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VIRTUAL REALITY SERIOUS GAME FOR SPACE SCIENCE COMMUNICATION: A CASE STUDY ON LUNAR ROVER

Ahmed Hegazy[1,†,*], Marco Rossoni[1,†], Marina Carulli[1], Giorgio Colombo[1], Monica Bordegoni[1]

[1]Politecnico di Milano, Dept. of Mechanical Engineering, Milano, Italy

ABSTRACT

The future of space exploration relies not only on technological advancements but also on public awareness and policy support. Sustaining long-term investments in lunar and planetary missions requires effectively engaging both the next generation and key decision-makers. However, traditional science communication methods often fail to reach audiences beyond academic and professional circles, limiting public engagement. Virtual Reality and Serious Games offer interactive and immersive experiences that make complex scientific concepts more accessible to non-experts, fostering broader support for space exploration initiatives.

This study evaluates the effectiveness of a Virtual Reality Serious Game designed to simulate the Lunar Zebro rover navigating the Moon's surface. The game aims to enhance engagement, simplify scientific concepts, and shape public perception of space missions. Through iterative development and user testing, the study examines the balance between education and entertainment. Preliminary findings indicate that while the game successfully engages users and communicates mission objectives, it is primarily perceived as an interactive experience rather than a standalone educational tool. These insights highlight the potential of VR Serious Games in science communication and their role in promoting future space exploration initiatives.

Keywords: Virtual Reality, Serious Game, User Experience.

1. INTRODUCTION

More than 50 years after the Apollo 17 mission, space exploration is experiencing a resurgence. These historic achievements mark the beginning of a new era of human space exploration, with a strong focus on establishing a sustained presence on the Moon [1].

The lunar South Pole and the far side of the Moon have emerged as key areas of scientific interest. The discovery of hydroxyl isotopes in permanently shadowed craters suggests the presence of lunar ice, a resource that could support future human habitation and fuel production for deep-space missions [2]. However, the Moon presents extreme environmental conditions that pose significant challenges for both life support and scientific experimentation, including severe temperature fluctuations, an almost nonexistent atmosphere, high radiation exposure, and pervasive lunar dust [3]. Additionally, the far side of the Moon is of great importance for radio astronomy, as it offers a natural shield from Earth-based radio interference. This region provides an opportunity to capture low-frequency cosmic signals, which are crucial for advancing our understanding of cosmic phenomena, dark matter, and the origins of the universe [4, 5]. Despite these scientific opportunities, securing funding for lunar scientific missions remains a major challenge, as public and political support often fluctuates based on perceived mission relevance and accessibility.

Traditional science communication methods, such as academic publications, public lectures, and educational documentaries, often fail to engage a broad audience beyond specialized scientific communities. These approaches are typically passive and require prior knowledge, making complex topics like space exploration difficult to grasp for the general public. Furthermore, conventional methods lack interactivity and immersion, both of which are critical for sustaining engagement and enhancing knowledge retention.

Virtual Reality (VR) offers a transformative approach to science communication by providing interactive, hands-on experiences that allow users to explore scientific concepts in a dynamic and engaging way. VR can simulate environments that are otherwise inaccessible, such as the surface of the Moon, allowing users to experience space exploration firsthand rather than passively consuming information. However, the mere use of VR alone is not sufficient; its effectiveness depends on structured, goal-oriented interaction. For this reason, VR-based educational tools should follow the principles of Serious Games [6], meaning they must be designed with a primary purpose beyond entertainment, such as education, training, or public engagement.

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†Joint first authors
*Corresponding author: ahmed.hegazy@polimi.it

Existing VR applications in space education have focused primarily on immersive experiences but often lack structured, goal-driven interactivity that enhances knowledge acquisition and public engagement. These applications serve as educational tools but do not fully leverage VR's potential for outreach, particularly in fostering public interest and political support for future space missions. While VR has been widely explored in science communication, little research has addressed its use as a serious game specifically designed to communicate scientific objectives while simultaneously engaging a broader audience.

This paper investigates the application of VR Serious Games with the primary objective of assessing user experience and educational effectiveness in communicating the scientific goals of a lunar exploration mission. The study examines the balance between educational value and entertainment in VR Serious Games and explores their potential as an interactive science communication tool. It also evaluates their viability as a promotional medium for space outreach, with a focus on Lunar Zebro, a miniature lunar rover designed for swarm exploration [7]. The paper first reviews state-of-the-art VR applications in space science communication, followed by a detailed description of the game's storyboard and implementation, structured across three levels. The subsequent section presents findings from user testing, including testing protocols, participant feedback, and necessary improvements identified across three development iterations.

2. RELATED WORKS

Science communication plays a critical role in ensuring the sustainability of space projects by fostering public engagement and support. As space missions become increasingly ambitious, maintaining a strong relationship between research and public outreach is essential for securing the necessary funding and political backing [8]. Public perception directly influences the availability of resources for space exploration, as greater awareness and appreciation of scientific advancements can lead to broader institutional and governmental support. Historically, investments in space programs have had a profound impact on society, as demonstrated by the Apollo program in the 1960s, which contributed to a surge in highly educated professionals in physical sciences, engineering, and mathematics. International collaborations, such as the International Space Station (ISS) and the James Webb Space Telescope (JWST), have further reinforced the importance of public support in advancing scientific exploration.

Serious games have emerged as an effective strategy for communicating scientific concepts to a wider audience. Studies show that game-based learning strategies enhance comprehension, particularly among children and non-experts, by making abstract scientific concepts more accessible [9, 10]. The gaming industry has extended its impact beyond entertainment, influencing fields such as education [11], healthcare [12], engineering [13], and politics [14]. Unlike conventional educational approaches, serious games engage users on both cognitive and emotional levels, fostering structured interaction and problem-solving [9].

Virtual Reality (VR) is increasingly recognized as a powerful tool for serious games, offering immersive environments that enhance engagement, improve knowledge retention, and facilitate skill acquisition [15]. Research has shown that VR-based serious games significantly impact learning outcomes by increasing user motivation, promoting interactivity, and strengthening knowledge transfer [16]. The added immersion provided by VR allows users to interact with scientific content in a way that traditional media cannot replicate, making it a promising avenue for science communication. However, while VR serious games aim to improve user experience and knowledge acquisition, their full potential in the context of space science communication remains underexplored [17].

