SOL977: Ingenious Revival, a Martian Simulation Game for STEM Engagement and Space Education

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Abstract: Interactive simulations and immersive environments offer a powerful means of enhancing education by replicating real-world challenges in virtual settings. In the context of space exploration, these tools provide learners with opportunities to engage in mission-relevant tasks, fostering exploration, problem-solving and experimentation. This paper presents *SOL977: Ingenious Revival*, a simulation-based game developed with the Unity game engine and 3D modeling tools such as Blender. The Martian environment is constructed using, among other sources, high-resolution Digital Terrain Models (DTMs) of Mars to support realism and immersion. The simulation places players in the role of a field technician responsible for restoring the functionality of NASA's Ingenuity drone after it sustains damage. The main goal is to replace a broken rotor blade in order to restore the vehicle's flight capability. This scenario is inspired by a real malfunction that occurred on Mars in January 2024. The player interacts with mechanical and electronic components by carrying out realistic maintenance procedures. They complete a series of mission-specific tasks including terrain navigation and equipment repairs within a simulated Martian environment. The repair process reflects authentic workflows with each action needing to be carried out in a specific order and under defined conditions. The player must use the right tools, follow written procedures and demonstrate a high level of attention to detail. This structure supports the development of critical thinking, problem-solving abilities and technical reasoning within a STEM-focused educational context. Preliminary evaluation that was conducted with high school students suggested that the game increased motivation, deepened conceptual understanding of STEM subjects and promoted interest in space-related careers. This project highlights the educational potential of interactive simulations to bridge theoretical knowledge with hands-on problem-solving, supporting more meaningful and applied STEM learning. It also demonstrates the transformative potential of interactive simulations in STEM education, bridging the gap between theoretical knowledge and practical experience. It finally showcases how simulation-based games can engage students and foster a deeper understanding of complex concepts, while also sparking interest in space exploration and technical careers.

Keywords: Educational technology, Immersive learning, Simulation-Based education, STEM engagement, Experiential learning

1. Introduction

As space-related industries continue to expand, the need for interdisciplinary STEM knowledge and practical skills is becoming increasingly important. Fields such as aerospace engineering, robotics and space systems demand both conceptual understanding and applied technical competence. However, traditional education often struggles to convey these domains in ways that highlight their interconnected and hands-on nature.

Interactive simulations have emerged as a promising tool to address this challenge. By offering immersive virtual learning environments, they provide a practical solution to the lack of hands-on experience among STEM students and engineers, while also enhancing engagement and deepening conceptual understanding.

To support this educational need, SOL977: Ingenious Revival was developed as a simulation-based game that replicates key aspects of space mission operations. Built with Unity and Blender, the simulation features a Martian terrain constructed using high-resolution Digital Terrain Models. Players carry out mission-relevant tasks including equipment diagnostics, terrain navigation and mechanical repairs. A central scenario involves replacing a damaged rotor blade on NASA's Ingenuity rover, inspired by real events from January 2024, when actual Ingenuity's rotor blade sustained damage permanently grounding the vehicle[1].

The game draws from space mission procedures, aviation maintenance and game-based learning strategies. It offers open-ended play without time limits, allowing players to experiment and develop technical skills at their own pace. Initial evaluations with high school students suggest the simulation effectively increases motivation and interest in space exploration and STEM fields.

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[1] Gonzaga Shireen (2024) 'NASA reports on Ingenuity Mars helicopter accident', *Earth Sky*, 17 December (Available at: https://earthsky.org/space/nasa-report-ingenuity-mars-helicopter-accident/) (Accessed: 30 April 2025)

This paper outlines the development and educational impact of *SOL977*. Specifically, section 2 reviews related theory and prior work; section 3 details the simulation's structure and highlights the main aspects of its development; section 4 presents evaluation results; and section 5 offers conclusions and future directions. Figure **1** shows gameplay screenshots of. The game is available for free download and use from its repository[2].

