Vehicle Telepresence Maneuvering with Live Video and 3D Point Cloud without Perceptible Communication Delays*

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Abstract

Telepresence is a technology that allows users to experience a real-time experience as if they were in a remote location. However, there is often a delay in communication before the user sees the image of the control feedback. Such communication delays significantly reduce the operability at the remote site so is the user's sense of agency in control of, for example, a remote vehicle. To reduce perceptible communication delays, we propose a remote vehicle maneuvering telepresence system that displays a predicted view by using odometry and 3D point clouds while showing live video when the odometry catches up with the vehicle's current pose. As a result of evaluation experiments, we confirmed that the proposed system significantly improves subjective operability and workload.

Keywords

Telepresence, Latency, Odometry

1. Introduction

Teleoperation is the electronic remote control of a machine or vehicle, and remotely operated vehicles (ROVs) have a wide range of applications on the ground, underwater, in the air, and in space [1]. Telepresence refers to "the feeling of being physically present at a remote or simulated location." Teleoperation with telepresence is expected to improve efficiency and reduce operator workload.

Remote control presents multiple challenges, one of which is delay in operation. In this study, we define it as the delay between the operator's input action (control command) and the corresponding video display [2]. Teleoperation in a delayed environment is difficult and very stressful for the operator. Also, it is observed as a high cognitive workload [3] and poor performance [2]. For example, an increased task completion time and reduced accuracy [4]. Overcoming the detrimental effects of delay in teleoperation can be accomplished by increasing the level of automation (i.e., reducing human control); providing information that increases the operator's situational awareness; or using predictive techniques.

There are several approaches to predictive technology to reduce the impact of delay. These approaches are categorized as dynamic system models and free models. Free model approaches include information superposition models [5], 3D graphic models [6], and image processing [7]. Information superposition [5] and 3D graphic models [6] can significantly reduce work time. However, they tend to require sophisticated algorithms, expensive equipment, and large amounts of information about the environment and the vehicle. Image processing-based approaches [7] can improve operator performance because it modifies delayed video to mimic the motion and the environment in real-time. When extensive information about the vehicle and its environment is not available, or when there is no opportunity to use expensive equipment, image processing can improve operator performance efficiently and inexpensively.

Based on existing image processing based techniques, we propose a method to adaptively switch between predictive display and normal RGB images (delayed live video) by applying position and orientation coordinate transformation to point cloud images generated from depth information acquired by a stereo camera mounted on a vehicle, depending on the vehicle status. This predictive display is based on stereo cameras and odometry, which can be applied to various vehicle configurations. This study focuses on operator performance and subjectively experienced workload while using the predictive display. Therefore, we investigate whether a simple predictive display can improve operator performance and reduce subjective workload during remote control. An experiment was set up to investigate changes in operator performance

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and workload when piloting a vehicle under the following three different video display conditions. The conditions were: 1) RGB video (delayed live video), 2) point cloud video (a naïve predictive display), and 3) automatic switching between RGB and point cloud video. Participants were asked to perform two simple navigation tasks: a driving task and an observation task using a vehicle captured by a first-person camera. Data collected included task performance, perceived workload, and demographics. A Likert scale questionnaire was administered to $N = 15$ participants to test two hypotheses related to task performance and subjective workload using ANOVA [8]. The results suggest that the proposed system actually improves subjective operability and workload.

2. Related research

The challenges of telepresence, delays, and their detrimental effects are described from two perspectives: operator performance and subjective workload. Means to compensate for delays, especially forecasting techniques, are described.

2.1. Issues in Telepresence

Draper et al. [1] defined telepresence as the perception of presence in a physically remote or simulated location. According to this definition, teleoperation is a subclass of telepresence [9]. It is hypothesized that telepresence is beneficial to mission execution and, furthermore, can lead to increased efficiency and reduced operator workload. Chen et al. [2] reviewed 150 articles that investigated factors related to telepresence and how they affect operator performance and related issues. They found eight main factors: field of view (FOV), orientation, camera viewpoint, depth perception, video quality, frame rate, time delay, and motion.

