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Effective and Immersive Teleoperation with Real-World Constraints

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Abstract— ***This study investigates the development of a telepresence system that leverages standard, industry-available hardware to support teleoperation in a cost-effective and accessible manner. Conventional telepresence solutions often rely on advanced technologies such as 360-degree or stereoscopic cameras, high-end haptic feedback devices, and specialized robotic platforms. While these approaches can deliver highly immersive experiences, they frequently involve significant implementation costs, limited accessibility, or insufficient locomotion support, which restrict their broader adoption. Consequently, there is a critical need for a telepresence method that balances usability, immersion, and affordability while maintaining precise and reliable control mechanisms. The proposed solution integrates commercially available virtual reality (VR) equipment with a mobile robotic platform to construct a virtual environment that enhances user interaction and spatial awareness. Real-time video input from the robot's onboard camera is projected into the VR environment, enabling users to perceive the remote physical space intuitively. To compensate for hardware limitations, the system incorporates visual cues that represent the robot's orientation, movement direction, and control latency. These cues play a crucial role in improving situational awareness and assisting users in making informed navigation decisions during teleoperation tasks. The study evaluates the system in terms of control simplicity, precision, and overall usability. Particular emphasis is placed on how the virtual environment mitigates latency effects and provides smooth locomotion feedback, resulting in a fluid user experience. The findings demonstrate that effective telepresence can be achieved using standard hardware, offering a practical alternative to more complex and expensive systems while maintaining immersive and accurate teleoperation capabilities.***

Keywords—Virtual Reality, Telepresence, Human-robotic Interaction, Teleoperation

I. INTRODUCTION

Since the creation of virtual reality (VR), users can explore and have unique experiences through virtual environments. Not only has VR helped with the sense of immersion in virtual environments, but it is also increasingly used with mixed reality to enhance user productivity in real-world environments. VR hardware can also create immersive interfaces for the teleoperation of robotics. Additionally, VR hardware is increasingly available to the broad public through today's hardware options, which include the Meta Quest 2, Meta Quest 3, HTC VIVE, Apple Vision Pro, and PlayStation VR2.

Even though VR has proven to aid in the teleoperation of robotics, there are still limitations in latency and control that hinder an identical performance to in-person locomotion. The robot will have a slightly slower response when rotating than the user. This delayed response perceived in the VR environment may lead to simulator sickness [1], [2].

For example, if the robot's video feed is directly mapped to the HMD, it can cause simulator sickness when the HMD and the robot's camera resolution are not the same. These differences could result in some portions of the video being omitted or distorted, worsening the user's experience. Latency, simulator sickness, and imperfect hardware will slow the response rate when controlling the robot in real-time. This delay can lead to a loss of immersion. This loss of immersion can negatively impact the user's performance while controlling the robot, especially in technical maneuvers. For example, the user may turn quicker than the robot's turning capability. This scenario would lead to a user standing still, while the video feed is still spinning as the robot is still turning. Therefore, when incorporating VR for the teleoperation of robotics, finding solutions to reduce the chance of simulator sickness and the loss of immersion is essential

This project's solution to the previously listed concerns is to create a virtual environment with a platform for the user and a floating screen that displays the robot's video feed. The floating screen will rotate around the user to indicate the robot's forward vector in the real world. Placing the robot's video feed in the virtual environment instead of mapping the video feed to the user's HMD will allow the HMD to maintain a 90Hz refresh rate regardless of the frames per second from the robot's video or any latency delays in the video feed. Maintaining this 90Hz refresh rate in the HMD will help reduce the risk of simulator sickness [2]. Additionally, the environment will include floating spheres surrounding the virtual platform. These floating spheres will move around the platform opposite to the robot's movements and rotations. For

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example, if the robot rotates counterclockwise, the floating spheres will rotate around the user clockwise to simulate the robot’s real-world movement in the virtual environment. Additionally, if the robot moves forward, the floating sphere will move in the opposite direction in the virtual environment.

The user will operate the robot using VR controllers for forward and backward movements. The user’s HMD’s rotations will command the robot to rotate if any changes are needed to keep the floating screen in front of the user in VR space. The user can walk freely in the virtual space without concern, as the virtual environment will also include a small barrier to indicate if the user is near a wall in the real world. This solution frees the user from the constraints of the robot’s physical limitations and latency concerns while allowing the user to take advantage of the VR’s immersion. For example, the user can look up and down in the virtual environment, even though the robot does not have this degree of freedom.