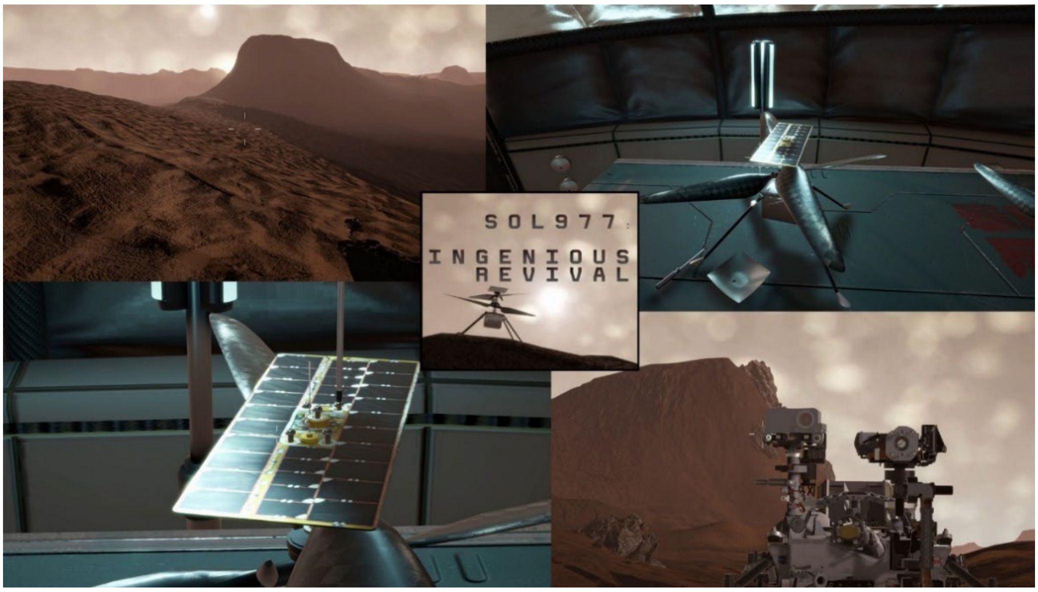


Figure 1: ***SOL977: Ingenious Revival*** **gameplay screenshots**

2. Background and Related Work

Interactive simulations and serious games have become increasingly influential in STEM education due to their ability to contextualize abstract concepts and simulate real-world problem-solving environments. They support exploratory learning by allowing learners to engage with content actively, rather than passively receiving information.

The benefits of simulation-based learning are well-supported in educational research. Active engagement with interactive systems has been shown to enhance motivation, foster conceptual understanding and improve knowledge retention (De Freitas and Jarvis, 2007)**.** These environments are particularly effective in high-stakes or technically complex domains like aerospace, where hands-on practice and contextual awareness are essential (Souza and Trivelato, 2004). In contrast to conventional didactic instruction, simulations support experimentation allowing users to learn by trial-and-error and understand concepts at their own pace.

Recent meta-analytic evidence supports the efficacy of non-immersive, PC-based educational simulations and serious games in advancing STEM learning outcomes. A 2022 meta-analysis of digital game-based learning across STEM disciplines found a moderate effect, suggesting meaningful gains in achievement over conventional instruction (Wang *et al.*, 2022). An even broader 2023 review examined 123 studies and reported clear advantages in learning outcomes when comparing digital STEM games to traditional methods, with simulation-type games (14 % of studies) contributing substantially to positive results (Gui *et al.*, 2023). Finally, a Bayesian meta-analysis of computer-based scaffolding within STEM problem-based learning found moderate effects across engineering, mathematics and technology, highlighting the value of computer environments in supporting higher-order thinking (Kim, Belland and Walker, 2017). These converging findings affirm that **screen-based simulations and serious games**, even without immersive VR, reliably bolster STEM knowledge, problem-solving skills and motivation.

