Immersive VR based Digital Twinning for Mobile Robotic Platforms

Author
Muhammad Faiq Malik
Regn Number
364542

Supervisor
Dr. Sara Ali

DEPARTMENT ROBOTICS AND ARTIFIAL INTELLIGENCE
SCHOOL OF MECHANICAL & MANUFACTURING ENGINEERING
NATIONAL UNIVERSITY OF SCIENCES AND TECHNOLOGY
ISLAMABAD
NOVEMBER 2023

Immersive VR based Digital Twinning for Mobile Robotic Platforms

Author

Muhammad Faiq Malik

Regn Number

364542

A thesis submitted in partial fulfillment of the requirements for the degree of

MS ROBOTICS AND INTELLIGENT MACHINES ENGEERING

Thesis Supervisor:

Dr. Sara Ali

Thesis Supervisor's Signature: ___________________

DEPARTMENT ROBOTICS AND ARTIFIAL INTELLIGENCE
SCHOOL OF MECHANICAL & MANUFACTURING ENGINEERING
NATIONAL UNIVERSITY OF SCIENCES AND TECHNOLOGY,
ISLAMABAD
NOVEMBER 2023

Declaration

I certify that this research work titled "*Immersive VR based Digital Twinning for Mobile Robotic Platforms"* is my own work. The work has not been presented elsewhere for assessment. The material that has been used from other sources it has been properly acknowledged / referred.

Signature of Student
Muhammad Faiq Malik
2021-NUST-MS-RIME-000364542

Copyright Statement

THESIS ACCEPTANCE CERTIFICATE

Certified that final copy of MS/MPhil thesis written by **Regn No. 00000364542 Muhammad Faiq Malik** of **School of Mechanical & Manufacturing Engineering (SMME) (SMME)** has been vetted by undersigned, found complete in all respects as per NUST Statues/Regulations, is free of plagiarism, errors, and mistakes and is accepted as partial fulfillment for award of MS/MPhil degree. It is further certified that necessary amendments as pointed out by GEC members of the scholar have also been incorporated in the said thesis titled. **Immersive VR based Digital twinning for mobile robotic platforms.**

Signature:

Name (Supervisor): Sara Baber Sial

Date: 6/12/23

Signature (HOD):

Date: 07/12/23

Signature (DEAN):

Date: 7-12-23

Acknowledgements

In the infinite grace and wisdom of Allah Subhana-Watala, I find my strength and guidance. It is with His divine light that I have been blessed and guided throughout this academic Endeavor and in all facets of my life. To Him, I owe all gratitude, for it is through His will that I have been fortunate to be surrounded by people who have been pillars of support and guidance.

My deepest appreciation goes to my cherished mother, who has been an ocean of love, resilience, and patience. Her Unconditional faith in me and her prayers have been the bedrock on which I have built my aspirations.

To my dear siblings, who have walked with me through thick and thin, your belief in me and your constant encouragement have been invaluable. I am also profoundly grateful to my supervisor, Dr. Sara Baber Sial, who has been a mentor for excellence. His expertise, insights, and dedication have significantly shaped this work. Throughout the journey of this thesis, he provided invaluable guidance, constructive criticism, and a reservoir of patience. His unwavering support and wisdom have been pivotal in turning my aspirations into reality.

A special note of thanks to my friends who have been an enduring source of safety, laughter, and reassurance. Their constant presence and belief in my capabilities, especially during moments of self-doubt, have been immensely uplifting.

Lastly, every soul who has contributed, even in the slightest way, to my academic journey has my heartfelt gratitude. Whether it was a word of encouragement, a gesture of support, or a piece of advice, I cherish it deeply. To all, may Allah shower His countless blessings upon you, and may He guide us in all our endeavors.

Dedicated to my exceptional parents and adored siblings whose tremendous support and cooperation led me to this wonderful accomplishment.

Abstract

This work deliberates building an intelligent and intuitive telepresence human robot interaction framework that liberates the human from handling technical difficulties and increases the resourcefulness of remote service robot. The complementing framework comes underutilization for tasks such as inspection, exploration, and feature collection from unknown, dynamic, and stochastic environments. Comparative to existing works it provides multimodal control and seeks user friendly features, realism and immersivity via a VR android application. The framework allows the user to switch the mode of operation from direct control to a collaborative/semi-autonomous one with the latter being controlled by an actor-critic network for autonomous local navigation. The user experience is also evaluated with real time experimentation and monitoring of human performance using BCI and analyzing results accumulated from the presence, usability, and sustainability questionnaires filled in by test subjects. Mean presence and usability scores of 97.6% and 94.71% supports the claim of this framework being immersive, intuitive, and collaborative with a simultaneous reinforcement from the Human performance metrics evaluation during the activity.

Key Words: *Virtual Reality; Telepresence; Mobile Robot Platform; Actor-Critic network; Autonomous obstacle avoidance*.

Table of Contents

List of Figures

List of Tables

CHAPTER 1: INTRODUCTION

Robotics is an exponentially growing industry with vast applications around 30 hundred thousand industrial robots are operating worldwide, and the current market value is estimated over 56$ billion. With a growth rate of 37% in professional service robots and 19% in domestic service robots over the previous year the interest in robotic applications is visible [1]. These mobile agents are being utilized for extraction tasks [2-4], space exploration [5,7], defense purposes [8,9] and industrial uses [10-12]. Moreover, the combination of VR and robotics can open new possibilities and open new industrial research horizons: Training and education [13-16], Manufacturing and Industrial Automation [17-19], Healthcare and Surgery [20], Urban and Infrastructure [21] and Aerospace [22]. Adaption of AI in all the described fields and advanced lithium-ion batteries [23] have enhanced the potential of Robotics to deliver in various fields. However, there is still room for improvement for these robotics applications to become more reliable and replicate human intellect by autonomous behavior. The vision of these applications to develop full autonomy is far from reached. For real world use even with the modern-day technology the robots with greater autonomous capabilities require human intervention due complex nature of real-world environments [24]. This complexity intensifies even more when these environments become remote.

This problem can be tackled through teleoperating such that transmission of supervisory commands from the human end over a communication network to the remote robot whilst receiving feedback consisting of robot and environment state back to the human. Teleoperated mobile robots or manipulators are being utilized for a variety of applications developed to handle harsh operating environments like areas of high radioactivity [25,26] aerial spaces [27,28] and in water bodies [29,30]. The success of these teleoperated systems lies with the operator's decisiveness regarding control commands given to the remote robotic platform. Perception of the remote environment [31] plays an important role in developing situational awareness for the human. This also leads to better engagement of the teleoperator. To cater for this requirement the design of the framework needs to be more immersive [32].

[33] and [34] introduced a framework that incorporates stereoscopic vison to enhance environmental perception using HMD with embedded imu sensors for tracking head movements to offer more user immersion. Although user dimensional perception increases with 3D visuals,

but the misalignment of these depth images incurs cognitive overload along with the requirement of increased communication network bandwidth.

Virtual environments that are a simulated space which replicates a physical environment with user interaction permittivity are also being considered as an aid for user immersion. [35-36] designed a 2D VE with haptic feedback to increase user's situational awareness. However, developing these virtual environments for general use is a nuisance since these are robot kind, location, and environment sensitive. To make these more generic and easier to transfer state of the art immersive incorporates Virtual Reality [37]. VR based HRI have also been inspired by the advent of modern VR headsets for social media [38,39] as well as video gaming [40,41]. Authors of [10] developed a VR to train operation crew for mobile industrial manipulation with the end goals being pick and place tasks. They also concluded the resourcefulness of inclusion of VR by monitoring key indicators like user acceptance his stress and fatigues levels.

The recent advancements in AI have leveraged the adaptability of automation of rather complex tasks and aid the control aspects of teleoperation. But with hardware limitations these intricate tasks due to their subjective nature can't be mitigated without human intelligence [42]. A more profound manner would be a collaborative control approach [43] harnessing potential of both human intelligence and robots. The efforts concerning a shared human robot interaction teleoperated architecture for industrial manipulator arm have been made by [44-45]. [46] used multiple manipulators to provide an occlusion free adaptive visual aid while teleoperating but none of these have exploited the functionality that comes with use of dynamic control over level of autonomy.

A plausible solution for this is provision of merging control from both ends' user and the robot whilst teleoperation research put forth by [47] utilizes potential field-based navigation by merging user provided references positions and lidar scan data from the robot to compute velocity commands for the mobile robot. However potential- field based approaches become problematic in [48] with relativity high-speed real-time domain making it less reliable. Rather than having to test a This work proposes a more profound solution for this which utilization of an actor critic network that predicts robot motion via velocity commands and makes the local obstacle avoidance autonomous thus providing a dynamic way of teleoperation which enable the user to operate in a fully teleoperated mode or in a semi-autonomous one making the process more seamless.

The study utilizes ROS for handling nidal communication. It is a Linux based open-source meta operating system framework which provides a platform for research and development of robotics in general, the availability of various multi-purpose packages to opensource libraries make it a favorable firmware [70]. ROS utilizes a connectivity network of different nodes, subscribing and publishing topics as messages. A node can be an executable passing some sensory data from a sensor for instance Lidar placed on a robot, this information is in form of an ordered text (message) under a port id with a name more commonly known as a topic. All of this builds up ROS packages that are required to perform tasks such as autonomous navigation etc.

In general studies comprehending VR based telecontrol of mobile robots can be divided in two categories, one where improvement in task performance such that reducing time needed to complete teleoperation and increasing in immersivity factor is the key goal. While the others are focused on interface quality, interaction ease with virtual environment in short, the Human Robot Interaction aspects. This work aligns the latter as its major and former as its minor goal. Thus, evaluation of the presented framework also revolves around measuring the success of achieving these goals.

1.1 Research background:

The integration of Virtual Reality (VR) with mobile robotics marks a pivotal advancement in technology, bridging immersive user experiences with practical robotic applications. This convergence, evolving from separate developmental paths, has given rise to a new realm of possibilities in remote operation, healthcare, space exploration, and emergency response. The journey towards this integration began with the early developments of VR in the 20th century, paralleled by the evolution of mobile robotics through advancements in automation and control systems. The marriage of these two fields was driven by the need to enhance remote operation capabilities, allowing for the control of robots in environments unsuitable or hazardous for humans.

Advancements in VR, particularly in Head-Mounted Displays (HMDs) and motion tracking systems, have been instrumental in creating realistic, responsive environments crucial for remote robot operation. Concurrently, mobile robots have evolved to incorporate sophisticated features such as autonomy, advanced navigation, and manipulation, essential for effective teleoperation. The integration of these technologies is a complex process, involving the transmission of sensory data from the robot to the VR system and the translation of user commands into robotic actions, necessitating seamless real-time communication and advanced control algorithms.

The applications of VR-based teleoperated mobile robots are diverse and impactful. In the military, these systems enable safer bomb disposal and reconnaissance missions. Space exploration has benefited significantly, with remote-controlled rovers and equipment reducing the need for human presence in hostile environments. The medical field has seen revolutionary changes with remote surgeries and examinations, particularly beneficial in remote or underserved regions. Industrial and agricultural sectors utilize these systems for operating machinery in inaccessible areas, enhancing safety and efficiency. In search and rescue operations, teleoperated robots navigate through hazardous environments, offering a safer and more efficient alternative to traditional methods.

Designing user interfaces for VR-based teleoperation focuses on intuitive controls, clear visual feedback, and ergonomics to ensure user comfort and prevent strain. Incorporating haptic feedback is a key aspect, enhancing control accuracy and immersion by providing tactile sensations that mimic real-life interactions. However, the deployment of these systems is not without challenges. Technical issues such as latency and bandwidth limitations can impact the quality and real-time aspect of teleoperation. Ethical and safety considerations, particularly in military and healthcare applications, are paramount, alongside the need for specialized user training and adaptation.

Looking to the future, advancements in VR and robotics promise to enhance the capabilities of teleoperated systems further. Developments in artificial intelligence, improved sensory feedback, and more intuitive control mechanisms are on the horizon. These enhancements have the potential to expand the applications of VR-based teleoperated robots into everyday life, potentially transforming sectors like education, entertainment, and personal assistance.

The fusion of VR with mobile robotics in the form of teleoperated interfaces represents a significant leap in remote operation technology. While it brings considerable benefits, addressing the accompanying challenges is crucial for its success. As research and development in this field continue, the potential applications and impact of these systems are vast, indicating a future where our interaction with and control over machines becomes increasingly seamless and integrated into various aspects of our digital world.

Robotics is an exponentially growing industry with vast applications Moreover, the combination of Virtual Reality (VR) and Robotics can open new possibilities and enhance various industries. Some relative use cases of VR with Robotics, along with relevant statistics:

1. Training and Education:
   - Use Case: VR can provide immersive training simulations, while robotics can offer hands-on practical experience.
   - Statistics: A study by PwC found that VR-based training resulted in a 30% faster learning time and a 12% increase in accuracy. Additionally, the global market for educational robots is expected to reach $1.7 billion by 2027 (Grand View Research).
2. Manufacturing and Industrial Automation:
   - Use Case: VR can be used for virtual assembly line optimization, while robotics can automate repetitive tasks and improve efficiency.
   - Statistics: [1] reported that the international sales of industrial robots reached 384,000 units in 2020, with the automotive industry accounting for around 30% of total robot installations.
3. Healthcare and Surgery:
   - Use Case: VR can assist in surgical planning and pre-operative simulations, while robotics can aid in minimally invasive surgeries.
   - Statistics: The global market for surgical robots is projected to reach $13.1 billion by 2027, growing at a CAGR of 22.6% from 2020 to 2027 (Grand View Research). Moreover, a study published in JAMA Network Open showed that VR surgical simulations resulted in a 230% improvement in surgical performance compared to traditional training methods.
4. Remote Operation and Telepresence:
   - Use Case: VR can enable remote operation of robots in hazardous or distant environments, providing real-time feedback and situational awareness.

    - Statistics: The market for telepresence robots is projected to reach $477.8 million by 2027, growing at a CAGR of 16.3% from 2020 to 2027 (Grand View Research).

5. Entertainment and Gaming:
    - Use Case: VR can offer immersive gaming experiences, while robotics can enhance physical interactions and haptic feedback.
    - Statistics: The global VR gaming market is expected to reach $70.57 billion by 2028, growing at a CAGR of 30.2% from 2021 to 2028 (Fortune Business Insights). Additionally, the sales of consumer robots, including entertainment robots, are projected to reach $15.1 billion by 2023 (Statista).

These use cases highlight the synergy between VR and Robotics, providing enhanced training, improved efficiency, advanced surgical capabilities, remote operation, and immersive gaming experiences. As the adoption of these technologies continues to grow, we can expect to see further innovation and expansion of their applications in various industries.

Given all these positive still there comes a gape when it comes to operating these robots that is be bridged. This research aims to integrate fully immersive Virtual Reality experience via a digital twin for a mobile robot platform. The proposed framework will work around the immersion factor of VR along with an intuitive interface for teleoperated human robot interaction.

1.2 Contributions:

Evaluation of previous and state of the art relating to immersive teleoperated mobile robot control framework highlight two major facts about lack of adaptability in level of autonomy and lapses in integration of multi-sensory feedback to tackle the full immersion in virtual reality. This work develops a new and improved virtual reality based Human robot interaction framework for exploring and navigating dynamic and stochastic environments while comforting and engaging the teleoperator in an intuitive and ergonomic manner.

This research focuses on introducing more user control over autonomy of the interaction with the mobile robot in a manner that incorporates task efficiency, higher user immersion in virtual environment and focuses on ergonomics of the teleoperation. The work is also validated with the real time experimentation utilizing tutlebot3 burger variant as the mobile robot choice and Oculus quest 2 for the VR headset. The work introduces the following improvements and innovations to the existing work.

