Intuitive Virtual Reality based Control of a Real-world Mobile Manipulator

Dinh Tung Le, Sheila Sutjipto, Yujun Lai, and Gavin Paul

Abstract— **This paper presents an integration of Virtual Reality (VR) interfaces with the control system of a real-world mobile manipulator, ultimately facilitating a natural and intuitive method for human-robot interaction. VR's ability to track movements in 3D space and translate performed motions provide an intuitive platform for users to explore and interact with the virtual environment. Coupled with intuitive controls, such as grabbing and pointing, the VR platform provides a compelling advantage that can be used to solve limitations of traditional remote robot teleoperation methods. This paper summarises the system implemented, which includes a simulation of the robot in Unity3d, as well as analyses critical results of accuracy and performance, from experiments with users of various experience levels. The method used for measuring accuracy with a simulated robot presented a utilitarian validation for contrasting the difference between 2D and VR 3D interfaces. Users' performance and experience under various levels of control latency, which is a crucial factor in remote online robot control, were also measured.**

I. INTRODUCTION

Robots are being deployed all over the world, most noticeably in factories for manufacturing, for construction [1], in the hospitality sector [2], for infrastructure maintenance [3] and in the medical sector for rehabilitation [4]. Robots can carry out activities perpetually with high repeatability and accuracy, and perform dangerous tasks in hazardous environments [5] to significantly reduce the risks of physical injury. Conversely, humans can exploit expertise and experiences in their fields to make crucial choices, providing creative and innovative solutions. Therefore, a robot system can achieve more productivity by adapting a form of human-robot interaction, most commonly robot teleoperation [6].

Traditional remote robot teleoperation methods that rely on 2D interfaces, such as control panels or GUIs, can be confusing for operators of complex systems [7]. During robot teleoperation, a constrained view of the robot's status, and limitations on translating user input into robot controls has been shown to reduce task performance [8]. Such systems often require extensive training and knowledge due to the limited visual feedback provided, and unorthodox methods of interactions employed. Furthermore, the elimination of human operators from their respective dangerous working environments, removes the instinctive localised perspective.

Virtual Reality's ability to track movements in 3D space and translate performed motions provides an intuitive platform to explore and interact with a virtual environment. Coupled with natural actions, such as grabbing and pointing, a VR platform provides an interface that leverages innate human actions to manipulate various aspects of the environment. These advantages make VR a suitable platform for robot teleoperation, improving visualisation and reducing both the background knowledge required, and the control limitations caused by physical distance.

Fig. 1. An operator using the VR interface to control the manipulator.

Researchers have investigated human-robot interaction methods that enable natural actions in the real world to be expressed in VR. These include the ability to inspect the robot and its environment either with a robot-centric view [9], where users can walk around the robot, or an ego-centric view, where the user assumes a first person view, as if they "were the robot" [10], [11]. VR and Augmented Reality (AR) have also been used to visualise robot intention and future positions; this has been shown to help users to predict potential collisions [12], [13], or adjust waypoints and poses for Programming-by-Demonstration tasks [14], [15], [16]. Studies on comparing 2D interfaces to 3D interfaces such as VR or AR have shown a significant increase in both user task performance and a reduction in workload for robot teleoperation tasks [17], [18], [12].

This paper presents an integration of VR interfaces with the control system of a real-world mobile manipulator, which was developed for an industry partner in the mining sector. The VR interface, developed with Unity3d, utilised the aforementioned advantages to create an enhanced teleoperation experience. The control and data collection framework of the robot was also designed to work with VR interfaces. A simulated robot has been created in Unity3d and serves as the main platform to conduct experiments to validate improvements in users' performance from 2D to VR 3D, as well as the effect of control latency.

