Usability Study of a Novel Triple-arm Mixed-Reality Robot Teleoperation System

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***Abstract*— The usability of a novel triple-arm mixed-reality robot teleoperation system is investigated. The system is developed to provide a sense of remote presence for the operator. Different types of interfaces and camera setups have been proposed previously. Our novel approach is to have a moving stereo vision camera mounted on a robotic arm in the remote scene controlled with a virtual reality (VR) headset. By streaming live stereo video into the VR headset in a video see-through configuration the operator experiences a sense of remote presence. The teleoperation task is done using two more robotic arms. These arms are set up in a mirror teleoperation setting so that the remote (follower) arm copies the movements of the control (leader) arm. To investigate the effect of latency on the operator a within-subject usability study of the system with 20 participants has been conducted. Participants completed a pick-and-place task sorting objects into marked containers in two conditions. In one condition, the camera robot arm was controlled by a joint position controller with low latency but jittery robot motion. In the other condition, the camera robot was controlled by a joint velocity controller with higher latency but smooth motion. Participants completed the System Usability Scale questionnaire after each trial. The task completion time and participants' head movement were also recorded as objective measures. The study result did not show a significant difference in any of the objective or subjective measures, although, the position controller scored higher overall. This could be due to the number of participants or the ability of people to adapt to the latency in the system and further analysis in future work is required.**

Teleoperation, Mixed-Reality, Human-Robot Interaction, Remote presence, System Usability

I. Introduction

The teleoperation of robots has been amongst the first forms of human-robot interaction. It is important to investigate the usability of any novel teleoperation systems as the operators (the end users) will be accustomed to traditional systems. In a traditional setup, an operator based in the control room used a joystick-like controller to move the robot around. Streaming video to the screen displays from cameras, either mounted on the robot or at a different point in the remote environment, was used to gain situational awareness. Such a setup is still being used in many sensitive applications such as search and rescue missions and remote inspection tasks. Mistakes of the teleoperator in sensitive applications could potentially endanger human lives, and lead to serious damage to the robot or other sensitive equipment. This shows the importance of having the highest possible level of situational awareness for the operator. In our work, the main application of robot teleoperation is decommissioning of old nuclear facilities. According to the World Nuclear Association, there are over 115 commercial reactors, 48 experimental reactors and 250 research reactors that are no longer functional and need to be dismantled and decommissioned [1]. In the UK alone, "the 2019 forecast is that future clean-up across the UK will cost around £124 billion spread across the next 120 years or so" [2]. Using robots for this application will increase efficiency as well as the safety of human operators [3]. The main challenge, however, is that the structure of a typical nuclear facility imposes the constraint of having minimal visibility of the remote robot's environment, as there are thick walls between the operators and the robot. Hence, the operators could not have an optimum situational awareness. The standard industry solution for increasing situational awareness is to install multiple cameras on the robot and to allow switching between cameras to monitor the environment from different viewpoints. Despite being successfully used in other applications, it has been shown that changing viewpoints increases cognitive load and slows the teleoperation process [4]. As an alternative, systems with moving cameras are investigated for teleoperation. To do so, a camera was mounted on a separate robotic arm and this arm movement was controlled either autonomously [4], [5] or manually by the operator [6], provided the best viewpoint on a screen display. These interfaces have significantly improved teleoperation performance [4]. There are also several screen- or tablet-based Augmented Reality (AR) interfaces reported in literature [7]–[9] mostly developed for controlling the robot on a touchscreen or having a simulation of a robot's action overlaid on the current pose of the robot so that the operator could predict the outcome. Nonetheless, there is no reported data on the performance of the teleoperation in these systems, especially, for manipulation precision as it is paramount in our application.

