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Experimental design of a virtual reality platform for lunar rover missions to reduce decision-making time and improve situational awareness

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In situ resource utilization (ISRU) technologies are a key advancement required to make long-term human habitation on the Moon and Mars viable. The upcoming Volatiles Investigating Polar Exploration Rover (VIPER) mission will provide crucial correlations between volatiles and the lunar environment and geologic setting to begin to understand the water content available for ISRU on the Moon. The mission, slated to launch in 2023, will require the coordination of multi-disciplinary teams across the country making real time decisions based on rover instrument data. The virtual Mission Simulation System (vMSS) is a virtual reality platform designed at MIT supporting the Resource Exploration and Science of our Cosmic Environment (RESOURCE) team to provide geographically distributed teams with a collaboration interface for planetary missions like VIPER. Herein we describe a preliminary assessment of the vMSS platform with a mobile rover platform integrating two onboard depth-cameras and synthetic instrument data representative of a VIPER onboard instrument, specifically the neutron spectrometer subsystem (NSS)[1, 2].

Current lunar rover exploration missions have their console positions set up such that the science operations team is separate from the science backroom team[2–5]. Logistically, this allows for the science backroom team to focus on detailed analyses to advise the operations team of potential new points of interest while the operations team can focus on the execution of the traverse. However, this physical separation can challenge communication of priorities and may become a detriment to maximizing science return. More efficient communication methods are needed to ensure this next phase of exploration provides every advantage to geological exploration. We propose vMSS[6, 7] to provide a collaborative environment equipped with visualization tools that can drive real-time science analysis of instrument data in easily digestible displays to allow the science analysis team to continuously monitor data streams during the rover traverse and rapidly communicate recommendations to the operations team.

We present a prototype vMSS with proposed testing to demonstrate effectiveness in real-time decision making, rover traverse planning, situational awareness and to determine a minimum image resolution to minimize communication bandwidth requirements. The VR platform is designed with two primary views: 1) a mini overview with a birds-eye map which allows for real-time traverse monitoring and 2) an immersive point-of-view which provides an annotat-

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able on the ground view of the surface. The rover used for this testing had an onboard Intel RealSense D435i depth-camera with integrated RGB imagery. The testing procedures were set up to test the user's ability to identify objects and obstructions, make real-time decisions, re-plan traverses and complete increasingly complex tasks within the VR environment. The rover was set up in manual mode with access to the maps for user decision making. These capabilities will be tested for mission planning, in-mission traverse, science station exploration and drill site selection and assessment. The test area was predefined with analog NSS data such that the user could view both the location's camera views and overlaid simulated instrument data. Preliminary data captures were completed for a basic traverse. Planned testing procedures are described herein.

VR environments are not generally recommended for long-term continuous use[8]; thus, it is important to identify the tasks where the usage of vMSS provides the greatest advantage. The experimental setup and early phase demonstration of vMSS will be the basis for determining the points during a rover mission when VR can reduce decision-making time, enable more efficient cross-team communication and reduce task loads.

I. Nomenclature

AR	=	augmented reality
ConOps	=	concept of operations
COTS	=	commercial off the shelf
DEM	=	digital elevation model
EAMD	=	exploration analog and mission development
ISRU	=	in situ resource utilization
HMD	=	Head Mounted Display
OT	=	operations team
RESOURCE	=	resource exploration and science of our cosmic environment
SSERVI	=	solar system exploration research virtual institute
ST	=	science team
vMSS	=	virtual mission simulation system
VR	=	virtual reality
XR	=	mixed reality

II. Introduction

The future of space exploration requires a paradigm shift. Mission complexity is increasing and with the advent of heavy lift launch capabilities and an increased cadence of lunar orbital and surface missions. With the goal of a permanent human presence on the Moon, we need to develop new enabling technologies and capabilities. In situ resource utilization (ISRU) is one of these key milestones. ISRU will enable human lunar exploration and may eventually support a lunar economy fuelling deep-space exploration. In order to develop the knowledge necessary for sustained ISRU missions, human-computer interaction needs to take a front-seat in mission planning[9]. By treating machines as collaboration tools, we stand to improve cross-discipline communication, improve real-time decision-making processes, reduce task loads and provide flexibility in both temporal and spatial planning. Volatiles prospecting missions will stand to benefit given the specificity of the knowledge required to make decisions around geologic and environmental data. Providing naturalistic visualization tools that multiple team members can use to analyse, discuss and interpret real-time data, has the potential to dramatically improve the scientific analysis necessary to develop ISRU on rover prospecting missions.

As is stated in the Artemis III Science Definition Team (SDT) report: "In situ instrumentation will be greatly beneficial in addressing a number of Artemis III science investigations, including instrumentation to support sampling [and] volatile monitoring"[10]. The recommendations specify the need for real-time transmission of data from the science instruments which will allow the science support teams to provide real-time feedback to the crew, and processed data which can help to convert raw data into tactical decision-making. Virtual reality has been suggested as a tool to address these requirements[11]. The Resource Exploration and Science of our Cosmic Environment (RESOURCE) team, funded by NASA's SSERVI (Solar System Exploration Research Virtual Institute) addresses in-situ resource utilization (ISRU) needs through a structured program directly linking science and exploration. The goal of RESOURCE is to characterize potential resources on SSERVI Target Bodies through scientific investigation and develop corresponding technologies and concepts of operations to enable resource exploration and ISRU. The MIT-led component of RESOURCE focuses on the optimization of the robotic and human interactions for missions to prospect for resources and conduct lunar ISRU. The MIT RESOURCE team has made preliminary strides in developing the virtual Mission Simulation System (vMSS) to do this.

One of the first steps in developing this functional VR platform is to provide a baseline environment. The context of it's use dictates the type of environment needed. For instance, when planning a long-range traverse path, one would expect a high level map. The Lunar Reconnaissance Orbiter (LRO) provides DEMs down to 5 m resolution for some locations, as well as other important datasets for traverse planning such as crater mapping, albedo, sun visibility and slope maps. Selecting sample sites based on in-situ geological features, however, would require high resolution maps on the cm/pixel scale. While low-resolution maps are available from orbital data, mission-specific payloads would be required to capture the resolution necessary for an on-the-ground perspective. Here we explore these early determinations of VR implementation requirements and assess the Concepts of Operations (ConOps) necessary for the different scenarios, and how these could be implemented using rover payloads.

Whether in virtual reality or on a desktop application, developing a three-dimensional map of the lunar surface has the potential to provide a basis for analysis tool development and an in-situ scale reference system. The tools that currently exist using 3D surface data, including MoonTrek and QuickMap, allow a user to draw a traverse path on a surface, calculate distances, elevations, sun-angle and overlay orbital data. These tools, however, do not give the detail necessary for in-situ geological analysis. This requires depth data to a higher resolution than available by orbital data alone. Structure-from-Motion (SfM) Photogrammetry is used in the Mars Curiosity rover to create digital outcrop models of the Martian surface[12]. The 3D models are created using datasets of images from a suite of 17 cameras on the rover. Key in this dataset is the need for images to overlap and to have similar optical parameters. The optical parameters on many of the Curiosity cameras differ widely, making photogrammetric reconstruction very challenging. Additionally, the reconstruction relies heavily on the two NavCam stereocameras which do have the same optical parameters and have large overlap. Stereocameras work by reflecting light off of an object and reading the reflection into two cameras separated by a known distance. A challenge with stereocameras for space applications is the necessity to know the distance between the two cameras to a high degree of accuracy. During take-off and landing the cameras experience extreme levels of vibration and are at risk of becoming misaligned requiring re-calibration before use, which can prove difficult to do remotely. Additionally, this process requires two cameras, increasing the payload mass requirement, with overlapping imagery, increasing the necessary transmission bandwidth.

Given the challenges of extracting depth data from stereocameras, we can explore other modes of depth-data collection. Depth cameras come in three major categories: structured or coded light, stereo depth and time-of-flight or LiDAR. Structured or coded light uses the deformation of a known light pattern to calculate distance to an object. Stereo-depth, as described above, uses the known distance between two cameras and the light reflected off of an object for triangulation. Time-of-flight and LiDAR calculate distance using the timed return of laser light reflected off of a surface. The stronger the laser used, the greater the distances time-of-flight cameras can measure. Both time-of-flight and structured light cameras require that the returned light be clearly distinguishable as the reflected emitted light and so can be susceptible to interference from sunlight or external light sources. This would be of benefit, however, in applications such as lunar night exploration or for 3D mapping of sub-surface structures, such as lava tubes, where there is little to no light.

