XROV: An Immersive eXtended Reality (XR) Interface for Lunar Rover Mission Control

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Abstract. The Moon is once again a focal point for space exploration, with interest extending from space agencies to private companies. Recent discoveries of lunar resources and the potential to develop a lunar economy based on in-Situ Resource Utilisation (ISRU) have accelerated the development of advanced robotic technologies. This is clear in the increasing number of missions, with three landers deployed in 2024, and an additional three as of March 2025. To ensure successful robotic lunar operations, reliable human supervision and control are essential, supported by advanced systems that enhance operator situational awareness. This paper presents the eXtended Reality interface for lunar ROVer Mission Control (XROV) - a novel system designed to enable immersive teleoperation and monitoring of lunar rovers. XROV provides operators with an online 3D virtual reconstruction of the rover's lunar surroundings using on-board sensor data, allowing them to visualize regions of interest from multiple perspectives and identify risks such as wheel-ground interactions and hazards with Artificial Intelligence (AI). Additionally, a Graphical User Interface (GUI) is proposed to improve human-robot interaction, displaying critical information such as rock coordinates, battery levels, and terrain elevation. XROV employs a human-in-the-loop approach, which is essential for ensuring adaptability and informed decision making during AI-assisted rover missions. The system was designed, implemented, and tested at the Lunalab, University of Luxembourg, where two experiments were conducted with different operators and real rovers. The results demonstrate the effectiveness of XROV in improving situational awareness, control, and user experience, making it a valuable tool for teleoperating rovers in hazardous and unexplored lunar environments.

Keywords: Extended Reality · Human-Robot Interaction · Space Robotics · Telerobotics

1 Introduction

Space agencies and the private sector have increased their interest towards the Moon, with the aim of developing a sustainable human presence [12, 41]. The Moon has unique scientific and economic values, as it is abundant in minerals and valuable natural resources. However, the hazardous and critical environmental conditions on the lunar surface make robots indispensable for lunar activities [10, 13], such as mining, collecting, and exploration [11, 26, 37]. However, it is not an easy activity for rovers, as future lunar missions will require them to traverse high-risk areas [11], such as unknown shadowed regions and ice-rocky polar areas. Such regions can jeopardize space missions as rovers can become trapped or damaged, wherein the inadequacy of current technology compounds this concern. For example, autonomous activities remain limited in hostile areas due to high risks and costs [3,4,24,53]. As an alternative, to adapt the rovers to the required reliable modes of operation, close monitoring and human control of rover activities are proposed to increase reliability and efficiency [5, 38].

In this context, rovers face challenges due to the complexity of the lunar environment. Future rovers will be remotely operated from an orbiting spacecraft (Gateway) or a Moon base [5, 11]. However, rover teleoperation has drawbacks that must be overcome with current technologies [42], as it usually relies on 2D visuals gathered by onboard cameras. This leads to a lack of telepresence and environmental awareness, limiting the user experience and causing a significant mental workload on operators. Operational effectiveness and mission success are affected due to limited depth perception, which increases risks and compromises safety. These challenges make operators feel disconnected from the remote environment, negatively impacting mission outcomes. Therefore, novel solutions are needed to enhance telepresence and perception in advanced lunar robotic operations for safe and efficient future missions.

This paper presents XROV, an immersive eXtended Reality interface for lunar ROVer mission control. It provides operators with immersive remote control and supervision of rover missions in hostile environments. Our system is developed for the lunar surface, suitable for different terrains and obstacles. XROV is a novel framework that integrates eXtended Reality (XR) to visualize a 3D environment reconstructed from rover sensor data alongside a human-rover Graphical User Interface (GUI) for easier mission understanding and interaction. It also overlays crucial information, such as detected rocks via Deep Learning (DL) and rover performance data. The experiments conducted demonstrate XROV's effectiveness in improving operator telepresence, confidence, and mission performance compared to 2D image-based teleoperation methods.

The paper's structure is as follows: Section 2 presents the related work and our key contributions. Section 3 describes the architecture and functionalities of the system. Section 4 describes and explains the experiment and the results, and Section 5 ends with the conclusion and future work.

2 Related work

2.1 eXtended Reality in Robotics

The application of XR with robots has expanded to various fields. This expansion is driven by XR's ability to improve operators' spatial understanding, deliver immersive experiences at remote sites, and even reduce costs.

In Earth applications, XR is utilized in a wide range of robotic applications. For example, a ground vehicle is used to reconstruct an environment in 3D for XR supervision [48]. Others employ a Mixed Reality (MR) interface for teleoperating mobile redundant manipulators in hostile environments [44], or Virtual Reality (VR) to teleoperate and supervise a robotic arm or digital twin remotely [33], humanoid arms [32] or remote robotic training [23]. Besides, XR is used to control robotic arms remotely, and it is enhanced by other sensory feedback, such as haptics [19].