This project will conduct several tests comparing the VR system with a traditional keyboard and monitor when operating the robot. These tests will check for simple control, accuracy, and spatial awareness.

II. RELATED WORK

Traditional telepresence allows the user to feel present in a remote location with typically limited user locomotion. Additionally, telepresence using an HMD can increase immersion for the remote user [3], [4], [5], [6] [7]. Telepresence incorporated using VR combined with an avatar to represent the remote user has also existed but has limited locomotion capabilities. One example is when telecollaboration projects the remote user to the same room as local users through AR visualization [7]. During this experiment, the real-world user views the remote user’s avatar through an augmented reality (AR) display, which helps increase a sense of presence [7]. This example used a 360-degree camera, which gives the user a great sense of presence. However, this experiment denied the user the ability for locomotion, which hinders the user’s telepresence experience [8]. This example relies on traditional VR controllers to convey the user’s interactions, which may have limited spatial presence for the user. One can increase the user’s spatial presence using controllers with a sense of naturalness [9].

Another example of telepresence is using VR combined with an avatar to represent the user at a remote location. This method allows the remote user to pilot a robot that projects an avatar for people in the real world to view. For example, an experiment by Brennan Jones, Yaying Zhang, Priscilla N. Y. Wong, and Sean Rintel used “Virtual Robot Overlay for Online Meetings” (VROOM) augments to convey telepresence [10]. During the experiment, the remote user used an HMD connected to the robot’s 360-degree camera and VR controllers to navigate the robot. The local user wore an AR device called the HoloLens to view the remote user’s avatar [10]. Additionally, the avatar was a life-like representation of the remote user. However, due to technological limitations, some aspects of the remote user were not properly captured, thus leading to a sense of uncanniness in the avatar, which hinders the local user’s experience.

Telepresence existed in 1980 [11] and has continued to see developments added to the field. These developments include how telepresence helped with gaming [12], benthic exploratory research [13], and research at NASA [14].

Human Robotic Interaction (HRI) allows users to control and interact with robotics. Additionally, VR can be an HRI device for robotic applications [15]. One example is when Naceri [16] presented the *Vicarios* VR interface, the basis for a robotic teleoperation interface. This interface highlighted the benefits of VR by creating an immersive visualization that allowed the freedom of viewport selection. Another example of VR used as an HRI device for robotic applications is when Stotke . [17] presented a robotic application incorporating VR as a teleoperation system. This robotic application was intended to traverse contaminated places inaccessible to humans.

Many of these solutions overcome their shortcomings by using hardware that would be out of the range of cost for the average consumer. However, those solutions are not practical due to their costs. This paper enhances immersion with the constraint of moderately priced hardware.

III. METHODOLOGY

With the formal review of different telepresence and HRI applications as a foundation, it is possible to propose a proper methodology that combines the appropriate design techniques to create a greater sense of immersion in telepresence. This project will incorporate an HMD to visualize the robot’s video feed location and the virtual environment. Additionally, this project will avoid using less accessible devices such as a 360-degree camera, instead using the robot’s built-in camera. The project will use Unity 3D and Visual Studios to develop the system software while incorporating the ROS TCP Endpoint. Additionally, another machine will incorporate ROS 2 - Humble to communicate with the robot and the system software. Fig. 1 showcases the Use Case Diagram for the system architecture.

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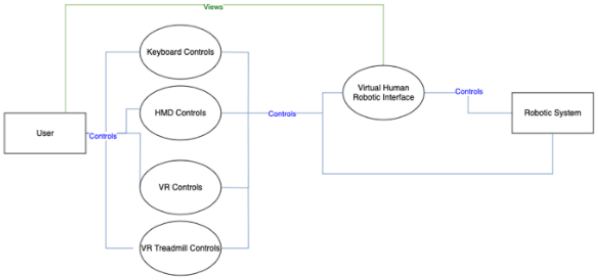

Fig. 1. Use Case Diagram

The robot (as seen in Fig. 2) contained the following specifications (however, this is not directly used for this research) [18]:

- The platform is a ROSbot 2R.
- CPU: is a Broadcom BCM2711 64-bit, Quad-Core ARM Cortex-A72, 1.5 GHz (ARM64, Raspberry Pi 4)
- GPU: Broadcom VideoCore VI
- 4GB of LPDDR4 RAM
- Inertial measurement unit (IMU): BNO055 (accelerometer + gyro)
- Distance sensor: VL53L0X (time-of-flight)
- Networking: 2.4 GHz and 5 GHz 802.11b/g/n/ac wireless LAN
- Locomotion employs a 4-wheel mobile platform with a DC motors skid steer system
- Powered by Li-ion batteries: 3 x 3500 mAh (with protection circuits)
- Red, Green, Blue, and Depth (RGBD) Camera: Orbbec Astra*
- Light Detection and Ranging LIDAR: Slamtec RPLIDAR A2 for its use of Light Detection and Ranging (LIDAR)

