

Extension of Projection Area using Head Orientation in Projected Virtual Hand Interface for Wheelchair Users

Kohei Morita^{1†}, Takefumi Hiraki¹, Haruka Matsukura¹, Daisuke Iwai^{1,2}, and Kosuke Sato¹

¹Graduate School of Engineering Science, Osaka University, Osaka, Japan
(Tel: +81-6-6850-6372; E-mail: {k.morita, hiraki}@sens.sys.es.osaka-u.ac.jp,
{haruka.matsu, daisuke.iwai, sato}@sys.es.osaka-u.ac.jp)

²PRESTO, Japan Science and Technology Agency (JST), Saitama, Japan
(Tel: +81-3-3512-3525)

Abstract: A projected virtual hand interface, which visually extends arms of users using projection images, enables wheelchair users to reach unreachable objects; however, its projection area is narrower than the reaching area required for the users. To address this problem, we propose a wheelchair system enhanced with a projected virtual hand that allows controlling a projection area using user's head orientation. The proposed system estimates the current orientation of a user's head and controls the pan and tilt of a projector accordingly to move a projection area considering the positional relationship with a projection plane. As users can operate the projection area simply by turning their head, this operation can be executed simultaneously with operations of a virtual hand using their hands. We propose a control model for projector rotation according to the user's head direction. The conducted user experience study has revealed that the proposed method enables users to perform pointing tasks in a shorter time compared with the existing method, and moreover, it has acceptable interface usability.

Keywords: virtual hand, projection, wheelchair, body augmentation, accessibility, augmented reality

1. INTRODUCTION

People often use 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 limits its reaching area; therefore, it is necessary to move the body or change a posture to increase the reaching distance. Specifically, such movements or changes are occasionally difficult for wheelchair users, and thereby this often deteriorates efficient communication using hands. Although wheelchair systems aiming to facilitate conveying user intentions have been proposed in several studies [1, 2], an interface enabling wheelchair users to extend the reaching area of hands over a large distance has not been investigated yet.

As a promising approach to address this problem, we consider virtual hand interfaces used to operate displayed or projected virtual hands. Such approach can be applied to avoid physical constraints. Virtual hand interfaces allow users to operate intuitively and efficiently in a virtual reality environment [3-6] and in an augmented reality environment using a projector [7, 8]. Although a projected virtual hand has the best compatibility with a wheelchair system among these methods, its projection area is narrower than the reaching area necessary for by wheelchair users. As a possible solution, Asai *et al.* [9] proposed a wheelchair system with a projected virtual hand by which 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 panel, users could switch the mode of operating the virtual hand and that of moving the projected area. However,

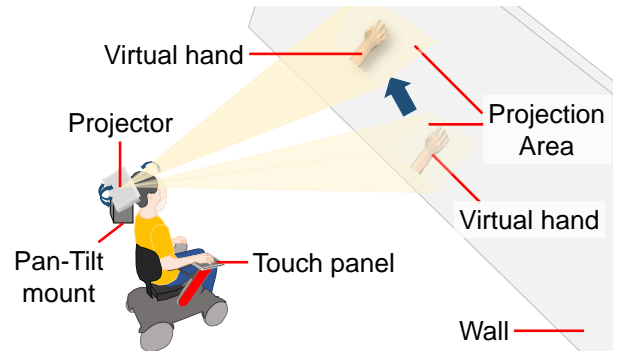


Fig. 1 Concept of the proposed system. It enables a user to control a projection area by their head orientation and a virtual hand by their hands on a multi-touch panel.

because of such mode switching method, users could not operate the virtual hand and move the projection area simultaneously, which hindered intuitive and efficient operation using the virtual hand.

A key idea to resolve this problem is to use the head orientation of a wheelchair user, as it is burdensome to move their body below their shoulders. Although the technology of eye tracking has recently been developed and made available easily, it is indicated that the operation using eye tracking has a higher error rate than the operation using the head direction [10, 11], which is why we focus on the operation method using head orientation. Several studies [12, 13] proposed executing a pointing operation using only the head orientation, while others [14-16] suggested the systems that combine selection of an operation target using the head orientation and specific operations performed by hands. These studies al-

[†] Kohei Morita is the presenter of this paper.

