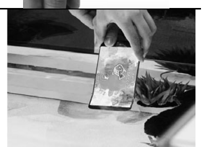
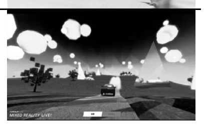
Table **A**.1 Examples of digital attractions.

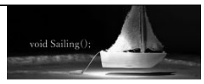
1	**Flying Paint** (https://flyingpaint.canvas-works.jp) Coloring and drawing activity using coloring pages. The pictures are displayed on the screen and move around.	
2	**NURIE STADIUM** (https://nurista.canvas-works.jp) A coloring book-style battle of insects. The user shakes a handheld device to control the bugs on the screen.	
3	**PhotoPhoto** (https://photophoto.canvas-works.jp) Sharing a favorite photo displayed on a monitor that shows a Christmas tree, a shrine, or similar scenes.	
4	**AR Zoo** (https://pro-radix.co.jp/tron/ar-zoo/) Synthesizes real-time camera footage with animated animals (CG animation) and displays it on digital signage	
5	**Eco Link** (https://www.siminplaza.co.jp/?tid=104282) Projection mapping at an ice-skating rink. Capable of projecting images suitable for different seasons.	
6	**Historical Experience AR** (https://www.nissha-comms.co.jp/products/ar_vr/articles/arscene1.html) Pointing a smart phone at an exhibit triggers the display of information, animations, and sound.	
7	**Cross Shinjuku Vision** (https://shinjuku.xspace.tokyo) Displaying three-dimensional images on a giant signage installed on a building. It includes effects such as talking to passersby.	
8	**Sekisui House's Projection Mapping** (https://www.canvas-works.jp/【制作実績｜セキスイハイム-様-常設型デジタル展/) As a sales tool, an interactive 'Touch and Learn Projection Mapping' has been introduced. Panels installed inside a model house feature illustrations of a living room, and various points are equipped with touch points (switches that start a video when touched).	
9	**Snow White Magic Mirror Digital Signage** (http://oh-ooh.com/?p=993) A mirror-shaped digital display is installed, inspired by the Magic Mirror from the movie 'Snow White'. When someone is reflected in the mirror, a message appears saying, 'My Queen, you are the fairest of them all.'	
10	**FXMIRROR** (http://www.fxmirror.net/en/main) A digital fitting system equipped with a large display and a camera that shows the full body. It reflects the user's facial expressions and body movements in real-time, allowing them to objectively see themselves wearing the outfits.	

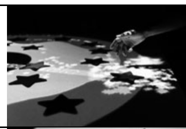
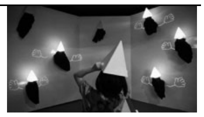
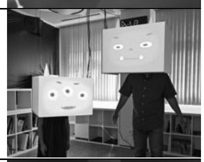
11	**Komaki Starlight Dome** （https://waivan.jp/wp/komakiekimae-illumination2017/） Using a smartphone, constellations appear in the dome's sky. It's a unique illumination that showcases the distinctiveness of Komaki, a city known for its aerospace industry.	
12	**Floor Planetarium** (https://toyamadays.com/archives/21004746.html) Digital art where constellations shine on the floor."	
13	**Sunari Festival VR Experience** （https://www.canvas-works.jp/vr プロジェクションマッピング須成祭/） Expressing the UNESCO Intangible Cultural Heritage 'Sunaari Festival' through VR and projection mapping.	
14	**HADO** (https://hado-official.com/) A futuristic sports activity 'HADO' that incorporates AR technology. Players wear a head-mounted display and arm sensors, enabling them to unleash special moves in sync with their body movements. It brings the world of magic to life with an overwhelming sense of presence.	
15	**Maybe? Ghost Shooting Gallery** (https://partners.eventbank.jp/case/3278/1228/) A large-screen shooting game that combines the fun of shooting down prizes in a shooting gallery with the excitement of a gun-shooting game where you defeat ghosts one after another. It's a digital shooting game that merges these two enjoyable experiences.	
16	**Robot Ride Car Shooting** （https://cerca-inc.com/その他/自動追従ロボット/ライド/） Scans the space and sets a course. A ride car that does not require rails or lines. It can also be combined with VR or MR technologies.	
17	**Water Screen** (https://partners.eventbank.jp/case/3259/1228/) An installation using a water screen, where fine control of water jets creates a screen. It projects 3D images representing the four seasons of Japan from projectors.	
18	**AR Mirror World** (https://partners.eventbank.jp/case/2913/1228/) In this setup, another version of oneself appears on the monitor or screen, as if reflected in a mirror. It allows for a unique experience where you can mimic yourself or play together.	
19	**Magic Touch Wall** (https://partners.eventbank.jp/case/2912/1228/) A content where touching illustrations drawn on the wall brings them to life. For instance, touching a clown starts it juggling, and touching a bird makes it fly away, thus animating the drawings.	
20	**Huis Ten Bosch Projection Mapping** (https://partners.eventbank.jp/case/2889/1228/) Large-scale projection mapping displayed on 'Stadhuis,' a reproduction of the city hall in Gouda, Netherlands, located in Huis Ten Bosch. It projects beautiful scenes of blossoming flowers and other impressive visuals.	
21	**The Great Magic Wall** (https://www.tanaka-denki.co.jp/biz-emo/product/asobeats/) "In front of the Great Magic Wall, when you move your hands or body, characters move in response and effects like stars appear. It's also possible to take photos on the spot and display facial photos.	
22	**Digital Coloring Circuit** (https://partners.eventbank.jp/case/2526/623/) Users can create own original car and make it appear on the circuit. After freely coloring a car and completing it, scanning it with a scanner makes it appear in 3D on the circuit.	
23	**Interactive Digital Art** (https://partners.eventbank.jp/case/2455/623/) Digital art where touching butterflies, petals on a huge wall, or fish in the water on the floor makes them move or approach humans, offering various interactive elements. Not just for viewing, but also for experiencing and playing.	

