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FULL PAPER

Study on portable haptic guide device with omnidirectional driving gear

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ABSTRACT

In the past, white canes, guide dogs, and guide helpers have served to assist visually impaired people when walking outdoors. However, these assistance methods have various limitations for extended and suitable usage. Therefore, our laboratory herein proposes a route guidance device that signals commands to the end-user by giving a sense of force to the thumb. The guide device is driven on the common plane with two degrees of freedom by using an XY stage with omnidirectional driving gear. The current prototype presents challenges for its practical implementation as a smooth, safe and reliable route guidance system. In this study, we conducted experiments aiming to optimize the combination of the update position of the intermediate target point and the presentation cycle in blindfolded clear-eyed people.

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KEYWORDS
Handheld haptic device; omnidirectional driving gear; route guide; Blind guide; visually impaired

1. Introduction

According to the WHO, the number of visually impaired people around the world was about 2.2 billion in 2019 [1]. Conventional means of walking assistance for the visually impaired people when they walk outside include white canes, guide dogs, and guide helpers [2]. White canes and guide dogs can detect obstacles, while guiding dogs can also lead its human user on a straight route or a corner, but they cannot guide their human users on specified trajectories to their destinations. Human users need to remember the exact routes to their destinations on maps in advance, and it is difficult and time-consuming to do so in their first visit. Furthermore, the number of guide dogs around the world is about 22,000 far fewer than the number of visually impaired people who need them [3]. In addition, the guide helper system in Japan has problems such as regional disparities and nighttime usage restrictions [4].

1.1. Previous works

Various route guide devices have been developed to solve the problems described above. In previous research, development of systems that guide people with voice, vibrations, electrical stimulation, shape transformation of device, and motion of mobile robot have been conducted.

1.1.1. Portable guide device with sound

As a guide device to the destination with voice, there is a GPS map information terminal 'Trekker Breeze' developed by Sullivan et al. at Humanware in Canada. The size of the Trekker Breeze is 60[W] × 29[D] × 129[H] mm, and its weight is 200 g. The human user can hear the current location and information about the surrounding environment by voice with a built-in GPS receiver [5].

Another technology for navigating the visually impaired is a smart white cane 'WeWALK' developed by Ceylan et al. at the Young Guru Academy in Turkey. The size of the WeWALK is 25[W]× 44[D]× 289[H] mm, and its weight is 280 g. It can be directly attached to a white cane. In addition to linking with smartphones for route guidance, ultrasonic sensors detect obstacles above the user's chest height and transmit the information by vibration [6].

'NavCog' should also be mentioned as a good example of the navigation method with voice information. It is an iPhone application that navigates a visually impaired person with voice guidance by providing the information about the direction and distance toward his/her destination. It has been developed by Asakawa et al. at IBM Co., Ltd. [7].

However, these voice guidance methods make it difficult for a human user to hear the environmental sound because of his/her concentration on the guidance voice.

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Thus, this guidance voice hinders the visually impaired from being able to avoid danger because sound from the outer environment sometimes warns of danger, and in the worst case, this disadvantage can cause an accident [8]. In addition, voice guidance is difficult to use due to language barriers and educational disparities, and it is necessary to adapt the language for each country.

1.1.2. Portable guide device with force sense

As a guidance device to a destination using force sense, 'Burunavi' was developed by Amemiya et al. at NTT Communication Science Laboratories. The size of the Burunavi is 18[W] × 18[D] × 37[H] mm, and its weight is 19 g. It presents direction by virtual force sense due to asymmetric vibration using a linear actuator. In addition to route guidance for the visually impaired people, it is also used for game applications using the sensation of being pulled, which is expected to reduce the cost of production. However, the direction presentation by vibrating, as used by Burunavi, is a virtual force sense presentation, and it is difficult to present the correct direction for any human user, including children and old people, with small vibrations. In order to guide a safe route on narrow roads, there is still the need to present a feasible implementation that can be easily understood [9].

Another technology for navigating the visually impaired is 'Animotus' developed by the team of Prof. Dollar at Yale University. The size of the Animotus is 60[W] × 60[D] × 40[H] mm. It is gripped from its lower section, and the device positioned at its top is driven to apply force to a human hand as a guiding system. However, Animotus is a large device because it uses two servomotors in upper and lower stages, respectively, and the sound from gears and motors can be unnecessary loud. Furthermore, since its translational motion and revolution motion are controlled by two servo motors independently to present the direction to its human user to be followed, a large latency occurs, and instantaneous navigation is difficult [10]. Alternative studies about similar portable guide device with force sense have been presented[11,12].

1.1.3. Guide method with electrical stimulation

The guidance device developed by Pfeiffer at University of Hannover navigates blindfolded pedestrians by stimulating human muscles with electricity. By sending a weak electric signal from the pad attached to the surface of a human thigh, a human leg naturally moves in the direction to be followed and the device guides the human user on the specified route. However, the perception with weak electrical stimulations shows large differences among individual users because it is closely related to differences of genders, ages, diseases, etc. [13,14]. Thus, this guide device cannot be considered to be appropriate for all cases.

1.1.4. Mobile robot with force sense

Several works have developed mobile robots for navigation of visually impaired people with force sense that mimic a real guide dog. One of them is 'LIGHBOT' developed by Tobita et al. at NSK Co., Ltd. The size of the LIGHBOT is 360[W] × 450[D] × 1050[H] mm, and its weight is 18,000 g. It is a mobile robot that can guide a human user indoors, such as in hospitals and public facilities. It is also possible to move with elevators by placing an augmented reality (AR) marker on the ceiling of each floor. A human user places his/her hand on the grip and sets the destination, then he/she will be towed to the destination, and if there is an obstacle on the route, LIGHBOT will automatically avoid it or stop [15]. 'CaBot' is another example of a mobile guide robot. It is a suitcase robot developed by Asakawa et al. at IBM Co., Ltd. [16]. However, these mobile robots are large and heavy. They are driven with wheels and cannot pass steps or enter narrow spaces, so they tend to limit the human motion range. The limitation of motion leads to stress in human users.

Other guidance devices with voice navigation and force feedback have been also developed [17,18].

To conquer the problems of these previous works shown above, the requirements of the guidance device in this research are presented as follows:

- Intuitive direction presentation that does not interfere with the living environment in which the human user lives.
- The guide device should be easily portable, and have a wide motion range. Namely, the device should be small and lightweight without any restriction on its degrees of freedom.
- The usage and functions of the guide device should not be restricted by age, gender of its human users and locations in which it is used.

1.2. Concept

Therefore, in this paper, we propose a haptic device that guides the visually impaired to a destination by applying a traction force to the thumb in the direction in which he/she should proceed. Just as a guide dog gives traction force to a human user through a harness and conveys information about obstacles and walking direction, the haptic guide device intuitively transmits the direction information to a human user by an actual translational

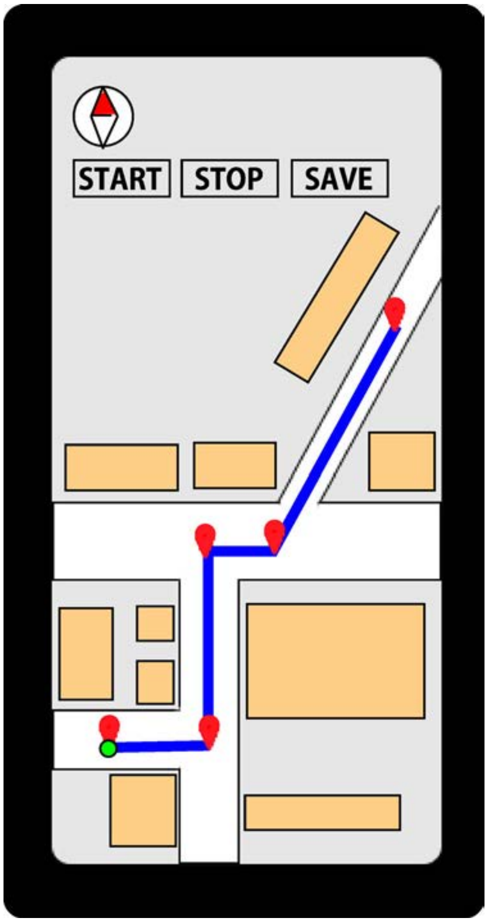

Figure 1. Draft of application screen.