- It seeks realism by incorporating multi-sensory feedback such as vision and sound to help increase operator’s immersive experience.
- The work also develops a standalone VR android application with an intuitive interface that prompts the user to opt between a fully teleoperation mode and a semi-autonomous one.
- A fully teleoperated mode gives the user complete control over the robot. This helps the framework to take advantage of human intelligence when robot the gets stuck whilst navigating through its environment.
- This framework enables operators to maneuver the robot in an unknown dynamic environment with the need of exploring and building a map of the environment prior to navigation.

The work also incorporates a study for validation of the efficiency and effective-ness of the framework by having multiple subjects of diverse age groups and back-grounds live through the experience whilst accumulating their feedback via surveys and monitoring them through BCI during experimentation.

CHAPTER 2: FRAMEWORK

2.1 Overview

The framework consists of VR headset and a mobile robot equipped with additional sensors in remote environment and a local workstation to traverse through the data stream coming from the mobile platform.

The remote work environment includes a space for navigation performed by the turtle Bot. While the local operator is perceiving the sensory feedback and providing control through a standalone VR android application running on Oculus quest 2 VR headset [70] with an 1832 × 1920-pixels display resolution per eye along with refresh rate of 90hz,128 GB of storage and 6GB of RAM. The device comes with a Qualcomm Snapdragon XR2 processor that enables it to handle state of the art VR android applications.

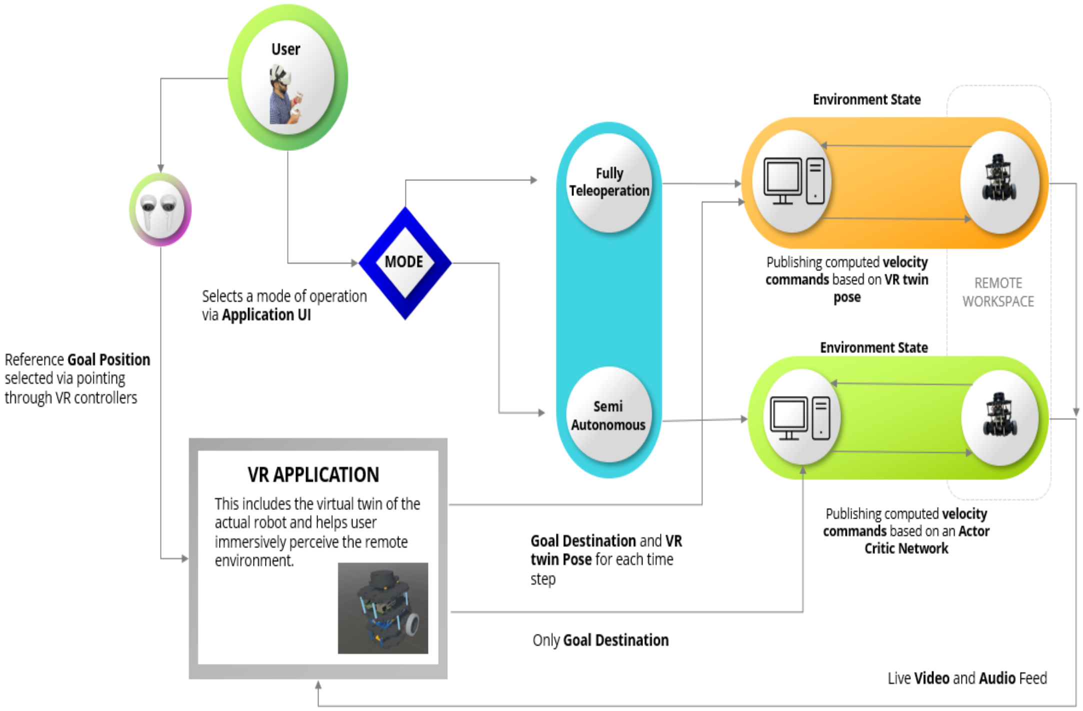


Figure 2.1. Framework conceptual architecture for Immersive Human Robot Collaboration

The VR application is developed using Unity Development Engine [71] and integrates packages for communication with local workstation. The virtual counter part of the turtle Bot provides aid in control of actual mobile platform and change in its pose is replicated by the actual robot whereas the visual and auditory feedback from the real-world is communicated back to the virtual environment.

The user interacts through oculus controllers in hand while receiving auditory and visual feed from the real world. Whereas all the remote robot data is transmitted to the workstation where its interpreted and manipulated to publish velocity messages back to the robot and relevant sensory data to the VR application. Upon starting the application, the user is provided with a choice to operate in complete teleoperated mode or a semi-autonomous one.

The local workstation also triggers the relevant nodes for communication. In the Fully Teleoperated mode the VR twin movement are replicated directly upon receiving pose information from VR application while in the Autonomous mode utilizes state of the art reinforcement learning modularity of TD3 [72] to make the local robot avoid obstacles using lidar sensor autonomously upon receiving goal position provided by the user operating through virtual interface.

2.2 Virtual Standalone Application

Standalone Virtual Reality (VR) applications are emerging as a transformative force in technology, reshaping how we interact with digital environments in both personal and professional realms. These self-sufficient systems, which operate independently from external hardware, offer numerous benefits that are revolutionizing various sectors. Their key advantage lies in their ease of access and simplicity. Unlike conventional VR setups that often require intricate configurations, standalone VR systems are all-encompassing, making virtual reality more approachable and less intimidating for a wider audience. This accessibility is particularly beneficial for educational institutions, small enterprises, and individual users who might find traditional VR setups too complex or costly.

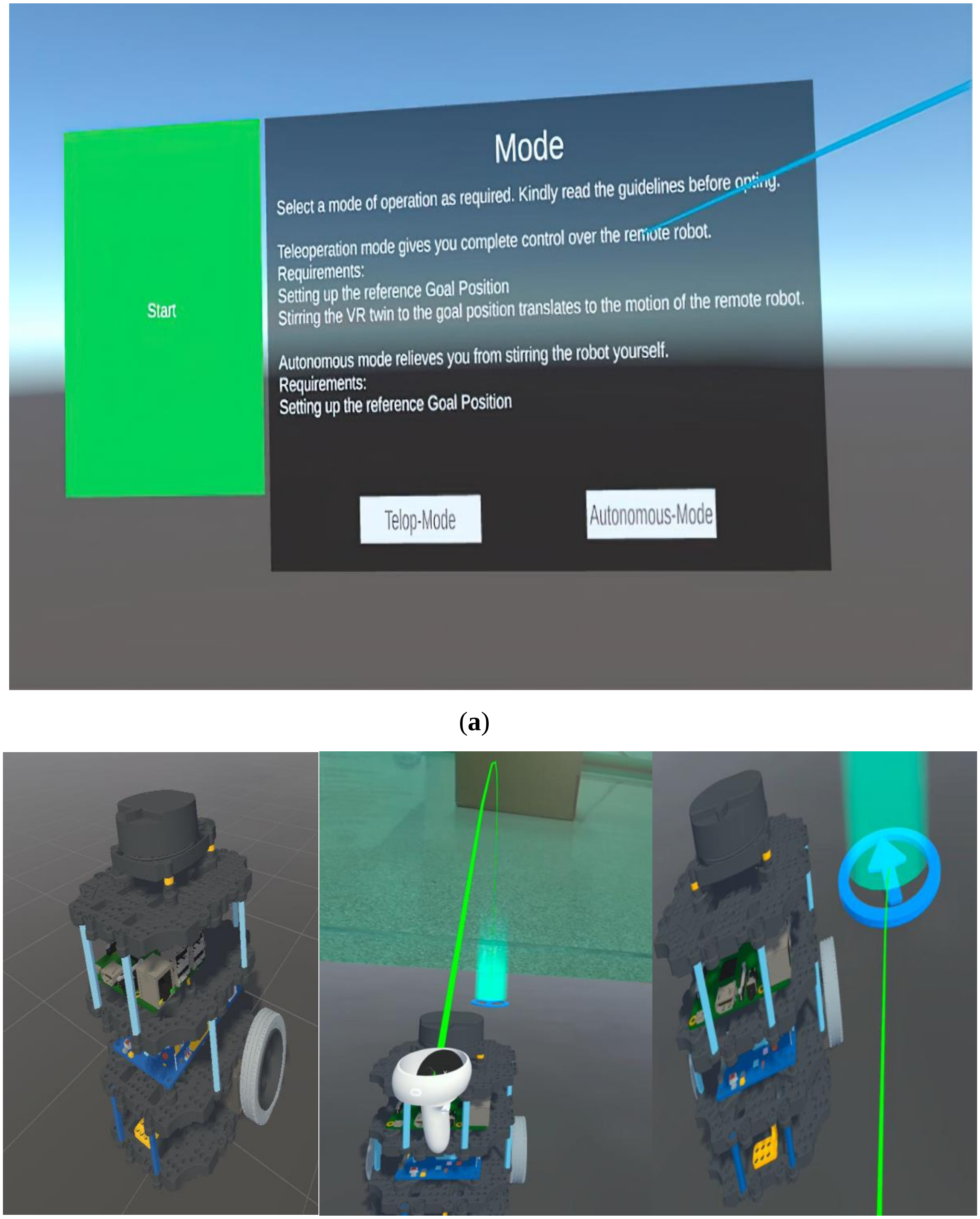
The mobility and flexibility of standalone VR applications are exceptional. Free from the constraints of a stationary system, they enable users to immerse in VR experiences in diverse environments. This mobility is a game-changer, particularly in education and business, where it allows for innovative, location-independent teaching methods and offers new avenues for immersive training and presentations.

Standalone VR applications also stand out for their cost-effectiveness. Their integrated design eliminates the need for expensive, high-powered computers and extra equipment, making virtual reality a more viable option for those with limited budgets. In the context of learning and training, the immersive and interactive nature of these applications presents a unique, experiential form of education. Medical students, for example, can practice surgeries in a risk-free virtual setting, while professionals in aviation and heavy machinery can train in safe, controlled VR environments, significantly reducing the risks and costs associated with real-life training.

In entertainment and gaming, standalone VR applications have ushered in a new era of immersive experience. They provide users with an engaging and realistic way to experience games and explore virtual worlds, far surpassing the capabilities of traditional gaming systems. Additionally, these applications are redefining the way teams collaborate, especially in remote working scenarios. They offer a virtual space where individuals can interact and collaborate as if they were in the same physical room, which is invaluable in fields that rely heavily on visual and interactive teamwork, such as architecture, engineering, and design.

The marketing and retail sectors are also leveraging standalone VR applications to create innovative customer experiences. Businesses can now design immersive virtual showrooms and interactive demos, providing customers with a novel way to engage with products. This not only enhances customer interaction but also serves as an impactful marketing strategy. Moreover, these applications are playing a crucial role in promoting physical health by encouraging users to engage in virtual activities that require physical movement, effectively combining fitness with entertainment.

Our VR application allows the user to select a mode of operation which integrates different functionality through a laser selection-based UI. The environment has a semi dome shape with a grid-based floor with each small square having an area of 1m^2 the use can adjust the floor level for best viewing point. The contrast of white grid lines over a charcoal-colored floor makes it convenient for the operator to select a goal point using a laser pointer as shown in figure 2.2b. The environment includes a gigantic, curved display that displays the live video feed coming from the robot’s camera. A 3D model that exactly replicates the actual robot is also placed in the environment. The incorporates every single detail from LDS senor to mounted onboard micro controllers.



Mode

Select a mode of operation as required. Kindly read the guidelines before opting.

Teleoperation mode gives you complete control over the remote robot.
Requirements:
Setting up the reference Goal Position
Stirring the VR twin to the goal position translates to the motion of the remote robot.

Autonomous mode relieves you from stirring the robot yourself.
Requirements:
Setting up the reference Goal Position

(**a**)

(**b**) (**c**) (d)

Figure 2.2. VR android application. (a) Application UI to select mode of operation (b) Grid based environment floor to aid in selection of goal position. (c) Selection of reference goal position via laser pointer. (d) User teleportation.

2.2 Modes of operation

Application prompts the user to opt for preferred mode of operation along with instructions of usage, behavior for each mode of operation.

- Fully Teleoperated mode: Upon selection of the goal reference position which is represented by a sky-blue shader as shown in figure 2a then user can maneuver the robot angularly as well as linearly using the oculus controllers in hand the robot. Since the virtual twin pose changes are communicated to the actual robot it can behave in synchronization while the user receives visual and auditory feedback in the environment.
- Semi-Autonomous mode: Likewise, the user initially must select the goal reference point and then just monitors the sensory feed coming from the real world whilst both the real robot and the virtual counterpart navigate autonomous avoiding any encountered obstacles.

User once in the virtual environment can explore the environment. User mobility in the environment is managed in the following ways.

- Physical Movement: The user moves around in the environment as the VR headset pose is being tracked constantly. The physical movement is bounded by the VR boundary drawn by the user initially. Omni directional treadmills can also be used to avoid this [52].
- Teleportation: The user can also teleport themselves from their present position to another just by selecting a teleportation destination as shown in figure 2b. The user can also adjust the direction of jump whilst selecting the destination. For better experience the user application restricts the user not to change the robot reference goal position whilst teleporting.

2.3 Conceptual Design:

The remote pc serves as a control node to mediate communication between VR headset and the robot. It runs the relevant functionality upon receiving the selected mode choice. Algorithm 1 describes the computational workflow whist operation in running in Fully Teleoperation mode and Algorithm 2 describes the Semi-Autonomous Mode.

The robot collects the percepts from the environment through a lidar sensor and a camera while its internal state via intelligent servo motors (dynamixel) [74] and compiles the data in form of serialized messages that can be sent over to the local workstation for manipulation. It is worth mentioning that the image stream is compressed locally by the onboard computer before sending it into the virtual environment.

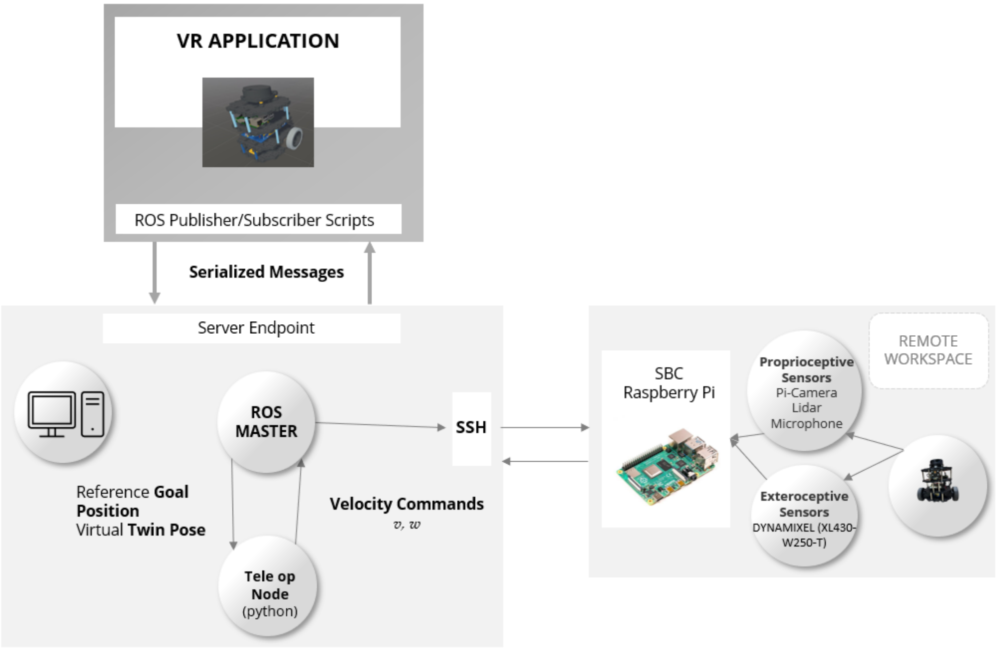


Figure 2.3. Workflow for Fully teleoperated mode of operation

The robot collects the percepts from the environment through a lidar sensor and a camera while its internal state via intelligent servo motors (dynamixel) [53] and compiles the data in form of serialized messages that can be sent over to the local workstation for manipulation. It is worth mentioning that the image stream is compressed locally by the onboard computer before sending it into the virtual environment.