There are also interfaces developed based on Virtual Reality (VR) to provide an immersive experience for the operator [10]–[14]. VR interfaces are implemented by using Head-Mounted Displays (HMDs) could provide an opportunity for steaming stereo vision video into the HMD, hence, a better depth perception. However, in most reported cases, the operator sees a Pointcloud presentation of the remote scene or does not work directly with the robot in the virtual environment and sees the environment like being in a virtual control room inside the robot similar to a cockpit of a

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plane. In addition, Zinchenko et al. [15] developed a control system for a 3DoF arm holding and guiding an endoscope for minimally invasive surgery. They reported 2 seconds of latency in controlling the robot using the HTC Vive HMD. This latency could be considered too high for many applications like safety critical and sensitive manipulation tasks.

Another recent effort to implement an immersive interface for a teleoperation was tried by Chen et al. [16]. Their interface provides a first-person view of the scene through an RGB-D camera mounted on a Baxter robot head. The operator can control the orientation of the camera, but unlike our setup the camera position is fixed. This means the operator has no maneuverability if the camera view is occluded. In addition, having the camera on the robot head increases the chance of such occlusions of the scene by the robots' arms. This is not the case in our setup as the camera is in front of the scene looking at the remote arm being controlled by the operator. Furthermore, our setup with 3 robotic arms replicates the operator side on the remote side. Out system has the camera robot arm calibrated in the same pose as the operator, which induces the feeling that the operator is sitting in front of the remote arm and is moving it by his/her hand.

In our previous work [17], we used a Ricoh Theta V 360° camera placed in front of a robot arm to stream video to a VR headset, in a mirrored robot teleoperation setup (Figure 1). This setup was designed considering our project requirement for nuclear decommissioning using robotic arms to sort nuclear waste which is mostly stored in barrels. However, because of the monocular nature of the Ricoh 360° camera (Figure 1), mounted on a fixed tripod in front of the remote scene, we found that the operator struggled to successfully perform a waste sorting task due to the lack of depth perception. In the next step, different camera setups were investigated in a virtual reality experiment [18]. Our experiment result revealed having a moving stereo vision camera mounted on a robot would provide the highest depth perception and the best performance of the operator. This becomes very important when considering the safety-critical nature of our application. The moving camera robot system, hence, was implemented and the result of a usability study of two different control modes for the camera arm is presented here. The experiment is conducted to investigate the effect of the increased latency with the smooth motion of the velocity controller against low latency but jittery movement of the position controller. The experiment setup and result is detailed in the following sections.

II. Method

To investigate the usability of a mixed-reality interface for a robotic teleoperation task, a video see-through system using an HTC Vive Head Mounted Display (HMD) and a Stereolab Zed stereo camera is used. The camera is moving around by a robotic arm copying the operator's head movements to create a sense of remote presence. This robot is controlled in two different modes. Participants performed the same task in

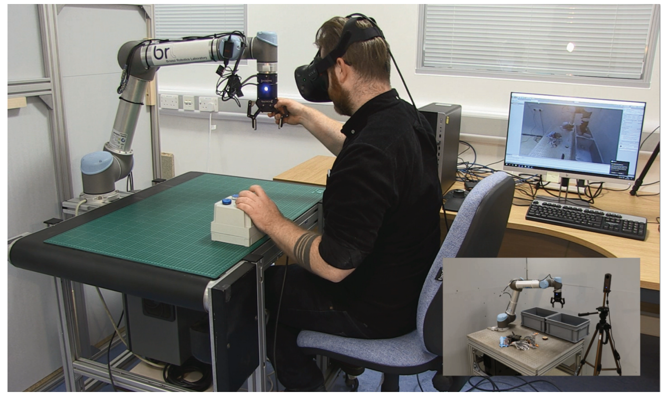

Fig. 1: Teleoperation using 360°camera video stream on HMD.

Fig. 2: The operator wearing an HTC Vive HMD and holding the teleoperation leader arm handle.

both control modes in a randomised order in a within subject user study to counterbalance any learning effect.