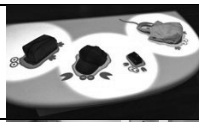
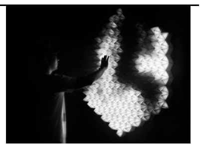
24	**Animal Chase** (https://www.tanaka-denki.co.jp/biz-emo/product/asobeats/) A piece where you can play tag with animals and various patterns projected on the floor. The animals and patterns run away or disappear.	
25	**Tsumiki DE Rhythm** (https://www.tanaka-denki.co.jp/biz-emo/product/asobeats/) By freely arranging blocks on a table, various rhythms can be created. Allows for the creation of unique rhythms	
26	**Cajon DE Game** (https://www.tanaka-denki.co.jp/biz-emo/product/asobeats/) A rhythm game using a cajon. Two players cooperate to hit arrows that appear one after another.	
27	**Keyboard Hockey** (https://www.tanaka-denki.co.jp/biz-emo/product/asobeats/) A new sensation competitive hockey game using a keyboard. Players hit the keys in time to get more balls into the opponent's goal for a win.	
28	**Aiming Music Box** (https://www.tanaka-denki.co.jp/biz-emo/product/asobeats/) A game where you use your shadow projected on the screen to catch falling notes into a music box. Catching many notes produces beautiful melodies and mysterious sounds.	
29	**Panet Hunt** (https://www.tanaka-denki.co.jp/biz-emo/product/asobeats/) A game where you hit balls at planets appearing on the wall to save many planets. After the game, overall power and level are displayed.	
30	**Rhythmic Drum** (https://www.tanaka-denki.co.jp/biz-emo/product/asobeats/) A cooperative rhythm game where players play instruments with sticks to the music. Aim for a high score by hitting arrows that fall from above in time with the music.	
31	**Trampolism** (https://www.tanaka-denki.co.jp/biz-emo/product/asobeats/) Jumping produces mysterious sounds and LED lights that synchronize and light up.	
32	**Planet Chase** (https://www.tanaka-denki.co.jp/biz-emo/product/asobeats/) Playing tag with planets and aliens projected on the floor makes mysterious sounds, and the aliens run away or disappear.	
33	**Drawing Paradise** (https://eventsolution.techceed-inc.com/oekakiparadise/) Scanning a colored drawing makes it appear and move within the projected image on the wall.	
34	**Paint Sandpit** (https://eventsolution.techceed-inc.com/paint-sunaba/) Art that creates various visual expressions by recognizing the shape of piled or carved sand with a depth sensor. The content of the projection changes with the height and depth of the sand, creating mountains and seas.	
35	**Bubble Touch** (https://eventsolution.techceed-inc.com/bubble-touch/) An installation where touching the displayed image creates or bursts bubbles, changing the image according to the touched bubbles.	
36	**Virtual Aquarium Experience** (https://eventsolution.techceed-inc.com/archglass/) An experience using AR glasses to explore an aquarium. Allows for summoning creatures and feeding them through gesture input.	
37	**DINO Race & Craft** (https://www.asobiski.com/dino-race) A game where you scan a dinosaur coloring and participate in a race. You can make the dinosaur run by stepping on a foot panel shaped like dinosaur footprints	