In Space applications, the European Space Agency (ESA) is conducting VR tests on remotely operating robotic arms and space vehicles for future missions [14]. Mars XLab, launched by ESA, is creating virtual testing for future human and robotic Mars exploration [16], and the X-aRM platform provides VR simulations to support astronauts with Extra Vehicular Activities (EVAs) using an arm exoskeleton with force feedback [17]. NASA is using XR to simulate space missions, train astronauts, and control robots in space [29,31]. Moreover, the virtual Mission Simulation System (vMSS) is being developed to improve real-time decision-making and communication between the team and the rover [18]. Other applications include telecontrolling rovers in simulated environments [15,49], using XR for robotic arm teleoperation on lunar bases [28], and utilizing AR to enhance astronaut efficiency and situational awareness during lunar EVAs [6].

Beyond the current XR developments, our work addresses a critical gap in lunar rover mission control. Unlike existing XR developments with robots, our approach integrates a system able to control and supervise a rover remotely, incorporating a tailored GUI that includes near-real-time 3D reconstruction of unknown lunar locations. This advance represents a step forward in the capabilities of Moon robotic missions.

2.2 3D Environment Reconstruction

In unknown environments, it is crucial to provide the most relevant information about the robot's surroundings to the operator. This is often implemented by 3D reconstruction methods that employ sensor data from depth cameras, LiDAR, and radar to generate a virtual representation of an environment. The results of 3D reconstruction can be generated from 3D point clouds, Digital Elevation Maps (DEMs), 3D meshes, and voxel grids [34,50]. This technique improves environmental understanding, hazard perception, decision-making and telepresence, allowing operators to perceive and understand the environment in 3D instead of 2D cameras or satellite images [48].

In terrestrial applications, the reconstruction of 3D environments has been investigated and applied in various cases. This field is crucial for robotic exploration in hostile environments, such as navigating through natural disasters [35,48], or performing search & rescue in areas that are not accessible by humans [27, 43]. They provide a visualization of unknown and potentially dangerous locations [27,35,43,48], especially when robots are deployed to assist humans in their exploration. However, 3D reconstruction has also expanded to other fields, including industry, building construction, and agriculture [7,39,52], where this enhances precision and efficiency, enabling detailed site analysis, better resource management, and optimized workflows.

In Space applications, this area of research remains limited. Some works use LiDAR data to identify and reconstruct craters for hazard avoidance [55] on the lunar surface, while others use DEMs to model the lunar surface [51,54]. Similarly, 3D environment reconstruction is used to model the Martian surface [8], and aid in the teleoperation of planetary robots [2]. Furthermore, 3D reconstruction has been used to select suitable habitats for future space missions [1].

Space vs Terrestrial. Key differences are found in the state-of-the-art related to the 3D reconstruction techniques. Space applications employ offline methods, while terrestrial ones use online 3D reconstruction. The inconvenience is that offline reconstruction limits operations by delaying the creation of the virtual environment and relying on 2D feedback. It decreases performance and increases risk in unknown environments. The reliance on offline reconstruction is a critical limitation to address for future planetary missions, as online reconstruction can improve operator awareness and safety.

Beyond the latest developments in 3D reconstruction, our work focuses on developing an online 3D reconstruction pipeline, specifically for space applications. We target the lunar environment, a location that will be heavily visited with the upcoming Artemis missions [30]. Our proposed pipeline leverages existing 3D reconstruction techniques, and merges them with XR technologies to create an immersive teleoperation system. The rover operator is immersed inside a virtual reconstruction of the rover's surroundings, updated as they explore an unknown area in near real-time.

2.3 Main Contributions

Beyond the state-of-the-art, this paper introduces the XROV system as a primary technological innovation. XROV enables rover teleoperation and supervision in a lunar environment, characterized by extremely challenging perception environments, such as uneven and unknown terrain, variable light and low illumination, and lack of significant features. XROV is designed to operate in these challenging scenarios, which are more complex than terrestrial applications. The lunar environment is reconstructed online in 3D using on-board rover sensor data. Operators are immersed in a 3D virtual environment, where they have access to crucial rover data via a GUI and can directly teleoperate and supervise using XR. Key contributions of XROV software include the following:

1. Online 3D reconstruction of unknown lunar environments, using 2D Delaunay triangulation [40], dynamically creating 3D meshes with color. XROV ensures adaptability to uneven and poorly illuminated lunar terrains.
2. A rock detection and visualization approach based on the YOLOv5 DL model, trained under varying illumination using 2D images from a custom dataset. The 3D reconstructed environment is complemented with detected hazards, supporting the operator in identifying their location during teleoperation.

3. A personalized GUI for the operator to visualize multiple parameters and risks of the environment and rover from different perspectives, with customized alerts created from rover sensor data.
4. A robust XR human-robot interface for conducting missions on the Moon and teleoperating rovers in hazardous lunar environments.
5. XROV validation and verification in a lunar analogue facility with real robots and multiple operators.

