MIXED REALITY TECHNOLOGIES

Supporting

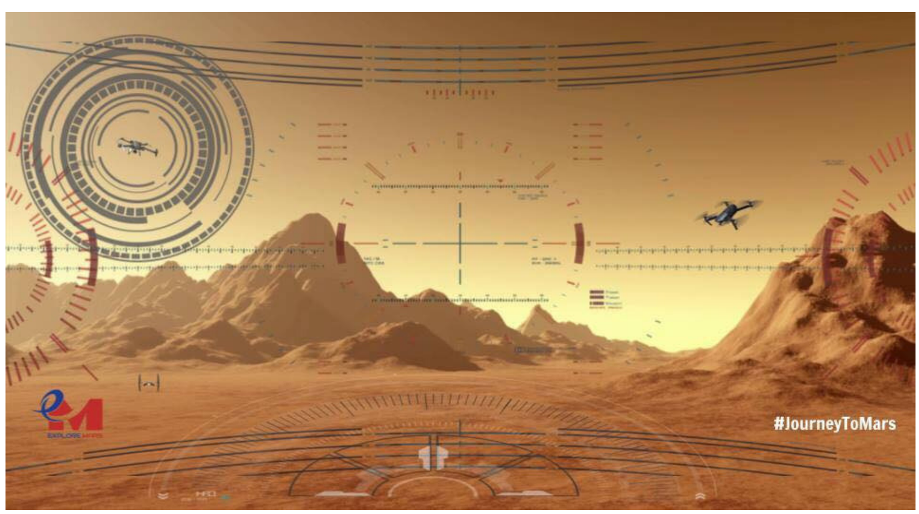
SPACE EXPLORATION

Explore Mars, Inc.'s Mixed Reality Workshop White Paper

INTRODUCTION

In December 2017, a workshop sponsored by Explore Mars, Inc. was held in Washington, DC to discuss the technological needs of a future Mars mission and potential applications of Virtual Reality (VR) and Augmented Reality (AR), hereafter referred to as Mixed Reality (MR). The interdisciplinary group included experts from the government, for profit, and non-profit sectors and spanned the domains of space mission architecture design, technologists, industry strategists, science management, and a retired astronaut.

The list of potential stakeholders at the intersection of space and MR is wide ranging, and includes government and policy makers, future crew members, the aerospace industry, field science teams, organizations providing MR content, platform, and hardware, entertainment and gaming, robotics and habitat designers and developers, STEAM educators, and citizen scientists. This white paper summarizes discussions during the workshop, describing key areas in which MR technologies are currently used, and provides recommendations for next steps.



OPERATIONS AND TRAINING

MR systems are currently employed in various operations and training activities, and have the potential for increasing their beneficial reach. The wide range of stakeholders include crew, mission controllers, designers and engineers, managers, scientists, media, and even the general public. Several example scenarios are described below.

Pre-flight Crew Training

MR training provides a complement to physical analog simulations. The cost and complexity of building, operating, and maintaining physical mockups, and of transporting astronauts and support staff to environments that simulate other planetary environments, can be significant. As an example, NASA currently maintains a 6.2 million gallon Neutral Buoyancy Lab containing mockups of International Space Station (ISS) modules and other vehicles. Separately, NASA also maintains a full-scale mockup of the ISS interior. Crew members, support personnel, and equipment are also transported to remote locations that approximate the geology, environment, resource scarcity, communications delays and remoteness of the Moon or Mars. In contrast to physical mockups, virtual analogs enable on-demand collaboration, referencing, and training. For example, NASA's Virtual Reality Lab (VRL) located at Johnson Space Center has been providing training for Extra Vehicular Activities (EVAs) since before the completion of the International Space Station (ISS) in VR using the Dynamic OnBoard Ubiquitous Graphic (DOUG). The same group also introduced training for the Simplified Aid for EVA Rescue (SAFER) jetpack, currently deployed as pre- and in- flight refresher training.

Mission Controller Training

Integrated training, involving full or partial teams of mission controllers, is essential to effective mission operations. Currently such training requires controllers to have access to a physical mission control room, either an operational one or one dedicated for training. VR/AR is not currently used for mission controllers, but it could reduce or eliminate the need for dedicated training spaces and increase opportunities for integrated training of geographically dispersed teams in a virtual control room. Such MR environments could also be used for articulating requirements for control interfaces, and for spatial markup of details to be modified or transmitted from Mission Control to the crew for use.

