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Navigation in Eight Cardinal Directions with Pseudo-Attraction Force for the Visually Impaired

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***Abstract*—We have proposed a haptic direction indicator that will help visually impaired pedestrians to travel a path and avoid hazards areas intuitively and safely by means of force-based navigation. The haptic direction indicator uses the pseudo-attraction force technique, which generates a pulling or pushing force in portable or mobile devices by exploiting the nonlinear relationship between perceived acceleration and physical acceleration. We have investigated the angular resolution of the pseudo-attraction force for the visually impaired in a static posture to design a practical haptic direction indicator. This paper describes a prototype of a crosshair haptic direction indicator based on our previous findings. An experiment was performed to clarify the perceptual characteristics when a visually impaired pedestrian is navigated by perceiving force sensation. The results show that most of the visually impaired participants could walk in a predetermined cardinal direction with the haptic direction indicator. Finally, we discuss the drawbacks of our system and design improvements.**

***Index Terms*—Haptics, Perception, Visually impaired, Assistive technologies**

I. INTRODUCTION

The two main factors related to wayfinding are orientation and mobility [1]. Physical mobility and the ability to recognize both the current and target locations and the required direction are essential. Location and direction recognition is achieved by interacting with the environment by means of various sensory clues. However, these abilities are sometimes disrupted. Many people with visual impairment have reported that they become disoriented if they fall and cannot find anyone to help them. Therefore, support devices that can provide orientation information are very useful in assisting autonomic walking.

Recent years has seen the growth of pedestrian navigation systems in mobile devices. These systems have deployed different sensory channels. However, visually impaired pedestrians cannot use visually based navigation. Therefore, many auditory feedback handheld devices for the visually impaired, such as Talking Signs [2] or similar acoustic information output devices [3], have been developed. Nevertheless, audio interfaces can be problematic when they conflict with other sounds or speech around the users, leading to difficulties in distinguishing and interpreting the sounds generated by the system [4]. Wearing headphones also prevents visually impaired pedestrians from hearing other ambient sounds that may be important for their safety during navigation. In addition, auditory information cannot be used in noisy situations, such as during a blast from a siren or on crowded streets.

Interaction based on touch may help overcome these issues, not only with regards to navigation for the visually impaired but also in challenging environments, such as a smoke-filled building or a crowded, noisy space. It has been reported that tactile interaction effectively assists visually impaired pedestrians in street crossing tasks [5]. In addition, navigation aids using several wearable vibrators in the form of a cap [6], rings [7], a vest [8], and a belt [9] have been proposed. However, this approach requires that users learn how to convert stimuli to information, which means that it is not intuitive and requires training since there are limitations in conveying semantically rich information via the tactile channel.

A kinesthetic approach has the potential to be more intuitive and expressive than cutaneous stimulation in conveying direction information since haptic devices can indicate a one-dimension direction directly. The intuitive comprehension of orientation information through haptic modality is thought to be important in the situations outlined above.

We have proposed a mobile haptic direction indicator for visually impaired pedestrians [10] based on a pseudo-attraction force method [11]. This paper describes a development of a crosshair haptic direction indicator that generating asymmetric oscillations in the eight cardinal directions, on the basis of the requirements suggested in our previous research [12], and presents an evaluation of the crosshair haptic direction indicator. The results clarify its feasibility for navigating visually impaired people in the eight cardinal directions.

II. APPPROACH

A. Pseudo-Attraction Force Technique

The pseudo-attraction force technique exploits the characteristics of human perception to generate a force sensation in mobile devices. In the technique, different acceleration patterns are produced in two directions to create a perceived force imbalance and thereby produce the sensation of directional pushing or pulling. Concretely, a strong acceleration is generated for a very brief time in one direction, while a weaker acceleration is generated over a longer period of time in the reverse direction. The weaker acceleration is not detected by the internal human haptic sensors, so the original position of

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the mass is ‘washed out’. The result is that the user is tricked into perceiving a unidirectional force. This force sensation can be made continuous by repeating the motions (See [13], [14] for details).