Focusing on space-related educational simulations, NASA's *Mars Rover Game*[3] demonstrate how game-based environments can teach mission planning, navigation and robotics through structured, interactive tasks while

[2] https://irisot.itch.io/SOL977-ingeniousrevival

[3] Available at: https://spaceplace.nasa.gov/explore-mars/en/

Rover Mechanic Simulator[4] offers a grounded example of technical gameplay, in which players are being guided through structured rover repairs with the use of step-by-step instructions. In contrast, *SOL977* promotes exploratory learning through mission-based tasks, where players face technical challenges and receiving guidance only when they seek it. The latter design reflects real-world mission conditions and draws on Situated Cognition (Brown, Collins and Duguid, 1989) and Gee's (2007) theory of learning through meaningful engagement, independent problem-solving and learner autonomy.

Additionally, the game mechanics are designed with elements of Cognitive Apprenticeship (Collins, Brown and Newman, 1987), that is, complex tasks are being gradually introduced with embedded guidance and scaffolding. The availability of mission instructions and feedback mechanisms as well as the structured increase in difficulty emulate expert guidance, helping learners acquire domain-specific skills and knowledge.

The simulation also draws on multimedia learning theory (Mayer, 2014), which emphasizes the role of visual and interactive elements in enhancing comprehension and supporting long-term knowledge retention. In *SOL977*, tasks such as equipment diagnostics or rover route planning are grounded in meaningful contexts, thereby activating analytical and procedural thinking.

The fidelity of these environments significantly impacts their effectiveness and their contribution to the overall educational outcome. Incorporating high-resolution Digital Terrain Models (DTMs) to reconstruct an accurate Martian environment enhances visual realism and authenticity, with these qualities being essential in simulation-based learning environments and particularly in aerospace (Shaffer *et al.*, 2005). The realistic Martian terrain combined with mission-authentic tasks reinforce learners' sense of presence and relevance, which is essential for cognitive investment.

Theoretical frameworks such as the Activity Theory-based model by Carvalho *et al.* (2015), provide a structure for analysing serious games in terms of learning goals, user roles and interaction mechanics. *SOL977* is informed by these principles with task structures and interactions with the virtual environment designed to support progressive learning.

The game also draws on Problem-Based Learning (PBL) principles (Hmelo-Silver, 2004) presenting learners with mission-relevant challenges, such as identifying and repairing a broken rover blade. These tasks require critical thinking and encourage learners to explore and implement solutions.

In alignment with Experiential Learning Theory (Kolb, 2014), the simulation provides a concrete, hands-on environment where students interact directly with tools, objects and the Martian terrain. This immersive experience supports a learning cycle that includes doing, reflecting and applying, thus promoting deeper understanding through active engagement.

To sum, SOL977 is based on principles of situated, experiential and problem-based learning, with combined technical accuracy and interactivity to support engagement and transferable STEM skills.

3. Design and Development

To support meaningful gameplay and science learning, *SOL977* combines educational goals with strong technical design. The simulation encourages critical thinking and spatial reasoning while reflecting realistic Martian constraints regarding equipment repairs. This section outlines the tools, architecture and design choices behind the experience.

3.1 Tools and Asset Pipeline

The Unity game engine[5] was the primary development platform, chosen for its support for 3D graphics, user-friendly editor and active developer community. Its frequent updates ensure compatibility with the latest graphical standards, while its scene system, collision detection and input handling were essential for scripting interactions with mission equipment.

[4] https://store.steampowered.com/app/864680/Rover_Mechanic_Simulator/?l=english&curator_clanid=29519836