Several VR applications have been developed to communicate fundamental space science concepts. Apollo VR 16 is a serious game that simulates a lunar roving mission, designed to increase student interest in space exploration. A comparative study evaluated engagement and usability by testing the PC version against the VR version. Findings revealed that VR players exhibited higher levels of interest and enhanced performance in space-related tasks. While the VR version required more time to complete, it provided a significantly more interactive and immersive experience, reinforcing its effectiveness as an educational tool [18].

Another example is Moon & Space Station VR, which is designed to engage children in space science by recreating a realistic space station and lunar environment. The simulation includes features such as a nuclear propulsion system, astronaut living quarters, and a laboratory, while a secret room with a bot rocket allows users to experience reduced gravity and explore a 360-degree space view. Studies on this project found that 80% of students demonstrated increased curiosity in space science, with most preferring the lunar simulation for its realism and immersion. This project highlights VR's potential as a powerful educational tool, making complex scientific concepts more engaging and interactive [19].

Although these VR applications demonstrate the value of immersive environments in science education, they primarily serve as passive learning tools rather than structured, goal-driven experiences. Most existing applications focus on observational learning rather than interactive problem-solving, limiting their potential for knowledge retention and public engagement. Furthermore, current VR implementations in space science rarely explore the role of serious games as a promotional medium for building public interest in upcoming space missions.

Different frameworks have been proposed for the development of VR-based serious games [20], yet few studies have examined their effectiveness in the context of space exploration beyond classroom learning. While prior work has demonstrated the benefits of VR in improving engagement, there is a lack of research into how VR serious games can be designed not only to educate but also to foster advocacy and funding support for space programs. Addressing this gap, this study also provide a preliminary investigation on how VR serious games can communicate scientific objectives while simultaneously serving as a tool for public engagement and outreach.

3. CASE STUDY: DESCRIPTION AND REQUIREMENTS

The challenges of lunar exploration inspired students at TU Delft to develop the first European and Dutch mini-rover, known as Lunar Zebro. The name "Zebro" derives from the Dutch term

"Zesbenige Robot", meaning "six-legged robot." Unlike conventional wheeled rovers, Lunar Zebro features a unique walking mechanism that allows it to traverse the Moon's rugged terrain with greater adaptability. The project envisions an affordable, small-scale robotic system capable of performing complex missions while operating collaboratively as a swarm [7]. Current lunar exploration missions rely on large, heavy rovers that serve as the primary means of planetary surface exploration. The success of such missions is highly dependent on the condition of a single rover, which increases both risk and operational costs. The Lunar Zebro project offers an alternative approach by introducing a distributed exploration strategy, where multiple small, autonomous rovers collaborate to complete tasks. In addition to its scientific objectives, the Lunar Zebro initiative aims to engage the public and inspire new generations by making space exploration more accessible.

The VR Serious Game here proposed was developed to communicate the significance of lunar exploration, the challenges posed by the Moon's environment, and the potential of Lunar Zebro rovers in future missions. The game is designed to provide an interactive experience that conveys scientific concepts in an engaging and accessible manner.

The development process required addressing several key technical considerations. The first requirement was to simulate the unique locomotion capabilities of Lunar Zebro, ensuring that the movement mechanics accurately reflected the rover's real-world performance. Additionally, the game needed to demonstrate how the swarm of rovers could collaborate to execute a mission, providing insight into the advantages of distributed exploration. The second major requirement was to illustrate the scientific significance of the lunar South Pole and the far side of the Moon, highlighting the challenges of these environments and the potential for scientific discovery.

Beyond scientific accuracy, the game was designed for public outreach events, introducing additional constraints. The duration of the experience was limited to under 10 minutes to accommodate live demonstrations in educational and promotional settings. Furthermore, this is a threshold commonly used to avoid cybersickness issues. The interface had to be intuitive and accessible, considering that many participants might have little prior experience with VR technology. Since the primary audience consisted of the general public rather than scientists or engineers, the language used in the game needed to be simple and engaging rather than highly technical. The VR experience also had to account for the user's unfamiliarity with VR interactions, ensuring smooth and intuitive gameplay.

The choice of hardware was another important consideration. The Oculus Quest 3 was selected equipped with two joysticks, as the platform for deployment due to its combination of affordable cost, high processing power, and extended battery life, making it suitable for use in public events. The standalone nature of the headset also allowed for an untethered experience, improving user comfort and mobility during gameplay.

4. GAME DESIGN AND STORYBOARD

The VR Serious Game takes place in three locations on the Moon, each corresponding to a level in the game: the lunar landing outpost, the Lunar South Pole, and the far side of the Moon. These locations introduce players to different aspects of lunar exploration, gradually increasing task complexity while maintaining an engaging and educational experience.

The first level is set at the lunar outpost, where the player arrives accompanied by a "master rover". As shown in Figure 1, several rovers are in hibernation mode, with their solar panels raised to recharge their batteries. After an audio introduction, the player is familiarized with the environment and mission objectives. Movement is facilitated through a teleportation system, activated by pushing the left joystick forward. A curved beam projects from the controller, indicating the teleportation destination, and upon release, the player is transported to the designated location.