OPERATIONS AND TRAINING

In-flight Crew Training

During the Space Shuttle program, a laptop computer-based simulation was used to provide refresher training for commander and pilot astronauts for the dynamic and critical approach and landing phase. For comparison, orbital missions lasted two weeks, whereas future Mars missions will have a duration spanning several years; thus, in-flight refresher training will likely be critical. Although the Mars landing itself is an obvious candidate for such training, astronauts are also likely to lose proficiency with less dynamic and more routine activities such as in-flight maintenance and science tasks to be performed on arrival.

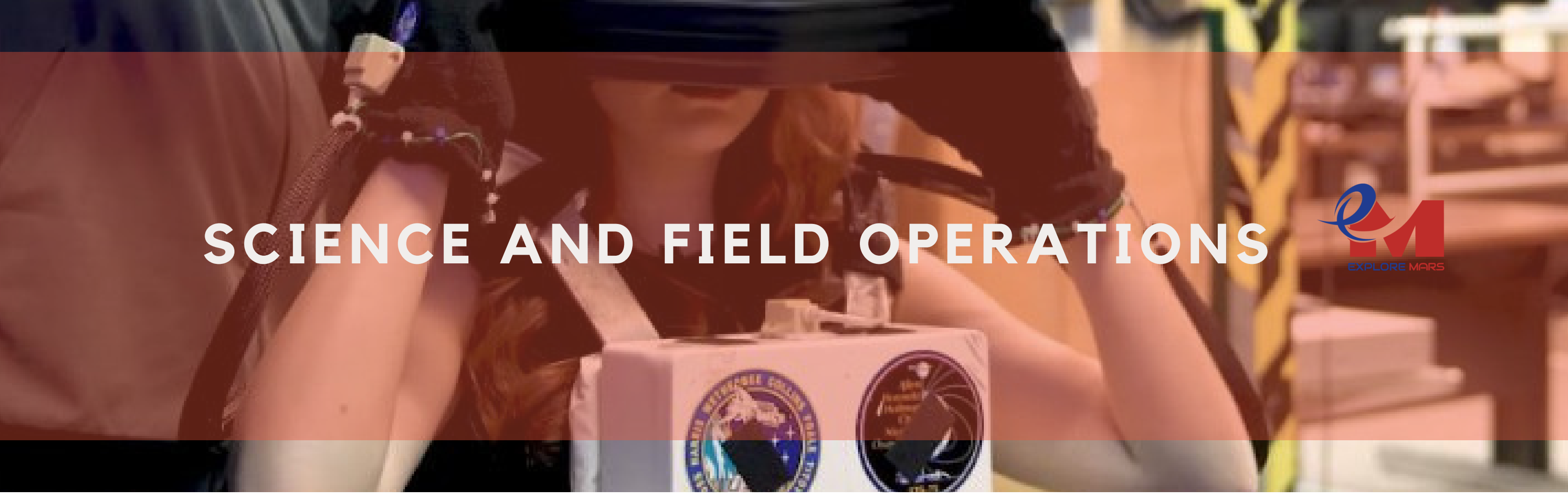
In-flight Crew Support

VR/AR may be able to provide not only advanced training, but real-time guidance in performing these activities such as cognitive aides and virtual assistants. Beyond simply providing instructions, VR/AR might be used to help prevent cognitive overload by focusing astronauts' attention on critical information or even actively suppressing distractions, so-called "diminished reality". Such support could provide the crew with improved autonomy, enhancing safety and reducing frustration caused by communications delay with mission control support teams.

OPERATIONS AND TRAINING

Ground based Support

For Mission Controllers, VR/AR could dramatically enhance situation awareness of the crews in flight. Rather than depending on verbal descriptions, two dimensional photos, or physical mockups, a controller using VR could be immersed in a virtual representation of the crew member’s environment for enhanced spatial situational awareness. Although the latency for a Mars mission makes these interactions impossible in real time, the length of a potential mission means that insights on crew experience may be useful to controllers planning upcoming activities even if reception is delayed by hours or days.