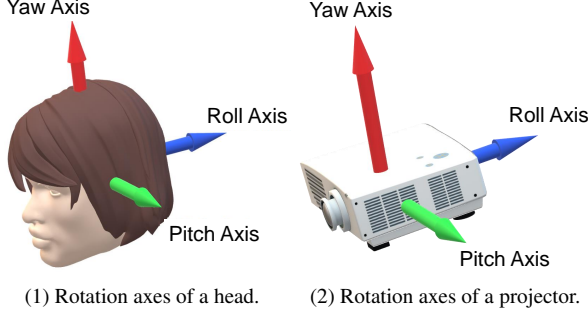


Fig. 2 Rotation axes of a head and a projector. We set the axes so that the gaze and projection directions coincide.

lowed making such assumption that wheelchair users can operate the projected virtual hand and its projection area intuitively and efficiently by using 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. Fig. 1 shows the concept of the proposed system. It enable a user to move the projection area by changing their head orientation and operate the projected virtual hand by their hands on a multi-touch panel. Users can roughly adjust the projection area to the target position by varying the head orientation and move the virtual hand using the panel. Owing to this operation method, users can operate the virtual hand and its projection area simultaneously, which means that users can operate the interface efficiently. To implement the proposed system, we have constructed a control model for rotation of a projector according to the user's head orientation. We have performed the user experience study and have confirmed that users can perform a pointing operation by the virtual hand in a shorter time comparing with the existing method described in [9]. Moreover, we conclude that the proposed system has acceptable usability as an interface.

The conference version paper has proposed the wheelchair system that needs a stationary wheelchair and a pre-measured distance from the projection plane in front of the user to the wheelchair system. In this paper, by implementing measurement of the distance to the projection plane and the wheelchair posture, we propose a wheelchair system with a projected virtual hand interface by which users can control the projection area using their head orientation without the stationary wheelchair and the pre-measured distance. Besides, we propose an application map navigation as that uses this system.

2. METHOD

In this paper, we propose a wheelchair system with a projected virtual hand interface to control the projection area by changing the head orientation. The system is used to calculate the rotation angle of the projector based on that of the user's head using the proposed model and to control a pan-tilt unit on which the projector is mounted.

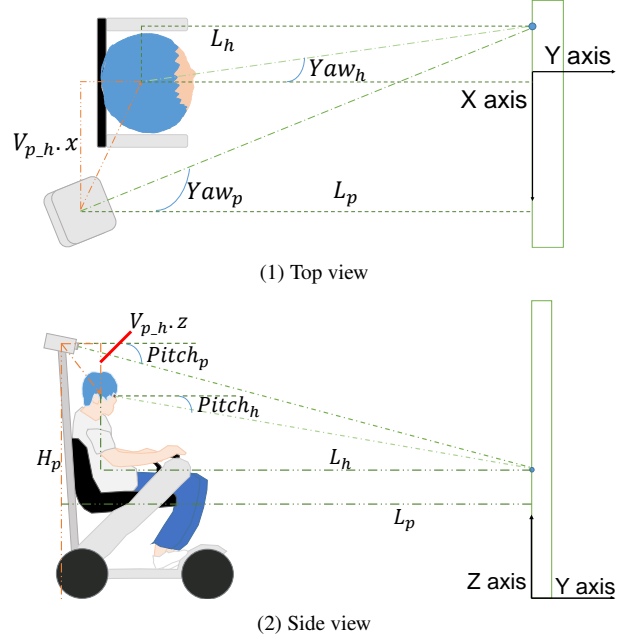


Fig. 3 Geometric relationship between the head orientation of a user and the rotation angle of a projector. We determine the rotation angle of the projector by the head orientation.