A major benefit of using time-of-flight is that it is a single camera with no position calibration dependency. An additional benefit of time-of-flight cameras is their increasing use in commercial industry. Commercial-off-the-shelf (COTS) components are now readily available, and with relatively minimal modification could be made flight ready for lunar applications.

The experiment described herein explores stereophotogrammetry and structured light COTS systems with consideration for their integration into a VR environment under varying operational conditions. We present preliminary depth data collection as well as a VR environment constructed using lunar orbital data with tools designed for traverse planning and monitoring. Future experiments will further examine the depth-data collection techniques including rendering pipeline development and the tools needed for in-situ geological analysis. We also describe the experimental setup for assessing the various ConOps for these tools.

III. Background

A. Virtual Reality for ISRU

Lunar field explorations during the Apollo missions provided some of the best understanding of lunar geology and history as well as early identification of resources that will be critical in establishing a permanent presence on the Moon[13]. Based on historical ground-based exploration missions, it is clear that traverses can be expected to increase in length and complexity over time, exemplified by the increase from the <1 km Apollo 11 traverse to the Apollo 17 traverse of 35 km (Fig. 1[14]). Because of the greater distances that we can expect to cover, we need to be able to have the flexibility to stop, change direction and look more closely at unexpected discoveries. Field geology relies not only on extensive pre-trip traverse planning, using all available mapping and sensing data, but must also be prepared for unforeseen discoveries that necessitate quick decisions based on observational data and deductions of relationships between rock units and instrument data that may impact the entire planned traverse[13], for example the discovery of orange soil during Apollo 17[15] (Fig. 1). During the Apollo missions, this required astronauts to be trained in geological field work and to be able to easily communicate in-field findings to the Mission Control Center (MCC) and allow the Science Support Room (SSR) to alter objectives in real-time and rapidly re-prioritize and communicate changes to the astronauts[14]. From the astronaut side, the identification of points of interest and need for rapid decision making would sometimes result in challenging communications with MCC and from a SSR perspective, rapid changes in scheduling without a full view of the impact to operations would result in an astronaut having nothing to do, a loss in science return potential.

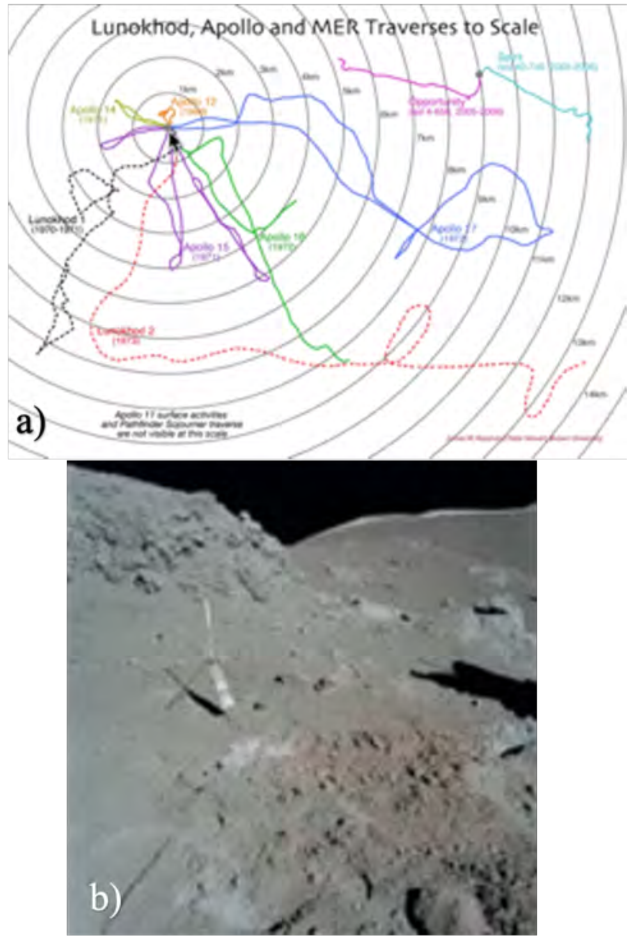

Fig. 1 a) Historical lunar and Martian traverses to scale from Scott et al., 2019 and b) Apollo 17 discovery of orange soil by astronaut Jack Schmitt on the lunar surface, image credit: NASA.

In order to understand the communication challenges between the science team (ST) in the SSR and the operations team (OT) in the MCC, it is important to understand the difference in decisional cadence between both teams. The OT is responsible for the health and safety of the spacecraft, which has a highly intensive decisional cadence that requires the team to follow and check in on specific tasks. The ST, on the other hand, is afforded the luxury of time but with finite information. The teams' decisions are not made on the same time scales. Because of the difference in time pressure and intensity of decision from moment to moment is so different between the two teams, there is a disparity between the priority of their decisions as well. This disparity can challenge communication between the two teams. In modern lunar missions where data can be provided to both teams at the same speed, we anticipate that the decision structures, procedures and processes will evolve. The weight of the scientific decisions will grow, the speed they come in and their need for immediate application will become more impactful over time. This will be especially true as we get into longer stay missions with decisions primarily made by the crew with input from the ST. This will mean that the decisional cadence of both the ST and the OT will begin to coincide and there will be a need to ensure both teams have the ability to make impactful decisions with confidence, in particular as their criticality increases in nature. They will both need to have qualified and quantified confidence in their decisions and will need tools to enable them to internalize their environment in a more meaningful way than what has previously been presented to them. vMSS is being designed to provide visualisation and analysis tools that can drive real-time science analysis of instrument data and a meaningful understanding of the immediate environment in easily digestible displays. This will allow the ST to monitor the rover traverse, and rapidly communicate recommendations to the OT in a collaborative environment in order to ensure mission goals are being met, such that output, or mission enhancing science is getting us to our goals.

1. Current applications of VR for science and operations

Looking to applications within the space industry as well as other industries we can find examples of use cases for both VR, augmented reality (AR) and mixed reality (XR). Looking at these examples can provide insight into when the technologies should be leveraged as well as what challenges have been overcome to accommodate them.

The first, and likely most relevant use case is the Mars Curiosity rover. Caravaca et al., 2020, demonstrated VR use in a geological setting on Mars with specific lessons learned for data latencies and in-simulation analysis tools[12]. In particular they identify the need for 3D geometry and scale to provide size references to the users allowing for more precise characterization and interpretations of outcrops, which is not easily done on a 2D screen. Using orbital data, the uppermost sections of the Kimberly outcrop in the Gale crater were suggested to have been part of a distant younger geological unit which would suggest a major unconformity in the Kimberly stratigraphic sequence. The authors focused on the reconstruction of the Kimberly outcrop in order to provide a to-scale, collaborative viewing platform in which the stratigraphy could be better constrained. Combining orbital imagery for context with over 2000 images from the rover's camera suite they reconstructed the outcrop with the surrounding area in low resolution (orbital data). The use of VR allowed them to identify new contacts that were barely visible in the original 2D images, make visual correlations by walking around the outcrop and improve measurement precision of drill-hole sites. A key benefit noted by the authors was the ability to have a to-scale impression of the environment while freely moving around within it. This would be lacking in both a 2D image and a 3D desktop rendering. This ties in critically then with the ability to ingest depth-data into the VR environment to enable this benefit. This example of a VR use-case suggests a benefit for the in-mission use case for in-situ geological analysis and scale awareness, as well as a post-mission analysis use case where mission data can be analyzed with correlative capabilities.

NASA's Virtual Reality Training Lab[16] is another example of VR for space applications. This has been used in a range of applications from mission operations training, such as for the Hubble telescope repair missions[17], to use as a countermeasure for space motion sickness and disorientation[18]. From the Hubble training, the astronauts found the VR environment, overall, to have a positive impact on their mission. Audio and visual cues were also noted as positive aids in using the VR tool.

