Immersive Virtual Reality Framework for Lunar Pressurized Rover Training and Interaction

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Dario Zamani[1,a *], Mehran Bahojb Ghalibafan[2,b], Marco Crestini[1,c], Matteo D'Aquila[1,d], Magesh Chandramouli[3,e], Alfonso Pagani[1,f], Marco Petrolo[1,g], and Erasmo Carrera[1,h]

[1]MUL 2 Lab, Department of Mechanical and Aerospace, Engineering, Politecnico di Torino, Corso Duca degli, Abruzzi 24, 10129 Turin, Italy

[2]Department of Architecture, Construction and Design, Politecnico di Bari, Via Edoardo Orabona 4, 70126 Bari, Italy

[3]Computer Graphics Technology, Purdue University Northwest, 2200 169th Street Hammond, IN, USA

[a]dario.zamani@polito.it, [b]m.bahojbghalibafan@studenti.poliba.it, [c]marco.crestini@studenti.polito.it, [d]matteo.daquila@studenti.polito.it, [e]mchandr@pnw.edu, [f]alfonso.pagani@polito.it, [g]marco.petrolo@polito.it, [h]erasmo.carrera@polito.it

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Abstract. This work presents an immersive Virtual Reality framework integrated into a digital twin architecture for the Lunar Pressurized Rover (LPR). The system enables both dynamic simulation of rover operations on simulated lunar terrain and static exploration of its internal layout. Users can interact in real time with cockpit controls, onboard systems, and functional subsystems such as navigation, power, and life support. The framework supports astronaut training, ergonomic assessment, and early design validation, offering a human-centered, cost-effective tool for developing and testing future lunar exploration vehicles.

Introduction

The development of Lunar Pressurized Rovers (LPR) necessitates innovative approaches to design, validation, and training, given the absence of prior operational experience, test campaigns, or physical prototypes [1-2]. To address these challenges, this work presents an immersive virtual environment integrated into a full digital twin architecture, enabling human-centered design exploration, interactive control simulation, and early design insight [3-4].

The virtual platform supports two complementary modes: dynamic simulation and static exploration. In the dynamic simulation mode, users operate a fully interactive digital replica of the LPR within a simulated lunar terrain (Fig. 1). The interface includes cockpit-mounted VR menus for real-time interaction with rover systems. The primary control panel allows users to initiate the rover, toggle between gear modes (Park, Neutral, Drive, and Reverse), and activate auxiliary systems, including Cruise Control and All-Wheel Steering (AWS). A secondary menu enables in-depth interaction with navigation, lighting, onboard cameras, power management, and telemetry displays, including speed, battery status, oxygen level, acceleration, wheel torque, and center of mass tracking. These features provide a realistic operational environment for astronaut and operator training, system diagnostics, and scenario testing [5-6].

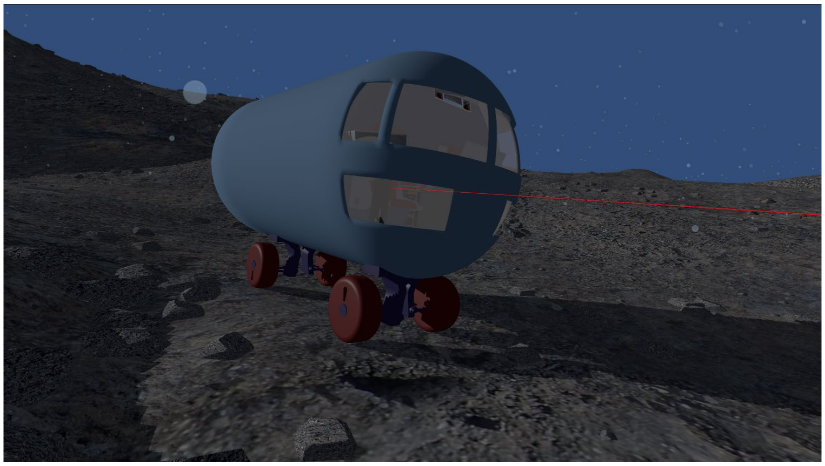

Figure 1. Simulated lunar terrain used in the dynamic mode for immersive operation of the Lunar Pressurized Rover (LPR), enabling real-time interaction with rover systems and environmental navigation.