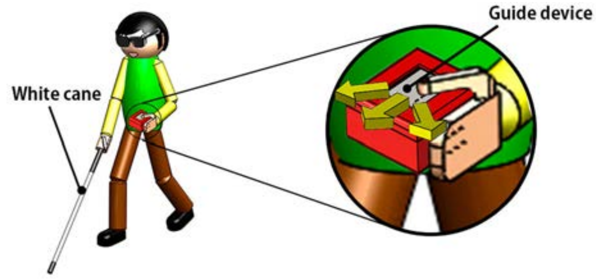

Figure 2. Conceptual image of haptic guide device.

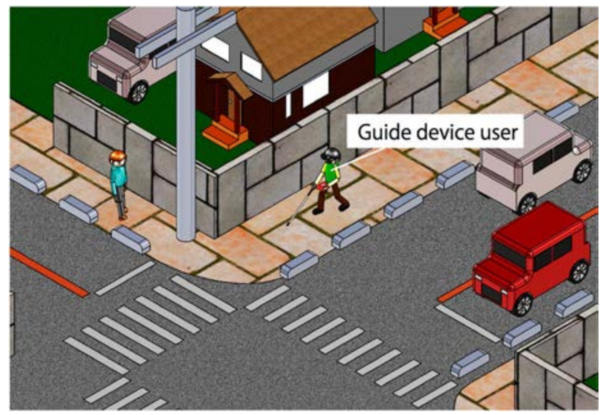

Figure 3. Conceptual image of the application of haptic guide device.

force created with the physical motion of its presentation part. Because the translational force and displacement of the presentation part of the haptic guide device are large enough, it can provide not only the tactile stimulation on the surface of human skin but also stimulation for kinesthetic sensibility by actively moving the joint of a human finger. By combining this with an information terminal such as a smartphone, a human user can acquire location information and the route information to his/her destination on the map, as shown in Figure 1. The haptic guide device is small light and is easy to carry. In addition, since a human user needs only his/her own thumb, it is less likely to interfere with the living environment, and to indicate a specific direction directly to the fingers, so it can be easily used by anyone, regardless of age, gender, or location of use.

The use of a white cane or a guide dog is compulsory by law for the visually impaired when they walk outside in Japan [19]. The white cane also plays the role of a 'symbol' to inform people around them that its owner is visually impaired. Therefore, the haptic guide device developed in this study is designed to be used together with a white cane DThe white cane is used by the dominant hand to recognize obstacles, and the haptic guide device is used by the other hand to guide the user to the destination (Figures 2 and 3).

2. Prototype of haptic guide device

2.1. Omnidirectional driving gear

The driving mechanism called 'Omnidirectional driving gear' (Figure 4) developed in our laboratory is used to drive the haptic guide device [20]. The omnidirectional driving gears are gears with a rack structure in two orthogonal directions in the same plane, and it is possible to drive two degrees of freedom in the same plane by transmitting power to each direction by the gears. Compared to the conventional XY stage with two upper and lower stages, the use of omnidirectional driving gears makes it easier to reduce the size and weight of the device [21].

2.2. Specifications of the prototype

The appearance of the latest prototype haptic guide device is shown in Figures 5–7, and the specifications are shown in Table 1. The haptic guide device consists of three structures: a fixed frame to hold the motor, a guide

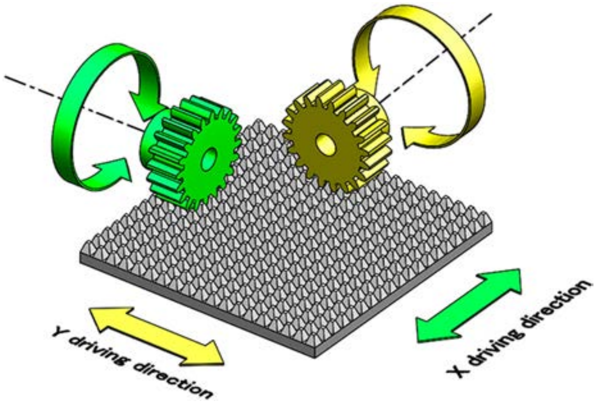

Figure 4. Omnidirectional driving gears.

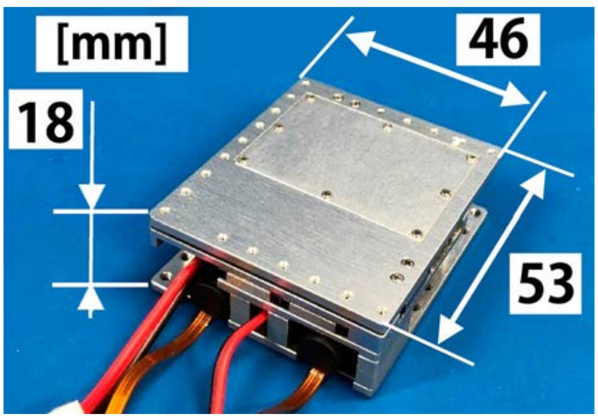

Figure 5. Overall view of haptic guide device.

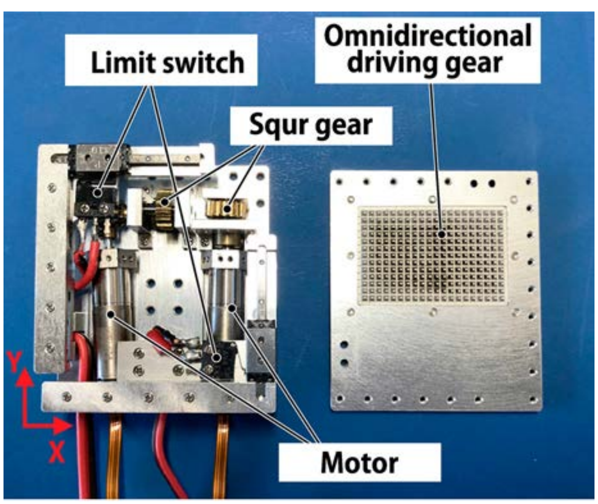

Figure 6. Inner mechanism of haptic guide device.

frame with a rail that can drive up to 14 mm, and a presentation part for presenting the direction in which the user should walk. The presentation part has an omnidirectional driving gear (Module 0.5) fixed on the back of the presentation section, and two motors are placed on the same plane. The size of the haptic guide device

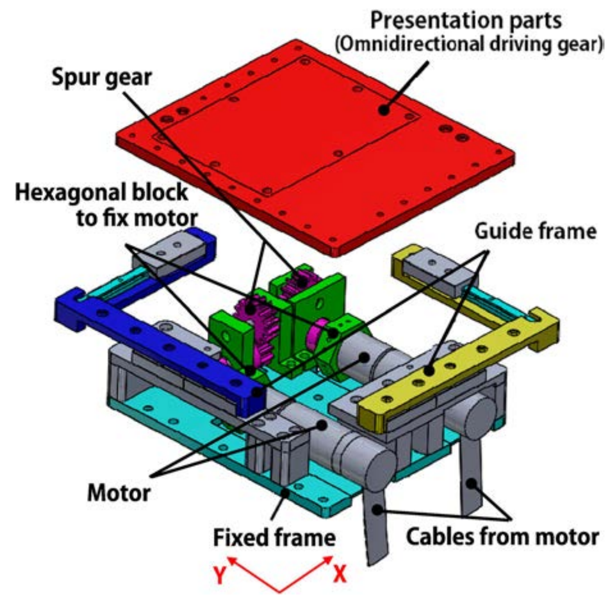

Figure 7. Structure of haptic guide device.

Table 1. Specifications of haptic guide device.