Algorithm 1. This describes conceptual design for the fully teleoperated mode of operation.

```
Mode Selection = {fully-teleoperation, semi-autonomous}
Global Goal Point = $P_{ref}$
Robot Current Position = $P_t$
VR-Twin-pose = $(x, y, \theta)$
While (Compressed Image Stream == True)
  If (difference $(P_{ref} - P_t) <> \varepsilon$ )
    If $\Delta x \ OR \ \Delta y \ != 0$
```

```
        Publish $v$
      If $\Delta\theta \; ! = 0$
        Publish $w$
    Else
      Destination arrived buzzer == True
```

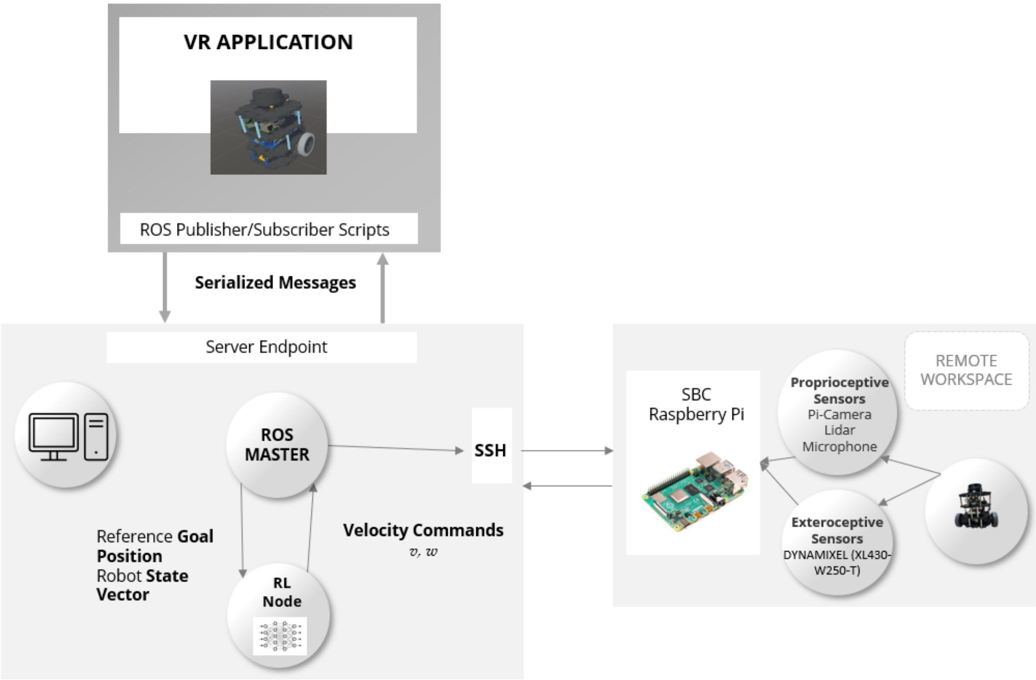


Figure 2.4. Workflow during Fully teleoperated mode of operation

Upon receiving the environment and robot state messages relevant data is vectored and fed into the pretrained actor critic network which return computes the desired velocity commands for the remote mobile robot to autonomous navigate while avoiding obstacles.

Algorithm 2. This describes conceptual design for the fully teleoperated mode of operation.

```
Mode Selection = {fully-teleoperation, semi-autonomous}
Global Goal Point = $\boldsymbol{P_{ref}}$
Robot Current Position = $\boldsymbol{P_t}$
VR-Twin-pose = $(\boldsymbol{x}, \boldsymbol{y}, \theta)$
```

```
While (Compressed Image Stream == True)
  While (Goal Point Reached == False)
    Update Environment State = (LDS readings, goal direction, distance remaining)
    Update Robot State = (Environment State, Last action ($v_p$, $w_p$) *)
    If (difference ($\boldsymbol{P}_{ref}$,$\boldsymbol{P}_t$) < > $\boldsymbol{\varepsilon}$ )
      ($v_c$, $w_c$) = TD3_action*
    Else
      Destination arrived buzzer == True
```

*Action computed from Twin Delayed Deep Deterministic Model.

Upon receiving the environment and robot state messages relevant data is vectored and fed into the pretrained actor critic network which return computes the desired velocity commands for the remote mobile robot to autonomous navigate while avoiding obstacles.

To achieve this local autonomous navigation in the unknown remote environment by the robot after receiving a reference goal position from the VR environment, this work utilizes a navigation structure that utilizes a deep reinforcement learning methodologies. A TD3 based reinforcement learning model is incorporated to develop the navigation policy [75,76]. This facilitates the execution of actions within a continuous action space through its actor-critic network. After locking in the goal coordinates, the robot initial distance from and heading towards the goal point are calculation given by (1) and (2) respectively. While once the robot starts moving relative angle between the robots heading and the heading towards the goal by aligning frames through angular difference computed by (3). This helps in obtaining the destination polar coordinates in robot's frame of reference.

$$d_g = \sqrt{\left(\boldsymbol{P}_{\boldsymbol{ref},\boldsymbol{x}} - \boldsymbol{P}_{\boldsymbol{t},\boldsymbol{x}}\right)^{\boldsymbol{2}} + \left(\boldsymbol{P}_{\boldsymbol{ref},\boldsymbol{y}} - \boldsymbol{P}_{\boldsymbol{t},\boldsymbol{y}}\right)^{\boldsymbol{2}}} \tag{2.1}$$

$$\alpha = tan^{-1} \frac{(\boldsymbol{P}_{\boldsymbol{ref},\boldsymbol{y}} - \boldsymbol{P}_{\boldsymbol{t},\boldsymbol{y}})}{(\boldsymbol{P}_{\boldsymbol{ref},\boldsymbol{x}} - \boldsymbol{P}_{\boldsymbol{t},\boldsymbol{x}})} \tag{2.2}$$

$$\theta_g = \alpha - \theta_t \tag{2.3}$$

A single environment state vector (s) comprising of; laser scan readings, polar destination coordinates, and previous action is feed to the action predicting neural network of the TD3 and an action is computed based upon this state vector and executed towards the destination point.

The first network (actor neural network) comprises three FC layers, with sigmoid activation function applied and the end of each. The last one is linked to the action predicting layer. The actions include v and w, representing the robot's linear velocity and angular velocity, respectively. The action predicting layer incorporates a tan hyperbolic activation function to constrain the output range from -1 to 1. Prior to application in the environment, the action a is represented as a tuple (v, w) is scaled by the upper bound of the linear velocity (v_{max}) and upper bound of the angular velocity (ω_{max}) using the following formula:

$$a = \left(v_{max} \left(\frac{v+1}{2} \right), w_{max}(w) \right) \tag{2.4}$$

The Q-value for a single state-action pair Q (s, a) is assessed by two critic networks. This helps coping with Q-value overestimates. While both critic networks share the same structure such that a three fully connected layers, their parameter updates are staggered, allowing for divergence in parameter values. These networks take a pair of the state s and action a as input. The states undergo processing through a fully connected layer followed by ReLU activation, resulting in output O_s. This output, along with the action, is directed into two separate transformation fully connected layers (TFC) of identical size, κ_1 and κ_2, respectively. Subsequently, these layers are combined in the following manner:

$$O_c = O_s \omega_{\kappa_1} + a \omega_{\kappa_2} + B_{\kappa_1} \tag{2.5}$$

Here, O_c denotes the unified fully connected layer (UFC), where ω_{κ_1} and ω_{κ_2} represent the weights of κ_1 and κ_2, respectively. Additionally, B_{κ_1} signifies the bias of layer κ_2. Subsequently, ReLU activation is applied to the combined layer, followed by a connection to the output with a single parameter representing the Q value. The minimum Q value from both critic networks is then chosen as the ultimate critic output to mitigate overestimation of the state-action pair value. The comprehensive network architecture is depicted in Figure 2.5. The policy is rewarded based on the function:

$$R\left(s_{t,}a_t\right) = \begin{cases} R_g,\ if\ d_t < \varepsilon \\ R_c,\ if\ collision \\ v_t - |w_t|,\ otherwise \end{cases} \tag{2.6}$$

The reward (R) for the state-action pair $\left(s_{t,}a_t\right)$ at timestep t depends on three conditions. If the distance to the goal at the current timestep (d_t) is below the threshold ε, a positive goal reward (R_g) is applied. In the case of a detected collision, a negative collision reward (R_c) is applied. If neither of these conditions is met, an immediate reward is applied, determined by the current linear velocity (v) and angular velocity (w). To steer the navigation policy toward the specified goal, a delayed attributed reward method is utilized, as outlined in the following calculation:

$$R_{t-1} = R(s_{i-1}a_{i-1}) + \frac{R_{t-1}}{i} \ \forall\ i = \{1,2,3, \ldots .k\} \tag{2.7}$$

Here, "k" represents the count of preceding steps during which rewards are adjusted. This implies that the positive goal reward diminishes progressively over the last "k" steps leading up to reaching a goal. The network has acquired a comprehensive local navigation policy capable of reaching a local goal and adeptly steering clear of obstacles based directly on the laser inputs.

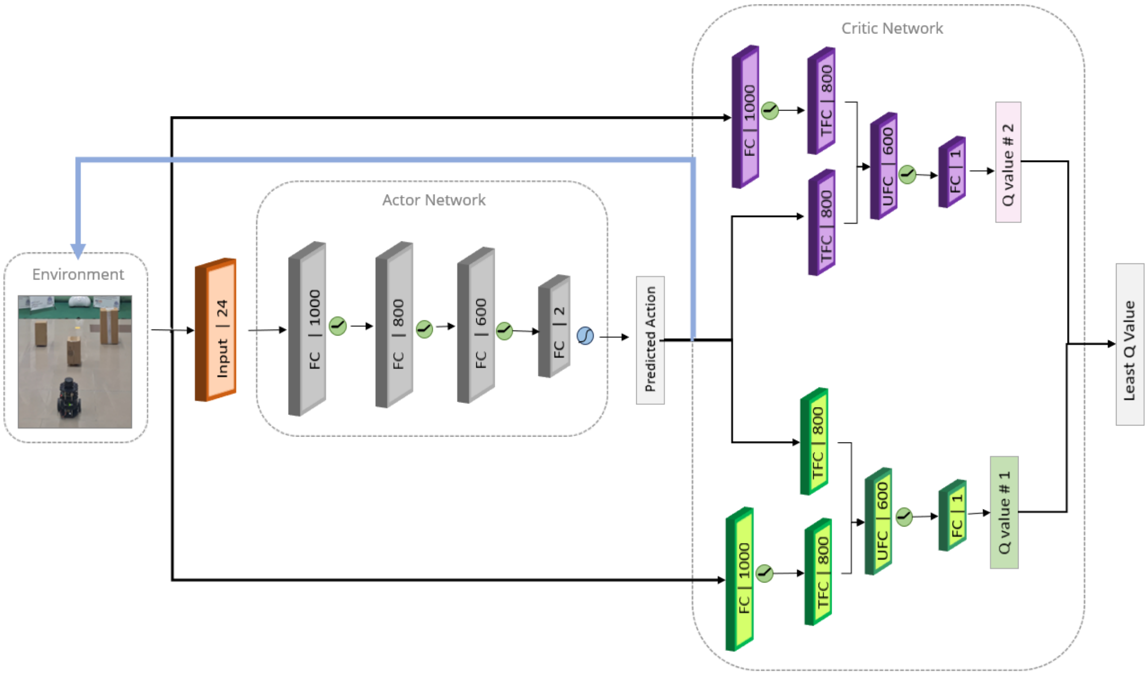
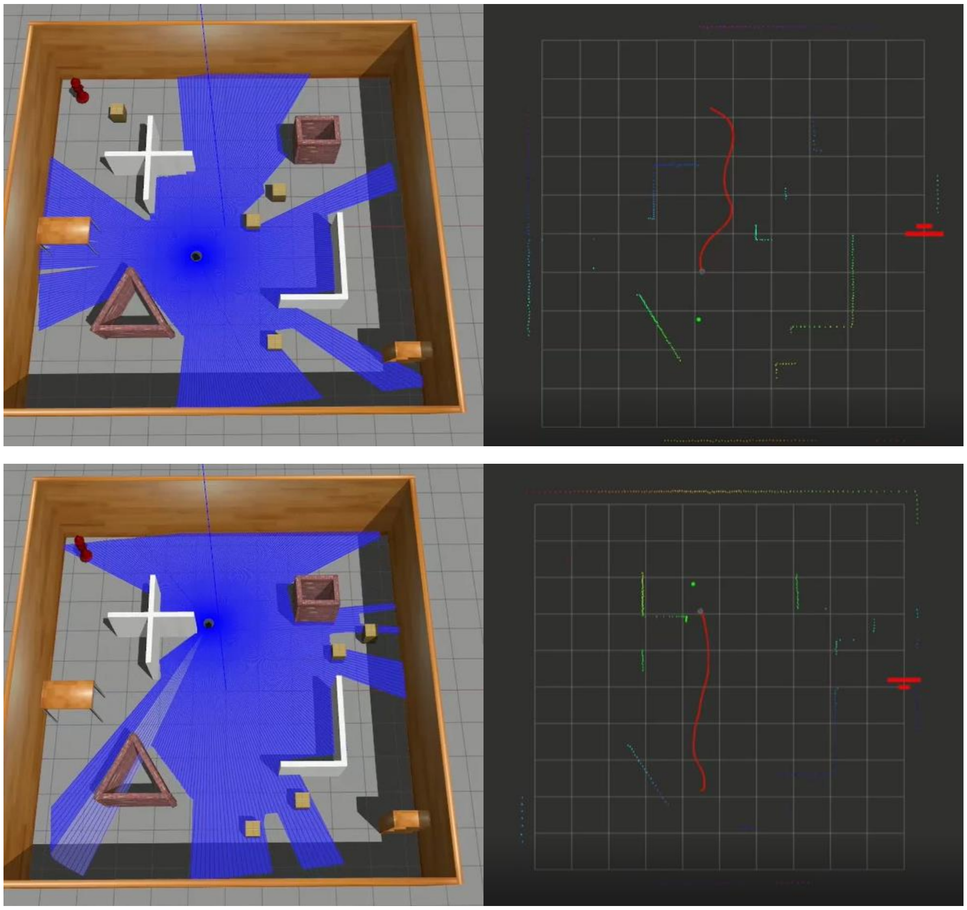


Figure 2.5. This describes the deep reinforcement learning model network structure consisting of actor and critic parts.

This local navigation learning through DRL occurred on a computer equipped with an NVIDIA GTX 3080 graphics card, 32 GB of RAM, and an Intel Core i7-10700K CPU. The network underwent training in Gazebo a physics simulator for 1200 episodes, taking approximately 10 hours. Each training episode concluded upon reaching a goal, detecting a collision, or completing 500 steps. The velocity limits, v_{max}, and w_{max} were set at 0.6 meters per second and 1 rad per second, respectively. Delayed rewards were updated over the last "$k = 12$" steps, and the parameter update delay was configured for every 4 episodes. The training environment was simulated in a 12x12 m-sized space cluttered with irregular shaped obstacles as illustrated in figure 6.

To guarantee the network's effectiveness in real-world situations beyond simulation, it was essential for it to acquire a generalized obstacle avoidance capability from laser data. To foster generalization and facilitate policy exploration, Gaussian noise was incorporated into both sensor and action values generated by the network. Furthermore, to enhance the simulation-to-real transfer, the environment underwent variation in each episode by randomly adjusting the positions of box-shaped obstacles.



