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Development of Virtual-reality Tactile Educational Tool for Visually Impaired Children (Haptic Device to Trace Contour)

Naoki Asakawa,[1*] Yuji Hashimoto,[2] Hiroki Wada,[3]
Yuko Shimomura,[1] and Keigo Takasugi[2]

[1]Advanced Manufacturing Technology Institute, Kanazawa University,
Kakuma-machi, Kanazawa City, Ishikawa Prefecture 920-1192, Japan
[2]Graduate School of Natural Science & Technology, Kanazawa University,
Kakuma-machi, Kanazawa City, Ishikawa Prefecture 920-1192, Japan
[3]Department of Art, Kinjo College,
1200 Kasama-machi, Hakusan City, Ishikawa Prefecture 924-8511, Japan

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In education for the visually impaired, tactile perception education, which uses tactile sensation to learn, for example, shapes, has become an important means of education. Tactile perception education uses tactile sensation information to form images of objects that differ from person to person, and the form must be expressed through linguistic information. However, there are problems such as the cost and space needed for the storage of teaching materials, as well as the difficulty of teaching dynamic information. In this study, tactile perception education using virtual reality (VR) as a solution to these problems is proposed. By using virtual objects in VR space as teaching materials for tactile perception education, the problems caused by using real objects can be solved, and a more flexible and wide-ranging education can be possible. The purpose of this study is to construct a VR system that can be used in education for the visually impaired with devices that enable the tactile perception of the contours of dynamic virtual objects, which is necessary in tactile perception education.

1. Introduction

1.1 Tactile teaching materials for visually impaired children

With at least 2.2 billion people worldwide experiencing visual impairments, a shortage of educational resources for them is a critical issue.(1) In particular, since visually impaired children typically use their sense of touch to recognize educational materials, such materials are very important for these children. In recent years, while tactile learning materials created using 3D printers have emerged,(2,3) many challenges remain, including the selection of optimal materials, colors, and finishes.

*Corresponding author: e-mail: nasakawa@se.kanazawa-u.ac.jp
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Tactile graphics and 3D learning materials can be mentioned as traditional tactile learning materials. There are three types of tactile graphics.

- Braille graphics: Objects are edited in Braille graphics editor and printed using a Braille printer. The Graphiti device[4] shown in Fig. 1 can also display images in real time.
- 3D copies (PIAF[5]): Drawings made with a black pen on a special sheet are raised by the heating process in the device.
- Raised-line drawings:[6] Strong pressure with a ballpoint pen is applied to special paper to raise drawing lines.

3D teaching materials like those shown in Fig. 2[7] were often made by teachers or manufacturers using clay or resin. However, with the popularization of 3D scanners and printers, they are now often made using 3D printers. However, there are some objects that are difficult to represent, such as the following.

Fig. 1. Graphiti graphic display.

Fig. 2. (Color online) Tactile educational materials.

- Moving objects: rolling balls, fluttering curtains, flying insects, etc.
- Growing and changing objects: plants, animals, living organisms, etc.

To represent those objects, a more dynamic system is required to be developed.

1.2 Conventional VR system

To address the challenges discussed in the previous section, virtual reality (VR) systems are considered a powerful means of representing objects. Generally, VR systems consist of the following three components.

(1) Visual information providing device

In recent years, head-mounted displays such as VR goggles have become popular. These devices achieve a high level of immersion by providing only visual information.

(2) Haptic device

Devices providing a sense of touch or movement are called haptic devices. Various types of device have been studied, such as tubes with liquid applied to the fingertips,[8] sliders, and rings worn on the fingers,[9] and pen-shaped devices with multijointed arms, as shown in Fig. 3.[10] Many of these devices have mechanisms that provide localized sensations or displacements to the fingertips to mimic the tactile sensation of the fingers.

(3) Tracking device

A tracking device capable of detecting the position of the hand and fingers is required. Typically, sensors installed on a base (such as the room, desk, or the user's body) detect the relative distance and orientation of the user's hand and fingers. In many cases, the device also requires scaling capabilities, as shown in Fig. 4.[10]

1.3 VR system for tactile educational materials

The purpose of this research is to develop an educational tool that allows visually impaired children to express dynamic changes in shape using VR technology. There has never been a shape presentation system for visually impaired people using a VR system.