Size	46(W) × 53(D) × 18(H) mm
Max size	60(W) × 67(D) × 18(H) mm
Weight	80 g
Motor	DCX08M
	Rated output:0.5 W
	Maximum continuous torque: 0.641 mNm
Gearhead	GPX08A(Reduction ratio:36)
Encoder	ENX8MAG(Resolution:128)
Material	A7075(main)
	SUS303 (fixture, omnidirectional driving gear)
	C3604(gear)
Module of omnidirectional driving gear	0.5
Motion range from center position	6.0 mm
Time cycle for force presentation	0.5 s

is 60[W] × 67[D] × 18[H] mm when the presentation part is driven to the maximum motion range. It is a small and light device with a mass of 80 g. Aluminum is used for parts that do not receive forces from the motor among the components of the haptic guide device, making a lightweight mechanism possible. The motor can be attached to the fixed frame at any angle by inserting its gearhead into a hexagonal block with its screw thread on its outer surface as shown in Figure 7. The two motors are aligned in parallel by using a bevel gear as the gear in the Y -axis direction and tilting the torque transmission direction by 90 degree. This parallel alignment of the two motors enables arbitrary deployment of their cables, and that also make it possible to miniaturize the whole structure of the haptic guide device. A limit switch is used to set the initial value of the position of the presentation part. When the presentation part moves to the lower left (direction of the origin of XY coordinates), the guide

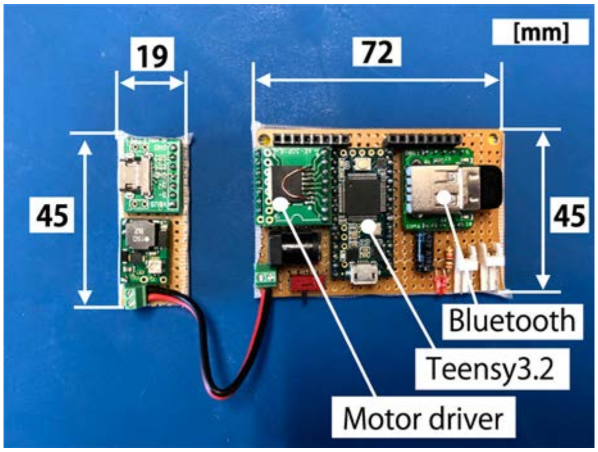

Figure 8. Control circuit of haptic guide device.

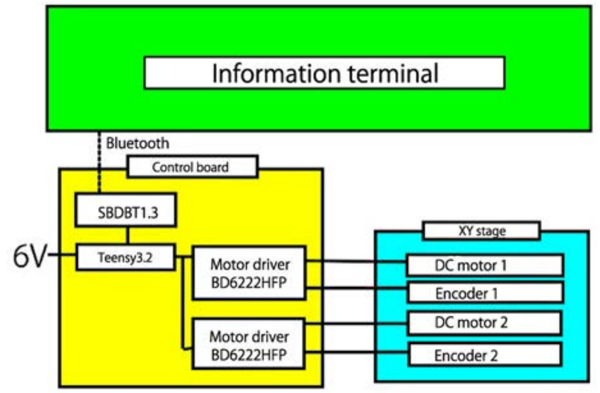

Figure 9. Schematic diagram of control system of haptic guide device.

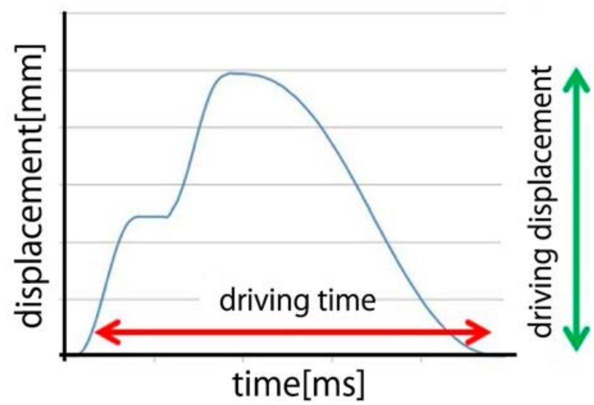

Figure 10. Drive motion.

frame that supports the presentation part pushes the limit switch installed on the fixed frame. After the limit switch is pushed, the position of the presentation part is judged to be adjusted to the initial position. After arriving at the initial position, the presentation part moves toward the forward directions in both of the X- and Y -axis with 7 mm and stays at the center position.

2.3. Control circuit

The control circuit of the haptic guide device is shown in Figure 8. A Teensy 3.2 microcontroller communicates with information terminals, such as PCs and smartphones, based on Bluetooth. The power supply is four AA batteries connected in series (6 V) or the mobile battery with output voltage increased to 6 V by a booster. A schematic diagram of the control system is shown in Figure 9. Based on the positional information read by the information terminal, we generate the directional information of the guide device and send it to the control circuit using the Bluetooth. The received information is processed by Teensy microcontroller and the guide device driven by wire.

2.4. Direction presentation method

A human user holds the haptic guide device and places a thumb on the presentation part. A braille plate fabricated with a 3D printer is attached to the presentation part. With multiple hemispheres with a diameter of 1 mm deployed in a cross shape (17 hemispheres in a vertical line and 15 hemispheres in a horizontal line) on the surface of the presentation part, a human user can recognize its orientation and reference position on the haptic guide device. The motor can provide large enough force to be recognized by a user even if the user's gripping force is very strong in comparison. On the other hand, when the user's gripping force is small, the braille can be utilized to make force of the motor recognizable by the user. The presentation part drives the plane in the direction of translational two degrees of freedom and indicates the direction to go by applying a traction force directly to the thumb. The direction of the haptic guide device is presented by the driving motion as shown in Figure 10. By driving at asymmetric speed, we can recognize a cycle accurately. In addition, it is possible to make the user recognize the presentation direction accurately by pulling twice fast on the way and slow speed on the way back [22,23]. As the direction of pulling is recognizable in the eight planar directions and left-right turn as shown in Figure 11. Among them, the combination of front, right-front, left-front and left-right turns is the most suitable for smooth path guidance. The relationship between this combination and the angle of the target direction as seen by a human user is shown in Figure 12. The left-right turn is used to turn the body around significantly. The amount of drive for the presentation parts from the center is 6 mm, and the turn indication is a circle with a diameter of 6 mm from the center. This driving amount of

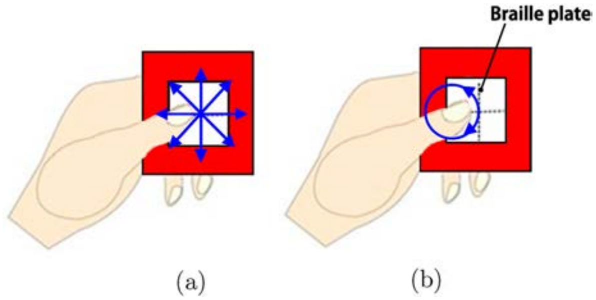

Figure 11. Presentation of directions. (a) Translations and (b) revolutions (CW, CCW).

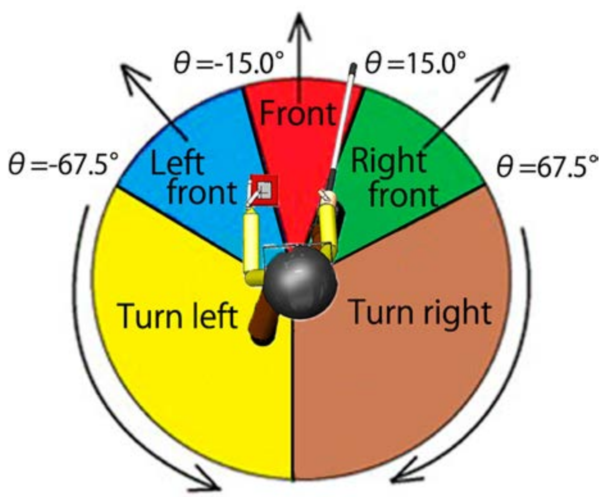

Figure 12. User and presentation direction.

6 mm was experimentally confirmed in this study as the minimum value that enables stable and accurate recognition when the user recognizes the direction. Based on this minimum value, the haptic guide device was made smaller by minimizing the drive amount of the presentation part. The motion of the haptic guide device is shown in Figures 13 and 14.

3. Guide method

The haptic guide device performs route search and guidance by linking with a dedicated Android smartphone application (Figure 15). Google Maps is used for map information and route search. The markers on the route are placed at right and left turning points and curves, referred to as waypoint. A human user takes the waypoint as an intermediate target point and follows it to reach the final destination.