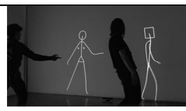
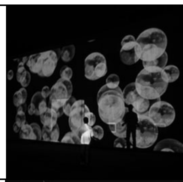
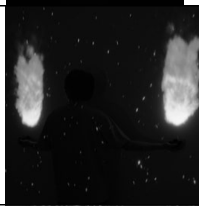
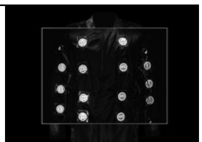
38	**Sky Work Costume - Transformation Signage** (https://partners.eventbank.jp/case/2071/561/) When a person appears on screen, the camera detects them and displays an airplane pilot's uniform matching their height. It also recognizes side profiles, showing the side view of the uniform. The transformation adapts to both adults and children.	
39	**Ball Game** (https://www.sasuke-interactive.com/contents/ballgame.html) A game where you protect a baby jellyfish engrossed in food by hitting enemies with a ball. There's no limit on the number of players, and the playtime is 1 minute.	
40	**Digital Aquarium** (https://www.sasuke-interactive.com/contents/aquarium.html) Paint your favorite fish, scan the drawing, and it appears swimming in a large projected ocean. You can also drive away predators by touching the screen. There's no limit on the number of players or playtime.	
41	**Paint Wall** (https://www.sasuke-interactive.com/contents/paintwall.html) Use a controller to graffiti on a wall. Choose colors from a tablet and paint on the screen. When 80% or more of a model like a car or airplane is painted, it changes its movement and flies away. Suitable for 1-3 players, with no set playtime.	
42	**Message Tree** (https://www.sasuke-interactive.com/contents/messagetree.html) Messages written by visitors are scanned and displayed on a screen, becoming part of a large tree. This participatory digital content turns many messages into a large tree, providing a memorable experience. There's no limit on the number of players or playtime.	
43	**RUN!RUN!RUN!** (https://www.sasuke-interactive.com/contents/run.html) "Choose a course, and a character appears to race with you. A foot sensor detects your running, moving the characters from left to right on the screen as you run. Suitable for 1-3 players, with a playtime of 1 minute.	
44	**Samurai SWORD** (https://www.sasuke-interactive.com/contents/samuraisword.html) An action game where you swiftly cut objects like fruits, monsters, and trees. Objects range from tiny rice grains to huge planets and treasure chests. Suitable for 1 player, with a playtime of 1 minute.	
45	**GET at UFO!** (https://www.sasuke-interactive.com/contents/ufo.html) Control a UFO on the screen by moving your hands. The faster you move, the faster and higher the UFO goes. Collect icons for points. Suitable for 1 player, with a playtime of 1 minute.	
46	**Balloon Fantasy** (https://www.sasuke-interactive.com/contents/balloon.html) An interactive content where moving hands and feet makes projected balloons bounce or burst. Suitable for 1-3 players, with no set playtime.	
47	**Moving Art** (https://www.sasuke-interactive.com/contents/movingart.html) Perform actions in front of framed famous paintings to make them come to life, revealing the artist's intent and hidden mysteries. It's an experiential way of appreciating art. Suitable for 1 player, with no set playtime.	
48	**Digital Tangram** (https://www.sasuke-interactive.com/contents/tangram.html) "An educational game where you fit 7 blocks into projected silhouettes on a table. Once complete, the blocks are colorfully illuminated, and the arranged objects like rockets or dinosaurs come to life. Engaging for both kids and adults. Suitable for 1-4 players, with no set playtime.	
49	**My Motion** (https://www.sasuke-interactive.com/contents/mymotion.html) A system that senses the movement of hands and feet, causing various changes like drawing trails or displaying effects. The changes automatically vary every few seconds. Suitable for 1-3 players, with no set playtime.	

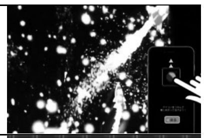
50	**PhotoShuShu** (https://shushuevent.studio.site) An interactive feature called 'Photo Shushu' where photos taken with a smartphone are 'whooshed' onto a screen.	
51	**The Sound of Mingling** (https://www.c-and.info/mingling) A digital art piece that changes visuals in response to sound. It identifies pitch and volume, altering the hues of ink.	
52	**Laser Gun and Sensor Survival Game** (https://partners.eventbank.jp/case/1783/730/) Laser guns with built-in speakers produce powerful gunshot sounds. With added vibrations and lights, it feels like experiencing a real-life video game.	
53	**VR Hang Glider** (https://valeur3.com/vr-hangglider/) "Offers a realistic flying experience using actual footage of flying through the sky. Participants hold onto a real hang glider fixed to the ground. Play-time is 2 minutes for 1 player.	
54	**VR Wheelchair Marathon** (https://valeur3.com/vr-wca/) Uses real footage of a wheelchair marathon for an authentic experience. Participants sit in an actual wheelchair fixed to the ground. Playtime is 20 minutes for 1 player.	
55	**VR Hot Air Balloon** (https://valeur3.com/vr-hotairballoon/) Provides a realistic experience of flying in a hot air balloon using actual footage. Participants board a real hot air balloon fixed to the ground. Play-time is 60 minutes for 1-4 players.	
56	**GITAL GOLDFISH SCOOPING** (https://www.aid-dcc.com/works/dgs/) Participants submerge a 'Galaxy S7 edge' into a 60-inch water tank at the booth. Goldfish appear on the device screen, and tilting the device controls their movement. The game uses sound and vibration for a realistic sensa-tion.	
57	**Virtual Golden Ratio Pouring** (https://www.aid-dcc.com/works/ogonhisosogi/) A web content where users tilt their smartphones to pour virtual beer, aim-ing to match a pre-set ideal pouring guide. The difference between the guide and the actual tilt and timing determines the result, scored in 10 stages. It uses liquid physics simulation and gyro sensors.	
58	**Asobi Glico** (https://www.aid-dcc.com/works/asobiglico/) Recognizing animal toys with a smartphone or tablet camera, the recog-nized toys move around the screen. It's a simple, touch-based experience designed to be intuitive and engaging for children.	
59	**DRAW and RELEASE** (https://www.aid-dcc.com/works/drawandrelease/) Draw on a smartphone screen using a dedicated app, then submerge it in a water tank at the booth. The drawing comes to life and moves from the smartphone screen to a monitor installed below the tank.	
60	**COROLLA! presents MIXED REALITY LIVE!** (https://www.aid-dcc.com/works/toyota_corolla/) A world-first MIXED REALITY LIVE experience, blending reality and vir-tual through goggles. The audience participates in the live event using spe-cial goggles (Hacosco), experiencing a unique mix of real space and 360-degree virtual reality.	
61	**Shadowing** (https://chomkorosier.com/about.php) Records shadows under a streetlamp and presents them to other passersby. It allows people to encounter someone who was there at a different time and leave their own shadow for the next person.	