The static exploration mode focuses on internal layout and functional inspection. Based on a functional flow diagram depicted in Fig. 2, the LPR is decomposed into five subsystems: cockpit, scientific workspace, EVA interface and airlock, crew and utility section, and emergency systems. Each subsystem is modeled with interactive elements and associated tasks, allowing users to explore the internal environment, interact with displays and equipment, and assess ergonomic configuration [7]. The cockpit section includes two reclining seats, multi-functional displays for navigation and system control, and a panoramic viewing system with integrated cameras (Fig. 3). The scientific workspace enables procedural interaction for tasks such as lunar sample handling, analysis, and storage.

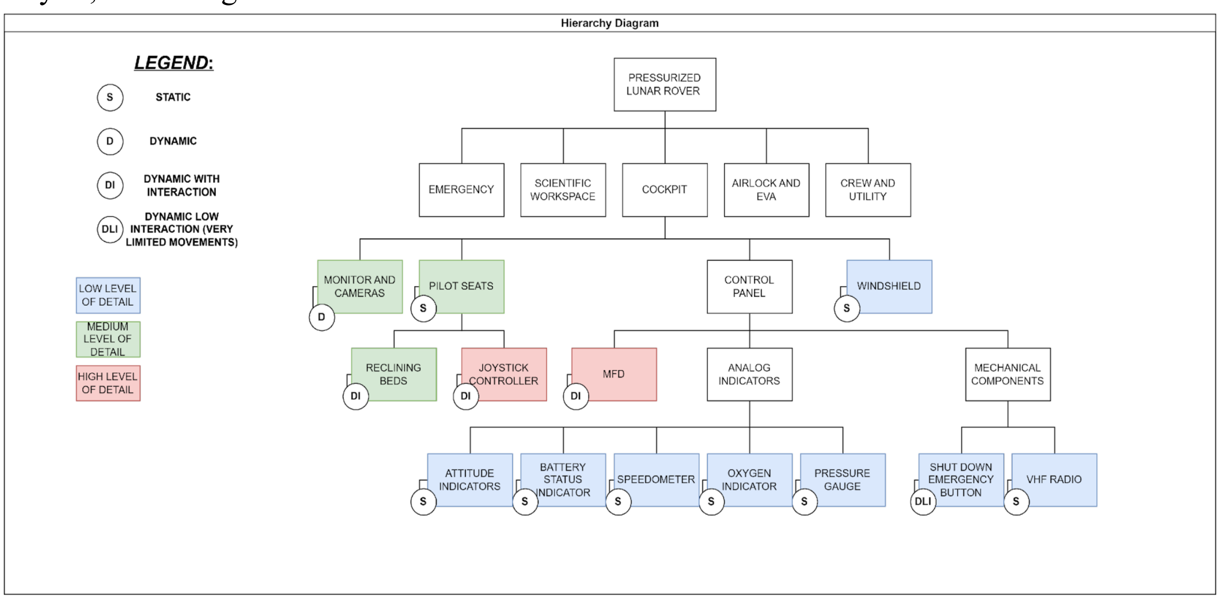

Figure 2. Hierarchical functional diagram of the pressurized lunar rover, showing subsystem decomposition and classification of components by interaction type (static, dynamic, interactive) and simulation detail level.

Together, these two modes provide an integrated environment for both system-level prototyping and mission-specific training [8]. The use of VR from the early stages of design provides a precise spatial perception of volumes and interfaces, which is critical in the absence of physical mock-ups. Human factors are integrated directly through spatial interaction and real-time feedback, improving the placement and accessibility of control systems [9]. Moreover, the virtual model can serve as the front end of a complete digital twin, enabling predictive maintenance through the real-time overlay of telemetry and diagnostic data [10]. This supports fault detection, system health monitoring, and mission planning with a proactive approach to rover operations.

