Telewheelchair: the Remote Controllable Electric Wheelchair System combined Human and Machine Intelligence

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Figure 1: Left: appearance of the Telewheelchair. Center: usage scene of our system in the library. Right: setup for evaluation.

ABSTRACT

Wheelchairs are essential means of transport for the elderly people and the physically challenged. However, wheelchairs need to be accompanied by caregivers. As society ages and the number of care recipients increases, the burden on caregivers is expected to increase. In order to reduce the burden on caregivers, we present Telewheelchair, an electric wheelchair equipped with a remote control function and computational operation assistance function. The caregiver can remotely control the Telewheelchair by means of a head mounted display (HMD). In addition, the proposed system is equipped with a human detection system to stop the wheelchair automatically and avoid collisions. We conducted a user study on the wheelchair in four types of systems and investigated the time taken to achieve tasks. Telewheelchair will enhance geriatric mobility and improve society by combining human intelligence and machine intelligence.

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AH2018, February 7–9, 2018, Seoul, Republic of Korea
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ACM ISBN 978-1-4503-5415-8/18/02…$15.00
https://doi.org/10.1145/3174910.3174914

CCS CONCEPTS

• **Human-centered computing → Virtual reality**;

KEYWORDS

Wheelchair, telepresence, virtual reality, nursing

ACM Reference Format:
Satoshi Hashizume, Ippei Suzuki, Kazuki Takazawa, Ryuichiro Sasaki, and Yoichi Ochiai. 2018. Telewheelchair: the Remote Controllable Electric Wheelchair System combined Human and Machine Intelligence. In *AH2018: The 9th Augmented Human International Conference, February 7–9, 2018, Seoul, Republic of Korea.* ACM, New York, NY, USA, Article 4, 9 pages. https://doi.org/10.1145/3174910.3174914

1 INTRODUCTION

Wheelchairs are essential means of transport for elderly people who have difficulty walking and for physically challenged persons with limited mobility. Electric wheelchairs began to appear on the market in the 1950's. Even people with diminished muscular strength can easily control wheelchairs. However, for elderly people who find it difficult to make correct judgments regarding distance and similar factors, it is always necessary for carers to be located near the wheelchair. An aging society is one of the critical global issues in recent times. In an aging society, the demand for wheelchairs and carers increases. However, owing to the lack of caregivers, the strain on carers is increasing. We need to consider how to reduce the strain on caregivers. Therefore, we have endeavored to meet this challenge by developing a new electric wheelchair system called Telewheelchair.

The fully automatic wheelchair is a sterling solution to eliminate the burden on caregivers accompanying user. If driving and recognition of the environment is carried out automatically, the caregiver need not constantly supervise the wheelchair user. Furthermore, the psychological burden faced by person riding a wheelchair is reduced if the wheelchair is operated by a machine without a caregiver's help. However, fully automatic operation is difficult, even while using technologies such as modern environmental sensors and artificial intelligence (AI). Therefore, as a preliminary step, we proposed developing an electric wheelchair combining human operation with automatic operation using AI. AI performs object recognition and environment recognition, and helps humans manipulates basic wheelchairs. In addition, the wheelchair is operable from a remote location. This eliminates the need for a caregiver to physically move a heavy wheelchair, thus further reducing the burden on the caregiver.

Telewheelchair (Figure 1 Left and Center) uses a VR system to remotely control an electric wheelchair. We installed an object detection system that employs deep learning, so that the wheelchair automatically stops when a person is about to collide with it. We conducted a user study (Figure 1 Right) on the operation of the wheelchair in four modes (normal mode, standby mode, display mode, and HMD mode) and investigated the achievement time of the task.

The contributions of our study are as follows.

- We conducted experiments on the operability of the wheelchair using an HMD and found that there was no significant difference between operability in a straight line and a right-angle curve.
- For remote operation, an immersive operation method using an HMD improved the stability more than an operation using a large display.
- In realizing the semi-automatic operation of an electric wheelchair (a hybrid of a human and a computer), we explored functions to be developed in future work.

2 RELATED WORK

2.1 Automatic Operation of the Electric Wheelchair

Since the 1990s, many researchers have been studying the automatic operation of electric wheelchairs. Gundersen et al. [12] presented an electric wheelchair equipped with a remote-control system via an HMD and an obstacle detection system with an ultrasonic sensor. Their system is very similar to the Telewheelchair and can be considered a basic system in the automatic operation of a wheelchair. We retrofitted their system using low-cost and simpler components by using general-purpose products and technology. Pires et al. [21] explored the usability of wheelchairs by conducting experiments on their operation using voice and joystick, and on obstacle detection and collision detection. The NavChair [17] has enhanced navigational functionality enabling guided door passage and wall following in addition to obstacle avoidance. Mazo [18] examined automatic driving by using various methods for environmental recognition and user's motion detection.

Some research focuses not only on designing a general-purpose electric wheelchair but also on automatic operation of specific motions. DECoReS [13] can be driven using orders as "go straight, fast" and "make a wide curve to the right". DECoReS can turn corners according to the user's preference. Kobayashi et al. [16] uses laser range sensors to move the electric wheelchair while keeping a certain distance from the accompanying carer. Passengers can communicate with their companions.

Many studies on automatic driving of wheelchairs have been conducted, but there is no fully automatic electric wheelchair that drive can without a human driver. Safety is important for elderly people and people with disabilities. With current automatic driving technology, it is difficult to fully automate the wheelchair from the viewpoint of safety. Therefore, we developed a semi-automatic electric wheelchair combining human operation and automatic driving.

