An Online Semantically Rich 3D Information System for Collaborative Exploration of Planetary Surfaces

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ABSTRACT

Interpreting complex planetary surfaces is vital for successful exploration. Spatial and semantic information are central to perception and presenting them effectively supports better decision-making. This paper presents an online semantically rich 3D information system that offers an immersive, high-fidelity simulation environment, accurately reproducing lighting and terrain conditions to support multi-disciplinary investigation of planetary surfaces. Built for both desktop and Virtual Reality (VR) environments, it allows researchers to transition from conventional isolated analysis to fully immersive collaborative exploration, where semantic perception and cognitive engagement are significantly enhanced. In the VR mode, researchers can experience spatial and semantic information simultaneously, improving the comprehension of topographic relationships and semantic classifications (Lv et al., 2017). The framework embodies the principles of Human–Data Interaction (HDI) (Sedig and Parsons, 2022), positioning users as active participants in the analytical process rather than passive observers. The collaborative exploration includes two major aspects: (1) user–system interactions, which establish coherent logic and facilitate the structured interpretation of spatial data and semantic information; and (2) user–user interactions, which support real-time communication through extension tools such as pointers or markers within the spatial and semantic domains, fostering deeper understanding among researchers across multiple disciplines (Seo and Gibbons, 2021). Using candidate landing sites at the lunar south pole as case studies, we evaluate the performance of the proposed online semantically rich 3D information system. Preliminary results indicate that the system enables users to interpret complex surface data more efficiently and intuitively than conventional observation methods.

1. INTRODUCTION

The ability to perceptually interpret complex planetary surface environments is essential for successful robotic or crewed exploration (Yang et al., 2022; Chen et al., 2021). Spatial and semantic information play a crucial role in scene perception (Malik et al., 2024), while their effective presentation and user interaction facilitate more accurate interpretation and decision-making. Conventional collaborative study on planetary surfaces by multidisciplinary researchers often requires a solid background in geo-information concepts and practical skills in geographic information system (GIS) software. Prior studies have shown that even when multiple disciplines investigate similar spatial constructs, the actual flow of knowledge between them remains weak, resulting in fragmented understanding and limited conceptual integration (Bruce et al., 2016). As a result, research efforts often proceed in parallel but isolated lines of investigation, limiting opportunities for meaningful integration and reducing the effectiveness of multidisciplinary collaboration, especially when addressing complex topics such as spatial reasoning.

The cognitive gap between researchers in interpreting planetary surfaces is a key obstacle to effective multidisciplinary communication in planetary surface exploration. Therefore, this paper presents a semantically rich 3D visualization system as a foundation for an online collaborative exploration framework (Figure 1) that provides a holistic and integrated visualization environment to support the understanding of complex professional landscape data. The online platform is designed to establish a system with a spatial database that allows data sharing and manipulation, alongside the proposed interactive engine to enable collaborative interpretation. This project prioritizes user experience as a means of directly enhancing data comprehension, grounded in the principles of visualization and cognitive enhancement informed by educational framework design. It enables users from diverse disciplinary backgrounds to immersively explore, then subsequently interprets planetary surfaces through semantically annotated elements (Lv et al., 2017) and interactive components, supporting deeper spatial understanding of complex terrain structures, which leverages advanced real-time rendering and large-scale terrain representation capabilities of modern game engines (Naweed et al., 2018).

Conventionally, researchers outside geology depend on supplementary verbal or written explanations from domain experts to interpret planetary surface data effectively. Furthermore, many planetary surface environments are difficult or impossible for humans to directly access, making them challenging to intuitively understand, especially for researchers with limited experience in landscape interpretation.

Therefore, this online semantically rich 3D information system introduces a shared contextual platform (García et al., 2019) within a virtual environment, integrated with semantic information, to overcome communication ineffectiveness (Saint-Léger et al., 2025) between multi-disciplinary researchers. With an immersive environment featuring audio prompts, semantic information, and precise lighting simulation, users can gain deeper understanding (Adigun, 2019) and perform practical tasks such as route planning or decision making for the actual sites. These features foster a strong sense of presence and agency (Makransky & Petersen, 2021), which in turn contribute to meaningful learning outcomes.