Fig. 3. (Color online) Example of a haptic device.

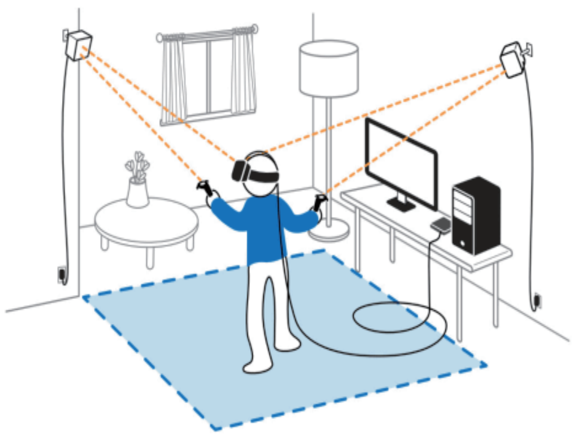


Fig. 4. (Color online) Example of a tracker.

The shape to be expressed is modeled as 3D CAD data, placed in the VR space, and dynamically transformed. As a simple case, we treat a 2.5-dimensional contour shape with reduced degrees of freedom. The system recognizes shapes whose outline is traced with both hands with the shape recognition actions performed by visually impaired people, as shown in Fig. 5. This system allows visually impaired people to easily learn by touching various shapes. However, while conventional VR technology has the potential to be used for the purposes of research, it has the following limitations.

- It relies too much on visual information.
- The feedback from the controller is vibration only. Thus, the amount of information is too small to convey tactile sensations.
- The accuracy of the hand position and posture obtained by the tracking system is too low to accurately represent the shape.

2. System Configuration

2.1 Overview

Figure 6 shows an overview of the system. The user can freely move the rotational angle of the device's arm. The radial displacement is given to the user by the system. The basic system operation is as follows.

(1) When the user operates the arm of the device, the rotational angle q at that time is read by the rotary encoder and sent to the virtual space.

(2) The radial displacement of the given rotational angle is calculated on the basis of the virtual object shape in virtual space and sent to the device.

(3) The device mechanism operates using the transmitted information and indicates the radial position r to the user.

(4) Thus, the radial displacement of r at a certain rotational angle q of the virtual object is reproduced in the real world.

(5) By performing these actions consecutively, shape recognition by tracing the contour is realized.

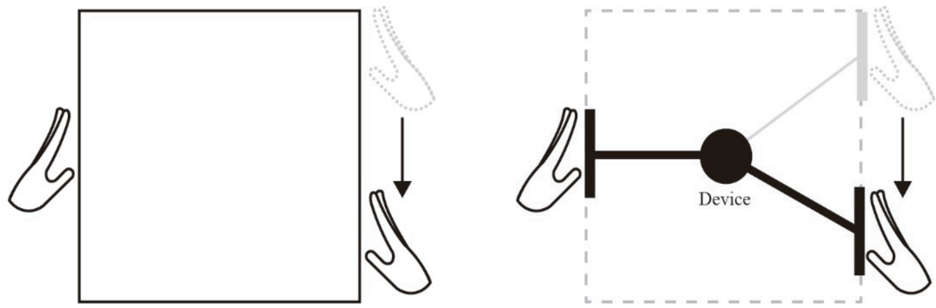


Fig. 5. Concept of the proposed system.