2.2 Operation System of the Electric Wheelchair

Many discussions on how to operate electric wheelchairs have been conducted. The focus of these discussions is how care recipients who cannot move their hands because of being bedridden or paralyzed can handle a wheelchair. Popular methods involve operating wheelchair using electrooculography (EOG) and voice. Barea et al. [3–5] identified the EOG using a neural network and operated an electric wheelchair. By corresponding to the direction of the line of sight, it is possible to identify whether the wheelchair is moving or stationary. Wastlund et al. [24] installed an obstacle detection function in addition to the EOG operation system. Mazo et al. [19] is a pioneer in the field of wheelchair operation using voice command. They developed a method to transition the state of the wheelchair via voice commands and perform various operations. Nishimori et al. [20] discriminated the voice command with a discrimination rate of 98% and operated an electric wheelchair. AI-Rousan et al. [1] used a neural network for voice recognition.

Various other methods are also used as operation systems for electric wheelchairs. An electric wheelchair developed by Deligiannidis et al. [6] can be operated using hand gestures. Guedira et al. [11] developed an electric wheelchair with a touch input device or tablet for operation input, for users who cannot use a joystick. Besides EOG, there is an electric wheelchair with electromyography (EMG) as input [8] and an electric wheelchair with electroencephalogram (EEG) as input [10]. ExtendedHand [2] is a system that allows a person riding in a wheelchair to manipulate neighboring items using virtual extended hands. Shiomi et al. [23] compares the comfort of an electric wheelchair with an ordinary wheelchair to identify whether the elderly prefer a machine-operated wheelchair.

There are few operation systems for electric wheelchairs using VR. However, research on operation system for other vehicles exists. Flying head [14] operated by synchronizing the position of the human head and the action of the unmanned aerial vehicle. An unmanned aerial vehicle works in accordance with a human's movements such as walking, looking, and crouching. Forster et al. [9]

developed stereoscopic 3D visualization in a fully immersive driving simulator and compared it with the driving simulator using the display. Weidner at el. [25] performed the Lane Change Task in a VR driving simulator and non-VR driving simulator and evaluated the performance in both system. They showed that VR and 3D driving simulators have significant advantages over conventional simulators.

3 DESIGN

As we described in section 1, the fully automatic wheelchair is the ideal solution to eliminate the burden on the caregiver who uses the wheelchair. However, fully automatic operation is difficult with current technology. We designed three scenarios based on the results of discussions with nursing care staff.

3.1 Scenario A

In scenario A the wheelchair is fully automatically operated. Replacing all wheelchair movements with the automatic operation is the best way to reduce the burden on caregivers. The carer does not need to push the wheelchair. Furthermore, conventionally each wheelchair needed a single dedicated caregiver. However, if a wheelchair could be operated automatically, one caregiver may manage multiple wheelchairs. In addition, care recipients can navigate to their favorite places without relying on their caregivers. This leads to a reduction in the psychological burden of the care recipient. Thus, in this scenario, elderly people and people with disabilities can act with greater autonomy.

However, there are some challenges. The first issue is safety. With current technology, it is difficult to fully recognize the environment and situation of the passenger. Therefore, unexpected accidents and passenger injuries may occur. Also, in terms of cost, it is difficult to install fully automatic operation systems in general electric wheelchairs.

3.2 Scenario B

In order to solve the problems encountered in scenario A, we considered that not all functionality needs to be covered by automatic driving; only certain specific functions could be automatically driven. In scenario B, only some functions are automatically operated. As a preliminary step of fully automatic operation, we considered developing an electric wheelchair combining human operation and automatic driving. The proposed system, Telewheelchair, performs object recognition and environment recognition using AI, to support human operation. Telewheelchair is not fully automatic, so in dangerous situations, it can be controlled by human operator. Also, by allowing a caregiver to operate from a remote location, the caregiver does not need to physically move the heavy wheelchair. This method wheelchair reduces the burden on caregivers. The remote caregiver wears an HMD and operates the wheelchair with the controller while watching the omnidirectional image from the viewpoint of the wheelchair. As remote control and obstacle detection are performed using images captured by a general-purpose omnidirectional camera, cost is similar to that of existing electric wheelchairs. As automatic driving technology develops, the weight of manual operation decreases, the percentage of automatic operation by AI increases, and it approaches scenario A.

3.3 Scenario C

Scenario C is a scenario focusing on better operability in order to make it easy to use the wheelchair in the field of nursing. We demonstrated an electric wheelchair developed based on scenario B to professionals in a nursing facility, and recorded their feedback. In nursing workspaces, most staff members were unfamiliar with the operation of the electric wheelchair and the operation of the joystick. Therefore, many insightful opinions were given on the operation system. Many professionals (nursing facility staff, 90% of whom were women) answered that the joystick is difficult to operate with respect to the operating system. This is considered to be due to a large deviation from the driver's consciousness, such as a time lag until the wheelchair starts to move against factors such as the stroke or reaction force, acceleration feeling, and straightness. These should be regarded as important issues in other operation systems for other such vehicles. In addition, most people were using HMD for the first time and they felt a strong feeling of strangeness when viewing the camera's viewpoint. Several people opined that they were more accustomed to controlling by arranging displays like a control room. The subjects pointed out that the perception of the operation is weak as the user's hand is not displayed at all in the image of the HMD. For staff who worked at a nursing care workplace, we considered that it is necessary to examine the operation system so that it is easy to operate, even with a controller and HMD that are unfamiliar objects for carers to use. Therefore, in order to achieve scenario C which emphasizes operability, in this study, we performed an experiment comparing the ease of operation of the four operation methods.