To generate the asymmetric back-and-forth motion of a small, constrained mass, we have adopted a slider-crank mechanism. In the slider-crank mechanism, the side-to-side force created by the motion of linkages is thought to be an obstacle preventing the user from sensing the desired direction, so we tried to cancel it out completely by using two identical mechanisms operating in mirror symmetry.

B. Design

In our previous research [12], we used one module with a turntable. The direction of the force display module was controlled with a stepper motor engaged by a belt with a belt pulley installed in the turntable. However, the rotation takes considerable time, thus losing immediacy.

A two-dimensional force can be generated not only by rotating one force display module but also through the summation of linearly independent force vectors. Therefore, the angular resolutions of pseudo-attraction force for the visually impaired were examined in order to fabricate a haptic direction indicator based on the summation of force vectors. The results show that the angular resolution under an eight-direction (compass) conditions was better than that under a twelve-direction (clock position) condition [12]. That indicated that the simple eight cardinal directions are enough for a human in a static posture to perceive a force vector on a two-dimensional plane.

When users move or rotate their bodies, i.e., dynamically explores the force vector, their angular resolution would be higher than that in a static posture. Therefore, we began by designing a haptic direction indicator that can generate force vectors in the eight cardinal directions and fabricated a crosshair haptic direction indicator as shown in Fig. 1. Four slider-crank mechanism pairs were embedded in the force display in the shape of a crosshair. By combining force vectors generated by each slider-crank mechanism, the force display can create a virtual force in eight cardinal directions on a two-dimensional plane.

III. EXPERIMENT

The purpose of the following experiment was to examine whether the haptic direction indicator based on the summation of force vectors could navigate visually impaired people in predetermined direction. We used the haptic direction indicator introduced above and tested an eight-cardinal-directional navigation in the gymnasium of the Kyoto Prefectural School for the Visually Impaired, Japan. The force vector was calculated and updated according to the holder’s yaw angle to compensate the rough angular resolution of the force vector of the haptic direction indicator.

A. Method

1) Participants: Twenty-three subjects whose ages ranged from 17 to 62 (twenty males and three females) with no history of neurological, cognitive, or sensory-motor deficits, other than blindness in the case of the blind participants, participated in the experiment. Participants experienced all conditions in random order. The research protocol was approved by the local ethics committees and all participants agreed to the experiment procedure. All participants gave their informed consent to participate in this study before the start of the experiment.

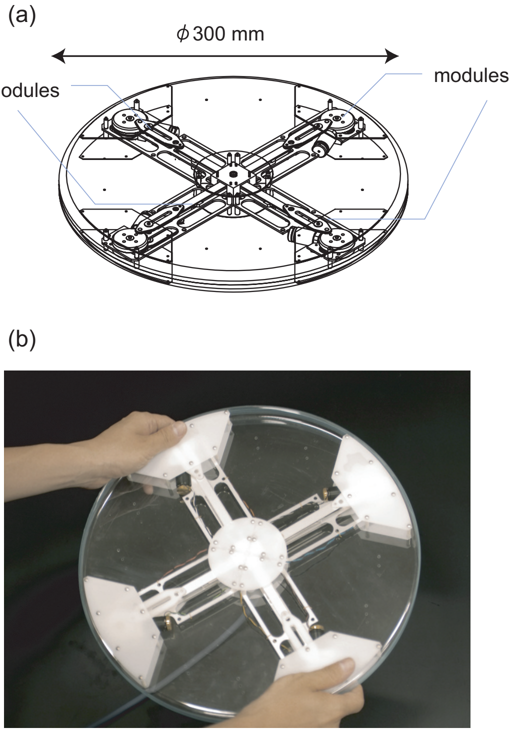

Fig. 1. Developed haptic direction indicator. One unit accommodates four modules (a). Each module has a mechanism for generating an asymmetric acceleration with the swinging slider-crank mechanism. Photograph of the haptic direction indicator (b).