2.2. Type of Delay

The literature [2] focused on delays in maneuvering commands, or operator input actions; and time delays, or the delay between the input action and the display of the corresponding image. There is an important distinction between these two delays, with different effects on performance [10, 11, 12]. The maneuvering command delays are outside the scope of this study; we consider only time delays. We focus on the perceived delay, i.e., the time between the operator's input of a maneuver command and the visual perception of the vehicle's response in the video. The delay creates a gap between the command given and the visual feedback showing the vehicle's response. This causes inconsistencies in the operator's perception. To correct this during maneuvering, the operator needs to remember the command given until he sees the vehicle perform the desired action in the video [3]. Furthermore, it must be psychologically connected to the previously entered command (the previous state of the vehicle), and then a new command must be entered based on this combination of information when new information appears in the video [13]. Thus, delays can degrade the operator's performance [2] and increase the subjectively perceived workload [13].

2.3. Approaches to Mitigate Delays

There are multiple approaches to mitigating the detrimental effects of delays. The first option is to increase the level of automation (LOA) to reduce operator workload and improve safety [14, 15, 16, 17]. The second option is to present the operator with previously given maneuvering commands to increase situational awareness, resulting in higher performance and reduced subjective workload [2, 18, 19]. The third option is predictive technology, which is a display, control algorithm, or graphical model that attempts to predict the state of the vehicle based on the current state of the vehicle and the commands entered by the operator. Chen et al. [2] conclude that the third option is the most promising solution when it is not possible to eliminate delay from the system and emphasize that predictive displays have been shown to reduce task completion time by up to 50%.

3. Proposed System

3.1. Prerequisite

We assume a situation in which a remote vehicle-type telepresence is remotely piloted. The user, hereinafter referred to as the "operator", is supposed to operate the vehicle and view the camera mounted on the vehicle by keyboard input while watching the PC screen.

In general, there is a delay between the time when a control command is inputted and when it is reflected in the image that the operator sees. This is due to the fact that data is transferred between the time when the input control command arrives at the remote vehicle and the time when the control command is executed and returned to the operator as a video image.

Therefore, the proposed system sends the operator's input to the remote location and at the same time reflects it in the local environment to present a video image that immediately reflects the maneuver. To achieve this, a stereo camera and an odometry calculation module are provided. The stereo camera can generate a 3D point cloud of the remote location by acquiring depth information in addition to RGB information. The odometry computation module is provided as standard when the remote control is

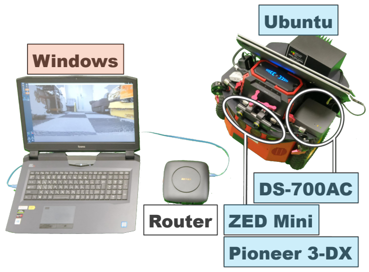

Figure 1: Prototype hardware configuration.

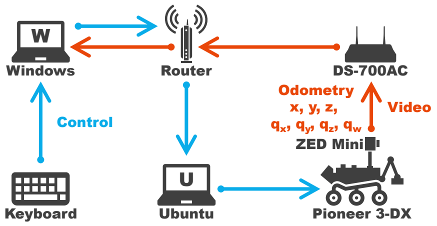

Figure 2: Communication relations of the prototype system.

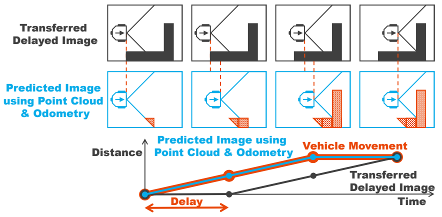

Figure 3: Movement of a virtual camera within 3D point cloud and movement of a vehicle in the real world.

realized by ROS. For example, a single command to move forward causes the vehicle to move 10 cm forward, and so on. The odometry computation module estimates the current position and attitude of the vehicle by integrating the angle of rotation of the wheels. By performing this estimation in the local environment as well, it can estimate how the remote vehicle should behave according to the input maneuvering commands, and render a 3D point cloud from the estimated position and orientation to present the operator with a realistic reproduced image that immediately responds to the maneuvering commands without waiting for the actual image to arrive. The realistic reproduced image that immediately responds to the control command is presented to the operator without waiting for the actual image to arrive. If the local environment and the remote vehicle's position and orientation are judged to match based on the amount of delay and odometry information, the delayed RGB image (live video) is presented as is, instead of the 3D point cloud. This prevents deterioration of the video quality at the remote location due to inaccurate or missing depth information when the vehicle is stopped.