Markers appear near the hibernating rovers, guiding the player to activate them. The player directs the master rover to navigate toward these markers, triggering the activation sequence. As the master rover reaches a marker, the dormant rovers lower their solar panels and become operational, following the master rover to the next location. This process continues until all rovers have been activated. Once complete, a teleportation circle appears, allowing the player to transition to the next level.
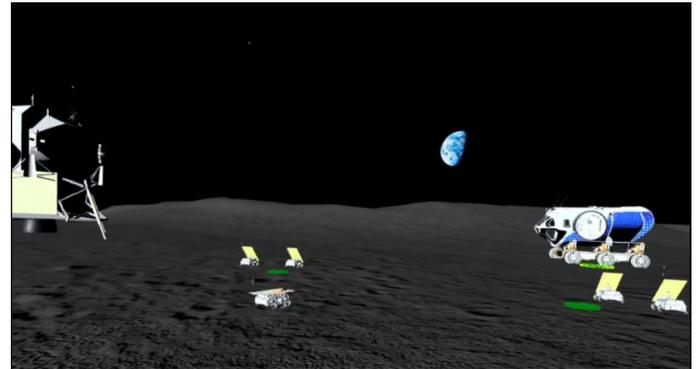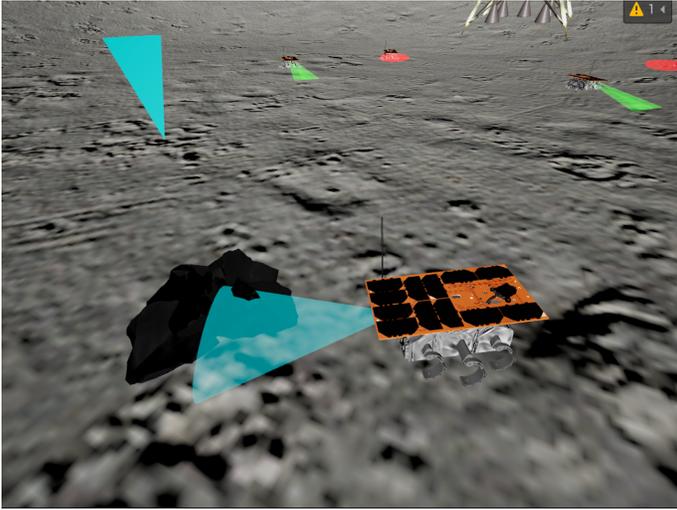

FIGURE 1: SCREENSHOT OF THE LUNAR OUTPOST

The second level takes place at the Lunar South Pole, where the player is accompanied by a fleet of Lunar Zebro rovers, each carrying a specific scientific payload. Throughout this stage, audio narrations provide information about the South Pole's unique conditions and scientific relevance, particularly the potential for lunar ice within permanently shadowed craters.
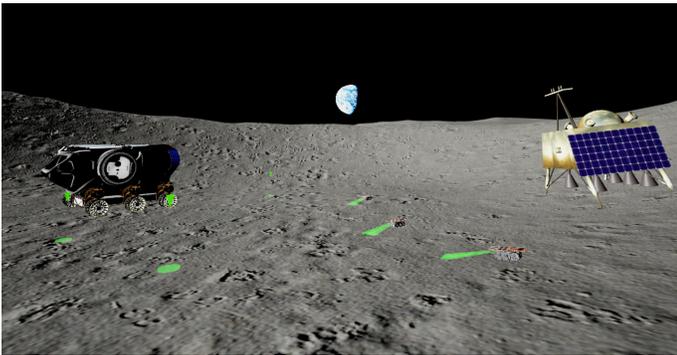
The first task involves mapping the crater floor (Figure 2a). Markers appear on the surface, each representing a region to be scanned. The player selects a target area, prompting the rover equipped with the topographic mapping payload to move toward it. As the rover advances, it emits a scanning beam, recording surface data along its path. Once all designated areas are mapped, a topographical representation of the crater is generated.

The second task focuses on lunar ice detection. A marker appears, guiding the player to an area where ice deposits are suspected. The player moves toward the designated location and activates a scanning beam, while the lunar ice detection rover autonomously navigates to the site. Upon arrival, the rover emits a beam to analyze the surface composition, confirming the presence of lunar ice and other valuable minerals (Figure 2b).

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In the final task, additional markers appear, indicating locations likely to contain precious minerals. The player selects these sites, prompting the designated mineral detection rovers to conduct scans. Once the analysis is complete, the player directs the fleet into a teleportation circle, transitioning to the final level.

(a)

(b)

FIGURE 2: SECOND LEVEL: (A) ROVER SCANNING FOR LUNAR ICE AND (B) ROVERS SCANNING THE CRATER'S BED.

The third level is set on the far side of the Moon, a region of significant scientific interest for radio astronomy. The player is surrounded by six Lunar Zebro rovers, arranged in a circular formation. An audio narration explains the importance of this location as a radio-quiet zone, ideal for capturing low-frequency cosmic signals.

The first objective is to position the rovers to form a virtual radio antenna. Markers appear, guiding the player to direct specific rovers toward these designated locations. As the rovers reach their positions, they align to establish the antenna structure. Once this initial configuration is complete, the task shifts to expanding the antenna's diameter. Additional markers appear, requiring the player to reposition the remaining rovers. Upon reaching their final locations, the antenna is fully deployed, marking the successful completion of the level.

The game design follows a gradual learning progression, ensuring that players become comfortable with the mechanics before encountering more complex challenges. The teleporta-
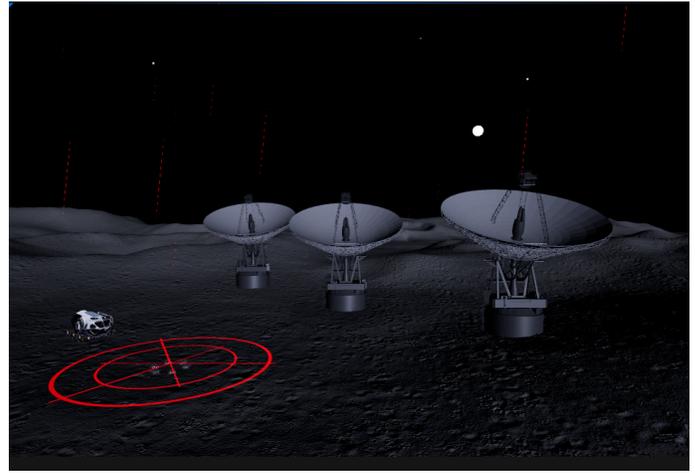

FIGURE 3: THIRD LEVEL SHOWING THE CONCEPT OF RADIO ASTRONOMY

tion system enhances movement efficiency while minimizing the risk of motion sickness, a common issue in VR environments. Interactive elements, such as rover activation, terrain scanning, and antenna deployment, create an engaging experience where players actively participate in scientific exploration rather than passively observing.

In the pre-production phase, a storyboard is designed considering the previous user requirements and needs as it is mentioned in Section 3. As previously mentioned, developing a VR serious game requires attention to scientific accuracy and acceptable realism. Before designing the game, it is essential to understand the details of the phenomena on the Moon, the sites and the lunar mission. It is also important to balance the entertainment aspect and ensure that it does not overshadow the authenticity of the real scenario. Therefore, for each lunar site it was designed based on a scientific reference. The development of the Lunar Zebro VR Experience has evolved through three major iterations, incorporating feedback from the Lunar Zebro team, industrial mentors, and academic supervisors. The storyboard described in this section and the following implementation (Section 5) refer to the last design iteration.