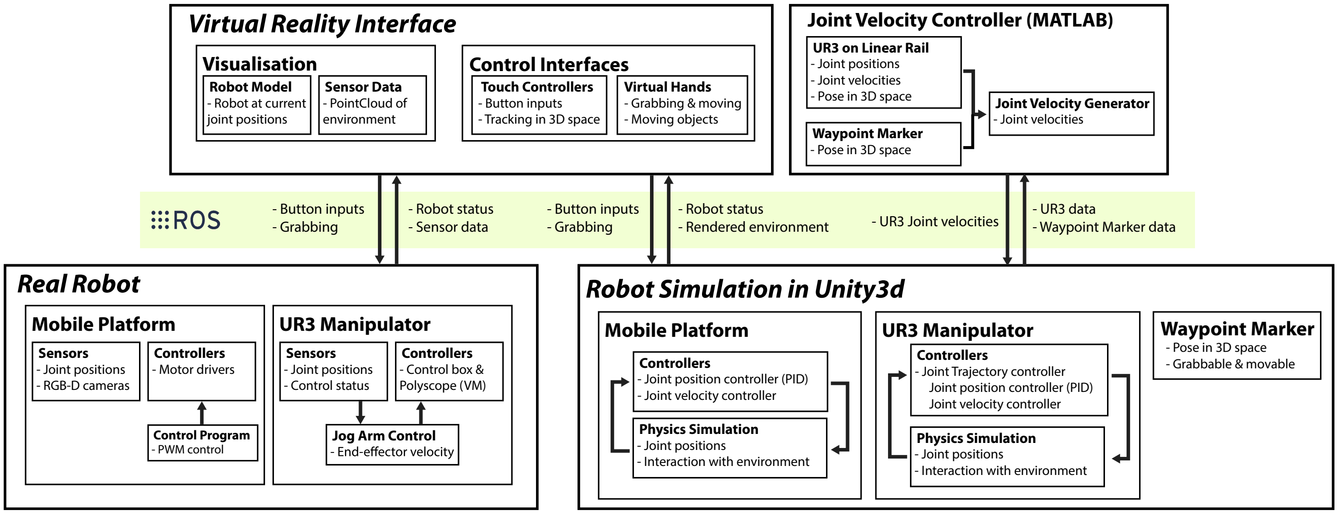


Fig. 2. System Overview

II. SYSTEM OVERVIEW

A. *Mobile Manipulator Platform*

The mobile manipulator was developed for an industry partner in the mining sector. It consists of a custom-built articulated mobile platform, and a 6 degree-of-freedom UR3 industrial robot arm (Universal Robots GmbH) attached to a linear rail. A control framework, shown in Fig. 2 that can both actuate the various motors on-board and the robot arm, was designed and implemented using the Robot Operating System (ROS) middleware interfaces. This enables the system to have various control schemes, and a VR interface.

B. *Simulated Robot in Unity3d*

The motion and behaviour of the real platform were analysed via video-recordings of the robot being controlled by an operator in several scenarios. This video analysis was combined with the CAD design of the robot to create a realistic physics-based simulated robot in Unity3d. Similarly, the control schemes of both the mobile platform and the arm were carried over, which allowed operators to seamlessly transition between controlling the real and simulated robot. This acts as a training tool for workers to become familiar with the system, and also as a domain for testing control algorithms before deploying to the real robot.

For the simulated UR3, a joint trajectory controller and joint velocity controller has been added, to mimic the controllers available on a real UR3 when interfaced through ROS. The Unity3d physics engine enables the robot to interact with elements within the simulated environment.

C. *VR Interface via Oculus Rift S*

The Oculus Rift S headset and Oculus Touch Controllers were utilised to manipulate the VR scene to view and control the robot. The headset provided pose tracking in 3D Space, updating the view of the scene accordingly. This system provides a robot-centric view of the robot, where users are able to walk around and view the robot from any angle.

The pose of the controllers are also tracked relative to the headset, and animated 3D models of the users' virtual hands in VR were used as the main interface to interact with the robot. These virtual hands prompt users with the instinctive action of grabbing and moving objects in the scene.

