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Utility of Remote Workers' Video of a Surrogate Telepresence Robot for Predicting Its Motion[1]

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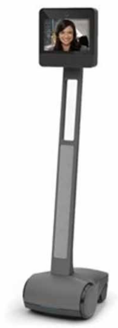


Figure 1: Beam® from Suitable Technologies

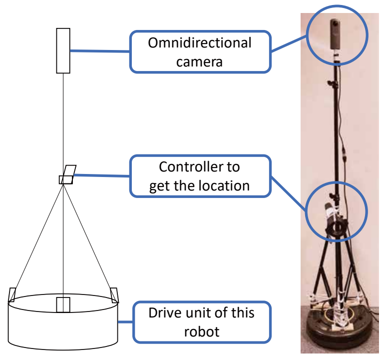


Figure 2: The telepresence robot used in this study

Abstract - This study focuses on environments where people and robots coexist and investigates how to support the coexistence of people and robots. This study assumes a situation in which local workers and telepresence surrogate robots operated from remote locations work in the same office. To investigate how to support the situation, we examined whether a person and a robot can pass by each other by using a technology that projects an image of the person who operates the robot onto the robot, which has been proposed to support physical cooperative work. The experiment results showed that a person could predict the robot's direction of travel and pass by looking mainly at the upper body of the remote person. This suggests the effect of projecting a human figure onto a robot in an environment where humans and robots coexist.

Keywords: Cooperative work, Physical interaction, Nonverbal cue, Telepresence robot

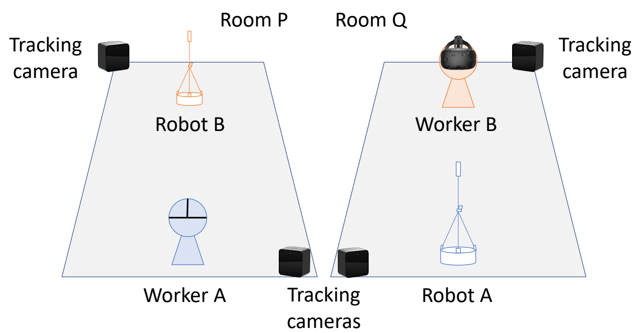


Figure 3: An environment of passing each other

1 INTRODUCTION

Remote work has recently become increasingly popular. Nevertheless, face-to-face work remains essential. This study considers a work environment in which telework and face-to-face work are combined. That is, some workers work in an office while others work at a remote location. In this environment, the remote worker operates robots in the office to communicate with other workers.

The robot assumed for use in this study is a surrogate telepresence robot, such as the Beam Pro from Suitable Technologies (now Blue Ocean Robotics of Denmark), with a mobile drive unit and a camera or monitor attached to the top of the robot. By using such a telepresence robot, workers in an office can move with the robot and communicate with remote workers via the robot. Such telepresence robots have been used in office environments [2], [3] and in non-office environments [4], [5], and various studies have argued for the usefulness of telepresence robots.

However, previous studies have not paid much attention to the coexistence between humans and robots. There needs to be more understanding of what kind of support is possible when humans and robots freely move through the same space. This study aims to achieve smooth coexistence between humans and robots. In order to examine what kind of assistance is available, this study focuses on a situation in which a person and a robot pass by each other in a narrow space as one

[1]This paper is an extended version of the IWIN proceeding [1].
[2]Home - Beam, `https://suitabletech.com/home` (Visited on Jul 21, 2023)
[3]Blue Ocean Robotics - We Create and Commercialize Robots, `https://www.blue-ocean-robotics.com/` (Visited on Jul 21, 2023)

of the situations in which a person and a robot coexist.

In an environment in which humans and robots coexist, humans and robots must behave cooperatively. Many studies have been conducted to support human-robot coexistence [3], [6]–[8], which is the aim of this research. We must determine what kind of assistance is needed for people and robots to coexist.

In cooperative work in a face-to-face environment or a remote environment with fixed displays, it is known that workers can guess their partners' actions by observing their facial direction, body movements, and other information, thereby being able to work without conflict or collision [9]–[11]. Additionally, whole-body movements are known to provide the viewer with emotional information such as credibility and persuasiveness, which is essential to work collaboratively [12], [13]. However, since robots lack such nonverbal information, humans and robots may not pass by each other well.

Inoue and Yuan have proposed a virtual reality (VR) system for collaborative work with physical movement. In the system, a human and a telepresence robot (as shown in Fig. 2) operated by another person in a remote place passed by each other, which is a form of collaborative work. This system shows the feasibility of a human and a telepresence robot passing by each other in the same workplace [14].

In this study, we examined the method by which Inoue and Yuan initially proposed that a video of a robot operator's whole body in a remote place is shown to a local worker who passes by a telepresence robot. We verified the effect of this method in an environment where humans and robots coexist based on objective and subjective data.

We examined the method by a passing-by task. A worker and a telepresence robot were placed in the same workspace in the passing-by task. Another worker in another workspace operated the telepresence robot. In the experiment, we arranged two pairs of a human and a robot in two workspaces (as shown in Fig. 3). Each worker faced a telepresence robot that moved synchronously with a remote worker and wore a head-mounted display (HMD) that displayed video captured by the camera attached to the robot, which was in a remote place. The worker could walk and see the remote worker's whole body through the HMD.