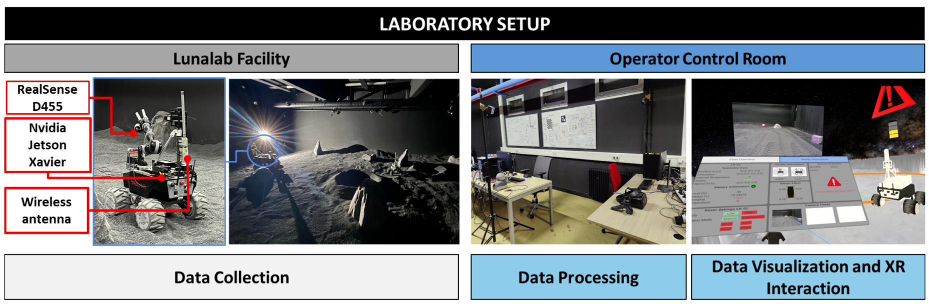


Fig. 1: Laboratory Setup. XROV obtains the environmental data in the Lunalab, which is processed and visualized in the control room area. The operator located in the control room supervises and controls the rover remotely.

3 XROV: immersive eXtended Reality for lunar rOVer mission control

XROV is a novel framework that enables mission supervision and remote control of lunar rovers using immersive technologies, 3D reconstruction techniques, and AI. Operators are immersed inside a 3D virtual reconstruction of the rover's environment, where they can directly teleoperate the rover, access crucial onboard data, and identify potential hazards that are present. Using XR, operators perceive and understand the robot's surroundings more effectively, while having access to a complete online 3D reconstruction of it's environment. A GUI provides the operator with access to rover telemetry and environment information.

3.1 XROV set-up

XROV's set-up is divided into two main parts, see Fig. 1. The rover, located in the LunaLab, a lunar analogue facility [10], and the operator, who is in the remote control room without direct visual sight of the rover to mimic realistic teleoperating conditions. The operator uses a VR system, which is composed of a VR rig and controllers, to teleoperate the rover as if they were on-site. XROV is comprised of the following subsystems:

Lunar Rover: We use the Robotnik Summit-XL robotic platform, equipped with several onboard sensors to capture environmental and telemetry data. It is equipped with a Nvidia Jetson Xavier computer for operation and data collection, a Realsense D455 RGB-D camera for visual information and a WLAN antenna for communication with both ROS and XR subsystems. The underlying Operating Systems (OS) are Ubuntu 18.04 and ROS melodic. The Lunar rover receives commands from the XR sybsystem and in turn transmits its on-board data.

ROS and XR PCs: The operator communicates with the robot and receives its telemetry and sensor information through the ROS and XR PCs. They are used to process and visualize sensor & telemetry data from the lunar rover, as well as transmit commands to be executed by the rover. The ROS PC acts as a middleware computer, receiving sensor data from the rover, processing it, and then transmitting it to the XR PC for visualization. Simultaneously, the ROS PC receives commands from the XR PC and transmits them to the rover for execution. A direct LAN connection is used between ROS-XR subsystems to communicate, and a WLAN connection between the lunar rover and ROS subsystem. Ubuntu 18.04 and ROS Melodic are used for the ROS PC, while the XR PC runs on Windows and hosts the Unity3D game engine [45] for VR teleoperation. A ROS bridge server facilitates data transfer, and the ROS-TCP Connector Unity3D plugin [21] enables XR-ROS PC communication.

3.2 System workflow

XROV's system workflow is designed to separate data collection, processing, and visualization into three separate phases. This constrains the robot to only collecting data and executing commands, leaving heavier processing and visualization on dedicated edge-computers. This separation is crucial in the context of lunar missions, because rovers are limited in terms of their processing capabilities.

Data Collection: While the operator explores the LunaLab with the lunar rover, visual data is collected using the Realsense D455 camera. The rover is controlled via a VR rig and 2 hand controllers from the control area. RTAB-MAP [25, 36], a Simultaneous Localization and Mapping (SLAM) software running on the rover, generates a 3D point cloud map of the LunaLab using the camera's depth information and provides odometry to localize it in the explored area. SLAM alongside on-board telemetry data are transmitted to the ROS PC for further processing.

Data Processing: The data collected from the rover (telemetry, visual, etc.) is then transmitted to the ROS PC for processing. Visual features captured by the camera are used as input to the YOLOv5 Convolutional Neural Network (CNN) [22]. The CNN detects hazards like rocks, whose 3D position w.r.t rover is computed. Telemetry (e.g. battery state, wheel effort, etc.), the 3D point cloud, and the positions of the detected hazards are instead retransmitted to the XR PC for visualization and further processing directly in Unity3D.

