Head orientation control of projection area for projected virtual hand interface on wheelchair

Kohei Morita, Takefumi Hiraki, Haruka Matsukura, Daisuke Iwai and Kosuke Sato

ABSTRACT
A projected virtual hand interface, which visually extends the arms of users using projection images, enables wheelchair users to reach unreachable objects; however, its projection area is usually smaller than the reaching area for its users. In our previous research, we developed a wheelchair system with a projected virtual hand system in which users can move the projected area via finger movements on a touch panel. However, it requires some time to move the projected area to the desired position. To address this problem, we propose a wheelchair system enhanced with a projected virtual hand that allows controlling a projection area using a user’s head orientation. The proposed system measures the current user’s head orientation and distance between a user and a projection surface. Then, it adapts the suitable pan and tilt of the projector by considering its positional relationship with the projection plane. As users can operate the projection area simply by turning their head, this operation can be executed simultaneously with operating a virtual hand using their hands. We propose a control model for projector rotation according to the user’s head orientation. We implemented a prototype based on the model and confirmed the system’s latency. The usability study revealed that the proposed method enables users to perform pointing tasks in a shorter time compared with the existing method. Moreover, it has acceptable interface usability.

1. Introduction
People often use their hands to convey their emotions and thoughts. For example, with the help of hands, it is possible not only to convey communication intent but also to express in a clearer manner the meaning of what is being said. However, the length of an arm limited its reaching area; therefore, it is necessary to move the body or change a posture to increase the reaching distance. Such movements or changes are occasionally difficult for wheelchair users, which often hinders efficient communication using hands. Although wheelchair systems that aim to facilitate the transmission of user intentions have been proposed in several studies, an interface enabling wheelchair users to extend the reaching area of their hands has been rarely investigated.

As a promising approach to address this problem, we considered virtual hand interfaces used to operate displayed or projected virtual hands. This approach can help avoid physical constraints. Virtual hand interfaces originate from an interface that uses the wrist’s shadow. These interfaces allow users to operate efficiently in a virtual reality environment and an augmented reality environment using a projector. As a projected virtual hand interface is relatively more compatible with a wheelchair system, we investigated this successful implementation where wheelchair users would hope to project their virtual hand onto arbitrary objects.

Although a projected virtual hand interface is relatively more compatible with a wheelchair system, without a way to extend the projectable area, its projection area will be smaller than the reaching area necessary for wheelchair users.

As a possible solution, our previous study proposed a wheelchair system with a projected virtual hand. Users can control a virtual hand and its projection area using a multi-touch panel mounted on a wheelchair. In this approach, by changing the number of fingers touching the touch panel, users could switch mode between operating the virtual hand and moving the projected area. However, because of this mode switching method, users could not operate the virtual hand and move the projection area simultaneously, which hindered an efficient operation using the virtual hand. In this work, we aim to develop a wheelchair system that can move a projected virtual hand to the desired position with more time-efficiency than the previous method while keeping acceptable usability. We evaluated the time efficiency of the system operation based on task completion time and the usability of the system through questionnaire surveys.
A key idea to resolve this problem is to use a wheelchair user’s head orientation, as it is burdensome to move their body below their shoulders. Although eye-tracking technology has recently been developed and made easily available, studies indicated that the operation using eye-tracking has a higher error rate than the operation using head direction [13,14], which is why we focused on the operation method using head orientation. Several studies [15,16] proposed executing a pointing operation using only head orientation, while others [17–19] suggested using systems that combine the selection of an operation target using head orientation and specific operations performed by hands. These studies allowed making such an assumption that wheelchair users can operate the projected virtual hand and its projection area efficiently by using a combination of head orientation and manipulation by hands.

In this paper, we propose a wheelchair system with a projected virtual hand interface by which users can control the projection area using their head orientation. Figure 1 shows the concept of the proposed system. The system enables a user to move the projection area by changing their head orientation and operate the projected virtual hand using their hands on a multi-touch panel. Users can roughly adjust the projection area to the target position by varying their head orientation and moving their virtual hand using the panel. Through this operation method, users can operate the virtual hand and its projection area simultaneously, which means that users can efficiently operate the interface.