Fig. 2. Demonstrates the ROSbot 2R robotic equipment

The project will focus on creating a virtual environment to place a moving screen to reflect the robot’s forward-facing direction. This virtual environment will resemble a control room with a center-placed platform for the user to stand while using the HMD. When the user rotates in the virtual environment, the robot will receive a signal to rotate in the real world. When the robot rotates in the real world, the floating screen in the virtual environment will also rotate around the user to act as a visualization for control latency. Therefore, this visualization completes the feedback loop between the user and the robot, allowing stability for the control of the robot. Additionally, the VR environment will depict the robotic system’s current orientation compared to the user. The virtual environment will also include a floating arrow that follows the user and informs the user of the robot’s current forward vector, as seen in Fig. 3.

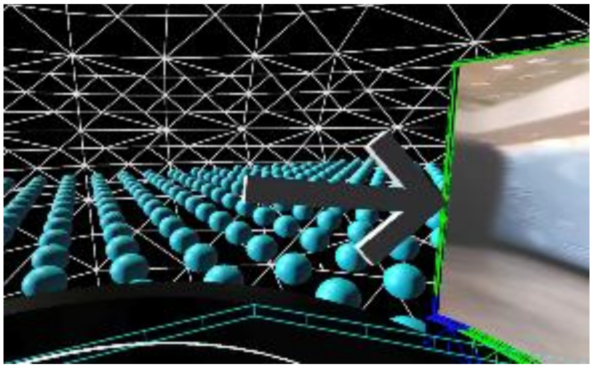

Fig. 3. The arrow guides the user toward the floating screen

Additionally, the virtual environment will include floating spheres surrounding the user’s platform and the floating screen, which will act as an orientation awareness

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grid, as seen in Fig. 4. This figure showcases the VR environment and the real-world VR equipment used to operate the robot is visible through the moving screen in this figure.

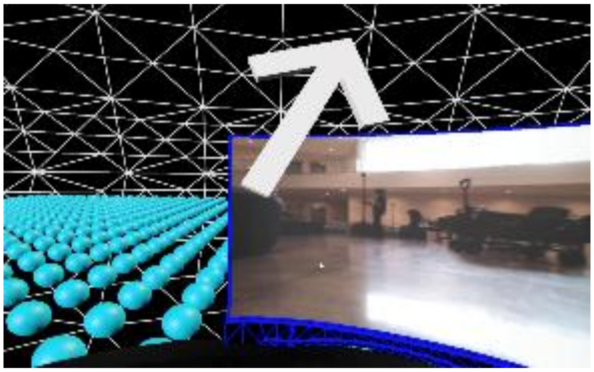

Fig. 4. Showcases the VR environment and the real-world VR equipment through the floating screen

These spheres will move towards and away from the platform to simulate the robot’s movements. This additional element to the virtual environment will help the user visualize the robot’s real-world movement even outside of the floating screen’s video feed from the robot. Fig. 5 demonstrates the VR environment.

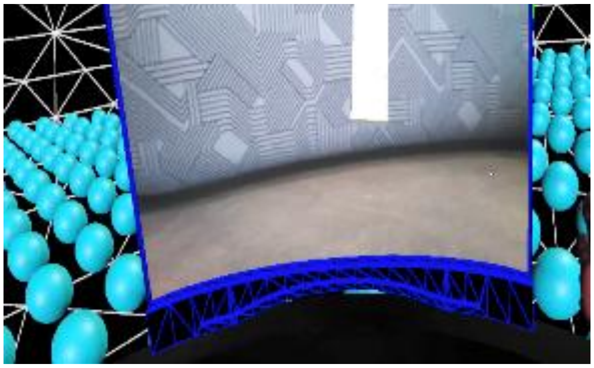

Fig. 5. Floating spheres surround the user in the VR environment

This project will have two separate control schemes to operate the robotics system. The first control scheme will incorporate an HMD while using VR controllers to operate the system. The HMD will allow the user to visualize the virtual space and the floating screen displaying the robot’s video feed. Further, the HMD will act as the input device to command the robot to make a rotation if the user looks away from the floating screen in either the left or right direction. This control scheme will also use the VR controllers to input the robot’s forward and backward movement commands. It also gives the user a more profound immersion while properly operating the system. The control to several of this project’s tests will incorporate a keyboard and monitor, giving the user a traditional experience as a comparison. The keyboard will allow input commands to either rotate or move the robot. This control scheme will display the robot’s video feed on the monitor without the floating screen in the virtual environment to match the robot’s real-world orientation.