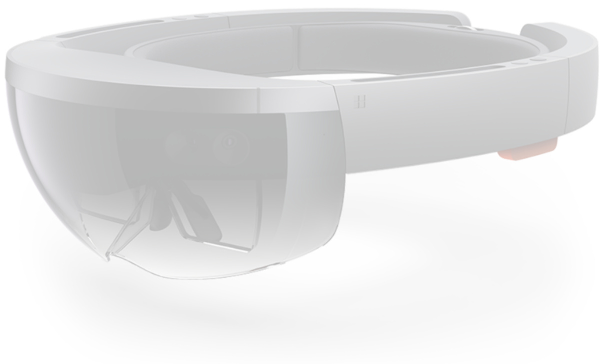


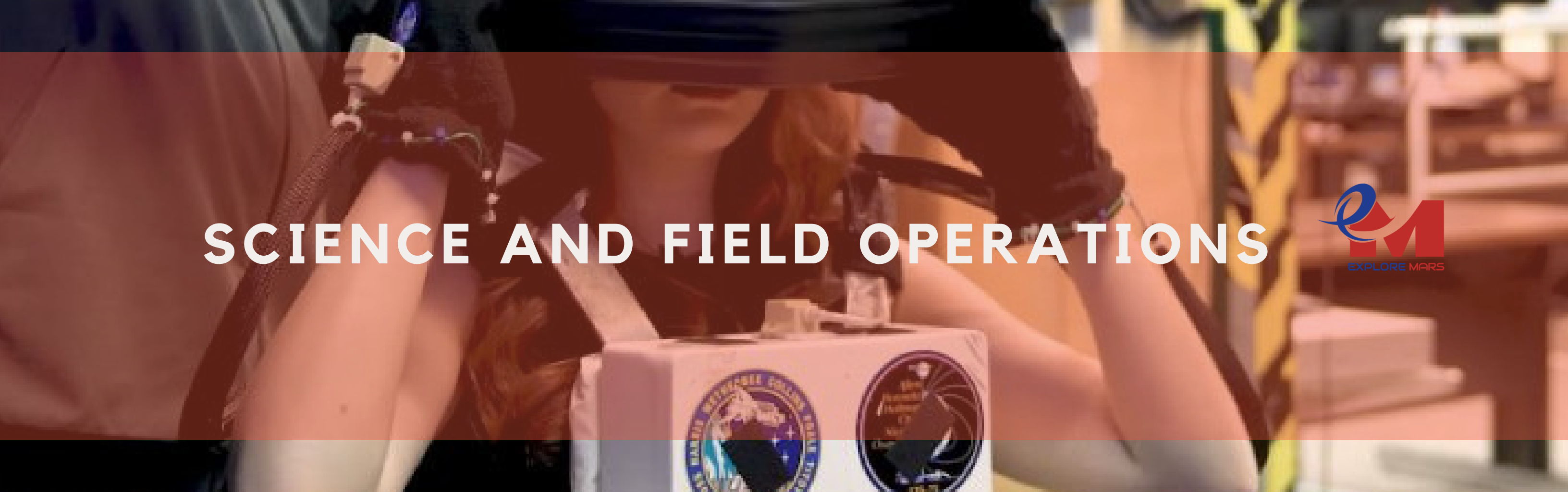
SCIENCE AND FIELD OPERATIONS

MR tools enable scientists and crew members to immerse themselves in the data sets for science field operations training, planning, analyses, and operations. The scope of applications for the use of VR and AR ranges from current scientific investigations and missions to how a Mars mission crew and remote science teams can use these technologies throughout the mission lifecycle.
Examples of the benefits of integrating MR into the science and field operations of a human mission to Mars include:

- Familiarization with the landing site;
- Planning science investigations for EVAs;
- Training and repetitive practice on procedures for instruments and complex sampling techniques;
- Intra-EVA decision support;
- Documenting and archiving EVAs through video and geolocation;
- Recall of field sites and lab work visited or conducted by current or past crews; correlation of data models captured in the field with existing datasets; and,
- Analysis of data on transit back to Earth.

Multiple NASA centers and missions are integrating VR and AR in a variety of ways to help with science planning, science operations, and data analysis, including the following:

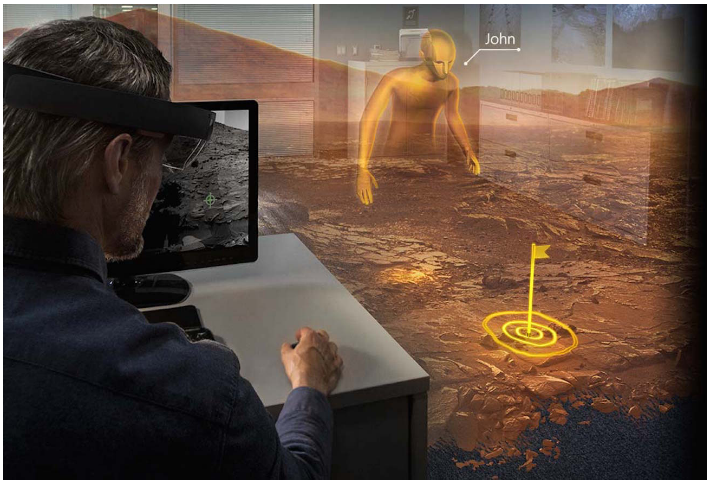




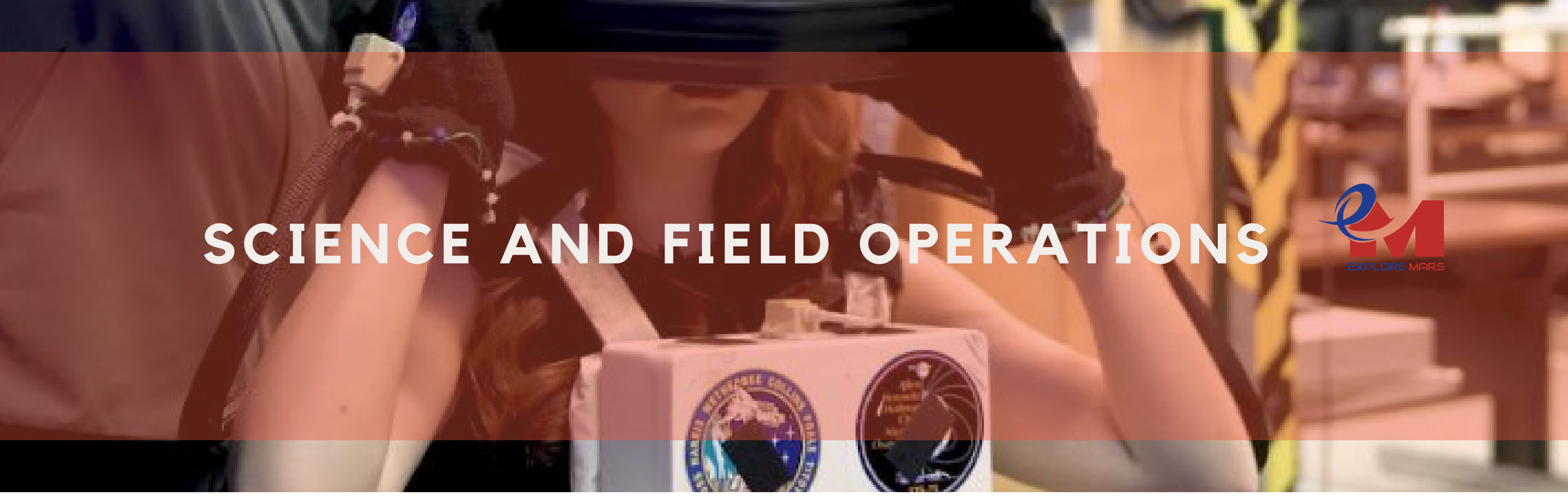
SCIENCE AND FIELD OPERATIONS

Science planning with AR

NASA Jet Propulsion Laboratory (JPL)'s OnSight Team (Team Lead: Victor Luo) uses AR for science planning on NASA's Mars Science Laboratory (MSL) mission. Panoramic images taken by the Curiosity rover at individual stations are rendered into a 3D landscape for use on the Microsoft Hololens. MSL Science Team members can work remotely, but still collaborate with each other and move freely around the same station AR scene of Mars to share observations, mark points of interest, and talk through science plans for that site. A scale model of MSL and the traverse path are added for context.



The NASA's Biologic Analog Science Associated with Lava Terrains (BASALT) team (PI: Dr. Darlene Lim, Bay Area Environmental Research Institute/NASA ARC) and the JPL OnSight team tested AR using the Microsoft Hololens to enable scientific decision-making both in the Inter- and Intra- EVA phases of their science-driven Mars analog mission. This field test took place on Kīlauea volcano, Hawaiʻi in November 2017.