We constructed a control model for the rotation of a projector according to the user’s head orientation and implemented the proposed system based on this model. We performed the latency evaluation and the user study of the proposed system. From the user study, we confirmed that users can perform a pointing operation using the virtual hand in a shorter time compared with the existing method [12], and the proposed system has acceptable usability as an interface.

Thus, the paper contributes the following:

1. A proposal and design of a system that enables users to control the projected area using their head orientation.
2. Evaluation of the latency between the movements of users’ head orientation and the projection area.
3. Investigation of the operation time and comprehensive usability of the proposed interface system, and accomplishment of more usability and higher time efficiency than the previous method [12].

Although the first and third contributions are based on the previous research [20], the second is a unique contribution of this paper.

2. Method

In this section, we present our proposed wheelchair system with a projected virtual hand interface that allows the control of the projection area by changing the user’s head orientation. We also discuss its control model. The system calculates the projector’s rotation angle based on the user’s head using the proposed model and controls a pan–tilt unit on which the projector is mounted. In addition to operating the projection area, users can operate the projected virtual hand in the area using a touch panel on a wheelchair’s armrest.

We developed a calculation model of a projector’s rotation angle using the rotation angle of a head. In this model, we assume the following:

- There is little movement in the user’s head centre.
- The plane projection surface is perpendicular to the wheelchair.
- The projector rotates at the lens’ centre.
- The head and sight directions are identical.
- There is no image height offset in the projector.
- The range scanner and wheelchair directions are identical.
- The roll angle of the head and the projector are zero up.

As shown in Figure 2, we set the rotation axes (roll, pitch, yaw) of a projector and a head relative to the wheelchair. Figure 3 represents the geometric relationship between the user’s head orientation and the rotation angle of the projector. We define the yaw and pitch angles corresponding to the head orientation and the projector rotation relative to the wheelchair as $\text{Yaw}_h$, $\text{Pitch}_h$, $\text{Yaw}_p$, and $\text{Pitch}_p$, respectively. The proposed system is used to control the rotation of a projector to match the intersection between the line extending from the centre of the user’s head in direction of a gaze and the projection plane and that between the line extending from the projector centre and the plane. The relationship between the angle of a head and that of a
The system calculates \( \text{Yaw}_p \) and \( \text{Pitch}_p \) from \( \text{Yaw}_h \) and \( \text{Pitch}_h \) and controls a pan–tilt unit using these angles.

For the projected virtual hand operation, we adopted the algorithm of the projected virtual hand interface proposed in our previous research [11]. In this projected virtual hand interface, the projected virtual hand moves with the control/display (C/D) ratio. Simultaneously, the position of the projected virtual hand is moved to the position of the average of the movement of each finger multiplied by the C/D ratio. In the proposed system, we implement a projected virtual hand interface based on our previous interface [11].

### 3. Implementation

In this section, we discuss the hardware and software implementation of the proposed system.

#### 3.1. Wheelchair system

Figure 4 shows the appearance of the proposed wheelchair system that was implemented based on an electric wheelchair (WHILL, WHILL Model C). A pan–tilt unit used to gaze at the projection area comprised a projector (ASUS, ZenBeam), two motors (Keigan, KeiganMotor), and two microcontrollers (M5Stack, M5Stack Gray) to control the motors. We
installed an aluminium tower on the back of the wheelchair and placed the pan–tilt unit, power banks (Omars, 10,000mAh Type-C 30W PowerDelivery), and a laser range scanner (SLAMTEC, RPLiDARA2) above a wheelchair back sheet. When the pan–tilt unit was stable (as shown in Figure 4), the projector’s height was 1.75 m. The laser range scanner mounted at the side of the pan–tilt unit and the height of the laser range scanner was 1.65 m. We placed a 10.8-inches tablet PC (Microsoft, Surface Pro 3) to manipulate the projected virtual hand on the right armrest and a joystick to operate the wheelchair on the left armrest. The size of this touch panel can be expected to be large enough for projected virtual hand operation since the size of this touch panel is larger than the user hand size and is equal to or larger than the touch panel used as the projected virtual hand interface in our previous research [11]. These arrangements could be switched according to the dominant hand of a user.