There are also examples of AR and VR use in non-space applications, such as military operations[19–21]. These may be heads-up-displays for fighter jets[19] or viewing goggles for drone pilots[20]. For most military operations, one of the main concerns is low latency. Given these devices are being used for real-time military operations it is critical that the display match the real-time data to a very high precision, not one of the main concerns for space applications where decisions are made cautiously and rovers are operated at very low speeds. However, for future applications with astronauts on a lunar surface EVA communicating with IVA crew members either on the lunar surface or in lunar orbit this will become increasingly important and will inform future iterations of VR research.

B. Mapping a 3-dimensional lunar environment

Because of the lack of atmosphere and known scale markers on the lunar surface, it is difficult to process depth-scale. This was notably observed on the second EVA of Apollo 14 as Pilot Ed Mitchell performed a 1.5 km traverse, which was supposed to extend to the rim of Cone Crater. Without being able to triangulate his position with known landmarks and because of the difficulty of estimating distances, he missed the crater rim by 100 m and had to abort this section of the traverse, Fig. 2 shows the traverse path[6, 22]. There is a need for modern tools to provide aid not only for future EVAs, but for near-term rover missions in which this depth-data will be critical to improving science return.

Orbital data, such as from the Lunar Orbiter Laser Altimeter (LOLA), provides low-resolution 3D maps of the lunar environment with digital elevation models (DEMs) ranging in resolution from >100 m down to 10 m resolution, however, the higher resolution maps are only available in small swaths of coverage and are challenging to achieve for polar sites. In order to achieve sub-metre resolution DEMs in specifically selected sites, it would either be necessary to plan extensive low-orbit telemetry missions with LOLA or a similar orbiter, or have the capabilities on board the rover in place. Table 1 lists different types of cameras which can provide depth-data along with examples of applications where these are used and the limitations for space applications.

Camera	**Depth range**	**Use Cases Space-based Limitations**	
Sterocameras	Camera-placement dependent	Autonomous vehicles, Mars rover, 3D film industry	Calibration of dual camera system, or need for overlapping imagery (single camera). Also suffers from occlusion.
Structured light	<10 m	3D scanners, computer vision, health care (3D reconstruction)	Limited by light emitter power, subject to occlusion
Time-of-flight	<10 m	measure distance and volume, object scanning, indoor navigation, obstacle avoidance, gesture recognition, reactive altimeters	Limited by light emitter power and wavelength, surface albedo can cause errors
LiDAR	>100 m	DEMs, remote sensing	Class of laser, cost, weight, surface albedo can cause errors

Table 1 Various types of depth-cameras and their limitations and use-cases.

As described above, the Mars Curiosity rover demonstrated this in-situ mapping capability for the Martian surface using the rover's pair of greyscale navigation cameras (Navcam), the RGB mast cameras (Mastcam), and the RGB Mars Hans Lens Imager (MAHLI), a colour high resolution microscope[12]. Orbital images from the High Resolution Imaging Science Experiment with 1 m/pixel resolution were used to create a basemap on which to overlay the higher-resolution rover camera data. Due to the use of various cameras and stereoscopic imagery several challenges were identified and needed to be overcome in image processing. This included non-optimal or inadequate points of view, non-overlapping images, non-consecutive views and changing lighting[12]. Additionally, in order to ensure as much overlap as possible for image correlation, over 2000 images were needed in RAW format from the Planetary Data System (PDS).

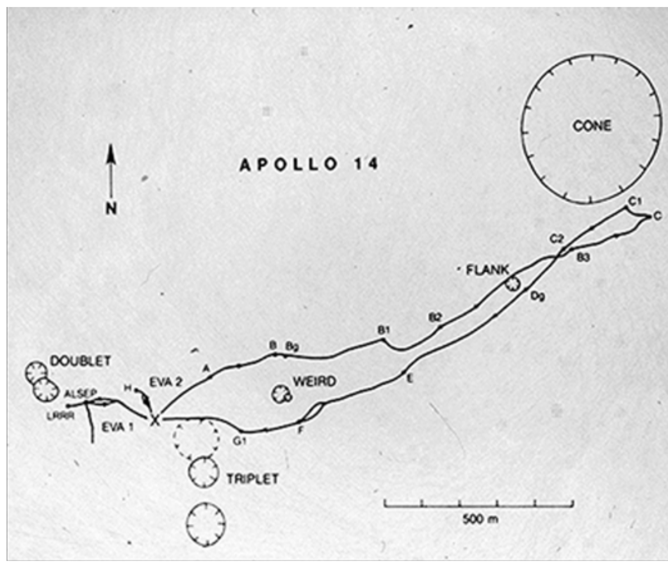

Fig. 2 Historical traverse path taken by Apollo 14 astronauts. The thick lines indicate the paths taken by the astronauts during the two EVAs. The letters identify sampling stations along the traverse of the second EVA. Prepared by the USGS and published by the Defense Mapping Agency for NASA.[22]

On Earth, DEMs are available to high levels of accuracy for many remote locations, in some cases available at sub-metre accuracy. These are often accomplished using LiDAR. LiDAR is a time-of-flight sensor which emits a pulsed laser light and measures the time for the reflected light to return to calculate an object's distance. LiDAR works in the 100's of metre depth-scale providing high-resolution depth maps for large areas. Because of the distance covered, not only does the laser need to be higher powered, but it also requires larger amounts of data. Thus, understanding how far the high-resolution data needs to extend could not only provide a reduction in data, but could suggest the use of lower-powered time-of-flight sensors, reducing weight and cost as well. Because of the complimentary nature of stereo-cameras, which can provide long-range depth-imagery but require careful calibration, overlapping imagery and can suffer from occlusion, and time-of-flight cameras, which can provide near-depth imagery, a fusion of the two camera types would provide precise 3D environmental reconstruction[23, 24]. Depth camera selection will rely heavily on the operation scenario for which the data is being used. The depth of view and resolution will be very different for a mission traverse planning scenario compared to a sample site selection or geological point of interest analysis scenario. These will be key influencing factors which we identify in our experimental setup.

An example use-case of orbital lunar DEMs is the Apollo Lunar lander simulator developed by Draper Laboratories commemorating the 50th anniversary of the Apollo 11 Lunar landing[25]. The simulator uses orbital data of different resolutions to display the lunar surface on a projection screen to simulate the last 100 seconds of flight. Because of the historical significance of the Apollo 11 landing site there are DEMs available at 2 m resolution from the Lunar Reconnaissance Orbiter's (LRO) Narrow Angle Camera (NAC). Lower resolution DEMs from the surrounding area were overlaid and blended with the higher resolution data to render the complete lunar scene. Fig. 3's lower left image shows the inset of higher resolution imagery onto the lower resolution background image.

