A Virtual Reality Mission Simulation System (vMSS) supporting Closed-Loop Mission Control

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Mission Control centers are a central component of all space missions. Their primary tasks are to command mission operations, monitor and analyze a large number of parallel data streams, as well as prepare for and respond to anomalies in real-time. Virtual Reality (VR) presents the opportunity to use a digital mission control environment to "speed up the loop" on reactive mission planning, control, data analysis, and collaboration. There are several core concepts that an immersive digital environment brings to a decision support system: tele-presence, real-time data visualization, interactivity, and real-time data analysis. This then gives high extensibility to virtually any task requiring coordinated mission operations where data must be analyzed, teams must collaborate, and decisions must be made under time constraints. Here we determine the benefits to situational awareness, collaboration, and mission flexibility through simulated mission activities approximating the Volatiles Investigating Polar Exploration Rover (VIPER) mission using data from Earth-based analog campaigns. Through the integration of visualization and analysis tools for two primary instruments - the near-infrared volatile spectrometer subsystem (NIRVSS) and the neutron spectrometer subsystem (NSS) – and working closely with the mission operations team, we can provide tools that are both high-value and high-utility. Focusing on situational awareness, collaborative team integration, and enabling new mission planning regimes, we designate critical elements for a simulated operations control platform in Virtual Reality.

Presented are preliminary tools or interaction, collaboration, and mission operations in a virtual environment. Focus will be on simulated mission operations, with collaboration and interactivity with instrument data between operators, planners, and scientists; and operational flexibility enabled by the virtual environment. Finally, we present a path-to-future for development of a highly scalable and highly capable collaboration and control environment.

Nomenclature

VR = virtual reality
AR = augmented reality
MR = mixed reality
VIPER = volatiles investigating polar exploration
RESOURCE = resource exploration and science of our cosmic environment
NIRVSS = Near-infrared and visible spectrometry system

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NSS = Neutron spectrometry system
vMSS = virtual mission simulation system
EVA = extravehicular activity
BASALT = Biological Analog Science Associated with Lava Terrains
ISRU = In situ resource utilization
SSERVI = Solar System Exploration Research Virtual Institute
SEXTANT = Surface Exploration Traverse Analysis and Navigation Tool

I. Introduction

MISSION control has been a central, consistently present component of all NASA missions, from the very early Mercury and Gemini missions to current crewed and uncrewed missions to the Moon, Mars, and beyond. The primary purpose of these centers has been to analyze many parallel data streams, monitor for off-nominal conditions, and respond to anomalies in real-time.[1] Simulated missions have shown that future operations would require a deeper degree of coordination and collaboration to adequately meet mission goals.[2] As mission complexity is set to become exponentially greater for future exploration missions, the ability to manage live data feeds and make real-time decisions is vital to mission safety and security. Scientists, engineers, specialists, and controllers will therefore be increasingly strained in mission support roles. Virtual Reality (VR), Augmented Reality (AR), and telepresence systems can help reduce operational strain by building upon historical frameworks for analytical tools and decision support systems.

The ultimate goal of the RESOURCE project is to target and explore potential resource deposits on SSERVI Target Bodies such as the Moon, near Earth asteroids, and the Martian moons through scientific investigation, enabling ISRU for future exploration missions. The MIT-developed component of RESOURCE aims to assess new operational concepts and capabilities enabled by new technological developments, and to optimize the human-robotic or human-computer interactions present at every stage of a human or robotic exploration mission. Specifically, the knowledge gap to be addressed by this work is in the determination of how the opportunities presented by immersive virtual systems should be implemented and optimized for productive workflows in a mission control environment.

Virtual and Augmented reality provides the ability to generate deeply immersive reconstructed environments that can mirror real environments in high fidelity, including down to functionality of computational systems or analytical tools. This capability can be leveraged to enhance future exploration missions on the Moon and Mars. Surface activities are currently heavily scripted, and risk assessments, science tasks, and traverse planning occurs within the Earth-based control center. In future missions, these mission control responsibilities will have to be shifted away from the Earth based operations center to a surface-based operations center staffed by mission crew members. This becomes critical in mission profiles involving Mars or habitation on the far side of the Moon, since the communication latency, which can be as long as 20 minutes one-way, will be too great to allow an Earth operations center to quickly react to mission anomalies. Initial work in the combined virtual offloaded operations center was undertaken as part of the BASALT (Biological Analog Science Associated with Lava Terrains) research project. One aspect of that project serving as a precursor to future virtual