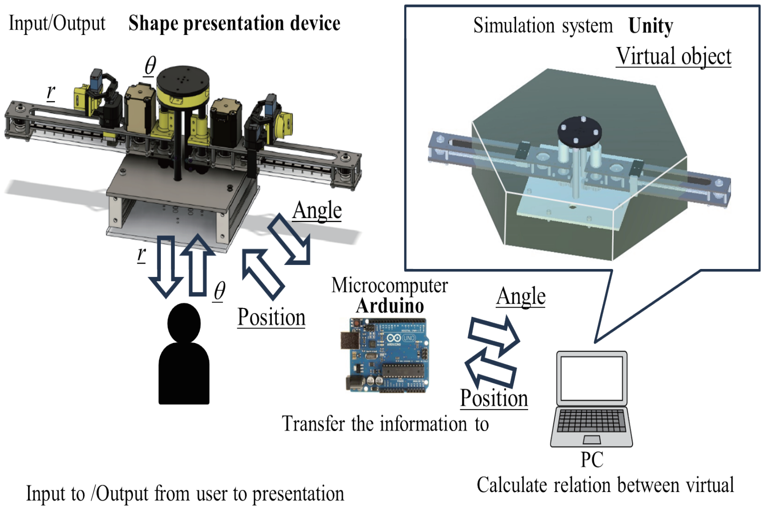


Fig. 6. (Color online) Configuration of the system.

2.2 Hardware

2.2.1 Shape presentation device

Figure 7 shows an overview of the shape presentation device. The specifications are as follows: size of 190 × 550 × 185 mm^3, weight of 3.4 kg, and shape with diameters of 270–450 mm to be presented. Since the system assumes contact from the outside, it cannot represent objects with hollow donut shapes. The shape presentation device serves as both a haptic device and a tracking device in a general VR system. When a user recognizes a shape by tracing, they move their hand along the contour of the shape and recognize the shape by sensing the displacement in the direction normal to the contour.

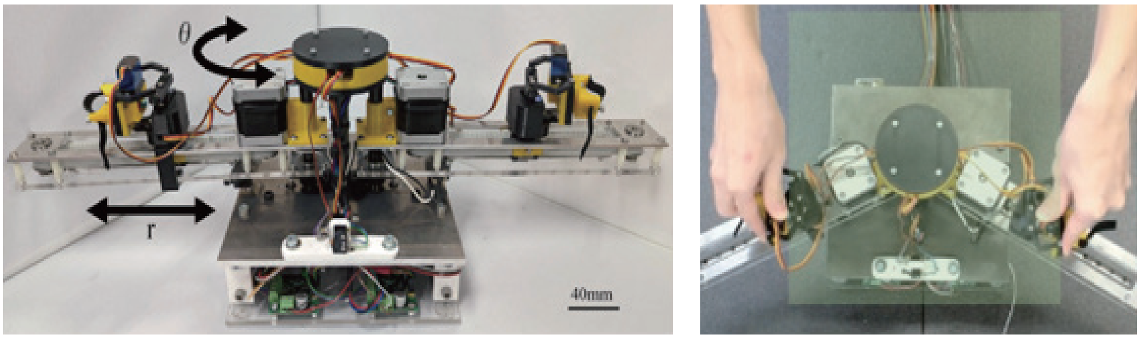
In this study, the object to be recognized is a plate shape, and the movement along the outline of the shape is defined as the θ direction, as shown in Fig. 7(a), and the direction normal to the outline of the shape is defined as r. Therefore, θ axes play the role of a tracking device and r axes play the role of a haptic device.

[Input from user] The θ axes can be moved independently, one on the left and one on the right, and the user can give each a rotational displacement from 0 to 180 deg. The arm can be moved freely, and the rotational angle is measured by the rotary encoder.

[Output to user] The r axes can also move independently, one on each side, and can perform translational movement of approximately 100 mm along the arm. The axes are driven by a stepping motor and timing belt to move linearly.

Consequently, the contour of the shape is expressed in a two-dimensional polar coordinate system by the parameters θ and r on the left and right sides, respectively.

The arm's translational axis is equipped with a normal presentation mechanism and an angle presentation mechanism that can express the normal and angle of a shape, respectively, allowing the user to understand more detailed characteristics of the shape, as shown in Fig. 8.



(a) (b)

Fig. 7. (Color online) Overview of the device: (a) front view and (b) top view.