In addition to operating the projection area, users can operate the projected virtual hand in the area using a touch panel on the armrest of a wheelchair. We develop a calculation model of the rotation angle of a projector using the rotation angle of a head. We set the rotation axes of a head and a projector, as shown in Fig. 2. Fig. 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 as Yaw_h , $Pitch_h$, Yaw_p , and $Pitch_p$, respectively. The proposed system is used to control the rotation of a projector in such way to match intersection between the line extending from the user's head center in direction of a gaze and the projection plane and that between the line extending from the projector center and the plane. The relationship between the angle of a head and that of a projector is calculated as follows:

$$L_h \tan Yaw_h - V_{p,h}.x = L_p \tan Yaw_p \quad (1)$$

$$\begin{aligned} & \frac{L_h}{\cos Yaw_h} \tan Pitch_h - V_{p,h}.z \\ &= \frac{L_p}{\cos Yaw_p} \tan Pitch_p \end{aligned} \quad (2)$$

where L_h is the distance between the head center and the projection plane; L_p is the distance between the projector center and the plane; $V_{p,h}.x$ and $V_{p,h}.z$ are x and z components of the distance from the projector center to the head center, respectively. These equations can be simplified as below:

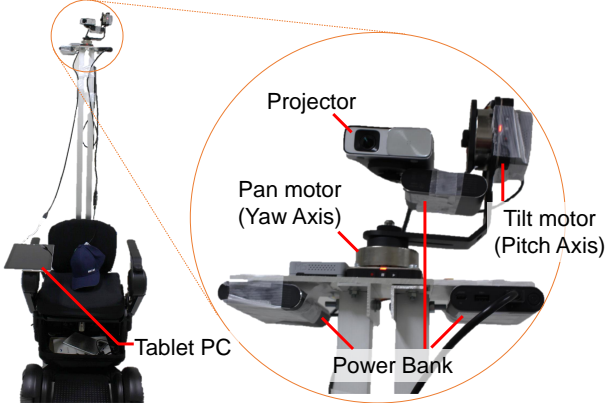


Fig. 4 Overview of our wheelchair system. A pan-tilt unit for moving the projection area comprised a projector and two motors. The pan and tilt rotation was controlled according to the head orientation. The tablet PC was used to manipulate the projected virtual hand.

$$Yaw_p = \arctan\left(\frac{-V_{p,h}.x + L_h \tan Yaw_h}{L_p}\right) \quad (3)$$

$$Pitch_p = \arctan\left(\frac{-V_{p,h}.z + \frac{L_h}{\cos Yaw_h} \tan Pitch_h}{\frac{L_p}{\cos Yaw_p}}\right) \quad (4)$$

The system calculates Y_p and P_p from Y_h and P_h and controls a pan-tilt unit using these angles.

3. IMPLEMENTATION

Figure 4 represents 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 the projection area comprised a projector (ASUS, ZenBeam), two motors (Keigan, Keigan-Motor), and two microcontrollers (M5Stack, M5Stack Gray) to control the motors. We installed aluminum rails on the back of testing the wheelchair and placed the pan-tilt unit and power banks (Omars, 10,000mAh Type-C 30W PowerDelivery) above the wheelchair. When the pan-tilt unit was stable (as shown in Fig. 4), the height of the projector was 1.75 m. We placed a 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. These arrangements could be switched according to the dominant hand of a user.

The system estimated the user's head orientation employing a microcontroller (M5Stack, M5Stack Gray) with the angular velocity integration function of a gyro sensor (Bosch Sensortec, BNO055) fixed on the user's head. This controller transmitted information about the current angle to the controllers of the motor via Wi-Fi. These controllers controlled pan and tilt of the projector by actuating the motors according to obtained information. The latency corresponding to the period from the moment of receiving the angle by the gyro sensor to that of sending instructions to the motors was about 104 ms.

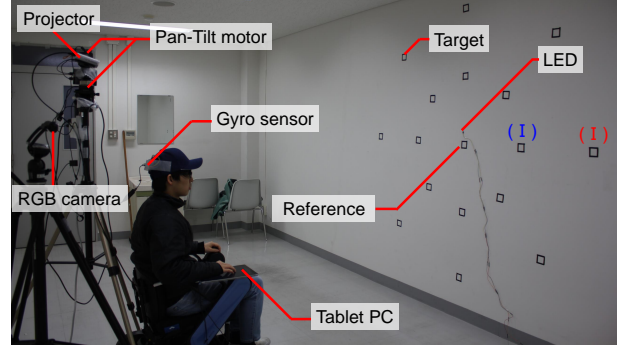


Fig. 5 Experimental environment. A reference area for pointing was set on the projection plane, and the other pointing target areas were set on circumferences of large and small circles. The participants executed the pointing operation from the target area (I) (red or blue).