5. IMPLEMENTATION

From a technical perspective, the game was developed using Unreal Engine (UE) 5.2, a game engine that enables high-performance VR rendering. The physics-based movement of the rovers was designed to accurately reflect real-world constraints, ensuring realistic interactions with the lunar terrain. The integration of spatial audio cues further enhances immersion, reinforcing mission objectives through dynamic voice guidance. The user interface was intentionally designed to be minimalist and intuitive, reducing cognitive load and making the experience accessible to users unfamiliar with VR technology. The following sections highlights some aspects of the implementations worth to be discussed.

5.1. High-fidelity Lunar Terrain

The South Pole, specifically its permanently shadowed regions, has become well known thanks to data collected by NASA's Lunar Reconnaissance Orbiter (LRO), which has been circling the Moon since 2009. The LRO gathers information about temperature, topography, and radiation levels, creating detailed information maps of the lunar South Pole craters [21].

NASA's Exploration Systems Simulation is also developing a graphical representation of the Lunar South Pole. This simulation provides a visualization of shadow patterns within the region's craters, influenced by the unique position of the Sun, which neither rises nor sets but instead hovers near the horizon. Additionally, the lunar topography in this area is highly irregular, with extreme variations in elevation between high and low regions. The deep crater floors remain in permanent darkness, as sunlight never reaches them. Some of these craters are among the coldest places in the solar system and act as traps for volatile compounds, such as lunar ice, which would otherwise sublimate under direct solar exposure due to the lack of an atmosphere [22]. Furthermore, from the perspective of a virtual camera positioned at the South Pole, Earth appears upside down and rotating backward due to the Moon's axial orientation.

Following the aforementioned references, the terrain has been created in the game engine using the Landscape tool exposed by UE. The environment and lighting in the three-game levels are carefully designed to match the visual references of the mission's location. In the 'Lunar Outpost,' the moon and Earth are visible in the sky. The direction of shadows for the moon's elevated and recessed features, including craters and mountains, is respected, as well as the shaded area of the Earth around the sun. Furthermore, to maintain scientific accuracy, the surface where the asset lander settles must be flat. This commitment to realism not only enhances the visual appeal of the game environment but also ensures alignment with scientific principles. Figure 4 shows the result obtained for the lunar outpost and south pole scenes.

5.2. Simulation of Cosmic Microwaves

The far side of the Moon is a unique location for radio astronomy, as it remains shielded from terrestrial radio-frequency interference, making it an ideal site for detecting faint cosmic microwave background radiation [5]. Scientists aim to deploy ultra-long wave radio telescopes to study the Dark Ages of the Universe, a period following the Big Bang when neutral hydrogen played a crucial role in cosmic evolution [23]. However, detecting these faint signals is challenging due to radio emissions that interfere with observations. To address this, astronomers have proposed various lunar telescope inspired by concepts dating back to the Apollo era [24].

In the gameplay, the representation of these concepts underwent multiple iterations to strike a balance between scientific accuracy and clarity for a general audience. The radiation field is visualized as an expansive region surrounding the initial rover deployment site. At the start, the player identifies a focal point where the rovers must position themselves to capture the first spectrum of cosmic rays. As the gameplay progresses, the antenna's radius expands, allowing for the detection of a broader spectrum of signals. To optimize performance and maintain a
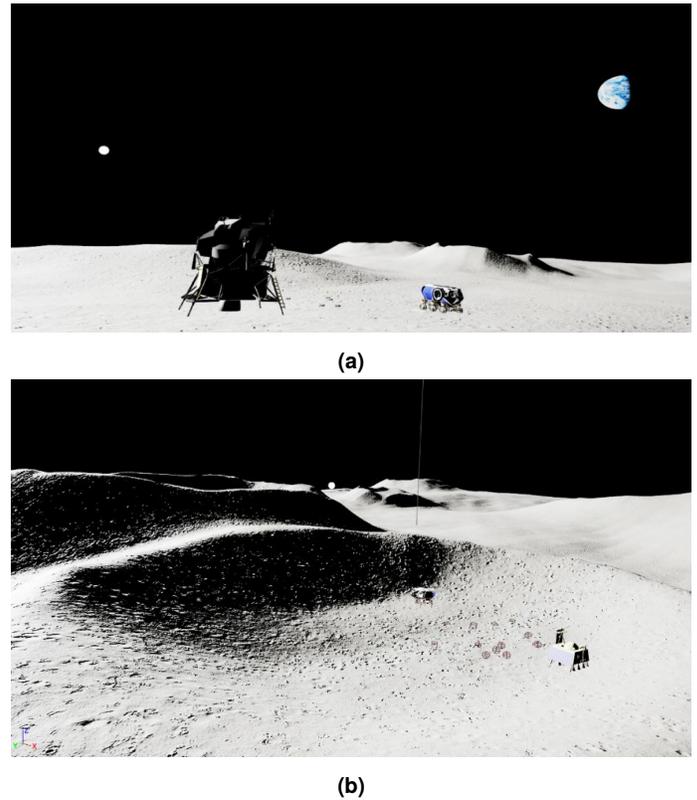

(a)

(b)

FIGURE 4: DETAIL OF THE TERRAIN IN THE (A) LUNAR OUTPOST AND (B) SOUTH POLE CRATER SCENES.

visually immersive experience, the radiation beams were initially rendered using multiple emitters, which proved computationally expensive. To resolve this, a Niagara particle system, tool inside unreal used for creating visual effects, was implemented, consolidating multiple radiation sources into a single dynamic effect. This system reduced rendering load while preserving the visual fidelity of the radiation beams, ensuring a seamless VR experience without compromising scientific representation.

5.3. Lunar Rover Rigging and Intelligence

The rover in the game features three primary movements: general locomotion, raising and lowering the solar panel, and adjusting the antenna arm. The animation process begins in Blender, where the rover is equipped with an armature system consisting of a primary bone for the hull and secondary bones for the legs, solar panel, and antenna arm. A third bone ensures that the antenna remains vertical as the solar panel moves. To achieve precise motion control, the rigged model is exported to Unreal Engine, where animations are managed using the internal Control Rig Blueprints. Figure 5 shows the lunar rover with the rigs overlay in Blender.