We analyzed how a worker moved while seeing the remote worker's whole body during the passing-by task based on recorded video of the experiment, a questionnaire survey, and interviews with the workers. The analysis result shows that a worker passing by a telepresence robot tended to look at the upper body of the remote worker's image. Additionally, workers using the system could predict where the robot was moving to [1]. This result suggests that the system displaying the remote worker's image, especially the worker's upper body, onto the robot can support situations in which humans and robots coexist.

2 RELATED WORK

We investigate a situation in which a human and a telepresence robot pass by each other, regarded as remote cooperative work between a local worker and a remote worker. In this chapter, we introduce remote cooperative work support.

2.1 Remote Communication Support Using Flat Fixed Displays

Unlike face-to-face environments, remote environments lack visual and nonverbal information, such as gaze information and body movements. Since nonverbal information is essential for smooth communication, studies have been conducted on communicating visual and nonverbal information with each other to facilitate remote collaboration.

Fixed displays are often used to communicate in remote workspaces. Previous studies have proposed systems that use worker gaze information [15], or that project a shared workspace or background to give users immersion and the feeling of being in the same room [16], [17]. Some proposed systems show images of remote workers on fixed displays. Methods of overlaying remote persons on the background of a fixed display [18] or showing a worker's life-size image on display [19] enable communication as if the workers are in the same space.

Other studies have proposed methods of conveying nonverbal information by projecting images of a remote worker instead of using flat displays [20], [21]. However, methods using flat displays or projections greatly restrict workers' body movements, and these methods cannot support remote cooperative work involving spatial movement.

2.2 Remote Communication Support Using AR and VR Technologies

Systems using VR and augmented reality (AR) technologies with HMDs have also been proposed to solve the problem of movement restriction, including systems that immerse a worker in the same virtual space with a remote worker [22], [23], systems that immerse a worker by displaying the remote workspace [24], and systems that can switch the image displayed on the HMD to other images captured from other viewpoint, such as another worker's point of view or a bird's-eye view [25]. Furthermore, some systems use surrogate avatars of workers for smooth communication [26]–[29]. These previous studies show that AR and VR technologies can reduce restrictions on worker movement. However, in collaborative work in a virtual space, workers do not have physical bodies and cannot interact in real space. Furthermore, using avatars can eliminate the nonverbal information of workers.

2.3 Remote Communication Support Using Telepresence Robots

Several studies have investigated telepresence robots, as we focus on in this study, to support communication in the office. A study by Shen et al. investigated the interpersonal distance between a person and a telepresence robot. American and Indian participants were tested in a situation in which the participant operated a telepresence robot to approach a co-worker working in an office. The results revealed that the worker operating the robot behaved similarly in terms of culture-specific distancing as in a face-to-face environment [2]. Myodo et al. investigated whether telepresence robots could facilitate informal communication in an office setting. Experiments using a telepresence robot to communicate between a remote supervisor and a subordinate in the office revealed that the supervisor's facial expressions were conveyed more strongly when the telepresence robot was used [3].

There have been studies using telepresence robots in environments other than the office. Newhart and Olson's study investigated the use of telepresence robots by children who cannot attend school due to illness. While they showed that the use of telepresence robots in schools could provide learning opportunities for children who are unable to attend school, they also pointed out that there is room for improvement in the school environment where telepresence robots are used, such as physical barriers in the school and the operability of the robots [4]. Another study examined the use of telepresence robots to allow remote users to attend academic conferences. In this study, telepresence robots were arranged at ACM international conferences such as CHI, CSCW, and UBICOMP/ISWC to observe the reactions of local attendees and their interactions with the telepresence robots' in conference activities. As a result, they revealed several insights about the requirements for telepresence robots and systems, which varied depending on the characteristics of each conference [5].

Other systems, including ThirdEye which presents both first- and third-person perspectives simultaneously to the operator of the telepresence robot [30], and the telepresence robot system to shop with a remote user [31], have been proposed. Additionally, robots with higher degrees of freedom, including MeBot and iRIS, which can change facial orientations and move their arms just like human beings [6], [32]–[35], have also been used in research.

However, these studies have yet to focus primarily on human-robot coexistence. In particular, nonverbal information that was claimed to be necessary for cooperative movement in flat fixed display environments, AR, and VR-based environments is not always conveyed because only what the robot can reproduce can be communicated to the other person.

Therefore, in this study, we use VR technology to give images of people in remote locations to the telepresence robot. By showing the remote worker the image of a person as they are, nonverbal information is communicated.

2.4 Passing by a Telepresence Robot

In general, robots need to ensure the safety of humans [36]. For example, studies have investigated collision avoidance between humans and autonomous robots by using sensors (e.g., [37]–[39]), predicted emotions from a person's face to take avoiding action [40], and designed or developed interfaces for human-operated robots [41]–[43]. However, little is known about situations in which a human passes by a human-operated robot.

Inoue and Yuan have proposed a VR system for smooth physical collaboration between a human and a robot and evaluated the system in a situation in which a human passes a surrogate robot-that is, a robot operated by another worker. The system provided video of the remote worker to a telepresence robot, and the local worker could see the remote worker's body through an HMD. Using an HMD removes restrictions of body movement, and showing the appearance of the remote worker to the local worker prevents them from missing nonverbal information when compared to using avatars [14]. However, their experiment was unrealistic: a worker only walked 1.0 m to pass by the robot. Furthermore, the evaluation was based on a small number of participants.