(a) **(b)**

Figure 2.6. Training overview. (a) The identical box obstacles being randomly placed after each episode, (b) The RVIZ [77] highlighting the robot path while reaching the goal marker.

Nomenclature

P_{ref}	Reference position passed from the virtual environment.
P_t	Current Robot Pose data calculated through odometry.
ε	Tolerance between set and reached position.
v_p	Previous action’s linear velocity
w_p	Previous action’s angular velocity
v_c	Current action’s linear velocity
w_c	Current action’s angular velocity
d_g	Robot’s initial distance from the goal point.
α	Robot’s initial heading towards the goal point.
θ_g	Relative angle between the robots heading and the heading towards the goal.

CHAPTER 3: EXPERIMENTATION

Utilizing questionnaires to garner insights from users of Virtual Reality (VR) interfaces is becoming a key approach for developers and researchers in the field. This method stands out for its ability to provide detailed feedback on user experiences, interface usability, and overall satisfaction. The value of questionnaires in this context can be examined through several lenses: the quality of data they generate, their impact on user engagement, and their overall practicality.

One major advantage of questionnaires is their ability to produce structured, measurable data. VR experiences are highly subjective, varying greatly among individuals. Questionnaires, particularly when employing scales like Likert, offer a way to quantify these experiences, making it easier to spot common patterns or areas for improvement across a diverse user base. This structured approach is particularly useful in VR, where experiences can range from purely recreational to highly specialized professional applications.

However, the effectiveness of questionnaires hinges significantly on their design. If a questionnaire is poorly crafted, with ambiguous or leading questions, the collected data may not accurately represent the user experience. Ensuring clarity and relevance in the questions is crucial. This includes avoiding language that might bias responses and aligning questions closely with the specific facets of the VR interface being assessed.

Engaging users in the feedback process is another critical aspect. Given the interactive nature of VR, embedding digital questionnaires within the VR environment could enhance participation rates. This method captures users' immediate reactions, which are vital for understanding their true experience. Moreover, incorporating the feedback process into the VR environment maintains the immersive experience and might yield more genuine responses.

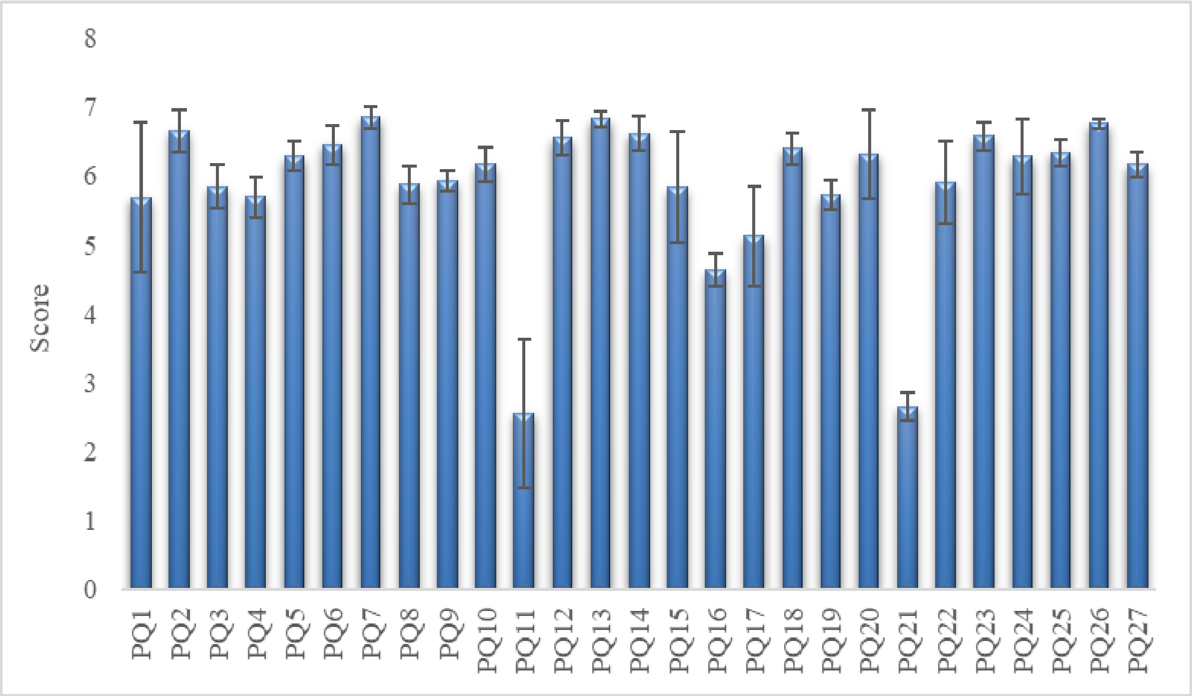
Anonymity in questionnaires is a noteworthy advantage, particularly in VR settings. Users might be reluctant to share negative feedback directly, but the anonymity provided by questionnaires can encourage more honesty. This aspect is essential in VR, where experiences are deeply personal and varied.

From a practical standpoint, questionnaires are an economical and efficient method for collecting feedback. They can be disseminated widely and quickly, making them a viable option even for entities operating with constrained resources. This cost-effectiveness is especially appealing for startups and smaller research teams in the VR industry.

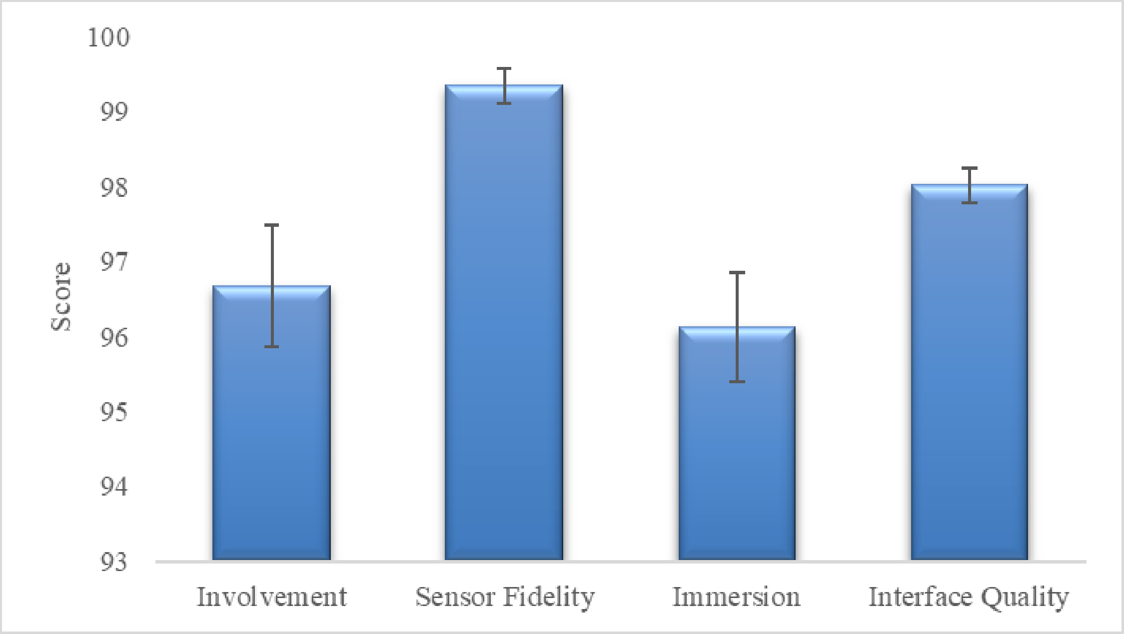
In summary, questionnaires are a valuable tool for obtaining user feedback on VR interfaces. They offer a way to systematically capture and analyze user experiences, engage users in the feedback process, and do so in a cost-effective manner. The success of this method, however, is contingent upon the thoughtful construction of the questionnaire itself, ensuring it accurately reflects the diverse and subjective experiences of VR users.

In alignment with references [57–62], various methodologies, including conventional application usability tests and user interviews, were implemented to underscore the benefits of the suggested approach. The participants in this study were tasked with completing three established questionnaires: PQ [63,64], IPQ [65–67], SUS [68] after completing a rescue operation in a remote arena settled for the robot to navigate in. Image stream coming from robot is compressed and published at a rate of 5hz while the odometry and sensor scan data is published at 30 Hz.

3.1. Dimensional Awareness



(a)



(b)

Figure 3.1. Results accumulated after user feedback on Presence Questionnaire (a) Mean score for each question along with deviation computed (b) Results category 1) involvement 2) sensor fidelity 3) Immersion 4) Interface Quality

The selection of PQ and IPQ was based on their widespread use in assessing the sense of presence in Virtual Environments (VEs), including factors such as realism, interface quality, and the quality of chosen devices. The System Usability Scale SUS questionnaire was employed to evaluate the usability of the proposed interface due to its brevity, precision, and extensive usage.

Specifically, the PQ was administered to assess the user experience within the Virtual Environment. 27 out of the total 29 questions from the third version of the PQ questionnaire were chosen based on the relevance to the nature of the proposed application. The PQ utilizes a liability scale of 1-7 and comprises four subscales: sensor fidelity, involvement, interface quality and immersion, this comprehensive set of questionnaires was employed to gather insights into various aspects of the user experience, presence, and usability associated with the proposed virtual reality interface.

Figure 3.1 depicts the results of the Presence Questionnaire (PQ). Figure 3.1a show-cases the mean and standard deviation for each PQ question, while Figure 10b exhibits the average, deviation, and total percentage for each PQ subscale. Remarkably, the Involvement score reached 96.7% with a standard deviation of 1.2, signifies that users were deeply focused on the virtual reality environment and actively participated in all presented facets.

The Sensor Fidelity score reached 99.4% with a standard deviation of 0.4, Suggesting that users can seamlessly interact with all objects within the virtual realm while perceiving from multiple perspectives. The Immersion score, with a standard deviation of 0.8, reached 96.1%, indicating that users could adeptly and effortlessly ac-climate to the Virtual Environment (VE), carrying out tasks without interruptions. Lastly, the Interface Quality score stood at 98.2% with deviation of 0.5 from the mean, indicating that users did not encounter any lapses or dysfunctionalities while being in the virtual environment throughout the tasks.

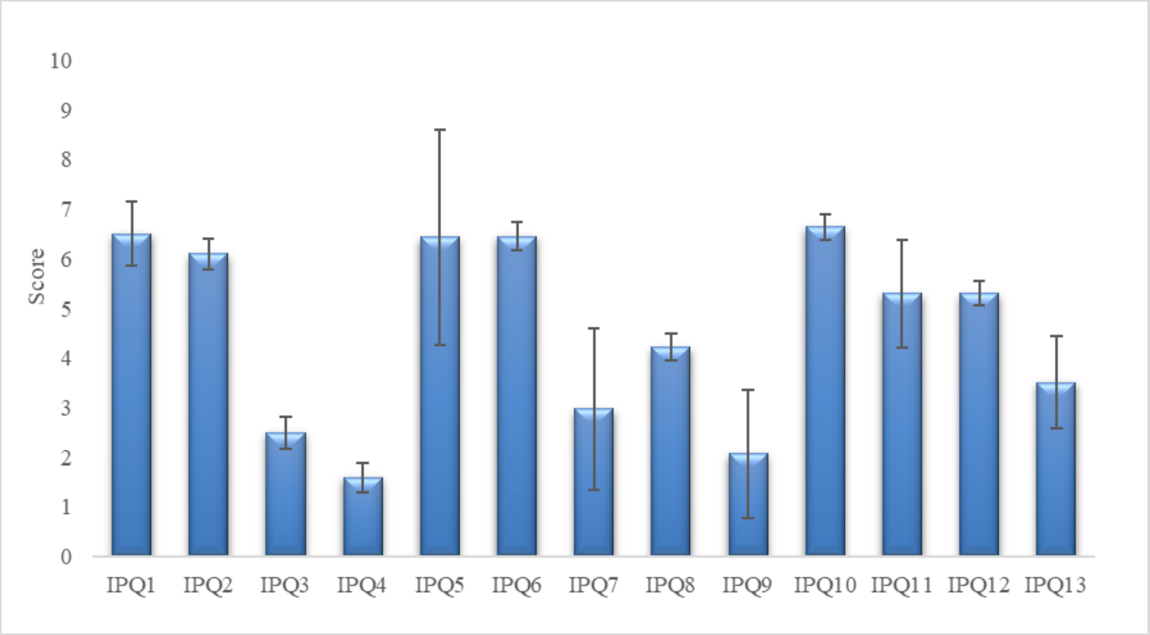
On the contrary, the I group Presence Questionnaire (IPQ) was implemented to gauge the sense of presence that users experienced within the designed Virtual Environment (VE) [69]. Comprising 13 questions, the IPQ evaluates three key subscales:

- Spatial presence: indicating the realization on user’s part of being physically present in the Virtual Environment.
- Engagement: measuring the attention and involvement experienced in the Virtual realm.
- Experienced realism: assessing the subjective perception of realism within the Virtual Environment.

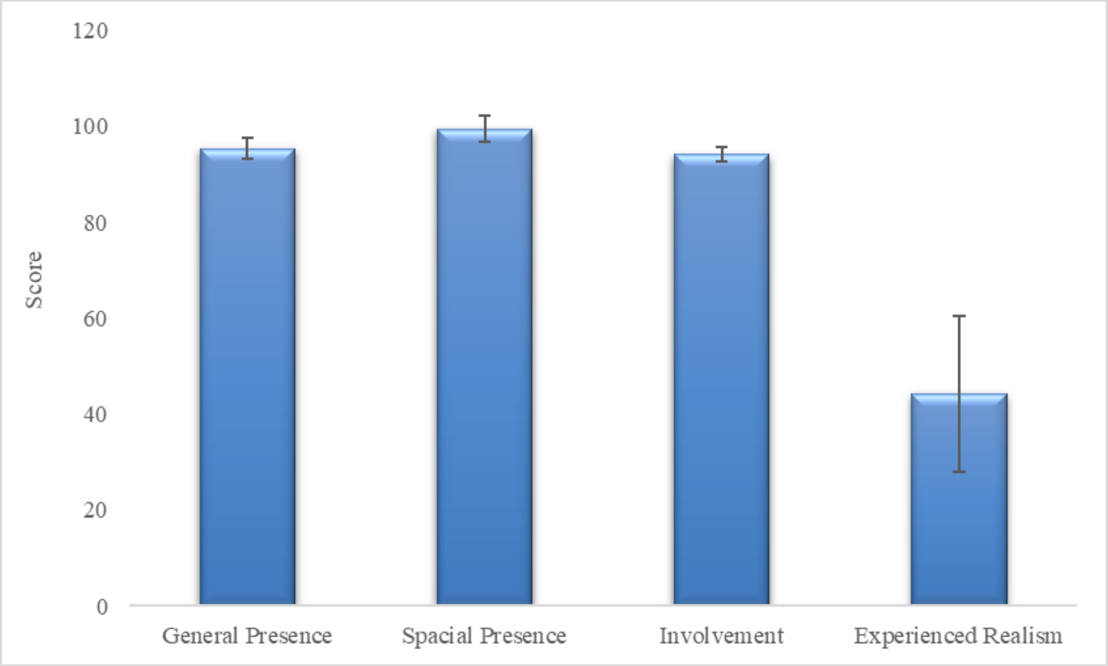
Additionally, the IPQ incorporates a general item gauging the overall "sense of being there," with notable emphasis on dimensional awareness.