Data Visualization and XR interaction: The XR subsystem, processes and displays the data from the ROS subsystem within an XR 3D reconstructed environment powered by Unity3D [45]. Through the VR rig, the operator visualizes and interacts with the remote environment and the rover in an immersive manner. Unity3D triangulates the 3D point cloud to reconstruct a high-fidelity 3D mesh of the rover's environment, providing the operator with an on-site feeling. A 3D model of the rover, updated with SLAM odometry to match its real position in the LunaLab, is displayed to the operator. Also, a GUI provides the operator with access to telemetry, sensor, and camera data. Moreover, other types of data, such as the hazards' location, battery levels, and the trajectory taken by the rover, are overlaid on the 3D environment for the operator, enhancing their immersive user experience.

3.3 Online 3D Environment reconstruction

Rover operators typically rely on 2D camera feedback, which hinders operational awareness and efficiency and compromises mission safety. Cameras deployed in space missions often suffer from limited Field of View (FoV) and do not offer depth perception. Thus, to have an improved sense of 3D awareness, compared to classical 2D, XROV generates a 3D mesh of the rover's environment and immerses the operator in it. The 3D reconstruction process, shown in Fig. 2, is summarized in four main steps:

1. The rover collects RGB and depth camera data, which is provided as input to RTAB-MAP's SLAM process, subsequently localizing the robot and generating a 3D point cloud.
2. The XR subsystem triangulates online the 3D point cloud using 2D Delaunay Triangulation to generate a 3D mesh.
3. The 3D mesh is displayed in Unity3D, visualized through the VR rig.
4. Repeat 1-3 while new environment features are collected to increment the 3D point cloud.

First, RTAB-MAP performs online SLAM and generates a 3D point cloud map of the rover's environment. This point cloud is then sent to the ROS PC and is constantly updated by RTAB-MAP while the camera captures new environment features. The XR PC in turn receives the point cloud through the ROS-TCP connector, and Unity3D iteratively reads the point cloud to extract individual 3D point cloud coordinates and their colors.

Unity3D uses the Triangle.NET [40] package, providing an implementation of 2D constrained Delauney Triangulation, and the Mesh scripting API [46] to generate 3D meshes. The point cloud provided by SLAM is composed of 3D coordinates (x, y, z) and assigned RGB values for each vertex. The extracted 3D point cloud coordinates are used to provide the x and z values to Triangle.NET for 2D triangulation. The y value (i.e. height) is stored until the triangulation is completed in 2D first. To optimize the triangulation process, we perform a dimension reduction from $3D \rightarrow 2D$, and create the triangle faces in 2D space. Afterwards, the 2D triangles are projected to 3D space using the stored height values to generate a 3D mesh. The mesh is then colored by extracting the assigned color values for each point cloud vertex in the mesh's triangles.

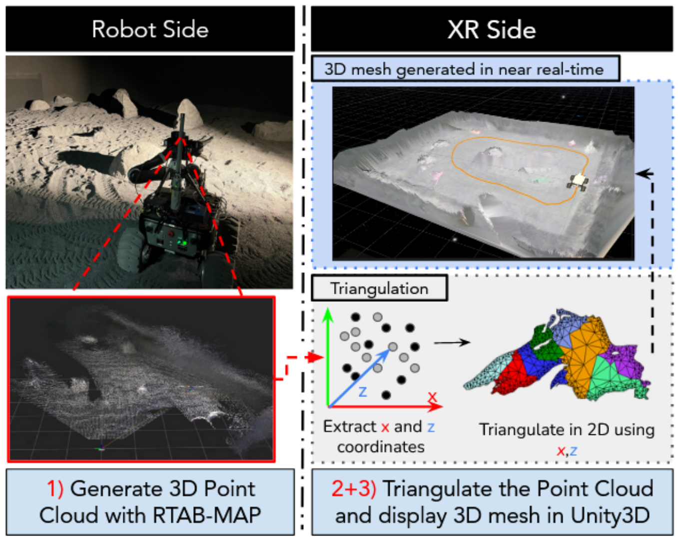


Fig. 2: 3D Reconstruction pipeline. This process is repeated as new point cloud data is generated in RTAB-MAP

3D mesh generation is a computationally expensive process, causing processing bottlenecks and affecting the user experience in VR. To minimize this, XROV updates the mesh only when a threshold is surpassed. Once the point cloud has grown sufficiently in size, Unity3D updates the 3D mesh with newly acquired points. This approach effectively minimizes computational overhead, improves the operator's experience in VR, and keeps their perception of the rover's environment continuously up-to-date.

3.4 Hazard visualization in 3D

The ability to identify environmental hazards (e.g. rocks, craters, etc.) and communicate their locations to the operator is crucial for safe and reliable teleoperation systems. To achieve this, XROV visualizes rocks in the rover's environment by overlaying 3D virtual markers in the reconstructed environment. These markers are placed above the identified rocks, acting as a visual aid for operators; see Fig. 3

A ROS wrapper for a YOLOv5 CNN is used [9], taking as input the rover's real-time camera feed. This allows XROV to detect rocks in the rover's view. The CNN outputs 2D bounding boxes around the detected rocks; see Fig. 3. To display them in the 3D virtual environment, their position w.r.t the origin frame of the 3D mesh is calculated.