IV. TESTING PROCEDURE

The testing procedure prescribes three different experiments. The first test creates a test for the use of the VR system’s simple controls. The second test evaluates the VR system’s precision when controlling the robot in confined spaces. The third test will measure the user’s situational awareness when using the VR system.

A. Test 1: System Use

This experiment will measure how quickly one can navigate unique mazes while using the VR system to control the robot. Additionally, this experiment will incorporate landmark discovery to gauge the user’s understanding of the surrounding real-world environment. This experiment measures the time required to find the landmark and exit the maze. This process is repeated three times for each maze so that the user has several opportunities to become familiar with operating the robot through the VR system (TABLE). The hypothesis is that the user will gradually improve their time through each attempt as they become familiar with navigating the robot through the VR system.

TABLE I. SYSTEM USE TESTING PROCEDURE

Steps	**Procedure**
Step 1:	Create a randomized location for the landmark in the maze.
Step 2:	A timer will start when the user enters the maze.
Step 3:	The user must find the landmark to leave the maze.
Step 4:	Once the user discovers the landmark, then the user must navigate to the end of the maze.
Step 5:	Once the user successfully leaves the maze through its exit, the timer will end.
Step 6:	Set up the next maze variation and repeat the above steps until the user has completed three trials.

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Fig. 6 demonstrates that the user has ample space to freely navigate the robotic system without worrying about colliding with obstacles.

Fig. 6. Test 1 using Maze 1.1

These users will also have a slightly different maze to ensure each user has a similar but unique maze for their attempt.

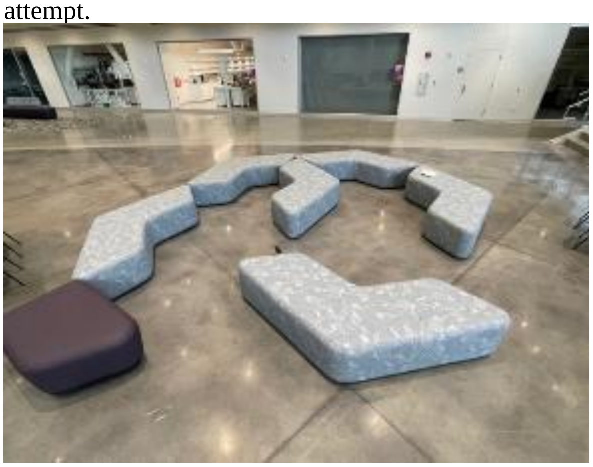

Fig. 7 and Fig. 8 show the additional mazes used for Test 1.

Fig. 7. Demonstrates Maze 1.2

Fig. 8. Demonstrates Maze 1.3

B. Test 2: Fine Motor Controls

The second test measures the user’s fine motor controls (

TABLE) with less-than-ideal hardware when piloting the robot through the VR system to traverse the tightly designed Maze 2, as seen in Fig. 9. This experiment will show if there is any loss in precision in the user’s control when using the VR system compared to a traditional monitor and keyboard. Therefore, this experiment will measure the time the user takes to complete the maze. During the run, the number of collisions will be recorded, contributing to a penalty for the user’s completion time. The hypothesis is that the VR system will introduce a small amount of error when controlling the robot compared to using a keyboard and monitor; however, the difference between the control schemes’ errors will be negligible.

Fig. 9. Demonstrates Maze 2, which introduces testing for fine motor controls

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TABLE II. FINE MOTOR CONTROLS TESTING PROCEDURE

Steps	**Procedure**
Step 1:	A timer will start when the user enters the maze.
Step 2:	The user must navigate to the maze’s exit with minimal collisions.
Step 3:	Once the user successfully leaves the maze through its exit, the timer will end.
Step 4:	Add a time penalty for each of the user’s collisions,
Step 5:	Repeat the above steps until the user has completed three trials.

C. Test 3: Situational Awareness

The third test will measure the user’s situational awareness. The maze will contain a single randomly placed landmark. Once the user reaches the maze’s center, the user must state the direction in which the now out-of-sight landmark is located (Fig. 10 shows the maze, the landmark, and the robot at the end of the maze). The user must state this direction by using the hours on a clock (right is hour three, backward is hour six, left is hour nine, and forward is hour twelve), as seen in TABLE and Fig. 11.