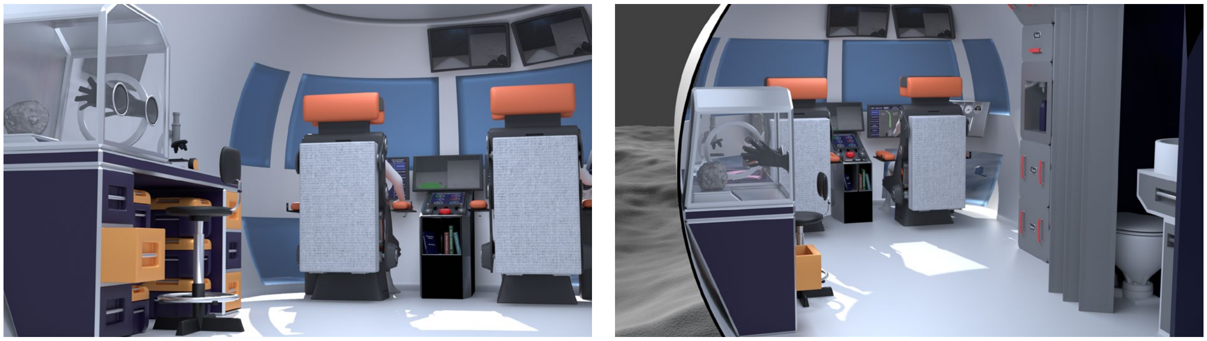

Figure 3. Interior rendering of the pressurized lunar rover showing the cockpit and scientific workspace. The configuration displays ergonomic seating, panoramic screens, multifunctional displays, and a dedicated area for lunar sample analysis and storage.

Cockpit Virtual Environment

One important section of the static exploration mode is the cockpit. In this area, users perform a sequence of tasks aimed at preparing the system for the lunar surface exploration mission. The first step is to perform a functional analysis to break down the cockpit into subsections; after a few iterations the component level is reached. The modeling phase is based on the items identified in the previous step, using aircraft and space systems as a reference for the necessary mesh detailing. Another important topic is the arrangement of elements around the seats: the first inspiration comes from a plane control panel, with a very high level of redundancy, then followed by a more automotive-centered layout, with less redundant components and with a higher distinction between the two crew members' functions. It is also essential to add ergonomic considerations to ensure that every object the crew must interact with is within reach and the configuration is guided by a principle of priority and frequency of use. The last important point is the creation of materials, aiming at reproducing the look and feel of a real environment to increase the sense of immersion. Before focusing on the actual software implementation, extensive preproduction work must be done to identify the precise input-output sequence that users will perform. This process has major impact on the time spent developing the simulation: very detailed studies for every single subtask to be achieved lead to a smoother implementation job. Virtual reality development focuses on establishing an effective interaction between users and the system's interface in front of them. C# scripts are the main way to bring models into life. The simulation is organized as follows: a script, called user interface manager, rules over the instruction messages that show up to guide the players; a second key script is the multi-functional display manager, it controls the navigation within the main interactable display. Additional scripts are created to provide specific methods needed during certain tasks or special out-of-nominal conditions. The result of this work is a sequence of five tasks, with instructions following the users along their path and marking the completion of each single required activity. The first one asks users to turn on the multi-functional display for the first time and to perform a check of the life-support system's status; two problems arise during the inspection of the menu, but users have the necessary support to solve them. The second task focuses on setting up the external camera views in the screens located in the cockpit around the pilot seat, serving as aid during the driving. The third guides the trip planning via the navigation menu and teaches users how to display all the critical data to be accessed during the rover's movement. Other two tasks demonstrate the configuration of the sleeping area and how to handle an emergency.

Unity Simulation

Unity was selected as the development environment due to its real-time rendering capabilities, integrated physics engine, VR compatibility, and versatility in simulating interactive systems. Given that stakeholder training represented a primary project objective, Unity's C# scripting environment enabled the development of customized interaction logic to enhance user engagement, manoeuvrability, and system responsiveness. A dedicated simulation terrain was constructed to evaluate rover performance under lunar like operational conditions. As illustrated in Fig. 4 an interactive menu system designed for a better manipulation. The system includes a main menu, where user can monitor the speed, time, energy level and Oxygen level. A lighting setup designed to imitate the lighting conditions on the Moon, with three groups of lights: wheel lights, interior lights, and headlights. A multi-camera system is also implemented, giving the user side-mirror views, wheel-mounted camera views, and a 360-degree camera for better awareness of the surroundings. In addition, a power-management panel allows the user to adjust the rover's power based on the situation, with numeric input controls to improve accuracy. A navigation display shows the path already travelled by using the stored movement data, and the data-logging system records important values such as position, velocity, acceleration, and each wheel's torque. The user can start or stop the simulation at any time, and the recorded data are exported as a .xlsx file for further analysis. All features are integrated into a VR interactive menu, where the right-hand controller is used for acceleration and braking, and the left-hand controller is used to interact with the menu, giving the user intuitive and efficient control during the simulation. These sections are integrated into an interactive menu accessible through the Meta Quest 2 VR headset. To ensure effective control of both the menu and the rover, the VR controllers are configured to provide maximum ease of use and operational efficiency. The right-hand controller is assigned to control the rover's acceleration and braking, while the left-hand controller is used to interact with the on-screen menu and its functions.