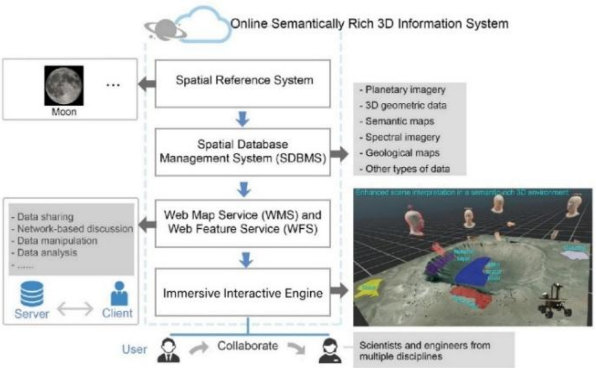


Figure 1. Framework of the online semantically rich 3D information system for collaborative exploration of planetary surfaces.

2. THE LUNAR SOUTH POLE AND DATASETS

The lunar south pole is an extreme environment, with persistently low solar elevation angles and the absence of atmospheric scattering that result in dramatic contrasts between light and darkness, along with extremely long shadows cast by mountains due to the low angle of incoming sunlight, which is far from everyday human experience.

This paper uses lunar south pole as case studies, with data from 80°S to 90°S, to reconstruct the local environment. Since human spatial cognition is largely shaped by daily environments on Earth, where solar elevations are higher and diffuse skylight is present, people find it difficult to intuitively imagine how extremely low solar elevation sweeping circle along the horizon, combined with direct incoming sunlight without diffusion from the atmosphere, produce dramatic and highly terrain-dependent light–shadow contrasts over time. Consequently, without professional training or strong three-dimensional spatial reasoning, it is difficult to accurately interpret sunlight movement and dynamic shadow distribution using conventional two-dimensional maps or images alone. This project models comprehensive sunlight illumination of the lunar south pole based on realistic attributes. There are several crucial attributes that are considered in the sunlight simulation. Since the Moon's rotating axis is almost perpendicular to the ecliptic plane with 1.5° tilted, the maximum solar elevation angle at the south pole is simulated as 1.5° with the Sun moving along the horizon. The extremely rarefied atmosphere of the Moon causes no absorption or scattering of sunlight, allowing it to reach the surface directly. Also, given that the Moon receives the same solar flux as the Earth, these attributes imply strong illumination in the scene, with sharp shadows due to the absence of atmospheric diffusion (Badescu, 2012). In addition, lunar regolith is a key indicator for the surface reflectance of Moon. Albedo data from Lunar Orbiter Laser Altimeter (LOLA) shows the average albedo in south pole is around 0.3 (Lucey et al., 2014), and this provides a clear and reliable reference for setting the material albedo of the 3D landscape models.

The VR system is developed using Unreal Engine 5. The terrain models are generated from Digital Elevation Models (DEMs) provided by NASA's Lunar Orbiter Laser Altimeter (LOLA). (Barker et al., 2023) The models cover 2 regions of the lunar south pole:

(i) An 80°S map covering an area of 606 × 606 km with a 20-meter resolution,
(ii) An 83°S map covering an area of 237 × 257 km with a 10-meter resolution.

These DEMs are co-registered (Wu et al., 2013) and used to generate slope maps and 3D visualization maps for the respective terrain models. Furthermore, Wide Angle Camera (WAC) images from NASA's Lunar Reconnaissance Orbiter Camera (LROC) (Robinson et al., 2010) are incorporated to verify the accuracy of lighting in the virtual scenes. This project selected two specific sites within the 83°S map as representative sample scenes.

The VR system features two types of virtual scenes presented at different scales:

(i) A regional-scale overview scene at approximately 1:200 scale, covering the broader illumination and shadow distribution across the 83°S latitude region.
(ii) A local-scale immersive scene at 1:1 scale, representing selected landing or exploration sites with true-to-scale terrain geometry.