A. Experiment Setup

A mirror teleoperation system has been used for performing a pick-and-place task. The system consists of two Franka Emika arms, one placed as the leader (controller) robot arm on the operator side and one placed as the follower robot arm on the remote side. The follower arm movement is synchronised with the leader robot arm and it copies its movement. A handle is mounted instead of the leader robot gripper so that the operator can move the robot around for performing the task (Figure 2). There is also a keypad on the table in front of the operator. A single key was used for opening and closing of the gripper. As for the interface, the operator sees the remote scene wearing an HTC Vive Head Mounted Display (HMD) through a Stereolab Zed stereo vision camera which is mounted at the end-effector position of a third Franka Emika arm. The video is streamed into the HMD and provides a video see-through ability. The robot arm is placed in front of the follower robot arm (Figure 3). The camera positioning and setup in front of the follower robot is calibrated in a way to have the camera at the same position and viewing angle as the operator in front of the leader robot arm. The camera arm is then controlled by the

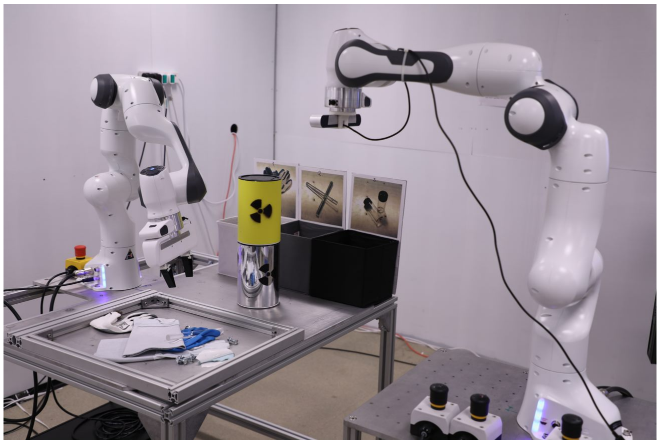

Fig. 3: The remote scene with the follower robot (left) and camera arm placed in front of the scene (right).

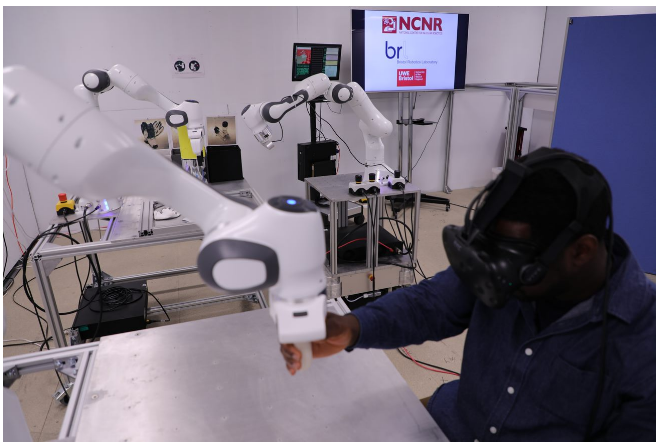

Fig. 4: The experiment setup, showing the operator controlling the leader arm and the camera arm in front of the remote scene controlled by the operator head movement.

HMD and the operator's head movement is synchronised with the camera arm movement. This creates a sense of presence at the remote scene for the operator. This is due to the fact that all the movement of the operator is copied by the camera arm and all the movement of the leader robotic arm moved by the operator's hand is copied by the follower robotic arm, as if the operator is sitting in front of the follower arm and moving it by his/her hand. The leader follower arm teleoperation setup were placed next to each other in this experiment(Figure 4), however, the leader-follower part of the system was tested for long distances (for example, between Bristol and Lincoln) as well.