4 IMPLEMENTATION

Figure 2 and Table 1 present an overview of our system. The system is divided into two parts: the electric wheelchair unit and the base station for remote operation. The electric wheelchair is based on TAO LIGHT Ⅱ -m of AISIN SEIKI CO,. LTD. The extension frame is attached to the handle of TAO LIGHT Ⅱ -m and the omnidirectional camera (RICOH R Development Kit) is attached at the tip of frame. The wheelchair is 70 cm in width, 100 cm in length, 135 cm in height, and the height of the lens of the omnidirectional camera is 130 cm. A microcomputer is connected to the controller. The microcomputer read the input of the joystick in the remote place and output the operation signal to the electric wheelchair.

4.1 Remote Control System

Telewheelchair wirelessly transmits the omnidirectional image from the electric wheelchair to the base station and the operation signal from the base station to the electric wheelchair to allow remote control. The operation signal was transmitted using Xbee ZB S2C from Digi International K. K. The maximum indoor / urban range is 60 m, and the maximum outdoor / line-of-sight range is 1200 m. We used CW-1 from IDX Company, Ltd. for transmitting the omnidirectional image. The maximum transmission distance of CW-1 is 30 m. It can transfer full HD (1920×1080 pixels) images.

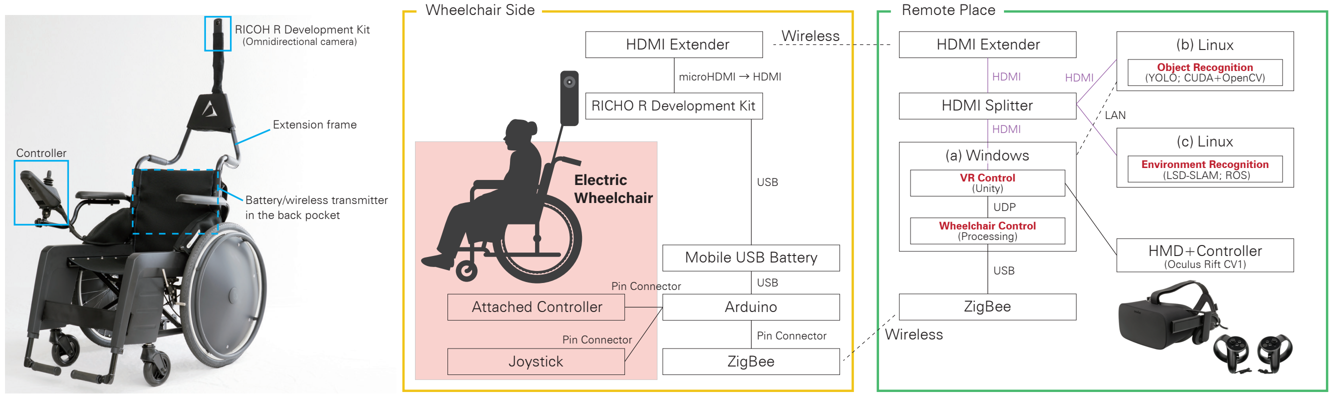

Figure 2: Overview of our system.

Table 1: Specifications of the Telewheelchair.

Electric wheelchair	TAO LIGHT Ⅱ -m [1] (AISIN SEIKI CO,. LTD.) 22 inch, Max speed 6 km/h width 70 cm, length 100 cm, height 135 cm
Omnidirectional camera	RICOH R Development Kit[2] (Ricoh Co., Ltd.) 1920×1080 px 30 fps
Wireless transfer system (operation)	Xbee ZB S2C[3] (Digi International K.K.)
Wireless transfer system (video)	CW-1[4] (IDX Company, Ltd.)
Head mounted display	Oculus Rift CV1[5](Oculus VR, LLC.)

The remote operator wears the HMD (Oculus Rift CV1, Oculus VR, LLC.) and operates the wheelchair with the controller (Oculus touch). Our system control the electric wheelchair according to the direction and inclination of the controller's joystick. On the screen, an arrow corresponding to the direction in which the joystick was brought down was displayed so that the traveling direction could be understood. In order to increase the operational perception, we input the sound of the tire when the wheelchair is operated as a tactile signal in the controller.

4.2 Operation Assistance System

Our system involves operation assistance with two kinds of computer vision: automatic stop by object recognition and environmental map creation by SLAM. These functions support the difficulty in grasping the circumstances around the wheelchair when it is being controlled remotely, compared with the case of operating the wheelchair by standing behind. The reason the ultrasonic sensor is not used for these functions is that by sharing the image of one omnidirectional camera with the three functions, we can reduce the components we need to equip the wheelchair with. It is also possible to add other functions such as computer vision.

YOLO [22] is a real-time object detection system using a single neural network. Although the accuracy of detection is inferior to that of approaches such as R-CNN, it is suitable for our system because of its high detection speed. We modified the original project program. When the area where the people label is detected exceeds the threshold value, the system invalidates the operation by the controller and stops the wheelchair. At the same time, we show a warning on the display.

LSD-SLAM [7] is one of the visual SLAM approaches of the monocular camera by ROS. This realizes a large-scale visual SLAM. By using this, we create bird's-eye view map of the area where the wheelchair has moved, making it easy to visualize the surrounding environment.

5 EVALUATION

We conducted a user study that runs the course by four operation methods in order to investigate the operability of the remote operation.

5.1 Participants

Twelve participants (four females, eight males, seven of whom were members of our laboratory) aged between 19 and 24 years (M = 20.75, SD = 1.78) participated in the experiment. All participants had normal or corrected vision; five wore glasses and two wore contact lenses. The average height of the participants was 166 cm (SD = 6.19). None of the participants had wheelchair users amongst their family or friends.