Solar illumination is simulated using directional light which is a parallel light source in Unreal Engine 5. The global solar direction is defined relative to the 90°S as a common reference frame, with a default solar elevation angle of 1.5°.The solar azimuth and elevation used in the virtual environment are derived from the sub-solar latitude and sub-solar longitude provided in LROC image metadata, which are converted into a global sun-direction vector in the lunar body-fixed coordinate system. As mentioned above, data from LOLA indicates that the average albedo at the lunar south pole is approximately 0.3. However, this physically defined value cannot be directly mapped to real-time rendering materials and is therefore used only as a reference for relative reflectance of the terrain.

3. OVERVIEW OF THE VR SYSTEM

3.1 Framework of the VR System

The VR system begins with a top-down view of the lunar south pole, highlighting the target region (85.5°S – 90°S) and the two selected exploration sites, as shown in Figure 2. In all subsequent scenes, users can freely adjust the solar illumination angle and teleport to any location on the terrain.

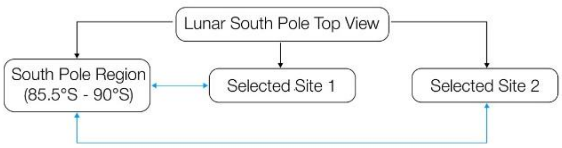


Figure 2. Framework of the VR system.

3.2 Universal Design for Learning Implementation

There is a significant gap between the design of virtual reality learning experiences and established educational theories. Although immersive virtual reality has been widely adopted for training and learning applications, much of the existing research has primarily emphasized experiential design factors, such as immersion and presence, rather than systematically grounding VR learning applications in instructional and learning theories. (Wehrmann & Zender, 2024) Therefore, the system was developed based on fundamental pedagogical considerations, framed by design questions such as: “What can participants learn from this?”, “How can they learn through this scenario?”, and “Why would they need to do this?”. To structure these considerations, the Universal Design for Learning (UDL) (CAST, 2024) framework was referenced as a guiding framework for system design.

There are three main categories in the UDL guidelines:

(i) Engagement (the “why” of learning): recruiting interest and motivation
(ii) Representation (the “what” of learning): perception, language and symbols, and comprehension.
(iii) Action & Expression (the “how: of learning): interaction, expression and communication, and executive function.

For Engagement (i), precise sunlight simulation allows users to reconstruct lighting conditions, motivating them to interact with the environment to identify potential routes or suitable locations in reality for further discussion. For Representation (ii), semantic maps such as slope and topographic overlays, as well as labeled crater features mapped onto DEM-based terrain models, provide intuitive visual cues that support landscape interpretation by users from diverse research backgrounds, aligning with the representation of geographic information in the immersive system. For Action and Expression (iii), adjustable sunlight angles allow users to observe "how" changes in solar position directly shape shadow distribution across the landscape. Furthermore, spatial annotation tools such as route drawing and map pins enable users to visually express proposed paths and observations, supporting communication and comparative evaluation.

3.3 Multi-user Collaboration

The online system will be built upon the proposed 3D visualization and interaction module. Planetary surface data and semantic layers are hosted in a centralized repository and accessed by users through local VR clients. The architecture incorporates a shared state framework that supports real-time interaction contexts across users. In addition, the system foundation is designed to support multi-user communication through spatial annotation tools, such as map pins and route drawing functions, which enable users to mark locations and paths directly within the 3D environment to facilitate discussion and joint interpretation. Immersive virtual environments can support collaborative activities by sustaining users’ attention and enabling intuitive interaction (Chika Emma-Ogbangwo et al., 2014) with interpretable environments. In the proposed system, semantic overlays mapped onto terrain geometry, such as slope, illumination, and hazard indicators, enable intuitive interaction by providing interpretable visual cues that allow users to immediately relate abstract data to physical landforms. In addition, the system’s responsiveness to the environment, reflected through interactive feedback such as audio prompts, adjustable lighting conditions, and spatial annotation tools, allow users to actively engage with the environment, which contributes to the sense of social presence (Zaheer, 2025).