We designed the system in a such was to allow the user to rotate the projector up to ± 60 degrees around the yaw (up/down) and pitch (left/right) axes. The range available range for moving the projection area was $7.6 \text{ m} \times 7.6 \text{ m}$ in the case when the wheelchair was placed 2.2 m away from the plane (as in the experimental setup).

4. EXPERIMENT

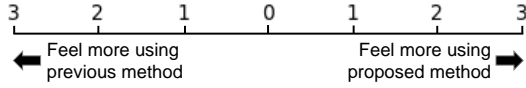
The presented experiment aims to evaluate whether users can operate the projected virtual hand intuitively and efficiently using the proposed method. We compared the proposed and previous methods [9] in terms of the task completion time and user experience. In the previous method, users can move the projection area of the system via the touch panel using four fingers and manipulate the virtual hand in the area by a single finger.

4.1. Experimental Setup

Figure 5 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 the unit due to the 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.

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 centered on the reference area: the large circle (diameter: 2 m) and the small one (diameter: 1m). We placed the target areas at 45° intervals (eight areas within each circle). We set an RGB camera behind the pan-tilt unit to detect pointing by the projected virtual hand at the height of 1.45 m. We turned off the room lights during the experiment. The measured luminance of the room was 0.47 lx.

Table 1 The items of a comparative questionnaire. The each item's rating scale is a 7-point Likert scale:



Index	Item
1	Which method did you feel abler to operate the system without beforehand practice?
2	Which method did you feel easier to remember how to operate the system?
3	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. Procedure

In the conducted experiment, we recruited eight participants (seven males and one female). The participants were all right-handed, aged from 22 to 24 years. We evaluated the task completion time of the projected virtual hand operation and user experience of the proposed interface. Each participant performed a task of pointing the target areas by operating the projected virtual hand using the proposed method and the previous method [9]. We measured the time required to complete the pointing operation. The participants responded to the system usability scale (SUS) questionnaire [17] after completing the task, and a comparative questionnaire as shown in Tab. 1 after responding the second SUS questionnaire. We considered the average of the SUS questionnaire scores to evaluate the usability of each considered as an interface.

The procedure of the experiment was described as follows. First, we explained to the participants the two operation methods and the pointing task. We determined the order of operations to be performed by the participants, so that there was no order effect among them. Next, the participants practiced the operation methods for two minutes, and then, executed the pointing task. Thereafter, the participants responded to the SUS questionnaire to provide their estimates corresponding to considered operation methods. As a next step, the participants performed the task following the same procedure but using the other operation method and then, answered the questionnaire accordingly and the comparative questionnaire. For each participant, it took about 30 minutes to complete the experiment.

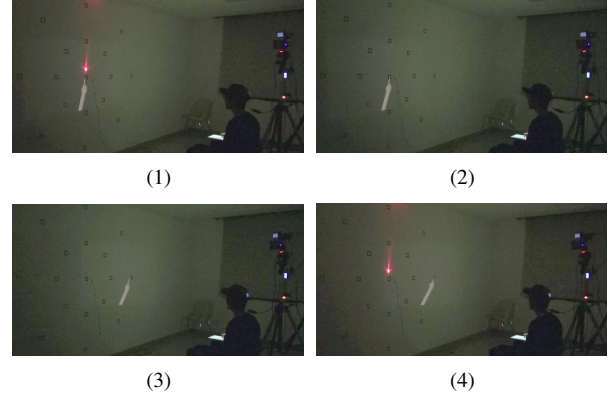


Fig. 6 Operation flow of the pointing task. At the beginning of the task, the participants point at reference area. Before pointing at the reference area. (b) After pointing at the reference area. (c) Before pointing at the instructed target area. (d) After pointing at the instructed target area.