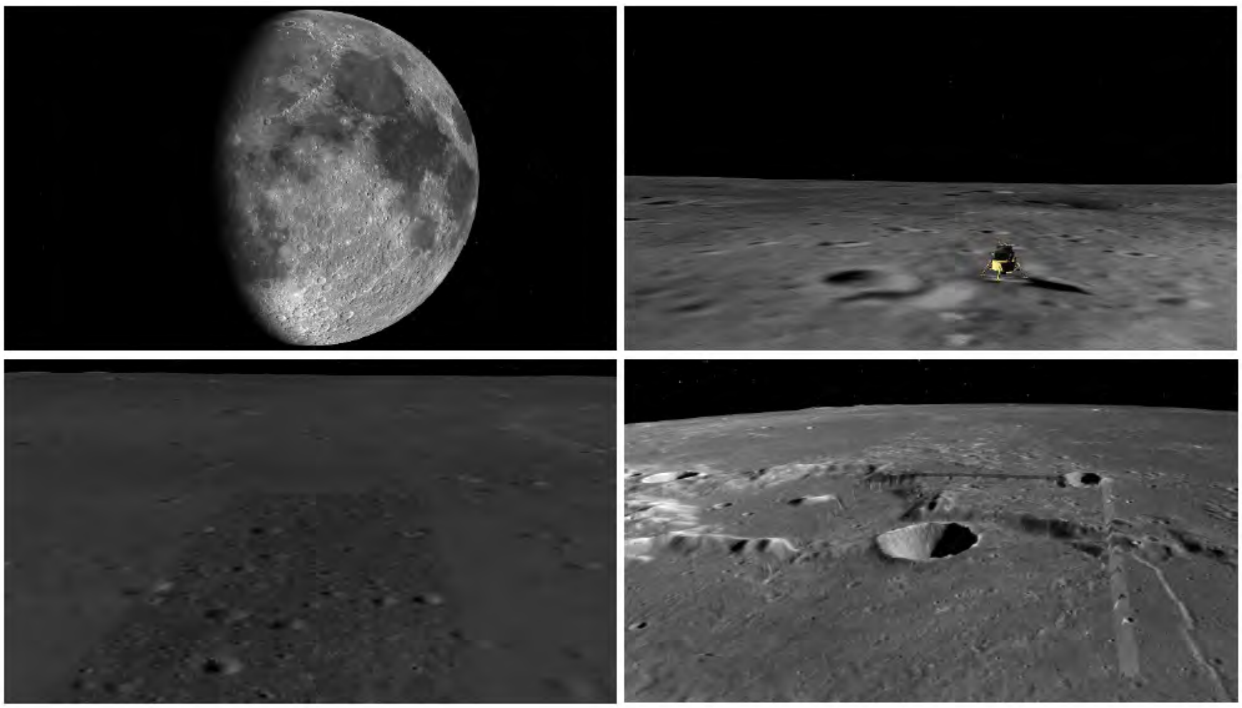

Fig. 3 Images from the Draper Image Generator. Top Left: Whole Moon. Top Right: Apollo 11 Landing Site with rendered Lunar Module. Bottom Left: Lunar Terrain with 50 cm/pixel imagery inset. Bottom Right: Lunar Terrain high-resolution inset with DEM Overlaid with LRO Imagery, figure and caption from Duda et al., 20202[25]

In this use-case, as in many LiDAR-produced DEM use-cases, sub-metre resolution is not necessary. The 2 m resolution provides adequate information to the lander pilot to be able to make a safe landing. Similarly, LiDAR-produced DEMs on Earth are often used to identify large-scale geological features such as fault lines, paleo-shorelines, crater rims, etc. As we reduce the scale of the science we want to perform or the size of the vehicle we want to control, the resolution of the depth-data needs to increase, but the distances covered by this high-resolution data can be reduced. Just as the Lunar Lander Simulator[25] only had high-resolution imagery over the area where the actual landing would occur, the peripheral imagery resolution could remain low. It is this boundary between high-resolution and low-resolution imagery that we can explore using different depth-data collection techniques. We expect that the 100's of metres of depth-data collected by LiDAR would not be required to sub-metre resolution, but instead would only need a dense point-cloud of high-resolution depth-data for the local 5-10 m view, which could be provided by a lower-powered laser time-of-flight camera.

IV. Experiment Design

A. Operations framework for VR mission control

The VR system, vMSS, will be tested for enhancements to ConOps as a support tool for the desktop user interface through three phases of mission operation: pre-mission, in-mission and post-mission. It is to be used for short periods (<1h) for mission planning, when points of interest occur, at waypoints, science stations, challenging terrain (ad-hoc), real-time data analysis during drilling and post-mission analysis to assess tools and data types needed for different operational requirements. vMSS includes two views. The first is a birds-eye-view for high level traverse planning and monitoring. This will include a-priori and orbital data with tools to allow for annotation and traverse planning (e.g. elevation and sun-angle profile calculations). The second is an immersive view enabling decision-making and in-simulation analysis based on real-time data. This will layer real-time payload data onto rendered depth-camera images, traverse paths and critical orbital data. The tools will eventually include manipulatable maps, instrument data visualisation, data layering (onboard and orbital), statistical analysis capabilities, databasing, correlative analysis and scale (early designs are shown in Fig. 4) as well as collaborative annotation. While we describe here the intended future experimentation for human assessment, these have not yet been accomplished as further data is needed to select the depth-data collection techniques. We present here the experimental setup and intended operations to be assessed.

The concepts of operations using VR are broadly applicable to exploration rover missions enabling greater scientific return for these time-constrained missions. The concept of operations, specifically the use cases where we will assess when the VR platform should be used (if at all), will be assessed using both quantitative and qualitative figures of merit[5, 26, 27].

The qualitative methods will include the use of NASA's Exploration Analog and Mission Development (EAMD) Capability Rating Scale (CRS), Fig. 5, Acceptability Rating Scale (ARS), Fig. 6, and Simulation Quality Rating Scale (SQRS), Fig. 7, completed by the users during each phase of the mission. These rating scales were developed by the NASA EAMD team at NASA JSC and have been used to develop, refine and evaluate human factors, human performance and ConOps for spaceflight and exploration-class missions[4, 5, 28–38]. We will also use the NASA Task Load Index (NASA-TLX) to correlate workload to various components of the VR platform by having users complete a questionnaire after each mission phase. The quantitative figures of merit include total time required for tasks, time spent in simulation, number of tasks completed in simulation, and achieving pre-identified data output requirements.

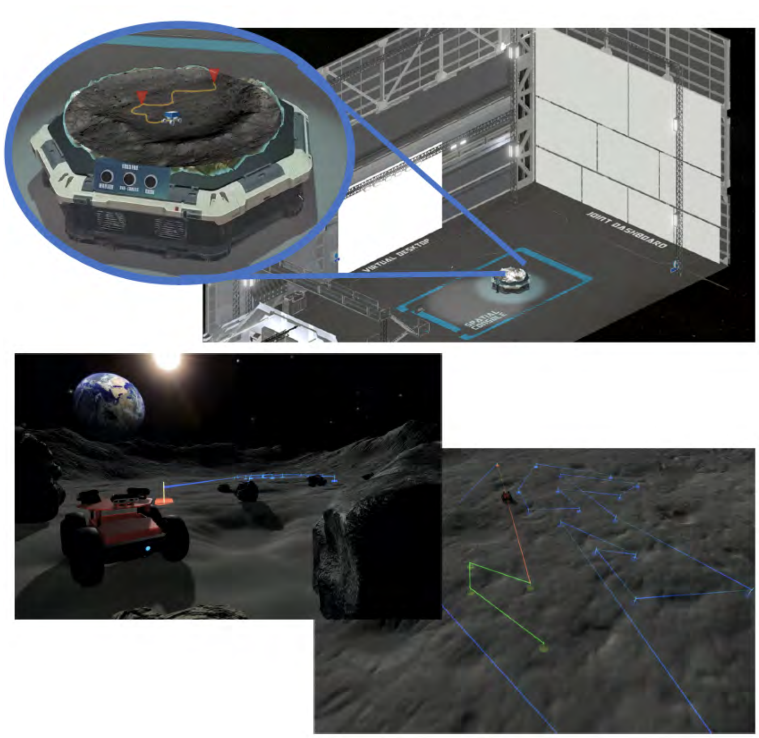

Fig. 4 Early development of the vMSS platform: top – early designs developed by Anandapadmanaban et al.[6] using a table-top birds-eye-view design, bottom – current design with immersive view.

We consider the three phases of operation in our experimental setups: pre-mission planning, real-time mission operations and post-mission data analysis. The pre-mission planning phase aims to facilitate traverse planning in VR acting as both a multi-user manipulatable mapping tool and a high-level story-telling tool for down-selecting landing sites and traverse paths. The real-time operations will have three observables including 1) execution of traverse path (time to complete), reducing workload (NASA-TLX) and improving communications between the science and operations teams (CRS, ARS, SQRS), 2) enabling real-time changes to traverse paths (time in VR), providing manipulatable,

Essential / Enabling		Significantly Enhancing		Moderately Enhancing		Marginally Enhancing		Little or No Enhancement		No Rating
Impossible or highly inadvisable to perform mission without capability		Capabilities are likely to significantly enhance one or more aspects of the mission		Capabilities likely to moderately enhance one or more aspects of the mission or significantly enhance the mission on rare occasions.		Capabilities are only marginally useful or useful only on very rare occasions		Capabilities are not useful under any reasonably foreseeable circumstances.		Unable to assess capability
1	2	3	4	5	6	7	8	9	10	NR

Fig. 5 NASA Exploration Analog and Mission Development Capability Rating Scale. Rates the capability of the technology as a tool for improving overall mission operations.[5, 26]

Totally Acceptable		Acceptable		Borderline		Unacceptable		Totally Unacceptable	
No improvements necessary		Minor improvements desired		Improvements warranted		Improvements required		Major improvements required	
1	2	3	4	5	6	7	8	9	10

Fig. 6 NASA Exploration Analog and Mission Development Acceptability Rating Scale. Rates the acceptability of the technology as a tool.[5, 26]

Rating	Criteria
1	Simulation quality presented either zero problems or only minor ones that had no impact to the validity of test data.
2	Some simulation limitations/anomalies encountered, but minimal impact to the validity of test data.
3	Simulation limitations/anomalies made test data marginally adequate to provide meaningful evaluation of test objectives.
4	Significant simulation limitations/anomalies precluded meaningful evaluation of major test objectives.
5	Major simulation limitations/anomalies precluded meaningful evaluation of all test objectives.