3.2. Hardware

The hardware used for the prototype is shown in Figure 1 and the communication of the system is shown in Figure 2. A ZED Mini was used for the stereo camera and a Pioneer 3-DX was used for the vehicle. To transfer the images from the stereo camera to the operator's PC, we used a USB device server, a product that allows network-connected USB devices to be used as if they were virtually connected to the PC with a USB cable.

In this environment, the delay from sending a control command to receiving the RGB image from the stereo camera on the PC was 565 ms. This delay was calculated using an external camera recording at 240 fps. The number of frames from the moment when a key is pressed to the moment that the movement is reflected in the image was counted. Based on this the delay duration in seconds was calculated. This test was conducted 20 times, and the average is the aforementioned 565 ms. This delay corresponds to the communication performance of the wireless local area network (LAN). Additionally, we intentionally buffered the RGB images in the PC before presenting them to simulate a telepresence environment with a large delay. This additional delay was set to 2 s (Figure 3). Instead of preparing a separate odometry calculation module for the vehicle, the output results from the odometry calculation module installed in the vehicle are shown directly to the operator's PC without buffering. This simplifies implementation and avoids the possibility of discrepancies between multiple odometry calculation modules, while allowing us to verify the usefulness of the proposed system.

3.3. Software

To render the 3D point cloud using the RGB and depth information acquired by the ZED Mini, we used `depth_sensing.py`, available on GitHub from Stereolabs, the distributor of the ZED Mini. The point cloud rendering part of this program was modified to render based on the vehicle odometry information. The movement of the virtual camera in the 3D point cloud and the movement of the vehicle in the real world as a result of the control is shown in Figure 3.

We implemented the system so that the control commands entered by the operator are sent to the vehicle via a socket communication. The program[1] available on

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[1] `https://github.com/kumahika/delivery_navigation`

GitHub that can control the Pioneer 3-DX was modified to control the vehicle via keyboard input.

4. Evaluation Experiment

4.1. Overview

To investigate the impact of the proposed method on the performance and workload when maneuvering a vehicle, we conducted an evaluation experiment comparing three feedback conditions. Participants were asked to perform a driving task in which they drove a vehicle on a route with repeated curves in all the different conditions, and an observation task in which they answered questions based on images from three monitors facing in various directions during the driving task. These tasks were designed because they involve multiple types of tasks, especially lateral movement tasks. The benefits of the prediction technique are highly task-dependent [2]. Since the maximum speed of the vehicle produces a ceiling effect, it is likely that the prediction display is more useful for tasks that involve lateral movement than for tasks that primarily involve long forward movement.

The following hypotheses are tested to investigate the effectiveness of the proposed method.

H1 An improvement in worker performance with a hybrid method when compared to single RGB and point cloud methods.

H2 An improvement in the subjective maneuverability of the worker with a hybrid method method when compared to single RGB and point cloud methods.

4.2. Experimental Conditions

The three conditions are RGB (delayed live video), PC (Point Cloud), and HB (Hybrid, i.e., the proposed method). As previously described, the intentionally added delay was 2 seconds for all conditions, meaning that the total effective delay was about 2.5 seconds.

RGB This is a naïve remote control method that presents RGB images (live video) with large delay as they are.

PC The 3D point cloud is drawn from the vehicle's estimated current position and orientation based on odometry information, and a reproduced image is presented that immediately reflects the maneuvering of the vehicle.

HB The proposed method combines RGB and PC. Normally, a PC is used, and is switched to RGB adaptively when the real vehicle catches up with the position and orientation of the virtual camera in the 3D point cloud.

Figure 4 shows what the operator sees in the video while the vehicle is moving forward, stopping, and turning in each of the three conditions. In RGB, the images are presented as captured by the camera in Figure 4(a) forward, Figure 4(d) stop, and Figure 4(g) turning. On the PC, the images are presented as a 3D point cloud in all cases shown in Figure 4(b) forward, Figure 4(e) stop, and Figure 4(h) turning. By immediately reflecting the maneuvering commands input to the virtual camera in the 3D point cloud, the reproduced image seen when the maneuver is reflected is presented without waiting time. However, the reproduced image using the 3D point cloud image has many missing parts, and therefore, the image quality is inferior to the RGB condition. In the proposed HB method, the camera presents the image as it captures it only when the vehicle is stopped (Figure 4(f)), and presents the image as a 3D point cloud when the vehicle is moving (e.g., forward (Figure 4(c)) or turning (Figure 4(i))). As soon as a maneuvering command is inputted, the system switches to presenting the image in the 3D point cloud, and when the vehicle catches up with the virtual camera, the system switches to presenting the image as it was captured by the camera.