2) Apparatus: The system consisted of a haptic direction indicator held by the participant (approximately 750 g), a small bag containing a battery and control device, and a subject’s position and orientation identification system based on an image processing system. A small coreless DC motor (1724 006 SR; FAULHABER) was used to rotate the crank in each module. A pinion gear on the motor engages with two crown gears in each module (reduction ratio: 10). The crown gears also work as two cranks that rotate in opposite directions. The rotational speed of the motor is controlled by the electronic governor system of the motor amplifier. Since each device had a tandem double-layer configuration, the side-to-side forces generated by the motion of linkages were well suppressed [13]. The reciprocating weight in the module had a mass of 40 g. The haptic directional indicator was covered with a plastic case. The case was 300-mm diameter and 27-mm height. The motors were powered by a 12-V with a battery (ENAX) and controlled by an additional custom-built controller switch.

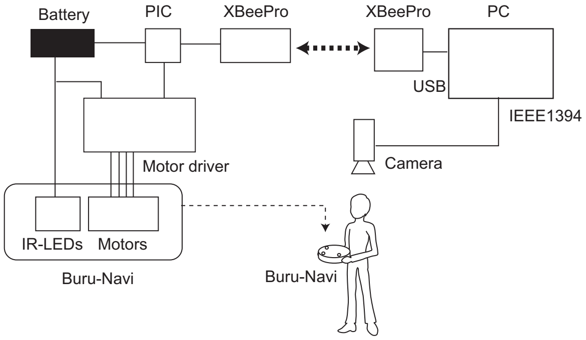

Fig. 2. System configuration.

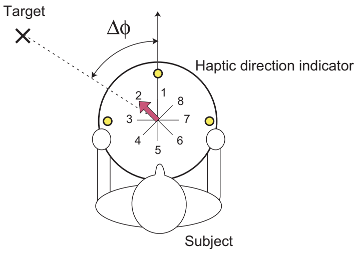

Fig. 3. One of the force vectors in the eight cardinal directions was selected according to the angular difference ($\Delta\phi$) between the subject and the target.

Figure 2 shows the system configuration of the experimental apparatus. The visually impaired subject moved by following the direction of the perceived force sensation. The direction of the force vector was controlled so that it faced the end point of the target direction as shown in Fig. 3. Control instructions were sent from the computer to the microcomputer via a ZigBee link (XBee-PRO ZigBee module, 60 mW; MaxStream) when required.

The subject's position and posture were detected by placing three super-high-luminance infrared LEDs (OD-100, OPTO Diode Corp., peak wavelength 880 nm) at the corners of a right-angled isosceles triangle (side length = 100 mm) on the haptic directional indicator. The infrared rays were captured by an IEEE1394 black and white CMOS camera (Firefly MV, FFMV-03MTM; Point Grey Research Inc.) with a wide-angle lens (field angle 175 degrees), which was hung by rope from the upper floor (about 3 m from ground). Since the beam angle of the LEDs was very wide (about 120 degrees), the camera could capture all LEDs unless the participant occluded the infrared rays. The positions and orientations of each LED were obtained by binarizing the brightness value from the acquired camera image with the OpenCV Library and calculating the position and orientation from the relationship with a right-angled isosceles triangle formed by three dots (Fig. 4).

3) Stimuli: The force vector of asymmetric oscillation (**F**) is given by

$$\mathbf{F}(t) = \sum_{j=1}^{4} m_j \frac{d^2 x_j(t)}{dt^2} u(j)\mathbf{e}_j \tag{1}$$

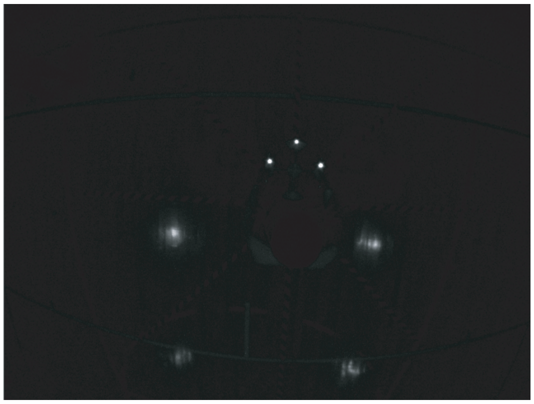

Fig. 4. Vision-based position and posture identification system. The three white dots in the picture are the infrared LEDs captured by a camera facing the ground from a height of about 3 m. Other white blobs are light reflection from floor, which did not affect the identification system.