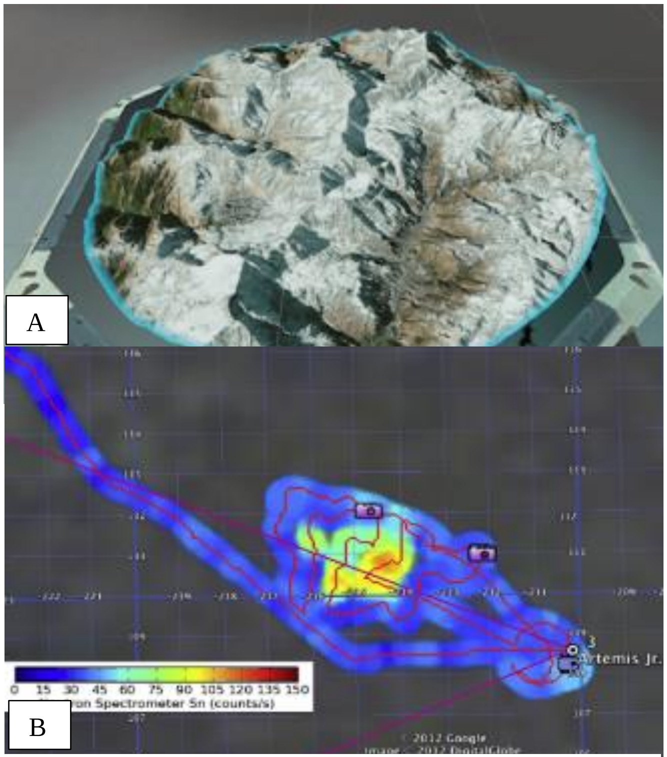

Figure 1. Superimposable VR datatypes: (a) co-registered "super" model of terrain altimetry and imagery. (b) neutron spectrometer data, reproduced from Heldmann et al.[11]

work is the SEXTANT (Surface Exploration Traverse Analysis and Navigation Tool) and Holo-SEXTANT, an embedded AR navigation tool. This work demonstrated the capability for an augmented reality navigation system that can be developed and deployed with commercially available hardware. It also showed that EVA (Extra-Vehicular Activity) related tasks can be enhanced through the use of an AR framework through increased communication ability, increased visualization ability, increased situational awareness, and decreased cognitive load.[3]

The baseline capability provided by a virtual or augmented reality system allows for the demonstration of several development areas essential to integrating collaborative immersive environments into a productive workflow. These development areas all contribute to a digital "decision support system" that mirrors the capabilities of current mission control but also expands on those capabilities, enabling greater situational awareness, lower cognitive loads, and faster decision making. Direct applications of the mixed reality interfaces are to both test and enhance the abilities of the Science Backroom Team to identify high priority scientific regions of intertest (ROI) in the field, and identify geologic qualities (structures, volatiles, soils, etc.) that are significant and indicative of the presence of ISRU-relevant deposits.

II. The Virtual Mission Simulation System

Mixed Reality Mission Control systems are preceded by a substantial body of work in developing and analyzing collaborative virtual environments, as well as teleoperation and telepresence in the field.[3–8] Through their decreasing costs and increasing power in standalone devices, there is ample space for development and deployment in operational workflows. In particular, MR tools designed for collaboration and rapid analysis of data can be structured around providing a substantial amount of decision support infrastructure. These decision support systems can answer several fundamental questions for functional workflows:

- What benefits do MR tools present to situational awareness and task load?
- How can the decision support tools be optimized to provide maximum utility to users?
- What unique methodologies must be used to allow team members within the mixed reality space to enhance operations?
- How can automation and machine learning be integrated into the decision-making process?

These questions are the critical knowledge gaps to be answered through this development and implementation pathway.

The Virtual Mission Simulation System (vMSS) is an implementation of an earlier VR system, known as the virtual mission control system (vMCC) by Anandapadmanaban at MIT.[9] vMSS is designed to demonstrate augmented display and interactivity capabilities in a "simulated mission control" setting for high-throughput data integration, interactivity, digital co-location, in an immersive three-dimensional virtual environment.

There are several principles that pose unique benefits through use and implementation of virtual systems. The most apparent benefit is the construction of dynamic specialized data visualizations and the ability to view multiple layers of data simultaneously, through construction of a geospatially co-registered terrain "super" model.[10] Figure 1A is a representative image of a co-registered super model of altimetry data and optical terrain data. Even more data types can be overlaid to give richer and easier-to-understand representations of spatial data such as 1B, a neutron spectroscopy data set from a science traverse[11]. The platform's capability will be further expanded to use generate

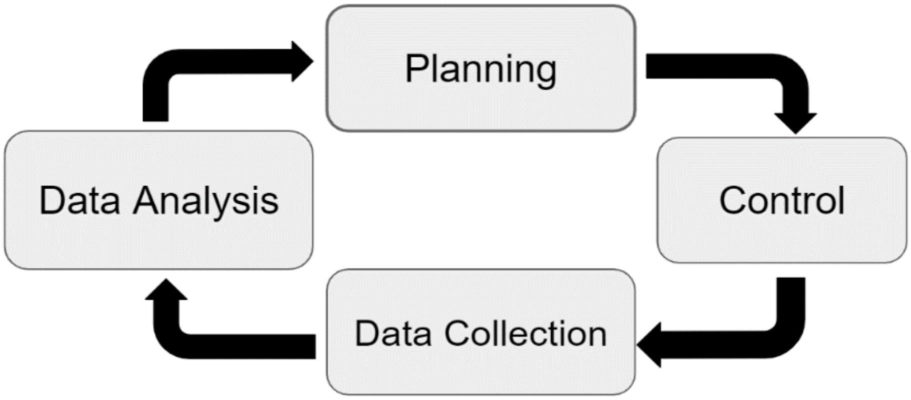

Figure 2. High level block diagram of closed loop mission control operations.

multi-source displays in real-time and allow for streamed data inputs when communication infrastructure allows. Effective use of this three-dimensional representation can dramatically increase the bandwidth of data intake that a single user is capable of. This comes with several caveats, however, as there are limits to the efficiency of data intake depending on the implementation of a visualization.[12] Another secondary benefit is the creation of intuitive natural user interfaces, which can reduce training time, as the 2D to 3D conversion does not need to occur mentally, the interface can be used effectively with less training and be easier to use.