Fig. 7 NASA Exploration Analog Mission Development Simulation Quality Rating. Rates the quality and reliability of the simulation representing a minimum level of fidelity for simulation quality.[5, 26]

layered and interactive displays of both a birds-eye-view map and an on-the-ground immersive display (CRS, ARS, SQRS), and 3) visualizing real-time instrument data overlayed onto both the regional map and the on-the-ground display to improve decision-making capabilities (NASA-TLX). The real-time operations tools will also be used to enable geological correlation between apriori and onboard instrument data by allowing for annotation of instrument data and caching of data using time-stamp and geolocation to associate with the lunar coordinate system. Finally, the post-mission analysis will be assessed (CRS, ARX, SQRS and time in VR) for ease of accessability to cached data and types of analysis done. Comparison to previous analog missions[2, 3, 5] will provide a baseline for functionality testing, in addition to time and functionality comparisons to the desktop user interface.

Expecting the decisional cadence of the OT and ST to become more in sync, we focus on developing a platform that not only provides the ST tools to make quick and informed decisions with a clear picture of the environment, but also provides them the capability to communicate these to the OT and allow the OT to understand and ingest the scientific reasoning as an integral part of the health and risk management components of their process. Part of our experimental studies will be to assess the use of VR to improve the ST's ability for analysis of real-time data and as a communication tool between the ST and the OT. In each of our experiments our users will represent the ST lead. We will provide them access to the ST experts (such as a geologist) who will be represented by a member of the RESOURCE team. The OT as well as a rover operator will be represented by members of the RESOURCE team as well providing guidance on constraints and approvals for mission decisions that the user makes.

There are two factors limiting the use for VR in the mission ConOps. The first is the need to minimize time spent in VR for comfort, the second is the bandwidth restriction for data transmission. Designing the ConOps with respect to these two restrictions requires consideration of both the data pipeline and the mission operations. Fig. 8 shows a top-level concept of operations which includes vMSS as a communications hub which can be used throughout the three phases of the mission (pre-, in- and post-mission). vMSS will act as both a central node for completing analysis on the integrated payload suite of data as well as enabling communication of decisions between the ST and the OT. The data pipeline will determine the extent of pre-processing to be done on incoming data prior to integrating into vMSS.

A more detailed ConOps was developed for the drill site selection, Fig. 9 as an example of task-oriented ConOps development for VR use-cases where decisional cadence between OT and ST will be matched. Here we consider inputs

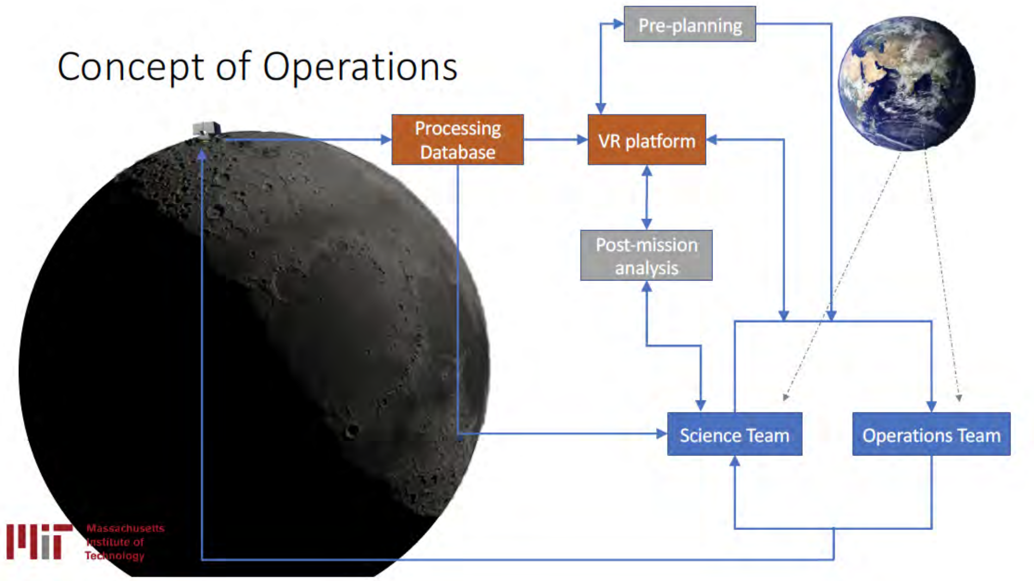

Fig. 8 Top level mission concept of operations for VR platform use

from additional rover payloads, including the Near-Infrared and Visible spectrum Spectrometer (NIRVSS) and the Neutron Spectrometer Subsystem (NSS). NIRVSS measures the reflectance spectrum of the lunar regolith. NIRVSS measures spectra between 1.6-3.4 microns, meaning it is sensitive to minerology and voloatiles, in particular water, which has diagnostic bands at 1.9 and 3.0 microns. Increasing water content appears as a decrease in reflectance, or a dip in the band depth. Measuring an increase in these 'dips' in reflectance demonstrates increasing water content[39]. NSS measures neutrons reflected from the lunar surace. On the Moon, low neutron flux is indicative of high water content, however, on Earth, a neutron emitter is used as an artificial neutron source. Thus, on Earth NSS reads higher levels of low-energy neutrons when interacting with hydrogen thus high neutron count is indicative of water. Combining these results with what is known about the region (albedo, rock type, etc.) provides the knowledge necessary to select a drill site where we expect higher levels of water content and thus want to explore below the surface.

Below we detail the experiments and analogue tests that will be conducted to assess VR use and mission use cases.

B. Human testing experimental design

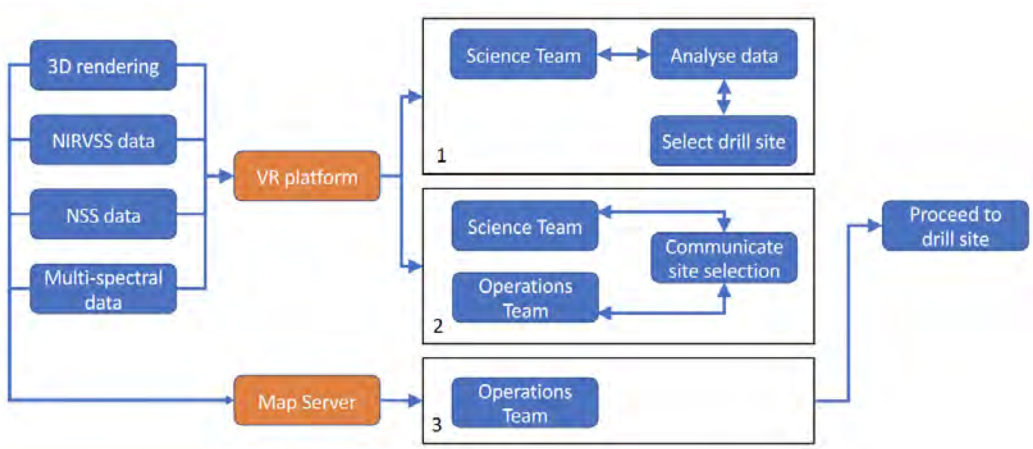

Fig. 9 Task oriented Concept of Operations for drill site selection.

The experiment proposed was designed to determine appropriate experimental setup for the three mission phases, develop an experimental procedure to compare the VR application with a desktop application and as a preliminary examination of tools necessary to assess VR benefit for mission operations.