62	**Quantum Space** (https://www.breezecreative.com/quantum-space) An interactive projection mapping on all walls of a room, creating real-time abstract visual expressions based on participants' movements and automated parameters.	
63	**Multiple Shadow House** (https://olafureliasson.net/artwork/multiple-shadow-house-2010/) An installation with a wooden frame and semi-transparent projection screens as walls. The screens are lit by differently colored lamps, creating vivid monochrome hues. Visitors entering this structure cast overlapping colored shadows on the walls.	
64	**Immersive Shadow: Bubbles** (https://www.artagenda.jp/exhibition/detail/8312) An interactive experience where you can touch and bounce colorful balls projected on the wall using your shadow.	
65	**Yubisaki ni Saku** (https://ponboks.com/playworks/yubisaki/) Moving your hand in front of the wall creates kaleidoscope-like, multifaceted floral patterns. Anyone can create unique flower shapes, regardless of their drawing skills.	
66	**Shadow+** (https://www.artagenda.jp/exhibition/detail/8312) Enjoy a mystical space where geometric patterns and vivid colors appear within your shadow, blending shadows and visuals.	
67	**Collision and Dispersion** (https://www.artagenda.jp/exhibition/detail/8312) Chase after many fragments spread on the floor, and they will gather or scatter based on their shape and color.	
68	**Throw, Hit, Spread** (https://www.nzu.ac.jp/blog/digital/nageru_consept) A playful installation where throwing balls at a 40-panel wall with sensors triggers the spread of images and sounds from each panel.	
69	**Fantasy Theater** (http://teruaki-tsubokura.com/works.php?ar_id=19) A theater featuring phantom creatures. Standing on stage, participants transform into legendary creatures and freely enact their stories.	
70	**void Sailing();** (http://teruaki-tsubokura.com/works.php?ar_id=18) A work depicting a small sailboat floating on water. However, the water is not real, and the boat sails on the imaginary waters created by human imagination.	
71	**Fantasy Diorama** (http://teruaki-tsubokura.com/works.php?ar_id=17) Running toy cars on a table creates roads and landscapes behind them. Flying them in the air transforms them into airplanes or helicopters, and linked cars become trains. This work visualizes the world of imagination created by children playing with cars.	
73	**Invisible Sculpture** (http://teruaki-tsubokura.com/works.php?ar_id=15) An empty display stand with a palpable presence. This art invites viewers to search and imagine the shape of an invisible sculpture. It explores the boundary between reality and virtual reality (VR), focusing on how the brain interprets the presence of something that doesn't exist.	
74	**Achromatic World** (http://teruaki-tsubokura.com/works.php?ar_id=14) A narrative-participatory live painting show. Participants enter a giant storybook world, chasing a shadow girl named 'Silue' who stole colors from forest animals. The immersive space features 20m long projection mapping, lighting, 3D sound, wind, bubbles, scents, and floor vibrations.	
75	**During the Night** (http://teruaki-tsubokura.com/works.php?ar_id=16) Expands the concept of live painting into a story with a beginning, middle, and end, similar to a play or movie. The audience physically experiences accidents and incidents in the story and helps complete the painting, thereby eliminating the distance between the artist and the viewer.	