3.1. Installation of target point

When a straight road is long and there is a distance to the next waypoint, the position error, which is the difference between the route and a human user's position, may increase while the haptic guide device presents the direction toward the waypoint. Therefore, in order to reduce the position error, the target point that moves on the route is used to determine the direction presented by the haptic guide device (Figure 16). The distance A, between the closest point from a human user to the route and the target point is defined by Equation (1). Let B[m] be the shortest distance between a human user and the route. When a human user is away from the route by a constant C[m] or more, A becomes 0 m, and priority is given to approaching the route. In other words, the larger the position error, the higher the priority of the haptic guide device along the route rather than the forward direction. When the target point reaches the waypoint, the target point stays on the waypoint so that the target point does not pass it. By making this target point the point that the haptic guide device aims at, a human user can walk to the destination along the route. In addition, if a human user deviates significantly from the route, he/she can be guided back to the route more quickly. If the value of the constant C is too large, it cannot follow the route. On the contrary, if it is too small, it will meander to the left and right around the route, resulting in many unnecessary movements. Currently, the constant C is set to 1.75 m.

$$A = \begin{cases} C - B & (B < C) \\ 0 & (B \geq C) \end{cases} \quad [m] \tag{1}$$

3.2. Update method of waypoint

The positional relationship between a human user, the route, and the waypoint, which is an intermediate target point, is shown in Figure 17. The waypoint is updated when the distance between the closest point from the user and the path to the waypoint (distance X) is less than or equal to an arbitrary distance R. The update distance R is an important numerical value to reduce the position error. If the update distance R is too small, the instruction from the haptic guide device to a human user will be delayed, causing the user to pass the waypoint. On the contrary, if it is too large, the update will be accelerated and the inside of the route will be walked. This brings a danger of overhanging the roadway and colliding with obstacles such as fences on the actual sidewalk. By optimizing the presentation cycle in the direction from the haptic guide device along with the update distance R, it is considered possible to give more detailed information to the user and update near the waypoint. The width of the sidewalk differs from country to country, but in this paper, we refer to Japanese law. According to the Road Structure Ordinance, the width of the sidewalk must be at least 2 m or more [24]. Therefore, if it is assumed that

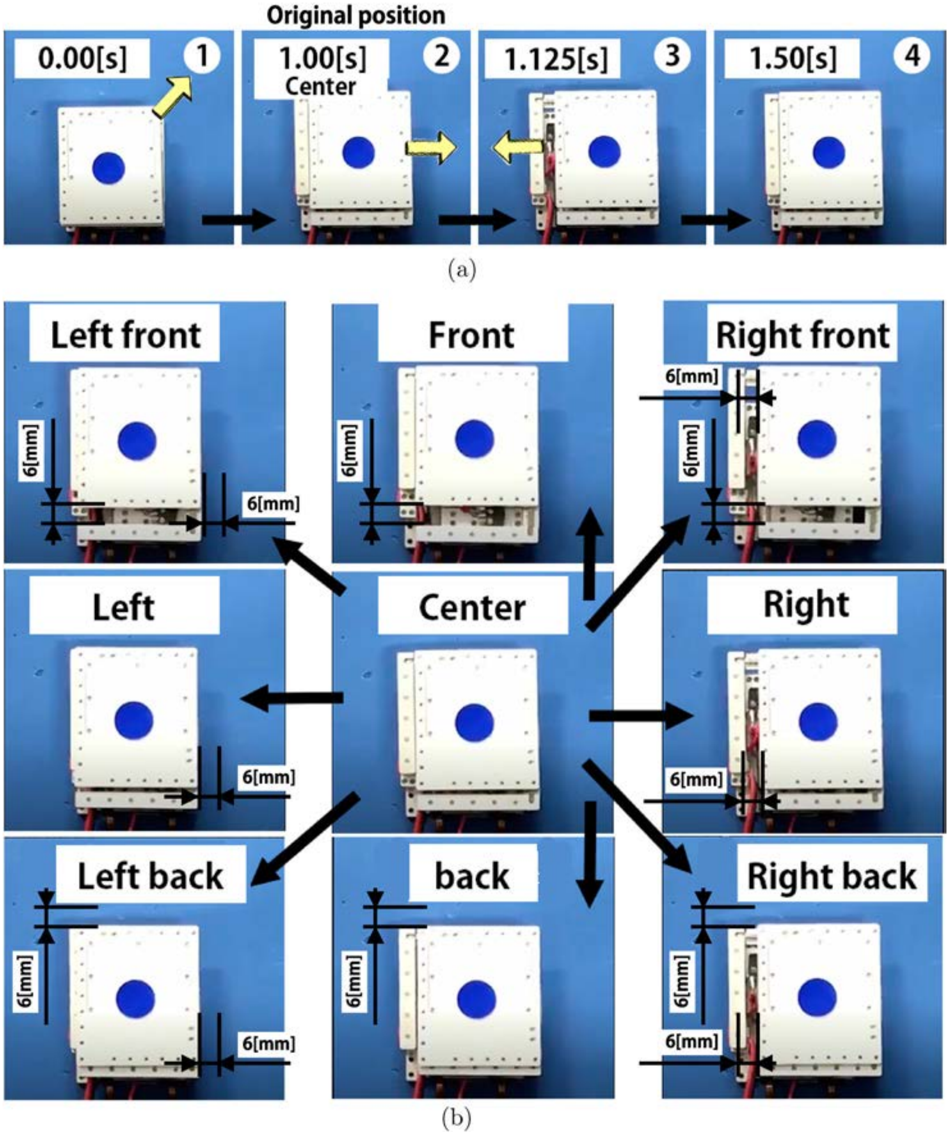

Figure 13. Translational motion of haptic guide device. (a) Elapsed time (translational motion to right). (b) Translational motion to each direction.

the haptic guide device is in the center of the sidewalk, it is considered safe if the position error between the path indicated by the haptic guide device and the path a human user actually walks is within 1 m.

4. Fundamental experiment to present direction

As mentioned in Chapter 1, the proposed haptic guide device is intended to be used together with a white cane. It is assumed that the human user will be guided by the haptic guide device expected with the fundamental and ordinary safety confirmation with a white cane against dangers in the route to be followed. Therefore, a white cane is supposed to be held in the dominant hand of the human user while walking outside. Accordingly the recognition ratio of presented directions from the haptic guide device when it is held in the opposite hand from the dominant hand of the human user should be as high as in the case of his/her dominant hand. This chapter introduces fundamental experiments conducted to examine the recognition ratio of the directions presented by the haptic guide device without walking of a human user. The recognition ratio was measured in both a right hand and a left hand of a human user sitting in a chair.

4.1. Experiments to measure correct answer ratio

The state of the human subject in this experiment is shown in Figure 18. The direction is randomly presented

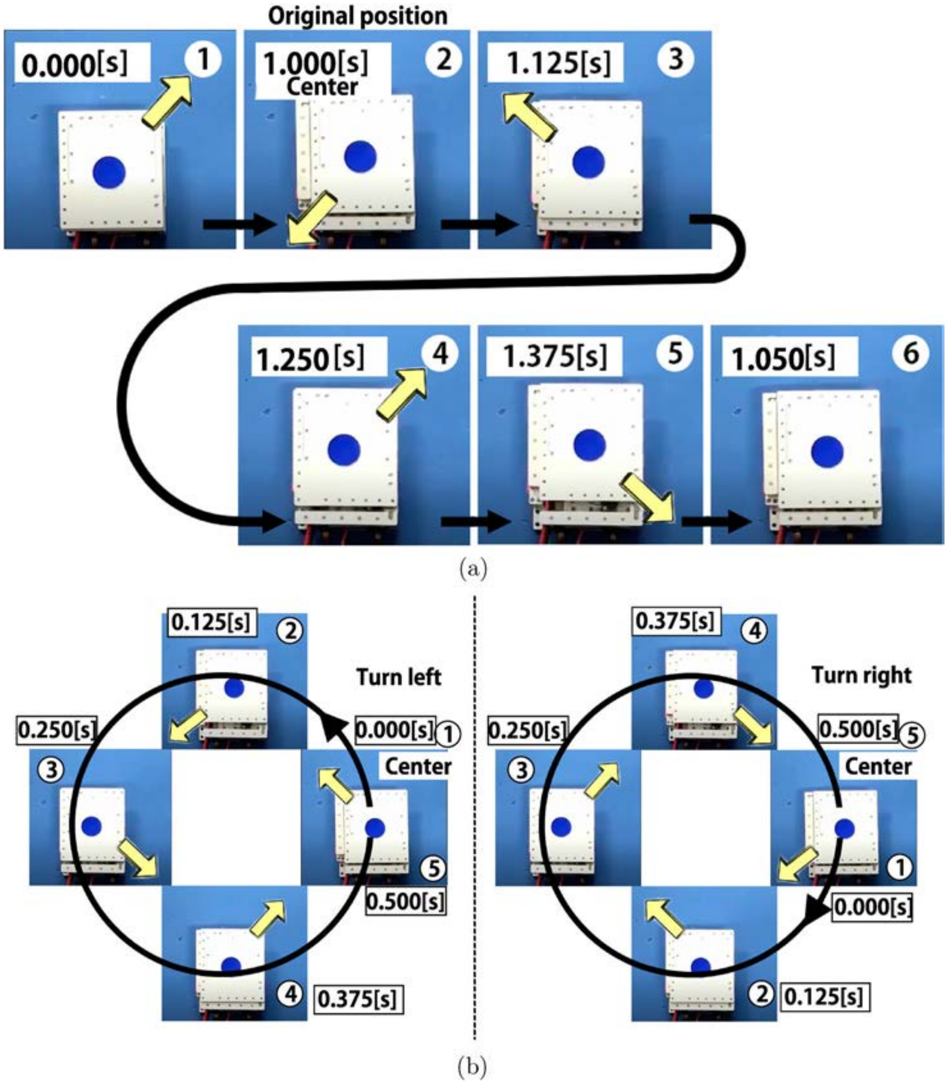

Figure 14. Revolution motion of haptic guide device. (a) Elapsed time (clockwise revolution motion). (b) Revolution clockwise and counterclockwise.