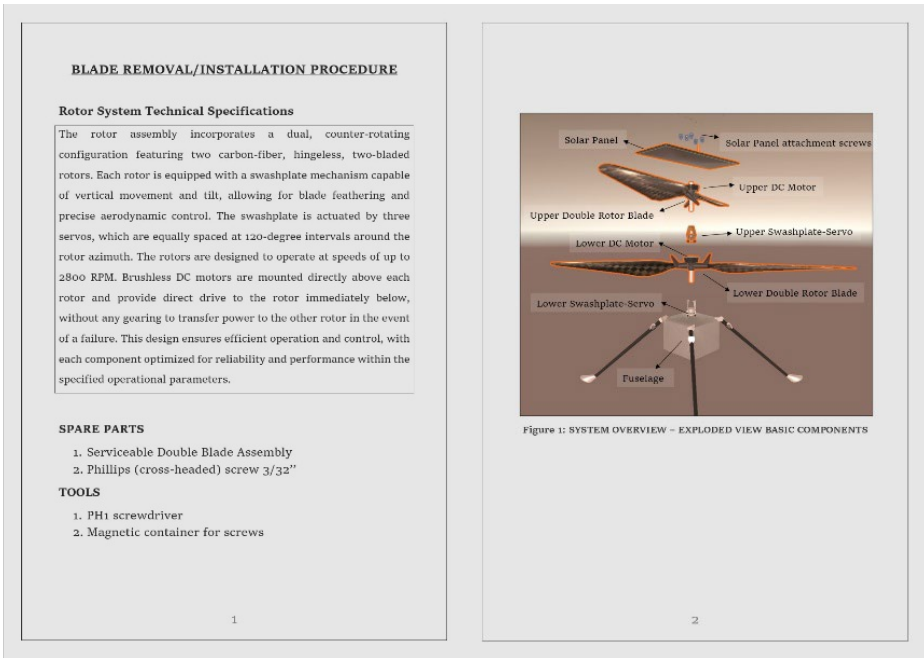
[5] https://unity.com/

Digital Terrain Models (DTMs) of Mars, captured by NASA's Mars Reconnaissance Orbiter and sourced from the Lunar and Planetary Laboratory at the University of Arizona[6], were processed in Blender[7], a free and open-source 3D modelling suite, in order to be optimized for Unity, maintaining also their terrain features.

3D models of Mars-origin meteorites were also used to enrich the environment, obtained from Astromaterials 3D[8] which provides free high-resolution scanned geological models.

3.2 Mission Structure and Gameplay Loop

In *SOL977*, the player's mission follows a goal-driven repair scenario. Players are presented with a high-level list of objectives through the game's User Interface (UI), which can be toggled anytime during gameplay. These include: a) locating the Ingenuity rover within the Martian landscape; b) retrieving the rover and bringing it back to the base station; c) consulting the Repair Procedure via an interface panel (Figure 2); d) diagnosing and replacing a specific faulty component; and e) completing a verification step to determine success.



BLADE REMOVAL/INSTALLATION PROCEDURE

Rotor System Technical Specifications

The rotor assembly incorporates a dual, counter-rotating configuration featuring two carbon-fiber, hingeless, two-bladed rotors. Each rotor is equipped with a swashplate mechanism capable of vertical movement and tilt, allowing for blade feathering and precise aerodynamic control. The swashplate is actuated by three servos, which are equally spaced at 120-degree intervals around the rotor azimuth. The rotors are designed to operate at speeds of up to 2800 RPM. Brushless DC motors are mounted directly above each rotor and provide direct drive to the rotor immediately below, without any gearing to transfer power to the other rotor in the event of a failure. This design ensures efficient operation and control, with each component optimized for reliability and performance within the specified operational parameters.

SPARE PARTS

1. Serviceable Double Blade Assembly
2. Phillips (cross-headed) screw 3/32"

TOOLS

1. PH1 screwdriver
2. Magnetic container for screws

1

Figure 1: SYSTEM OVERVIEW – EXPLODED VIEW BASIC COMPONENTS

2

Figure 2: The first two pages of the Repair Procedure in-game manual that the user consults

This sequence, also shown diagrammatically in Figure 3, is a finite set of user-driven events. The structure supports a trial-and-error loop. If the repair is unsuccessful, feedback is provided, prompting the user to retry.

[6] https://www.lpl.arizona.edu/

[7] https://www.blender.org/

[8] https://ares.jsc.nasa.gov/astromaterials3d/

Upon success, a reward is triggered and the session ends. This design enhances engagement and incorporates engineering logic as well as spatial reasoning tasks.