76	**Tsukumogami** (http://teruaki-tsubokura.com/works.php?ar_id=10) Standing in front of the screen and moving allows you to see 'Tsukumogami' forms. The work represents human figures using discarded objects, encouraging viewers to reconsider the importance of treasuring possessions.	
77	**Vertexceed** (http://teruaki-tsubokura.com/works.php?ar_id=9) In the 3D CG world, everything is made of triangles formed by three 'vertices.' This work explores these vertices as the origin of the digital space, connecting the real and digital realms. By touching multiple 'vertices' on the wall, users can 'exceed' (go beyond) the real space into the digital.	
78	**Nanairo Komichi** (http://teruaki-tsubokura.com/works.php?ar_id=7) What appears to be a simple path becomes interactive when people walk on it, with colors and lights emanating and blending with those from others. The resulting art changes over time and can never be seen in the same way again.	
79	**Shadow Touch** (http://teruaki-tsubokura.com/works.php?ar_id=1) An installation that challenges the notion that shadows are created when light is cast on objects, creating an interactive space that blurs the line between reality and digital, achieved through digital technology and illusion.	
80	**ensemble silhouette** (http://msnr-mymt.net/works/ems/index.html) An interactive music device that lets strangers connect through sound, creating unexpected melodies. By placing star silhouettes on flowing staff lines, various melodies play, forming a mysterious ensemble.	
81	**toatope** (https://ponboks.com/playworks/toatope/) Inspired by shadow play, this interactive artwork animates shadows of hands cast on a table, giving life to shadow creatures of varying sizes and shapes.	
82	**Mate** (https://ponboks.com/playworks/mate/) Putting on a pointed hat of your favorite color activates 'mates' (companions) of the same color that mimic your movements. Tilt your body or jump, and the mates respond similarly, enhancing the sense of companionship.	
83	**Black Cat Cross** (https://ponboks.com/playworks/kuroneko/) Six black cats that look at you when you approach. Even when a person moves, squats, or jumps, they continue to stare at the person's face. Their side profiles differ, revealing unique traits and hidden aspects from different angles. This interactive work focuses on the crossing of gazes between participants and the cats	
84	**kotonoha** (https://ponboks.com/playworks/kotonoha/) Speaking into a hole transforms spoken words into walking shapes that roam freely. Expressions like 'thank you' or 'idiot' change the shape, suggesting that words carry the speaker's emotions and personality.	
85	**Yukue On** (https://ponboks.com/playworks/yukue/) Voices blown into an entrance become lines of light running on the table's paths, eventually reaching an exit and transforming into various sounds. This interactive piece lets users enjoy the journey of sound.	
86	**Denden Musubi** (https://ponboks.com/playworks/denden/) An interactive work inspired by the concepts of communication and connection. Panels create various lines of light when connected, resembling inter-panel communication or invisible ropes.	
87	**Mr. Facebox** (https://ponboks.com/playworks/mrfacebox/) A face box that interacts with the expressions of the person wearing it. Opens its mouth, blinks, and moves its pupils in sync with the wearer. Imagines a future where people choose faces like clothes or avatars.	
88	**Miru Ensemble** (https://ponboks.com/playworks/ensemble/) An interactive visual representation of ensemble and harmony in music. Placing hands on the wall generates music and animations. Moving hands while holding creates a shared musical experience.	

89	**Katachi no Sumika** (https://ponboks.com/playworks/katachi/) Shapes find their home in various forms placed on a table. The shapes change to fit the objects, exploring different forms and stories of 'shape'.	
90	**Haguruma to Susumu** (https://ponboks.com/playworks/haguruma/) A space-themed interactive work with planetary and flying objects on gears that move when stepped on. Combines motorized mechanisms with pose detection programming.	
91	**Kanaderu Sagashi** (https://ponboks.com/playworks/kanaderu/) Placing musical note panels on a table makes tadpoles swim to them, creating ripples and sounds. Arranging multiple panels creates various musical connections, inviting playful exploration.	
92	**mimi Action** (https://ponboks.com/playworks/action/) Pressing the cushion's center releases light particles of various shapes, which return to the cushion when released. The cushion's small world bursts into the exhibition space, creating a wondrous atmosphere.	
93	**Tsukurite** (https://ponboks.com/playworks/tsukurite/) An interactive work where moving user's hands inside creates puppet characters that mimic the movements. Making shapes like rock or paper moves and assembles blocks, building houses and forests, expanding a town.	
94	**PLRAY** (https://ponboks.com/playworks/plray/) Pushing a tabletop light sends beams into the monitor, animating as if they have a will of their own. It creates a mysterious sensation of communicating with light, blurring the line between physical and digital spaces.	
95	**Kaogocco** (https://ponboks.com/playworks/kaogocco-park/) An experience where faces are the focus. Sitting in a chair and moving your face brings it to life as various animals. The movements and expressions are memorized, creating animated behaviors.	
96	**Actors** (https://ponboks.com/playworks/actors/) An interactive piece where everyday objects like clocks, backpacks, and dishes 'act.' Speaking lines into a mic animates these objects with mouths, eyes, and mustaches, syncing their speech.	
97	**Hitokoto Motion Kotom** (https://ponboks.com/playworks/kotom/) Draw words or pictures on a tablet, stand in front of a camera with a speech bubble panel, and your creation comes to life as brushstroke motions within the panel. It's a machine that creates unique mini-videos based on your drawings and words.	
98	**new angles** (https://www.designboom.com/design/super-nature-new-angles-interactive-light-installation/) A collection of hexagonal objects that emit various colors. The installation responds to movements and gestures of participants, creating a softened, mimicking light.	
99	**The Wonderwall** (https://www.trendhunter.com/trends/wonderwall-by-likearchitects) An interactive experience where walking on a circular, sensor-equipped object triggers colorful light emissions.	
100	**Interactive Typographic Installation** (http://www.notabenevisual.com/#/works/in-order-to-control/) Participants' shadows transform into letters. They step into a letter-projected area and project the letters onto their bodies, creating a fascinating blend of shadow and typography.	
101	**Colored Shadow** (https://www.exploratorium.edu/exhibits/colored-shadows) Colorful shadows of participants and objects are displayed, moving in sync with their real-life movements.	