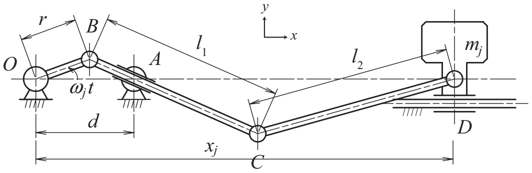

Fig. 5. Overview of the slider crank mechanism of one module [13] in the haptic direction indicator. In the haptic direction indicator, each module represents one of the four cardinal directions, with each directional signal being generated using one motor.

where m_j is the weight in module No. j, and $\ddot{x}_j$ is the acceleration generated by module No. j. The $u(j)$ works as a switch of output module No.j. If $u(j)$=0, there is no output from module No. j. The $\mathbf{e}_j$ is the unit vector on the two-dimensional plane, where $\mathbf{e}_j \cdot \mathbf{e}_{j+1}$=0, $|\mathbf{e}_j|$=1, $\mathbf{e}_j \cdot \mathbf{e}_{j+2} = -1$. The acceleration $\ddot{x}_j$ is given by the second derivative with respect to time of the motion of the weight x_j. The equation for the motion of the weight in module No. j is

$$x_j(t) = l_1 \cos(\omega_j t + \theta_{0j}) + \mu_j (d - l_1 \cos(\omega_j t + \theta_{0j})) + \sqrt{l_3{}^2 - \{l_1(\mu_j - 1)\sin(\omega_j t + \theta_{0j})\}^2} \tag{2}$$

where

$$\mu_j = \frac{l_2}{\sqrt{l_1{}^2 + d^2 - 2 l_1 d \cos(\omega_j t + \theta_{0j})}}, \tag{3}$$

and $x_j(t)$ = OD, d = OA, l_1 = OB, l_2 = BC, l_3 = CD, and $\omega_j t$ = AOB in Fig. 5. The ω_j is the constant angular velocity, and t is time. In the device, d = 28 mm, l_1 = 15 mm, l_2 = 60 mm, and l_3 = 70 mm. θ_{0j} is the initial angle of the crank in module No. j.

4) Procedure: A subject held the haptic directional indicator with both hands and stood at a marked point while being guided by an experimenter. After perceiving a haptic stimulus generated by the haptic directional indicator, the subject walked according to the perceived force direction.

Fig. 6. Overview of the experiment. Subjects held the haptic direction indicator with both hands.

The error between the subject's and target's positions was calculated every 150 ms, and then the direction of the presented force vector was updated. The walk trajectory was recorded by the overhead camera and by an experimenter. When the subject stopped for 2 s around the target area, the system automatically finished and recorded the direction. When the subject walked through the camera-captured area, the experimenter recorded the direction according to the closest reference line on the floor.

The orientation of the force vector was varied between 0 and 360 degrees on the horizontal plane in 45-degree steps. The stimulation was presented until the subject reached the target area, went out of camera range, or all LEDs were not captured. The stimuli were randomly supplied from the eight directions per each subject. Each subject responded for five trials.

B. *Results*

Figure 6 shows the overview of the experiment. In the experiment, sometimes a part of subject's body occluded an overhead camera. In that case, the haptic stimuli were not provided until all three LEDs were captured. That caused large variance of the completion time (1 sec to 10 sec). Average completion time was 2.5 second.