Sasaki et al. evaluated the VR system through a more realistic experiment with more participants. They reported the results of a questionnaire survey and interviews with participants, which revealed that a worker passing by a robot looked at the human body to predict where the robot was moving to [1]. In this paper, we show results of objective and subjective data, which support the previous claim that a worker looks at the upper body when passing a robot for smooth movement.

3 ENVIRONMENT WHERE A WORKER AND A TELEPRESENCE ROBOT PASS BY EACH OTHER

In this study, we focus on a situation in which a local worker and a telepresence robot operated by a remote worker pass by each other in the same space to investigate how to support the coexistence of humans and robots. In this section, we explain the situation in which a worker and a telepresence robot pass by each other.

3.1 Overview of the Environment

The environment in which a worker and a robot pass by each other is shown in Fig. 3. Two pairs of a worker and a mobile robot equipped with a 360-degree camera (as shown in Fig. 2) were arranged in two separate workspaces. The robots moved according to the position of the remote workers: for example, when worker A moved forward, robot A also moved forward. Each robot moved, synchronizing its respective worker's position, as shown in Fig. 4.

Workers wore HMDs that showed videos captured from the camera of their respective robots; therefore, worker A could see the video of worker B in room Q, acquired by robot A's camera through the HMD, and worker B could see worker A in room P acquired by robot B's camera through the HMD. In this way, an environment was set up in which the local worker and the telepresence robot operated by the remote worker passed by each other. Figure 5 shows an image of the worker in the remote location as presented through the HMD.

Originally, to analyze the system's effectiveness, it was not necessary to prepare two sets of workspaces as shown in Fig. 3, but only one workspace was needed, with one worker, one robot, and one remote worker operating the robot. However, by arranging the worker and robot as shown in Fig. 3, two situations occurred for the two workers, in which the remote worker is operating the robot in front of each worker, and two samples can be obtained at the same time per experiment trial.

3.2 Implementation of the Environment

The environment was constructed as shown in Fig. 3. To eliminate differences between facilities, we set up two rooms

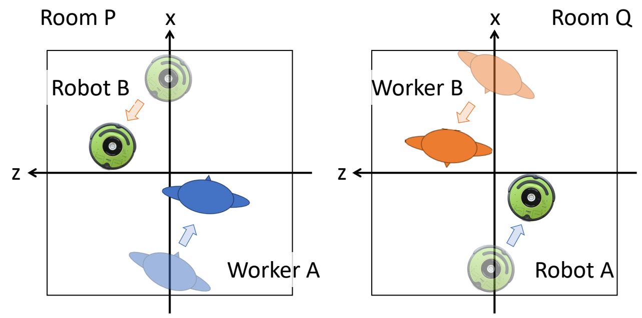


Figure 4: Synchronization between the workers and the robots

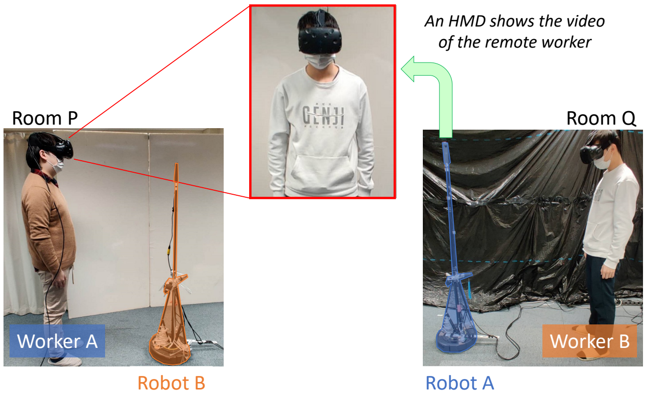


Figure 5: The view in the HMD

of the same size and shape, and the robots and sensors in both rooms were the same. Two tracking cameras were set up on the diagonal of each workspace to establish the positional standard.

The workers and the robots' acquired position and orientation information was sent to a PC, which sent commands to each robot to move, synchronizing the position of the remote workers.

We used VIVE™ products from HTC Corporation[1] in this experiment. The VIVE™ products can obtain position and orientation information by receiving optical lasers from the tracking camera via sensors embedded in the HMD and the controller.

The mobile robot shown in Fig. 2 was the iRobot® Create 2 from iRobot Corporation[2]. iRobot® Create 2 is a mobile robot that can rotate in any direction and move forward and backward. The two wheels on the robot can be commanded separately, and by making one wheel move slower than the other wheel, the robot can rotate while moving forward.

A height-adjustable tripod for the camera was placed on top of the mobile robot. A VIVE™ controller was attached to the tripod. A RICHO[3] 360-degree camera, the Theta V™, was attached to the tip of the tripod to capture first-person images to be presented to the remote worker. The 360-degree camera eliminated the need to move the camera with the worker's orientation, allowing the HMD to adjust its field of view to the worker's small movements.

The images captured by the robot were transmitted to the HMD using WebRTC technology. This entailed a delay from when the camera acquired the image to when it was displayed on the HMD. This delay was an average of 0.43 seconds (SD: 0.10 seconds) based on the preliminary measurements (N=16).

3.3 Synchronization of Worker and Robot Position

In this system, the same systems to match the positions of the worker and the robot were prepared for the two workspaces. Each worker's position was represented by x and z coordinates in Unity™[4]. After obtaining the workers' position information, the PC sent the position coordinates of worker A in the coordinate system of room P to robot A in room Q, and it sent the position coordinates of worker B in the coordinate system of room Q to robot B in room P. Each robot moved based on the location information of the remote worker, as shown in Fig. 4.