A. Enabling Mission Control Decision Loops in VR

Mixed Reality tools can be effective in complex usage scenarios such as in mission control operations. Here, intuitive analytical and decision-making tools are critical for success, as the several teams involved in mission operations need to have high-bandwidth communication and analysis utilities to ensure successful completion of all mission goals while staying within the mission constraints. The previously laid out principles work together in an effective VR implementation to free mission operations from the constraints of traditional 2D software. Figure 2 is a high-level block diagram of mission control operations, visualized as a closed-loop control scheme where each transitional arrow between blocks represents a decision step. These steps are conducted by operators who are typically interfacing with multiple monitors for individual analysis and huddled around a single screen for collaborative analysis. 2D screen space, divided into different visual representations of data, is spread across multiple applications and data regimes. Only after substantial analysis time, with complex internal models generated to combine all the disparate data types into a comprehensible workflow, are conclusions reached and decisions made. This workflow is non-optimal for either collaboration or rapid data visualization, that rapid decision workflows demand, and anomaly response (which demands collaboration and data visualization) causes strain on this flow.

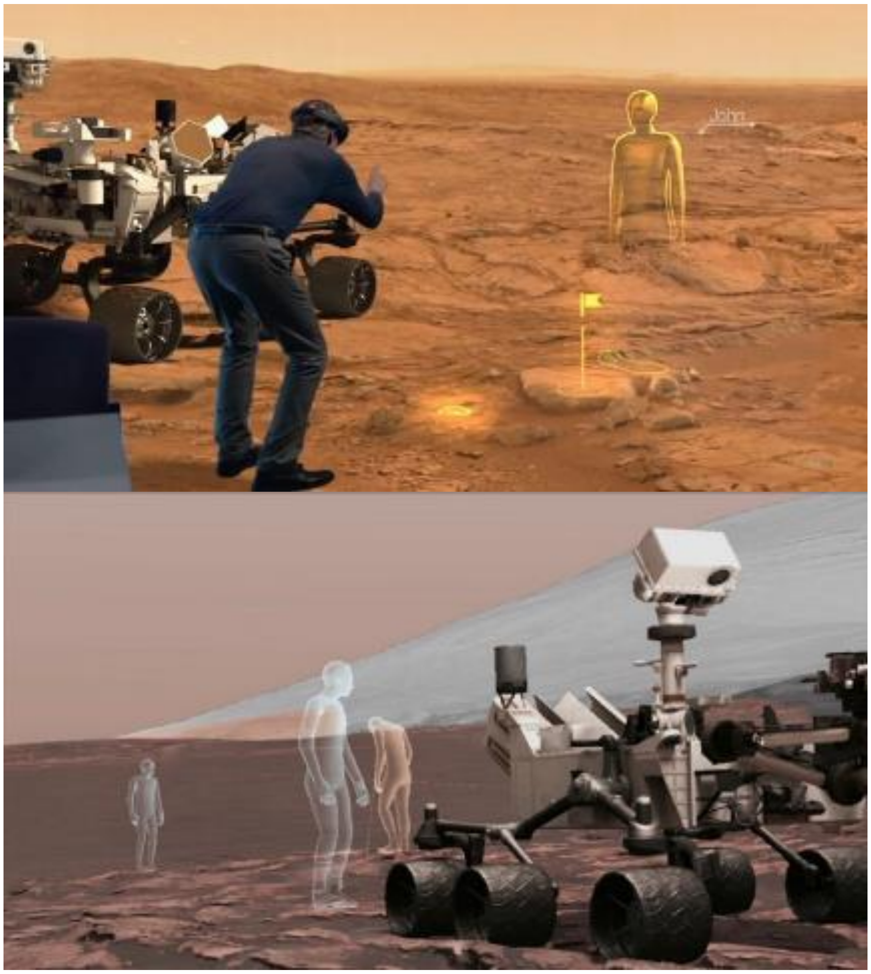

Figure 3. Concept view of Mixed Reality and fully virtual mission operations on Martian surface, from JPL OnSight software suite.