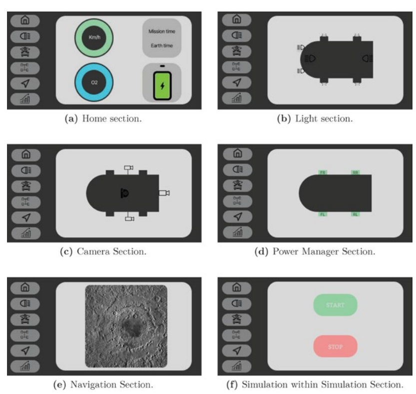

Figure 4. The interactive menu of the Roover.

Scientific Workspace Virtual Environment

The scientific workspace is the LPR's onboard workbench used in static exploration to inspect internal layout, equipment, and conduct moon sample analysis experiments. In this mode, users can explore the laboratory and interact with instruments to complete the related tasks. The workspace is modeled around a workbench equipped with different useful tools for measurement and inspection, a microscope, and a local monitor for task prompts and readouts. A sealed chamber (glovebox) with integrated gloves enables manipulation of regolith while preventing dust dispersion inside the rover (Fig. 4). Visual fidelity focuses on highly interactive tools, including baked textures for regolith to preserve surface detail in real time. As with the cockpit, the scientific workspace was first decomposed through a functional analysis. Before implementation, a detailed input–output storyboard was created for each subtask (inputs: grabs, button presses, tool contacts; outputs: UI prompts, instrument readings, state changes). This upfront mapping shortened implementation time and ensured that every interaction in VR corresponds to an explicit, verifiable outcome. As seen in the previous section, the task sequence is implemented in Unity through C# scripts that manage state transitions and user interactions. A VR storyboard shows the workspace as a sequence of tightly scoped training tasks whit event-driven scripts that handle collisions, grabs and UI prompts:

- Sample selection & setup: The user opens the sealed box UI, selects a sample/object set, and confirms to lock into glovebox view with the chosen items inside.
- Weighing, sizing, and subdivision: Inside the glovebox, the trainee weighs the sample (balance readout on UI), measures dimensions, fractures it with a hammer, and repeats measurements on fragments—all with immediate UI feedback.
- Microscope analysis: After exiting glovebox view, a selected fragment is placed in the microscope; here it’s possible to zoom/rotate controls for close inspection and to gather more data.
- Data capture & verification: Results are recorded in a notebook UI; a “Check Answers” step flags correct/incorrect entries and reports a score on the bench monitor.
- Emergency drill (workspace-linked): If an onboard alert triggers, the trainee leaves the bench, wears a suit in a prescribed order, and returns to diagnose the fault via the workspace monitor, reinforcing cross-section readiness while remaining anchored to lab operations.

Figure 4. VR rendering of the sealed-box interior showing the sample measurement and tool selection. The configuration displays interactive hands, various instruments, and a panel for choosing what to bring inside the box.

Conclusions

By integrating immersive simulation, functional modeling, and predictive analytics, the proposed framework reduces development time and costs, enhances system reliability, and facilitates real-time operational decision-making in planetary surface missions. The developed virtual environments for the cockpit and scientific workspace demonstrate how VR can effectively support human-centered design, procedure validation, and astronaut training. The approach enables early evaluation of ergonomics, system accessibility, and task sequences before physical prototypes exist. Future developments will extend the framework toward a fully integrated digital twin with real-time telemetry, haptic feedback, and interactive mission simulations.

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