D. *Joint Velocity Controller*

To enable higher-level control of the UR3 arm, a Joint Velocity Controller, which uses Resolved Motion Rate Control (RMRC) [19], was programmed in MATLAB. Using Peter Corke's Robotics Toolbox [20], a robot model mounted on a linear rail was constructed in MATLAB. The controller continually subscribes and updates the robot's status, such as joint states and pose of the base, and the user's desired end-effector pose. The controller then calculates the necessary joint velocities, and addresses kinematic singularities using the Damped Least-Squares approach [21]. Additionally, the joint velocities were limited to the UR3's specified limits.

E. *System Integration and Communication*

Robot Operating System (ROS) serves as the communication backbone (i.e. the middleware) between internal components of the real and simulated robot, and external interfaces like Unity VR. ROS#[1] is an open-source library in C# for communicating with ROS from .NET applications, e.g. Unity3d. Through ROS#, Unity connects to a ROS Network with a RosBridge WebSocket NET connection using TCP/IP protocols, enabling it to work over the Internet.

In system consists of a Raspberry Pi 4 hosting ROS that connects to a Windows PC running the Unity3d VR application via an Ethernet cable. The Unity3d application publishes robot data such as joint states and base pose, and subscribes to control commands such as desired joint velocities/trajectory, and start/stop commands. All task- and experiment-related data, including the user inputs are sent via the ROS Network.

[1] The ROS# library is available here: https://github.com/siemens/ros-sharp

III. EXPERIMENT

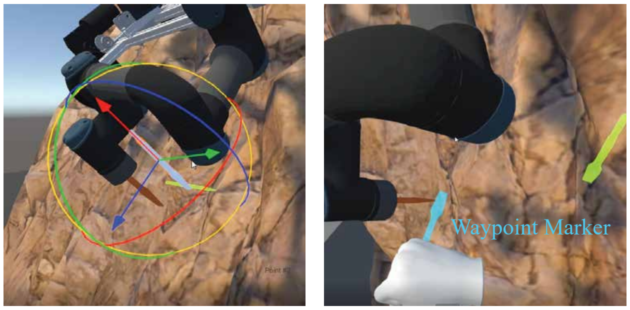
The experiment was designed to investigate the intuitiveness of a 3D VR interface in comparison to a 2D interface manipulated by a mouse and keyboard. Additionally, the effect of control latency on the task performance was examined. A user study was conducted, where participants were asked to perform a robot-control task that resembled a practical and relevant use of the mobile manipulator.

Users were asked to manipulate a detached 3D model of the end-effector tool, called the "Waypoint Marker" (Fig. 3), to guide the robot towards a desired end-effector tool pose. The robot used RMRC to follow the Waypoint Marker continuously as the user attempted the task. Users were also asked to indicate when they had completed the task, with the goal specified as, "as close as possible, and as quickly as possible". The relevant quantitative measures recorded from the experiments were the poses of the robot end-effector tool relative to the desired poses, task completion times, and subjective cognitive workload.

A. Participants

A total of 10 volunteers (8 male, 2 female), with ages ranging from 22 and 26 (*M* = 23.1, *SD* = 1.59), participated in the experiment. Participants provided informed consent and completed a questionnaire prior to the experiment. The questionnaire asked participants to self-assess their experience with VR and working with robots, on a linear scale of 1-10 from *No experience* to *A lot of experience*. On average, participants reported little experience with VR (*M* = 2.7, *SD* = 2.06). Only 2 participants reported a 5 or higher on a scale of 1 to 10 of prior VR experience, with 4 participants selecting 1. Participants reported an intermediate level of experience in working with robots (*M* = 5.2, *SD* = 2.62). However, 2 participants reported a 1 on a scale of 1 to 10 for experience with robots, and 1 participant reported a 10.

B. Interfaces



(a) (b)

Fig. 3. The two interfaces given to the users to complete the task: (a) 2D interface; (b) 3D VR interface.

1) 2D Interface: Fig. 3a shows the 2D interface where participants used a flat screen monitor to view the scene, and a keyboard and mouse interact and alter the view of the scene and manipulate the Waypoint Marker. To navigate the view of the scene, a combination of right and middle mouse click, drag, and scroll input was implemented. To translate and rotate the Waypoint Marker, users were given an option of using the arrow and number pad keys, using the Waypoint Marker's transform Gizmo, or a combination of both. Keyboard shortcuts were also available when using the Gizmo, to switch between translation or rotation axes, as well as between global or local frame of reference. This interface closely resembles 3D CAD design software like SolidWorks or Blender. The users were asked to press the *space* key to indicate task completion.