The multi-modal display and interactivity capabilities of a VR system enable “fast” decision-making loops by providing an interface to continuously monitor procedures, navigation, and live data to make real-time adjustments in planned excursion paths - thereby maximizing science return while also minimizing risk to the overall mission. Implementation of substantial automation tools in the data processing and analysis toolkit is essential to the speed of the mission control loop, and depends on two key features of autonomous and semi-autonomous operations; development of transparent decision making protocols for autonomous system trust,[13] and teleoperative field control in a virtual environment.[14]

Mixed reality systems were demonstrated as effective tools to enhance communication in the Biological Analog Science Associated with Lava Terrains (BASALT) field campaign, and provided substantial guidance for integrating AR into surface science operations.[15]

Additionally, a baseline need of the system is to be highly flexible, to address any significant mission operations changes, and to tailor usage scenarios to produce maximum productivity within a single hour in early implementations of the system. While ultimately the intent is for users to interact with the system for extended periods, upwards of several hours, industry human factors research has demonstrated that early development VR sessions are most effective when limited to an hour or shorter[16] help to maintain comfort and reduce the occurrence of visually induced motion sickness, a long-known side effect of high fidelity virtual environments.[17]

B. Speeding up the Mission Control Loop

A mixed reality mission operations center presents the ability to speed up the decision-making process on reactive control by providing the high bandwidths required to perform real-time visualization and real-time analysis of streaming data through intuitive and interactive decision support tools via 3D data and collaborative environments. This virtualized type of mission operations has high extensibility to virtually *any* task requiring coordinated task operations where data is analyzed in a collaborative setting to inform the decision-making process, since the fundamental mechanism of the "high bandwidth" is reducing the cognitive load from dense and difficult-to-parse data displays. The theory behind cognitive load is built upon previous work by Atkinson and Shiffrin, who presented the "multi-store" model of memory, where memory consists of a "sensory" storage, short-term memory, and long-term memory.[18] Cognitive load theory builds upon this by relating the amount of information that can be held in working memory with the type of information that is stored – and attempting to prevent an overload in the working memory.

Cognitive Load Theory identifies two types of "loads" that modulate whether information is easier or more difficult to digest and store, based on representation. The first type is intrinsic load, which refers to challenges fundamental to understanding content, and the second is extrinsic load, which is focused on representation of content. Extrinsic load can be decreased through novel developments that lead to better design in representations and interactables. The ability to work with data in full 3D co-registered terrain supermodels is the key component of this architecture. Once present, then instrument data can be combined with 3D map data to reduce the cognitive load in interpreting that instrument data, relating it to the current mission plan, and make rapid adjustments to the mission in real time.

Rapid decision making, a product of the decreased cognitive load from the virtual mission display environment, allows the mission control loop to run faster when compared to a more traditional organizational structure of the "flight control" team separated from the "science backroom" and support teams.[19] In the traditional structure, science teams operate on a time span of minutes – to – days, and do not have the situational awareness required to make rapid mission decisions while maintaining minimal risk status. Instead, priority is given toward mission safety and security, potentially an overabundance of caution, ultimately reducing science capability of the campaign.

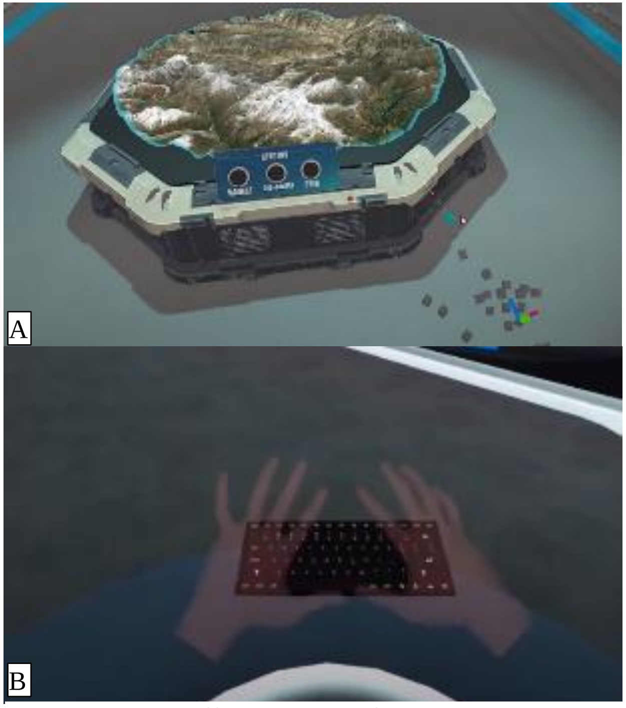

Figure 4. Two different types of hand-approximating interfaces within the vMSS platform. (A) Unity core hand model. (B) Oculus 2 hand-tracking display interface.

III. Implementation

The vMSS (Virtual Reality Mission Simulation System) takes the lessons learned from the pathfinding analog missions and also recommendations from the VIPER science team specialists to integrate data visualizations from the near-infrared volatile spectrometer subsystem (NIRVSS) and the neutron spectrometer subsystem (NSS) payload instruments. The platform's primary objective is to provide a system for development and testing of decision support system infrastructure, and enable rapid iterative decision making for space operations.