102	**EGO** (http://www.exile.at/ego/) Recognizes participants' movements and displays them as abstract stick figures, emphasizing and distorting the movements to explore the relationship between subjective and objective perspectives.	
103	**Audience Into Bubble** (https://www.facebook.com/nightmuseumkanazawa/posts/2458553447761780/) Participants' faces turn into bubbles and are projected on the wall. An interactive art piece where every visitor becomes part of the exhibit.	
104	**The Magic Arts** (https://www.facebook.com/nightmuseumkanazawa/posts/2458553447761780/) An interactive work where various effects are projected in response to hand movements. Participants can feel like a magician controlling fire or a skilled swordsman, capturing these moments in photos or videos.	
105	**Interactive Omikuji** (https://www.facebook.com/nightmuseumkanazawa/posts/2458553447761780/) Users ring a projected bell rope, summoning a dragon from behind a torii gate that reveals their fortune. Depth sensors detect hand movements for ringing the bell.	
106	Rain (https://www.facebook.com/nightmuseumkanazawa/posts/2458553447761780/) Participants step under projected moving umbrellas to shelter from the rain. Staying under an umbrella long enough stops the rain and reveals a rainbow. Participants are displayed as primitive humans who can catch the rain.	
107	**KAGE** (https://plaplax.com/works/217/) An interactive installation where touching cones on the floor makes their shadows move and transform into various shapes.	
108	**Temari to Kage** (https://www.jstage.jst.go.jp/article/inctkiyoupre/49/0/49_KJ00005074903/_pdf/-char/ja) An experience where participants grab projected temari (handballs) using a device in front of them. An intuitive and simple shadow play.	
109	**Chainy × Fireworks Design** (https://furo.org/ja/works/chainy/exhibition.html) Choose and combine fireworks to enjoy them visually and tactually on a 15m large screen. Chairs with multiple rotating tactile elements (motors) provide tactile feedback.	
110	**Music Concert for the Deaf** (https://japanphil.or.jp/concert/20180422) ORCHESTRA JACKET: A jacket with small speakers that convert sound into vibrations, offering a full-body sound experience. SOUND HUG: A simplified balloon device of the ORCHESTRA JACKET concept. It has a small vibrating speaker inside, allowing users to feel the speed and rhythm of music through vibrations. Also includes LEDs that visually represent the music.	 
111	**Kukkuru** (https://www.canvas-works.jp/works/いりふねこども館｜デジタルアート/) An educational content where letters are combined to form words. It's intuitively operable and enjoyable for everyone from small children to adults.	

112	**Digital Hanabi** (https://www.canvas-works.jp/works/experiencedigitalart-hanabi/) Throw icons from a smartphone towards a screen to launch fireworks. No app installation is needed; participation is easy with just a QR code scan.	
113	**Camera-ju** (https://www.asobiski.com/camera-ju) A digital content using digital cameras. Pictures of children taken with the camera are printed on the face of a Santa origami, and folding the printed Santa completes the origami, combining digital and analog experiences.	
114	**AR Signage** (https://www.canvas-works.jp/works/experiencedigitalart-3dhalloween/) When people stand in front of the monitor screen, they transform into Halloween monsters. The three contents include a giant pumpkin, a horned devil, and a witch with a broom, offering a wide range of mystical experiences for both children and adults.	
115	**Wall and Floor Projection Content** (https://www.canvas-works.jp/works/spaceproductiondigitalart-otoginomori/) A permanent wall and floor projection content. It responds to people with sensors, changing visuals or transforming landscapes over time, offering a variety of worldviews to enjoy.	
116	**VR Home Run** (https://www.frontier-i.co.jp/fdb/detail01.html) An immersive baseball experience that can be enjoyed indoors. Participants compete by hitting balls for points.	
117	**Spapa! Fruit VR** (https://www.frontier-i.co.jp/fdb/detail02.html) A controller in hand becomes a sword or an electric saw, cutting fruits and zombies in front of you. Scores accumulate as you slice the targets.	
118	**VR Urban Escape** (https://www.frontier-i.co.jp/fdb/detail03.html) An exhilarating shooting game where participants experience the thrill of crossing a narrow bridge, feeling a sense of vertigo when looking down.	
119	**I am fish!** (https://www.frontier-i.co.jp/fdb/detail04.html) An interactive digital attraction where participants turn into fish and appear on the display	
120	**Crab-san Dash** (https://www.frontier-i.co.jp/fdb/detail06.html) "An exhilarating race attraction where the avatar 'Crab-san' runs in sync with the participant's stepping movements.	

Appendix B

Instruction Manual of Big Ben (Chapter5)

All instruction manuals in the creation activity study are shown in Figure B.1, Figure B.2. and Figure B.3