2) 3D VR Interface: Fig. 3b shows the 3D VR interface where participants used an Oculus headset to view the scene, and could change their perspective by naturally moving their heads around in 3D space. To manipulate the Waypoint Marker, users could reach out and grab it with either hand, which is achieved by pressing the button in the middle of either Touch controller. Users could see their virtual hands in VR performing the grabbing action, and the Waypoint Marker also snapped and self-aligned to the centre of the hand executing the grabbing. The *right trigger* and *X* button on the controllers were used to trigger the servoing movement and register task completion respectively.

C. Experiment Design and Procedure

With the Waypoint Marker, users controlled the robot through sets of 5 desired end-effector tool poses, which were randomly defined within the robot's reach. These 5 poses were used in every section of the experiment, in identical order for all participants.

While progressing through the poses in a set, after each pose participants were required to indicate task completion. This would prompt the current desired pose to disappear from the scene and the robot returned to its Home configuration, before the next desired pose appeared.

The experiment consisted of three sections: in Section A, the participants controlled the Waypoint Marker with mouse and keyboard inputs while in Section B and Section C, the Oculus headset and controllers were used. The participants were asked to go through the set once in Section A and B; and three times (3×5 poses) in Section C.

In Sections A and B, a minimal ($<$1ms) control latency was applied. The results between the two sections were used to compare a 2D interface and a 3D VR interface. Users were randomly selected to begin with either Section A or B first, and this was counter-balanced to ensure that an equal number of participants completed each variation.

In Section C, which proceeded after Section A and B, three levels of control latency were applied: minimum ($<$1ms), medium (500ms) and high (1000ms), one for each of the three sets of poses. The order of the sets was randomly chosen for the participants, who were not informed of the nature and order of the differences.

Before initiating Section A and B, participants were provided with an explanation of the control schemes and layouts, and subsequently given 2 minutes to familiarise themselves with each interface before starting the tasks. In Section C, participants were not allocated time to become familiarised with the system, and completed the specified fifteen tasks without pausing or taking off the headset. The experiment took approximately one hour for each participant.

D. Experimental Measurements

1) Objective Task Accuracy: The task accuracy was defined as the difference (error) in position and orientation of the centre of end-effector tool between the manipulated robot and the desired robot. The position error was determined by calculating the distance between the aforementioned transforms, using [X,Y,Z] coordinates. The orientation error was determined by calculating the average of the difference (error) in roll, pitch and yaw values, extracted from the Quaternion rotation between the two transforms. The range of the roll rotation is 0-90 degrees, and 0-180 degrees for pitch and yaw rotations, due to the end-effector tool possessing bilateral symmetry along its centre.

2) Objective Task Completion Time: Task completion time was determined as the elapsed time between when the current desired pose appeared and when the user pressed the designated button to indicate task completion.

3) Subjective Cognitive Workload NASA-TLX: After finishing the task with each interface (Section A and B), participants were asked to complete the NASA-TLX, a subjective measure of perceived cognitive task workload widely used in human-robot interaction research. The workload is measured on six subscales: mental demand, physical demand, temporal demand, effort, frustration, and performance. Five of the subscales are rated from 0 (low demand) to 100 (high demand) and the performance subscale is rated from 100 (perfect) to 0 (failure). The NASA-TLX score is calculated by taking the average of the six sub-scale scores, after reversing scores on the performance subscale.

4) Subjective User Experience: After Section C, participants were asked if they felt a significant difference between the sets of tasks, without prior knowledge of the different latency settings. Participants were also asked to rank the three sets, based on the perceived difficulty controlling the robot.