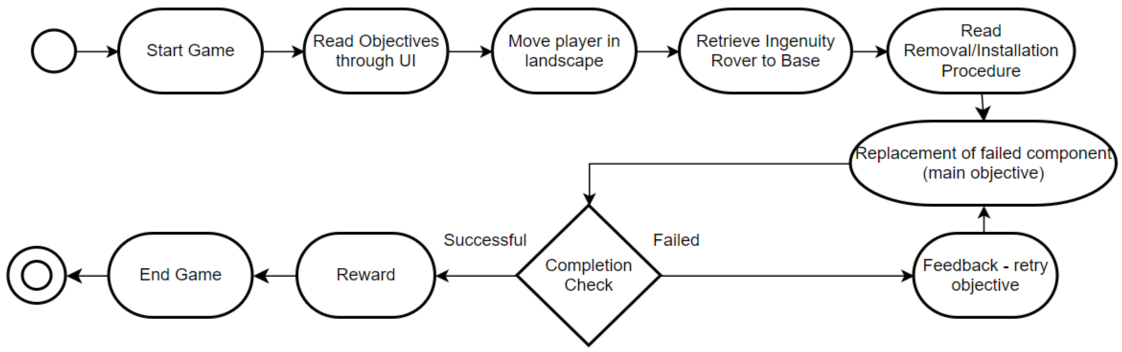


Figure 3: Flow of the simulation gameplay

In stricter terms, the simulation guides the player through a cyclical process of detection, manipulation, validation and feedback. This process encourages logical thinking and hands-on problem solving, helping players build spatial reasoning and procedural skills essential in engineering.

3.3 Object Interaction and Component Replacement Procedure

The main goal is to replace the damaged mechanical part to make Ingenuity operational again. This simulates real aerospace maintenance, where faulty components are replaced rather than repaired on-field, maintaining the mission's pace.

Players interact with essential parts (rotor blades, electronic units and fastening screws) through a first-person camera, keyboard and mouse. Unity's raycasting system ensures that only relevant, tagged objects respond to input. This helps maintain precision avoiding unwanted interactions.

Repairs follow a fixed sequence based on real engineering logic. For example, players must remove screws before detaching the solar panel or replacing the rotor blade in the correct order. Incorrect steps are blocked, prompting players to consult the manual and adjust their approach. Parts lock into place when installed correctly. The simulation checks tool use and task order, encouraging careful observation and reasoning.

3.4 Diagnostic and Feedback Systems

At the end of the repair, the system evaluates the player's work through an in-game diagnostic interface. By interacting with the Rover Communication Platform, players test the rover's condition as the system scans for missing or faulty components and checks that all screws are reattached. It then provides feedback highlighting any issues, such as a faulty part or incomplete steps. This encourages players to review their work while adding a sense of closure to the task.

4. Evaluation Methodology and Student Feedback

To assess the educational impact and user experience of SOL977, a structured evaluation was conducted with 1st-year senior high school students (ages 15–16) at a public lyceum in Pafos, Cyprus. The goal was to gather feedback from a relevant age group through a questionnaire completed after hands-on interaction with the simulation.

4.1 Participants and Procedure

No pre-screening for STEM interest was applied, ensuring a representative group of general education learners. Students participated in small teams of 6 to 8. Each session began with a short presentation introducing Ingenuity's mission and outlining the simulation's goals to provide context and encourage engagement. After each student interacted with the simulation, they anonymously filled out a digital questionnaire via Google Forms, with data collected solely for research purposes.

4.2 Evaluation Design

The questionnaire employed a 5-point Likert scale to capture student perceptions related to the simulation. The scale ranged from 1 (Strongly Disagree) to 5 (Strongly Agree).