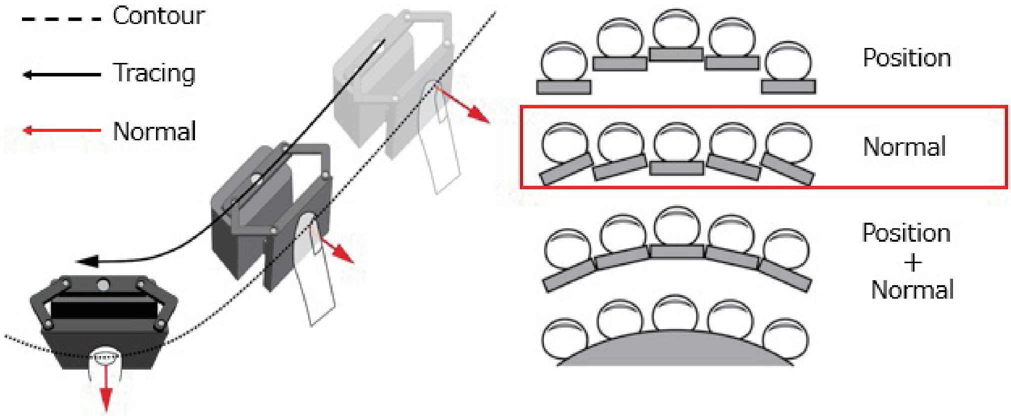


Fig. 8. (Color online) Shape enhancement using normals: (a) representation of surface features by normals and (b) improved shape expression using normals.

2.2.2 Microcomputer

To control the movement of the axes, microcomputers are employed. Two Arduino UNO units[11] are used to drive the r axes and normal presentation mechanisms. An Arduino MEGA unit is used to measure rotational angles via the rotary encoder.

2.2.3 Personal computer

To expand virtual space and control microcomputers, an AT-compatible personal computer (Core i7-9750H, RAM 16 GB, Windows 10) is used.

2.3 Software

To design a virtual space, Unity,[12] a game development platform provided by Unity Technologies, is used as the development environment. In this research, Unity is used for the following purposes.

(1) Place the CAD data of the device and the virtual object to be presented in the virtual space.
(2) Obtain shape information of virtual objects (object surface position, normals).
(3) Calculate the contour position of the virtual object corresponding to the current rotational displacement of the device and send it to the device.
(4) Reflect input information in the virtual device in the virtual space.

When data for devices or objects defined in CAD are imported into a VR space, they behave in accordance with certain physical laws within the virtual space. By configuring interference settings, it is also possible to detect interference within the virtual space.

3. Principle of Contour Tracing

3.1 Calculating shape contours using Ray

In the system, when the user moves the arm of the shape presentation device along the contour of a virtual object, the system continuously displays the position and normal direction of the contour at that point. The operating principle of the system is that the user can feel as if they are tracing the contour of an object through their movements. The procedures are as follows.
(1) Define the shape and mechanism of the shape presentation device using CAD.
(2) Place the device data in the virtual space.
(3) Define the presentation shape using CAD.
(4) Place the presentation shape data with the device data. The placement is shown in Fig. 9. Here, a rectangular shape is placed as an example.
(5) A half-line called a "Ray" is generated around the θ axes (rotational axes of the device). Half-lines are generated at an interval of 0.36 deg in accordance with the resolution of the stepper motor.
(6) The position of the intersection point between a Ray and the contour of the presented shape is calculated, and the distance between that point and the θ axes is calculated as shown in Fig. 10.
(7) The normal direction of the presented shape at that point is also calculated as shown in Fig. 8(a).

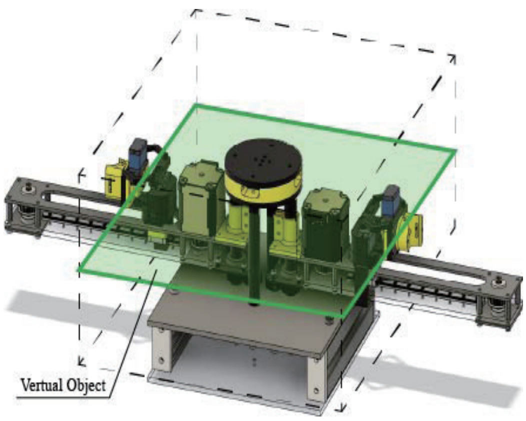


Fig. 9. (Color online) Relationship between object in VR space and device.