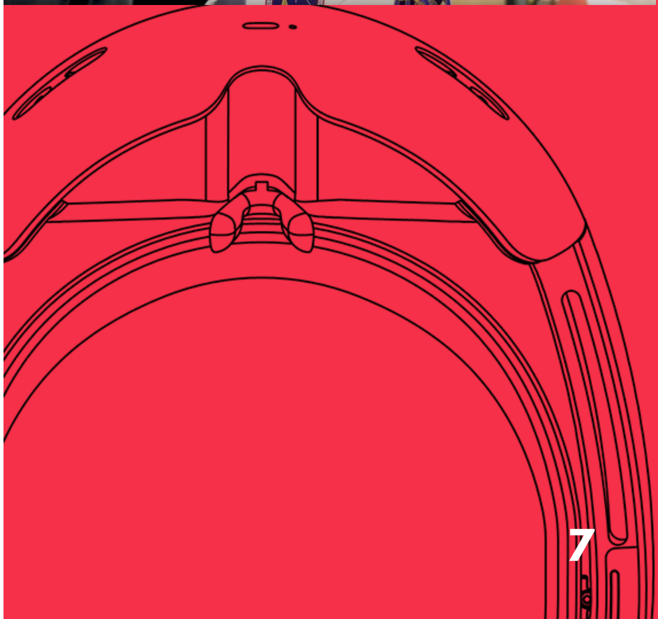
SCIENCE AND FIELD OPERATIONS

Science Operations with VR/AR

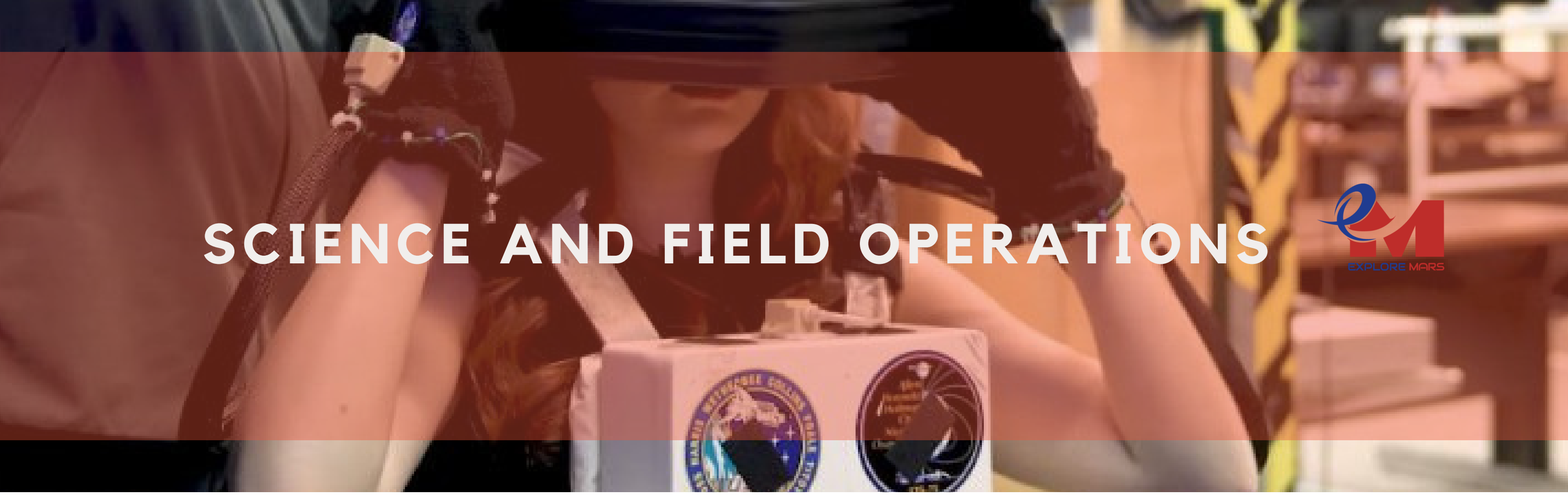
NASA JSC's Hybrid Reality and Advanced Operational Concepts Lab (Team Lead: Frank Delgado) creates VR environments that blend with and allow interaction with the surrounding physical world. For example, when the user reaches out and grabs a handlebar in VR International Space Station they also grab onto an actual handlebar in the physical world matched to that same location. The hybrid/mixed reality concept also applies to working with tools and instruments where the user can hold a drill in VR and at the same time be gripping an actual drill or mockup of the tool in their hand. The team has also used VR on JSC's Active Response Gravity Offload System (ARGOS) which can simulate the user operating on the Moon, Mars, or in microgravity. The system has been used to support the tasks evaluations and scientific studies of the impact of microgravity on human balance.