The experimental hypotheses for the beta test using only an immersive VR point-of-view are:

- Users with access to VR will be able to consume data and select drill-sites more quickly compared to a desktop application.
- Users with access to VR will be able to re-plan rover traverses more easily compared to a desktop application (reduced task time).
- VR usage will be more beneficial to in-mission tasks compared to pre-mission planning (based on NASA EAMD rating scales).
- Users will be able to select a final landing site based on traverse data more quickly in VR.

We developed a baseline test using an immersive VR environment in Unity with an Oculus Quest headset and a mini rover from RoverRobotics.

The experiment is designed to have a user run a simulated lunar rover exploration mission in three phases (pre-, in- and post-mission) with an overall mission goal to find and select a site with high expected water content for a future human landing site.

Discrete tasks will be assigned for each mission phase with evaluations to be completed by the user after each phase. Given the goal of this experimentation will be to assess preliminary designs of the VR environment and the ConOps we will recruit users with geological field work experience but not necessarily VR experience to assess the most basic usability of the platform while gleaning the geologically relevant requirements..

The rover was developed with three Intel RealSense D435i stereo depth-cameras mounted onto a custom payload mount to provide real-time images and depth data, Fig. 10. Only a single RealSense camera will be used for this preliminary experiment, with the additional two cameras available for experimentation with multiple cameras in future tests.

The environment is designed with three levels of obstacles, Fig. 11:

1) (light grey): There is some risk of driving the rover over these obstacles as they may be worse than they appear from orbital data, but you can drive over them.
2) (mid grey): These pose a higher risk and will most likely damage the rover.
3) (dark grey): These are no-go obstacles. The rover will not be able to drive over them and any attempt to do so will destroy the rover.

Fig. 10 RoverRobotics mini rover with custom payload mount for three Intel RealSense D435i cameras (forward facing and two rear facing cameras positions 45° from backward). An additional GoPro camera was mounted on the rover.

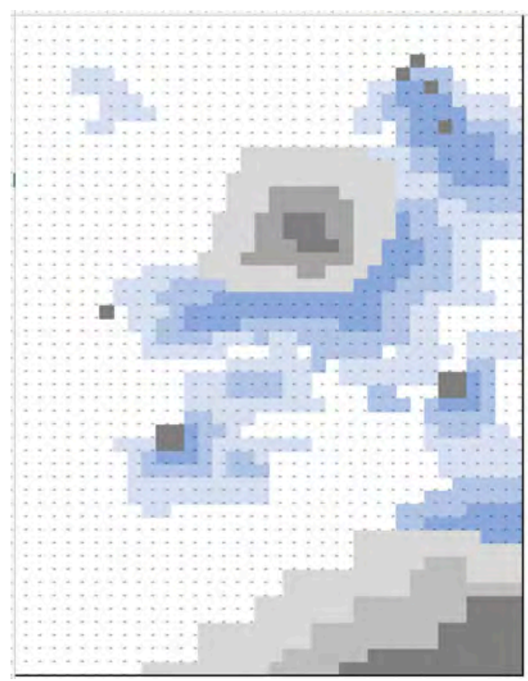

Fig. 11 Simulated lunar environment mirrored in real indoor environment (MIT Media Lab) and a virtual environment (Unity for Oculus Quest). Darker shades of grey indicate more dangerous terrain (larger obstacles) and darker shades of blue indicate higher neutron count and thus higher regolith water content.

Additionally, simulated neutron spectrometry data was created for the environment based on data from the Mojave

Volatiles Prospecting (MVP) analog experiment performed in 2015 by J. Heldmann et al.[1, 2, 39–41]. Here, we chose to simulate Earth-based data to be consistent with both the MVP data and to provide continuity with future experiments should we be able to integrate the MVP neutron spectrometer system (NSS) as a payload. Thus, low neutron count, 26 neutrons per second (nps), indicates no water content and higher neutron counts are indicative of higher water content. Three levels of neutron counts were established with increasing intensity of blue to indicate greater water content (light-blue: 55 nps, mid-blue: 70 nps and dark-blue: 81 nps). The environmental grid (Fig. 11) will be mirrored both in the real environment and in the VR environment with neutron spectrometer data to appear in real-time along the rover traverse path.

The rover will be driven manually with position and depth-data transmitted to the VR environment using SLAMCore, a simultaneous localization and mapping (SLAM) software developed for the Intel RealSense cameras and ROS (Robot Operating System). SLAMCore tracks and stores the location of natural features to create a live point-cloud which is used to calculate the real-time position of the rover[42]. Additionally, the height mapping configuration of SLAMCore creates a height-map in real-time of the environment using the RealSense depth-data.

The three mission phases are outlined as follows with the user repeating the experiment once in VR and once on the desktop application:

1) **Pre-mission:** The first phase of the mission will be to plan a traverse path. Looking at the orbital data of the landing site in either the Desktop or VR application, the user will select between 3 and 10 waypoints in the order to be executed. A traverse path will be manually built by connecting the user's selected waypoints in the order selected with straight lines.
2) **In-Mission:** The user will observe the incoming data (depth-camera and neutron spectrometer) along their selected traverse. Neutron data and depth-camera imagery will be updated automatically as the rover progresses. The user will select 3 drilling locations over the duration of the traverse selecting locations that show high water content (high neutron counts). The following method will be followed for site selection:
    1) At each waypoint the rover will stop for one minute while the user decides if they would like to drill at this location or anywhere along the previous traverse section (up to the last waypoint).
    2) When the user selects a drill site, the rover will remain in its location until they indicate they are ready to move on.
    3) The user will deposit a drill flag at the selected location indicating its selection and communicate the selection and reasoning to the Operations Team.
    4) Once the Ops Team approves/denies the selection the user will indicate they are ready to proceed, the drill data will appear at the selected site and the rover will continue along the pre-planned traverse.

   Prior to the in-mission component a simulation operator will place an 'unforeseen' obstacle along a user selected traverse path. During the mission the rover will stop at this obstacle and the user will be asked if they wanted to attempt to go over it or if they want to re-plan the traverse around it.
3) **Post-mission Analysis:** The user will review all of the data that the rover collects and select their human landing site. Included in this final data will be:
    - Neutron data along all completed traverse paths
    - Depth-camera imagery at each waypoint
    - Simulated drill site depth-profiles of water distribution beneath the surface.

   Once they select their site they will be asked to annotate the map (drop a flag) at the selected site and explain their selection to the Operations Team.

Each task (waypoint selection, mission traverse, obstacle avoidance and landing site selection) will be timed comparing completion time in VR and in the desktop application. Additionally, the NASA EAMD Rating Scales will be completed after each mission phase along with questions regarding the usability of the VR and preference over the Desktop application. A summary of experiment metrics are shown in Table 2.

V. Preliminary Hardware and Software Assessment

Within the scope of this paper we present the preliminary design of the immersive VR environment using orbital data and include tools to monitor the traverse on a birds-eye-view minimap, view and edit waypoints and traverse paths in the immersive point of view and observe rover motion. We also demonstrate preliminary depth-data collection techniques using a COTS stereocamera, the Intel RealSense D435i and a COTS smartphone-based structured light camera with integrated RGB imagery, the Lumentum VCSEL.

Independent Variable	Dependent Variable	Metric
Task (objective, complexity)	Time to complete task	Time
VR usage (VR vs. Desktop)	Task Performance	Based on defined objective performance metrics in experimental design (e.g. correct place to "drill" based on simulated neutron data)
VR environment	Subjective feedback to gather information about: Tasks where VR assisted the most, General feedback on VR environment, Confidence in decision making within VR (Would you use this?)	Post-experiment questionnaire: Capabilities based on NASA EAMD rating scales and subjective questions.

Table 2 High-level summary of the beta testing design.

A. Virtual Reality Environment Design

The virtual environment was developed in Unity 2020.1.8f1 featuring a first-person view, compatible with the Oculus Quest 2 HMD, and a top-down view that is inspired by real-time strategy (RTS) video games for mission planning. The environment was developed using orbital data to provide a preliminary view of how it would appear on the lunar surface. To enhance the photo realism, several visual components were added. For instance, the sky-box generated with high resolution textures, along with models of debris and rocks were downloaded from the Unity asset store, and from the Quixel Megascans library [43]. A 3D model of the the RoverMini by RoverRobotics was rigged into the Unity scene with the appropriate materials and shaders, mimicking the physical rover. Locomotion, navigation and mission planning were provided through custom C# scripts, built directly into the game engine. Finally a post-processing effects stack helped tune the overall look and feel of the environment.