Fig. 10. Illustrates the ROSbot 2R at the end of Maze 3

For example, if the landmark is in the direction of hour four and the user believes that the landmark is at hour six, then the user’s situational awareness is off by two hours. This experiment will report if there is any difference in spatial awareness between the two control schemes – VR or keyboard/monitor. Situation awareness is crucial as the user needs to understand their surroundings properly (Fig. 13). This awareness will increase immersion and productivity when navigating using the VR system. The hypothesis is that the VR system will have higher accuracy with situational awareness than the keyboard and monitor.

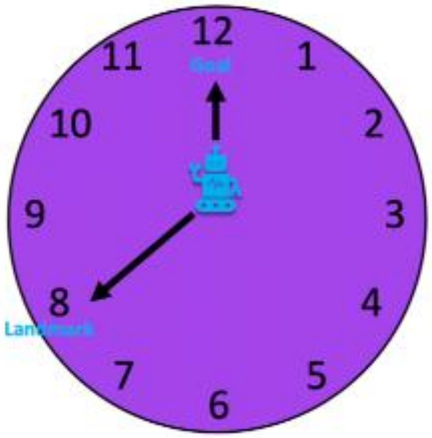

Fig. 11. Illustrates the robot facing the goal and where the landmark is regarding the robot. Additionally, the clock demonstrates the direction in which the landmark is placed regarding the robot and the goal

TABLE III. SITUATIONAL AWARENESS TESTING PROCEDURE

Steps	**Procedure**
Step 1:	Create a randomized location for landmark in the maze.
Step 2:	The user will start at the maze’s entrance and enter the maze.
Step 3:	The user must find the landmark in the maze.
Step 4:	Once the user discovers the landmark, then the user must navigate to the end of the maze, where there will be a stop-station.
Step 5:	Once the user has arrived at the stop-station, the user must state where the landmark is from the stop-station using the direction by using the hours on a clock (right is hour 3, backward is hour 6, left is hour 9, and the stop-station/ the user’s forward is hour 12).
Step 6:	Repeat the above steps until the user has completed three trials.

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Fig. 12. Demonstrates Maze 3

V. RESULTS AND ANALYSIS

D. Test 1: Basic Use

Once testing for the VR system's basic use was completed, there was an interesting pattern between several users (

TABLE). Four of the five users had worse completion times for their second attempt when compared to their first and third attempts. The reason likely for the slower attempt is that the users decided they wanted to take a more thorough approach when reattempting the experiment. However, likely after realizing that being overly thorough led to a worse completion time, the users improved on their final attempt. The fifth user had, across the board, an improved completion time after each additional attempt, which matched the hypothesis. Four of the five users had their fastest completion attempt on their final trial. Therefore, while the original hypothesis was that the users would gradually improve after each attempt, the reality was that most users need their third and final attempt to show that the system's controls are clear and straightforward when using the VR headset to navigate the robot in the real-world environment.

TABLE IV. BASIC SYSTEM USE TEST RESULTS

Trials	**Users**				
	User 1	**User 2**	**User 3**	**User 4**	**User 5**
Trial 1	41.79	32.64	39.45	31.8	3:24.83
Trial 2	1:39.04	1:30.01	55.8	1:14	46.15
Trial 3	48.87	28.05	36.69	1:08.07	31.61

Fig. 13. The ROSbot 2R placed in the Maze 1.4

E. Test 2: Fine Motor Controls

The second test covered the user's fine motor controls using the VR system. The hypothesis was that a keyboard and monitor would have superior precision, but the VR system would still have a comparable completion time. The experiment's results supported the hypothesis as User 1 had a corrected completion time (after applying the time penalty for any collisions) that was either worse or the same as the keyboard and monitor user's completion time. The matching corrected completion time was the second attempt, which was one minute and two seconds. If the penalty from User 1's collision was not added, the user would have beaten the keyboard and monitor user.

User 2's first attempt had a corrected time of one minute and 46 seconds (due to one collision), which was significantly behind the keyboard and monitor user's first attempt was 54.73 seconds. User 2 completed their second attempt within 58 seconds, four seconds faster than the keyboard and monitor user at one minute and two seconds.