The rover's movement is based on a synchronized leg cycle, where three legs move while the other three remain grounded to maintain balance and stability. To prevent a sliding effect, a reciprocating Z-axis motion is introduced, ensuring the leg movement aligns with the terrain. In Unreal Engine, motion rig logic is implemented using a delta-time-based function, controlling motion cycles to ensure smooth transitions. The rotation of each leg

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FIGURE 5: LUNAR ZEBRO ROVER RIGGING.

follows a time-based mapping, enabling alternating movement cycles. Additionally, a jumping motion is introduced by interpolating position values along the Z-axis, simulating natural terrain adaptation and movement over uneven surfaces.

To simulate the swarm behavior of the rovers, it is essential to implement a collision-avoidance mechanism that ensures smooth movement towards the final destination while preventing rovers from colliding with one another. This is achieved using the Reciprocal Velocity Obstacles approach, exposed by UE 5.2, which dynamically calculates the velocity vectors of each agent, allowing them to adjust their trajectories in real time. This system ensures that each rover moves autonomously and efficiently while maintaining coordinated navigation, essential for multi-agent exploration missions.

5.4. Performance and Level of Detail

After completing game development, it is essential to conduct a comprehensive performance analysis to ensure a smooth gaming experience and efficient resource utilization. This process, known as game profiling, aims to identify and mitigate bottlenecks that could negatively impact gameplay. Game profiling involves evaluating the game's GPU and memory usage, optimizing resource allocation, and refining rendering techniques to enhance overall performance.

In VR game development, profiling is initially conducted within Unreal Engine before being tested directly on the VR headset. This dual approach provides a thorough assessment of resource-intensive elements that may degrade performance. Ensuring optimal frame rates and stability is particularly crucial in VR experiences, as even minor frame delays can cause motion sickness and discomfort.

To monitor and evaluate performance metrics, the OVR Metrics Tool is utilized. This tool provides real-time insights into key parameters such as frame rate, heat generation, GPU and CPU throttling, and the occurrence of frame tears and stale frames per second. By analyzing these factors, adjustments can be made to enhance rendering efficiency and maintain a seamless experience.

In early development stages, several performance challenges were encountered. The initial versions featured a high polygon count and high-resolution textures, particularly in the lunar landscape and imported assets from Unreal Engine mega-scans. These elements significantly increased rendering load. To optimize performance, the polygon count of the landscape was reduced while maintaining a moderate resolution. Additionally, Level of Detail (LOD) techniques were implemented to dynamically adjust asset quality based on the player's distance. The LOD setting was increased from 1 to 3, ensuring that distant landscapes were rendered at lower detail, thereby reducing computational overhead.

A similar optimization strategy was applied to the Lunar Zebro rover model. Since the rover is a central element in the game, its polygon count could not be excessively reduced without causing visual deformation. Instead, the LOD variation was increased to 5, allowing the rendering quality to dynamically adjust based on the player's proximity. This ensured that the rover maintained high visual fidelity when viewed up close while reducing rendering load when viewed from a distance.

Another performance bottleneck was identified in assets containing opaque materials and complex lighting components, which were computationally expensive to render. To mitigate this, the number and size of these assets were reduced or replaced with less demanding alternatives when possible. Additionally, the rendering pipeline was configured following the optimization strategies suggested in [25]. In the game environment, location markers were initially designed as opaque objects but were later replaced with cones of light, which illuminated the designated areas with solid cylindrical beams. These light cones were further optimized to only appear when necessary, such as during specific actions in the second level, including topographic scanning or rock analysis for lunar ice and minerals. Further optimizations were applied to the third level, where the antennas above the rovers were originally implemented using textures with opacity volumes, which increased rendering complexity. To enhance performance, the antennas were redesigned in Blender as fully shaped objects, reducing the need for expensive transparency calculations.

One of the most significant performance challenges was observed in the radiation beams used in the third level. These beams initially relied on a large number of particle emitters, significantly increasing rendering costs. To address this, the level design was revised to consolidate multiple radiation sources into a single Niagara system with a reduced number of particles while maintaining a longer shape volume. This approach effectively reduced computational load while preserving visual quality.

Through these optimizations, the game achieves a balance between high-fidelity visuals and smooth performance, ensuring an immersive and comfortable VR experience. The implementation of LOD techniques, efficient material rendering, and optimized particle systems significantly enhances frame stability and resource efficiency, ensuring the game to run above 72 frame per second when deployed on the Meta Quest 2.

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6. USER TESTING AND RESULTS

The testing process was conducted in three distinct stages. The first stage involved internal testing within a Virtual Reality development team, focusing on game quality and interaction mechanics. The second stage was conducted in collaboration with the Lunar Zebro team to ensure scientific accuracy and refine the user experience. The final stage involved public testing, which was crucial for assessing user engagement and knowledge retention.

6.1. Testing with the Technical Teams

The first two testing sessions were conducted with the technical team at TU Delft. These sessions did not follow a predefined protocol; instead, testers were asked to explore the application and provide feedback through post-interviews, reporting inaccuracies and suggestions.

Feedback from these early sessions highlighted several key issues: (i) unintended rover controls, where the player directly controlled the rover, deviating from the mission's intended autonomous operation; (ii) slow gameplay and inaccurate lunar textures, which reduced immersion; and (iii) limited scientific depth, as the game initially focused more on traditional gaming mechanics rather than scientific exploration.

Based on this feedback, major revisions were implemented before the final release. The landscape was redesigned for realism, game performance was optimized, and the game mechanics were restructured into sequential tasks. The rover control system was adjusted so that instead of direct player control, users could now designate movement locations, better reflecting the actual mission's operation.

These changes resulted in significant improvements in conveying the mission objectives, though some challenges remained, such as repetitive gameplay and unrealistic rover movement (sliding effect). Additionally, a radiation detection system was introduced, where rovers formed a virtual antenna to capture a wider range of radiation spectra. These refinements contributed to a more immersive and mission-driven experience, with improved mechanics that better aligned with real-life autonomous rover operations. Public testing was conducted exclusively on the final version of the game.