The system uses Unreal Engine 5 as the development platform, which supports VR multiplayer development due to its advanced networking tools for synchronization (Emio et al., 2020). The commercial VR game STRIDE, a parkour adventure developed by Joy Way demonstrates the technical feasibility of multiplayer functions like synchronization and voice communication in Unreal Engine development (Baker, 2022; Way, 2022). Furthermore, Unreal Engine’s C++ framework allows flexible implementation of complex networking requirements (Berrezueta-Guzman & Wagner, 2025), enabling future technical extensions by specialized developers.

4. SYSTEM DEVELOPMENT

4.1 Software Usage

ArcMap is used for DEM preprocessing, including spatial clipping or resolution down-sampling to support multi-scale terrain integration. Shaded relief, slope, and topographic maps are generated to serve as reference layers for validating lighting consistency and terrain feature visibility. Blender, together with the Blender GIS plugin, is used to convert raster DEM data into terrain meshes. Scaling is then applied to match the spatial scale of the virtual scene. Unreal Engine 5 serves as the main visualization platform, responsible for material shading, dynamic solar illumination, semantic data visualization, and immersive VR interaction.

4.2 Shadow Casting

In the 1:200 scale scene, the 80°S map is used as a background map to cast approximate shadows from the surrounding mountains onto the primary scene (Figure 3). The background map is intentionally set to invisible in the runtime scene due to the rendering costs.

Similarly, in the 1:1 scale scene, the 83°S map is used as a background map to cast shadows generally from the surrounding mountains onto the primary scene (Figure 4), and it is also set to invisible during runtime to reduce rendering costs. Due to multi-resolution terrain integration constraints, the far-field terrain is not geometrically stitched to the high-resolution local DEM. To avoid model clipping, the regional terrain is vertically offset and therefore provides only approximate shadow cues rather than precise shadow boundary prediction

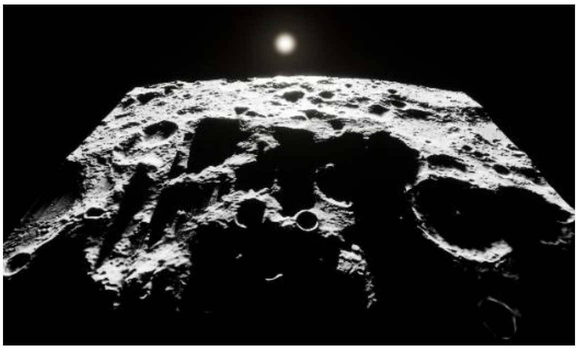


Figure 3. 1:200 scale scene with 80°S map as a background map

Figure 4. 1:1 scale scene with 83°S map as a background map

4.3 Curvature

To accurately simulate lighting conditions at the lunar south pole, planetary curvature is a critical factor because local solar elevation is directly governed by latitude. Therefore, curvature is explicitly applied to the regional-scale terrain models (80°S and 83°S maps) based on the Moon’s diameter of 3,474.8 km.

4.4 Deformation

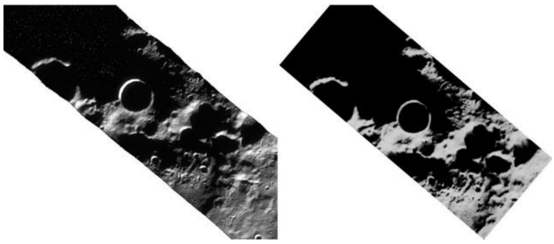
Beyond curvature, regional scale surface deviations (Araki et al., 2009) play a critical role in controlling solar illumination geometry at the lunar south pole. Therefore, DEM representations should account for regional shape deviations to ensure accurate illumination and geometric modeling. In this study, regional deformation is calibrated by cross-validating simulated illumination against multiple LROC WAC images with known sub-solar latitude and sub-solar longitude metadata. The terrain geometry is iteratively refined until the simulated illumination vectors and shadow distribution in Unreal Engine closely match the metadata and illumination patterns observed in all reference images. Regional deformation is applied in a symmetric and structured manner to reduce irregular bias and to maintain spatial coherence across the terrain, ensuring that geometry adjustments reflect consistent large-scale shape variations rather than random local modifications.