5.2 Experimental Design

We created four operation methods and a course which has six tasks. For each operation method, measure the task execution time. We attached the reflective markers to Telewheelchair for recording

[1]http://www.keepable.net/product/wheelchair/, (last accessed December 24, 2017. In Japanese).
[2]http://ricohr.ricoh/en/, (last accessed December 24, 2017).
[3]https://www.digi.com/products/xbee-rf-solutions/2-4-ghz-modules/xbee-zigbee, (last accessed December 24, 2017).
[4]http://www.idxtek.com/products/cw-1/, (last accessed December 24, 2017).
[5]https://www.oculus.com/rift/, (last accessed December 24, 2017).

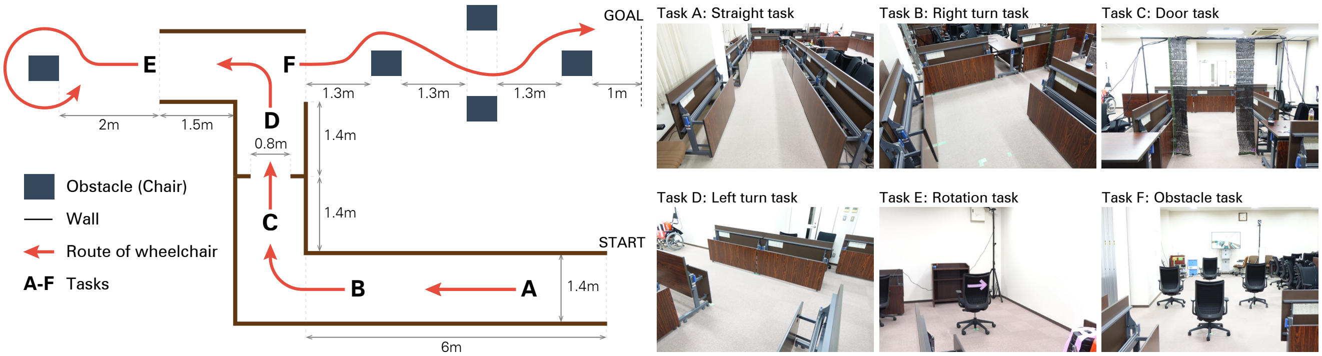

Figure 3: Routes used in experiment.

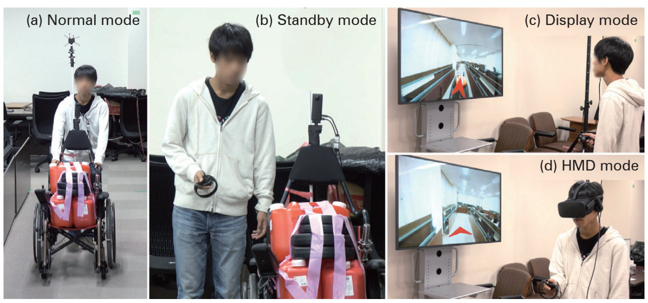

Figure 4: Four operation methods.

the locus of Telewheelchair using motion capture system by OptiTrack. We also load a weight of 52.5 kg, i.e., the average bodily weight of a 60-year-old woman. The speed limit of Telewheelchair was 3 km/h.

The course is shown in Figure 3. The following six tasks (A-F) are set in the course. Subjects continued running from the start to the goal. Each task was selected from routine actions. The width of aisles and doors were selected based on equipment standards of nursing care facilities stipulated in Japan[6]. We selected the minimum width from the facility standards. The width of the passage was 1.4 m and that of the door is 0.8 m. We used chairs (width 60 cm, length 60 cm, height 100 cm) as obstacles.

Task A : Straight task Participants ride through the passageway 1.4 m wide and 6 m long. We measured the time between the Telewheelchair entering the passageway and reaching the end of it.

Task B : Right turn task Participants turns right at a corner 1.4 m wide. We measured the time between the Telewheelchair entering the corner and reaching the end of the corner.

Task C : Door task Participants pass the door 0.8 m wide that is narrower than the passageway. They need to drive the wheelchair such that they do not hit the wall. We hung the sheets 0.3 m wide on each side of the 1.4 m wide passageway and created a 0.8 m wide door. We measured the time between Telewheelchair passing a point that is 1.4 m before the door and reaching a point 1.4 m after the door

Task D : Left turn task Participants turns left at a corner 1.4 m wide. We measured the time between Telewheelchair entering the corner reaching the end of the corner.

Task E : Rotation task Participants drive the wheelchair around an obstacle in a clockwise direction. We place a chair as the obstacle 2 m from the end of a passageway. We measured the between when Telewheelchair exiting the passageway and turning around the obstacle, until it returns to the passageway.

Task F : Obstacle task Participants need to drive the wheelchair so that it does not hit any obstacles. We place four chairs as obstacles every 1.3 m from the end of passageway. Participants could avoid the obstacles with any route. We measured the time between Telewheelchair exiting the passageway and reaching the goal of the route.

We set up four operation methods (Figure 4).

Normal mode This mode is a general operation method operated with the handle of the wheelchair.

Standby mode Subjects operate with the controller by standing next to Telewheelchair.

Display mode Only the front part of the expanded whole omnidirectional image is displayed on the display. Subjects watch only this images and operate the wheelchair with the controller.

HMD mode Subjects wear HMD and operate with controller. Subjects can operate while watching the surroundings freely.