Using the generated bounding boxes, we compute their center pixel. The center pixel gives a rough approximation of where to place the 3D virtual marker. Then, the center pixel is deprojected from 2D into 3D space using the depth in-

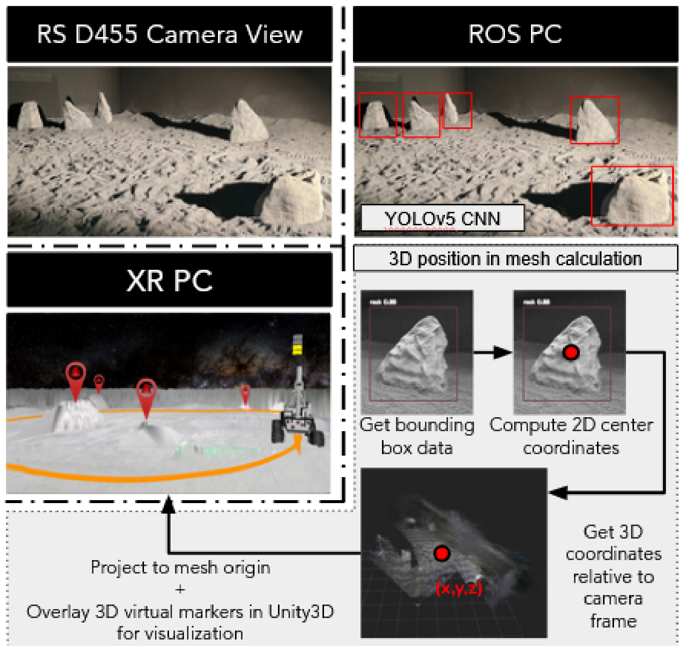


Fig. 3: Hazard detection and visualization using YOLOv5 CNN and Unity3D.

formation from the camera, including its intrinsic and extrinsic calibration data. The result of the deprojection gives us the rocks' location relative to the rover. To obtain the 3D coordinates w.r.t the 3D mesh frame, a frame transformation from the rover to the mesh is applied; see Fig. 3

3.5 Graphical User Interface

Through XROV's GUI, operators have access to crucial rover and environmental data within the XR environment during missions. This data is accessible by activating the GUI with the left VR controller and visualizing it in different panels. Navigating the GUI is possible using the VR controllers in a point-and-click fashion. A raycast is implemented to act as the operator's cursor when navigating through the different panels of the GUI. That said, XROV's GUI is comprised of two main panels:

Rover Information panel contains on-board data of the rover that the operator is controlling. Telemetry data (i.e. position & orientation, speed, and battery information) are displayed within this panel. Furthermore, the rover's wheel effort alongside terrain pitch are equally accessible. In parallel, the operator can directly consult the rover's camera view for teleoperation purposes, which can be further enlarged if needed. Finally, crucial alerts like the loss of the rover's odometry are directly displayed on the GUI to update the operator rapidly.

Fleet Overview panel includes a general view of operational rovers, such as their status (active/idle) and their position in the 3D environment. Detected rocks are listed here by unique ID and position in the environment. At the same time, the operator can access environmental information (surface temperature, Sun & Earth position), as well as their location in the XR environment. Moreover, from this panel, the operator can change their camera Point of View (PoV) in XR, choosing between three options: 1) Top-Down (i.e. the birds-eye view of the environment), 2) First-Person (i.e. default, like being on-site), and 3) Free-Floating (i.e. operator PoV can be placed anywhere in the environment).

3.6 Operator Functionalities

Operators intract with the rover and the environment in VR by moving around the 3D virtual environment in a teleport-like fashion. This is achieved by pointing the controller towards a certain location that they wish to virtually transport themselves. They can also rotate their PoV using the controllers without needing to turn their heads in real life, reducing physical effort. The robot is teleoperated by sending velocity commands directly from the hand controllers.

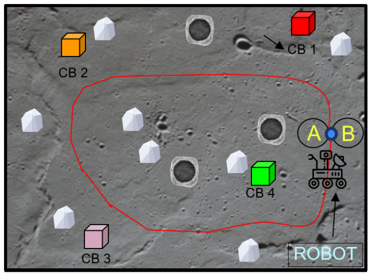
4 Experiments

The XROV framework has been validated through two experiments: 1) Comparison of 2D and 3D visualization with XROV in complex environments (Section 4.3), and 2) XROV framework testing and validation (Section 4.4). The purpose of the first experiment is to establish a clear basis on whether 3D and XR augment current teleoperation approaches. This is subsequently followed by the second experiment, allowing us to further test and evaluate XROV in different conditions, should the first test lead to convincing results. Both experiments consisted of teleoperating a rover in the Lunalab from point A to point B. Figure 4 shows the different configurations of the Lunalab used for each experiment. The participants' path included small craters and rocks to be detected and avoided while relying on the 3D reconstructed environment, the YOLOv5 DL model, and the on-board camera feed.