The Scientific Hybrid Reality Environments (SHyRE)

Project (PI: Dr. Kelsey Young, NASA GSFC) is funded by NASA Science Mission Directorate (SMD) to create a hybrid reality environment of a remote field location in Hawaiʻi. The objective is to test science operations concepts and science data integration into a realistic looking and interactive remote landscape with high scientific fidelity.

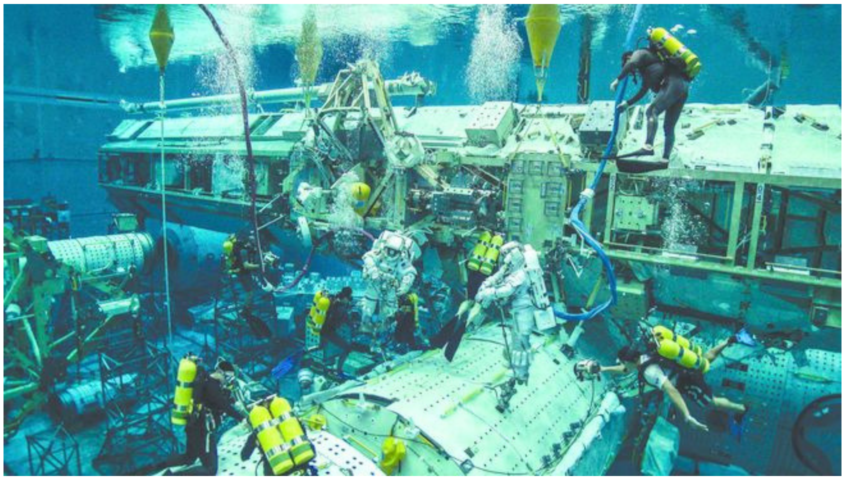


The NASA Extreme Environment Mission Operations (NEEMO) project (Mission Director: Marcum Reagan, NASA JSC) conducts a series of integrated analog tests to evaluate the science operations requirements and procedures, technology needs, and possible mission architectures for future planetary exploration. The Aquarius habitat, the world's only operational undersea research facility, is located off the Florida Keys and enables crews of up to six to live underwater for days/weeks at a time.



SCIENCE AND FIELD OPERATIONS

The last two missions (NEEMO 21 and 22) have used AR during EVA operations by equipping IV (intravehicular) crew members with Microsoft Hololens units. The IV crew can assist with procedure execution and communication with science support teams as well as maintain situational awareness over the EV crew's location through monitoring their real-time video feeds using AR.



Science Analysis with VR

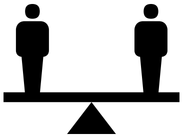
The Goddard Space Flight Center (GSFC) VR/AR group (PI: Tom Grubb, NASA GSFC) has developed several pilot projects, including their LandscapesVR project for analysis of terrain data in VR. Scientists can import digital terrain models (raster files, GeoTiffs) derived from photogrammetry and pointclouds collected by lidar (airborne, ground-based) to explore and evaluate complex spatial terrains from remote locations and views not obtainable on a 2D screen.

Analog Site Analysis and Field Site Design

Teams from NASA-Ames Research Center (ARC) conducting field tests for Atacama Rover Astrobiology and Drilling Studies (ARADS) in the Atacama Desert in Chile and at Haughton Crater in Canada's high Arctic have used a variety of 3D mapping and imagery techniques to document site conditions and terrain, including drone surveys, 360-degree imaging, stereo video capture and depth mapping to generate photogrammetric inputs and point clouds for site models in development.

HUMAN FACTORS & BEHAVIORAL HEALTH

Human factors and behavioral health include the impact of sex/gender, age, culture, and demographics on ergonomics and human machine interactions, as well as individual and team behavioral health and task performance. Although human factors and behavioral health for mission support is also an important consideration, we focused on the crew as the key persona to limit the scope of this topic. Machines include onboard physical systems, software, and robotics.



Ergonomics and Fit Testing

Human simulations have been used extensively to evaluate anthropometry and biomechanics within confined spaces (see standard NASA-STD-3000). Customizations of human models for different height and body shapes can be used to inform physical designs of equipment for feasibility and ease of maintenance tasks as well as spacecraft interiors. Traditional 3D modelling tools used in architecture have begun to incorporate Commercial Off the Shelf (COTS) VR devices for enhanced visualization capabilities, and can be leveraged for design of habitable spaces.