4.2.1. Pointing Task

The participants pointed at each target area by operating the projected virtual hand. They executed the pointing operation starting from the target area (I) (red or blue), as shown in Fig. 5. When initiating from the red/blue (I) area, the participants started to point at the outer/inner circumference areas clockwise. After pointing the eight target areas at the outer/inner circumference, the participants started to point at the inner/outer circumference areas clockwise. We determined the order of starting points so that there was no order effect among the participants.

Figure 6 shows the operation flow until the moment when the participant completes pointing at a single target area. At the start, the experimental system turns on the LED indicator (Fig. 6a). After the participants observe the LED lighting, they need point to the reference area. When the system recognizes a pointing action by capturing the blue box with the index finger of the virtual hand using an RGB camera, it turns off the LED indicator (Fig. 6b). Next, the participants point at the instructed target area (Fig. 6c). When the system recognizes this pointing action, it turns on the LED again (Fig. 6d). The participants repeat this operation flow to complete the task.

4.3. Results and Discussion

The average task completion time was 85.52 s ($SD = 13.44$ s) in the case of the previous method [9] and 72.32 s ($SD = 14.20$ s) with the proposed method. We performed the paired t -test and confirmed that there was a significant difference between these two task completion times ($p < 0.05$).

The average score of SUS was 65.3 for the previous method and 68.4 for the proposed one. According to the result of the previous investigation [18], we can conclude that the adjective rating of the previous method 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

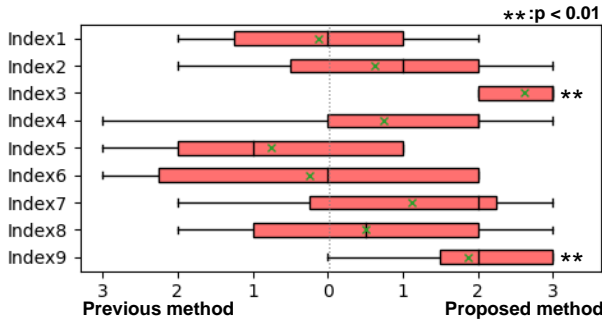


Fig. 7 Result of the comparative questionnaire. Zero indicates that the participants feel the same when using the proposed method and when using the existing method.

than 80.3. Therefore, the projected virtual hand interface based on the proposed method has acceptable usability for the participants.

Figure 7 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. We performed the paired *t*-test and confirmed that there were significant differences in Index 3 and 9 ($p < 0.01$).

The result of Index 3 indicates that the proposed method provides users more time efficient operation of the projection virtual hand than existing one. From this indication, it can be assumed 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. It can be assumed that the usability results from the efficient operation caused by the simultaneous operation.

We received the following comments from the participants after the conducted 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, 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.

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 in the case when pointed targets area near the reference. Users can move the projection area quickly and intuitively 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 also considered that the gap between the calculated gaze direction and the real direction caused the issue mentioned in the third comment, as we designed the model

based on the assumption that the head orientation had to match the gaze direction. Funatsu *et al.* [19] 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. CONCLUSION

In the present paper, we propose the projected virtual hand interface that enables wheelchair users to control the movement of the projection area using their head orientation. We construct a control model of pan-tilt rotation of a projector according to the 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 the user's head. To conclude in applicability of the proposed approach, we conducted the user study and revealed that users were able to perform pointing operations by the virtual hand in a shorter time by using the proposed method comparing with the previous one [9]. We concluded that the proposed system demonstrated acceptable usability as a user interface.

As future work, we will investigate usability of the proposed approach by using a standalone wheelchair system because in the present study, we used the emulated system for the experiment. We will adapt the control model for mitigate for the gap between the head orientation and gaze direction, and develop auto-navigated wheelchair with the system.

ACKNOWLEDGMENT

This work was supported by JSPS KAKENHI Grant Number JP16H02859 and JST PRESTO Grant Number JPMJPR19J2, Japan.