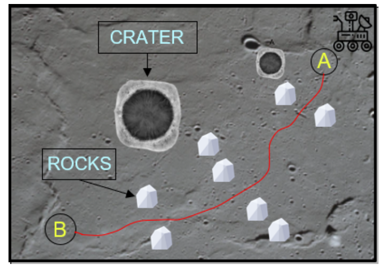
Two groups of participants were defined (see Section 4.1) to carry out one experiment respectively. In the first one, we used a Leo rover [47] within a limited version of XROV (see Sec 4.3 for details), while in the second experiment, we utilised the SUMMIT-XL rover [10]. Both rovers were teleoperated in XR, where users were immersed within the virtual 3D reconstructed environment.

4.1 Users

Ten participants contributed to the experimentation of XROV, separated into two distinct user groups: A) without prior experience in teleoperation and B) with prior experience in teleoperation. Group A was used in the first experiment and subjected to a lighter version of XROV to establish a strong basis for our



(a) LunaLab scenario for XROV validation.



(b) LunaLab scenario for 2D vs 3D XROV comparison.

Fig. 4: Experiments setup and rover path in an analogue facility.

hypothesis. Group B was used in the second experiment to further test the complete version of XROV under different conditions.

In the first experiment, five users (four male and one female) were selected with different ages (M=35.2, SD=8.67, min=22, max=49). For the second one, we selected five users (four male and one male) of diverse ages (M=28.6, SD=7.86, min=20, max=40). Further, all participants were from the Interdisciplinary Center for Security, Reliability and Trust (SnT) at the University of Luxembourg. They were selected to ensure diversity and improve the validity of the experiment and evaluation of the XR application. The study followed the principles of the Declaration of Helsinki, with participants giving informed written consent and ensuring their confidentiality and anonymity.

Before the experiments were conducted, the participants received training on how to use the system, familiarized themselves with the controls and received feedback from instructors. In parallel, additional material and resources were provided to clarify questions before initiating the experiment process.

4.2 Metrics

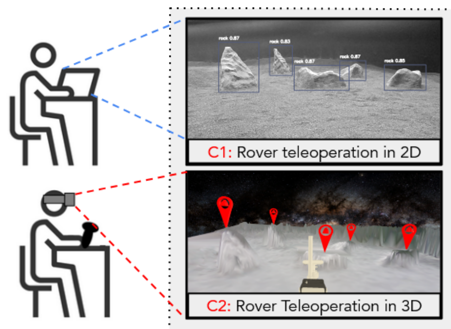
Qualitative and quantitative metrics were obtained to gather relevant data during and after the experiments. These include user feedback questionnaires, user performance, and system performance. In addition to those, the NASA Task Load Index (NASA TLX), a subjective workload assessment tool has been used after each test. It uses a scaling system that divides the workload into six dimensions: mental, physical, and temporal demand, frustration, effort and perceived performance. Each of these measurements are rated within a 100-point range [20].

4.3 Experiment: XROV 2D vs 3D comparison

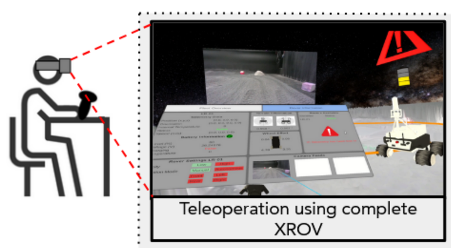
The performance and comparison of XROV under 2D and 3D conditions have been assessed under two Conditions (C); see the differences in Figure 5.

- C1: The operator teleoperated the rover using 2D visual feedback from the rover's onboard camera displayed on a PC screen.
- C2: The operator teleoperated the rover using XR, visualizing the environment as a 3D mesh.

Both experiments utilized the XROV's setup. However, they differed in the method of visualizing the rover's environment: the first condition used a 2D screen, while the second employed an XR Head Mounted Display (HMD). In each condition, the rocks have been labelled differently to be more adapted to each visualization mode. Further, to avoid bias, participants completed tasks in different orders using a randomization approach: two started with 2D and three with 3D.



(a) Operator environment visualization in 2D.



(b) Operator environment visualization in 3D VR.

Fig. 5: Operator visualization feedback of the environment and rocks detected performing the experiments.

Results After each experiment condition, each operator filled out one NASA TLX forms. Figure 6 displays the aggregated results obtained from both experiments, where each bar represents the average score for each dimension.