4 EXPERIMENT

This study focuses on environments where humans and robots physically coexist and aims to support coexistence. In particular, this study assumes an environment where humans and robots work in the same office. Among the problems that can occur when humans and robots coexist in such an environment, this study focuses on situations where a human and a robot pass by each other in a narrow space, such as a corridor or passageway. In order to support the situation, this study examined the effectiveness of a telepresence robot system developed for real-world cooperative work support [14].

4.1 Passing-by Task

In order to verify how adding a worker's video to each robot would support the situation in which a worker and a robot pass by each other, we experimented with a passing-by task (approved by the Ethics Review Committee of the Faculty of Library, Information and Media Science, University of Tsukuba (Notification number: 20-15)).

In the passing-by task, workers A and B at two remote locations passed by robots B and A, respectively (as shown in Fig. 3), and a previous study [14]. However, in the previous study [14], the initial distance between the worker and the robot was only 0.5 m, and the travel distance was 1.0 m, which was too short for a passing-by experiment. Therefore, in this study, we set the travel distance between the worker and the robot to 3.0 m.

The workspaces were set up in an area of our laboratory. The workspace size was approximately 2.0 m wide by 4.0 m long. Two lines were drawn 3.0 m apart in each workspace;

[1]VIVE - VR Headsets, Games, and Metaverse Life, `https://www.vive.com/` (Visited on Dec 10, 2022)

[2]Coding Robots, Learning Library & STEM Outreach | iRobot Education, `https://edu.irobot.com/` (Visited on Dec 10, 2022)

[3]Ricoh Global | EMPOWERING DIGITAL WORKPLACES, `https://www.ricoh.com/` (Visited on Dec 10, 2022)

[4]Unity Real-Time Development Platform | 3D, 2D VR & AR Engine, `https://unity.com/` (Visited on Dec 10, 2022)

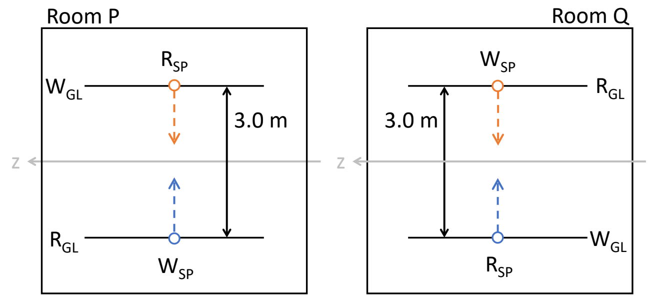


Figure 6: Passing-by task

one indicated the worker's starting point (W_{SP}), and the other indicated the robot's starting point (R_{SP}). We ensured that each line's z coordinates were the same (see Fig. 6). When the experimenter signaled the start, the workers at each starting point started walking toward their goal lines. The robots also moved forward in each workspace because each robot moved in synchronization with a worker's position. The workers and the robots moved forward, slightly shifting directions to avoid collisions. We defined task completion as the time that both workers' bodies crossed their respective worker goal lines (W_{GL}) and both robots' bodies crossed their respective robot goal lines (R_{GL}) in both workspaces. We observed the workers' movements from when they started walking to task completion.

4.2 Experiment Conditions

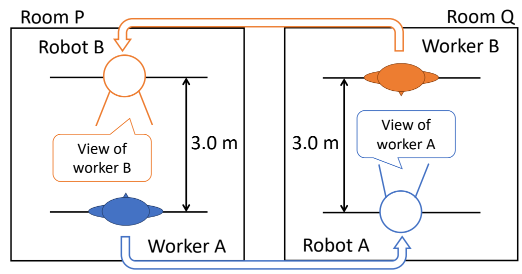
In face-to-face environments, people are known to avoid collisions and coordinate their movements by seeing the other person's actions. Thus the appearance of the person is essential for predicting the other person's movements [9]. For robots and humans to coexist in the same space, methods have also been studied in which the robot captures the human's image with a camera and acts to avoid collisions [39]. However, as we focus on in this study, in an environment where a human and a surrogate robot operated by a human coexist, how a person moves when the other's image, i.e., the robot's operator, has not been studied before, excepting Inoue and Yuan's study [14]. So, we need to reveal the effect of showing the whole body to a person in an environment with a telepresence robot.

In this study, we conducted an experiment to investigate the effect of projecting the operator's entire body image onto a robot through an HMD when the human and the telepresence surrogate robot pass by each other in an environment where they coexist.

We compared two conditions in the experiment based on what workers could see through the HMDs during the passing-by task. One is the **human condition**; in this condition, as described thus far, workers were wearing HMDs at both remote locations, and each HMD displayed the video from the camera mounted on the robot (as shown in Fig. 7).

The other is the **robot condition**; in this condition, worker A's HMD displayed the see-through video in front of them (as shown in Fig. 8). Unlike the human condition, worker A had to move while looking at robot B, although worker B moved

(a)



(b)

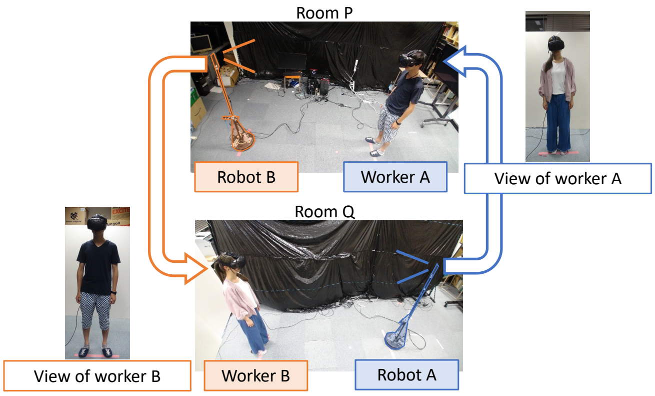


Figure 7: The human condition: (a) an overview; (b) the view of each worker.

while looking at worker A to operate robot B during the task. So, situations were not symmetrical between the participants in a pair. Therefore, only worker A, who performed the task while looking at the robot, was subject to the analysis, and worker B was not. Robot A, which passed by worker B and was operated by worker A, was not used in the robot condition.