Figure 7 shows the number of accuracy trials. Eleven visually impaired subjects (47.8 %) could correctly walk along a predefined direction in all trials. However, two subjects (8.7 %) could not walk along a predefined direction at all; one of the two walked in the opposite direction in all trials.

We calculated the angular error between the stimulus and response. The angular error is the angular difference between the orientation of the stimulus and that from the marked point to the subject's final position after walking. Figure 8 shows the scatter pattern of the responses as a function of the stimuli for all the subjects. The size of the radius shows the percentage of the responses from all subjects. The results show that the predominant responses were on the same line, which means that the subjects responded to the direction correctly.

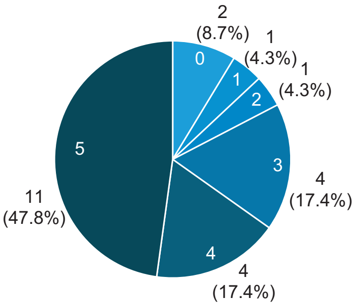

Fig. 7. Ratio of successful attempts in the five trials of the experiment with corresponding number of subjects and percentage of the all subjects. Inner numbers are the number of successful attempts in the five trials.

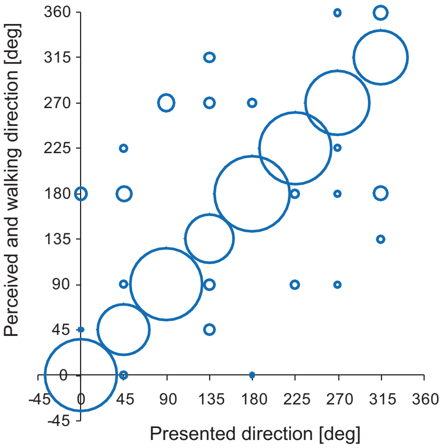

Fig. 8. Scatter pattern of the responses as a function of the stimuli for the 23 subjects. The 0 deg was defined as the forward direction.

After the experiment, we received some comments from the subjects. Some participants stated that it was difficult to perceive force sensation in the cross directions, i.e., SW, SE, NW, or NE. Participants also gave bad feedback on the gross weight and size of the haptic direction indicator. Because some of them usually use a cane to walk alone, they could not hold the device with both hands.

IV. DISCUSSION

For the four cardinal directions (i.e., North, East, West, South), almost all subjects seemed to perceive the force sensation clearly and walk in the direction. However, in the cross directions, it seemed to be difficult for them to perceive force sensation.Figure 9 shows examples of trajectories of subjects walking in cross directions. There seemed to be two strategies: Some walked straight, while others walked in a zigzag, staircase way.

We speculate that the case of zigzag walking was due to the hardware configuration and subject's strategy of force perception. To generate the force vector crossly, two modules in the haptic indicator were driven simultaneously. However, they claimed that it was harder to perceive the force vector generated by two modules than it was to perceive that by single module. Since the presented force vector was changed