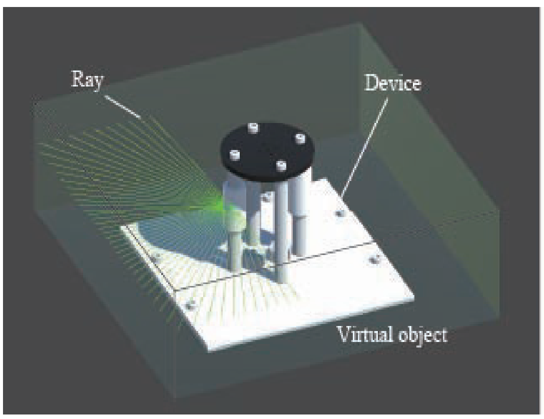


Fig. 10. (Color online) Contour represented by the intersection of the object and ray.

With the above steps, for a given presentation shape, the radial position r at the arm angle of θ can be calculated. Increasing the movement speed reduces accuracy owing to the inadequate reaction speed. As a result of testing, the practical limit was found to be about 2 mm at 50 deg/s.

3.2 Case of dynamic shape changes

The calculations shown in the previous section are updated at Unity's frame rate, so even in the case of a presentation shape that undergoes dynamic changes, it is possible to follow deformations at the timing of the frame rate (30 fps). Figure 11 shows how a Ray changes to track dynamic changes in shape.

4. Experiment: Static Shape Evaluation

4.1 Conditions

The constructed system presented static shapes and evaluated whether the shapes could be correctly judged.

- The subjects were five sighted people in their 20s who were instructed to draw the results on paper. They wore eye masks during the experiment.
- Three types of shape were prepared.

(a) Right square with three keen protrusions
(b) Circle with four rounded protrusions
(c) Right square with three continuous protrusions and a protrusion on opposite side

As with general tactile learning, subjects are given verbal hints about the shape beforehand, and then the subjects identified the details of the shape using the device and drew the shape. The system is evaluated on the basis of whether the illustrated shape captures the characteristics of the given shape.

4.2 Results

The experimental results, which were obtained from the subjects, are shown in Fig. 12. Although some of the shapes had incorrect protrusions or corners, it appears that the characteristics of the shapes were generally reproduced. In this experiment, not only the

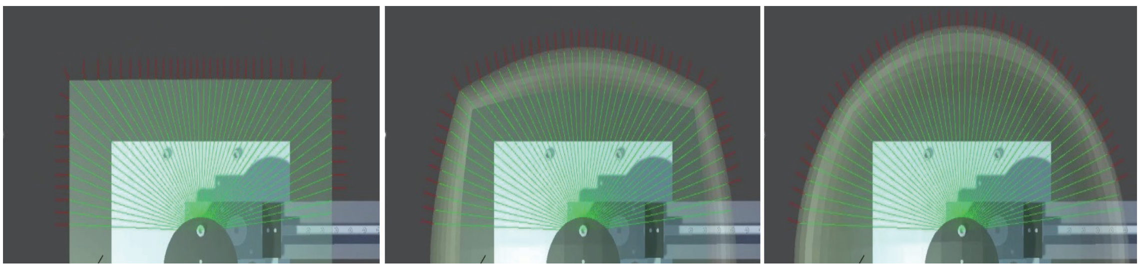


Fig. 11. (Color online) Dynamic shape change (rectangle to circle).