A. Near-InfraRed and Visible Spectrometry System

The NIRVSS instrument assesses surface hydration and mineral mixtures by measuring reflectance spectra of the target surface. NIRVSS target spectra is between 1.6 µm and 3.4 µm, specializing in mineralogy spectra and low-temperature volatiles with specific attention to water, with two characteristic absorption bands at 1.9 µm and at 3.0 µm. Readings from the instrument appear as lower reflectance in specific regions (usually displayed as a "dip" in the band, and depth is extracted as a measurement relative to a baseline reference spectra, with output being a "ratio spectrum."[20] Raw spectral data from in the onboard database is processed relative to the reference spectral calibration to produce the ratio spectrum, which is displayed to the user. The user can define and modify band depth thresholds and slope parameters which are then plotted on the traverse map. Figure 5 shows two implementations of this data, both on a traditional 2D interface (5A), and on a VR-based 3D interface (5B, 5C)

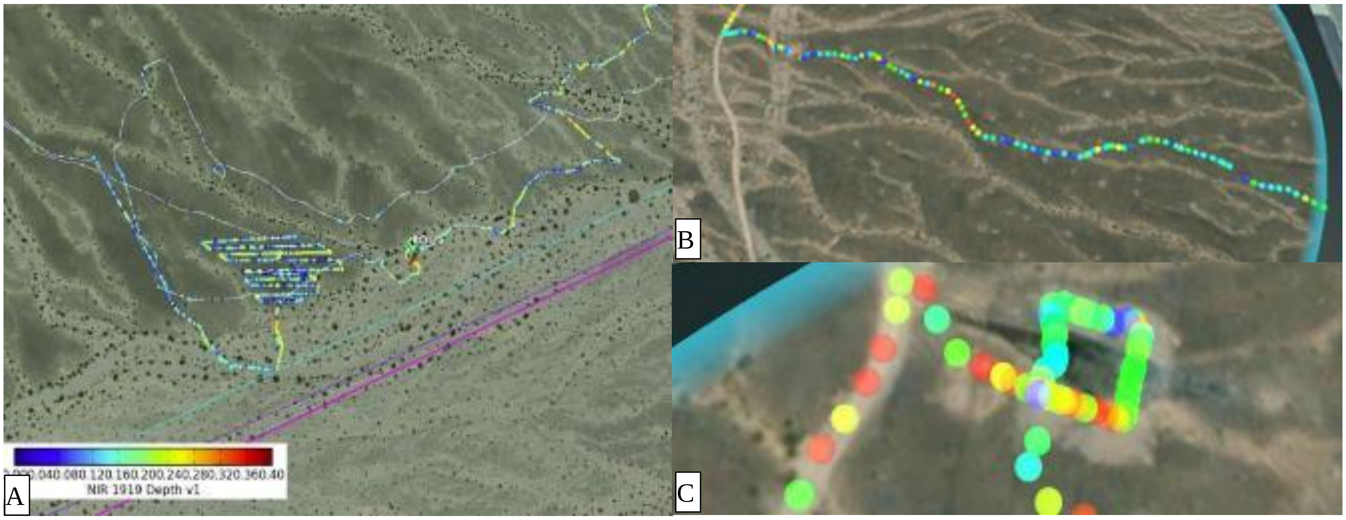

Figure 5. Comparison of MVP traverse data when displayed on a standard 2D map (A), and when that same data is projected on a 3D virtual map (B, C). Note that the resolution limit is much more apparent in C than in A, as interactivity such as zooming / tilting is much more intuitive in VR maps, and smooth regions do not show as much nuance as very dramatic changes in geography, such as the mountain in figure 1.

B. Neutron Spectrometry System

The NSS instrument is used to gauge volumetric hydration content as well as variations in elemental composition of a target surface. Neutron detection is a valuable hydration-finding tool through the way galactic cosmic rays (GCRs) interact with surface regolith. Particularly, interactions between GCRs and regolith particles frees neutrons from the component elements of the soil, which are then moderated through interaction with hydrogen atoms. Neutron flux measurements are related to surface hydrogen content, and therefore water presence can be found.[21]

C. Field Site Replication

Field site data will first be used to create a multi-channel immersive 3D reconstruction of the site. The field site will be characterized with data mapping several key geological markers. These maps will be updated with photogrammetry, and this imagery will be used to create high resolution texture maps of the environment. The 3D models generated from the precursor data will then be rendered in the multi-user virtual environment and displayed to allow a user to see the field with field site-like fidelity. Multiple users will be able to virtually visit the field site, collaborate, and annotate the environment. Using augmented reality devices to interact with the virtual platform (Figures 3, 4) users may also virtually "co-locate" during operations either in a conference room analogue or a flyover of the field site reconstruction (Figure 6). This will allow a direct comparison to traditional field operations; particularly in establishing what relevance the enhanced data processing and planning capabilities have to scientific goals, and to what extent high utilization of the digital environment increases task performance, and task completion. The two view types in figure 6 highlight two separate planning regimes, a sub-scale overview mode (Fig. 6A) for traverse planning, annotation, monitoring of surface operations, and broad-area data overlays; and a real-scale flythrough mode (Fig. 6B) for environmental previews, high-definition science analysis, and annotation / caching of waypoint data. The second view would be a deeply immersive perspective that makes use of continuous imagery from surface imagery and streaming instrument data.