to the subject, who sits in a chair and wears an eye mask, earplugs, and headphones. The driving sound of the haptic guide device that was recorded in advance was made to flow from the headphones as white noise, and the information such as the sound of gears and motors in the haptic guide device during the experiment was cut off, so that the presented direction was confirmed only the haptic information. A human subject holds the haptic guide device and reacts to the direction of the force transmitted to the thumb. At this time, the hand holding the haptic guide device is divided into the dominant hand and the non-dominant hand. Right-handed people were selected as human subjects considering the experimental evaluation. After practicing for two minutes for each subject, the subject was provided stimulation from the haptic guide device five times each in three directions of translation and two directions of clockwise and counterclockwise revolutions, as shown in Figure 19. Since the human hand holding the haptic guide device is switched between left and right, the presentation was performed 50 times in total.

4.2. Experimental result of presentation of directions

The human subjects of this experiment were selected according to the following criteria:

- A right-handed healthy person in his or her 20s who is physically and mentally healthy and has no disabilities.

  The following were exclusion criteria:

- Have some disabilities.

Figure 15. Android application screen.

- Left-handed.
- Not agree to participate in the experiment.

Eventually, 10 subjects joined this experiment.

The experimental results are shown in Figures 20 and 21. The error bars in each graphs represent the standard deviation. Since all the subjects are right-handed, the left hand is considered the non-dominant hand. With both of right and left hands, a correct answer rate of 90% or more was obtained in each translation and revolution, as shown in Figure 20. As observed in Figure 21, the average of correct answer rate of all the experiments was over 95%.

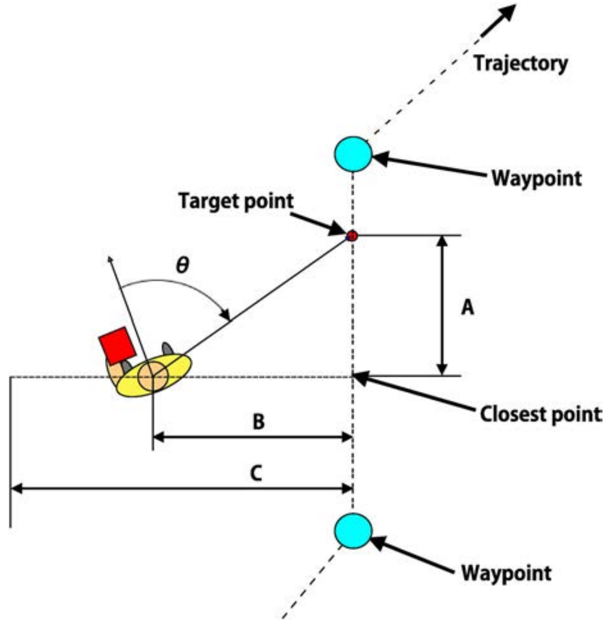

Figure 16. Target point on trajectory.

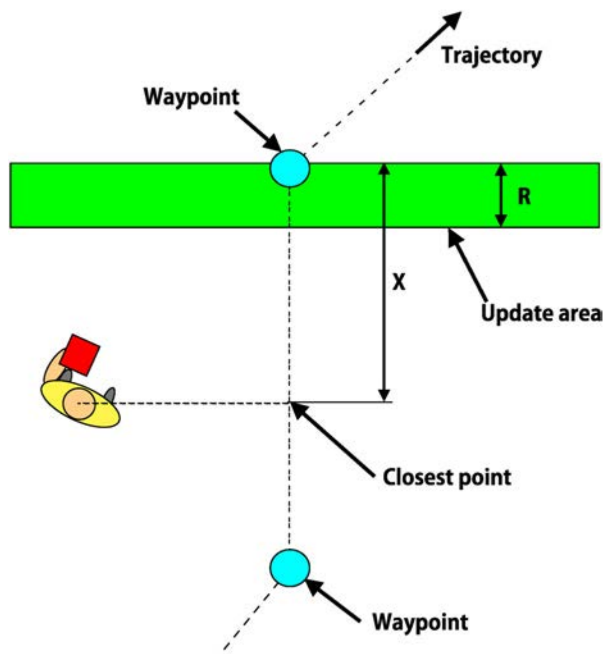

Figure 17. Waypoint update method.

From this experimental result, correct answer rate can be considered high enough regardless of a hand that held the haptic guide device. After experiments, some of the human subjects said 'I did not feel the difference that would affect the answers according to which hand I used'. and 'I can recognize the presented direction when I get used to it no matter which hand I use'. Although there were some individual differences in the length of time to be spent by human users to get used to the haptic

Figure 18. Subject of experiment to present directions.

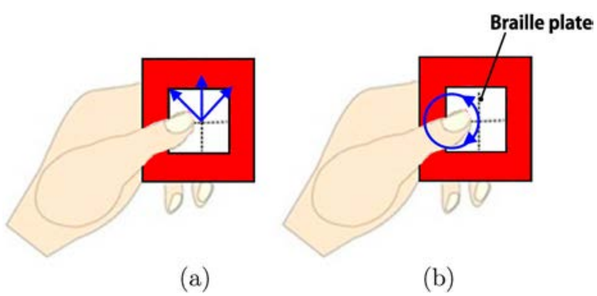

Figure 19. Presentation of directions. (a) Translations and (b) revolutions (CW, CCW).

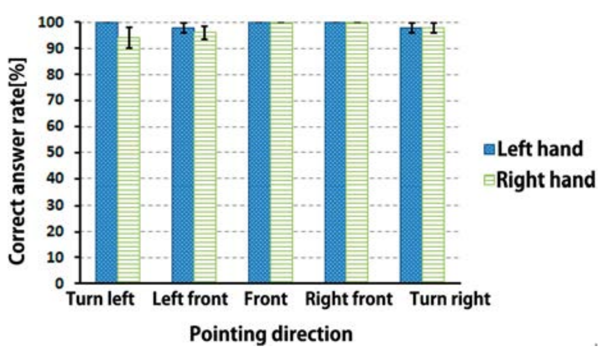

Figure 20. Average correct answer rate for each presentation direction.

guide device, precise recognition of the presented directions can be realized after proper and enough practice of a human user.

5. Guidance experiment using motion tracking system

The function of the 'direction' presentation was proved to be good enough in the previous chapter with sitting human subjects. In this chapter, the function of the 'trajectory' presentation is examined with walking human subjects. To present trajectory, the method with the waypoint was adapted because it is appropriate to the physical motion of the planar omnidirectional driving gear that has two degrees of freedom in one plane. A navigation experiment was conducted aiming at safe and smooth route guidance with a small position error. This chapter describes the outline of the induction experiment and its results.

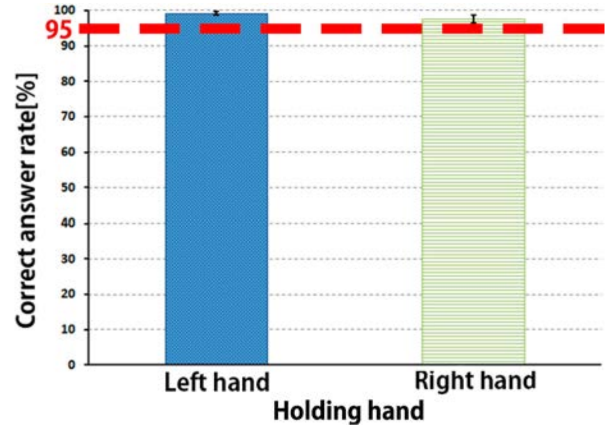

Figure 21. Average correct answer rate by hand holding haptic guide device.