B. Depth-data collection

In order to conduct an early assessment of the data types we would be using and their functionality for the experiment, we collected depth-data via two cameras. The first was using the Intel RealSense D435i, Fig. 14. This is a stereocamera with a 87° horizontal field of view (FOV) and 58° vertical FOV, a 1280 x 720 depth output resolution and capture rate of 90 frames per second. The D435i has an integrated RGB camera with a 69° horizontal FOV and a 42° vertical FOV at 2 MP resolution. The camera can be operated directly using the associated software - RealSense Viewer - or through the SLAMCore software used to control the mini rover. We collected *ply* files directly through the RealSense Viewer as well as a complete traverse using the SLAMCore software as *png* files, IMU data and odometry data. The IMU and odometry data can later be used to overlay the images onto a complete map of the terrain by associating imagery with location for image stitching.

We also collected a complete 3D depth-rendering of the terrain using the Lumentum VCSEL Structured Light with integrated RGB camera. This camera is built into the iPhone 12 Pro with associated processing and rendering capabilities built in. Here the data was captured manually using the camera from a hand-held position and fully encircling the central obsta-

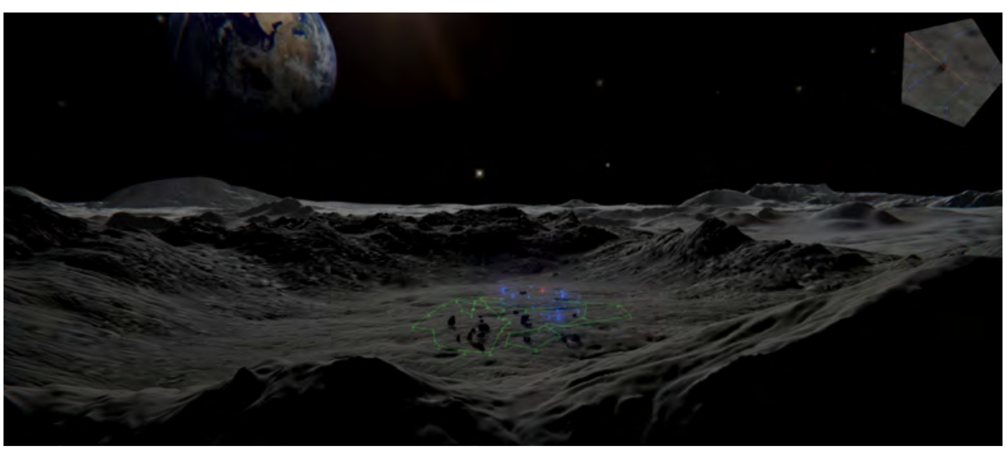

Fig. 12 Mission planning user interface similar to Real Time Strategy (RTS) video games.

Fig. 13 First and third person views of the RoverMini within the virtual lunar environment.

cle.

The data was collected as *jpeg* and *json* files as well as a fully rendered *obj* file, accomplished with the built-in iPhone processing software.

An example of the D435i *png* file captured over the complete traverse is shown in Fig. 15. A single waypoint *ply* file view is shown in Fig. 15. Because these are unstitched, these are single capture and provide only the FOV of the camera itself in one position.

Fig. 15 shows the complete 3D rendering captured by the Lumentum camera. The data size required for the complete rendering (*obj*) is 30.8 MB. Compare this to the complete traverse in *png* files from the D435i, for an unstitched continuous capture, which is 1.3 GB and 44.1 MB for the 8 waypoint captures in *ply* format.

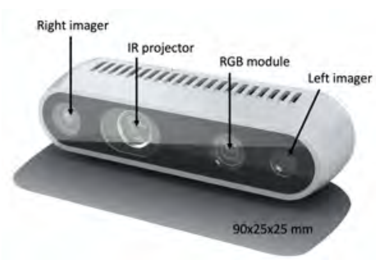

Fig. 14 Intel RealSense D435i stereo and RGB integrated depth camera.

Here we can conclude some critical factors:

- The smallest bandwidth requirement is available from the optimized Lumentum dataset - minimizes image overlap during processing.
- The height of the mini rover provides a challenge in capturing a complete dataset, thus minimizing situational awareness benefits
- the low-angle capture of the *ply* data causes artifacts from ground reflection which make depth-data interpretation challenging.
- Data captured using structured light provides more accurate representations - however this could be an artifact of the variation in processing or the height of the data capture.

The results from these early data captures demonstrated the necessity to first examine depth-data capture techniques in more detail prior to human assessment. In order to accurately assess the benefits of using VR for ConOps and to properly identify mission critical operations for VR and the tools necessary to improve science return, we first need to identify the best method for developing the baseline VR environment.

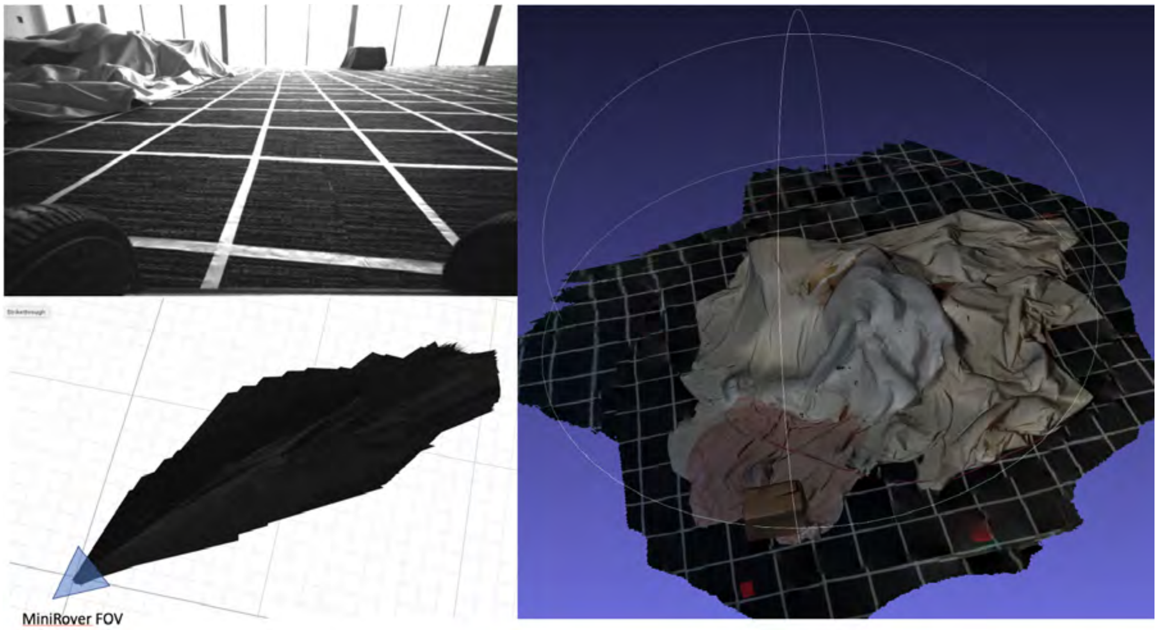

Fig. 15 Depth-camera views. Top-Left: Intel RealSense D435i stereo and RGB integrated depth camera snapshot from a complete traverse - captured using SLAMCore software. Bottom-Left: Intel RealSense D435i stereo and RGB integrated depth camera single waypoint depth-data capture - captured using RealSense Viewer. Right: Lumentum VCSEL structured light and RGB integrated depth camera for full environment capture - rendered as obj file with iPhone integrated software.