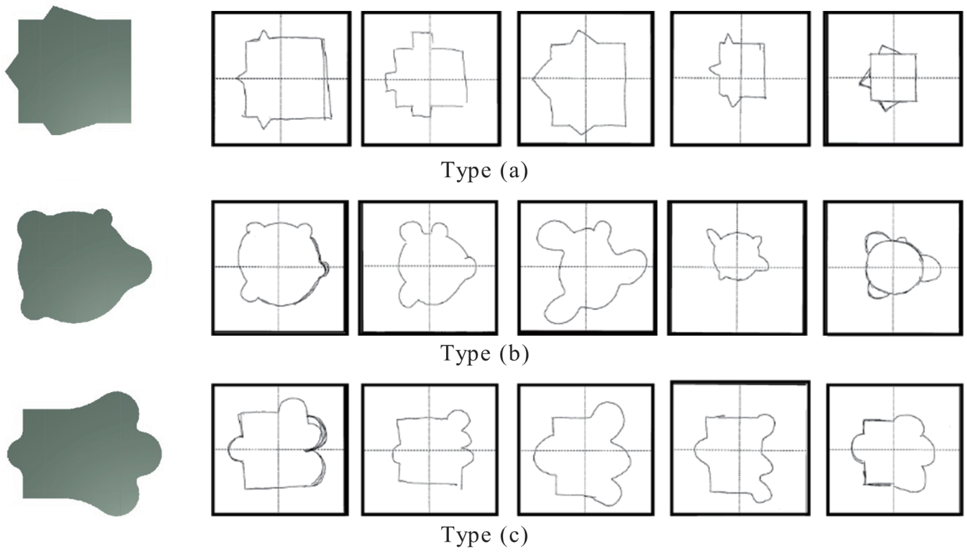


Fig. 12. (Color online) Results of the static experiment.

subjects' cognitive ability but also their drawing ability affected the results, so the experiment was conducted on sighted subjects and the evaluation was limited to a qualitative one. In the future, quantitative experiments should be conducted with visually impaired people.

5. Experiment: Dynamic Shape Evaluation

5.1 Conditions

The system presented shapes with movement and evaluated whether the movement of shapes could be correctly judged. Since it would be difficult to evaluate if the shape was also changed at the same time, the experiment was limited to rectangular shapes.

- The subjects and other conditions were the same as described in the previous section.
- Three types of movement shape were prepared as shown in Fig. 13.

(a) Shift for x, y direction (30 mm)
(b) Rotation (90 deg, CW/CCW)
(c) Expansion and contraction (±30 mm)

An example of the instructions during the experiment is as follows.
"*We are going to change the rectangle. Please tell us how it changes.*"
(*Operate the device*)
"*Please tell us what the change was*"
(*Subject answers*)
"*Here is the next change*"
…

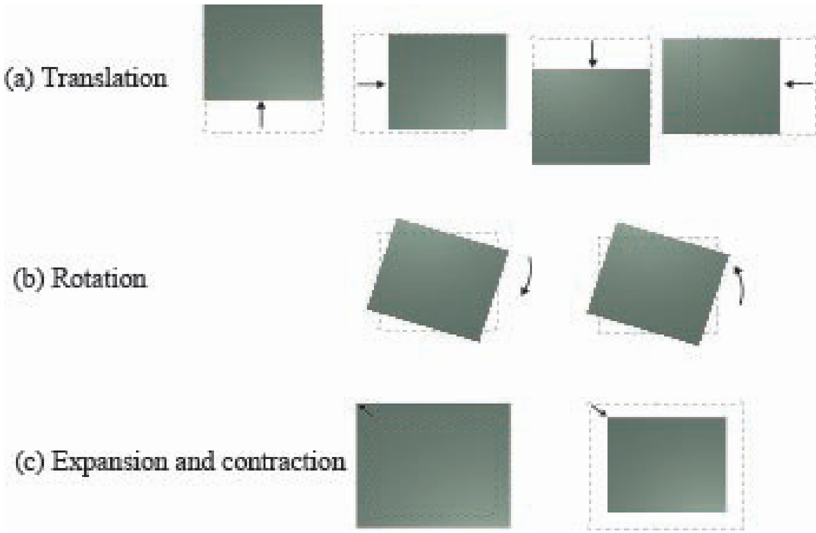


Fig. 13. (Color online) Dynamic experiment.