In a game-based learning assessment setting, the structured format of Likert-type scales allows for the aggregation of users' subjective feedback, thereby producing quantitative data on their perception of a game's usability (Ifenthaler, Eseryel and Ge, 2012). In general, questionnaires with 5-point Likert scales are considered useful tools for post-game evaluations by game designers, as they effectively capture user impressions of realism and learning value (Harteveld *et al.*, 2010). Particularly, they are efficacious in STEM simulations, where user experiences are compared across different design stages and measurable feedback on learning outcomes is essential (Bellotti *et al.*, 2013).

The evaluation instrument combines three established frameworks:

- **MEEGA+ (Model to Evaluate Educational Games for Computing Education)** was used to shape the learning outcomes, perceived educational value, challenge balance and STEM motivation items. MEEGA+ is specifically designed for educational games and has strong alignment with the objectives of *SOL977*, particularly in capturing cognitive and motivational impact (Petri, Gresse von Wangenheim and Borgatto, 2018).
- **EGameFlow (Educational GameFlow Model)** guided the design of items measuring engagement, immersion, autonomy and clarity of goals. It provides a structured way to assess how game elements promote focus, enjoyment and meaningful participation in educational contexts (Shu-Hui, Wann-Yih and Dennison, 2018).
- For usability and interface interaction, elements were adapted from the **System Usability Scale (SUS)** by Brooke (1996), such as ease of use, confidence in interaction and integration of system functions. Although the original SUS 10-item format was not used verbatim, the structure of statements was clearly influenced by its phrasing and focus.

The final questionnaire was presented bilingually in Greek and English for accessibility and organized into three thematic sections: (a) Usability and User Experience, (b) Engagement and Immersion and (c) Learning and Educational Value. Each section included 4–6 Likert-scale rated items, followed by two open-ended questions. A total of 28 responses were collected from the target demographic. While this modest sample size provides valuable exploratory data, the insights should be interpreted as preliminary.

4.3 Summary of Student Impressions

Preliminary analysis of the data showed that students responded positively across most dimensions. In particular:

- **Usability** received strong scores, with most participants agreeing that controls were responsive and easy to get familiar with.
- **Engagement** was also rated highly with several comments highlighting the realism of the Martian environment and the enjoyment of "fixing the drone".
- Regarding the **educational value**, a majority of students reported that they had learned something new about engineering procedures and space exploration as a whole.

No critical usability issues were identified, although a few students noted initial confusion before discovering the help menu. That suggests that minor onboarding improvements could enhance the user's experience.

These initial findings suggest that SOL977 has the potential to create a playful yet informative experience that combines science content with meaningful interaction. While the responses indicate student engagement and perceived educational value, these outcomes should be viewed as exploratory. Further evaluation with broader and more varied participant groups is needed to substantiate these impressions.

Some indicative evaluation results are shown in Figure 4.

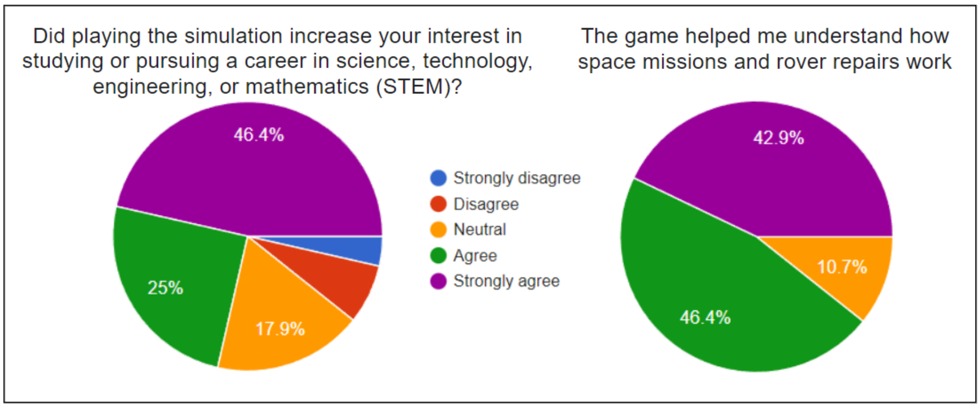


Figure 4: Indicative evaluation results of *SOL977: Ingenious Revival* by high-school students

4.4 Thematic Insights from Open-Ended Responses

To complement the quantitative evaluation, two open-ended questions were included in the post-game questionnaire to gather qualitative feedback on (a) how the simulation engaged students' critical thinking and (b) potential areas for improvement. These responses were thematically analysed to identify patterns of sentiment and recurring suggestions.