C. Depth-data capture experimentation

Prior to completing human-based testing, as described in Section IV, the specific depth-data collection technique needed to be identified. This experiment needs to compare multiple available depth-cameras as well as available VR capable cameras. The experiment was conducted in July and August of 2021 on a granitic beach in Marblehead, Massachusetts using the Spot rover from Boston Dynamics, Fig. 17. The results of this experiment will be presented at IEEE AeroConf 2020. We tested a 360 VR camera (Insta360 One), two stereocameras (Intel RealSense D435i and the built in Spot cameras), and two time-of-flight cameras (Intel RealSense L515 and Velodyne VLP16) focusing on their depth of view, field of view, resolution (point cloud density), bandwidth requirements, processing requirements for VR and ability to function in different lighting conditions.

These results will allow us to select the appropriate depth-data collection techniques for the different mission phases and to better represent the data pipeline that will be available to achieve the VR for operational use.

VI. Conclusions and Future Work

We continue to develop the vMSS platform and tools through hardware testing, VR software development and integration, and human in the loop considerations. Beyond the Spot Robot experiment performed at Marblehead, MA, we plan to do assessments of the resolution and bandwidth requirements for in-situ geological considerations. We will test the depth-data, RGB imagery and associated tools to determine the requirements needed to identify geological points of interest and sample site selection. Once the depth-data collection technique has been selected, the tools described in Section IV will be incorporated into vMSS. With this integrated tool we will then conduct the above-described human experiments to assess the usefulness of VR for the different phases of mission operation.

Working with artist Yevgeny Koramblyum and the MIT Operations in the Lunar Environment course (Space Exploration Initiative), we developed a manipulatable concept demonstration of the vMSS tool (Online Platform), Fig. 18. Our current work aims to functionalize the depth-data integration into the virtual environment described in Section V.A.

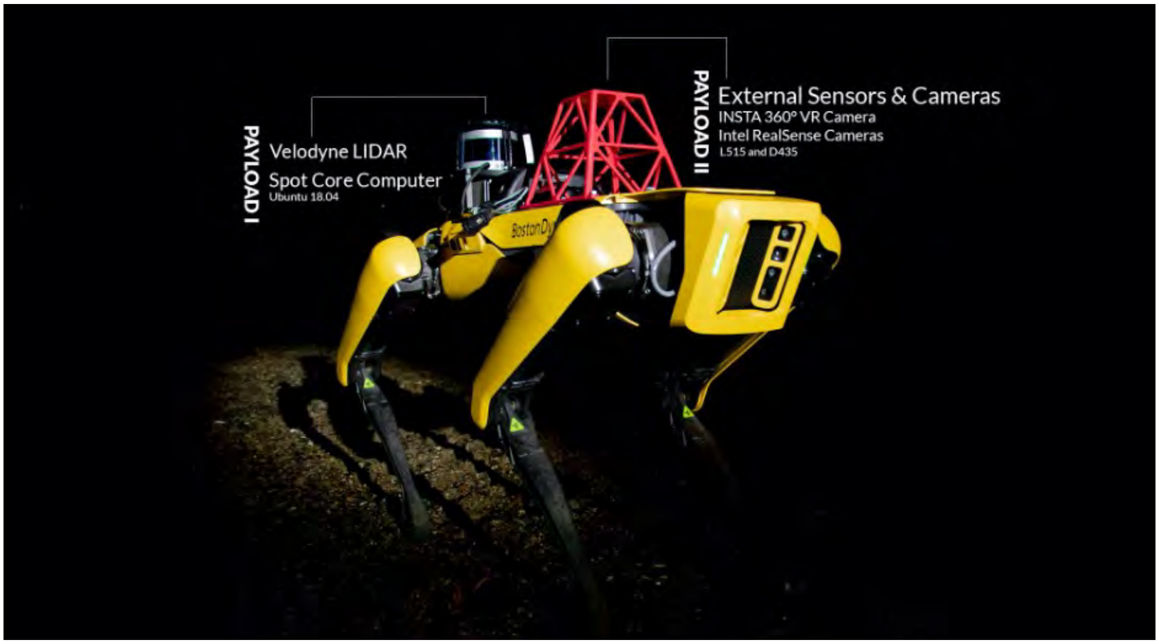

Fig. 16 Boston Dynamics Spot robot with first payloads mounted: Velodyne LiDAR puck, SpotCORE onboard computer, and custom payload tower (red).

Fig. 17 Boston Dynamics Spot robot 360 Video with LiDAR viewer.

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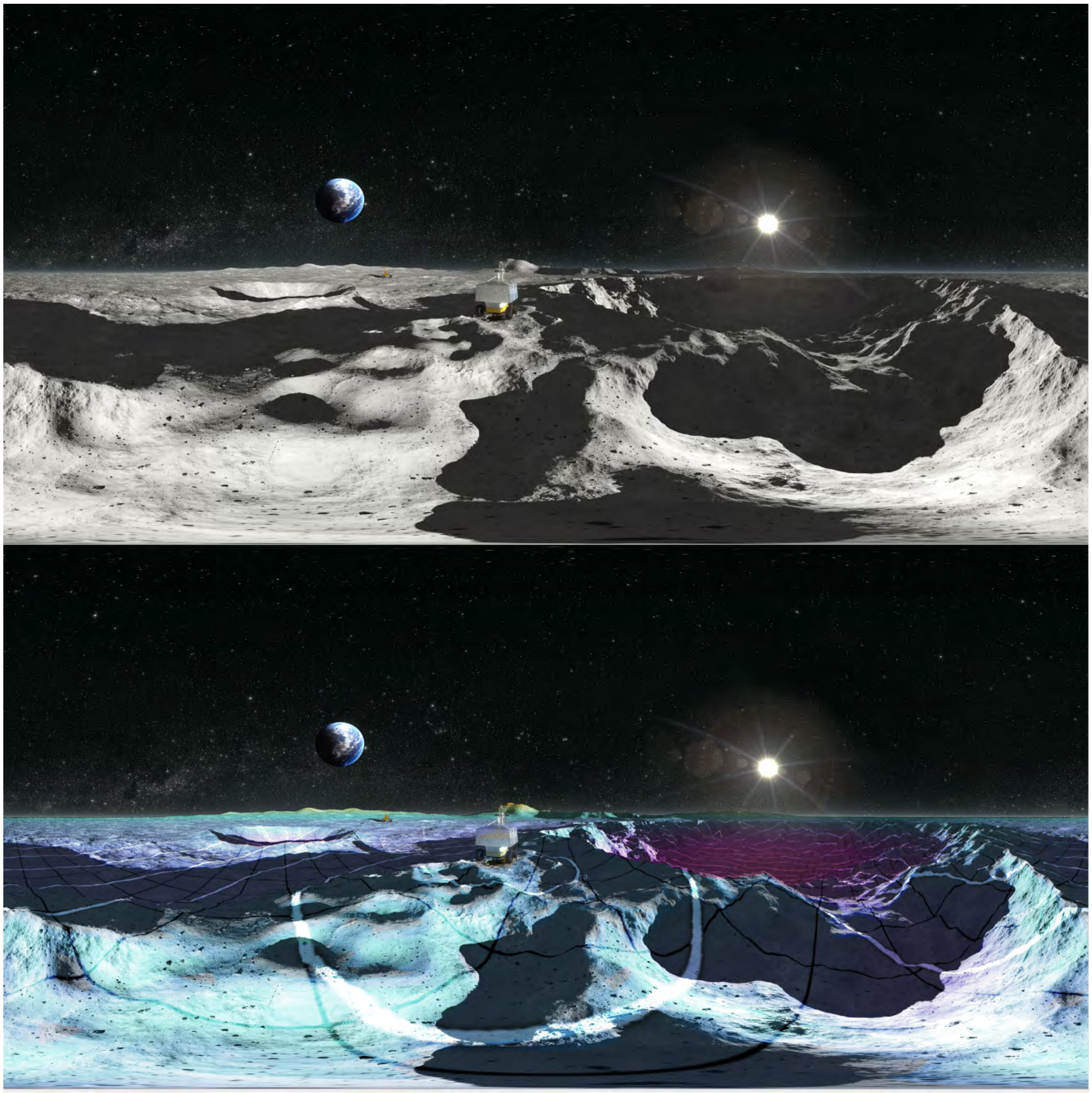

Fig. 18 Artist Yevgeny Koramblyum's rendering of the vMSS immersive environment concept. Top - environment with no overlays, bottom - environment with depth-map and distance markers overlayed. Rendering was done in association with MIT's Space Exploration Initiative.

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