The following procedures are conducted to reduce the deformations:

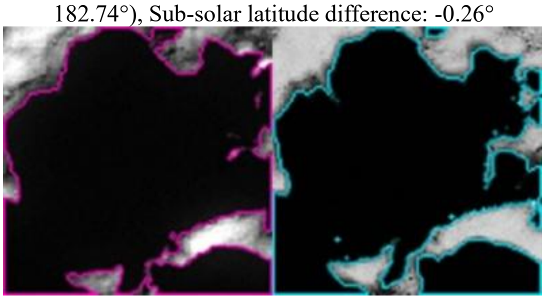
(1) Import shrink-wrapped DEM models from a spherical surface defined by the mean lunar radius.
(2) Configure directional light in Unreal Engine
(3) Adjust the lighting to match the illumination patterns of all the WAC images
(4) Cross-check with the metadata sub-solar latitude and sub-solar longitude from the WAC images.
(5) Iteratively deform the DEM models until the simulated illumination vectors match the metadata.

4.5 Validation of the Rendering Results

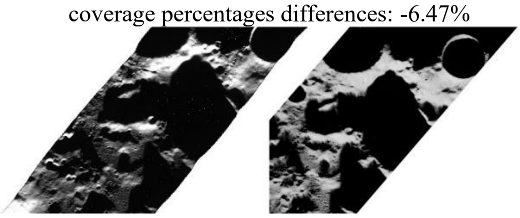
Figure 5 illustrates image comparisons between the WAC images (left) and the Unreal Engine rendered scenes (right), with simulated illumination vectors (sub-solar latitude and sub-solar longitude). Furthermore, for each image pair, a square region of interest (ROI) was manually selected through visual alignment to represent a comparable terrain area. The selection of each ROI was guided by distinctive and complex shadow patterns, ensuring that the selected area contained sufficient variation for comparative analysis. Within each ROI, shadow regions were outlined and the proportion of shadowed area relative to the total ROI was calculated. The resulting shadow-coverage percentages from the Unreal renderings were then compared with those derived from the corresponding WAC images, allowing an approximate assessment of illumination consistency between the simulated environment and the reference dataset. Eight sets of WAC images are compared with their corresponding rendering results. The maximum difference in sub-solar latitude alignment is 0.71°, while the maximum difference in shadow coverage is 6.47%.



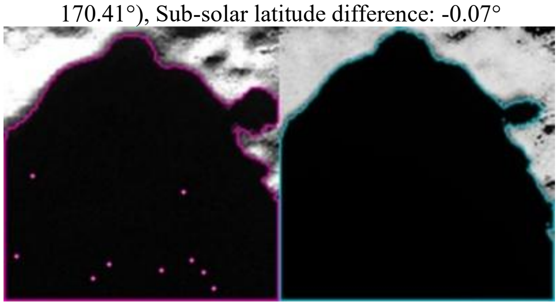
(a) WAC: (1.31°, 182.74°); Unreal Engine: (1.05°, 182.74°), Sub-solar latitude difference: -0.26°



(b) WAC: 83.33%; Unreal Engine: 76.86%, shadow-coverage percentages differences: -6.47%



(c) WAC: (0.92°, 170.41°); Unreal Engine: (0.85°, 170.41°), Sub-solar latitude difference: -0.07°



(d) WAC: 80.20%; Unreal Engine: 79.47%, shadow-coverage percentages differences: -0.73%

Figure 5. Comparison of the rendering images from the developed VR system with real WAC images

4.6 Illumination Bias Analysis

In the illumination simulation, areas between longitude 115.42° and 182.74° exhibit excessive curvature, producing stronger illumination than expected and therefore requiring reduced illumination angles. Conversely, areas between longitude 191.77° and 257.34° appear overly flat, resulting in weaker illumination and requiring increased illumination angles to compensate for insufficient lighting (Figure 6).

After deformation, the terrain remains uneven, with one side appearing overly flat and the other overly curved. However, the remaining bias is less than 1°, and the overall shadow distribution is approximately preserved.