The feedback from IPQ is depicted in Figure 3.2. Precisely, Figure 8a illustrates the average user rating along with its dispersion for each IPQ question, while Figure 8b represents the same, and total percentage for each IPQ subscale. Notably, the general presence score reached 95.45% with a standard deviation of 2.2, indicating that users felt as if they were inside the Virtual Realm. The spatial presence score achieved 99.5% with a standard deviation of 2.8, suggesting that users felt physically present within the VE. The involvement score, at 94.1% with a standard deviation of 1.6, reinforced the involvement scores from the PQ, confirming that users engaged actively and maintained focus on all elements of the Virtual Environment.

Finally, the encountered realism rating registered at 44.3% with a standard deviation of 16.2, signifying that user consistently perceived themselves in a VE, devoid of realistic objects. This aligns with the intended goal of the proposed approach, prioritizing a natural and user-friendly VE suitable for most contemporary commercial VR headsets. It is worth noting that the avoidance of heightened realism aligns with the objective of not designing an overtly "realistic" scenario, considering the associated computational costs and the need for specialized hardware, such as graphic cards.



(a)



(b)

Figure 3.2. Results accumulated after user feedback on Igroup Presence Questionnaire (a) Mean score for each question along with deviation computed (b) 1) General Presence 2) Spatial Presence 3) Involvement 4) Experienced Realism

3.2 System Acceptance

Concerning the System Usability Scale (SUS) questionnaire, the comprehensive assessed usability achieved a score of 94.71 out of 100, with a minimum of 79.5, a maximum of 100, and a standard deviation of 4.18. This indicates that the presented immersive framework interface achieved a notably elevated usability level. Additionally, Figure 9 visually presents the data gathered the questionnaire responses were accumulated. It's noteworthy that most participants showed interest in using the application, citing its user-friendly nature. Participants found the interface easy to navigate and highlighted the seamless integration of all functionalities. Furthermore, the users perceived the proposed interface as consistent and reported a high level of confidence in its usability.

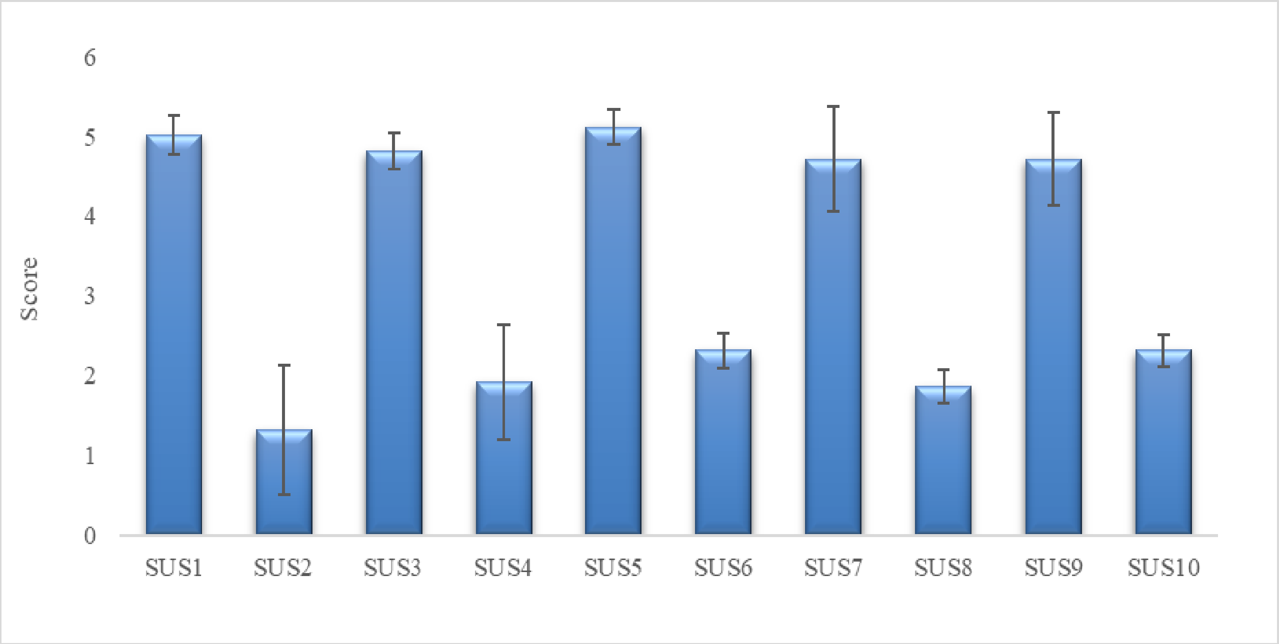
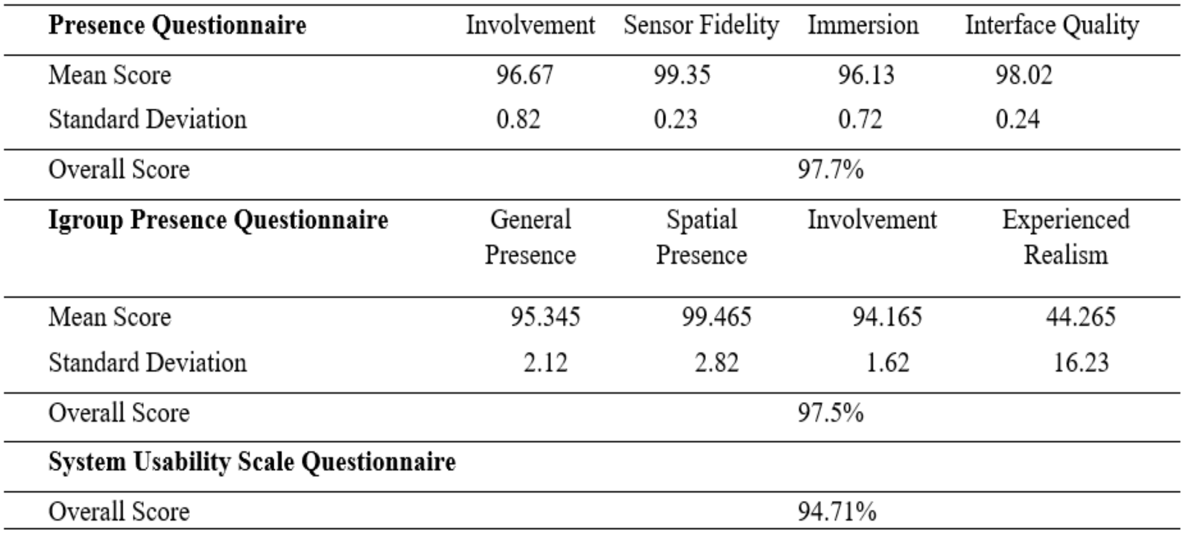


Figure 3.3. Results accumulated after user feedback on System Usability Scale Questionnaire

To summarize the findings from the questionnaire feedback Table 1 it is worth mentioning that the results show significant improvement than a similar work presented by [47].

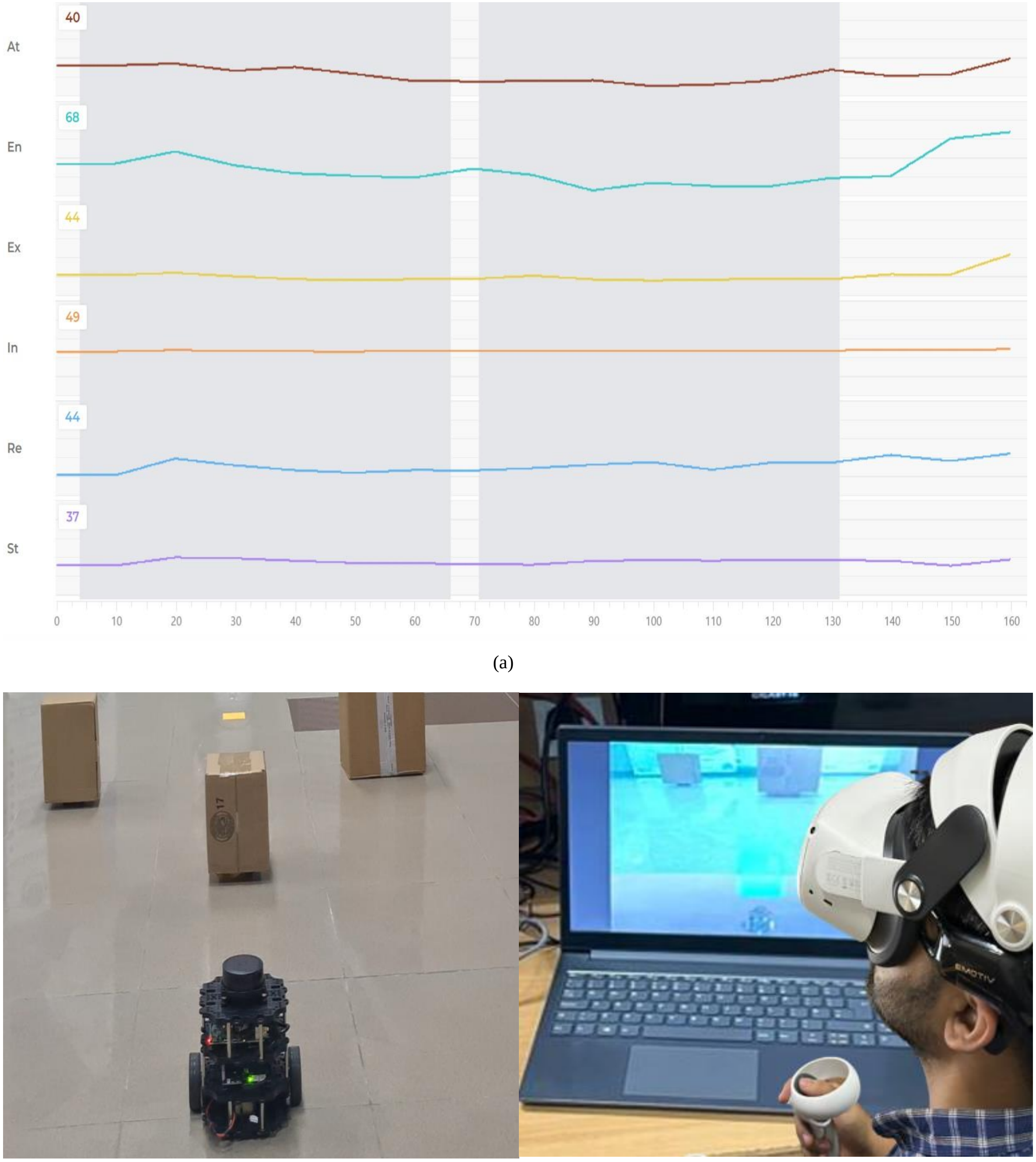
Table 3.1. Results from Questionnaires User Feedback.



Presence Questionnaire	Involvement	Sensor Fidelity	Immersion	Interface Quality
Mean Score	96.67	99.35	96.13	98.02
Standard Deviation	0.82	0.23	0.72	0.24
Overall Score			97.7%	
Igroup Presence Questionnaire	General Presence	Spatial Presence	Involvement	Experienced Realism
Mean Score	95.345	99.465	94.165	44.265
Standard Deviation	2.12	2.82	1.62	16.23
Overall Score			97.5%	
System Usability Scale Questionnaire				
Overall Score			94.71%	

3.3 Cognitive Workload

To further analyze the operator’s behavior, we simultaneously validate the operator’s performance via inspection through emotive insight BCI Emotive. It provides an innovative user interface for Human-Computer interaction, utilizing the latest advancements in neurotechnology. Emotive Insight 2.0 is a wireless neuroheadset with 5 semi-dry electrodes, capable of high-resolution detection of the user's real-time thoughts, emotions, and gestures. In various crucial aspects such as durability, comfort, affordability, user-friendliness, hygiene, and non-intrusiveness, this headset outperforms other electroencephalogram monitoring devices. The EEG sensors—AF3, AF4, T7, T8, and Pz5—are strategically placed on the human head following the standard 10-20 international system for electrode placement [90]. Due to the low amplitude of the acquired signals, amplification is necessary. The Emotive headset offers amplification and filtering capabilities for EEG signals within the frequency range of 0.3 to 45Hz, along with removal of additional noise at frequencies ranging from 50 Hz to 60Hz. Although the signals reaching the users operate at 128Hz, they are captured from the scalp at an amplified rate of 2048Hz. We utilized the provided Emotive’s API to receive Human Performance metrics driven from the operator’s brain activity during the task as illustrated in figure 10a.



(a)

(b)

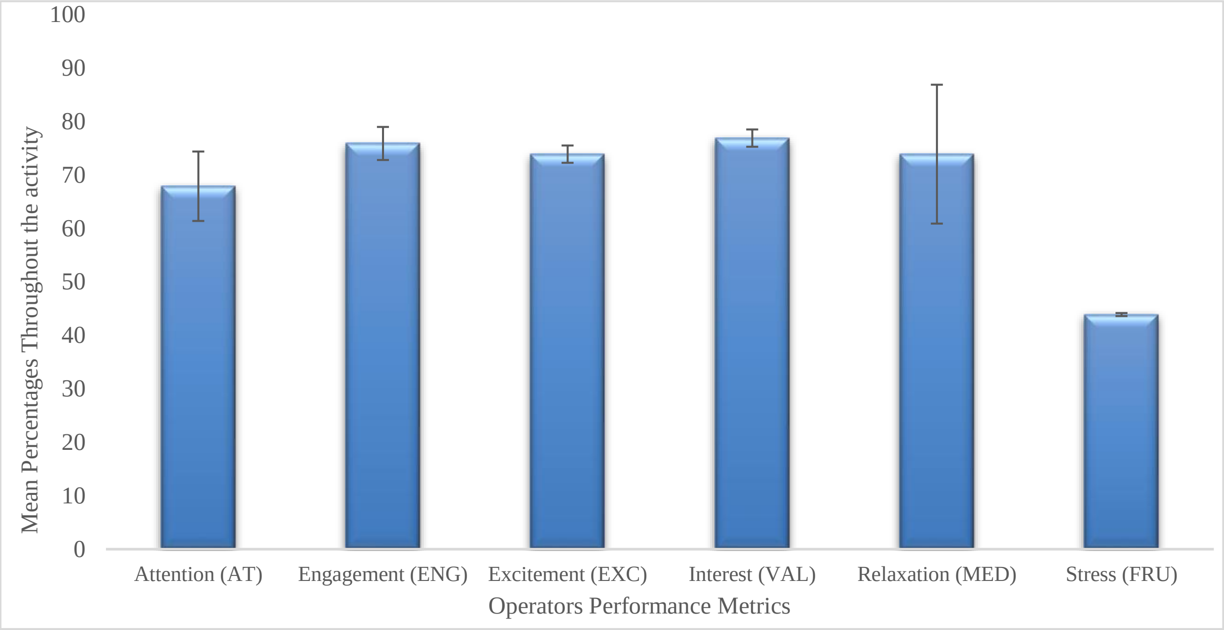
Figure 3.4. BCI data collection overview. (a) Human Performance metrics such as attention, engagement, excitement, interest, relaxation, and stress percentages presented on y axis vs duration of the task (b) Depiction of user performance the rescue task while being monitored through Emotive Insight EEG headset.

amplitude of the acquired signals, amplification is necessary. The Emotive headset offers amplification and filtering capabilities for EEG signals within the frequency range of 0.3 to 45Hz, along with removal of additional noise at frequencies ranging from 50 Hz to 60Hz. Although the signals reaching the users operate at 128Hz, they are captured from the scalp at an amplified rate of 2048Hz. We utilized the provided Emotive's API to receive Human Performance metrics driven from the operator's brain activity during the task as illustrated in figure 10a.