HUMAN FACTORS & BEHAVIORAL HEALTH

Behavioral Health

A substantial amount of prior work exists within NASA's Human Research Program that can inform the application of MR to support crew health and performance. While the topics above focus on training and augmenting task performance, NASA has also funded research efforts to examine MR for psychological wellness. Social VR has existed in the commercial world since 2003 in the form of Linden Lab's Second Life, and has been used for gaming as well as social support for those coping with chronic diseases or other life circumstances. Considering the unprecedented duration and isolation of future long duration missions, behavioral health may pose as a critical risk, and VR has also investigated as a countermeasure for sensory and social monotony for long duration isolation missions.

In a project named ANSIBLE (A Network of Social Interactions for Bilateral Life Enhancement) (Subcontractor: SIFT, LLC), researchers created a persistent virtual world which enabled human-human and human-virtual agent communications while accommodating for delayed communications. They tested the system with a team of six crew members at the Hawaii Space Exploration Analog and Simulation (HI-SEAS) analog during a twelve month experiment in 2015, the longest isolation mission on U.S. soil. Others have evaluated the use of virtual reality experiences and 360 degree spherical photographs as stress reduction intervention. Outside the space exploration domain, VR provides training in "soft skills" such as negotiation and conflict management. AR has also been used for for biometric feedback and data-enabled mindfulness and self-management.

COLLABORATION

WITH PRIVATE SECTOR, GOVERNMENT AGENCIES, AND INTERNATIONAL PARTNERS

Interoperability

The Simulations Interoperability Standards Organization (SISO) has been the key driver of standards for interoperability since 1996. The non-profit works in close collaboration with key stakeholders in the government, such as Defense Modeling and Simulation Office (DMSCO) and NATO Modeling and Simulations Group (NMSG), as well as universities and private industry. In 2015 an initial paper was proposed to create a standard for Space Reference Federation Object Model to support interoperability for space simulations, including training, analysis, mission support, and engineering. (https://www.sisostds.org/StandardsActivities/DevelopmentGroups/SRFOMPDGSpaceReferenceFederationObjectModel.aspx).
NASA has been a key driver together with a Swedish company called Pitch Technologies, ESA projects and the Russian space industry. Conversations have started to create a workgroup for virtual reality interoperability.

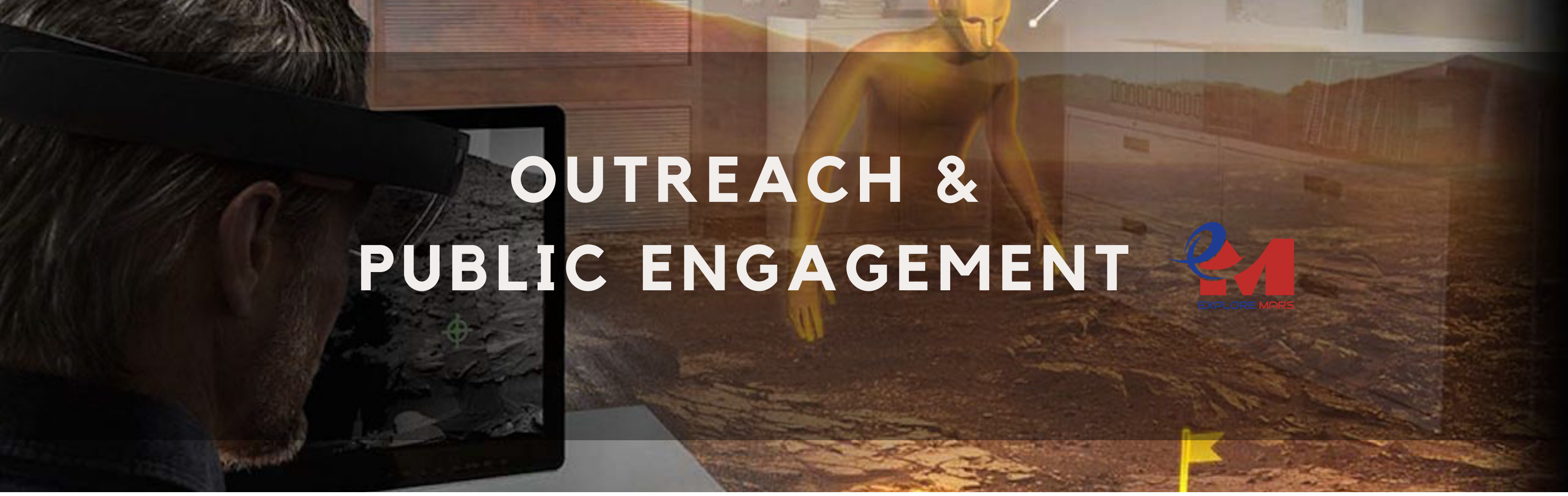
COLLABORATION

WITH PRIVATE SECTOR, GOVERNMENT AGENCIES, AND INTERNATIONAL PARTNERS

Collaboration between VR Industry, other U.S. Government Agencies, and Space Exploration