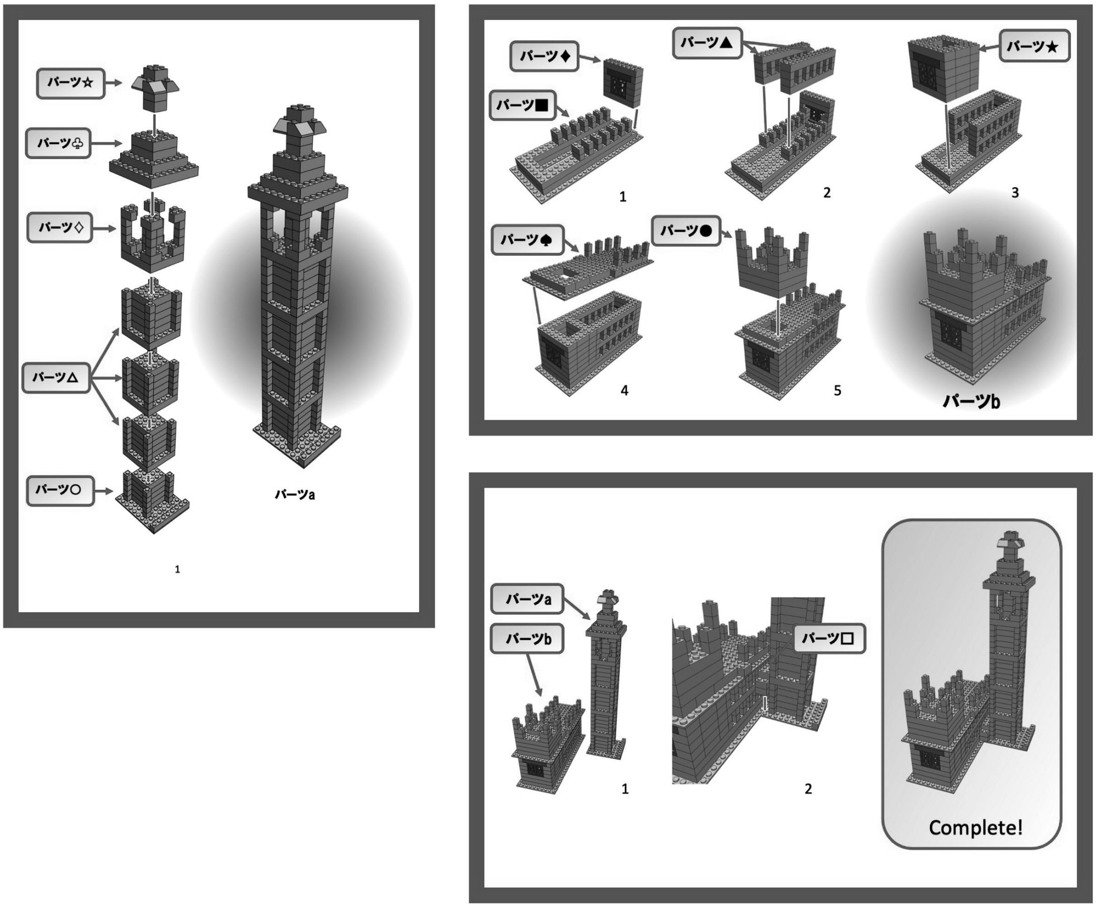


Fig. B.1 Instruction manuals for assembling parts.