5.3 Procedure

Each participant was briefly informed of the purpose of the study and told that they could abort the study and take a break at any time. Further, they were provided with a consent form to sign and a demographics questionnaire to complete. Subjects traveled the route (Figure 3) in four operation modes (Figure 4), respectively. Four operation modes were randomly presented to each subject. To identify potential influences on the results, the participants also completed a Kennedy's Simulator Sickness Questionnaire (SSQ) [15] immediately before and after the experiment of display mode and HMD mode.

[6]http://www.mlit.go.jp/common/000234983.pdf, (last accessed December 24, 2017. In Japanese).

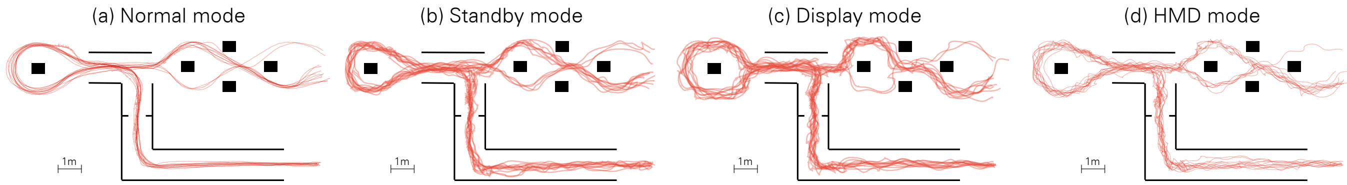

Figure 5: Result of operation path.

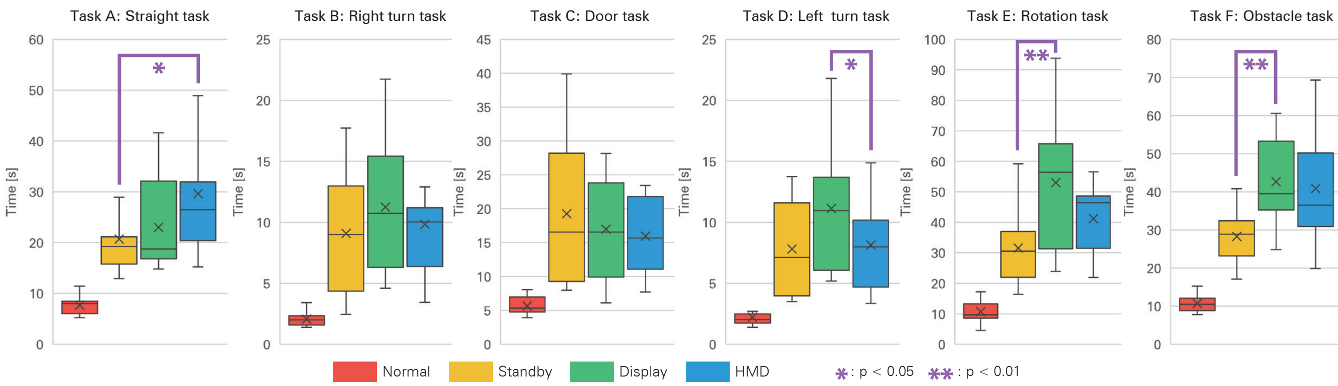

Figure 6: Result of operation time for tasks.

- **Normal mode** Normal mode is the operation method in which Telewheelchair is operated directly using a handle. At first, participants are given a maximum of 5 min to practice. After that, they drive the test course.
- **Standby mode** Standby mode is the operation method in which the participants stand next to the Telewheelchair and control it with a controller. At first, participants are given a maximum of 5 min to practice. After that, they drive the test course.
- **Display mode** Display mode manipulates the wheelchair while watching the display image of only the front part of the omnidirectional image. Participants use the controller to operate the wheelchair and they do not look at the wheelchair directly. At first, participants are given a maximum of 5 min to practice. They answered the SSQ before driving through the test course. After driving through the test course, they answered the SSQ.
- **HMD mode** HMD mode manipulates the wheelchair while wearing the HMD with the controller. Participants can look around the omnidirectional image. At first, participants are given a maximum of 5 min to practice. They answered the SSQ before driving through the test course. After that, they drove the test course and answered SSQ.

At the end of each operation mode, the participants answered two questions. The first question is the difficulty of operation the wheelchair, on a five-level Likert scale. The second question is the discomfort in the relationship between wheelchair control and wheelchair movement, on a five-level Likert scale. For each question, we made a free writing field. Participants ranked each operation in order of ease of the operation method after testing the four operation modes.

6 RESULT

6.1 Simulator Sickness Questionnaire (SSQ)

We analyzed the SSQ scores with t-test, and did not find any significant difference between pre-SSQ and post-SSQ scores in display mode and HMD mode. In display mode, SSQ total scores before the experiment averaged 23.7 (SD = 38.1), and the average post-experiment total score was 22.4 (SD = 24.0). In HMD mode, SSQ total scores before the experiment averaged 27.7 (SD = 20.7), and the average post-experiment total score was 38.0 (SD = 44.4).

6.2 General Results and Statistical Analysis

The operation path of all participants under all conditions is shown in Figure 5. The operation time for each task under all conditions is shown in Figure 6.

At first, we calculate the time required for each task from the data of the motion capture. We excluded data that is over +2.5SD from the time required for each task as outliers. Five data points were excluded from 72 data points (12 participants × 6 tasks). We analyzed the time required for each task, in the standby mode, display mode, and HMD mode, using Friedman's test and multiple comparison. We used SPSS Statistics version 24 for analysis. It is obvious that there is a difference in the time required, between the normal mode and other control mode because there is a difference the velocity of the wheelchair people are pushing and electric wheelchair. Thus, we did not include normal mode in the analysis.