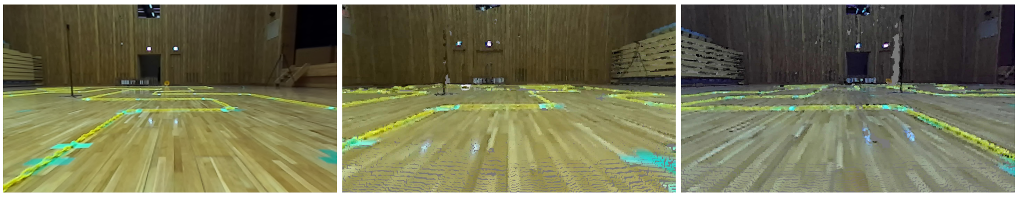
To avoid order effects and learning effects, the order in which the conditions were implemented was randomized using the 3 × 3 Latin square method. Participants were not informed of the characteristics and functions of each condition, and their ability to use them was left to their intuitive comprehension.

4.3. Participants

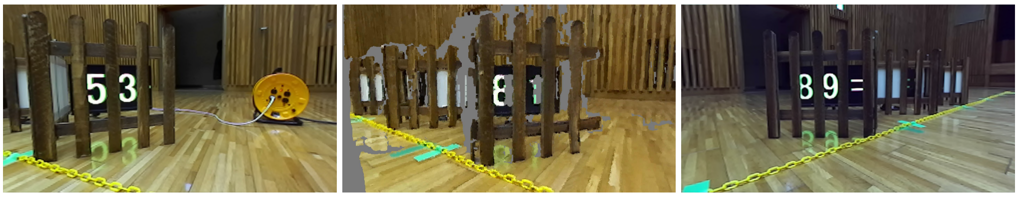
$N = 15$ volunteers participated (age range: 22-28 years, average age: 23.5 ± 1.5 years, 3 females). All experiments in this research were approved by the ethical review board of the Nara Institute of Science and Technology with review code 2022-I-41.

4.4. Task

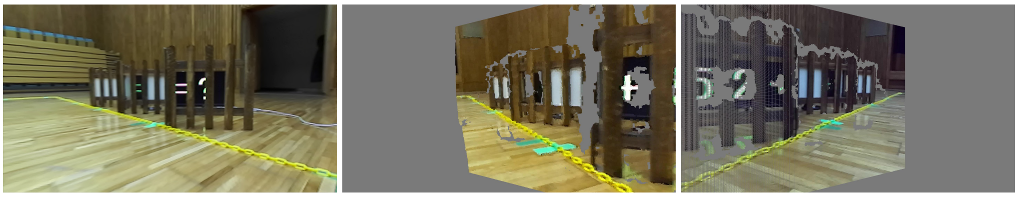
In general, experiments on forecasting technology measure performance using two metrics: course completion time and task score. The former measures the time required to complete a course for the task of moving a vehicle along a predefined path. In the latter case, the task is to move toward a given target and complete the indicated task. In this experiment, the participants were asked to look over a fence and answer formulas displayed on three monitors facing in different directions. The formulas included addition with a decimal point (e.g., $12 + 3.4 = ?$), and the task was designed in such a way that the participants would make a mistake if they overlooked the decimal point.



(a) RGB: Moving forward (b) PC: Moving forward (c) HB: Moving forward

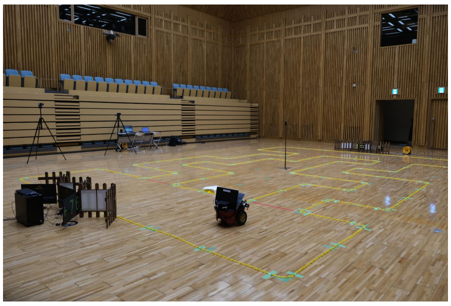


(d) RGB: Standstill (e) PC: Standstill (f) HB: Standstill

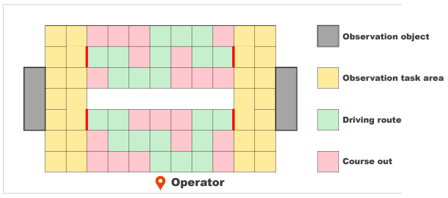


(g) RGB: While turning (h) PC: While turning (i) HB: While turning

Figure 4: Relationship between video and vehicle condition for each condition.