E. Hypotheses

From the experiments, users were expected to achieve higher accuracy and performance, lower task completion time, and lower cognitive workload using the VR 3D interface when compared to the 2D interface. It also expected that the accuracy, performance and task completion time would be negatively affected, to an increasing extent, as the control latency intensifies. Therefore, 2 hypotheses were considered:

- **H1:** The user will quantitatively achieve better results using the VR 3D interface than the 2D interface to complete the task. Better results will be associated with (a) higher accuracy in both position and orientation, (b) lower task completion time, (c) higher performance, and (d) lower cognitive workload NASA-TLX score.
- **H2:** The user task results will have an inverse relationship with the control latency, whereby as the latency increases, the task results will worsen. Performance deterioration will be associated with (a) reduced accuracy in both position and orientation, (b) an increase in task completion time and (c) a decrease in task performance.

IV. RESULTS

A. Performance Comparison: 2D Interface vs 3D VR Interface

1) Accuracy: Two paired sample t-tests were conducted to examine the differences in task accuracy in terms of position and orientation between the 2D interface and the 3D VR interface.

There was a statistically significant difference of accuracy in position (distance in metres), $t(49) = 2.94$, $p = 0.005$, Cohen's $d = 0.416$, between the 2D interface ($M = 0.072$, $SD = 0.143$) and the 3D VR interface ($M = 0.012$, $SD = 0.009$). We also observed a statistically significant difference of orientation accuracy (average error in degrees for roll, pitch, and yaw angles), $t(49) = 2.59$, $p = 0.012$, Cohen's $d = 0.367$, between the 2D interface ($M = 10.361$, $SD = 14.306$) and the 3D VR interface ($M = 5.340$, $SD = 3.353$).

The data supports hypothesis H1 by demonstrating that users were able to produce significantly better task results with the 3D VR interface than the 2D interface. Specifically, there was an 83% and 48% improvement in accuracy for position and orientation, respectively.

2) Task Completion Time: Each user's task completion time analysed was the average time taken to complete a single task in the set of 5 tasks in the experiment, with both the 2D interface and 3D VR interface. Afterwards, a paired sample t-tests were conducted to examine the differences in the mean task completion time of all users.

There was a statistically significant difference of the average task completion time (in seconds), $t(9) = 4.46$, $p = 0.002$, Cohen's $d = 1.411$, between the 2D interface ($M = 108.12$, $SD = 55.87$) and the 3D VR interface ($M = 39.33$, $SD = 16.11$). This 64% reduction in task completion time, from the 2D interface to 3D VR interface, supports hypothesis H1.

3) Subjective Cognitive Workload: Participants reported notably lower cognitive workload, reflected on the NASA-TLX scores, on their experience completing the task with the 3D VR interface ($M = 40.25$, $SD = 14.73$), compared to the 2D counterpart ($M = 64.67$, $SD = 15.79$). The difference is statistically significant, $t(9) = 3.31$, $p = 0.009$, Cohen's $d = 1.046$, supporting hypothesis H1.

Overall, a 37% reduction in user subjective cognitive workload was found between the 3D VR and 2D interfaces, with 5 of 6 subscales having a significant decrease in average workload. However, there was a 36% rise in the *Physical Demand* subscale, as VR users were more physically active when moving around and holding their arms out.

B. Effects of Control Latency

Three Spearman's rank correlation analysis were conducted to find the relationship between control latency and the users' task results for position and orientation accuracy, and average task completion time.