We installed a gyro sensor with the angular velocity integration function (Bosch Sensortec, BNO055) to measure the wheelchair orientation, a microcontroller (ELEGOO, ELEGOOUNO R3) to send the wheelchair orientation data received from the gyro sensor, a Wi-Fi router (Buffalo, AirStation WSR-1166DHP2), and a power bank (Aceyoon, ACY-PB20000L) for the router. We also installed a laptop PC (Lenovo, IdeaPad S340) to acquire the sensor data and transmit calculated projector orientations under the wheelchair seat. The system estimated the user’s head orientation using a microcontroller (M5Stack, M5Stack Gray) and the gyro sensor fixed on the user’s head. In this system, we used 9-DOF IMU sensors instead of the gyro sensors. Moreover, the drift of each gyro sensor is very small due to the integration of its hybrid sensors.

We designed the system in such a way that allows the user to rotate the projector up to ±60 degrees around the yaw (up/down) and pitch (left/right) axes. The available range for moving the projection area was 7.6 m × 7.6 m in the case when the wheelchair was placed 2.2 m away from the plane (as in the experimental setup of Experiment B).

### 3.2. Distance estimation

The proposed system estimates the distance from a user to the projection surface using the measured distance and orientation data by the laser range scanner. The distance to the projected surface is obtained from the front portion of the measured range data with the median filter.

### 3.3. Data processing flow

The proposed system transmits the sensor data to the laptop PC, calculates the rotation angles of the projector, and transmits each rotation angle to the microcontroller for the motor. The microcontroller fixed to the user’s head acquires the angle information from the gyro sensor and transmits the head orientation to the laptop PC via Wi-Fi. The microcontroller fixed to the wheelchair also acquires the angle information and transmits the wheelchair orientation to the laptop PC via wired communication. Similarly, the laser range scanner sends the laptop PC distance information to projection planes via wired communication.

The laptop PC acquires the sensor data such as the head orientation, the distances from projection surfaces and the wheelchair orientation; calculates the rotation angles of the projector from the acquired sensor data; and transmits each angle to the microcontroller for the motor controlling the projector orientation. Each microcontroller receives the rotation angle and rotates the motor to match the projector orientation with the received angle.

In the control of the projected virtual hand, the tablet PC detects the user’s touching information on this tablet, calculates the virtual hand posture and position, and sends a virtual hand image based on the calculated posture and position to the projector.

### 4. Experiment

#### 4.1. Experiment A: latency evaluation

In this experiment, we evaluate the latency of the proposed system. We defined the time when the microcontroller sends the read command to the gyro sensor as the time of the head orientation acquisition. In addition, we defined the time when the microcontroller sends the execute command to the motor as the time of the motor rotation start. According to the time definitions, we measured the latency from acquiring the head orientation to starting the motor rotation and found that the average latency time was 18 ms.

Also, we measured the time spent from the motor rotation to reaching the target. Figure 5 represents the average time spent for the motor rotation, where the least-square approximate straight line to the measured time showed that the motor rotation took an average of 7 ms per degree and 663 ms as an offset time.
we set the nine rotation angle from 5 degrees to 45 degrees as the target angle. The system rotates up to 60 degrees. However, based on our observation, the measurements were made up to 45 degrees, since it is expected that other angles can be predicted by approximating a straight line from data up to 45 degrees. The least-square approximate straight line to the rotation time showed that the motor rotation takes an average of 7 ms per degree and 663 ms as an offset time. The estimated latency that elapses from the acquisition of the head orientation to the movement of the projection area to the gaze position on the projection planes can be calculated as the sum of the latency and the motor rotation time. This indicates that the latency is at least 681 ms and, 716–996 ms for the motor with 5–45 degrees rotation.

4.2. Experiment B: user study

This experiment aims to evaluate time efficiency and usability of the proposed virtual hand interface as compared to the previous one [12]. We compared the proposed method and the method we reimplemented based on the previous methods [12] in terms of task completion time and usability based on users’ subjective evaluation.

4.2.1. Participants

In the conducted experiment, we recruited eight non-handicapped participants (seven males and one female) who have not participated in any similar experiment. The participants were all right-handed, aged 22–24 years old. Three participants corrected their eyesight with contact lenses, and the other participants had normal, naked eyes.