6.2. Public Testing

Public testing took place in a controlled indoor environment at Politecnico di Milano, with participants primarily consisting of university students and researchers. Each session included multiple participants, ensuring a comprehensive assessment of user interactions.

Before gameplay, participants were provided with an introductory explanation of the project through a Lunar Zebro animation video, followed by a briefing on the lunar south pole and the far side of the Moon.

To evaluate user expectations, experience, and learning outcomes, two questionnaires were administered. First, a pre-gameplay questionnaire which collected user demographics and prior knowledge of lunar exploration, covering topics such as lunar topology mapping, lunar ice, and radio astronomy. After the game, a post-gameplay questionnaire assessed aspects such as enjoyment, ease of control, clarity of instructions, realism, and scientific comprehension. Participants rated various elements on a scale of 1 to 4, provided qualitative feedback on gameplay challenges, and offered suggestions for improvement. It should be noted that in this case, a custom questionnaire was chosen over standard ones, such as the Post-Study System Usability Questionnaire, because the primary objective of this study was to preliminarily evaluate the effectiveness of scientific concept communication rather than focusing on usability or engagement indicators.

A total of 20 participants took part in the study, all university students aged between 20 and 30, with an average age of 29. Among them, 33% were designers, 8% were architects, and 59% were engineers from various disciplines.

The testing yielded a first set of quantitative results, capturing measurable user ratings, which are reported in Table 1.

TABLE 1: RESULTS FROM THE EXPERIMENTS WITH THE PUBLIC.

	Average Rating
Enjoyment	3.42/4
Ease of control	3.58/4
Clarity of instructions	3.29/4
Scientific clarity	3.58/4

The numerical ratings from user feedback indicated an overall positive reception. The game received an average rating of 3.42 out of 4 for enjoyment, suggesting that participants found it engaging. The interface was rated 3.58 out of 4 for ease of control, indicating that most users found the interaction mechanics intuitive. However, clarity of instructions received a slightly lower rating of 3.29 out of 4, suggesting room for improvement in guiding players more effectively. Lastly, the scientific clarity of the game was rated 3.58 out of 4, demonstrating a strong educational impact and confirming the game's effectiveness in conveying key scientific concepts.

Moreover, the post-test questionnaires highlighted several points reflecting subjective user experiences, which are discussed in the next section.

7. DISCUSSION

A qualitative analysis and interpretation of the users feedbacks provided further insights into the game's entertainment value and educational effectiveness. Participants found two key elements most engaging: the lunar environment and the Lunar Zebro rover. Some players highlighted the detailed lunar landscape, Earth's visibility, and the immersive movement mechanics as their favorite aspects. Others enjoyed controlling the rover and observing its movement, appreciating its detailed design.

On the other side, several players struggled with understanding the audio instructions, with some difficulty in hearing the guidance or experiencing audio overlaps. Users suggested adding subtitles to improve clarity. Others found teleportation mechanics somewhat inconsistent, with occasional difficulties moving to the designated areas. Some players were also confused about rover movement mechanics, expecting more direct control rather than point-and-click navigation. Additionally, some found the joystick

controls imprecise and requested more visual guidance. Another challenge was the ergonomics of the Oculus headset, particularly for users who wear glasses. Some participants found it difficult to wear comfortably, and many had to remove the face strap, leading to discomfort and marks on their faces.

Interestingly, players unfamiliar with the Lunar Zebro project tended to focus more on the gaming experience itself rather than the scientific aspects of the mission. When asked for suggestions, most responses were about improving the game, such as adding more levels, incorporating a low-gravity effect, or enabling rover charging mechanics, rather than discussing the real-world mission challenges.

Observations from gameplay sessions and post-game discussions provided additional insights into user behavior and engagement. Many users did not immediately recognize the ambience and breathing sounds designed to simulate an astronaut's experience inside a suit. Some participants suggested including on-screen text-based instructions to supplement the audio. Others noted that first-time players often focused more on the game mechanics than on the scientific content and only absorbed the educational material on subsequent playthroughs. A few players reported experiencing dizziness, likely due to high-contrast visual transitions. Others appreciated the detailed lunar environment but noted that the lighting contrast could sometimes be jarring. Some suggested using headphones to improve immersion and overcome issues with low in-game voice instructions, particularly in noisy environments.

Some participants felt the UI could better simulate an astronaut's control system, such as incorporating a futuristic sci-fi interface with interactive knobs and buttons instead of traditional game menus. Additionally, the teleportation circle's design was occasionally confusing, as it resembled the rover movement indicator, causing players to unintentionally skip levels. Users suggested making the teleportation marker a vertical "gate" instead of a flat circle on the ground to better convey its purpose.

Players generally enjoyed observing rover movements, but some requested clearer indicators to confirm when a rover was executing a command. Others suggested a UI panel displaying rover tasks and a live map for better mission tracking. Some players found it challenging to differentiate between the right and left joystick functions, particularly for teleportation versus rover movement.

In general, a common reaction among first-time users was a "wow" effect upon entering the lunar environment. However, some players felt lost during transitions between levels and suggested visual markers to indicate the next objectives. Observers also noted that when multiple participants played, those who watched others before playing tended to avoid the mistakes their peers made, highlighting the benefit of group-based learning experiences. Additionally, some players had difficulty distinguishing between real-world physical boundaries and in-game boundaries, leading to instances where they nearly collided with physical objects despite the VR environment's safety markers. The user testing process provided valuable insights into both the strengths and areas for improvement in the Lunar Zebro VR experience. The game was well-received, with high ratings for enjoyment, control intuitiveness, and scientific accuracy. However, improve-

ments in audio instructions, UI clarity, teleportation mechanics, and headset ergonomics would enhance the overall experience. The testing also confirmed that while the game effectively communicates scientific concepts, first-time players often focus on gameplay mechanics rather than mission knowledge, suggesting that repeated playthroughs or additional interactive elements could enhance learning outcomes. Feedback gathered through quantitative ratings, qualitative responses, and direct observations will guide future iterations of the Lunar Zebro VR game, ensuring that it continues to evolve as an educational and engaging tool for awareness of lunar exploration.