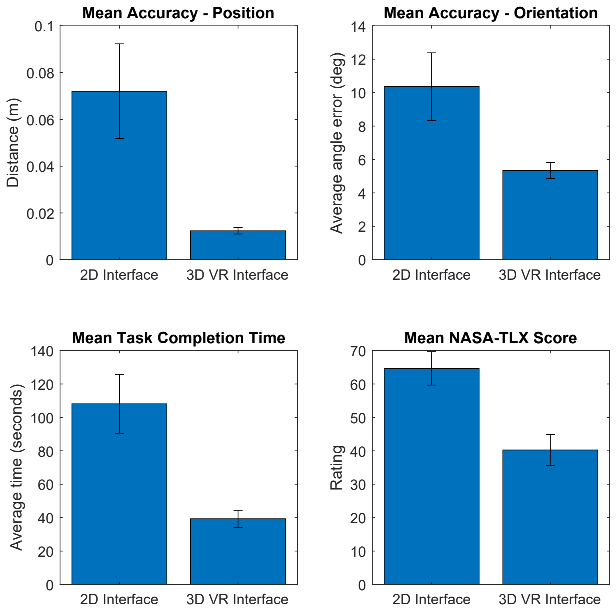


Fig. 4. Results showing the significant differences in task accuracy, completion time and cognitive workload when users performed the task with the 3D VR interface, compared to the 2D interface (smaller is better). Error bars are showing standard errors.

1) Accuracy: A 37% and 39% drop of mean position accuracy was observed, from minimum latency ($< 1ms$) to $500ms$ and from $500ms$ to $1000ms$, respectively. However, the relationship between latency and mean position accuracy only approached statistical significance with $r(1) = 0.994, p = 0.064$. Therefore, hypothesis H2 is only partially supported by the position accuracy measurements. There was no significant change in orientation accuracy between the different levels of latency, nor was there a statistically significant Spearman's correlation coefficient.

2) Task Completion Time: There was a 9.7% and 38.9% increase in users' mean task completion time, from minimum latency ($< 1ms$) to $500ms$ and from $500ms$ to $1000ms$, respectively. This data partly supports hypothesis H2. However, a statistically significant relationship was yet to be established, with $r(1) = 0.939, p = 0.222$.

Although no statistical significance were implied from Spearman's rank correlation analysis, for both accuracy and task completion time, the mean and standard deviation values change as the latency increases. Standard deviation could be considered as the *precision* of the users, and as the system became unresponsive with higher latency, users found it difficult to reliably reproduce comparable task results.

3) User Experience: All participants responded affirmatively to the question of whether they felt a difference between the 3 sets of tasks with different levels of latency. All users also ranked the set of tasks where the latency was $1000ms$ to be the most "difficult to control". Interestingly, 57% of participants ranked their experience with the set of tasks with $500ms$ to be less "difficult to control" than the minimum latency case.

V. DISCUSSION

A VR-based control system has been implemented to demonstrate the efficacy of using 3D VR interfaces for robot teleoperation. The results from the subsequent experiment demonstrated the advantages over 2D interfaces, by showing statistically significant differences, in both objective and subjective measurements. Furthermore, by using a simulated robot and environment to accurately collect relevant data, a novel and effective approach was introduced to measure quantitative information about the human-robot collaboration experience and outcomes.

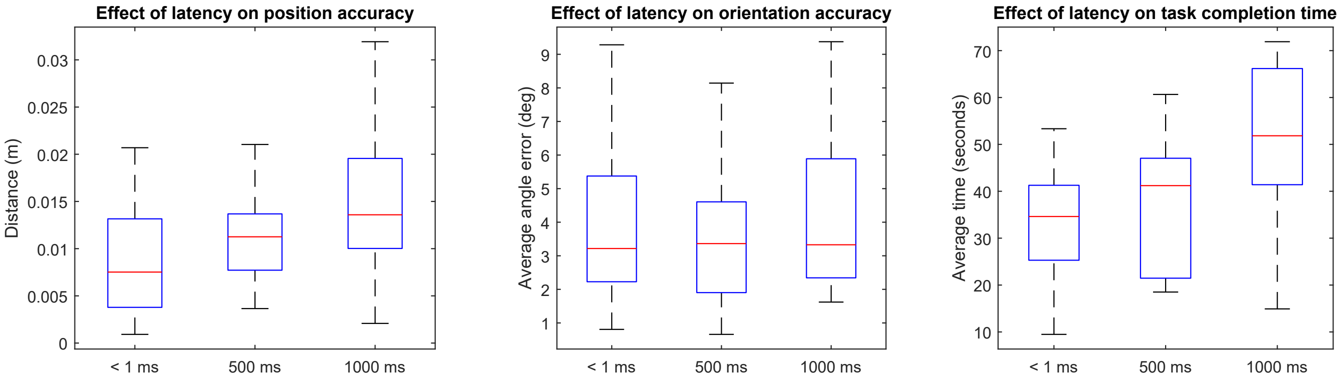
The performance of different user groups were analysed and compared: novice users (who ranked themselves in the range of 1-3 in prior experience with robots) and intermediate users (4-6 in prior experience accordingly). Intermediate users performed better than the self-proclaimed novices in all of the objective criteria. However, with the 3D VR interface, novice users were able to perform at a significantly closer level to the more experienced users, compared to when using the 2D interface. Specifically, a decrease from 177% to 52% in difference of mean orientation accuracy was recorded; and from 35% to *negative* 3% in difference of mean task completion time, where the novice users achieved the task faster. This further reinforces the use of VR as an intuitive universal interface between humans and robots.