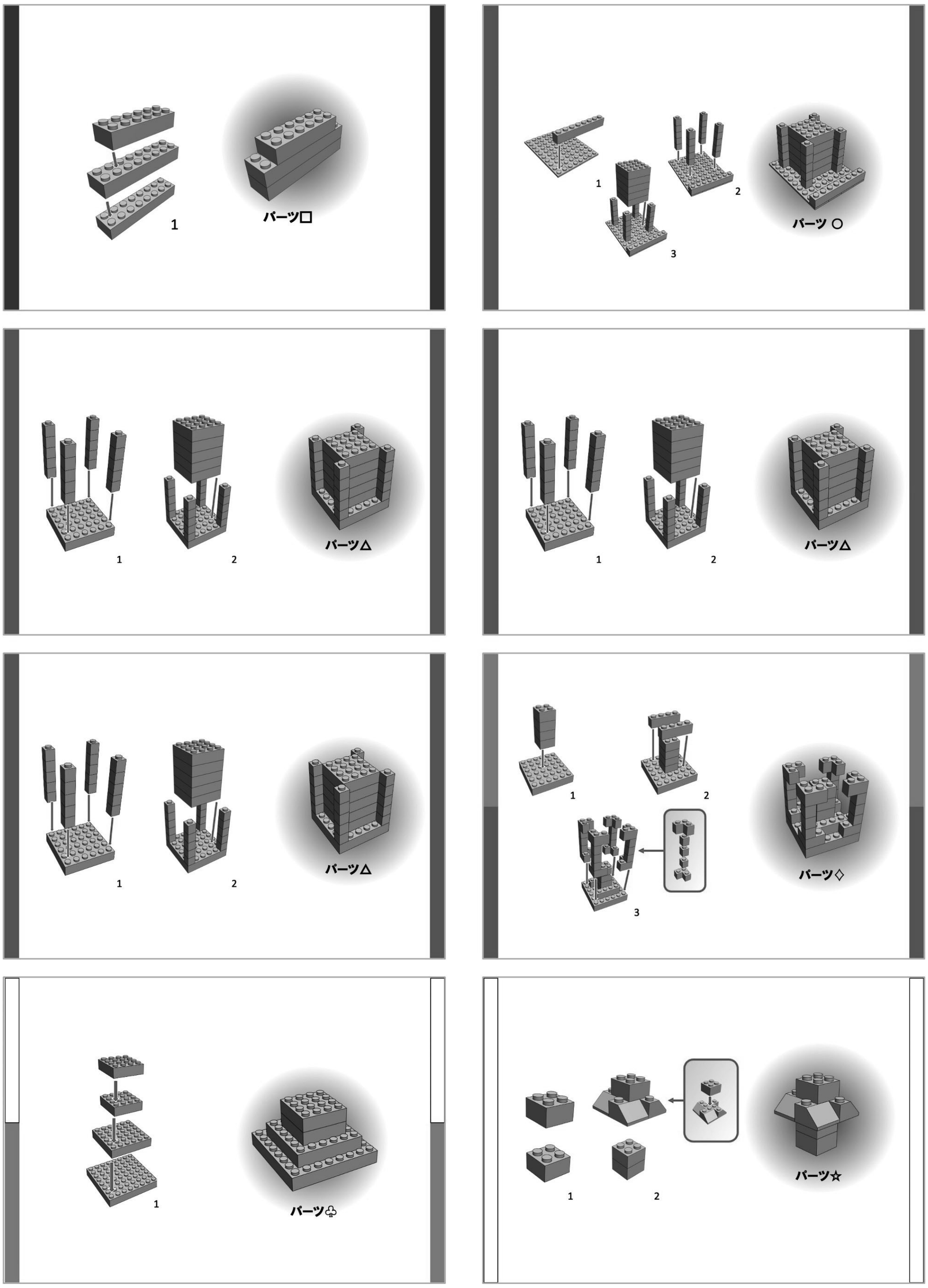


Fig. B.2 Instruction manuals for creating parts a.

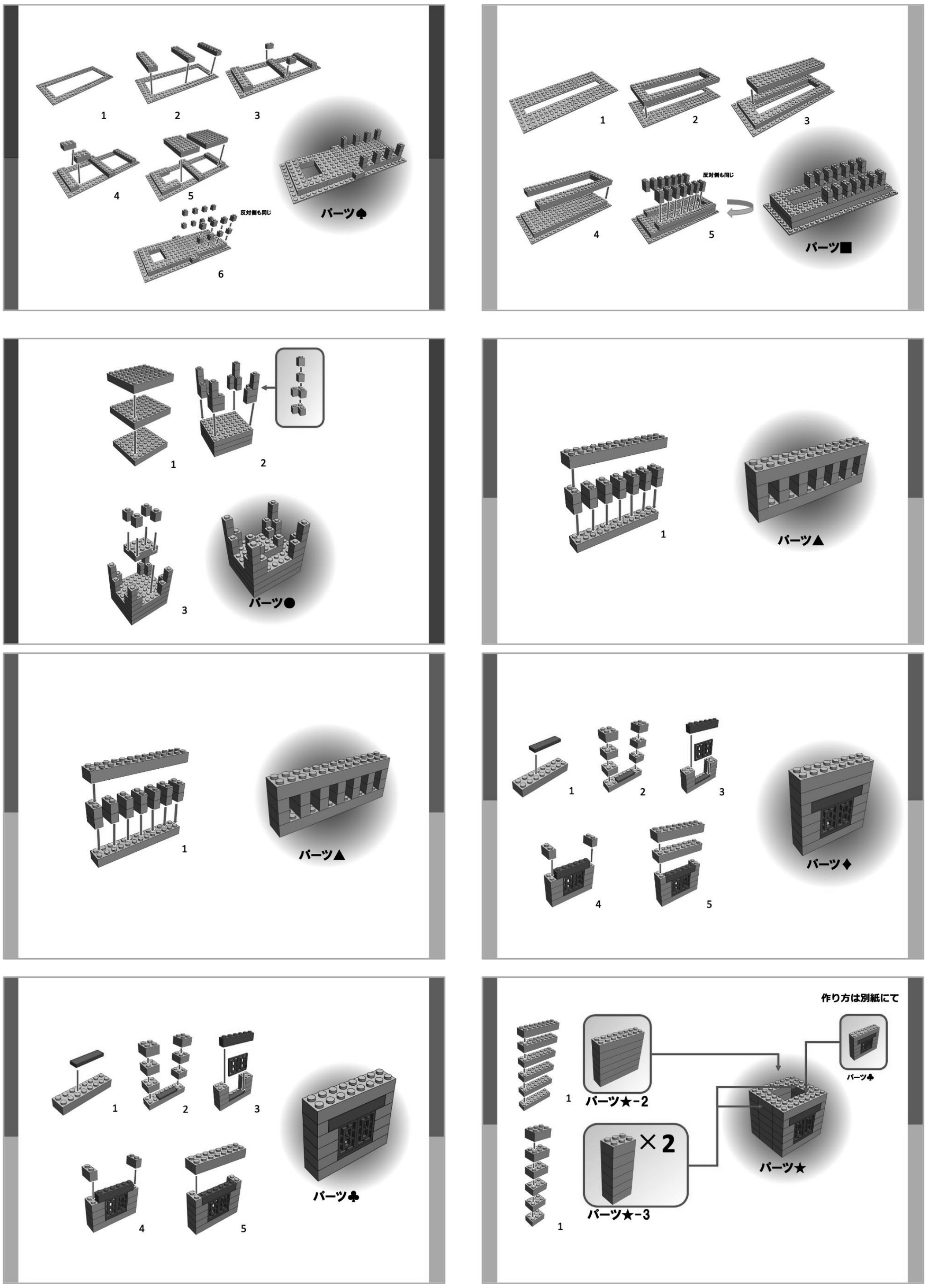


Fig. B.3 Instruction manuals for creating parts b.