8. CONCLUSION AND FUTURE DEVELOPMENT

Virtual Reality and serious gaming are rapidly evolving fields that offer innovative ways to engage audiences with complex scientific concepts. This study assessed the impact of the Lunar Zebro VR experience, focusing on both its educational value and entertainment aspects. Through iterative development and extensive user testing, the game has demonstrated its effectiveness as a science communication tool for conveying the Lunar Zebro mission. However, user perception indicates that the experience is primarily viewed as interactive and engaging, rather than a formal educational tool. Participants praised the VR environment for its intuitiveness, ease of control, and immersive nature, while also finding the scientific explanations accessible and well integrated into the gameplay. These results confirm the game's potential in enhancing public engagement and fostering interest in lunar exploration.

Despite its strengths, user testing revealed several challenges. Some participants reported difficulties in following audio instructions, navigating the user interface, and using the VR headset, particularly for those who wear glasses. Additionally, users expressed a desire for more interactive elements and clearer guidance throughout the experience. The current version of the game leans toward entertainment over education, aligning with its intended use in public outreach events as an engaging introduction to the Lunar Zebro project. Rather than serving as a standalone educational tool, the VR experience functions as a complementary visualization aid, providing an interactive medium to showcase how the Lunar Zebro rover represents a simpler and more cost-effective approach to lunar exploration.

Future developments should focus on balancing scientific depth and entertainment value to maximize learning outcomes without compromising engagement. Several key enhancements can be implemented to refine the experience. Improving the instruction system through subtitles, clearer audio guidance, and interactive mission prompts would enhance user comprehension. The user interface could be refined by incorporating sci-fi-inspired control panels or holographic UI elements, creating a more immersive astronaut-like experience. Enhancements in navigation and interactivity, such as refining teleportation mechanics, improving rover control feedback, and introducing interactive mission tools, would allow users to engage more actively with the lunar environment. Addressing VR headset ergonomics, particularly for users who wear glasses, remains a priority and could involve testing alternative adjustment methods or compatibility solutions. Additionally, expanding gameplay content by

incorporating new mission scenarios, increasing interactivity, and introducing challenges related to lunar exploration would provide a more comprehensive and engaging experience.

By implementing these improvements, the Lunar Zebro VR experience can evolve into an even more impactful tool for science communication. Beyond its entertainment value, it holds significant potential to educate users on the importance of robotic exploration, bridging the gap between scientific outreach and interactive technology. As VR continues to advance, its role in public engagement, education, and space advocacy will further expand, making immersive experiences like this an essential component of future science communication strategies.

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REFERENCES

[1] Creech, Steve, Guidi, John and Elburn, Darcy. "Artemis: An Overview of NASA's Activities to Return Humans to the Moon." *2022 IEEE Aerospace Conference (AERO)*: p. 1–7. 2022. IEEE. DOI 10.1109/aero53065.2022.9843277.

[2] Li, Shuai, Lucey, Paul G., Milliken, Ralph E., Hayne, Paul O., Fisher, Elizabeth, Williams, Jean-Pierre, Hurley, Dana M. and Elphic, Richard C. "Direct evidence of surface exposed water ice in the lunar polar regions." *Proceedings of the National Academy of Sciences of the United States of America* Vol. 115 No. 36 (2018): p. 8907 – 8912. DOI 10.1073/pnas.1802345115. Cited by: 466; All Open Access, Green Open Access, Hybrid Gold Open Access.

[3] Carpenter, J. "ESA Strategy for Science at the Moon." Technical report no. European Space Agency. 2019. URL https://exploration.esa.int/s/WmMyaoW. Accessed: November 2, 2025.

[4] Maccone, Claudio. "Moon Farside Protection, Moon Village and PAC (Protected Antipode Circle)." *Acta Astronautica* Vol. 154 (2019): p. 233–237. DOI 10.1016/j.actaastro.2018.02.012.

[5] Mimoun, David, Wieczorek, Mark A., Alkalai, Leon, Banerdt, W. Bruce, Baratoux, David, Bougeret, Jean-Louis, Bouley, Sylvain, Cecconi, Baptiste, Falcke, Heino, Flohrer, Joachim, Garcia, Raphael F., Grimm, Robert, Grott, Matthias, Gurvits, Leonid, Jaumann, Ralf, Johnson, Catherine L., Knapmeyer, Martin, Kobayashi, Naoki, Konovalenko, Alexander, Lawrence, David, Feuvre, Mathieu Le, Lognonné, Philippe, Neal, Clive, Oberst, Jürgen, Olsen, Nils, Röttgering, Huub, Spohn, Tilman, Vennerstrom, Susanne, Woan, Graham and Zarka, Philippe. "Farside explorer: unique science from a mission to the farside of the moon." *Experimental Astronomy* Vol. 33 No. 2–3 (2011): p. 529–585. DOI 10.1007/s10686-011-9252-3.

[6] Hare, Ryan, Ferguson, Sarah and Tang, Ying. "Enhancing student experience and learning with iterative design in an intelligent educational game." *British Journal of Educational Technology* Vol. 56 No. 2 (2024): p. 551–568. DOI 10.1111/bjet.13526.

[7] Tejeda, J. M., Fajardo, P., Verma, M. K. and Verhoeven, C. "The Complete Set of Thermo-mechanical-Radiation Methods, Simulations and Results for a Swarm of Nanorovers Deployed on the Moon's Surface (Lunar Zebro Mission)." *Advances in Astronautics Science and Technology* Vol. 5 No. 4 (2022): p. 317–334. DOI 10.1007/s42423-022-00115-7.

[8] Phillips, James and Ma, Yanni. "Understanding the Frontier's Role in Shaping the Upcoming Generation's Perceptions of NASA and Space Exploration." *AIAA AVIATION FORUM AND ASCEND 2024*. 2024. American Institute of Aeronautics and Astronautics. DOI 10.2514/6.2024-4906.

[9] Lugmayr, Artur, Sutinen, Erkki, Suhonen, Jarkko, Sedano, Carolina Islas, Hlavacs, Helmut and Montero, Calkin Suero. "Serious storytelling – a first definition and review." *Multimedia Tools and Applications* Vol. 76 No. 14 (2016): p. 15707–15733. DOI 10.1007/s11042-016-3865-5.