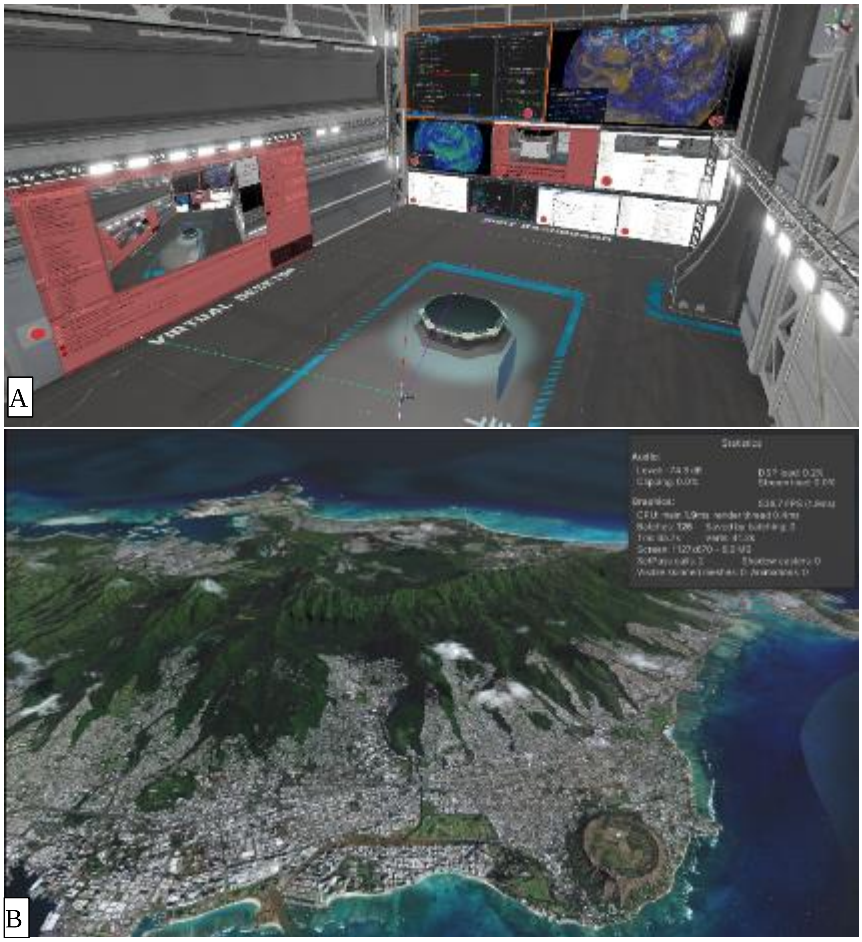

Figure 6. User Views within vMSS. (A) "Hangar" view with several static 2D interfaces and central 3D spatial console interfaces (B) "Flyover" view, where target region is recreated at full scale, allowing users to become deeply immersed in the environment

D. Tools and Interactivity

To compliment the two viewing modalities, a suite of prototypical user tools has been developed for functional user testing. These tools are all organized into a "hand toolkit" menu system that is always synchronized with the user's hand and is easily accessible.

The selector tool (7A) is the primary interactive tool for users in the virtual space, functioning as a pointer, a course, and an interaction tool. This tool acts as an extension of the user's hand allowing them to interact with an object, such as a button or a loaded model) from significant distances.

The laser tool (7B) is a communication support tool that mirrors real-world laser pointers. Functioning similarly to the selector tool, it can be used to point at any part of the vMSS environment or any virtual objects. The laser tool is visible to all other users and is ray casted in the environment to synchronize the laser point at the appropriate target for all users.

The 3D draw tool (7C) is a marking tool that allows for annotating the virtual environment at any location. Users can draw arrows, paths, and even link together different virtual elements, or erase segments of their drawings. This is largely meant for broader, less precise annotation between collaborators to communicate concepts quickly.

The last tool is the Paint tool (7D), which is partially analogous to the 3D draw tool as a texturing and highlighting annotation tool. The paint tool acts much like a paint spray, and projects a 2D texture modification when used in 3D space. These four tools can all be used synergistically together, and future work will investigate user performance with these tools in a variety of use scenarios.

IV. Path for Future Operational Development and Testing

The vMSS software as a technology demonstrator will help both scientists and mission operators understand and adapt to the new possibilities of mission control structure, and reactive decision making / mission planning. There are several stages to the fully integrated end-goal.