The times required for each task in normal mode were shorter than those in other control modes. There were no significant differences in right turn task and door task (Right turn task: $\chi^2(2, 12) = 0.667$, n.s.; Door task: $\chi^2(2, 12) = 0.167$, n.s.).

There was significant difference in straight task ($\chi^2(2, 12) = 8.167$, $p < 0.05$). The result of multiple comparison was that the time required of HMD mode is longer than that in standby mode ($p < 0.05$) in the straight task.

There was significant difference in left turn task ($\chi^2(2, 12) = 6.500$, $p < 0.05$). The result of multiple comparison was that the required time of display mode is longer than HMD mode ($p < 0.05$) in left turn task.

It was found that there was no difference in the required time for many tasks of each operation mode in straight, right turn, door, and left turn tasks. However, there was a significant difference in rotation and obstacle task (Rotation task: $\chi^2(2, 12) = 15.167$, $p < 0.01$; Obstacle task: $\chi^2(2, 12) = 9.500$, $p < 0.01$). The result of multiple comparison was that the time required for display mode is longer than that in standby mode ($p < 0.01$) in rotation and obstacle task. As compared to the normal, standby, display, and HMD modes stagger the pathways of straight and curve. In display mode, participants operated the wheelchair to turn at right angles around the obstacles in rotation and obstacle tasks. In other modes, participants operated the wheelchair to turn around the obstacles smoothly. The times required for rotation and obstacle tasks in display mode is longer than those in standby mode because it take more time to turn at right angles around the obstacles.

6.3 Qualitative Results

Figure 7 shows the questionnaire results. There was significant difference in answers relating to the difficulty of the operation ($\chi^2(2, 12) = 14.800$, $p < 0.01$). The result of multiple comparison was that operations using display mode are more difficult than normal mode ($p < 0.01$). There were significant differences in responses related to the feeling of discomfort between movement and operation ($\chi^2(2, 12) = 16.851$, $p < 0.01$). The result of multiple comparison was that the operation of display mode causes more discomfort than operations in normal mode ($p < 0.01$). Many participants said normal mode was the easiest in which to operate the wheelchair. Standby mode was considered second-easiest. Display and HMD modes were ranked third and fourth in terms of ease-of-use, but the ranking differed amongst participants. Participants who are familiar with VR found HMD mode easier than display mode, while participants using VR for the first time felt that display mode is easier than HMD mode.

P1, P5, and P8 felt that the normal mode made them more tired than other control modes because in normal mode, they needed to control the heavy wheelchair manually. P1, P4, P8, P9, P11, and P12 felt that display mode was difficult to operate the wheelchair because it difficult to visualize the distance from the wall. P8 and P9 perceived a time delay in the video and control in HMD mode.

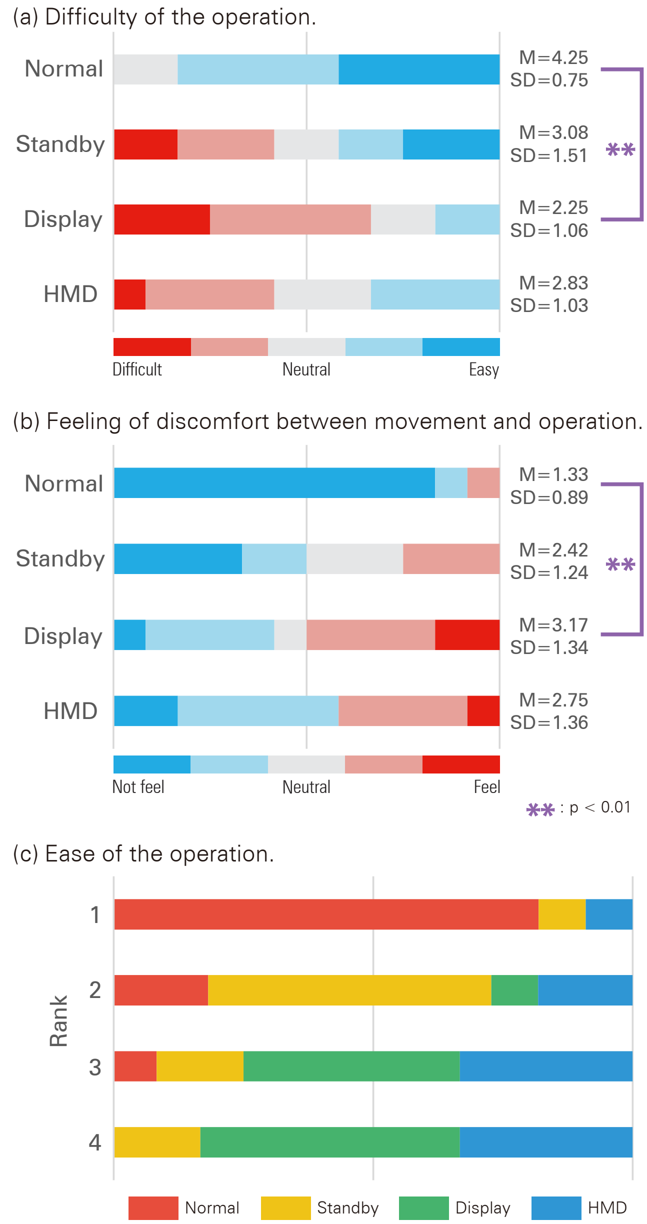

Figure 7: Qualitative results.