B. Interface Setup

The camera robot arm was controlled using a Ubuntu machine with a real-time kernel. The operator's head movements (6 DoF), captured by the HMD through HTC tracking base stations, were used in a Unity 3D simulation with a Franka Emika arm model to determine the end-effector position and orientation of the model being synchronised with the HMD. Through solving the inverse kinematics, the simulated robot joints' values were calculated. As the Unity 3D simulation was running on a computer running Microsoft Windows 10 the joint values were sent through a TCP/IP socket server to the Ubuntu computer to control the camera robot arm. Two different joint controllers, namely position control and velocity control (both in joint space), were implemented using C++ and libfranka API. The joint position control implemented the received joint values as fast as the safety constraints of the robot allowed it. In this way, the camera robot arm was always following the operator head movement with the least latency (near real-time). The lower latency was at the expense of sharp acceleration and deceleration causing some jittery movements. To reduce jittery movements the second control mode was developed. The velocity controller was developed with a trigonometric velocity profile providing a smooth motion yet increasing the latency of the camera arm following the operator's head. The latency in this control mode varied depending on the operator head movement's speed.

C. Task, Instructions and Procedures

Participants were asked to pick several objects placed on the table in the remote scene and sort them into container boxes labelled with photos of the objects. Objects included a pair of gloves, two cylindrical rods (L= 192 mm, D = 17 mm) and two cylindrical containers (L = 130 mm, D = 42 mm). These objects have been chosen in collaboration with partners from the nuclear industry to resemble objects that could be found in a nuclear facility. There were also two cylinders mimicking nuclear container barrels placed as obstacles in between the objects and the containers. Participants were instructed not to collide with the barrels. This task was designed to be similar to a nuclear waste sort and segregation procedure. Before performing the task through the mixed-reality interface, participants had a chance to practice with the mirror teleoperation system. Participants then wore an HTC Vive HMD and after adjusting the headset and the initialisation of the camera arm they could start moving their heads to control the camera arm. They were asked to be seated throughout the experiment to prevent any accidental fall as the experimental rig was wired. Please refer to [19] for a report of a usability study of a wireless version of the system.

D. Participants

20 participants took part in the experiment, 16 of which were male. Participants were staff and student members of the Bristol Robotics Laboratory and had an average age of 30.3 ($STD = 5.68$) ranging between 23 and 45 years old. Participants were all right-handed, reported normal or corrected-to-normal eyesight (6 wearing glasses). Before taking part, participants were asked to rank their pre-existing experience in 4 categories on a scale ranging from 0 (for no experience) to 100 (for highly experienced). The experience categories were Virtual Reality (VR) ($Ave = 35.75, STD = 26.62$), 3D gaming ($Ave = 34.75, STD = 31.31$), 3D CAD Design ($Ave = 54.5, STD = 32.24$) and Robotic Teleoperation ($Ave = 31.75, STD = 35.07$). Informed consent

was obtained from all individual participants included in the study. The study was reviewed and approved by the Ethics Committee of the University of the West of England, Bristol. Please note that due to the Covid-19 pandemic participants could only be chosen from the pool of people who were in the robotics lab to avoid increasing the risk of infection.

E. Subjective and Objective Measures

To subjectively assess the system interface, the System Usability Scale (SUS) questionnaire was used [20]. The questionnaire provides a standard subjective measure to assess the system usability. Participants completed the questionnaire after completing the task using the interface in either control mode. As for objective measures, the task completion time and the total head displacement of the participants were recorded. The displacement was calculated in all movement directions, namely Left-Right, Up-Down, Forward-Backward, using the absolute value of each movement as shown in Equation (1).

$$TotalDisplacement = Sum_i(abs(Pose_i - Pose_i - 1) \quad (1)$$

III. Results

A one-way analysis of variance (ANOVA) and further Tukey tests were performed on all the recorded objective and subjective measures. No significant difference was found between the two conditions (using joint position controller: P-control, and using joint velocity controller: V-control) in any of the measures. The data recorded was also sorted based on the order of the task completion. Again, no significant difference was found, although there is an obvious improvement in the task completion time and the SUS score for the second trial. This could point to a learning effect, however, to get a significant difference the experiment needs to be repeated with more participants.