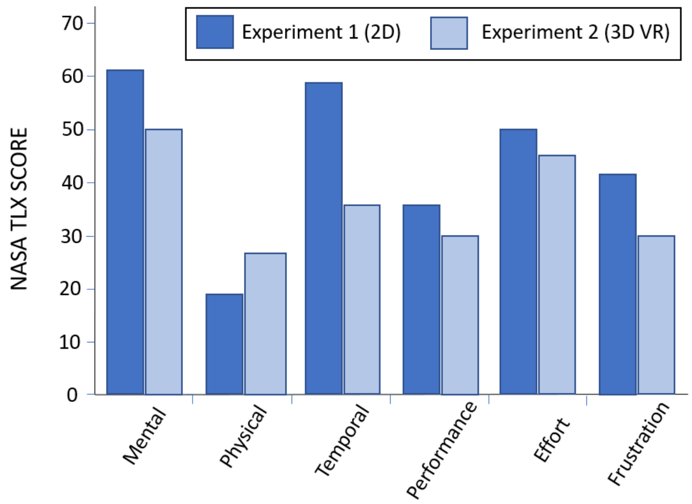


Fig. 6: Average teleoperation workload from NASA TLX; (1) experiment with camera feedback and (2) experiment with 3D VR feedback.

The experiments' outcomes show that the perceived mental/temporal demand, effort and frustration to conduct the task were reduced by 6 to 25 % when using the XR system. The physical demand increased by 7% using XR, but this result is coherent as employing an HMD implies making more movements with the head to visualize different perspectives of the environment. Interestingly, the participants' perceived a reduction in their performance (i.e., how well they feel that they have performed) when using XR, although quantitative metrics say the opposite. During the first experiment, the number of rock collisions while teleoperating the rover was greater (M=2.4) than during the second experiment (M=1.6). The mean time to complete the path of $\sim$ 20 m was 5 min 28 s for C1 and 5 min 30 s for C2. Furthermore, the overall NASA-TLX workload score (w_{score}) for 2D teleoperation was $w_{score} = 51.068$, whereas for 3D teleoperation with XR it was $w_{score} = 39.22$. We note a decrease of 23.20% in terms of workload score when using 3D teleoperation with XR.

Additionally, we asked participants to provide feedback on some questions: (1) Which system is more immersive? (2) Which system is better to plan missions or explorations? (3) Which system is easier to teleoperate the rover with? (4) With which system did you feel safer avoiding rocks? (5) With which system were you able to understand the environment better?

The participants agreed that XR is more immersive than 2D and helps to understand the environment better. XR provides a 3D experience that simulates physical presence and allows direct interaction with the environment. Users felt safer while driving the rover and avoiding obstacles. For VR users, XR was perceived as more realistic and enabled them to see the shapes of the rocks from different perspectives, allowing them to observe the recreated space and how the rover moves. In contrast, while teleoperating in 2D, users stated that it was significantly harder to perceive whether a collision had occurred or not. However, with XR, users noted that they were capable of visualizing the rover from a 3rd person perspective and had a clearer understanding of how to avoid collisions. In addition, they remarked that the rover's movement was smoother and more responsive when teleoperating in XR than with the camera. This is likely due to XR's immersive experience, which enhances depth perception and spatial awareness, making control more intuitive and precise. Also, four out of the five users thought it was safer and more reliable to teleoperate the rover by combining XR with the option to view the rover's camera feed side by side with the reconstructed environment.

4.4 Experiment: XROV validation

Unlike the first experiment in Section 4.3, participants in Group B had experience in classical teleoperation methods. This background was necessary to test the entirety of XROV's functionalities, with the main goal of determining whether XROV enhances lunar rover teleoperation through the use of XR technologies.

Participants were tasked with exploring the Lunalab directly from the XR environment by teleoperating the rover. During the experiment, they were asked to voice their overall experience while simultaneously performing a series of tasks along the way (i.e. accessing GUI information and changing the teleoperation view, among others). Their actions and overall use of XROV were closely observed, and the experiment coordinators took note of user performance metrics (i.e. task completion time, rover collision, etc.). At the end of the experiment, participants were asked to reflect on the experiment verbally before completing two qualitative questionnaires.

Results In addition to the verbal feedback provided by the users, which is elaborated later in this section, the participants first filled out a qualitative internal questionnaire reflecting on their overall experience with the experiment. Questions such as: (1) How comfortable was the experience? (2) How would you rate the immersion factor? (3) Did you experience any difficulties during the experiment? (4) Would you choose 2D or 3D teleoperation?, were included.

In terms of comfort and immersion level, 80% rated this metric a 4/5. Similarly, 80% of users did not experience any difficulties while interacting with XROV, and all users preferred using our approach over their experience with classical teleoperation methods.

With respect to the NASA-TLX questionnaire, we refer to Fig. 7. We note an overall $w_{score} = 26.83$, which indicates a relatively low workload index. The perceived physical (12), mental (24) and temporal (34) demands are relatively low compared to those obtained from the first experiment. The results of the second test are coherent with those obtained in the first one, showing that even with experienced users in teleoperation, XROV suggests a significant improvement over 2D teleoperation approaches.