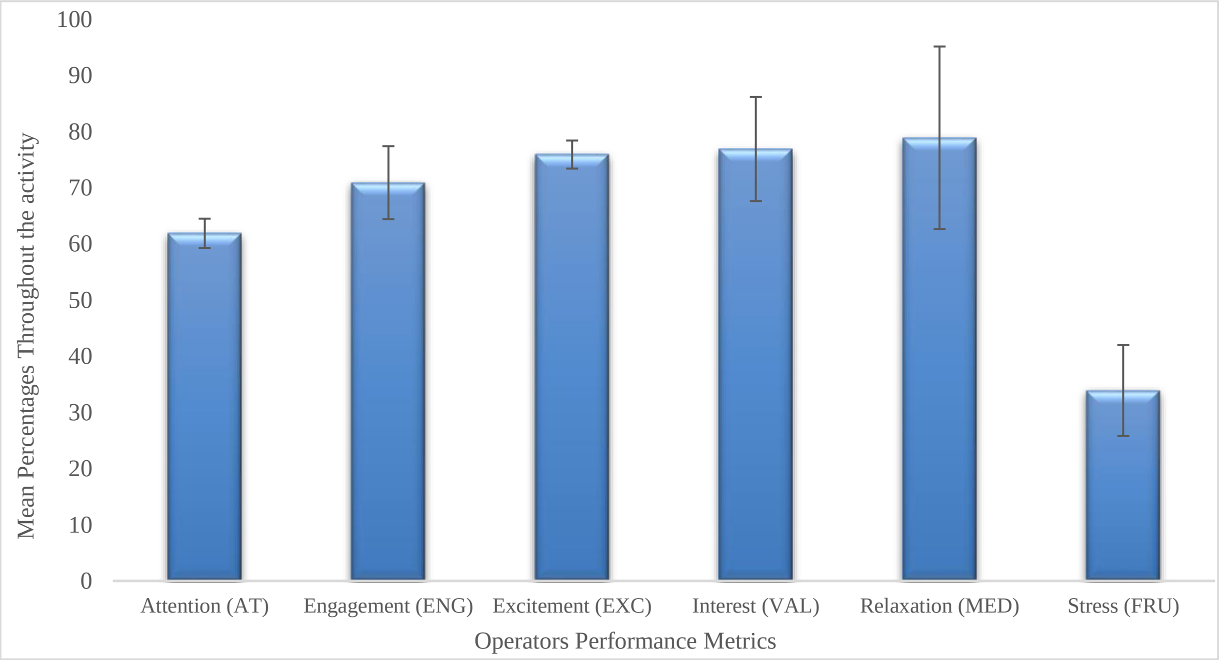
Each user participating in the study was required to complete a simple task with the result being the robot reaching the goal position while operating in both modes of control fully teleoperated and semi-autonomous respectively. The performance metrics such as attention, engagement, excitement, interest, relaxation, and stress percentages were reported as illustrated in figure 11 along with their average and standard error highlight effectiveness of the interface. Mean stress and relaxation values during both modes suggest that the operator feels more at ease and shows a better performance while the robot navigates autonomously. This shows the advantage of having dynamic operator control over the remote mobile robot during the teleoperation.

Table 3.1. Human performance metrics calculated from brain activity monitoring through Emotive Insight 2.0.

Operation in Fully teleoperated mode	Attention (AT)	Engagement (ENG)	Excitement (EXC)	Interest (VAL)	Relaxation (MED)	Stress (FRU)
Mean Score	67.4	75.3	73.7	76.1	73.4	43.9
Standard Deviation	6.43	3.09	1.62	1.62	12.98	3.28
Operation in Semi-Autonomous mode						
Mean Score	61.21	70.32	75.61	76.115	78.12	33.92
Standard Deviation	2.58	6.49	2.49	9.27	16.23	8.12



(a)



(b)

Figure 3.5. BCI Evaluation results: (a) Performance metrics during Fully Teleoperation mode of control. (b) Performance metrics during Semi-Autonomous mode of control.

CHAPTER 4: CRITICAL REVIEW

4.1- Relevant SDG Area:

Robotics plays a crucial role in various industries and has a significant impact on productivity, safety, and economic growth. Here are some statistics that highlight the importance of robotics:

Economic Impact:

- The IFR predicts that the installation of industrial robots will increase by an average of 12% per year from 2020 to 2023.
- A study by the Boston Consulting Group estimated that by 2025, the global market for robotics will reach $87 billion, with an annual growth rate of 10%.

Employment and Labor Productivity:

- According to the World Economic Forum, the adoption of robots and automation technologies is expected to create 12 million net job opportunities by 2025 across various industries.
- A study conducted by the Centre for European Economic Research found that for every additional robot per thousand workers in manufacturing industries, employment increased by 3%.
- The Organization for Economic Co-operation and Development (OECD) reports that productivity growth in countries with higher robot density is significantly higher than in countries with lower robot density.

Manufacturing Industry:

- The automotive industry is one of the largest users of robotics. In 2020, around 113,000 industrial robots were installed in the automotive sector, accounting for approximately 30% of total robot installations.
- The use of robotics in manufacturing processes can lead to cost savings and increased efficiency. A study by PwC estimates that robotization can reduce manufacturing labor costs by up to 16% in high-wage countries.

Healthcare Industry:

- The demand for robotics in the healthcare industry is growing rapidly. The international medical robotics market is projected to reach $25 billion by 2024, according to Market Research Future.
- Surgical robots are revolutionizing healthcare by enabling minimally invasive procedures, reducing patient trauma, and improving surgical precision. The use of surgical robots can lead to faster recovery times and reduced hospital stays.

Safety and Workplace Injury Reduction:

- The use of robots in hazardous and physically demanding environments helps protect human workers from potential injuries. A study by NIOSH reported a 61% reduction in injury rates when robots were introduced in manufacturing settings.

The proposed project also utilizes Virtual Reality (VR) technology to leverage the robotics framework. Th VR has gained significant importance across various industries and has shown remarkable potential in transforming user experiences and driving business growth. Few statistics that highlight the importance of VR technology:

Training and Simulation:

- VR technology has proven highly effective in training and simulation applications, allowing users to experience realistic scenarios in a controlled virtual environment.
- According to a study by PwC, VR-based training resulted in a 90% increase in knowledge retention compared to traditional training methods.
- Walmart implemented VR training programs across its stores and reported a 70% improvement in employee performance and a 29% increase in customer satisfaction.

Healthcare and Medical Training:

- The medical industry has embraced VR technology for training healthcare professionals, medical simulations, and patient treatment.
- A study published in JAMA Network Open found that VR surgical simulations resulted in a 230% improvement in surgical performance compared to traditional training methods.

Real Estate and Architecture:

- VR technology is revolutionizing the real estate and architecture industries by providing immersive virtual property tours and 3D visualizations.

- A study by the National Association of Realtors (NAR) revealed that 77% of homebuyers found virtual tours beneficial in their search process, and 41% of buyers purchased a home they initially viewed through a virtual tour.
- The use of VR in architecture and construction enables stakeholders to visualize and experience designs before construction, reducing errors and improving client satisfaction.

These statistics illustrate the increasing importance of VR technology across industries such as training, healthcare, real estate, and entertainment. VR provides immersive experiences, enhances training effectiveness, improves customer engagement, and drives revenue growth. As technology continues to advance and become more accessible, the potential applications and benefits of VR are expected to expand further.

The growing importance of robotics as discussed in various sectors, including manufacturing, healthcare, and beyond not only enhances productivity and economic growth but also contributes to job creation, improved workplace safety, and increased efficiency in industries worldwide.

This aligns the project with the SDG no 9 ***Industry, Innovation and Infrastructure*** and SGD no 8 ***Decent Work and Economic Growth.*** According to the World Bank, the informal sector in Pakistan employs a high percentage of the workforce. Deploying the proposed framework Recycling can provide formal employment opportunities to many of these workers, thereby reducing poverty and increasing the standard of living. This aligns perfectly with SGD no 11 for ***Sustainable Cities and Communities*** as the proposed project will not only provide effective and smart applications in discussed fields but also will create opportunities for local administration to sell out the indigenous product and services and utilize the generated funds on city development.

4.2- Problem Statement:

Major reasons include bringing national research at the forefront of billion-dollar robotics and VR industries. Making Robotics more accessible and operatable through smart use of VR based digital twins to perform more natural interaction between assistive robots and humans. The proposed research not only carves path for inclusion of VR in Robotics but also presents improvements on framework level.

4.3- Objectives of the project:

The major advantages of the proposed work are twofold. First the framework will provide a more improved and immersive thus a natural manner to teleoperate assistive robots. Second being the flexibility to shift operation modes from fully autonomous to teleoperation to help robot maneuver in complex and dynamic environments.

According to Industry-ALL around 60 accidents occurred in Pakistan mines in 2022 alone compromising several human lives and financial loses utilization of this research for mine inspection can help curtail these.

Government allocated a budget of 173m for bomb disposal services with the use this technology this can be significantly brought down without putting human lives in danger as well.

Apart from these the potential applications of VR-based interfaces for mobile robot teleoperation in Pakistan span a wide range of sectors, reflecting the country's unique blend of industrial, agricultural, and technological landscapes. These applications promise to transform various aspects of life and work in Pakistan, offering innovative solutions to longstanding challenges and opening up new opportunities for development and progress.

In the industrial sector, Pakistan, with its growing focus on manufacturing and industrialization, stands to benefit significantly from the deployment of VR-based teleoperated robots. These robots can be used in manufacturing plants and factories for tasks that are hazardous or require precision beyond human capability. For example, in the textile industry, one of the largest sectors of Pakistan’s economy, teleoperated robots can handle dangerous or repetitive tasks, reducing the risk of accidents and improving overall efficiency. Similarly, in the automotive industry, VR-based teleoperation can be used for precision assembly and quality control, ensuring higher standards and better outcomes.

Agriculture, a cornerstone of Pakistan's economy, is another area where VR-based teleoperated mobile robots can have a transformative impact. These systems can be employed for various agricultural tasks such as planting, harvesting, and pest control. The precision and efficiency offered by teleoperated robots can significantly increase crop yields and reduce labor costs. Moreover, in areas where certain crops or conditions pose risks to human workers, teleoperated robots can perform tasks without exposing workers to hazards, thereby enhancing safety in the agricultural sector.

In the field of healthcare, Pakistan's medical sector could leverage VR-based teleoperated systems for a variety of applications. Telemedicine, supported by VR technology, can enable specialists to perform surgeries or offer consultations remotely, a significant advantage for rural or remote areas where access to specialized healthcare is limited. In medical training, VR-based teleoperation can provide a safe and realistic environment for students to practice surgical procedures, enhancing their skills without the risks associated with practicing on real patients.

The potential of VR-based teleoperated robots in education extends beyond medical training. In Pakistan, where educational resources are often limited, particularly in remote areas, these technologies can provide interactive and immersive learning experiences. Students can explore virtual laboratories, participate in simulated archaeological digs, or conduct scientific experiments in a controlled, virtual environment, thus overcoming the limitations of physical resources and geographical barriers.

Disaster management in Pakistan, a country frequently challenged by natural calamities such as earthquakes, floods, and landslides, is an area where VR-based teleoperated mobile robots can significantly contribute. The introduction of these advanced technological systems can revolutionize the way disaster response and recovery operations are conducted, offering safer, more efficient, and effective means to manage the aftermath of such events.

In the context of Pakistan, which lies on active seismic zones and experiences substantial monsoon rains leading to flooding, the application of teleoperated robots can be a game-changer in minimizing the impact of these disasters. One of the primary advantages of using VR-based teleoperated robots in disaster management is their ability to access areas that are either too dangerous or inaccessible for human responders. For instance, in the aftermath of an earthquake, buildings may be left unstable, and aftershocks can further exacerbate the risks. Teleoperated robots, controlled by operators from a safe distance, can navigate through the rubble and debris, reaching areas that rescue teams might find challenging or impossible to access.

The use of VR interfaces allows operators to have a more immersive and detailed understanding of the disaster site. Equipped with cameras and sensors, these robots can provide real-time data and visuals of the affected areas, which is crucial for assessing the situation and planning rescue operations. This visual feed can be enhanced with additional data layers, such as thermal imaging, to locate survivors trapped under debris. Moreover, the immersive nature of

VR ensures that operators can make more informed decisions, as they get a first-person perspective of the environment, which is not possible with traditional remote-controlled devices.

Another significant application of these robots is in the assessment of structural damage. In the aftermath of disasters, it’s crucial to evaluate the integrity of buildings and infrastructure to prevent further casualties. Teleoperated robots can be equipped with sensors and tools to conduct these assessments more quickly and accurately than human teams, who may take longer to cover the same area and are at risk of injury or worse in structurally compromised environments.

In flood situations, where vast areas can be submerged, and currents can be strong and unpredictable, teleoperated robots can be invaluable. These robots can be designed to navigate waterlogged areas, providing critical information about water levels, the speed of flows, and identifying safe paths for rescue or relief operations. They can also aid in delivering essential supplies to areas cut off by floodwaters, ensuring that affected populations receive the necessary aid.

The versatility of teleoperated robots means they can be adapted for various tasks in disaster scenarios. They can carry equipment, such as medical supplies or communication devices, to affected individuals, or be used to establish temporary communication networks, which are often disrupted in the wake of major disasters. This functionality is particularly important in the initial stages of a disaster response when timely communication can save lives.

Moreover, these robots can also be employed for longer-term disaster recovery efforts. In the rebuilding phase following disasters, they can assist in clearing debris, transporting materials, and even in basic construction tasks, speeding up the recovery process and reducing the burden on human workers.

Training and preparedness are crucial components of effective disaster management. VR-based teleoperation systems can be used in training scenarios, allowing rescue teams to simulate various disaster situations and practice their response in a controlled, virtual environment. This type of training is invaluable, as it prepares responders for a range of scenarios, ensuring they are better equipped to handle real-life situations.

Environmental monitoring and conservation efforts in Pakistan can also benefit from the deployment of VR-based teleoperated systems. Robots can be used to monitor wildlife, track environmental changes, and even collect data in hazardous or inaccessible areas, such as highaltitude regions or dense forests. This would allow for more effective conservation strategies and better understanding of ecological changes without putting human lives at risk.

The realm of defense and security in Pakistan is an area where the application of VR-based teleoperated mobile robots can bring transformative changes. Given the unique geopolitical and security challenges faced by the country, integrating advanced technological solutions such as these can significantly enhance the capabilities of security forces, ensuring better protection for the nation and its citizens.

In the context of national defense, Pakistan’s strategic and operational environment necessitates a multifaceted approach to security. The use of VR-based teleoperated robots can augment the capabilities of defense forces in several key areas. One of the primary applications is in surveillance and reconnaissance. In border areas or conflict zones, these robots can be deployed to conduct surveillance missions, providing real-time intelligence without exposing personnel to direct threats. The VR interface allows operators to have a comprehensive, immersive view of the terrain, enabling them to gather detailed information about enemy positions, movements, or suspicious activities. This capability is crucial for strategic planning and decision-making in defense operations.

Teleoperated robots are also invaluable in counterterrorism and anti-insurgency operations. In urban settings or complex terrains where terrorists or insurgents might be hiding, sending in human forces can be risky. Teleoperated robots, on the other hand, can enter these high-risk areas to carry out reconnaissance, disarm explosives, or even neutralize threats if equipped with the appropriate tools. The operators, safely located at a distance, can maneuver these robots through narrow alleys, inside buildings, or in tunnels, providing them with a tactical advantage.

Another significant application is in the field of explosive ordnance disposal (EOD). Pakistan, having experienced numerous incidents involving explosives, can benefit greatly from the use of teleoperated robots in detecting and disarming bombs or improvised explosive devices (IEDs). The VR interface provides EOD personnel with a detailed and immersive view of the device, allowing for more precise and careful handling. This not only ensures the safety of EOD personnel but also minimizes the risk of collateral damage during the disarmament process.