In both conditions, workers were not allowed to talk to each other to stimulate visual information transfer between workers' movements. Therefore, during the experiment, workers moved based only on visual information. In comparing the two conditions, we analyzed the effect of displaying the remote worker's full-body image to the local worker during the passing-by task.

4.3 Participants

Six pairs of 12 graduate students (all male) participated in the experiment. Of the 12, five had never used an HMD before this experiment. Only one of the six pairs had never met each other before.

4.4 Procedure

The experiment consisted of a within-participant design; Table 1 shows the experiment's procedure. First, each pair was assigned to the human or robot condition, which were counterbalanced. In each condition, participants were assigned to be workers A or B and then moved to the remote workspaces rooms P or Q. After the experimenter explained the system, the participants practiced the passing-by

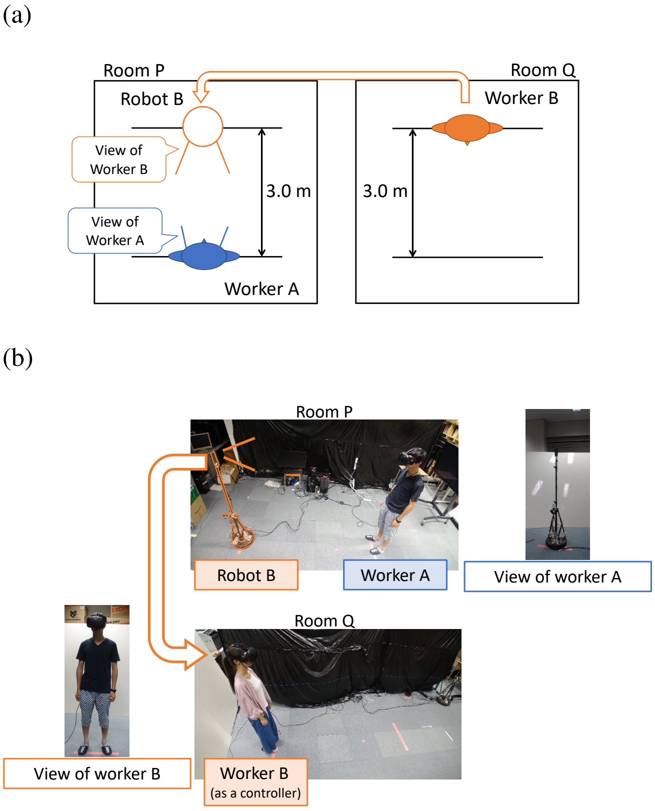


Figure 8: The robot condition: (a) an overview; (b) the view of each worker.

task twice to familiarize themselves with the task and use of the system. The experimenter delineated the placement of the goal line and how far the participants could move in the workspace, explaining until both participants understood the task. The experimenter also asked participants to walk without bumping into the robot and did not mention how fast or long they should walk.

After the practice rounds, the participants performed the task once. After the task, the sequence was repeated under another condition. The robot condition differed from the human condition in that worker A passed by robot B, but worker B walked alone-that is, the robot condition was asymetrical. Therefore, after completing the task, workers A and B switched roles and performed the task (including practice rounds) again. As a result, the task was performed a total of six times (one time for each pair) for all pairs in the human condition and 12 times (two times for each pair) in the robot condition (excluding the practices).

One experimenter was assigned to room P, and another was assigned to room Q, to prevent workers from colliding with the robot and from catching their feet on the cords connecting the robot and the PC during the experiment.

A questionnaire survey was conducted after the task in each condition. According to previous studies investigating remote cooperative work through robot assistance, whether workers are satisfied with remote cooperative work involving robots depends on the presence of the partners and the feeling that they are collaborating with the partners [44], [45]. Therefore, in this study, ten questions involving subjective evaluations were posed, asking not only about the robot's usability but also about the presence of the partner and the sense of being in the same room with the robot. Participants responded to the evaluation items using a 7-point scale ranging from "strongly disagree" to "strongly agree." The questionnaire items are shown in Table 2.

In both conditions, we also conducted open-ended interviews after the task was completed. Participants were asked to respond freely to questions about their impressions of the task and the system.

4.5 Data Collection

The coordinates of the workers and the robots were acquired using HMDs worn by workers and controllers mounted on mobile robots. In the human condition, coordinates were acquired for six workers and six robots in six pairs and two locations; in the robot condition, coordinates were acquired for 12 workers and 12 robots in six pairs and one location (Room P). The frequency of coordinate capturing was five times per second (every 0.2 seconds), the same as the frequency at which coordinates were exchanged between the HMD and the PC.

To examine how the workers passed by each other in response to the visual information presented, we obtained the video that the HMD showed the workers during the task. HMD videos were not gathered during practice rounds, so there were 12 videos for six pairs in two rooms in the human condition and 12 videos for six pairs in one room (Room P) performing the task two times in the robot condition. Thus, a total of 24 videos were obtained across both conditions.