The outcome of the SUS questionnaire based on each control mode of the camera arm, and based on the order of the trials are shown in Figures 5 and 6, respectively. The mean SUS score for the P-control condition was 81.7 with $STD = 13.8$ and for V-control it was 75.13 with $STD = 17.7$ (Figure 5). The mean SUS score based on he order of trial was 76.97 with $STD = 16.7$ and 79.88 with $STD = 15.6$ for the first and the second trial (Figure 6). One-way ANOVA did not reveal any significant difference neither between control modes ($F = 1.63, p < 0.2093$) nor the order of the trials ($F = 0.31, p < 584$).

As for objective measures, the mean task completion time and the total displacement in different directions of head movement are depicted in Figures 7-10. Tests revealed no significant difference in task completion time when comparing control modes ($F1.8, p < 1893$) or the order of the trials ($F = 3,37, p < 0.0759$). Although, the task completion time has clearly reduced on average in the second trial.

One-way ANOVA also did not reveal any significant difference in head movement of any direction when comparing two control modes (left-right: $F = 1.06, p < 0.3101$, forward-backward: $F = 1.54, p < 0.224$, and up-down: $F = 1.1, p < 0.3027$) or based on the order of the trials (left-right: $F = 0.91, p < 0.3466$, forward backward: $F = 0.72, p < 0.4013$, and up-down: $F = 2.78, p < 0.1052$). However, in all conditions, the head movement in the up-down direction was significantly less than in other directions. As an example, the comparison of the total head displacement for all trials is depicted in Figure 11. Tests revealed a clear significant difference ($F = 28.72, p < 1.46e - 10$) between Up-Down head movement and Left-Right and Forward-Backward head displacement. A similar significant difference between head movement in the Up-Down direction and the Left-Right and Forward-Backward directions was observed when only analysing data per condition or order of the trials.

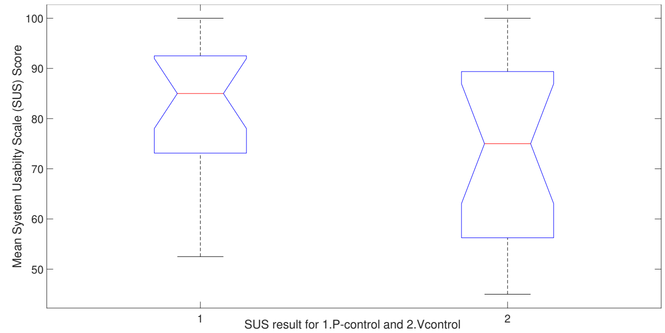

Fig. 5: Mean system usability for each camera arm control mode.

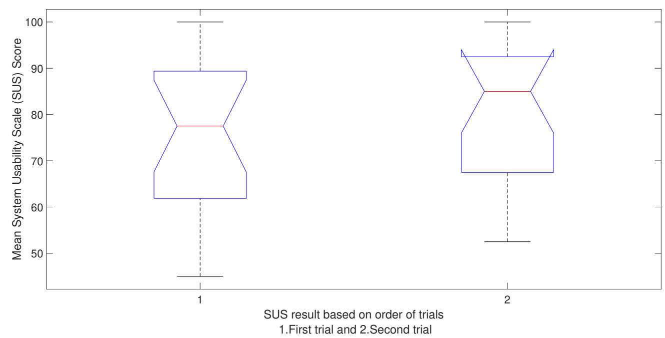

Fig. 6: Mean system usability scores based on trials order.

IV. Discussion

The mixed-reality teleoperation system usability was assessed in this experiment by employing 20 participants. Participants were all involved in robotics research, however, the result of the self-assessment questionnaire showed participants' mean self-rated familiarity with robotics teleoperation and virtual reality on the 100-point scale were $Ave = 31.75, STD = 35.07$ and $Ave = 35.75, STD = 26.62$, respectively. Further analysis showed no strong correlation between the users' past experience and the recorded objective and subjective measures. For instance, the cross-correlation value between SUS score for P-control mode and V-control modes and past VR experience were -0.18 and 0.32, and for past Robotics Teleoperation experience were -0.09 and -0.02, respectively. Similarly, no correlation between task completion time and any recorded measure was found.