The maritime domain presents another area where VR-based teleoperated robots can be effectively utilized. For a country like Pakistan, with a significant coastline and strategic maritime interests, safeguarding sea lanes and coastal areas is crucial. Teleoperated underwater robots can be employed for a variety of tasks, including underwater surveillance, mine detection, and the inspection of ships or infrastructure for security threats. These robots can operate in depths and conditions that are challenging for human divers, providing vital intelligence and ensuring maritime security.

In addition to active defense operations, teleoperated robots can play a crucial role in training and simulation. VR-based training environments can simulate a wide range of scenarios, from battlefield conditions to counterterrorism operations. This immersive training is invaluable for defense personnel, providing them with experience and preparation that traditional training methods may not offer. It also allows for the rehearsal of complex operations, reducing the risk of casualties and improving the success rate of real-world missions.

Furthermore, the use of teleoperated robots in defense and security can extend to peacekeeping and humanitarian missions. In international peacekeeping operations, where Pakistan has been a significant contributor, these robots can be used for tasks like patrolling, surveillance, and the clearing of explosives, reducing risks to peacekeeping personnel and enhancing mission effectiveness.

In the broader context of national security, teleoperated robots can be deployed for critical infrastructure protection. Vital installations such as nuclear facilities, power plants, and strategic communication networks can be monitored and protected using these robots. They can patrol perimeter fences, inspect suspicious packages, and even respond to security breaches, ensuring the integrity of these crucial assets.

Moreover, the cultural and archaeological sectors in Pakistan can make use of VR-based teleoperation for exploring and preserving historical sites. Robots can access areas that are too fragile or dangerous for humans, helping in the restoration and study of ancient structures and artifacts. This would not only contribute to the preservation of Pakistan’s rich cultural heritage but also enhance the understanding of historical contexts.

Finally, in the urban development and infrastructure sector, teleoperated robots can be used for tasks such as maintenance of high-rise buildings, inspection of bridges and dams, and construction in hazardous environments. This would not only ensure safety but also increase efficiency and reduce the time and cost associated with these tasks.

The applications of VR-based interfaces for mobile robot teleoperation in Pakistan are vast and varied, offering promising solutions across multiple sectors. From industrial manufacturing to agriculture, healthcare, education, disaster management, environmental conservation, security, cultural preservation, and urban development, these technologies have the potential to drive significant advancements and improvements. As Pakistan continues to embrace technological innovation, the adoption of VR-based teleoperated systems could play a crucial role in addressing the country's unique challenges and harnessing its potential for growth and development.

CHAPTER 5: CONCLUSION

This study focused on the development of an immersive remote-control framework designed for complex teleoperated tasks through mobile robotic platforms and achieves the purpose of providing aid to human operators in executing tasks such as remote exploration for feature collection. The combination of virtual realm and multi-sensory feedback help increase the situational awareness by immersing the user in a virtual environment while remotely operating the robot system for task execution and thus enhancing user performance. With novel adaptable control mode functionality, the proposed approach offered two main advantages. Firstly, the virtual environment enhances the teleoperation of these robots, providing a more natural and effective means to perform tasks. Secondly, the collaborative synergy between the human operator, offering adaptability to complex situations, and the robot, equipped with obstacle-avoidance capabilities, results in a user-friendly approach capable of handling challenging scenarios, such as escaping from trap situation. Experimental results, utilizing a Burger variant of Turtlebot3 equipped with a 360º LiDAR and additional visual and auditory sensors demonstrated the resourcefulness and ease of the virtual reality interface. Although the work strives to work on the immersion factor of the teleoperator potential room for improvement in visuals from the remote is there that can be filled through 3D point cloud depictions. Feasibility and immersion measuring feedback questionnaires involving users of various age groups and diverse fields indicated that the proposed framework application is comforting and engaging for the teleoperator in an intuitive and ergonomic manner. To minimize the stochastic elements of an unknown, environment the interface utilizes deep reinforcement learning modularity to cope with exploration challenges that come with dynamic and continuous environments. However prior knowledge about the environment may help in highlighting difficult or no-go areas within the remote environment for the user in virtual realm. This research study deployed the TD3 module for obstacle avoidance by mobile robot in semi-autonomous mode of operation, while using a 2D Lidar to gather environment percepts but to make the system more robust a 3D lidar or a hybrid sensor approach including a depth vision camera may provide a better alternative to compute the environment state vector.

In traversing the landscape of teleoperation, this thesis has embarked on an exploration of the symbiotic relationship between Virtual Reality (VR) and remote-control technologies. The amalgamation of these two realms presents an unprecedented avenue for redefining the way we interface with and manipulate environments from a distance. As we conclude this journey, it becomes evident that the integration of VR into teleoperation systems is not just a technological enhancement; rather, it signifies a profound shift in the dynamics of human-machine interaction and control. The narrative woven through the literature review brings to light the evolutionary trajectory of teleoperation, from its foundational principles to the contemporary challenges faced by conventional interfaces. The deficiencies of traditional systems, ranging from limited perceptual feedback to a lack of spatial awareness, act as a catalyst for the exploration of innovative solutions. The emergence of VR, with its capacity to immerse operators in synthetic environments, stands out as a transformative force that addresses these shortcomings.

Immersive visualization stands tall as a cornerstone in the realm of VR-based teleoperation. The ability to transpose operators into a virtual realm, providing an unparalleled sense of presence, offers a paradigm shift in how we perceive and interact with remote environments. This facet is particularly impactful in industries where precision and spatial awareness are paramount, such as manufacturing. The virtual environment becomes a canvas for operators to navigate complex machinery with heightened accuracy, transcending the limitations imposed by traditional interfaces.

Human factors and ergonomics emerge as crucial considerations in the development of VR-based teleoperation interfaces. As we delve deeper into the immersive capacities of VR, the potential for motion sickness and operator fatigue surfaces as critical challenges. Designing interfaces that prioritize operator comfort and well-being becomes imperative, calling for a holistic understanding of the psychological aspects associated with prolonged interaction in virtual spaces.

The applications of VR-based teleoperation extend across diverse industries, each revealing unique facets of its transformative potential. Real-world case studies, ranging from medical surgeries to manufacturing operations, underline the tangible benefits observed in terms of increased efficiency and improved outcomes. In medical teleoperation, the fusion of VR and telepresence has facilitated remote surgeries, offering a lifeline in situations where expert intervention is geographically distant. Yet, the celebration of successes in the realm of VR-based teleoperation is accompanied by a recognition of persistent challenges. Technological barriers, including latency issues and the demand for robust network infrastructure, remain focal points of ongoing research. The financial implications associated with the deployment of VR systems pose a pragmatic challenge, particularly in industries with limited resources. Standardization efforts become imperative as the adoption of VR technologies spans across diverse sectors, necessitating a unified framework for seamless integration.

Looking toward the horizon, the trajectory of VR-based teleoperation promises a tapestry of possibilities and challenges. The continuous refinement of VR technologies is poised to overcome current limitations, unlocking new dimensions for application and expanding the frontiers where teleoperation can thrive. The synergy between VR and artificial intelligence presents an exciting avenue for autonomous decision-making and adaptive systems that can augment human capabilities. In envisioning the future of VR-based teleoperation, collaboration emerges as a linchpin for success. Interdisciplinary endeavors that converge insights from computer science, human-computer interaction, engineering, and psychology will fuel the engine of innovation. Industry collaboration and sustained investment in research and development will be instrumental in bridging the gap between potential and implementation.

To conclude, this thesis has endeavored to unravel the layers of possibility woven into the fabric of VR-based teleoperation. From immersive visualization to haptic feedback and considerations of human factors, we have navigated through the intricacies of this convergence. Real-world applications and case studies have illustrated the transformative impact in various domains, while acknowledging the hurdles that demand collective attention.

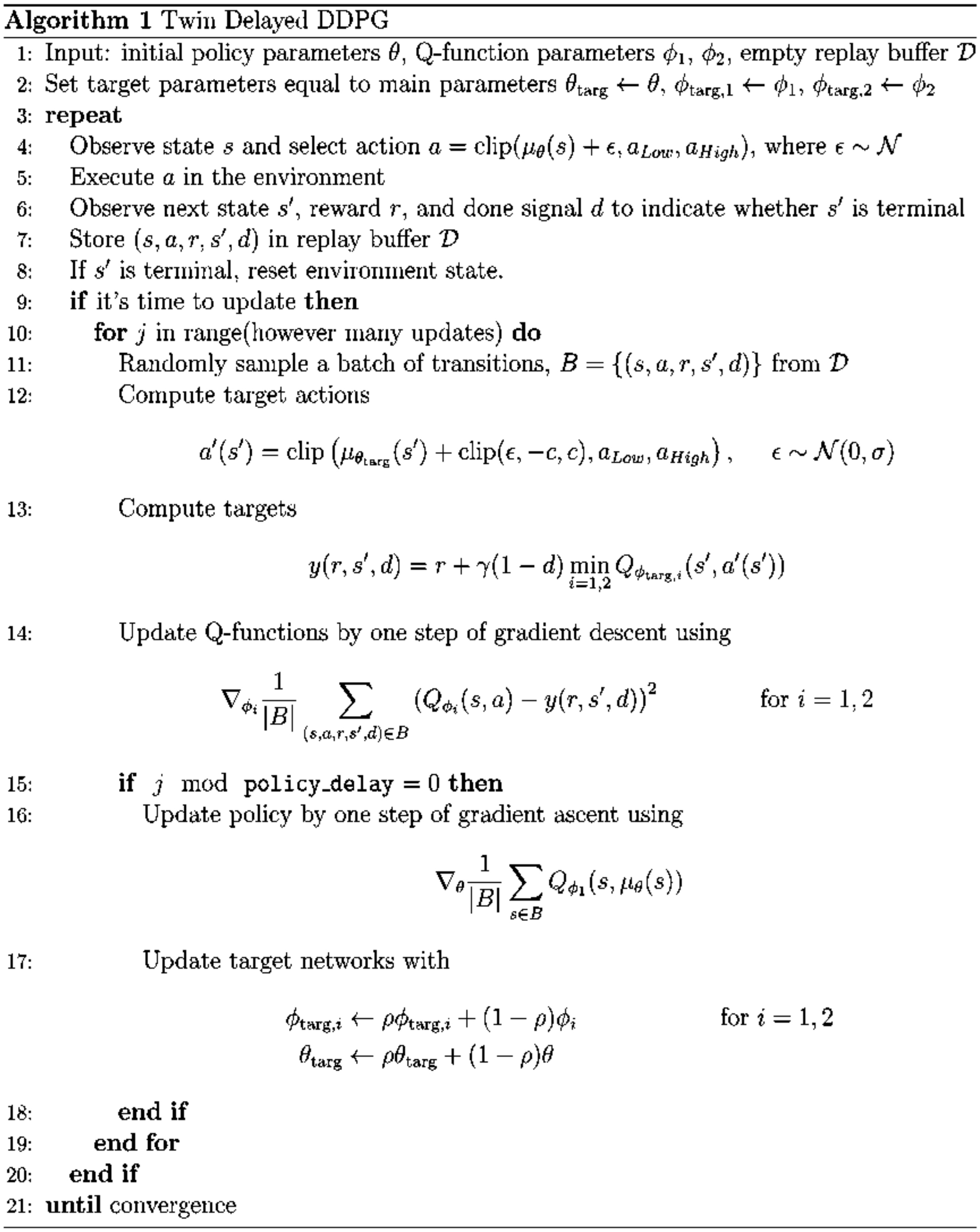
As we stand on the precipice of a new era in teleoperation, where the boundaries between the real and the virtual blur, it is incumbent upon us to approach this juncture with a keen awareness of the promises and challenges it entails. The trajectory toward widespread adoption of VR-based teleoperation is not merely a technological evolution; it is a societal shift that demands ongoing research, collaborative innovation, and a shared commitment to realizing the profound potential embedded in this transformative technology. The fusion of VR and teleoperation is not merely a convergence of technologies; it is an evolution that has the potential to redefine the contours of human interaction with remote environments, ushering in a new era of exploration and advancement.

APPENDICES

6.1- Appendix A

This includes pseudo code and supplementary mathematics for the reinforcement learning algorithm used.

6.1.1- Twin Delayed Deep Deterministic Policy Gradient Algorithm:



Algorithm 1 Twin Delayed DDPG

```
Input: initial policy parameters $\theta$, Q-function parameters $\phi_1$, $\phi_2$, empty replay buffer $\mathcal{D}$
Set target parameters equal to main parameters $\theta_{\text{targ}} \leftarrow \theta$, $\phi_{\text{targ},1} \leftarrow \phi_1$, $\phi_{\text{targ},2} \leftarrow \phi_2$
repeat
    Observe state $s$ and select action $a = \text{clip}(\mu_\theta(s) + \epsilon, a_{Low}, a_{High})$, where $\epsilon \sim \mathcal{N}$
    Execute $a$ in the environment
    Observe next state $s'$, reward $r$, and done signal $d$ to indicate whether $s'$ is terminal
    Store $(s, a, r, s', d)$ in replay buffer $\mathcal{D}$
    If $s'$ is terminal, reset environment state.
    if it's time to update then
        for $j$ in range(however many updates) do
            Randomly sample a batch of transitions, $B = \{(s, a, r, s', d)\}$ from $\mathcal{D}$
            Compute target actions
                $$a'(s') = \text{clip}\left(\mu_{\theta_{\text{targ}}}(s') + \text{clip}(\epsilon, -c, c), a_{Low}, a_{High}\right), \quad \epsilon \sim \mathcal{N}(0, \sigma)$$
            Compute targets
                $$y(r, s', d) = r + \gamma(1 - d) \min_{i=1,2} Q_{\phi_{\text{targ},i}}(s', a'(s'))$$
            Update Q-functions by one step of gradient descent using
                $$\nabla_{\phi_i} \frac{1}{|B|} \sum_{(s,a,r,s',d) \in B} \left(Q_{\phi_i}(s, a) - y(r, s', d)\right)^2 \qquad \text{for } i = 1, 2$$
            if $j$ mod policy_delay $= 0$ then
                Update policy by one step of gradient ascent using
                    $$\nabla_\theta \frac{1}{|B|} \sum_{s \in B} Q_{\phi_1}(s, \mu_\theta(s))$$
                Update target networks with
                    $$\phi_{\text{targ},i} \leftarrow \rho \phi_{\text{targ},i} + (1 - \rho)\phi_i \qquad \text{for } i = 1, 2$$
                    $$\theta_{\text{targ}} \leftarrow \rho \theta_{\text{targ}} + (1 - \rho)\theta$$
            end if
        end for
    end if
until convergence
```

REFERENCES

[1] IFR International Federation of Robotics (no date) World Robotics 2023 report: Asia ahead of Europe and the Americas, IFR International Federation of Robotics. Available at: https://ifr.org/ifr-press-releases/news/world-robotics-2023-report-asia-ahead-of-europe-and-the-americas (Accessed: 11 November 2023).

[2] Saputra, R.P.; Rakicevic, N.; Kuder, I.; Bilsdorfer, J.; Gough, A.; Dakin, A.; de Cocker, E.; Rock, S.; Harpin, R.; Kormushev, P. ResQbot 2.0: An Improved Design of a Mobile Rescue Robot with an Inflatable Neck Securing Device for Safe Casualty Extraction. Appl. Sci. 2021, 11, 5414.

[3] Habibian, S.; Dadvar, M.; Peykari, B.; Hosseini, A.; Salehzadeh, M.H.; Hosseini, A.H.M.; Najafi, F. Design and implementation of a maxi-sized mobile robot (Karo) for rescue missions. ROBOMECH J. 2021, 8, 1.

[4] Sun, Z.; Yang, H.; Ma, Y.; Wang, X.; Mo, Y.; Li, H.; Jiang, Z. BIT-DMR: A Humanoid Dual-Arm Mobile Robot for Complex Rescue Operations. IEEE Robot. Autom. Lett. 2022, 7, 802–809.