The questionnaire survey results and the interview transcripts were also used for subjective evaluation.

5 RESULT

In the experiments conducted in this study, there was the possibility of collisions between the robot and the worker. However, no cases of collisions occurred between the robot and the worker. There were two cases in which a worker's leg was touched lightly by the robot in the human condition, but since none of these cases resulted in worker injury, the experiment was not interrupted.

In this chapter, we present the results of our analysis of the quantitative data (the users' movements and the direction of the users' field of view) and of the qualitative data (the questionnaire evaluation) [1].

5.1 The Workers' Movement

Table 3 shows the mean values of the workers' walking time, workers' walking distance, workers' walking speed, robots' moving distance, robots' moving speed during the task, and time from commencement of walking to passing the robot (N=12). A one-way MANOVA (two levels of condition: human condition and robot condition) with the dependent variables of worker walking time, worker walking distance, worker walking speed, robot moving distance, robot moving speed, and time from commencement of walking to passing the robot was conducted to test differences in the

Table 1: The experiment procedure

Procedure	Human condition	Robot condition
1.	Workers A and B stood on their respective start points (see 7(a)).	Workers A and B stood on their respective start points (see Fig. 8(a)).
2.	Workers were informed of the system and practiced the task twice.	Workers were informed of the system and practiced the task twice.
3.	Workers performed the task once.	Workers performed the task once.
4.	Workers filled out the questionnaire.	Worker A filled out the questionnaire.
5.	-	The role of workers A and B were switched, and they stood at their respective start points.
6.	-	Workers were informed of the system and practiced the task twice.
7.	-	Workers performed the task once.
8.	-	Worker A filled out the questionnaire.
9.	Workers were interviewed after both conditions had been conducted to completion.	

Table 2: Questionnaire items

	Items
Q1	After using the system, I felt uncomfortable in a way similar to motion sickness.
Q2	The video was clear and pretty.
Q3	I felt like the remote person was in the same room with me.
Q4	I could clearly perceive the motion of my partner.
Q5	I felt like I passed the other person in the same room.
Q6	The field of view changed naturally in line with my movements.
Q7	I perceived the movements and directions of my partner.
Q8	I could predict where my partner was moving to.
Q9	My partner's movement looked realistic.
Q10	The experience in the virtual environment was consistent with experiences in real life.

means between the conditions, but no significant differences were found ($F(1,6) = 0.37,\ p = .89$).

5.2 Workers' Fields of View During the Task

Figure 9 shows an example of the video displayed on the HMD during the experiment, which the worker was viewing. This image presents the worker's field of view (FOV), which is categorized into three patterns based on where the center of the FOV (red dot in Fig. 9) was facing: the upper body, the lower body, or the floor. The definitions of the direction of the worker's FOV are shown in Table 4. For example, when the center of the worker's FOV was above the waist in the human condition, the worker was considered to be looking at the upper body; in the robot condition, when the center of the worker's FOV was facing the drive part, the worker was considered to be looking at the lower body. The measurements were taken from the start of walking to the point of passing each other. The worker and the robot faced either the upper body, the lower body, or the floor, and they never faced another direction until they passed each other. The average time

Table 3: Averages of movements of workers and robots

	Human condition	Robot condition
Walking time [s]	12.28 (SD: 3.04)	11.67 (SD: 3.61)
Walking distance of the worker [m]	3.64 (SD: 0.29)	3.67 (SD: 0.38)
Walking speed of the worker [cm/s]	31.2 (SD: 6.96)	33.7 (SD: 8.19)
Moving distance of the robot [m]	2.94 (SD: 0.58)	2.73 (SD: 0.78)
Moving speed of the robot [cm/s]	24.3 (SD: 2.72)	24.4 (SD: 3.50)
Time from starting walking to passing by the robot [s]	7.27 (SD: 1.48)	7.30 (SD: 2.91)

spent looking at each part is shown in Table 4, and the average ratio for all pairs is shown in Fig. 10.

The one-way MANOVA (two levels of condition: human condition and robot condition) conducted with the dependent variable of the ratio of time spent looking at each viewing body part showed significant differences ($F(1,22) = 11.30,\ p = .0002$). We also conducted corresponding Bonferroni t-tests, which revealed significant differences in the following six items (as shown in Fig. 10):

- Time spent looking at the upper body in the human condition vs. time spent looking at the lower body in the human condition ($t(11) = 7.16,\ p = .0003$)
- Time spent looking at the upper body in the human condition vs. time spent looking at the floor in the human condition ($t(11) = 11.38,\ p < .01$)
- Time spent looking at the upper body in the human condition vs. time spent looking at the upper body in the robot condition ($t(11) = 5.73,\ p = .002$)
- Time spent looking at the upper body in the human condition vs. time spent looking at the lower body in the robot condition ($t(11) = 4.37,\ p = .02$)
- Time spent looking at the upper body in the human condition vs. time spent looking at the floor in the robot

Table 4: Time viewing body parts

Definition	Human condition: Direction of the center of the FoV	Human condition: Mean/SD [s]	Robot condition: Direction of the center of the FoV	Robot condition: Mean/SD [s]
Upper body	Above the waist	6.88 / 2.01	Above the center of the robot (including the prop and 360-degree camera)	1.40 / 2.24
Lower body	Below the waist and above the floor	0.38 / 1.27	Below the center and above the floor of the robot (including the prop)	3.25 / 2.40
Floor	Floor	0.00 / 0.00	Floor	2.65 / 2.94