4.2.2. Experimental setup and conditions

Figure 6 shows the experimental environment. We separated the pan–tilt unit from the wheelchair and installed it behind the wheelchair using a tripod, as we tried to eliminate factors such as shaking due to high-speed operation. We placed the wheelchair 2.2 m away from the projection plane and the tripod 0.3 m behind it. The height of the projector in the pan–tilt unit was 1.75 m, and it was consistent with that of the implemented system. A male participant who is 1.7 m tall was adopted as the representative participant. The head height and relative position to the projector were 1.3 and 0.45 m, respectively. The representative values were used for all participants in this experimental setup.

We placed a reference area for pointing by the virtual hand at the height of 1.2 m on the projection plane and a LED indicator above this area. We set the other pointing target areas on circumferences of two circles centred on the reference area: the large circle (diameter: 2 m) and the small circle (diameter: 1 m). The target areas on the small circle were placed at a distance where the projection area could spatially contain the reference area and one of the target areas on the small circle. Meanwhile, the target areas on the large circle were placed at a distance where the projection area could not cover them and the reference area.

In the previous method [12], the user can control the position of the projection area and operate the projected virtual hand via the touch panel. By touching the touch panel with four fingers, the user can switch to position control mode, where the user can move the position of the projection area vertically and horizontally by sliding with four fingers up, down, left and right on the touch panel. In addition, by touching the touch panel with a number of fingers other than four, the user can switch to virtual hand operation mode, where the user can move the virtual hand with a C/D ratio, the procedure of which was introduced in our previous work [11]. In the conducted experiment, the participants were instructed to perform the projected virtual hand operation and point with only one finger, so the only difference between the proposed and previous methods [12] is whether the position of the projection area is controlled by head orientation or hand movement on the touch panel.

When a front-facing projector casts the projected virtual hand on a projection surface 2.2 m away from the user, similar to the experimental setup, the wheelchair can move the projected virtual hand 50 mm on the projection surface by moving the real hand 1 mm on the touch panel in both operation methods. The position of the projection area in the previous method [12] is controlled by the value such that when...
the real hand moves 1 mm on the touch panel, the pan–tilt unit rotates the projector by 0.841 degrees.

To summarize the above description, this user study had two conditions: target position (inside or outside) and pointing method (suggested or previously).

4.2.3. Pointing task
The participants pointed at each target area by operating the projected virtual hand. Before starting the pointing task, they were instructed to point at the target area as quickly as possible and instructed in what order they had to point at the target once. They executed the pointing operation starting from the target area (I) (red or blue), as shown in Figure 6. When initiating from the red/blue (I) area, the participants started to point at the far/near circumference areas clockwise. After pointing the eight target areas at the far/near circumference, the participants started to point at the near/far circumference areas clockwise. We determined the order of starting points so that there was no order effect among the participants.

Figure 7 shows the operation flow until the moment when the participant completes pointing at a single target area. At the beginning of each pointing task, the experimental system turns on the LED indicator on the reference area (Figure 7(a)). The moment the LED turns on, they begin to point to the reference area. After the system confirms that the participants’ hand exists on the reference area by the camera, it turns off the LED indicator (Figure 7(b)). Next, the participants begin to point at the target area instructed in advance. The moment the system recognizes the completion of each pointing action to the target area, it turns on the LED again (Figure 7(c)) in order to restore the participants’ hand position at the reference area.

In the acquisition of pointing by the projected virtual hand, we used camera monitoring with a visual projected marker. The visual projected marker is a blue box-shaped and projected on the tip of the index finger of the projected virtual hand. The visual projected marker is discriminated from other colours such as the colour of the projected virtual hand and the background colours of the target areas by certain colour thresholds. We defined the timing when the marker entered into the target area as the time when the participant completes pointing at the target area. The acquisition process has a latency of about one frame.