The mean SUS score for the P-control mode is 81.71 with $STD = 13.8$, categorising the interface in the "Excellent"

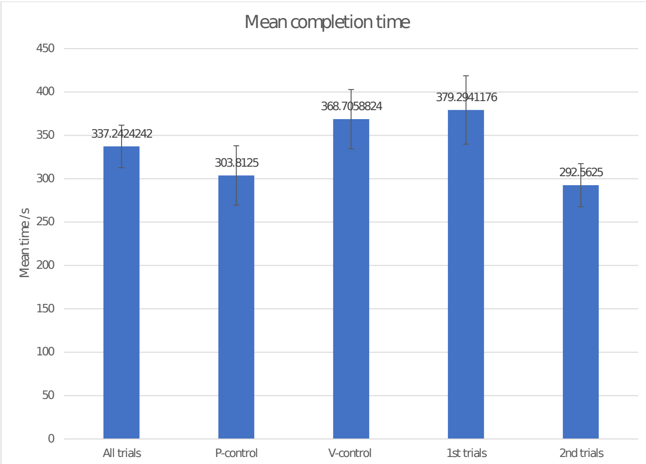

Fig. 7: Mean task completion time for all trials, each control mode and based on the order of the trial. Error bars are ±1SEM.

Fig. 8: Mean total head displacement in the left-right direction for all trials, both control modes and based on the order of the trials. Error bars are ±1SEM.

or "Grade A" tier [20]. As for the V-control mode, the mean SUS score is 75.13 with $STD = 17.7$ placing it in the "Good" or "Grade B" tier. Nonetheless, no significant difference between the two control modes was found when performing a one-way ANOVA. This could be due to the number of participants, though, in the debrief 2 participants indeed mentioned they noticed no difference between the two control modes. In addition, 3 participants mentioned they preferred the V-control mode despite the higher latency as there was a smoother camera movement and mentioned they could adapt to the latency. Yet, the majority preferred less latency in the system; although having more participants could potentially change the outcome of the SUS assessment in favour of either control mode, not having a significant difference in the data could also show participants ability to adapt well to both systems.

In terms of the objective measures, a smaller task completion time was recorded for the P-control mode with no significant difference ($F = 1.8, p < 0.19$) to the V-control. This again could be due to the small number of participants. It is noteworthy, when sorting the recorded time based on

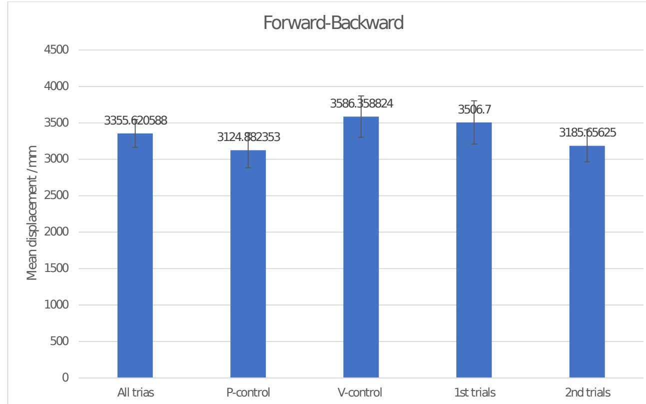

Fig. 9: Mean total head displacement in the forward-backward direction for all trials, both control modes and based on the order of the trials. Error bars are ±1SEM.