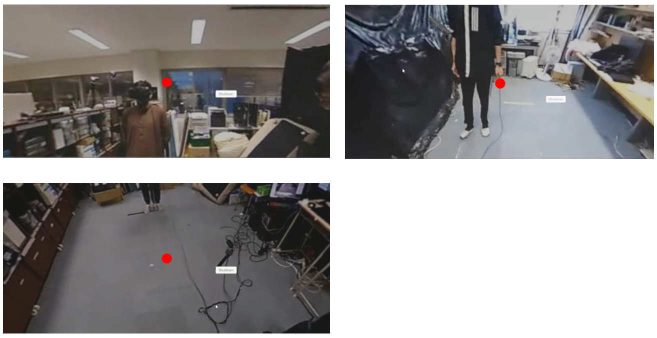


Figure 9: Screenshots displayed to workers. The upper left shows the worker looking at the other worker's upper body; the upper right shows the worker looking at the other worker's lower body; the lower left shows the worker looking at the floor.

condition ($t(11) = 5.28,\ p = .004$)

- Time spent looking at the floor in the human condition vs. time spent looking at the lower body in the robot condition ($t(11) = -4.50,\ p = .01$)

In particular, the first five items indicated that more time is spent looking at the upper body in the human condition than in either of the two conditions, implying that the worker is looking at the upper body longer because they can see the human image.

5.3 Questionnaire

Ratings were treated as a score from 1 to 7, and a Wilcoxon signed-rank test was conducted for each question item; the results are shown in Table 5. In particular, the scores of four questions were significantly higher in the human condition than in the robot condition: Q4 "I could clearly perceive the motion of my partner" ($p < .01$); Q7 "I perceived the movements and directions of my partner" ($p < .01$); Q8 "I could predict where my partner was moving to" ($p < .01$); and Q9 "My partner's movement looked realistic" ($p < .05$).

6 DISCUSSION

In the human and the robot conditions, a significant difference was found in the direction of the worker's face during the task: workers in the human condition spent relatively more time looking at the upper body of the remote worker, while

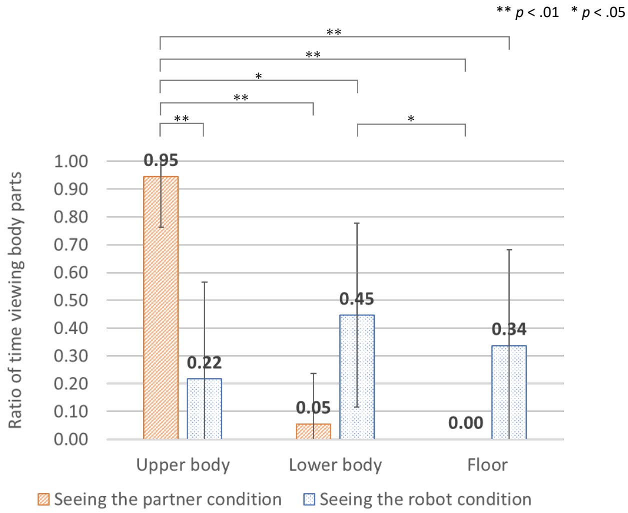


Figure 10: Time viewing body parts. Asterisk(s) show significant differences, and error bars show standard deviations.

workers in the robot condition spent more time looking at the lower body and the floor. First, we discuss the results of the questionnaire survey and the interviews.

In the questionnaire survey, as mentioned in section 5.3, there were significant differences in the following items: Q4 "I could clearly perceive the motion of the partner", Q7 "I perceived the movements and directions of my partner", and Q8 "I could predict where my partner was moving to." These differences are considered to have occurred because the human whole-body image was presented exactly as the remote robot's camera captured it in the human condition.

In addition, in the interviews, participants in the human condition provided such comments as "I could predict the robot's path when looking at a human (P3)" and "I could clearly see its [the robot's] direction of movement when looking at a human (P5)." In contrast, participants in the robot condition provided these comments: "I could not see the robot's direction of movement (P2, P7)" and "I was confused about the robot's direction of movement (P8)." Based on the comments' differences, the local workers seemed to predict the robot's movement in the human condition, in which the human image was seen in the HMD. In contrast, the robot's direction of movement was unpredictable in the robot condition, in which the robot's image was seen in the HMD.

The result of the interviews suggests that the worker in the

Table 5: The study's questionnaire; p-values are the results of Wilcoxon signed-rank test.

(** $p < .01$, * $p < .05$, † $p < .10$)

	Items	Mean / Median / Mode in the human condition	Mean / Median / Mode in the robot condition	p-value
Q1	After using the system, I felt uncomfortable in a way similar to motion sickness.	4.0 / 5 / 2, 5, 6	4.3 / 5 / 5	.79
Q2	The video was clear and pretty.	5.1 / 5 / 5	4.3 / 4.5 / 3, 5	$.08^{\dagger}$
Q3	I felt like the remote person was in the same room with me.	6.3 / 6.5 / 7	5.5 / 6 / 6	.13
Q4	I could clearly perceive the motion of my partner.	6.3 / 6 / 6	5.3 / 5 / 5	$.008^{**}$
Q5	I felt like I passed the other person in the same room.	5.3 / 5.5 / 5, 6, 7	5.6 / 5.5 / 5	.69
Q6	The field of view changed naturally in line with my movements.	5.5 / 5.5 / 5	5.4 / 5.5 / 5	1.00
Q7	I perceived the movements and directions of my partner.	6.1 / 6 / 6	4.6 / 4.5 / 4	$.003^{**}$
Q8	I could predict where my partner was moving to.	6.2 / 6 / 6	4.2 / 4 / 4	$.001^{**}$
Q9	My partner's movement looked realistic.	5.8 / 6 / 6	4.2 / 4.5 / 5	$.02^{*}$
Q10	The experience in the virtual environment was consistent with experiences in real life.	5.6 / 5.5 / 5	4.8 / 5 / 4, 5	.16