7 DISCUSSION

7.1 Required Time for Operation

We researched the time required for each task. In straight, door and curve tasks, there is no significant difference between standby, display and HMD modes. However, display mode takes more time than standby mode during operations including turning over 90 degrees. It is caused by participants attempting to turn squarely around the obstacles at display mode. They could turn the wheelchair diagonally because they could look around it at standby mode and HMD mode. However, we consider that they operated the wheelchair to turn squarely because they could not look around wheelchair in display mode. Therefore, it can be said that there is no difference in any operation mode as long as only straight ahead and right-angle curve paths are considered. However, we believe that standby mode and HMD mode are superior to display mode in an environment that include not-right-angle curves.

7.2 Difficulty in Operation

We enquired about the difficulty of the operation and feeling of discomfort between movement and operation as part of the qualitative evaluation. From the result, we found that display mode is more difficult than normal mode. We consider that this is caused by difficulty in sensing the perspective in display mode. It shows that standby mode and HMD mode are superior to display mode from the point of view of difficulty of the operation.

Some participants felt that operating the wheelchair was difficult. There were some opinions that it was difficult to obtain perspective-related information in at display mode and HMD mode. The image shown on display is distorted with wide angle lens in order to be able to indicate a wide range of wheelchair viewpoint on a single display. We consider that participants could not sense the perspective because of distortion. To solve this problem, we need to use multiple displays to show a wide-angle view without distortion. In HMD mode, the operator is unable to see the binocular vision even if they use the HMD because we use a monocular omnidirectional camera to record the view from the wheelchair. Therefore, participants could not get accurate perspective-related information. We need to use the 3D omnidirectional cameras to realize binocular vision.

In addition, some participants perceived a delay between the operation of the controller and the movement of the actual wheelchair. The base wheelchair of Telewheelchair is accelerated slowly to prevent a jump start even if the controller moves suddenly. Therefore, some participants who try to control the electric wheelchair feel that it is slow to accelerate. In addition, the delay also occurs due to video transmission and image processing in Unity. When the operator performs an operation to turn, they feel a sense of incongruity of operation. To resolve this, we need to add image processing functionality such as pre-move the image to offset the gap between the wheelchair's movement and image delay.

We also found that standby mode and HMD mode have similar difficulty of control. Therefore, we can choose the operation mode depending on the use case. Operators could use HMD mode when they control the wheelchair remotely and standby mode when controlling the wheelchair while standing near it. Standby mode reduces the burden of the care giver because it needs lower human power than control the wheelchair manually.

7.3 Limitation

The transmission distance in the current system extends up to 30 m, depending on the specification of the wireless device. We cannot operate wheelchairs when there is a physical barrier between them and their controllers. In the current system, we communicate with wheelchair directly via the wireless device on it. We need to use Wi-Fi or 4G network to enable functionality over longer transmission distance.

In case where a caregiver remotely controls the wheelchair, they could not correspond if the care recipient on a wheelchair performs dangerous actions. The wheelchair user may operate the controller attached to the wheelchair, or suddenly stand up or fall down. In order to allow caregivers to monitor the state of the wheelchair user, it is necessary to attach the camera that photographs the care recipient or a sensor that detects motion.

8 CONCLUSIONS

We developed a novel electric wheelchair system, called Telewheelchair, that includes remote control and AI support. In this study, we experimented with four operation modes to evaluate controllability. We found that HMD mode is superior as compared to using display mode to control a wheelchair remotely. We also found that the method to operate while standing next to the wheelchair is as useful as using HMD. In future, we can enhance the functionality of the system by adding an AI function and certain other functions that are crucial in nursing care sites in order to reduce the burden of the caregivers. We believe that Telewheelchair can contribute significantly towards improving the quality of life of wheelchair users while keeping them safe, and simultaneously aid caregivers in their responsibilities.

ACKNOWLEDGMENTS

We would like to thank University of Tsukuba and AISIN SEIKI Co., Ltd. for supporting this work. We are also thankful to all the members of the Digital Nature Group at University of Tsukuba for discussion and feedback. We thank Shiga Tatsuya and Yoshikuni Hashimoto for their insightful comments and Ayaka Ebisu, Hiroki Hasada, and Shouki Imai for their help in documenting this work.

REFERENCES

[1] M Al-Rousan and Khaled Assaleh. 2011. A wavelet-and neural network-based voice system for a smart wheelchair control. *Journal of the Franklin Institute* 348, 1 (2011), 90–100.

[2] Yuki Asai, Yuta Ueda, Ryuichi Enomoto, Daisuke Iwai, and Kosuke Sato. 2016. ExtendedHand on Wheelchair. In *Proceedings of the 29th Annual Symposium on User Interface Software and Technology.* ACM, 147–148.

[3] Rafael Barea, Luciano Boquete, Luis Miguel Bergasa, Elena López, and Manuel Mazo. 2003. Electro-oculographic guidance of a wheelchair using eye movements codification. *The International Journal of Robotics Research* 22, 7-8 (2003), 641–652.

[4] Rafael Barea, Luciano Boquete, Manuel Mazo, and E López. 2002. Wheelchair guidance strategies using EOG. *Journal of Intelligent & Robotic Systems* 34, 3 (2002), 279–299.

[5] Rafael Barea, Luciano Boquete, Manuel Mazo, Elena López, and Luis Miguel Bergasa. 2000. EOG guidance of a wheelchair using neural networks. In *Pattern Recognition, 2000. Proceedings. 15th International Conference on*, Vol. 4. IEEE, 668–671.