The results from TABLE illustrate that to accomplish the VR immersion, the user will have to compromise on the amount of accurate control that the user possesses over the robot. For example, the users experienced an average loss of 39.63% of control (when comparing corrected completed times with the keyboard and monitor user) during Test 1. Interestingly, the users experience an average gain in control during Test 2 of 3.33%. During Test 3, the users experienced an average loss of control of 32.16%. Therefore, these results indicate that there is still room for improvement in the VR controls to allow for the same results as a keyboard and monitor the user.

TABLE V. FINE MOTOR CONTROLS TEST RESULTS

User 1			
Trials	**Original Time**	**Collisions**	**Corrected Time**

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Attempt 1	1:02	2	1:12
Attempt 2	0:57	1	1:02
Attempt 3	1:10	1	1:15
User 2			
Trials	**Original Time**	**Collisions**	**Corrected Time**
Attempt 1	1:41	1	1:46
Attempt 2	0:58	0	0:58
Attempt 3	1:16	0	1:16
Control (Keyboard)			
Trials	**Original Time**	**Collisions**	**Corrected Time**
Attempt 1	0:53.73	0	0:53.73
Attempt 2	1:02	0	1:02
Attempt 3	0:51.22	0	0:51.22

F. Test 3: Situational Awareness

The final test was for situational awareness (TABLE). The average user completed their first attempt within 45 minutes of accuracy, their second attempt with an average accuracy of 30 minutes, and their third attempt with an average accuracy of one hour and 45 minutes. Therefore, the average accuracy of the users was one hour and zero minutes. The keyboard and monitor user completed their first attempt with an accuracy of one hour and 30 minutes, their second attempt within an accuracy of one hour and 30 minutes, and their third attempt with an accuracy of one hour. When comparing the VR system users to the keyboard and monitor user, the VR users have an improved accuracy of 20 minutes, which is in line with the hypothesis stating an improvement when using the VR system over the keyboard and monitor.

TABLE VI. RESULTS USING THE HOUR (DIRECTION) CONJECTURED BY THE USER AND THE ACTUAL ANSWER.

Control (With Keyboard)	**Conjecture**	**Actual**
Attempt 1	1:30	3:00
Attempt 2	7:30	6:00
Attempt 3	7:00	6:00
User 1	**Conjecture**	**Actual**
Attempt 1	7:00	7:30
Attempt 2	12:30	1:00
Attempt 3	2:00	4:00
User 2	**Conjecture**	**Actual**
Attempt 1	7:00	8:00
Attempt 2	1:00	1:30
Attempt 3	4:30	6:00

VI. FUTURE WORK

Future work will include expanding the devices used to enhance the telepresence given through the VR teleoperation of the robotic system. One way to improve the user’s telepresence could include a VR treadmill. This VR treadmill will act as the input for the robot’s movement and rotation, allowing the HMD to rotate freely in the VR environment without needing to control the robot’s rotation. Further tests will be performed to determine whether the treadmill is more intuitive than the HMD rotation control schema. This change to the system would allow for vestibular sensations and proprioception, ideally increasing the user’s sense of presence while operating the robotic system in a remote location [19]. This change could also allow for the integration of additional user interface elements into the VR environment.

Additionally, the Unity-ROS 2 connection will be upgraded. This upgrade will remove the need to include a WebSocket bridge, as the Unity project itself will be a native ROS 2 participant. This change to the system could reduce the computer resources needed to run the program, leading to a broader range of usable hardware and VR equipment.

Integrating mapping based on the remote location with the current system could replace the floating field of spheres, improving situational awareness. The system could use a known map of the remote location or dynamically map it with a simultaneous localization and mapping algorithm (SLAM).

VII. CONCLUSION

This project created a VR system that combined an HMD, a virtual environment, and a robotic system to allow the user to experience a telepresence solution. This project demonstrated visualizing the control latency with the moving screen reflecting the robot’s current physical direction. With this technology, the primary objective was completed, and a VR experience was created using hardware readily available to the average user. Regardless of this limitation, the VR system had to provide an acceptable performance while providing simple navigation controls, high precision, and increased situational awareness.

Three different tests during this study supported these elements. The first test demonstrated a reasonable use for teleoperating the robot through VR. Users were allowed to familiarize themselves with the basic controls through three attempts to operate the robot. The second test illustrated that the VR platform provided competitive precision compared to the keyboard and monitor schema. The last test confirmed that the VR system improved the user’s

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situational awareness, which aligned with the hypothesis. In conclusion, this study created a VR solution for teleoperating a robot without expensive hardware, achieving an immersive precision and situational awareness solution for telepresence through teleoperation.

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