Table 1. The items of System Usability Scale (SUS) questionnaire. Each item’s rating scale is a 5-point Likert scale, where the smallest scale position indicates strong disagreement and the largest scale position indicates strong agreement.

| Index | Item                                                                 |
|-------|----------------------------------------------------------------------|
| 1     | I think that I would like to use this system frequently             |
| 2     | I found the system unnecessarily complex                            |
| 3     | I thought the system was easy to use                                |
| 4     | I think that I would need the support of a technical person to be   |
|       | able to use this system                                             |
| 5     | I found the various functions in this system were well integrated    |
| 6     | I thought there was too much inconsistency in this system           |
| 7     | I would imagine that most people would learn to use this system     |
|       | very quickly                                                         |
| 8     | I found the system very cumbersome to use                           |
| 9     | I felt very confident using the system                              |
| 10    | I needed to learn a lot of things before I could get going with this|
|       | system                                                              |

Table 2. The items of a comparative questionnaire. The operation method 1 represents the first operation method used by the participant, and the operation method 2 represents the last used operation method. Each item’s rating scale is a 7-point Likert scale.

| Index | Item                                                                 |
|-------|----------------------------------------------------------------------|
| 1     | With which method did you feel able to operate the system without   |
|       | beforehand practice?                                                |
| 2     | Which method did you feel easier to remember how to operate the    |
|       | system?                                                             |
| 3     | With which method did you feel faster to move the projected virtual |
|       | hand?                                                              |
| 4     | Which method did you find simpler?                                  |
| 5     | Which method did you find more tiring when operating the system?   |
| 6     | Which method enabled you to move the virtual hand to a target       |
|       | position more accurately?                                           |
| 7     | Which method enabled you to operate the system more comfortably?    |
| 8     | Which method did you feel easier to operate the system?             |
| 9     | Which method did you want to use when you operate the system?      |
4.2.4. Questionnaire survey

The participants responded to the system usability scale (SUS) questionnaire [21] as shown in Table 1 after completing the pointing task, and a comparative questionnaire as shown in Table 2 after responding to the second SUS questionnaire.

SUS is a simple, 10-item scale that gives a global view of subjective assessments of usability, where the smallest scale position indicates strong disagreement and the largest scale position indicates strong agreement on each item. The SUS score is calculated from all item score contributions. Each score contribution is converted from 0 to 4 value from each scale position. In the case of odd number items, the score of the smallest scale position is set to 0, and the score increases as the scale position increases. In the case of even number items, the score of the largest scale position is set to 0, and the score increases as the scale position decreases. By multiplying the sum of the score contribution of each item by 2.5, we finally obtain the SUS score, which ranges from 0 to 100.

4.2.5. Procedure

We evaluated the task completion time of the projected virtual hand operation and usability of the proposed interface. Participants performed a task of pointing the target areas by operating the projected virtual hand using the proposed method and the previous method [12]. We measured the task completion time required to complete the pointing operation. We obtained the pointing task completion time by adding the time required to point to the reference area to the time required to point to the target area. We also conducted two questionnaires, one SUS and one comparative questionnaire. We considered the average of the SUS questionnaire scores and the comparative questionnaire to evaluate the usability of each interface.

The procedure of the experiment was described as follows. First, we explained the two operation methods and the pointing task to the participants. We determined the order of operation methods and starting target position (near or far) to counterbalance the experimental conditions, so that we expected no order effect among the participants. Next, the participants practiced the operation methods for 2 min, and then, executed the pointing task. Thereafter, the participants responded to the SUS questionnaire to evaluate the usability of the operation method used immediately before. As a next step, the participants performed the task following the same procedure but using the other operation method and then answered the questionnaire and the comparative questionnaire accordingly. The practice time was long enough for the participants. For each participant, it took about 30 min to complete the experiment.

4.2.6. Results and discussion

The average task completion time in the previous method [12] was 50.49 s (\(SD = 7.05\) s) in the far position and 35.03 s (\(SD = 8.97\) s) in the near position, while it was 42.55 s (\(SD = 10.43\) s) in the far position and 29.77 s (\(SD = 5.35\) s) in the near position in the proposed method. We conducted a two-way factorial analysis of variance on the conditions and found a significant difference in the operation method factor (\(F(1,7) = 6.95, p = .013, \eta^2 = 0.4983\), proposed method < previous method [12]) and the target position factor (\(F(1,7) = 29.62, p < 0.01 \eta = 6.0 \cdot 10^{-6}, \eta^2 = 0.8088, \text{near position} < \text{far position}\)). However, we did not find the interaction effects (\(F(1,7) = 0.64, p > 0.10 \eta = .43, \eta^2 = 0.0837\)).