(a) A view from a third-person perspective



(b) Description of each location

Figure 5: Test course.

4.5. Experimental environment

A 17.3-inch laptop computer with an Intel Core i9-9900K CPU 3.60 GHz and Windows 10 was used as the operator's remote control computer. The laptop screen functioned as a monitor, and the WASD and QEZXC keys on the keyboard were used to control the vehicle. The M key was used to record the time stamps that the participants themselves pressed at the beginning and end of each of the two tasks. The keyboard and mouse were used to answer the questionnaire.

A photograph of the test course is shown in Figure 5(a) and its description in Figure 5(b). The green area in Figure 5(b) was the driving task route, and the red area was judged to be out of course. No time limit was set for the driving task, and participants were instructed to drive as safely as possible. If the participants went off course, the number of times they went off course was recorded while the driving task and the experiment continued. The course line of the test course consisted of plastic chains so that the experimenter would be able to recognize by sound when the vehicle went off the course or rode up on the course. The participants, who were the operators, were not aware of the sound of the plastic chain because they were wearing noise-canceling headphones playing white noise during the maneuver.

We used three monitors facing different directions at the two observation points (Figure 6) placed in the gray area shown in Figure 5(b). Each of the three monitors displayed a different formula which flowed from right to left. A fence was placed in front of the monitors so that the monitors'

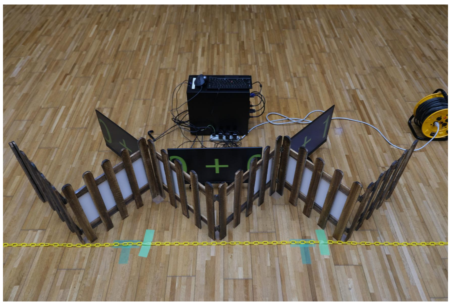


Figure 6: Three monitors facing different directions.

screens are visible only from the front. The operator moved the vehicle within the observation task area, the yellow area in Figure 5(b), and maneuveres it to a position where the monitor screen was visible. The purpose of this arrangement was to prevent the operator from completing the observation task without maneuvering the vehicle, and to encourage the operator to maneuver the vehicle to the position in front of each of the three monitors. The observation task was terminated by having the operator verbally answer all of the formulas displayed on each of the three monitors. The number of incorrect answers and their causes were recorded.

4.6. Experimental procedure

Participants were first briefed on the experimental flow using slide materials after reviewing the experimental environment to understand the situation and the issues involved. Participants were seated in a chair at a desk with a laptop computer, with their backs to the area where the vehicle was moving. During the experiment, participants did not have direct visual contact with the moving vehicle and wore headphones playing white noise to avoid the auditory perception of the vehicle. After agreeing to participate in the experiment, participants completed a demographic questionnaire. The experiment was described in terms of the experimental procedure, the test course, the types of tasks, the content of each task, and the maneuvering method. At the beginning of each condition, there was a 30-second practice period to familiarize themselves with the conditions. Thereafter, the participants performed the driving task and the observation task consecutively, with the end of the observation task marking the end of one condition. In the driving task, the experiment was continued even if the vehicle went off the course, and the number of times this occurred was recorded by the experimenter. In the observation task, participants were asked to answer a total of three questions on three monitors, and the number of incorrect answers was also recorded by the experimenter. Participants were not informed of the predictive display or how it worked. Therefore, the use of the prediction display was left to the intuitive understanding of the individual participant.

4.7. Measurements

Participants' subjective delay experience in each condition was investigated, and a perceived delay time question was asked in the questionnaire to compare each condition. By asking about perceived delay, we hoped to provide an indication of the effectiveness of the predictive display in reducing the perceived delay of the system.