[6] L Deligiannidis, WD Potter, BJ Wimpey, H Uchiyama, R Deng, S Radhakrishnan, and D Barnhard. [n. d.]. HelpStar Technology for Semi-Autonomous Wheelchairs. In *the Proceedings of the 2005 International Conference on Computers for People with Special Needs, CPSN*, Vol. 5. 1–7.

[7] Jakob Engel, Thomas Schöps, and Daniel Cremers. 2014. *LSD-SLAM: Large-Scale Direct Monocular SLAM.* Springer International Publishing, Cham, 834–849. https://doi.org/10.1007/978-3-319-10605-2_54

[8] Torsten Felzer and Bernd Freisleben. 2002. HaWCoS: the hands-free wheelchair control system. In *Proceedings of the fifth international ACM conference on Assistive technologies.* ACM, 127–134.

[9] Yannick Forster, Svenja Paradies, and Nikolaus Bee. 2015. The third dimension: Stereoscopic displaying in a fully immersive driving simulator. In *Proceedings of DSC 2015 Europe Driving Simulation Conference & Exhibition.* 25–32.

[10] Ferran Galán, Marnix Nuttin, Eileen Lew, Pierre W Ferrez, Gerolf Vanacker, Johan Philips, and J del R Millán. 2008. A brain-actuated wheelchair: asynchronous and non-invasive brain–computer interfaces for continuous control of robots. *Clinical Neurophysiology* 119, 9 (2008), 2159–2169.

[11] Youssef Guedira, René Farcy, and Yacine Bellik. 2016. Tactile Interface to Steer Electric Wheelchairs. In *Actes De La 28IÈMe ConfÉRence Francophone Sur L'Interaction Homme-Machine (IHM '16).* ACM, New York, NY, USA, 230–236. https://doi.org/10.1145/3004107.3004132

[12] RT Gundersen, Stephen J Smith, and Ben A Abbott. 1996. Applications of virtual reality technology to wheelchair remote steering systems. In *Proc. of 1st Euro Conf of Disability, Virtual Reality & Assoc. Technology.* 47–56.

[13] Komei Hasegawa, Seigo Furuya, Yusuke Kanai, and Michita Imai. 2015. DECoReS: Degree expressional command reproducing system for autonomous wheelchairs. In *Proceedings of the 3rd International Conference on Human-Agent Interaction.* ACM, 149–156.

[14] Keita Higuchi and Jun Rekimoto. 2013. Flying head: a head motion synchronization mechanism for unmanned aerial vehicle control. In *CHI'13 Extended Abstracts on Human Factors in Computing Systems.* ACM, 2029–2038.

[15] Robert S. Kennedy, Norman E. Lane, Kevin S. Berbaum, and Michael G. Lilienthal. 1993. Simulator Sickness Questionnaire: An Enhanced Method for Quantifying Simulator Sickness. *The International Journal of Aviation Psychology* 3, 3 (1993), 203–220. https://doi.org/10.1207/s15327108ijap0303_3 arXiv:http://dx.doi.org/10.1207/s15327108ijap0303_3

[16] Yoshinori Kobayashi, Ryota Suzuki, Yoshihisa Sato, Masaya Arai, Yoshinori Kuno, Akiko Yamazaki, and Keiichi Yamazaki. 2013. Robotic wheelchair easy to move and communicate with companions. In *CHI'13 Extended Abstracts on Human Factors in Computing Systems.* ACM, 3079–3082.

[17] Simon P Levine, David A Bell, Lincoln A Jaros, Richard C Simpson, Yoram Koren, and Johann Borenstein. 1999. The NavChair assistive wheelchair navigation system. *IEEE transactions on rehabilitation engineering* 7, 4 (1999), 443–451.

[18] Manuel Mazo. 2001. An integral system for assisted mobility [automated wheelchair]. *IEEE Robotics & Automation Magazine* 8, 1 (2001), 46–56.

[19] M Mazo, FJ Rodríguez, JL Lázaro, J Ureña, J Carlos Garcia, E Santiso, and PA Revenga. 1995. Electronic control of a wheelchair guided by voice commands. *Control Engineering Practice* 3, 5 (1995), 665–674.

[20] Masato Nishimori, Takeshi Saitoh, and Ryosuke Konishi. 2007. Voice controlled intelligent wheelchair. In *SICE, 2007 annual conference.* IEEE, 336–340.

[21] Gabriel Pires and Urbano Nunes. 2002. A wheelchair steered through voice commands and assisted by a reactive fuzzy-logic controller. *Journal of Intelligent and Robotic Systems* 34, 3 (2002), 301–314.

[22] J. Redmon, S. Divvala, R. Girshick, and A. Farhadi. 2016. You Only Look Once: Unified, Real-Time Object Detection. In *2016 IEEE Conference on Computer Vision and Pattern Recognition (CVPR).* 779–788. https://doi.org/10.1109/CVPR.2016.91

[23] Masahiro Shiomi, Takamasa Iio, Koji Kamei, Chandraprakash Sharma, and Norihiro Hagita. 2014. User-friendly autonomous wheelchair for elderly care using ubiquitous network robot platform. In *Proceedings of the second international conference on Human-agent interaction.* ACM, 17–22.

[24] Erik Wästlund, Kay Sponseller, and Ola Pettersson. 2010. What you see is where you go: testing a gaze-driven power wheelchair for individuals with severe multiple disabilities. In *Proceedings of the 2010 Symposium on Eye-Tracking Research & Applications.* ACM, 133–136.

[25] Florian Weidner, Anne Hoesch, Sandra Poeschl, and Wolfgang Broll. 2017. Comparing VR and non-VR driving simulations: An experimental user study. In *Virtual Reality (VR), 2017 IEEE.* IEEE, 281–282.