The average scores of SUS were 65.3 for the previous method [12] and 68.4 for the proposed method. According to the result of the previous investigation [22], we can conclude that the adjective rating of the previous method [12] is “Poor”, as its score is less than 68, and that of the new proposed method is “Good”, as its score is greater than 68 and less than 80.3. Therefore, for the participants, the projected virtual hand interface based on the proposed method has acceptable usability.

Figure 8 shows the results of the comparison questionnaire. For each item in the result, zero indicates that the participants feel the same when using the proposed method and when using the existing method [12]. We performed the paired t-test and confirmed that there were significant differences in Index 3 and 9 (\(p_{\text{index3}} = 1.9 \cdot 10^{-6}, p_{\text{index9}} = .0038\)).

The result of Index 3 indicates that the proposed method provides users more time efficient operation of the projection virtual hand than the existing one [12]. It can be assumed from this that the combination of the head orientation and hand operation enables a user to operate the projected virtual hand and control the position of projection area simultaneously, and the efficiency is attributed to the simultaneous operation. In addition, the result of Index 9 indicates that the
proposed method has higher usability than the existing method [12]. It can be assumed that the usability results from the efficient operation caused by the simultaneous operation. Also, in spite of the expectation that fatigue surfaced since the proposed method required users to turn their heads to the desired position, this user study did not provide any clear evidence that the proposed method caused more fatigue than the previous methods [12]. When people want to see an interesting unique object, it is natural to turn their head towards it. Since such movements are frequently done on a daily basis, there seems no difference in fatigue between the two methods in this experiment.

We received the following comments from the participants after the experiment: (1) they were able to point at distant target areas quickly when using the proposed method, (2) for near target areas, they were able to point more easily using the previous method [12], and (3) the projection area was occasionally closer to the reference area than the target one, when they pointed at distant target areas using the proposed method.

The two-way factorial analysis of variance did not show the interaction effects, although we received the first and second comments. Although the first comment indicates that the proposed method works effectively, when a user seeks to point targets far from the reference area, the second comment suggests that the proposed method has an issue when pointed targets are near the reference. Users can move the projection area quickly by using the proposed method; however, instability in their head orientation sometimes results in movements of the projection area that they do not intend. When users point at targets near the reference area, the disadvantages of the unintentional movements can become noticeable. We instructed the participants that the position of the projection area and the position that their head directs were identical when the proposed method was used; however, comment 3 was reported. We designed the physical control model on the assumption that head orientation and gaze direction coincide, however, there was a psychological gap between the head orientation and the actual gaze direction, and some participants perceived the direction that deviated from the actual head orientation to the gaze direction as their head orientation. Funatsu et al. [23] reported that the gap between the head orientation and the gaze direction increased when the head direction deviated from a front, which supports this observation.

5. Limitation and discussion

In this section, we discuss all the experimental results and limitations of the proposed system.

5.1. Latency of pan–tilt unit

The latency evaluation experiment revealed that the implemented system takes at least 681 ms from acquiring the user head orientation to moving the projection area to a target position. People can feel a delay if the visual information is delayed by more than 200 ms as they move their hands [24]. From this finding, we assume that the user can perceive the latency of the projection area position control in the proposed system. We also assume that the latency affects the result of the comparative questionnaire that represents system comfortability (Index 7) in experiment B. We can simply reduce this latency by employing a high-speed motor with a shorter rotation time or a pan–tilt mirror instead of the motor we used.

5.2. Attachment position of pan–tilt unit

To cover a large projection area, we mounted the pan–tilt unit supporting a projector and fixed it on top of a wheelchair in the proposed system. This placement led to the top heavy configuration and concern about the falling of the unit.

One way to solve this problem is to install the pan–tilt unit at a lower position than the user. The pan–tilt unit installed at a lower position than the user provides a smaller projectable range than the pan–tilt unit installed above the user’s head, or an obstacle of low height obstructs the projection.

Another method to cover a large projection area is controlling multiple pan–tilt units simultaneously and combining all the projection area projected by each pan–tilt unit. We require the alignment of all the projection area projected by all the pan–tilt units, the fusion of the projected image, and a control model to determine all the pan–tilt unit from the user’s head direction. We also assumed that the measurement errors of the distance and the projector orientation, and the influence of noise caused the misalignment. Thus, it is necessary to investigate the effect of the projection image misalignment on the wheelchair users’ perception.