The experiment on the effects of various levels of latency in a robot live servoing task have shown that real-world online robot teleoperation can significantly benefit from a higher-level control system. An over-the-internet controlled robot would suffer from high and varying latency on both ends, and would require a certain level of semi-autonomy to operate continuously and effectively, even with humans in the loop. Thus, such a system needs to empower users to provide high-level controls and decisions. VR has the potential to be the ideal platform, as it not only offers the immersive experience that simplifies the interfacing complexity, but also a gentle learning curve for novice users.

VI. CONCLUSION AND FUTURE WORK

This paper presented a novel and intuitive VR-based control interface for a real-world mobile manipulator. The interface utilised natural actions to let users perform a live-control task, in an environment simulating online robot teleoperation. The experiments conducted provided empirical evidence that users achieved significantly better results via a 3D VR interface than a 2D interface with mouse and keyboard. Additionally, the results showed effects of latency on user experience and performance on lower-level online robot control systems.

In the future, there are potential improvements over the existing interface that can be implemented to provide a more authentic simulation for remote online control, such as introducing visual latency. There is also the need to develop a semi-autonomous control system on the robot that incorporates sensor data, and to implement additional higher-level VR control functionality.



(a) (b) (c)

Fig. 5. Results showing the effects of control latency on task accuracy ((a) position and (b) orientation); and (c) completion time.

ACKNOWLEDGMENT

This research is conducted in collaboration with Ausdrill from the Perenti group, in particular thanks to Clint Ricetti and Raegan Rumbold for their assistance with the HALO platform design. We acknowledge Pham Dinh Thong Vu for his efforts in designing and building the mobile manipulator HALO platform. Also, thanks to UTS:RI and UTS:CAS for providing the resources and labs to carry out this research.

REFERENCES

[1] P. Shakor, J. Renneberg, S. Nejadi, and G. Paul, “Optimisation of different concrete mix designs for 3d printing by utilizing 6dof industrial robot,” in *Proceedings of the 34th International Symposium on Automation and Robotics in Construction (ISARC)*. Tribun EU, s.r.o., Brno, July 2017, pp. 268–275.

[2] S. H. Ivanov, C. Webster, and K. Berezina, “Adoption of robots and service automation by tourism and hospitality companies,” *Revista Turismo & Desenvolvimento*, vol. 27, no. 28, pp. 1501–1517, 2017.

[3] G. Paul, S. Webb, D. Liu, and G. Dissanayake, “A robotic system for steel bridge maintenance: Field testing,” in *Proceedings Australasian Conference on Robotics and Automation (ACRA)*, 2010, pp. 1 – 8.

[4] Y. Lai, S. Sutjipto, M. D. Clout, M. G. Carmichael, and G. Paul, “GAVRe2: Towards Data-Driven Upper-Limb Rehabilitation with Adaptive-Feedback Gamification,” in *2018 IEEE International Conference on Robotics and Biomimetics (ROBIO)*, 12 2018, pp. 164–169.

[5] J. Trevelyan, W. R. Hamel, and S. C. Kang, “Robotics in hazardous applications,” in *Springer Handbook of Robotics*. Springer International Publishing, 1 2016, pp. 1521–1548.