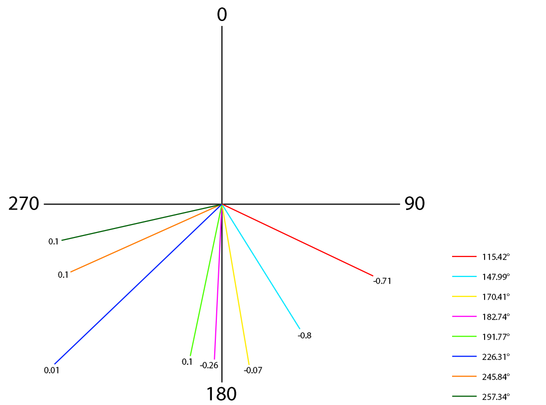
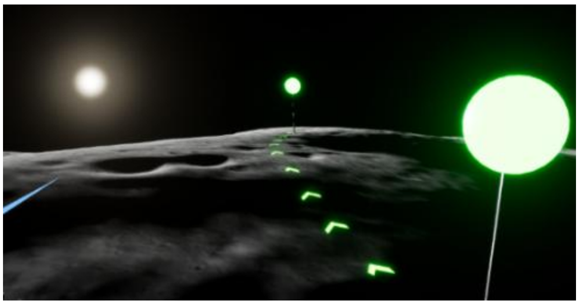


Figure 6. Correlation between sub-solar longitude and the differences in sub-solar latitude alignment between LROC WAC images and Unreal Engine rendered results.

5. MAIN FUNCTIONS OF THE VR SYSTEM

5.1 Visualization for Interpretation

A functional VR prototype was implemented in Unreal Engine 5, integrating multi-resolution DEM terrain, semantic overlays, interactive tools such as spatial annotations, sunlight angle adjustment and torch light.



(a) Sunlight simulation on the 1:1 landscape

(b) Topographic map overlaid on the 1:1 landscape

Figure 7. Examples of typical scenes of the VR system.

Figure 7 shows that overlaying semantic maps, such as slope or topographic maps rendered with color ramps and accompanied by contextual reference information, allows users to immediately and intuitively interpret geospatial attributes.

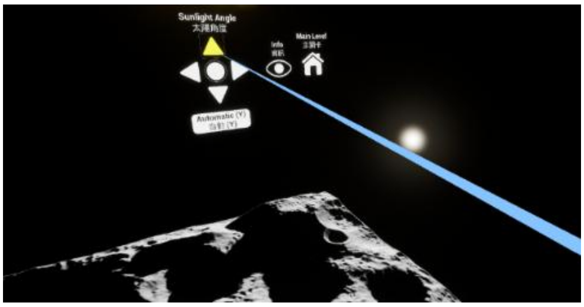


Figure 8. Sunlight angle adjustment.

Adjustable sunlight angles enable users to directly observe how variations in solar position shape shadow distribution across the terrain (Figure 8). Furthermore, lighting conditions can be reconstructed using NASA LROC WAC metadata, grounding the interaction in scientifically referenced parameters.

Figure 9. Torch light.

The torch light function trains users to comprehend local terrain geometry in dark environments by interpreting surface shape through torchlight reflections (Figure 9).

5.2 Audio Support for Spatial Awareness

Audio prompts serve as another complementary perceptual cue that guides user attention and supports spatial awareness, enabling terrain conditions to be interpreted without cognitive overload caused by visual inspection. For example, when users navigate from a first-person VR perspective, steep slopes may not always be visually apparent until the users are very close to the slopes. Audio prompts can function as anticipatory warnings, drawing attention to terrain risks that might be out of the user's perception. This mechanism highlights the inherent limitations of human or robotic vision while fostering greater situational awareness.

5.3 Navigation interface

A navigation interface is implemented to display the user's real-time position within the overall terrain map (Figure 10). By maintaining geographic awareness, the system reduces disorientation and enhances users' understanding of their relative location within the broader terrain context.