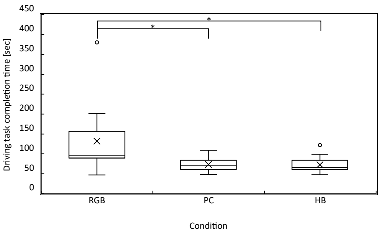
As evaluation indices, four items were used: time, the number of times each maneuver key was entered, the number of times each maneuver key was released, and the vehicle's xyz coordinates, quaternion number, and movement speed were recorded from the time the participant started the experiment until the end. These indices were continuously collected during the execution of the task in each condition. After each condition, the participants were asked to respond to a questionnaire created with Google Forms. The questionnaire consisted of 15 questions: 10 Likert-type questions in which participants were asked to select one of seven levels from 1 (strongly disagree) to 7 (strongly agree), and five open questions in which they were asked to write freely about the content of the questions.

See Figure 8 for the text of each question.

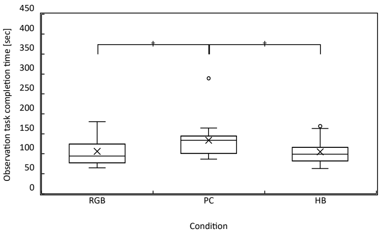
4.8. Result

The task completion time for each of the driving and observation tasks in each condition is presented in a box-and-whisker diagram. Tests were conducted to confirm if there were any significant differences, as shown in Figure 7. A one-way repeated measures analysis of variance (ANOVA) was conducted to determine if the differences in the three conditions were statistically significant. The Holm method was used to correct for multiple comparisons. For the driving task, there was a significant difference between RGB and HB ($p<0.05$), and the proposed condition reduced the task completion time. For the observation task, a trend toward significance was found between PC and HB ($p<0.10$). Also, there was no significant difference between RGB and HB. Therefore, we confirmed that the proposed condition was as efficient as RGB for the observation task. From these results, **H1** "Significant improvement in worker performance" was supported.

The Likert scale ratings in each condition are presented in a box-and-whisker diagram for each question, and tests were conducted to confirm significant differences, as shown in Figure 8. Simply treating the ratings as an interval scale [8], a one-way repeated measures analysis of variance (ANOVA) was conducted to determine if the differences per question in the three conditions were



(a) Driving task.



(b) Observation task.

Figure 7: Task completion time. (†: p<0.10, *: p<0.05)

statistically significant. The Holm method was used to correct for multiple comparisons. Of the 10 Likert-scale questions, PC and HB were found to be significantly different from RGB in nine of the questions, respectively, supporting the alternative hypothesis. The remaining question was about "how easy it was to see the image". Significant differences were found between RGB and PC, and HB and PC, respectively. These results supported the alternative hypothesis.

Significant differences between RGB and PC, and between RGB and HB were confirmed for impression, sense of security, comfort, discomfort, operability, and delay, at $p<0.001$. A significant difference of $p<0.01$ was found between RGB and PC, and between RGB and HB in the sense of being able to control by one's own will.

For the question of visibility, a significant difference of $p<0.001$ was confirmed between RGB and PC, and between PC and HB.

A significant difference of $p<0.001$ was found between RGB and PC, and between PC and HB in the question of whether the pilot was able to maneuver as intended. A significant difference of $p<0.01$ was found between RGB and HB. A significant difference of $p<0.01$ was found between the RGB and PCs in the sense of local control. A significant difference of $p<0.001$ was found between RGB and HB.

From these results, we confirmed that **H2** "Significant improvement in subjective maneuverability of the worker" was supported.

4.9. Comments per condition

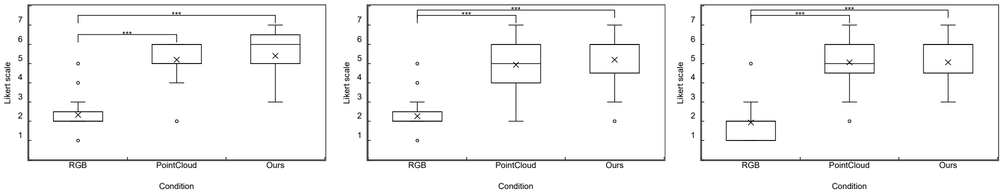
Below we list representative participants' comments obtained for each condition per question. Overall, the comments were more positive for the HB condition than for the others.