[6] M. A. Goodrich and A. C. Schultz, *Human-robot interaction: a survey*. Now Publishers Inc, 2008.

[7] B. P. Dejong, J. E. Colgate, and M. A. Peshkin, “Improving teleoperation: Reducing mental rotations and translations,” in *Proceedings - IEEE International Conference on Robotics and Automation*, vol. 2004, no. 4. Institute of Electrical and Electronics Engineers Inc., 2004, pp. 3708–3714.

[8] P. Chotiprayanakul, D. Liu, and G. Paul, *Effect of View Distance and Movement Scale on Haptic-Based Teleoperation of Industrial Robots in Complex Environments*, 6 2011.

[9] R. Hetrick, N. Amerson, B. Kim, E. Rosen, E. J. d. Visser, and E. Phillips, “Comparing Virtual Reality Interfaces for the Teleoperation of Robots.” Institute of Electrical and Electronics Engineers (IEEE), 6 2020, pp. 1–7.

[10] J. I. Lipton, A. J. Fay, and D. Rus, “Baxter’s Homunculus: Virtual Reality Spaces for Teleoperation in Manufacturing,” *IEEE Robotics and Automation Letters*, vol. 3, no. 1, pp. 179–186, 1 2018.

[11] A. Pereira, E. J. Carter, I. Leite, J. Mars, and J. F. Lehman, “Augmented reality dialog interface for multimodal teleoperation,” *RO-MAN 2017 - 26th IEEE International Symposium on Robot and Human Interactive Communication*, vol. 2017-Janua, pp. 764–771, 2017.

[12] E. Rosen, D. Whitney, E. Phillips, G. Chien, J. Tompkin, G. Konidaris, and S. Tellex, “Communicating and controlling robot arm motion intent through mixed-reality head-mounted displays,” *International Journal of Robotics Research*, pp. 1–16, 2019.

[13] F. Muhammad, A. Hassan, A. Cleaver, and J. Sinapov, “Creating a Shared Reality with Robots,” in *ACM/IEEE International Conference on Human-Robot Interaction*, vol. 2019-March. IEEE Computer Society, 3 2019, pp. 614–615.

[14] C.-H. Chu and P.-C. Li, “Augmented Reality (AR) based Robot Path Planning for Programming by Demonstration,” *Asia Design Engineering Workshop*, no. December, 2016.

[15] D. Araiza-Illan, A. De San Bernabe, F. Hongchao, and L. Y. Shin, “Augmented Reality for Quick and Intuitive Robotic Packing Re-Programming,” in *ACM/IEEE International Conference on Human-Robot Interaction*, vol. 2019-March. IEEE Computer Society, 3 2019, p. 664.

[16] M. Ostanin and A. Klimchik, “Interactive Robot Programing Using Mixed Reality,” *IFAC-PapersOnLine*, vol. 51, no. 22, pp. 50–55, 1 2018.

[17] D. Whitney, E. Rosen, E. Phillips, G. Konidaris, and S. Tellex, “Comparing Robot Grasping Teleoperation Across Desktop and Virtual Reality with ROS Reality,” in *ISRR*, 2017.

[18] S. Y. Gadre, E. Rosen, G. Chien, E. Phillips, S. Tellex, and G. Konidaris, “End-User Robot Programming Using Mixed Reality.” Institute of Electrical and Electronics Engineers (IEEE), 8 2019, pp. 2707–2713.

[19] Y. Umetani and K. Yoshida, “Resolved Motion Rate Control of Space Manipulators with Generalized Jacobian Matrix,” *IEEE Transactions on Robotics and Automation*, vol. 5, no. 3, pp. 303–314, 1989.

[20] P. Corke, “MATLAB toolboxes: Robotics and vision for students and teachers,” *IEEE Robotics and Automation Magazine*, vol. 14, no. 4, pp. 16–17, 12 2007.

[21] C. W. Wampler, “Manipulator Inverse Kinematic Solutions Based on Vector Formulations and Damped Least-Squares Methods,” *IEEE Transactions on Systems, Man and Cybernetics*, vol. 16, no. 1, pp. 93–101, 1986.