5.1. *Method of guidance experiment with ARToolkit*

In the actual guidance, the smartphone application is used as described in Chapter 3, but there is a problem that the position accuracy of GPS that can be acquired by the smartphone is not sufficient. So in this experiment, in order to guide an arbitrary route, information about a human subject's current location and heading is acquired by implementing the ARToolkit [25,26]

As shown in Figure 22, human subjects wore an eye mask and a hat with an AR marker, and has the haptic guide device in the non-dominant hand. Circuits and power supplies were placed in a waist pouch. A simplified version of the data flow is shown in Figures 23 and 24. A USB camera was installed above the experimental site, and information about the subject's current position and traveling direction was calculated by PC with the image of AR marker sent from the camera. Initially, the human subject is asked not to move his/her head so that the *Y* -axis direction of the haptic guide device is set on the traveling direction. In processing, the position of the target point on the guidance path was calculated based on the information read by the USB camera, and the direction to be indicated by the haptic guide device was determined. The information of the pointing direction was

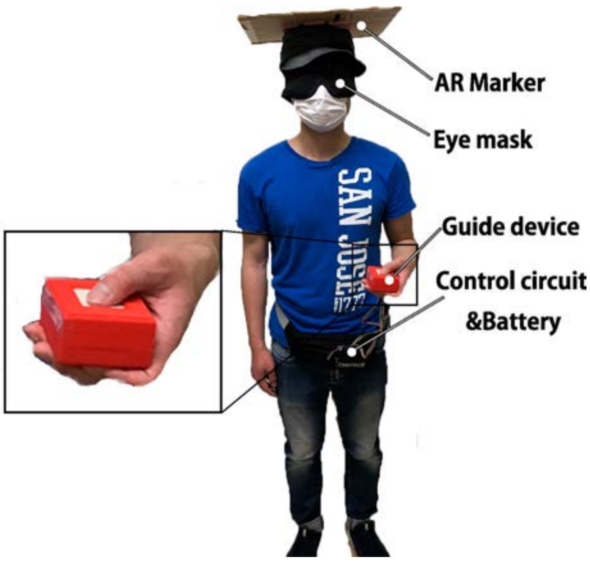

Figure 22. Human subject for experiment to evaluate trajectory navigation.

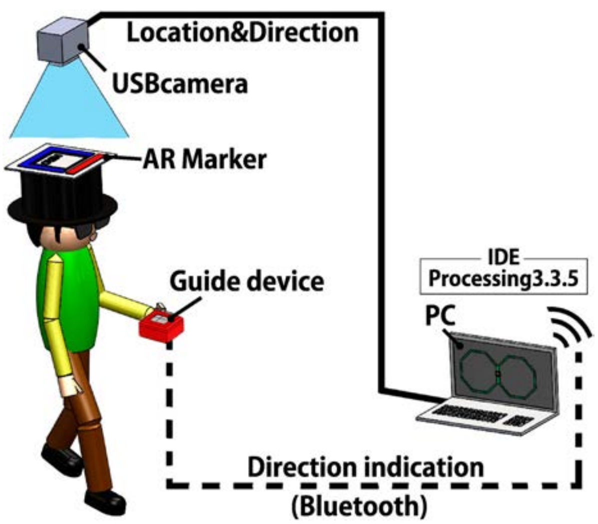

Figure 23. Data flow in motion tracking experiment.

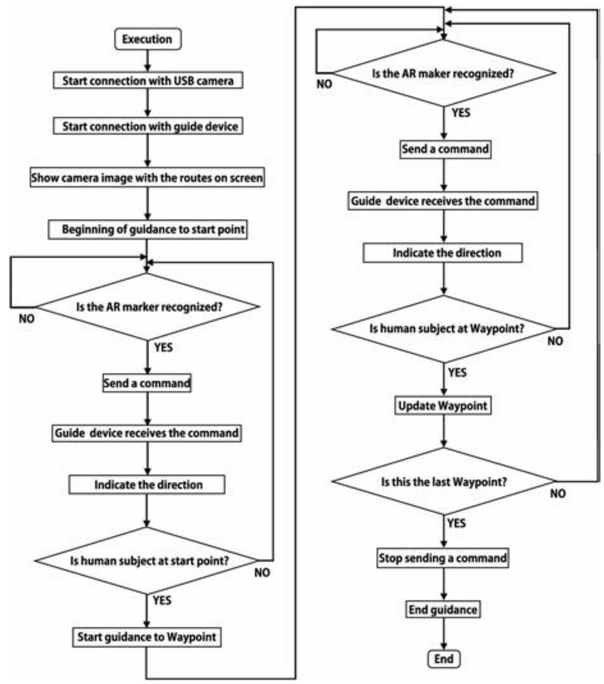

Figure 24. Flowchart of motion tracking experiment with ARToolkit.

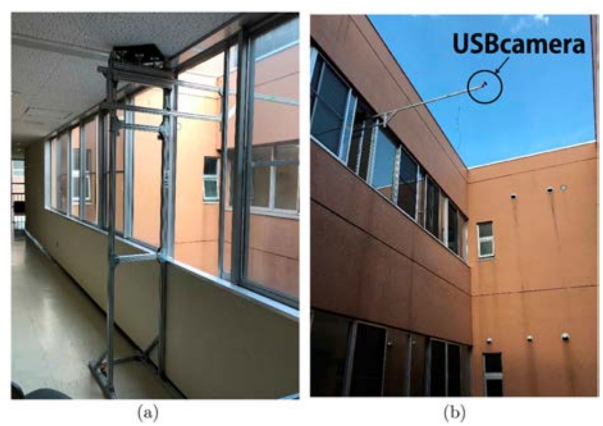

Figure 25. Experimental equipment. (a) Fixed camera base. (b) Seen from the experimental site.

transmitted from the PC to the haptic guide device using Bluetooth, and the haptic guide device communicated the information to the subject by haptic force.

The actual experimental environment and equipment are shown in Figures 25 and 26. The USB camera was installed at the tip of the cantilever structure, attached to a fixed base, and extended from the window on the second floor of the facility. The height of the camera was 6.00 m. The experimental range was 3.80 m vertically and 6.00 m horizontally. In addition to the human subject, the experiment manager was responsible for the operation of the PC and gave instructions on the experiment, and there was an assistant who watched a human subject to avoid risk.

5.2. *Optimization of waypoint update position and time cycle*

As described in Chapter 3.2, by optimizing the combination of waypoint's updated position R and the direction presentation cycle (time cycle) of the haptic guide device, safe and smooth route guidance with less position error will be possible. Therefore, we conducted an experiment to optimize the waypoint update position and direction presentation cycle. The route guided in this experiment is shown in Figure 27. The starting point is randomly determined from three points (green points) using random

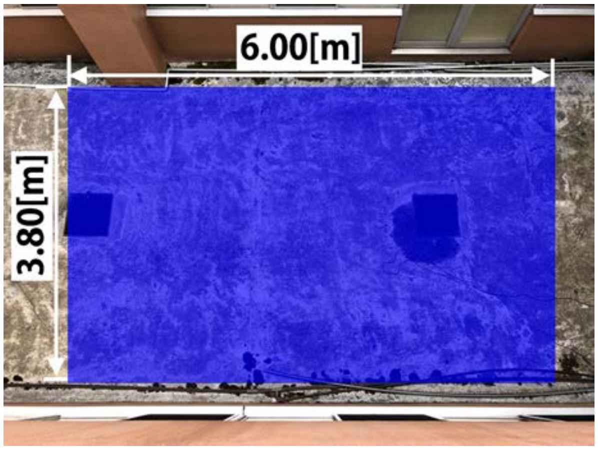

Figure 26. Experimental site.

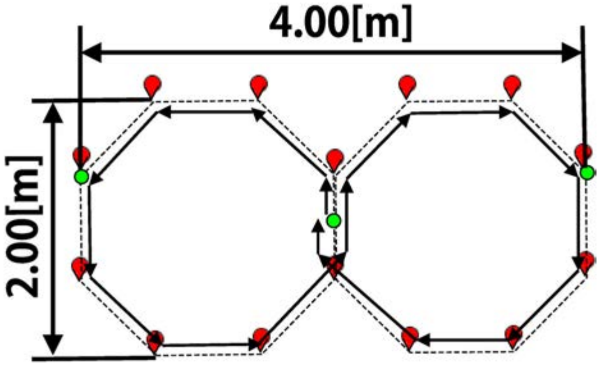

Figure 27. Route for human subject in navigation experiment.

numbers generated by the Box Muller's method. The red marker indicates the waypoint on this route.