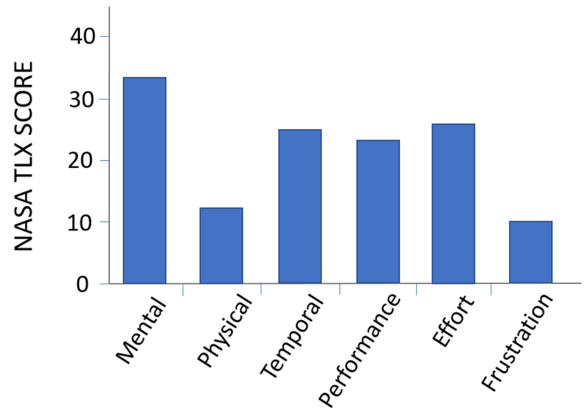


Fig. 7: Average teleoperation workload from NASA TLX during XROV validation.

The participants further noted that the system performance is highly robust, with minimal drops, making it suitable for teleoperation missions. The GUI was also praised as user-friendly and very insightful in collecting crucial telemetry. Users also expressed satisfaction with XROV's functionalities, highlighting the ability to change teleoperation views (FPV - TPV), visualize the rocks in the environment, and combine the camera view with the 3D environment to navigate. Further, the 3D reconstruction of the environment was positively perceived and described as "realistic" and "detailed". Overall, users collectively expressed that XROV is "highly usable" and "innovative".

Metric	Value
CPU load at start	45-50%
GPU load at start	20-30%
Frames at start	120 fps
Latency at start	8 ms
CPU load during mapping	65-75%
GPU load during mapping	50-75%
Frames during mapping	30-60 fps
Latency during mapping	15 ms
Number of times odometry is lost	0

Table 1: System performance results

In terms of the participants' performance metrics, the average experiment duration was around 27 minutes for 15 meters. Users navigated in the GUI 9 to 20 (average = 13.6, SD = 4.72), none lost the odometry of the rover, teleoperated the rover around 10 to 26 (average = 12, SD = 9.02). We can deduce from these results that, on average, users were keen on using the system and were able to do so without experiencing any major roadblocks (e.g. poor performance/usability).

Finally, XROV's system performance is shown in Table 1. We note an increase in CPU and GPU loads when participants are mapping the Lunalab, yet still in acceptable margins. The Frames per Second (FPS) also drop from 120 FPS to around 60 FPS while mapping. This is expected as storing and reconstructing more visual information of the environment produces larger processing requirements over time.

5 Discussion

The XR system significantly reduces the cognitive and mental load of operators despite showing a slight increase in physical demand for using HMD devices. Although participants reported a decrease in perceived efficiency with XR, objective metrics show fewer collisions with rocks, demonstrating its effectiveness. Users appreciated the immersive nature of VR over 2D techniques, finding it more intuitive and safer to understand the environment during lunar missions. Thus, this technology improves the efficiency of operator decision making and exploration. The experiments conducted demonstrate XROV's effectiveness in improving operator telepresence, confidence, and mission performance compared to traditional 2D image-based teleoperation methods.

These observations hold for both Groups A and B. With Group A, we achieved a basis for our initial claim, which allowed us to further evaluate XROV to a larger extent through the second experiment with Group B. The results obtained from the second experiment correlate and support those obtained in the first. Even experienced teleoperation users noted that XR is preferred over 2D and provided positive feedback on the use of XROV.

Furthermore, XROV's performance tests provide us with insightful information on the overall function of the system. CPU and GPU loads remain at acceptable levels, with suitable FPS for VR use (30-60 FPS). Of course, XROV was tested with hardware available on Earth; thus, we are conscious that in real lunar scenarios, these results may differ due to several factors, such as bandwidth and hardware limitations. Nevertheless, the results obtained allow us to evaluate the potential benefits of deploying XR-based teleoperation systems instead of classical approaches in lunar applications. Future exploration missions on the Moon will require robust teleoperation solutions, and based on the results obtained, XR can be a promising alternative.

6 Conclusion and Future work

This work introduces XROV, an innovative rover teleoperation system that uses XR to control lunar missions, which has been validated in a lunar analog facility. This enhanced XR teleoperation system immerses operators in a 3D virtual reconstruction of the rover's environment with autonomous rock detection, allowing remote control and monitoring of the rover. It also includes a GUI to access crucial data and navigate the rover more securely with automated alerts. This approach overcomes limitations of current teleoperation methods, such as limited immersion and operational awareness, by providing a more dynamic and responsive system for exploring unknown lunar terrains. Although designed primarily for lunar exploration, the principles and techniques developed have potential applications for monitoring vehicles or robots in other environments or celestial bodies, such as Mars. We further argue that having access to functionalities, such as those provided by XROV, offers a substantial advantage over current teleoperation approaches. Operators in the future will no longer need to rely on 2D visual feedback from on-board cameras, which lack depth information, have a limited FoV, and imply the use of multiple screens to supervise and control a single robot. Instead, they can directly supervise and control rovers through a more accessible, robust, and intuitive system.

Looking ahead, XR applications should expand in scope and functionality, including space robotic operations such as rendezvous, docking, assembly, and robotic arm tasks. In addition, it could be applied to terrestrial environments, improving user experience in areas such as robot fleet management in warehouses, e-commerce, and more.

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