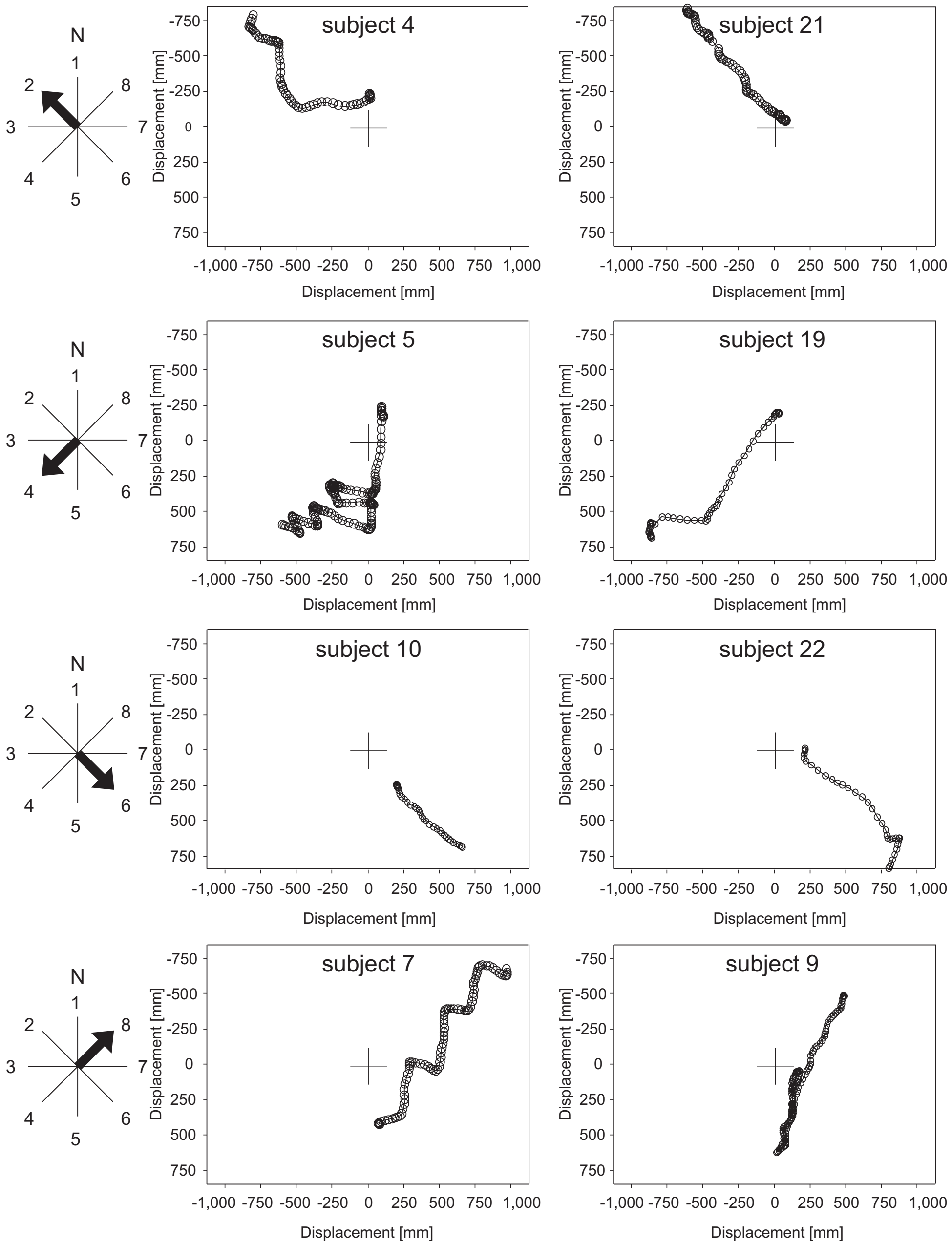

Fig. 9. Trajectory of some subjects in the experiment. Open circles indicate the position of the subject recorded every 150 ms. The arrows (left) show the directions of the stimulus.

according to the subject's position and orientation, they may have walked back-and-forth (or right-and-left) so as to drive only one module.

From the comments after the experiment, there is much room for improving the haptic direction indicator, mainly in noise, size, and weight. The noise emitted by the gear could be reduced by using direct drive or friction drive. The gross weight and size could be reduced by using other mechanical designs so that the device could be held in one hand. However, the mass of the reciprocating weight to generate an oscillation would have to remain in order for a clear force sensation to be perceived. Reducing the gross weight without reducing the oscillation amplitude is a very difficult problem. Since our previous research has provided us with some miniaturization criteria [11], we will try to use those criteria to reduce the gross weight of the haptic direction indicator.

V. CONCLUSION AND FUTURE WORK

We reported an investigation that clarifies the feasibility of a mobile haptic direction indicator to navigate the eight cardinal directions for visually impaired people. The results indicate that they can be navigated to the predetermined direction effectively. Future work includes navigating the visually impaired pedestrians to more complicated routes, such as those in urban navigation, and redesigning to make the haptic directional indicator smaller and lighter so that it can be held with one hand.

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