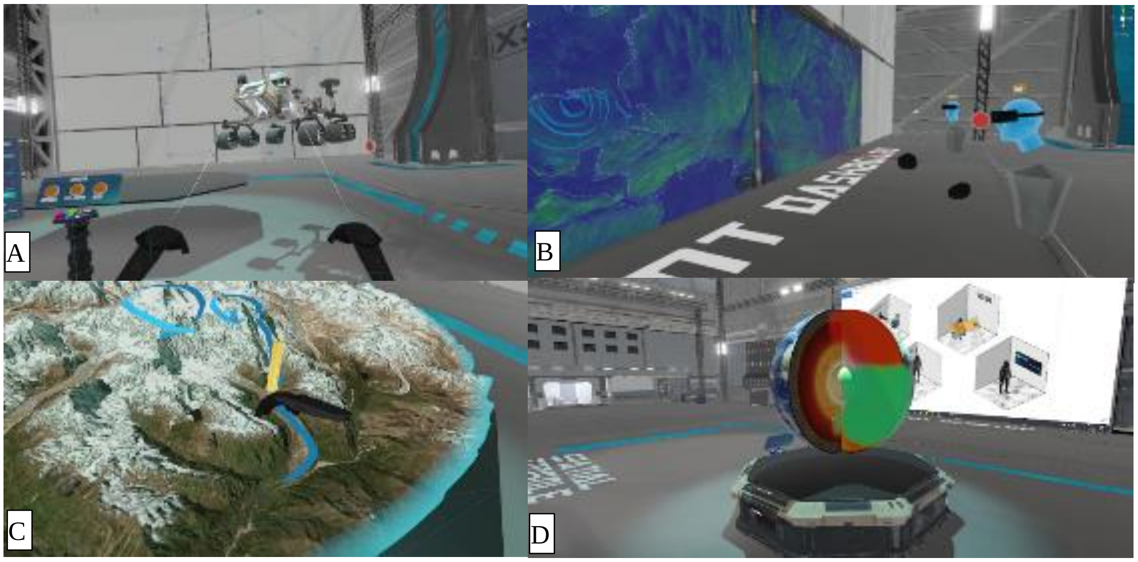

Figure 7. Prototypical VR interactivity tools. (A) selector tool, (B) laser tool, (C) 3D draw tool, (D) Paint tool

A. VMSS Development

Utilizing several available lunar datasets, and building a highly extensible data system into the vMSS platform, the additional capabilities to be added are:

- Develop lunar polar coordinate system
- Integrate orbital altimetry into the mapping utility
- Integrate local surface mapping data into the map display utility
- Integrate wider array of surface spectral data capabilities
- Expand toolkit from user testing and integration
- Add geo-correlative capabilities to edited and annotated datasets

B. VR platform user testing

Early assessments of the VR mission control platform will be performed with both experts (NASA science team and mission control staff) as well as non-experts to evaluate cognitive load, analytical bandwidth, and communication efficiency. These tests will use implemented and simulated imagery / data from available data sets, and user interface specific changes. A focus area for these tests will be on both application-specific visualizations and interactivity. The vMSS system is currently capable of operating on any OpenVR-capable VR system,[22] as well as the Oculus Quest 2 standalone VR system. Both systems are largely similar in the design and functionality of the overall interface, but usability tasks are critical in maximizing utility of the system for data display and data analysis, as demonstrated in Figure 5. In this example, infrared data from the Mojave Volatiles Prospector campaign (MVP)[23,24] is brought into vMSS as a proof-of-concept for display of traverse data, and a high-level discovery of critical features of functions for data visualization in VR. Our results from early concept testing show that data collection regime / apparent resolution is extremely important to the efficacy of the display, as some implementations are no more useful or could even be *less* useful if not properly implemented (such as in Figure 5.C), where data overlap is denser than the resolution of the display itself.

C. Mission simulation and Rover Testing

While the development is geared toward a VIPER-like rover mission, with similar instruments and using datasets from previous analog research campaigns, the system is meant to be mission-agnostic with some degree of customization for each mission. Other missions such as the Commercial Lunar Payload Services (CLPS), and Artemis programs will each involve the same kind of mission planning, data analysis, and flexible operations that vMSS is constructed for. Therefore, vMSS will be developed in a mission-agnostic manner, to allow for direct implementation into any near-term mission type that utilizes 3D altimetry and surface experiment data products.

The rover testing will undergo two stages of development: (a) low fidelity laboratory environment, and (b) high fidelity field testing with a hypermobile roving platform. This phase of development is primarily focused on the overall end-to-end integration of software features, while also identifying any problem areas / inefficiencies in the design that serve as obstacles to the final goal of enhancing science products. The first stage will prove the baseline platform viable, while the second stage is an investigation on optimization for the system as a functional whole – focusing on situational awareness, decision-making, and in-situ data analysis by experts.

First, we will construct a mock roving vehicle outfitted with a suite of sensor hardware, including a LiDAR sensor, Stereo/RGB-D cameras, Near-IR sensors, and other multispectral sensing equipment. We will capture data in a controlled lab environment by driving the rover along a planned path and then import and integrate the captured data into vMSS for multi-user VR science and analysis tasks. Ideally, we will create an RGB mesh using the captured LIDAR point cloud and images from the RGB-D cameras. Once this 3D terrain/environment mesh is imported into vMSS, we will create a system for viewing, manipulating, and augmenting the imported mesh in VR.

This system will allow for overall mission performance evaluation as well as task performance metrics for individual users. Those performance metrics will include total interest regions identified, total mapped area, and identification efficacy for mission metrics, and time to complete task, task performance and accuracy of completing manual tasks like tasks such as path planning, object and obstacle identification, and hazard analysis.

V. Conclusion

There are several key aspects of mission control and mission operations that can be enhanced through utilization of a virtual environment: task performance, task load, scientific goals, mission flexibility, and mission extensibility. The vMSS platform has presented broad opportunity for tool development and decision support frameworks to support Earth-based Mission Control Center operations. Preliminary tools are able to be integrated into collaborative workflows, and interactivity with 3D datasets is intuitive and naturalistic. Direct progress will be made toward advanced virtual command and control systems, as well as collaborative automation in a functional field environment. These capabilities are critical for near-future lunar exploration missions that involve substantial human and robotics teams, with special considerations and design decisions necessary for emergent utility to arise from the utilization of virtual tools. Additionally, the vMSS platform is well suited for direct implementation of AR into mission workflows, extending the capability from VR-only to a hybrid digital interface that gives significant gains to situational awareness, collaboration, and mission assurance.