REFERENCES

- [1] Atsushi Watanabe, Tetsushi Ikeda, Yoichi Morales, Kazuhiko Shinozawa, Takahiro Miyashita, and Norihiro Hagita. Communicating robotic navigational intentions. In *Proceedings of the 2015 IEEE/RSJ International Conference on Intelligent Robots and Systems - IROS '15*, pages 5763–5769, Dec. 2015.
- [2] Razali Tomari, Yoshinori Kobayashi, and Yoshinori Kuno. A Framework for Controlling Wheelchair Motion by using Gaze Information. *International Journal of Integrated Engineering*, 5(3):40–45, 2013.
- [3] Ivan Poupyrev, Mark Billinghurst, Suzanne Weghorst, and Tadao Ichikawa. 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*, pages 79–80, 1996.
- [4] Hrvoje Benko, Christian Holz, Mike Sinclair, and Eyal Ofek. NormalTouch and TextureTouch: High-fidelity 3D haptic shape rendering on handheld vir-

- tual reality controllers. In *Proceedings of the 29th Annual ACM Symposium on User Interface Software and Technology - UIST '16*, pages 717–728, Oct. 2016.
- [5] Dongwoo Lee and Jae In Hwang. 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*, pages 657–658, Mar. 2015.
 - [6] Merwan Achibet, G ry Casiez, Anatole L cuyer, and Maud Marchal. 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*, pages 317–326, Apr. 2015.
 - [7] Shuhei Ogawa, Kohei Okahara, Daisuke Iwai, and Kosuke Sato. A reachable user interface by the graphically extended hand. In *Proceedings of the 1st IEEE Global Conference on Consumer Electronics - GCCE '12*, pages 210–211, 2012.
 - [8] Yuta Ueda, Yuki Asai, Ryuichi Enomoto, Kai Wang, Daisuke Iwai, and Kosuke Sato. Body cyberization by spatial augmented reality for reaching unreachable world. In *Proceeding of the 8th Augmented Human International Conference - AH '17*, pages 19:1–19:9, Mar. 2017.
 - [9] Yuki Asai, Yuta Ueda, Ryuichi Enomoto, Daisuke Iwai, and Kosuke Sato. ExtendedHand on wheelchair. In *Adjunct Proceedings of the 29th Annual ACM Symposium on User Interface Software and Technology - UIST '16 Adjunct*, pages 147–148, Oct. 2016.
 - [10] Yuan Yuan Qian and Robert J. Teather. 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*, SUI '17, pages 91–98. Association for Computing Machinery, 2017.
 - [11] Mikko Kyt , Barrett Ens, Thammathip Piumsomboon, Gun A. Lee, and Mark Billinghurst. 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*, pages 1–14. Association for Computing Machinery, 2018.
 - [12] Shoko Nakasako, Yuuki Abiko, Satoshi Iwaki, and Kazuhiro Taniguchi. Hands-free interface for seamless pointing between physical and virtual objects. In *Proceedings of 2014 the World Automation Congress - WAC '14*, pages 376–381, Oct. 2014.
 - [13] Nigel Sim, Constantinos Gavriel, William W. Abbott, and A. Aldo Faisal. 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*, pages 735–738, 2013.
 - [14] Mark Ashdown, Kenji Oka, and Yoichi Sato. 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*, pages 1188–1191, 2005.
 - [15] Mathieu Nancel, Olivier Chapuis, Emmanuel Pietriga, Xing Dong Yang, Pourang Irani, and Michel Beaudouin-Lafon. 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*, pages 831–840, 2013.
 - [16] Marcos Serrano, Barrett Ens, Xing Dong Yang, and Pourang Irani. 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*, pages 161–171, Aug. 2015.
 - [17] John Brooke. SUS: A 'Quick and Dirty' Usability Scale. In *Usability Evaluation In Industry*, chapter 21, pages 207–212. Taylor & Francis Group, Jun. 1996.
 - [18] Jeff Sauro. *Customer analytics for dummies*. John Wiley & Sons, 2013.
 - [19] Nobuhiro Funatsu, Tomokazu Takahashi, Daisuke Deguchi, Ichiro Ide, and Hiroshi Murase. A Study on Gaze Estimation Using Head and Body Pose Information. In *Proceedings of the 2013 International Workshop on Advanced Image Technology - IWAIT '13*, pages 231–235, 2013.