4.9.1. RGB

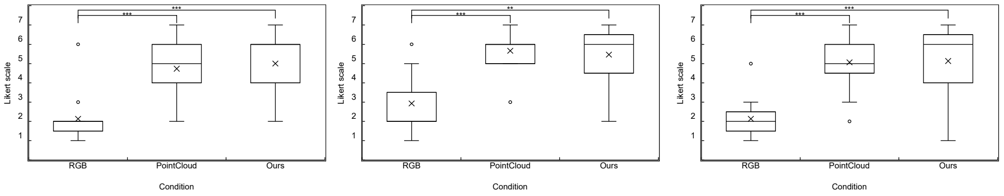
- "There was a considerable delay, and it took some time for the intended operation to be reflected, during which time I felt uneasy." (Male, 23 years old),
- "The delay was so large that I felt insecure about whether the input was correct or not." (Male, 22 years old),
- "I felt a considerable delay, which made it difficult to make fine adjustments and made me uneasy." (Male, 22 years old),
- "I felt uneasy because I did not know how much I had to press a button to move forward or backward." (Female, 24 years old)
- "If there had been no delay, I would have been able to control the vehicle as intended." (Male, 23 years old).

4.9.2. PC

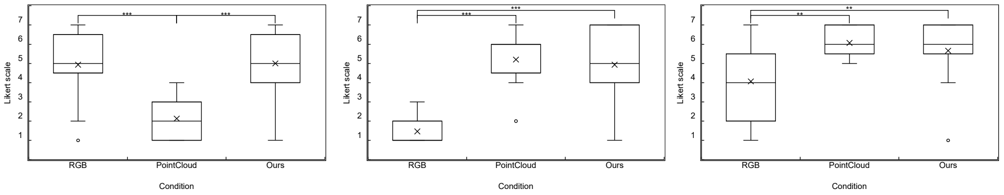
- "The robot responded quickly, so it seemed to stop when the timing was right." (Male, 25 years old),
- "The robot's position was easy to grasp without any delay." (Male, 22 years old),
- "There was no stuttering or switching of images, and I felt that the robot could be operated comfortably." (Male, 23 years old),
- "I was able to control the robot as I expected." (Male, 23 years old),
- "There was no problem in driving, but the image was unclear when performing observation tasks." (Male, 23 years old),
- "The image was rough and there was no image when turning." (Male, 24 years old), and
- "When the visibility of the image was extremely poor, I strongly felt that it was a remote control." (Male, 24 years old).



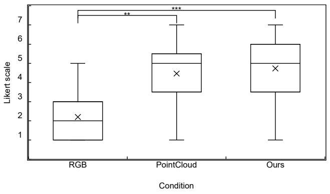
(a) Good impression of the maneuver. (b) Secure in maneuvering. (c) Comfort in maneuvering.



(d) Comfortable with the controls. (e) Maneuvering as intended. (f) Operability was good.



(g) The video was easy to view. (h) Not notice any major delays. (i) Piloting of my own volition.



(j) Feeling that piloting the vehicle locally, not remotely.

Figure 8: Likert scale questionnaire results. (*: p<0.05, **: p<0.01, ***: p<0.001)

4.9.3. HB (Proposed Method)

- "It was the easiest to maneuver." (Male, 24 years old),
- "It was easy to operate with little delay." (Female, 24 years old),
- "The front/rear maneuvering was almost no delay at all." (Male, 24 years old),
- "The observation task was quite comfortable, although the impression was not so different from other conditions when driving." (Male, 23 years old),
- "The response time was fast, so it seemed that the camera stopped when the user wanted it to stop." (Male, 25 years old),
- "There was some discomfort in the switching between low and high-quality images." (Male, 23 years old),
- "The field of view was narrow and it was difficult to operate when turning, although I did not feel much delay when moving straight ahead." (Male, 23 years old),
- "It was stressful to have to wait until the delay was resolved because the image did not catch up with the rotation." (Male, 24 years old), and
- "While turning, there was a delay while waiting for the image to be displayed." (Male, 24 years old).

5. Conclusions

Dealing with delays is one of the major challenges in telepresence. Therefore, we proposed a telepresence system that automatically switches between predictive images and live images using 3D point clouds according to the situation. It also presents images that show the user's maneuvering immediately so that the user does not perceive any delay in the images. As a result of evaluation experiments, we confirmed that the proposed system actually improves subjective operability and ease of viewing. In the future, we aim to resolve issues such as the phenomenon of the edges of the screen being blurred and many parts not being rendered when turning on PCs and HBs. This can be achieved, by switching between RGB images and 3D point cloud-reproduced images and by devising a new method for rendering point clouds.

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