human condition predicted the robot's next move by looking at the upper body but that the worker in the robot condition could not predict the robot's movement by looking at the upper body. This may be why the worker looked at the lower body, which is the robot's moving part, longer in the robot condition to try to predict where the robot would go. This indicates that presenting an image of the worker's upper body is important to predict the remote worker's action when cooperative work involving movement is performed across remote locations.

Previous studies have also proven the importance of having the human image in collaborative work. A study of a collaborative bicycle repair task in face-to-face and remote contexts found that the visual cues in the human image could provide the grounding for their conversation and the task [10]. Another study involving a remote collaborative task of assembling a toy was conducted in a specially designed space where the local worker and a table were surrounded by eight fixed displays showing a remote worker; it found that the local worker could predict the remote worker's movement by seeing the upper body of their remote worker and could thus prepare for the following action [11]. Unlike these studies of predefined collaborative work in a fixed place, our study demonstrates the usefulness of showing the human video when passing a robot, as this helps predict the robot's moving direction.

So far, we have mentioned that by projecting human images onto a robot, a person can predict the robot's direction of travel. We will further discuss other effects of human images on robots.

Considering the worker's FOV, a robot with an image of a person can not only predict the actions of the remote worker but also prevent the worker from being unable to see its surroundings by looking down. This study considered a situation in which workers and surrogate robots worked together in the same workspace. Walking while looking down can lead to a collision with a robot, another person, or an object, not only in a narrow spaces but also in other spaces in an office. Presenting a human video can prevent collision with others during remote cooperative work.

It is important to see the other person passing by when passing each other. However, the robot with no person's image lost various sources of human information, such as body movements and gaze, which may cause a certain sense of anxiety that the human may collide with the robot. Conversely, giving a human image to a robot may help remove this insecurity and give a sense of safety, such as "I can avoid collision with the robot."

It should be noted that this study has limitations.

In this experiment, for safety reasons, robots with a low center of gravity and concentrated major parts (including the drive unit on the bottom surface) were used, which is the same model as the cleaning robots that are currently available in relatively large numbers. Since this mobile robot has a geometrically symmetrical shape, it is difficult to determine the direction in which it is moving, especially when looking at the figure of the robot, as in the robot condition. If this were a humanoid robot in which the direction of movement was more perceptible than a symmetrical-shaped robot, the experimental results of this study might be different. In any case, the findings of this study may be helpful in building a telepresence robot system using current major mobile robots, like the one used in this study.

In the current experiment, the workers' walking speed was approximately 30 cm/s, which is slower than the speed at which humans generally walk. Various factors should be considered:

- The workspace was small.
- The worker's foot could have caught on the cord connecting the robot and the PC.
- Two practice rounds were insufficient for confident walking with the HMD.

We hope to study and analyze the results of higher walking speeds in the future.

Finally, we discuss applying our findings to the real world. This study assumes an in-company environment where people and robots come and go freely. Therefore, besides a corridor, people and robots move in various places and situations, and it is hard to establish rules such as "any persons must keep to the left, and any robots must keep to the right." In previous studies in which robots moved in office environments or other environments with humans (e.g., [46] and [47]), the experiments were conducted in environments that allowed movement within the same space without restrictions on movement for both the persons and the robot. As in these studies, in studying ways for humans and robots to coexist, it is also necessary to consider methods that do not depend on rules. Thus, our findings on the effectiveness of showing the person's whole body may be helpful in situations where humans and robots coexist.

However, preparing the equipment is more burdensome than in a conventional environment. In our environment, the robots need to acquire the position of a remote person and show the remote person to each other. We used sensors to realize the former and HMDs to realize the latter. In the future, it will be possible to reduce the burden of system construction and the user by using a camera attached to the HMD to acquire location information through image recognition or by using AR glasses, which are lighter and less burdensome for the user. Additionally, to use our findings, a space for the robot operator to walk around is necessary. This research scenario is feasible if, for example, a satellite office or coworking space is used as a remote office. In addition, these devices that can freely walk in place in 360 degrees (e.g., the systems of [48], [49], or the Virtuix™ Omni and Cyberith Virtualizer used in [50]) can be used to realize this environment in a smaller physical space.

7 CONCLUSION

The purpose of this study is to support human-robot coexistence. Assuming an office where humans and telepresence surrogate robots work in the same place, we focused on a situation in which a human and a robot pass by each other. This study uses a VR system that presents a remote user's whole-body image to the robot [14], which was initially proposed to support real-world cooperative work between a human and a robot. We verified how the system could support the passing-by of a human and a robot. We conducted an experiment and analyzed subjective and objective data from the passing-by task. The results show that workers using the system looked at the human upper body to predict the robot's movement. This indicates that in an environment where humans and robots coexist, projecting a full-body image of a person onto a robot is helpful for smoothly moving in the same physical space.

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