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References

1. Watts, J. C., Woods, D. D. & Patterson, E. S. Functionally distributed coordination during anomaly response in space shuttle mission control. *Proc. Annu. Symp. Hum. Interact. with Complex Syst. HICS* 68–75 (1996) doi:10.1109/huics.1996.549494.
2. Bell, E. R. *et al.* Mission control team structure and operational lessons learned from the 2009 and 2010 NASA desert RATS simulated lunar exploration field tests. *Acta Astronaut.* **90**, 215–223 (2013).
3. Anandapadmanaban, E. *et al. Holo-SEXTANT: An augmented reality planetary EVA navigation interface*. *Proceedings of the 48th International Conference on Environmental Systems* (2018).
4. Sheridan, T. B. *Space Teleoperation Through Time Delay: Review and Prognosis*. *IEEE TRANSACTIONS ON ROBOTICS AND AUTOMATION* vol. 9 (1993).
5. Currie, N. J. & Peacock, B. *International Space Station Robotic Systems Operations - a Human Factors Perspective*. *Proceedings of the Human Factors and Ergonomics Society Annual Meeting* vol. 46 (2002).
6. Peñín, L. F., Matsumoto, K. & Wakabayashi, S. *Force reflection for ground control of space robots*. *IEEE Robotics and Automation Magazine* vol. 7 (2000).
7. Malone, T. B. & Permenter, K. E. *HUMAN FACTORS ISSUES IN TELEROBOTIC SYSTEMS FOR SPACE STATION FREEDOM SERVICING*.

8. Liu, A. M., Oman, C. M., Galvan, R. & Natapoff, A. Predicting space telerobotic operator training performance from human spatial ability assessment. *Acta Astronaut.* **92**, 38–47 (2013).
9. Anandapadmanaban, E. vMCC: A Virtual Reality Framework for Augmenting Mission Control Operations. (Massachusetts Institute of Technology, 2020).
10. Beaton, K. H. *et al.* Mission enhancing capabilities for science-driven exploration extravehicular activity derived from the NASA BASALT research program. *Planet. Space Sci.* 105003 (2020) doi:10.1016/j.pss.2020.105003.
11. Heldmann, J. L. *et al.* Real-time science operations to support a lunar polar volatiles rover mission. *Adv. Sp. Res.* **55**, 2427–2437 (2015).
12. Dasgupta, A., Arendt, D. L., Franklin, L. R., Wong, P. C. & Cook, K. A. Human factors in streaming data analysis: Challenges and opportunities for information visualization. *Comput. Graph. Forum* **37**, 254–272 (2018).
13. Hayes, B. & Shah, J. A. Improving Robot Controller Transparency Through Autonomous Policy Explanation. doi:10.1145/2909824.3020233.
14. Stotko, P. *et al.* A VR System for Immersive Teleoperation and Live Exploration with a Mobile Robot. *IEEE Int. Conf. Intell. Robot. Syst.* 3630–3637 (2019) doi:10.1109/IROS40897.2019.8968598.
15. Lim, D. S. S. *et al.* The BASALT Research Program: Designing and Developing Mission Elements in Support of Human Scientific Exploration of Mars. *Astrobiology* **19**, 245–259 (2019).
16. Berg, L. P. & Vance, J. M. Industry use of virtual reality in product design and manufacturing: a survey. *Virtual Real.* **21**, 1–17 (2017).
17. Hettinger, L. J. & Riccio, G. E. Visually Induced Motion Sickness in Virtual Environments. *Presence Teleoperators Virtual Environ.* **1**, 306–310 (1992).
18. Atkinson, R. C. & Shiffrin, R. M. Human memory: a proposed system and its control processes. *K. W. Spence J. T. Spence (Eds.), Psychol. Learn. Motiv.* **2**, 89–195 (1968).
19. Deans, M. *et al.* A Preliminary Examination of Science Backroom Roles and Activities for Robotic Lunar Surface Science. 7–8 (2008).
20. Elphic, R. C. *et al.* Neutron Spectrometer Prospecting During the Mojave Volatiles Project Analog Field Test. *Science (80-.).* **330**, 463–468 (2010).
21. Siegler, M. A. & Paige, D. A. Subsurface Ice Stability on the Moon. in *Lunar Polar Volatiles 2018 (LPI Contribution No. 2087)* (2018).
22. Wang, W., Suga, Y., Iwata, H. & Sugano, S. OpenVR: A software tool contributes to research of robotics. in *2011 IEEE/SICE International Symposium on System Integration, SII 2011* 1043–1048 (2011). doi:10.1109/SII.2011.6147593.
23. Roush, L. *et al. Attempt of Serendipitous Science During the Mojave Volatile Prospector field Expedition*.
24. Heldmann, J. L. *et al.* Mojave volatiles prospector (MVP): Science and operations results from a lunar polar rover analog field campaign. *Nasa.Gov* **94035**, (2015).