[10] Zyda, M. "From visual simulation to virtual reality to games." *Computer* Vol. 38 No. 9 (2005): p. 25–32. DOI 10.1109/mc.2005.297.

[11] Berardinucci, Francesco, Colombo, Giorgio, Lorusso, Marcello, Manzini, Massimo, Terkaj, Walter and Urgo, Marcello. "A learning workflow based on an integrated digital toolkit to support education in manufacturing system engineering." *Journal of Manufacturing Systems* Vol. 63 (2022): p. 411–423. DOI 10.1016/j.jmsy.2022.04.003. URL http://dx.doi.org/10.1016/j.jmsy.2022.04.003.

[12] Cattaneo, Andrea, Savodelli, Anna, Amroussi, Amin, Cavallo, Maria Sofia, Pesenti, Debora, Ragazzi, Maria, Rota, Cristian and Vitali, Andrea. *Virtual Reality with Moodle for Training in Telemedicine*. IOS Press (2025): DOI 10.3233/shti250193. URL http://dx.doi.org/10.3233/shti250193.

[13] Vitali, Andrea and Rizzi, Caterina. "A virtual environment to emulate tailor's work." *Computer-Aided Design and Applications* Vol. 14 No. 5 (2017): p. 671–679. DOI 10.1080/16864360.2016.1273584. URL http://dx.doi.org/10.1080/16864360.2016.1273584.

[14] Ullah, Mohib, Amin, Sareer Ul, Munsif, Muhammad, Yamin, Muhammad Mudassar, Safaev, Utkurbek, Khan, Habib, Khan, Salman and Ullah, Habib. "Serious games in science education: a systematic literature." *Virtual Reality & Intelligent Hardware* Vol. 4 No. 3 (2022): p. 189–209. DOI 10.1016/j.vrih.2022.02.001.

[15] Urgo, Marcello, Terkaj, Walter, Mondellini, Marta and Colombo, Giorgio. "Design of serious games in engineering education: An application to the configuration and analysis of manufacturing systems." *CIRP Journal of Manufacturing Science and Technology* Vol. 36 (2022): p. 172–184. DOI 10.1016/j.cirpj.2021.11.006.

[16] Damianova, Nadia and Berrezueta-Guzman, Santiago. "Serious Games Supported by Virtual Reality—Literature Review." *IEEE Access* Vol. 13 (2025): p. 38548–38561. DOI 10.1109/access.2025.3544022.

[17] Menin, Aline, Torchelsen, Rafael and Nedel, Luciana. "An Analysis of VR Technology Used in Immersive Simulations with a Serious Game Perspective." *IEEE Computer Graphics and Applications* Vol. 38 No. 2 (2018): p. 57–73. DOI 10.1109/mcg.2018.021951633.

[18] Cao, Lizhou, Peng, Chao and Hansberger, Jeffrey T. "Usability and Engagement Study for a Serious Virtual Reality Game of Lunar Exploration Missions." *Informatics* Vol. 6 No. 4 (2019): p. 44. DOI 10.3390/informatics6040044.

[19] R, Saran., S.P, Shrikesh., V, Vamsidharan. and V, Sangeetha. "Virtual Reality Based Moon And Space Station." *2021 3rd International Conference on Signal Processing and Communication (ICPSC)*: p. 481–484. 2021. IEEE. DOI 10.1109/icspc51351.2021.9451691.

[20] Checa, D. and Bustillo, A. "A review of immersive virtual reality serious games to enhance learning and training." *Multimedia Tools and Applications* Vol. 79 No. 9–10 (2020): pp. 5501–5527. DOI 10.1007/s11042-019-08348-9.

[21] Mitrofanov, I. G., Sanin, A. B., Boynton, W. V., Chin, G., Garvin, J. B., Golovin, D., Evans, L. G., Harshman, K., Kozyrev, A. S., Litvak, M. L., Malakhov, A., Mazarico, E., McClanahan, T., Milikh, G., Mokrousov, M., Nandikotkur, G., Neumann, G. A., Nuzhdin, I., Sagdeev, R., Shevchenko, V., Shvetsov, V., Smith, D. E., Starr, R., Tretyakov, V. I., Trombka, J., Usikov, D., Varenikov, A., Vostrukhin, A. and Zuber, M. T. "Hydrogen Mapping of the Lunar South Pole Using the LRO Neutron Detector Experiment LEND." *Science* Vol. 330 No. 6003 (2010): p. 483–486. DOI 10.1126/science.1185696.

[22] Bingham, Lee, Kincaid, Jack, Weno, Benjamin, Davis, Nicholas, Paddock, Eddie and Foreman, Cory. "Digital Lunar Exploration Sites Unreal Simulation Tool (DUST)." *2023 IEEE Aerospace Conference*: p. 1–12. 2023. IEEE. DOI 10.1109/aero55745.2023.10115607.

[23] Bandyopadhyay, Saptarshi, Mcgarey, Patrick, Goel, Ashish, Rafizadeh, Ramin, Delapierre, Melanie, Arya, Manan, Lazio, Joseph, Goldsmith, Paul, Chahat, Nacer, Stoica, Adrian, Quadrelli, Marco, Nesnas, Issa, Jenks, Kenneth and Hallinan, Gregg. "Conceptual Design of the Lunar Crater Radio Telescope (LCRT) on the Far Side of the Moon." *2021 IEEE Aerospace Conference (50100)*: p. 1–25. 2021. IEEE. DOI 10.1109/aero50100.2021.9438165.

[24] Bandyopadhyay, Saptarshi, Lazio, Joseph, Stoica, Adrian, Goldsmith, Paul, Blair, Brad, Quadrelli, Marco, de la Croix, Jean-Pierre and Rahmani, Amir. "Conceptual ideas for radio telescope on the far side of the moon." *2018 IEEE Aerospace Conference*: p. 1–10. 2018. IEEE. DOI 10.1109/aero.2018.8396801.

[25] Rossoni, Marco, Pozzi, Matteo, Colombo, Giorgio, Gribaudo, Marco and Piazzolla, Pietro. "Physically Based Rendering of Animated Point Clouds for EXtended Reality." *Journal of Computing and Information Science in Engineering* Vol. 24 No. 5 (2023). DOI 10.1115/1.4063559.