In addition, since the pan–tilt unit is fixed to the wheelchair in the present wheelchair system, there is a concern that the pan–tilt unit may fluctuate during the projected virtual hand operation, which may affect the time efficiency and accuracy of the operation. Therefore, it is necessary to estimate the effects of fluctuation on the time efficiency, the accuracy of operation, and the system usability in field situations.

5.3. Assumption of the position control model

We have assumed that the projection plane is flat and directly opposite to the surface in the proposed system. However, the situation where the projection planes are flat and directly opposite is limited in reality. By
estimating the distance to the gazed position on the projection plane, it is possible to project the image onto a surface other than the opposing projection surface. However, when the projection surface is curved or bent, the projection image is deformed. In the user experiment in this study, we concluded using a typical value of 175 cm head height of a representative participant. However, when the difference in head height is large, such as when used by children and tall people, it is necessary to adjust the height parameter according to the user. It is necessary to develop a model that measures the shape of the projection surface and generates a distorted projection image according to the surface shape.

6. Conclusion

In the present paper, we proposed a projected virtual hand interface that enables wheelchair users to control the movement of the projection area using their head orientation. We constructed a control model of pan–tilt rotation of a projector according to a user’s head orientation. We implemented the proposed wheelchair system by installing a pan–tilt unit with a projector to an electric wheelchair and a gyro sensor to evaluate rotation of a user’s head. In addition to the implementation and evaluation, we measured the latency of the pan–tilt motor rotation. To investigate the applicability of the proposed approach, we conducted a user study and found that users were able to perform pointing operations by the virtual hand in a shorter time by using the proposed method as compared with the previous method [12]. We concluded that the proposed system demonstrated acceptable usability as a user interface.

For future research, we will investigate the usability of the proposed approach by using a standalone wheelchair system, as used an emulated system for the experiment in the present study. We will adapt the control model to mitigate the gap between the head orientation and gaze direction.

Disclosure statement

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References

[1] Watanabe A, Ikeda T, Morales Y. Communicating robotic navigational intentions. In: Proceedings of the 2015 IEEE/RSJ International Conference on Intelligent Robots and Systems – IROS ’15. Piscataway: Institute of Electrical and Electronics Engineers (IEEE); 2015. p. 5763–5769.
[2] Tomari R, Kobayashi Y, Kuno Y. A framework for controlling wheelchair motion by using gaze information. Int J Integr Eng. 2013;5:40–45.
[3] Xu H, Iwai D, Hiura S, et al. User interface by virtual shadow projection. In: Proceedings of 2006 SICE-ICASE International Joint Conference. Piscataway: Institute of Electrical and Electronics Engineers (IEEE); 2006. p. 4814–4817.
[4] Shoemaker G, Tang A, Booth KS. Shadow reaching: a new perspective on interaction for large displays. In: Proceedings of the 20th Annual ACM Symposium on User Interface Software and Technology – UIST
'07. New York: Association for Computing Machinery; 2007. p. 53–56.

[5] Hiraki T, Fukushima S, Naemura T. Sensible shadow: tactile feedback from your own shadow. In: Proceedings of the 7th Augmented Human International Conference – AH ’16. New York: Association for Computing Machinery; 2016. p. 1–4.

[6] Poupyrev I, Billinghurst M, Weghorst S, et al. The go-go interaction technique: non-linear mapping for direct manipulation in VR. In: Proceedings of the 9th Annual ACM Symposium on User Interface Software and Technology – UIST ’96. New York: Association for Computing Machinery; 1996. p. 79–80.

[7] Benko H, Holz C, Sinclair M, et al. Normaltouch and texturetouch: high-fidelity 3D haptic shape rendering on handheld virtual reality controllers. In: Proceedings of the 29th Annual ACM Symposium on User Interface Software and Technology – UIST ’16. New York: Association for Computing Machinery; 2016. p. 717–728.

[8] Lee D, Hwang JI. Design and evaluation of smart phone-based 3D interaction for large display. In: Proceedings of the 2015 IEEE International Conference on Consumer Electronics – ICCE ’15. Piscataway: Institute of Electrical and Electronics Engineers (IEEE); 2015. p. 657–658.