In the first experiment, two ways of updating the waypoint R in Figure 17, 0.250 m and 0.750 m, and two types of the time cycle, 1.00 s and 0.500 s, were prepared and combined. In other words, a total of four types of experiments were conducted, and the tendency of the overall combination was examined.

In the second experiment, the time cycle is set to 0.500 s, and the waypoint update position R in Figure 17 is selected from five types of 0.250 m, 0.500 m, 0.750 m, 1.00 m, and 1.25 m. Based on the unit that 'the time required for walking is 1 minute per 80 m', which is the standard for calculating the time required to walk to the destination of real estate in Japan, 0.667 m par 0.500 s [27]. Considering that the assumed haptic guide device user is a visually impaired person, and that in the experiment, a sighted person was blindfolded and walks as a subject, the update position R was changed from 0.250 m to 1.25 m. The transition of the position error due to the change of the update position R of the waypoint was measured, and the optimum update position was derived.

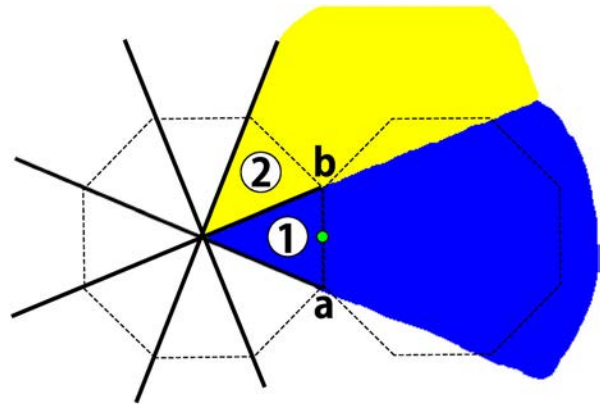

Figure 28. Arbitrary route 'ab' for Area 1.

5.3. Position error calculation method

The calculation method of the position error in this route is described here. As shown in Figure 28, the route was divided into eight equal parts from the center of each octagon that composes it, and one specific route is determined in each area. For example, the specific route in Area 1 is the line segment 'ab'. The area is updated as the subject progresses, and the specific route is also updated. The position error is the distance between the subject and the route in that area.

5.4. Experimental result

The subjects of this experiment were selected according to the following criteria:

- A healthy person in his or her 20s who is physically and mentally healthy and has no disabilities.

The following were exclusion criteria:

- Have some disabilities.
- Not agree to participate in the experiment.

Eventually, 10 subjects joined this experiment.

5.4.1. Experiment 1

The state of the actual experiment is shown in Figure 29. Nine among 10 subjects were able to walk the path within a position error of 1.00 m in all combinations. Figure 30 shows the walking route of the subject who passed the route at more than 1.00 m when the time cycle was 1.00 s and the update position was 0.250 m. In addition, the time required for this subject was 57.0 s, which was shorter than other subjects, and it is considered that the presentation after the update of the waypoint was not early enough. The trajectories of the human subjects

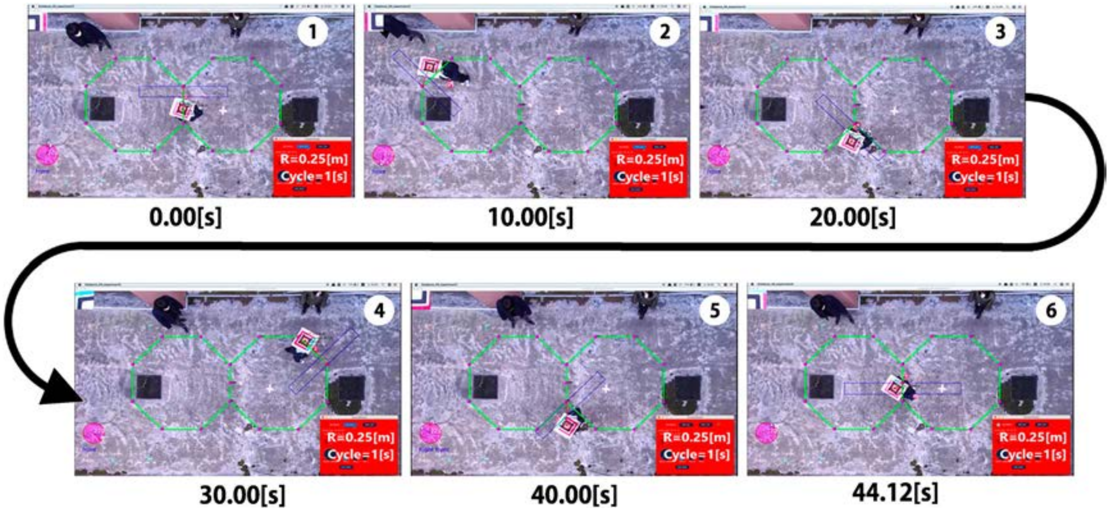

Figure 29. Guided motion of human subject in experiment.

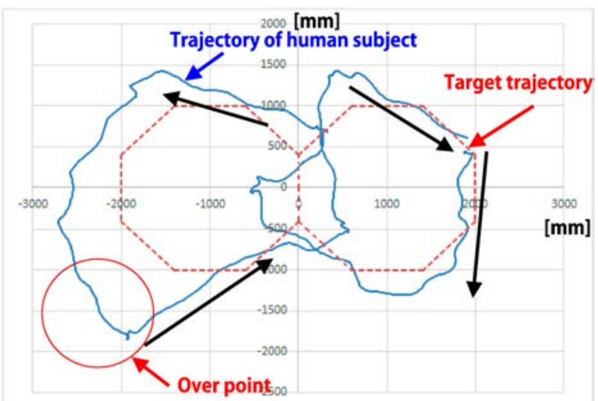

Figure 30. Example of subjects who have passed more than 1.00 m.

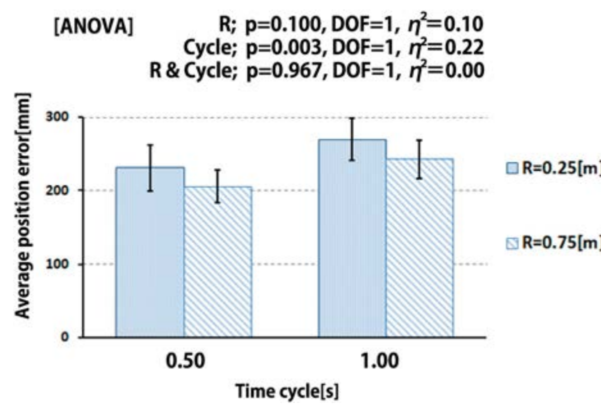

Figure 31. Average position error in experiment 1.

show the tendency of the human subjects to go back to the desired path after walking outside of it with the displacement of only several hundreds of millimeters and turning their bodies around significantly. This fact and the experimental result of that all human subjects reached the goal eventually suggest that the haptic guide device can guide human subjects along the desired path correctly enough.

Figure 31 shows a graph of the average position error of the entire route for each subject, and the vertical line of the graph means the averaged values of the data of all 10 subjects. Next, Figure 32 shows a graph of the values of the average of the maximum position errors when each subject passed the entire route under each condition for all 10 subjects. In addition, Figure 33 shows a graph of the values of the average time required for all 10 subjects to pass through the entire route under each condition. The error bars in each graphs represent the standard deviation. From the experimental results shown in Figure 31 and Figure 32, the position error with the time cycle of 0.5 s was smaller than that with the time cycle of 1.00 s. Therefore, it can be seen that the position error decreases as the time cycle is shortened. In addition, the time required for $R = 0.750$ m was shorter than that for $R = 0.250$ m in Figure 33 regardless of the time cycle. The results of the two way repeated measures ANOVA are shown at the top of each graph. From the result of Figures 31 and 32, a significant difference appears depending on the change in time cycle.