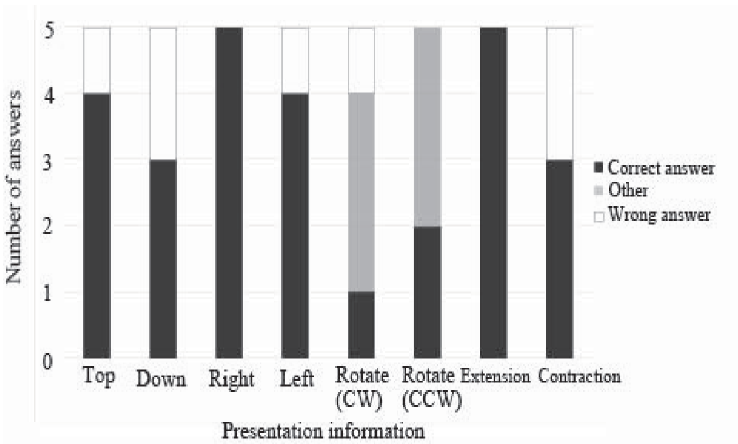


Fig. 14. (Color online) Results of dynamic experiment.

5.2 Results

The results are shown in Fig. 14.

Shift: [Is the direction of movement correct?] The information presented and the answers generally matched, suggesting that the motion was generally recognized.

Rotation: [Is the rotation direction correct?] The most common response was rotation in a way that could not be determined as either clockwise or counterclockwise.

Expansion and contraction: [Has the shape gotten bigger or smaller?] The information presented generally matched the answers, suggesting recognition.

The reason for the many errors in the rotation experiment is considered to be that when the hand is in motion, the movement and change are perceived as a composite, making it impossible to correctly recognize the change in the object. When presenting dynamic changes, it is considered that it is necessary to present the hand in a fixed position.

6. Conclusions

A system that provides a VR contour tracing system on the basis of tactile sensation information for the education of visually impaired children was designed, and the following results were found.

(1) In static experiments, the presented and recognized shapes matched well, suggesting the possibility of using this method as part of a standard tactile education technique.

(2) In dynamic experiments, some movements could not be correctly recognized. It was found that recognition is difficult when it is not possible to distinguish between tracing and object movements.

To make the system more practical, the following challenges must be overcome in the future.

- A method that can independently assess cognitive ability and the ability to express what is perceived must be devised.
- To improve the recognition rate in dynamic experiments, a method to set a reference point to make it easier to grasp the position in space must be devised.
- Experiments with many visually impaired people must be conducted to clarify the problems with the system.

Acknowledgments

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About the Authors

Naoki Asakawa received his B.S., M.S., and Ph.D. degrees from the University of Electro-Communications, Japan, in 1989, 1991, and 1997, respectively. From 1991 to 1998, he was a research associate, from 1998 to 2002, he was a lecturer, and from 2002 to 2010, he was an associate professor at Kanazawa University. Since 2010, he has been a professor at the same university. His research interests are in the application of robots, applications for visually impaired people, and CAD/CAM.
(nasakawa@se.kanazawa-u.ac.jp)

Yuji Hashimoto received his B.S. and M.S. degrees from Kanazawa University, Japan, in 2020, and 2022, respectively. His research interests are in CAD/CAM and machine tools.

Hiroki Wada received his B.S. and M.S. degrees from Kanazawa College of Art, Japan, in 2006 and 2011, respectively. Since 2011, he has been an assistant professor at Kinjo College. His research interests are in art and building various systems for visually impaired people. (h_wada@kinjo.ac.jp)

Yuko Shimomura received her Ph.D. degree from Kanazawa Institute of Technology in 1998. From 2001 to 2004, she was an associate professor at Kinjo University. In 2004, she became a professor at the same university. Since 2020, she has been a researcher at Kanazawa University. Her research interests are in building various systems for visually impaired people.
(Shimo@kinjo.ac.jp)

Keigo Takasugi received his B.S., M.S., and Ph.D. degrees from Kanazawa University, Japan, in 2004, 2006, and 2012, respectively. Since 2016, he has been an associate professor at Kanazawa University. His research interests are in CAD/CAM and machine tools. (ktaka@se.kanazawa-u.ac.jp)