4.4.1 Engagement with critical thinking and problem-solving

Many students highlighted that the game prompted them to "think more about next steps", "solve small logical problems" and "follow a procedure carefully". The immersive design was reported to "make them think like real engineers" and enhanced their focus. Even brief responses like "It engaged me creatively" and "It made me think of what the next step is", reinforce that the procedural nature of the simulation encouraged reflective reasoning.

4.4.2 Suggested improvements

Suggestions clustered mainly around three themes:

- **Usability Enhancements**: A number of students indicated that the controls were occasionally confusing or unintuitive, suggesting the addition of a short tutorial or guide (e.g., "I would make the controls easier or add a guided tutorial").
- **Content Expansion**: Some responses expressed interest in more varied or extended gameplay (e.g., "More content and missions").
- **Feedback and Interface Cues**: Others recommended that feedback to the user should be more explicit (e.g., "It should show a warning when you're holding an object").

These qualitative insights reinforce the positive reception of the simulation's design and point to feasible improvements that could further enhance educational value and user experience in future versions.

4.5 Limitations

Although the evaluation offers useful early feedback, several limitations must be acknowledged. The sample consisted of 28 students from a single public lyceum in Cyprus, which limits the generalisability of the findings to wider populations. Participants shared similar educational backgrounds and cultural contexts, which may not reflect the diversity of secondary-level learners more broadly.

Additionally, the study did not employ a control group or pre/post-testing design, restricting the ability to infer learning gains or isolate specific effects of the simulation. The use of self-reported questionnaire data, while informative for user experience, may also be subject to bias and lacks triangulation with objective performance metrics.

5. Conclusion and Future Work

SOL977: Ingenious Revival demonstrates how simulation-based learning can support STEM education through immersive, task-oriented gameplay. By integrating realistic engineering workflows into an accessible interactive setting, the simulation encourages technical curiosity and problem-solving.

Field evaluation with senior high school participants produced encouraging early feedback. Students found the experience engaging and informative, with many reporting increased interest in space technology and engineering. Feedback also identified areas for improvement, such as clearer visual cues and more detailed instructions, pointing to opportunities to enhance usability and user support.

Future development will expand *SOL977*'s content and functionality, introducing new mission scenarios and mechanical challenges. One planned addition is a scoring system to provide players with real-time feedback on performance, based on accuracy and efficiency. A multiplayer mode would allow users to collaborate on diagnostics and repairs, more accurately reflecting real-world engineering teamwork and further promoting problem-solving skills.

From a research perspective, future studies should adopt more rigorous methodologies to better evaluate SOL977's educational effectiveness. This includes pre- and post-testing designs, control groups and the use of analog environments (e.g., physical Martian repair simulations) to compare experiential outcomes. For example, future experiments might involve one group performing a repair in a Mars analog suit after using the simulation, while a control group attempts the same task without prior digital training.

Moreover, expanding participant recruitment to include students from technical or vocational schools could reveal how such simulations support learners with more hands-on engineering backgrounds. These learners may find particular value in the procedural and mechanical aspects of SOL977, regardless of whether they intend to pursue space-related careers.

In conclusion, while SOL977 shows clear promise, its educational impact cannot yet be definitively established. Further large-scale, multi-institutional studies are needed to validate its applicability across diverse learner populations and settings. Nonetheless, with ongoing refinement and evidence-based design, SOL977 has the potential to become a valuable tool for both formal and informal STEM learning environments focused on space exploration and applied engineering.

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Ethics Declaration: No ethical clearance was needed for the research referred to in this paper.

AI Declaration: Generative AI was used to check whether particular English phrases in the authors' work were grammatically or syntactically correct.

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