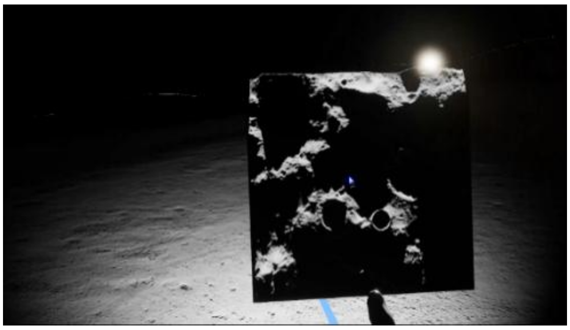


Figure 10. Navigation interface display.

5.4 Real-Scale Distance Measurement

Users can plot points on the surface and get the real-scale distance between the points (Figure 11). This reflects the true metric scale derived from the underlying geospatial dataset, enabling accurate interpretation of terrain dimension.

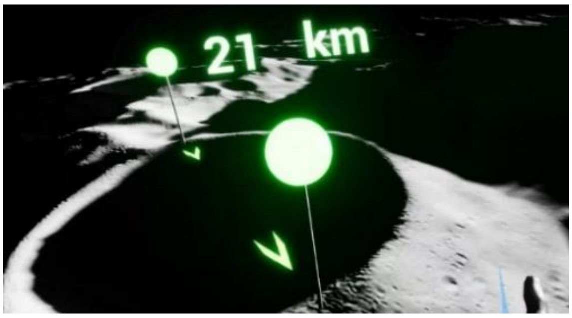


Figure 11. Real-scale distance measurement.

5.5 Metric Scale Reference Object

A 2 m³ cube can be spawned within the environment as a human-scale reference object (Figure 12). In the absence of familiar environmental cues, users may misjudge terrain height or surface variation. The cube provides an immediate and intuitive metric benchmark, supporting perceptual calibration of spatial dimensions and improving interpretation of topographic geometry.

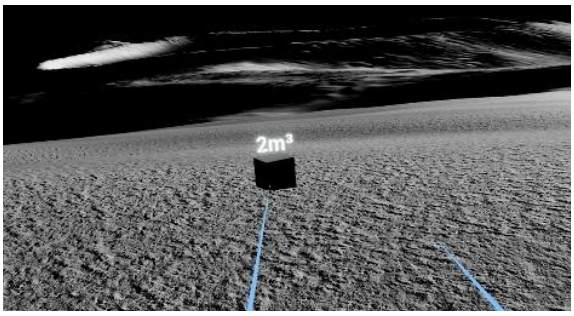


Figure 12. A 2 m^3 cube as a metric scale reference object.

The above two complementary functions support the interpretation and perception of spatial scale. The absence of familiar environmental cues in the lunar south pole landscape may lead to misinterpretation of terrain dimensions. These functions provide quantitative and perceptual support to improve scale awareness during exploration.

5.6 AI-based Semantic Extraction

In addition, Artificial Intelligence (AI)-based analysis on rendered viewpoints is introduced as an extended application from the prototype, enabling the detection and quantification of small surface elements such as rock fragments (Figure 13). The dataset is enabled by the proposed system, which provides controllable illumination and 3D representation of rock fragments to support reliable annotation under extreme lunar south pole conditions.

A sequence of images is rendered from the scene in different camera positions and angles. The first 1,000 images are annotated by domain experts (e.g., geologists), as shown in Figure 14. The annotations are then verified in a separate stage to ensure consistency and semantic accuracy. The resulting high-quality labels are used to train an initial semantic segmentation model. This extension highlights the potential of machine-assisted interpretation, which supports human understanding of surface geo-information.

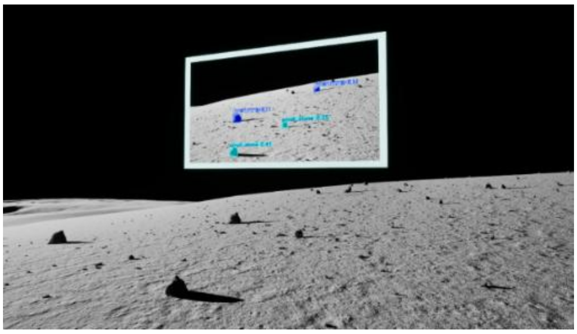


Figure 13. AI-based rock labelling viewpoint.