There are many parallel efforts to facilitate collaboration between the MR industry and space exploration efforts. For example, the Explore Mars hosted workshop that resulted in this white paper included NASA personnel, academia, as well as private industry participants including large and small businesses. Separately, in early 2018, Jim Adams (former deputy CTO NASA) and Marcus Anzengruber met with Rob Ambrose (Chief, Simulations & Robotics, JSC) and Oculus to explore astronaut training at NASA with use of AR and VR.

Furthermore, the U.S. Air Force is in the process of standing up a AR/VR hub for the new pilot training program in Austin, TX. The planning and organization is underway for day long cross-disciplinary workshops and colloquia to enable introductions, familiarize stakeholders with new initiatives and existing work, and establish priorities for future collaborative developments. The goal of these efforts is to increase awareness of space related training and operational needs among non-traditional stakeholders and facilitate dual use.



OUTREACH & PUBLIC ENGAGEMENT

Outreach and Public Engagement

This topic includes the use of MR technologies to reach the broadest audiences, including scientists, citizen scientists, educators, STEM specialists, space enthusiasts, and youth, among others.

Recent activities include JPL NASA's Mars2030 (Project Lead: Julian Reyes), Lockheed Martin's Mars Bus, Hewlett Packard's Mars Home Planet, HTC Vive's Destination Mars Surface, Mars City Design's MR Workshop and several other MR projects.

With rovers providing data including photos from Mars, VR creators and space enthusiasts alike are anxious to utilize the data, but creators often find data conversion challenging. Open source data and software can reduce the technical barriers for continued development of non-scientific experiences from NASA, the aerospace industry, and independent producers to sustain and grow public engagement.

CONCLUSION & RECOMMENDATION

Advances Needed

Work will be needed in several areas to make the use of VR/AR feasible for operations and training. VR/AR systems must be made suitable for space missions, e.g. testing and adaptation as needed for the microgravity environment, minimizing weight and maximizing safety, mobility and reliability. As with other technologies, “space-rating” validation is likely to increase costs. Developing a wide range of space mission applications and thus driving a stronger demand for such systems may help to keep costs down. Enhancements that reduce mass and increase safety and reliability may be applicable, and thus costs may be shared with other users with “mission critical” applications, such as aviation, the military, or public safety agencies.

A related challenge is the rapid pace of development of VR/AR technology. Any change will require new testing to verify that safety and reliability are maintained. The proliferation of rapidly developing systems has already led to different standards and in the near term it may be challenging to select one that is likely to be prevalent, or even to survive at all.

Space missions, and Mars missions in particular, involve significantly different communications capabilities than terrestrial applications of VR/AR. Wired connections with Gbps throughput or wireless ones with hundreds of Mbps throughput far exceed what would be available between Earth and Mars. While technologies such as laser communications are likely to increase data rates, the Earth-Mars link will presumably always be a choke point and will certainly always impose a latency (delay) of 4-24 minutes one way. Evaluations are needed for data requirements streamlining through onboard models. It will be necessary to characterize minimalist transfer of field data, markups and inquiries between models held concurrently at Mission Control, scientist workspaces and onboard mission vehicles. MR applications will need to adapt to these limitations, presenting a special challenge for space mission MR designers.

CONCLUSION & RECOMMENDATION

Within the larger technology community, MR's development of user-friendly functions will be fundamentally needed for the wide variety of applications, from visualization for science planning, to Just In Time (JIT) training, to analysis of analog and mission data sets, to potential communication tools for collaboration between Earth and Space. Use of 360 and/or stereo cameras may also be useful to record activities including EVAs, enhancing current archival video capabilities for use during or after the mission.

Considering the unprecedented duration of a future Mars mission, the extraordinary operating conditions of a future Mars crew, the lack of real time communications, and the limited crew size, it will be crucial to utilize best practices developed and learned from AR adoption in industrial applications (e.g. manufacturing, mining, and construction). It will be crucial that designs are not a one-size-fits-most solution, but that they are customizable to accommodate individual baseline differences, as well as adaptable as individual crew needs evolve through the duration of the mission.

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