By shortening the time cycle, passing of waypoint was suppressed and position error was reduced. Considering the subjects' opinions of that they get tired when the time cycle is too short, a time cycle of 0.500 s is considered to be effective. In addition, as the update position became longer, walking inside the route led to a decrease in position error and required time. However, from the result of ANOVA, no significant difference in the position error due to the change of the update position was

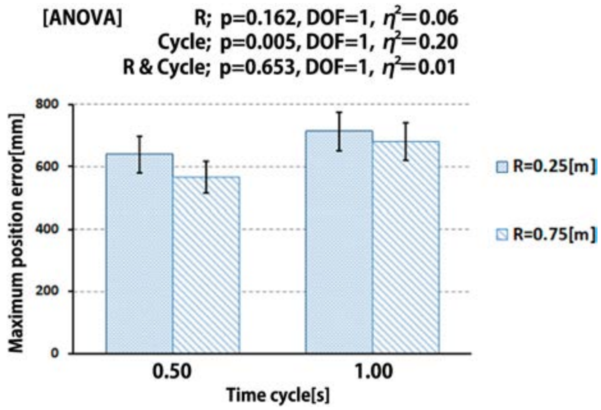

Figure 32. Maximum position error in experiment 1.

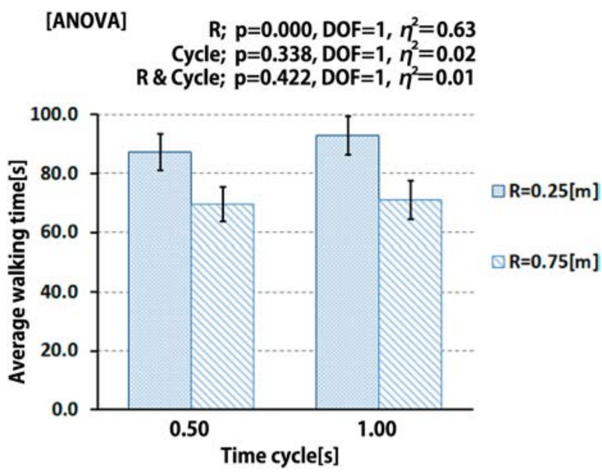

Figure 33. Walking time in experiment 1.

found, and sufficient evaluation could not be performed in this experiment.

5.4.2. Experiment 2

Based on Experiment 1, an additional experiment was performed with the time cycle fixed at 0.500 s. Experiments were conducted with 10 subjects different from those in Experiment 1. The experimental results at the update positions 0.250 m and 0.750 m are those of Experiment 1. Two subjects at the update position of 1.00 m and one subject at 1.25 m could not keep the position error within 1.00 m.

Figure 34 shows a graph of the average position error of the entire route for each subject, and the vertical line is the averaged values of the data of all 10 subjects. Next, Figure 35 shows a graph of the values of the average of the maximum position errors when each subject passed the entire route under each condition for all 10 subjects. In addition, Figure 36 shows a graph of the values of the average time required for each subject to pass through the entire route under each condition for all 10 subjects. The

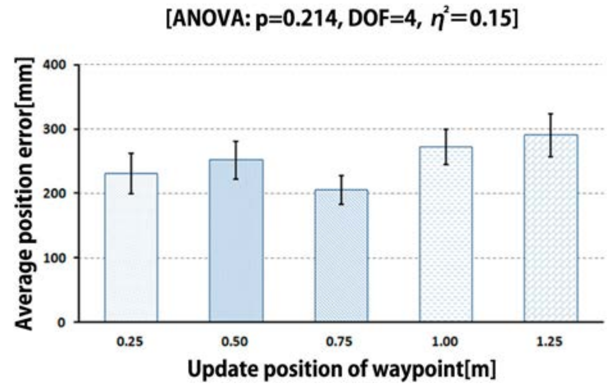

Figure 34. Average position error in experiment 2.

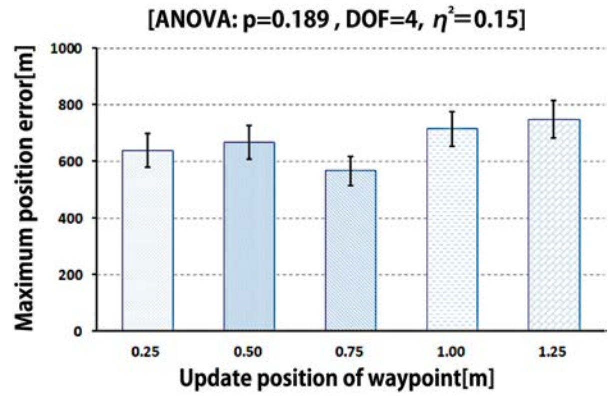

Figure 35. Maximum position error in experiment 2.

error bars in each graphs represent the standard deviation. From the experimental results, in Figures 34 and 35, there is a slight deviation due to the difference in subjects, but the convex curve appears with the minimum value at the update position around 0.750 m. This convex curve means that when the update position was small, the position error became large by human subjects' walking outside the route, and when the update position was large, the position error became also large by human subjects' walking inside the route. The results of the one way repeated measures ANOVA are shown at the top of each graph. This result shows that the effect size(η^2) not related to the number of subjects was more than 0.14 in all cases. Although no significant difference was observed, a substantial effect is expected on the experiment.

From the viewpoint of the maximum position error, it is generally considered that the updated position of 1.00 m or more is not suitable for the guiding system of the haptic guide device. When the human subject perceives a command from the haptic guide device, he/she tends to walk a few steps in the indicated direction before recognizing the next orientation command. For a human subject with a large stride, this course is small

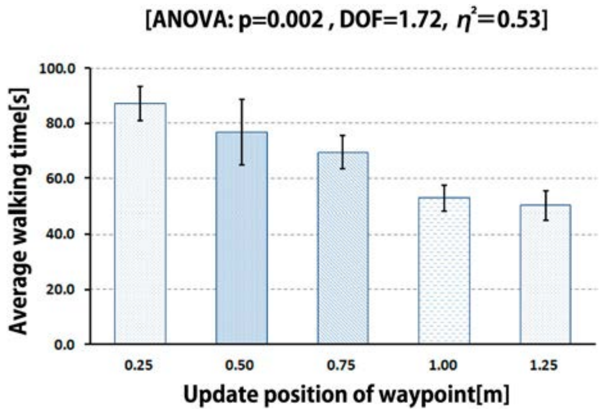

Figure 36. Walking time in Experiment 2.

and he/she can easily deviate from it. Therefore, the maximum positional error admitted for our calculations was about 0.5 m. However, the maximum positional error is expected to be smaller than the error in this experiment since the actual sidewalk does not have many sharp curves. Therefore, for safe and smooth route guidance, the updated position of 0.75 m with the shortest required time and little route error is adopted.

The results of the human haptic force obtained in this experiment are listed below.

- It is considered that the direction presentation with a presentation cycle of 0.500 s matches the general stride length (equivalent to 0.667 m par 0.500 s), and it is considered that there is almost no feeling of fatigue on the fingers.
- There is a margin of about 0.750 m required for a walking person to recognize the direction of travel using the haptic force and start moving in the direction actually recognized.
- However, an instruction for the next route given before 1.00 m or more, results in a human user's walking inside the route.

6. Conclusions

In this paper, a portable route guidance device using haptic force as the solution for the shortage of guide dogs for visually impaired people was designed and developed. Because the omnidirectional driving gear that is used for the haptic guide device can produce output force based on its reliable power transmission by its gear structure that is sufficient to stimulate kinesthetic sense in addition to tactile sense by moving joints of a human finger, it can intuitively guide a human user to certain direction toward their destination on the correct route in a map.

The experiments with sitting human subject proved that the correct answer rate was always more than 95% no matter which hand the human subject used to grab the haptic guide device. So non-dominant hand can be used to hold the device and get the correct enough information about the direction to follow the route to the destination.

The navigation system of the developed haptic guide device prioritizes to make its human user follow the correct route to the destination, so the system sets a target point that reflects the relationship between the position of its human user and the route that should be followed. Through the experiment, the presentation cycle and the update position of the intermediate target point have been optimized to prevent a human user fs passing of the intermediate target point. The positional error of the human user from the trajectory was controlled within 1.00 m by using the presentation cycle of 0.500 s and the update position of 0.75 m from the intermediate target point. As a result, it was made possible to walk a route with a total length of 15.0 m for a human user within one minute under safe and smooth guidance. According to the experiments in this paper, presenting the direction information to a human user by directly moving the skin and joints of his/her fingers by real force was proved useful to guide a walking human user correctly in the required direction and route.

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