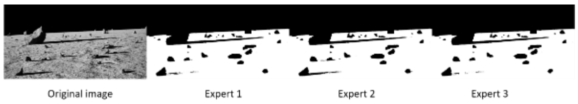


Figure 14. Labels of flat regolith by merging the annotations from different annotators.

6. EVALUATION

To evaluate the effectiveness of the project system, an experiment was conducted on 8 participants with various backgrounds on planetary exploration research, including remote-sensing, planetary science and robotic visions. Participants were organized into two profiles: those experienced with GIS-based workflows and those who obtained geo-information through indirect methods such as online information sources or peer consultation. The evaluation focuses on two aspects, comprehension enhancement on geo-information, and improved understanding of the logical relationships between landscape features and lighting conditions.

Two task-oriented evaluation scenarios were designed to compare conventional geospatial analysis workflows with the proposed VR system.

Task A – Geo-information Interpretation. Participants estimated the time typically required to obtain and interpret slope and topographic information from DEM data using their usual approaches. This was compared with the time spent performing similar interpretation tasks within the VR environment. In addition, participants also rated how the integrated semantic–geometric representation improve their understanding of geo-information.

Task B – Illumination Analysis. Participants compared the estimated time required when using usual approaches to analyse shadow distribution or lighting conditions with the real-time solar rotation function implemented in the VR system. Perceived enhancement in understanding relationships of landscape geometry and solar illumination was assessed through participant ratings.

Eight participants completed Task A. Recorded timing showed that seven participants required less time to obtain and interpret terrain information in the VR system compared with their usual approaches. The reduction in time was mainly attributed to more direct understanding through integrated semantic–geometric representation, as well as the ability to switch efficiently between semantic layers within the virtual environment.

For Task B, all participants completed lighting interpretation faster using the real-time solar rotation function in VR than with their conventional or indirect approaches to understanding illumination conditions.

In addition to recorded timing, participants rated perceived comprehension enhancement on a five-point scale. Enhancement in semantic geo-information understanding reached a median score of 4/5. Understanding of lighting logic in relation to landscape geometry achieved a higher median rating of 4.5/5, reflecting clearer interpretation through real-time solar interaction. The effectiveness of VR for expression and spatial communication, compared with conventional GIS annotation approaches, also received a median rating of 4.5/5.

7. CONCLUSIONS AND DISCUSSION

The main contribution of this paper is the establishment of an interpretation bridge for multi-disciplinary researchers to enhance collaborative exploration effectiveness, through a simulation system developed and verified using scientific datasets. It highly focuses on the practical interpretation of the geo-information datasets realized in the simulated environment, with research like Human–Data Interaction and Universal Design for Learning as a guiding framework to apply on semantic information integrated with landscape geometry. By bringing geospatial datasets into a semantically integrated 3D immersive environment, the system demonstrates an interpretative potential of geospatial data beyond conventional visualization approaches. Besides the interpretation of geo-information, the system also supports users’ understanding of spatial extent in both quantitative and perceptual ways.

Using candidate landing sites at the lunar south pole as case studies, the system demonstrates another core contribution, which is the verification of solar illumination reconstruction. NASA LROC WAC data were used to verify the reconstruction of solar illumination not only through visual comparison but also the angular relationship between solar vectors and terrain geometry based on metadata. This positions the system not merely as a 3D interactive simulation, but as a scientifically informed application that enables users to cross-reference observational metadata with reconstructed illumination conditions. Researchers can therefore explore shadow distributions within a spatially immersive environment grounded in real-world parameters.

The evaluation focuses on two primary values of the system: enhancement of geo-information interpretation related to landscape geometry, and improved understanding of terrain–illumination relationships. Preliminary results indicate that the system enables users to interpret complex surface data and extreme environments more efficiently and intuitively than conventional observation methods.

For future work, online architecture will be implemented based on the system foundation, like the functions, framework, and environments demonstrated in this study. In addition, AI-based analysis will be further applied on real surface imagery, such as panoramic datasets, and the AI semantic extraction can annotate rock fragments for users to have deeper comprehension on landscape surface.

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