[5] Schuster, M.J.; Müller, M.G.; Brunner, S.G.; Lehner, H.; Lehner, P.; Sakagami, R.; Dömel, A.; Meyer, L.; Vodermayer, B.; Giubilato, R.; et al. The ARCHES Space-Analogue Demonstration Mission: Towards Heterogeneous Teams of Autonomous Robots for Collaborative Scientific Sampling in Planetary Exploration. IEEE Robot. Autom. Lett. 2020, 5, 5315–5322.

[6] Jia, X.; Sun, C.; Fu, J. Mobile Augmented Reality Centred Ietm System for Shipping Applications. Int. J. Robot. Autom. 2022, 37, 147–162.

[7] Yin, K.; Sun, Q.; Gao, F.; Zhou, S. Lunar surface soft-landing analysis of a novel six-legged mobile lander with repetitive landing capacity. Proc. Inst. Mech. Eng. Part C J. Mech. Eng. Sci. 2022, 236, 1214–1233.

[8] Kot, T.; Novák, P. Application of virtual reality in teleoperation of the military mobile robotic system TAROS. Int. J. Adv. Robot. Syst. 2018, 15, 1–6.

[9] Kavitha, S.; SadishKumar, S.T.; Menaga, T.; Gomathi, E.; Sanjay, M.; Abarna, V.S. Military Based Voice Controlled Spy Bot with Weapon Detector. Biosci. Biotechnol. Res. Commun. 2020, 13, 142–146.

[10] Grabowski, A.; Jankowski, J.; Wodzy ´nski, M. Teleoperated mobile robot with two arms: The influence of a human-machine interface, VR training and operator age. Int. J. Hum.-Comput. Stud. 2021, 156, 102707.

[11] Li, C.; Li, B.; Wang, R.; Zhang, X. A survey on visual servoing for wheeled mobile robots. Int. J. Intell. Robot. Appl. 2021, 5, 203–218.

[12] Szrek, J.; Jakubiak, J.; Zimroz, R. A Mobile Robot-Based System for Automatic Inspection of Belt Conveyors in Mining Industry. Energies 2022, 15, 327.

[13] N. Hoehner, J. Rodewald, M. O. Mints, and V. Kammerlohr. The next ¨ step of digital laboratories: Connecting real and virtual world. In The 17th International Conference on Virtual-Reality Continuum and its Applications in Industry, pp. 1–2, 2019.

[14] F. Longo, L. Nicoletti, and A. Padovano. Emergency preparedness in industrial plants: A forward-looking solution based on industry 4.0 enabling technologies. Computers in industry, 105:99–122, 2019

[15] A. Rukangu, A. Tuttle, and K. Johnsen. Virtual reality for remote controlled robotics in engineering education. In 2021 IEEE Conference on Virtual Reality and 3D User Interfaces Abstracts and Workshops (VRW), pp. 751–752. IEEE, 2021.

[16] Vahdatikhaki, K. El Ammari, A. K. Langroodi, S. Miller, A. Hammad, and A. Doree. Beyond data visualization: A context-realistic construction equipment training simulators. Automation in construction, 106:102853, 2019.

[17] H. Arnarson, B. Solvang, and B. Shu. The application of virtual reality in programming of a manufacturing cell. In 2021 IEEE/SICE International Symposium on System Integration (SII), pp. 213–218. IEEE, 2021.

[18] D. Concannon, R. Flynn, and N. Murray. A quality of experience evaluation system and research challenges for networked virtual realitybased teleoperation applications. In Proceedings of the 11th ACM Workshop on Immersive Mixed and Virtual Environment Systems, pp. 10–12, 2019.

[19] M. F. Falah, S. Sukaridhoto, M. U. H. Al Rasyid, and H. Wicaksono. Design of virtual engineering and digital twin platform as implementation of cyber-physical systems. Procedia Manufacturing, 52:331–336, 2020.

[20] H. Laaki, Y. Miche, and K. Tammi. Prototyping a digital twin for real time remote control over mobile networks: Application of remote surgery. IEEE Access, 7:20325–20336, 2019.

[21] E. Isleyen and H. Duzgun. Use of virtual reality in underground roof fall hazard assessment and risk mitigation. International Journal of Mining Science and Technology, 29(4):603–607, 2019.

[22] S. K. Tadeja, Y. Lu, P. Seshadri, and P. O. Kristensson. Digital twin assessments in virtual reality: An explorational study with aeroengines. In 2020 IEEE Aerospace Conference, pp. 1–13. IEEE, 2020.

[23] McNulty, D., Hennessy, A., Li, M., Armstrong, E., & Ryan, K. M. (2022, October). A review of Li-ion batteries for autonomous mobile robots: Perspectives and outlook for the future. Journal of Power Sources, 545, 231943. https://doi.org/10.1016/j.jpowsour.2022.231943

[24] Pekka Appelqvist, Jere Knuuttila, Juhana Ahtiainen, Development of an Unmanned Ground Vehicle for task-oriented operation-considerations on teleoperation and dela, in: 2007 IEEE/ASME international conference on advanced intelligent mechatronics, Zurich, Germany, 4-7 September, 2007, 2007, pp. 1–6.

[25] Bandala, M.; West, C.; Monk, S.; Montazeri, A.; Taylor, C.J. Vision-Based Assisted Tele-Operation of a Dual-Arm Hydraulically Actuated Robot for Pipe Cutting and Grasping in Nuclear Environments. Robotics 2019, 8, 42.

[26] Abi-Farraj, F.; Pacchierotti, C.; Arenz, O.; Neumann, G.; Giordano, P.R. A Haptic Shared-Control Architecture for Guided Multi-Target Robotic Grasping. IEEE Trans. Haptics 2020, 13, 270–285.

[27] Suarez, A.; Real, F.; Vega, V.M.; Heredia, G.; Rodriguez-Castaño, A.; Ollero, A. Compliant Bimanual Aerial Manipulation: Standard and Long Reach Configurations. IEEE Access 2020, 8, 88844–88865.

[28] Isop, W.A.; Gebhardt, C.; Nägeli, T.; Fraundorfer, F.; Hilliges, O.; Schmalstieg, D. High-Level Teleoperation System for Aerial Exploration of Indoor Environments. Front. Robot. AI 2019, 6, 95.

[29] Brantner, G.; Khatib, O. Controlling Ocean One: Human–robot collaboration for deep-sea manipulation. J. Field Robot. 2021, 38, 28–51.

[30] Sivcev, S.; Coleman, J.; Omerdi´c, E.; Dooly, G.; Toal, D. Underwater manipulators: A review. Ocean Eng. 2018, 163, 431–450.

[31] Mel Slater, Beau Lotto, Maria Marta Arnold, María Victoria Sánchez-Vives, How we experience immersive virtual environments: the concept of presence and its measurement, Anuario de PsicologíA 40 (2009) 193-210.

[32] Shin, D. (2019) 'How do users experience the interaction with an immersive screen?', Computers in Human Behavior, 98, pp. 302–310. doi: 10.1016/j.chb.2018.11.010.

[33] Henrique Martins, Rodrigo Ventura, Immersive 3-D teleoperation of a search and rescue robot using a head-mounted display, in: Proceedings of the IEEE Conference on Emerging Technologies & Factory Automation, Mallorca, Spain, 22–25 September, 2009, 2009, pp. 1–8.

[34] Vaughan, Ryota Mizutani, Don Kimber, Evaluating stereoscopic video with head tracking for immersive teleoperation of mobile telepresence robots, in: Proceedings of the Tenth Annual ACM/IEEE International Conference on Human-Robot Interaction Extended Abstracts, Portland, USA, 2–5 March, 2015, 2015, pp. 43-44.

[35] Jim Blascovich, Social influence within immersive virtual environments, in: The Social Life of Avatars, Springer, London, 2002, pp. 127–145.

[36] Mario Gutierrez, Renaud Ott, Daniel Thalmann, Frédéric Vexo, Mediators: Virtual haptic interfaces for tele-operated robots, in: Proceedings of the 13th IEEE International Workshop on Robot and Human Interactive Communication, Kurashiki, Okayama, Japan, 22-22 September, 2004, 2004, pp.515–520.

[37] Mojtaba Noghabaei, Khashayar Asadi, Kevin Han, Virtual manipulation in an immersive virtual environment: Simulation of virtual assembly, in: Proceedings of the Computing in Civil Engineering, Atlanta, Georgia, 17–19 June, 2019, 2019.

[38] Shafer, D.M. The Effects of Interaction Fidelity on Game Experience in Virtual Reality. Psychol. Pop. Media 2021, 10, 457–466.

[39] Ho, J.C.F.; Ng, R. Perspective-Taking of Non-Player Characters in Prosocial Virtual Reality Games: Effects on Closeness, Empathy, and Game Immersion. Behav. Inf. Technol. 2020, 41, 1185–1198.

[40] Navarro, R.; Vega, V.; Martinez, S.; Jose Espinosa, M.; Hidalgo, D.; Benavente, B. Designing Experiences: A Virtual Reality Video Game to Enhance Immersion. In Proceedings of the 10th International Conference on Applied Human Factors and Ergonomics/AHFE International Conference on Human Factors and Wearable

Technologies/AHFE International Conference on Game Design and Virtual Environments, Washington, DC, USA, 24–28 July 2019.

[41] Tao, G; Garrett, B.; Taverner, T.; Cordingley, E.; Sun, C. Immersive virtual reality health games: A narrative review of game design. J. Neuroeng. Rehabil. 2021, 18, 31.

[42] Bukhori I, Ismail ZH. Detection of kidnapped robot problem in Monte Carlo localization based on the natural displacement of the robot. International Journal of Advanced Robotic Systems. 2017;14(4). doi:10.1177/1729881417717469.

[43] Johnson, M.; Vera, A. No AI Is an Island: The Case for Teaming Intelligence. AI Mag. 2019, 40, 16–28.

[44] Solanes, J.E.; Muñoz, A.; Gracia, L.; Martí, A.; Girbés-Juan, V.; Tornero, J. Teleoperation of industrial robot manipulators based on augmented reality. Int. J. Adv. Manuf. Technol. 2020, 111, 1077–1097

[45] Selvaggio, M.; Abi-Farraj, F.; Pacchierotti, C.; Giordano, P.R.; Siciliano, B. Haptic-Based Shared-Control Methods for a Dual-Arm System. IEEE Robot. Autom. Lett. 2018, 3, 4249–4256.

[46] Nicolis, D.; Palumbo, M.; Zanchettin, A.M.; Rocco, P. Occlusion-Free Visual Servoing for the Shared Autonomy Teleoperation of Dual-Arm Robots. IEEE Robot. Autom. Lett. 2018, 3, 796–803.

[47] Solanes, J.E.; Muñoz, A.; Gracia, L.; Tornero, J. Virtual Reality-Based Interface for Advanced Assisted Mobile Robot Teleoperation. Appl. Sci. 2022, 12, 6071. https://doi.org/10.3390/app12126071.

[48] Xu, Z., Hess, R. and Schilling, K. (2012) ‘Constraints of potential field for obstacle avoidance on car-like Mobile Robots’, IFAC Proceedings Volumes, 45(4), pp. 169–175. doi:10.3182/20120403-3-de-3010.00077.

[49] Meta, Facebook Reality Labs (Redmond, DC, USA). Oculus Quest 2 Hardware Details. Available online: https://www.oculus. com/quest-2/ (accessed on 11 November 2023).

[50] Unity (San Francisco, CA, USA). Unity Real-Time Development Platform. Available online: https://unity.com/ (accessed on 11 November 2023).

[51] Twin Delayed DDPG - Spinning Up documentation. Available at: https://spinningup.openai.com/en/latest/algorithms/td3.html (Accessed: 11 November 2023).

[52] Virtuix (Austin, TX, USA). OmniOne Hardware Details. Available online: https://omni.virtuix.com/ (accessed on 11 November 2023)

[53] Robotis (Lake Forest, CA, USA). Turtlebot3 Hardware Details. Available online: https://www.robotis.us/turtlebot-3/ (accessed on 4 March 2022).

[54] S. Fujimoto, H. Hoof, and D. Meger, "Addressing function approximation error in actor-critic methods," in Proc. Int. Conf. Mach. Learn., 2018, pp. 1587–1596.

[55] R. Cimurs, I. H. Suh and J. H. Lee, "Goal-Driven Autonomous Exploration Through Deep Reinforcement Learning," in IEEE Robotics and Automation Letters, vol. 7, no. 2, pp. 730-737, April 2022, doi: 10.1109/LRA.2021.3133591.

[56] Wiki.ros.org. Available at: https://wiki.ros.org/rviz/UserGuide (Accessed: 11 November 2023).

[57] Blattgerste, J.; Strenge, B.; Renner, P.; Pfeiffer, T.; Essig, K. Comparing Conventional and Augmented Reality Instructions for Manual Assembly Tasks. In Proceedings of the 10th International Conference on PErvasive Technologies Related to Assistive Environments, Island of Rhodes, Greece, 21–23 June 2017; pp. 75–82.

[58] Attig, C.; Wessel, D.; Franke, T. Assessing Personality Differences in Human-Technology Interaction: An Overview of Key Self-report Scales to Predict Successful Interaction. In Proceedings of the HCI International 2017—Posters' Extended Abstracts, Vancouver, BC, Canada, 9–14 July 2017; Stephanidis, C., Ed.; Springer International Publishing: Cham, Switzerland, 2017; pp. 19–29.

[59] 70. Franke, T.; Attig, C.; Wessel, D. A Personal Resource for Technology Interaction: Development and Validation of the Affinity for Technology Interaction (ATI) Scale. Int. J. -Hum.-Comput. Interact. 2018, 35, 456–467.

[60] Du, J.; Do, H.M.; Sheng, W. Human-Robot Collaborative Control in a Virtual-Reality-Based Telepresence System. Int. J. Soc. Robot. 2021, 13, 1295–1306.

[61] Uboe, J. Introductory Statistics for Business and Economics: Theory, Exercises and Solutions; Springer International Publishing AG: Cham, Switzerland, 2017; ISBN 9783319709369.

[62] Hess, R. Blender Foundations: The Essential Guide to Learning Blender 2.6; Focal Press: Waltham, MA, USA, 2010. Available online:

https://www.sciencedirect.com/book/9780240814308/blender-foundations (accessed on 11 November 2023).

[63] Witmer, B.G.; Singer, M.J. Measuring Presence in Virtual Environments: A Presence Questionnaire. Presence Teleoperators Virtual Environ. 1998, 7, 225–240.

[64] Witmer, B.G.; Jerome, C.J.; Singer, M.J. The Factor Structure of the Presence Questionnaire. Presence Teleoperators Virtual Environ. 2005, 14, 298–312.

[65] Schubert, T.; Friedmann, F.; Regenbrecht, H. The Experience of Presence: Factor Analytic Insights. Presence Teleoperators Virtual Environ. 2001, 10, 266–281.

[66] Regenbrecht, H.; Schubert, T. Real and Illusory Interactions Enhance Presence in Virtual Environments. Presence Teleoperators Virtual Environ. 2002, 11, 425–434.

[67] Schubert, T. The sense of presence in virtual environments: A three-component scale measuring spatial presence, involvement, and realness. Z. für Medien. 2003, 15, 69–71.

[68] Brooke, J. “SUS-A Quick and Dirty Usability Scale.” Usability Evaluation in Industry; CRC Press: Boca Raton, FL, USA, 1996; ISBN 9780748404605.

[69] Insight - 5 channel wireless EEG headset (2023) EMOTIV. Available at: https://www.emotiv.com/insight/ (Accessed: 11 November 2023).

[70] A. Redjaimia, "Multi-Agent System and Events Plan Construction Using PDDL", Journal of Computer Science & Systems Biology, vol. 08, no. 06, 2015. Available: 10.4172/jcsb.1000208.