[9] Achibet M, Casiez G, Lécuyer A, et al. THING: introducing a tablet-based interaction technique for controlling 3D hand models. In: Proceedings of the 2015 CHI Conference on Human Factors in Computing Systems – CHI ’15. New York: Association for Computing Machinery; 2015. p. 317–326.

[10] Ogawa S, Okahara K, Iwai D, et al. A reachable user interface by the graphically extended hand. In: Proceedings of the 1st IEEE Global Conference on Consumer Electronics – GCCE ’12. Piscataway: Institute of Electrical and Electronics Engineers (IEEE); 2012. p. 210–211.

[11] Ueda Y, Asai Y, Enomoto R, et al. Body cyberization by spatial augmented reality for reaching unreachable world. In: Proceedings of the 8th Augmented Human International Conference – AH ’17. New York: Association for Computing Machinery; 2017. p. 1–9.

[12] Asai Y, Ueda Y, Enomoto R, et al. ExtendedHand on wheelchair. In: Adjunct Proceedings of the 29th Annual ACM Symposium on User Interface Software and Technology – UIST ’16 Adjunct. New York: Association for Computing Machinery; 2016. p. 147–148.

[13] Qian YY, Teather RJ. The eyes don’t have it: an empirical comparison of head-based and eye-based selection in virtual reality. In: Proceedings of the 5th Symposium on Spatial User Interaction – SUI ’17. New York: Association for Computing Machinery; 2017. p. 91–98.

[14] Kyö M, Ens B, Plumsomboon T, et al. Pinpointing: precise head- and eye-based target selection for augmented reality. In: Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems – CHI ’18. New York: Association for Computing Machinery; 2018. p. 1–14.

[15] Nakasako S, Abiko Y, Iwaki S, et al. Hands-free interface for seamless pointing between physical and virtual objects. In: Proceedings of 2014 the World Automation Congress – WAC ’14. Piscataway: Institute of Electrical and Electronics Engineers (IEEE); 2014. p. 376–381.

[16] Sim N, Gabriel C, Abbott WW, et al. The head mouse – head gaze estimation ‘In-the-Wild’ with low-cost inertial sensors for BMI use. In: Proceedings of the 6th IEEE/EMBS International Conference on Neural Engineering – NER ’13. Piscataway: Institute of Electrical and Electronics Engineers (IEEE); 2013. p. 735–738.

[17] Ashdown M, Oka K, Sato Y. Combining head tracking and mouse input for a GUI on multiple monitors. In: Proceedings of the 2005 CHI Conference Extended Abstracts on Human Factors in Computing Systems – CHI EA’05. New York: Association for Computing Machinery; 2005. p. 1188–1191.

[18] Nancel M, Chapuis O, Pietriga E, et al. High-precision pointing on large wall displays using small handheld devices. In: Proceedings of the 2013 CHI Conference on Human Factors in Computing Systems – CHI ’13. New York: Association for Computing Machinery; 2013. p. 831–840.

[19] Serrano M, Ens B, Yang XD, et al. Gluey: developing a head-worn display interface to unify the interaction experience in distributed display environments. In: Proceedings of the 17th International Conference on Human-Computer Interaction with Mobile Devices and Services – MobileHCI ’15. New York: Association for Computing Machinery; 2015. p. 161–171.

[20] Morita K, Hiraki T, Matsukura H, et al. Extension of projection area using head orientation in projected virtual hand interface for wheelchair users. In: Proceedings of the SICE Annual Conference 2020. Piscataway: Institute of Electrical and Electronics Engineers (IEEE); 2020. p. 421–426.

[21] Brooke J. SUS: a ‘Quick and Dirty’ usability scale. Abingdon: Taylor & Francis Group; 1996. p. 189–194.

[22] Sauro J. Customer analytics for dummies. New York: Wiley; 2013.

[23] Funatsu N, Takahashi T, Deguchi D, et al. A study on gaze estimation using head and body pose information. In: Proceedings of the 2013 International Workshop on Advanced Image Technology – IWAIT ’13. 2013. p. 231–235.

[24] Shimada S, Qi Y, Hiraki K. Detection of visual feedback delay in active and passive self-body movements. Exp Brain Res. 2010;201:359–364.