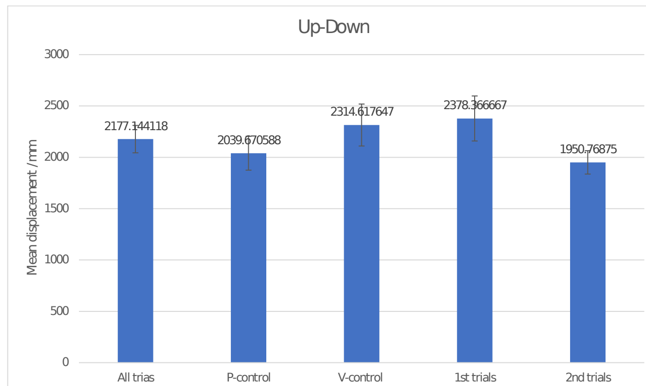

Fig. 10: Mean total head displacement in the Up-Down direction for all trials, both control modes and based on the order of the trials. Error bars are ±1SEM.

the order of the trials, the gap between task completion for the first and second trial increases, although not significantly ($F = 3.37, p < 0.0759$) yet the learning effect can be clearly observed. As the order of the trial and the starting control mode was randomised this should have counterbalanced the learning effect in the recorded data for control modes.

The recorded head movement showed a significantly less motion in the Up-Down direction, this could be due to the fact participants were seated for the duration of the trials. Nonetheless, it is likely that to acquire a good situation awareness and depth perception the Left-Right and Forward-Backward movements are the main crucial elements. This suggests that, in case a simpler system is required, the camera can be mounted on a fixed-height actuation system with movement to the left, right, forward, backward and the addition of a pan-tilt joint at the mounting point of the camera. While such a system simplifies the implementation and reduces the cost, it does not guarantee a user-friendly interface. For instance, in our experiment, participants' movement for this specific task could be divided into two main movement approaches when trying to look at the sorting containers. Some people moved on a curve to the right and backward, while others preferred to look closer at the scene and moved

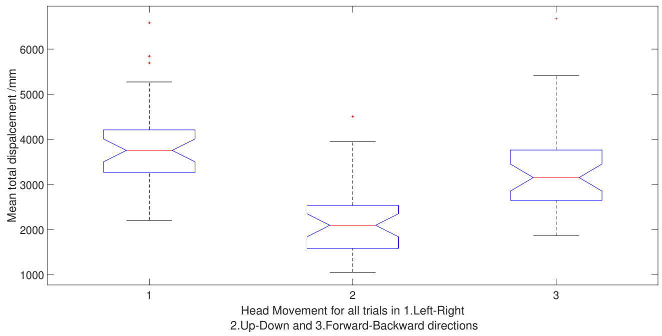

Fig. 11: Mean total head displacement in the Left-Right, Up-Down and Forward-Backward direction for all trials.

on a curve to the right and forward. Using a constrained actuation system will limit the operators to move on the sharp left, right, forward and backward motions. On the other hand, a constrained actuation system would be more predictable and reduces the collision probability making the system safer. Hence, a comprehensive analysis, by considering the operator preference, implementation cost and the system safety, is required to find the right trade-off between these factors when implementing the interface depending on the application.

V. Conclusion and Future Work

In this paper, a user study for a novel mixed-reality interface for teleoperation is presented. A high usability score for the triple-arm mixed reality teleoperation system suggests participants have found the system useful and acceptable for such a teleoperation task. This is promising for further deployment of the system to a sort and segregation task in the nuclear decommissioning process.

The result shows a significant difference between the head movement in the Up-Down direction and the other two Left-Right and Forward-Backward directions. This suggests there is a possibility to simplify the system. Nonetheless, as the participants were seated for the duration of the experiment, this needs to be investigated in a standing setup in which the operator can stand up and move around freely. As such, for any application with a restricted area in the control room, as well as the need for simple implementation and lower cost, a fixed height constrained actuation system with a translational motion to the left, right, backward and forward with a pan-tilt joint for the camera mount could potentially be the solution.

The effect of the change of latency in the camera arm movement when using two different control modes on the objective and subjective measures is analysed. No significant difference was found between the two control modes in any of the measures, although the P-control mode has scored better in all measures and the majority of the participants mentioned, in the debrief, they preferred the lower latency. Hence, in our future work we are aiming to reduce the latency by implementing predictive filters and evaluate the system in a new user study.

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