Mixed Reality Interfaces for the Moon and Beyond: Advancing Surface Telerobotic Interfaces in the NASA Artemis Program. M. E. Walker, J. O. Burns, D. J. Szafir. Center for Astrophysics and Space Astronomy, University of Colorado (michael.walker-1@colorado.edu, jack.burns@colorado.edu, daniel.szafir@colorado.edu).

Introduction: NASA's Artemis program embodies the world's desire to return to the lunar surface and marks the beginning of a persistent human presence in our solar system outside of Earth and its orbit. However, to successfully achieve planned mission goals, humans will likely need to turn to the field of robotics to support these human missions to the Moon and beyond. With the recent focus on orbital stations (such as the lunar Gateway), robots will be powerful enablers for not only astronauts on planetary surfaces, but scientists on Earth and astronauts in orbital outposts as well.

Since the advent of Mars exploratory missions with the robotic rovers of Spirit and Opportunity, considerable hardware and software advancements have been made to provide robots with improved capabilities to better explore space's hostile environments. Unfortunately, the interfaces (e.g., the means in which scientists interact with such robots and take advantage of their full set of state-of-the-art features) have not seen the same level of development and technological advancement as the robots themselves. The high-level design of these interfaces has largely remained the same for decades, forcing scientists to view the rich, three-dimensional data returned by exploratory robots on outdated, two-dimensional monitors.

HMD Teleoperation Interfaces: Alternate, novel head-mounted display (HMD) mediums that harness the full dimensionality of our reality are now readily available to consumers and scientists alike. This next generation of HMD-based mixed reality (MR) teleoperation interfaces is currently positioned to reshape robot-mediated space exploration by merging both real and virtual worlds.

While past efforts integrating robotics and HMD displays were hampered by limitations in underlying virtual reality (VR) and augmented reality (AR) technologies (often relying on custom-built HMDs with limited fidelity), recent industry developments are increasing the availability of standardized, consumer-grade ARHMD technology capable of providing rich, intuitive, visual feedback. These advances are providing an opportunity for a new design space: distal robot teleoperation mediated by hands-free HMD interfaces that utilize VR and/or AR technology.

VR HMD Teleoperation Interfaces: In the VR HMD design space, a stereo video pass-through camera can be mounted on a robot (Figure 1) that streams duel video feeds (one for each of the user's eyes) to a remote operator allowing them to see the robot's point-of-view from within a VR HMD. By utilizing the stereoscopic displays built into these headsets, operators are able to see from the robot's perspective with complete depth, unlike that of traditional two-dimensional monitors.

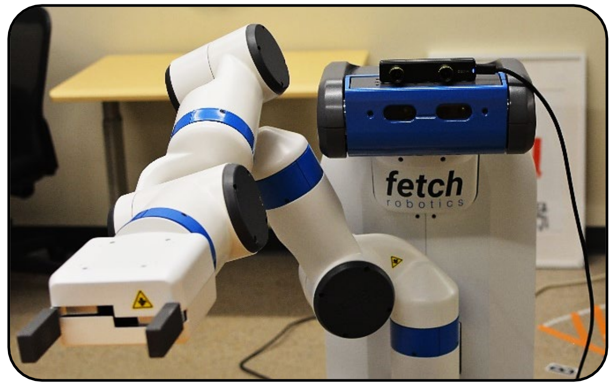

Figure 1: *A Fetch Mobile Manipulator robot with a 7-DOF arm utilized for simulating long-distance teleoperation assembly tasks.*

VR HMD interfaces also separate users from their outside world and fully encloses them within the HMD interface. This immersion bestows upon operators the sensation of embodying the robot and are able to feel as if they're actually looking out of the "eyes" of the robot. Additionally, research has found that the immersion provided by VR HMD robotic interfaces improves situational awareness without increasing the workload of operators, even in the case of multi-agent systems [1].

VR HMD interfaces inherently provide features absent in standard teleoperation interfaces, specifically that of depth perception through stereopsis and improved immersion. Through research, interface designers can learn how to best leverage the inherent benefits VR HMDs have to offer, in the context of robotic space exploration.

Preliminary VR HMD Experiment & Results: To begin our own evaluation of the benefits VR HMD interfaces hold over two-dimensional traditional displays, a preliminary experiment was run. The experiment's objective was to measure and compare operator performance improvements when using a consumer-grade VR HMD interface against a traditional 2D monitor teleoperation interface baseline. The experiment task consisted of various assembly subtasks that one might see in a real lunar assembly mission, such as the deployment of lunar far side radio relays [2] (Figure 2). A 2x1 within-subjects experiment (N=12)

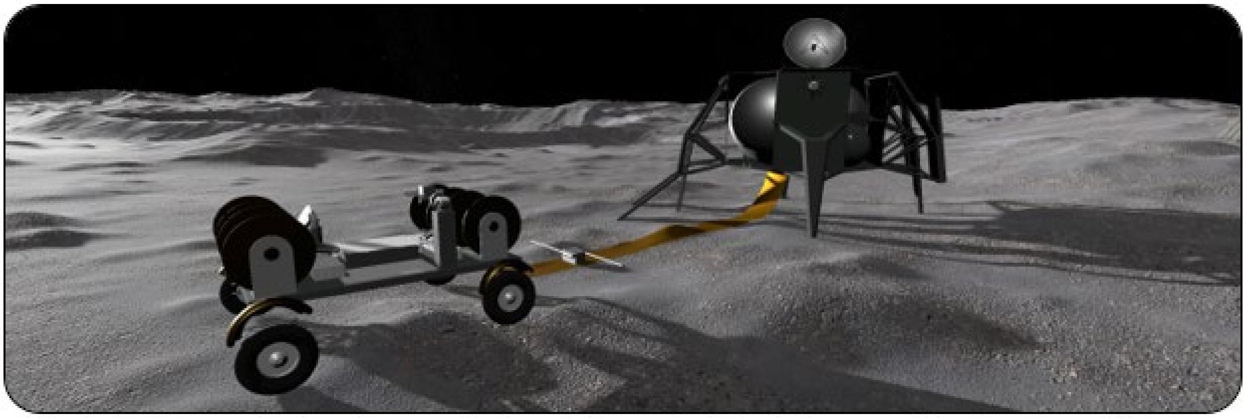

Figure 2: *Use cases for telerobotics on the lunar surface include the deployment of low frequency radio arrays.*

was run, with both interfaces using identical control inputs and found efficiency improvements in precision stacking and sorting subtasks when using the VR HMD interface. In addition, ten of the twelve participants rated the VR HMD condition as the subjectively preferred interface for assembly subtasks.

MR HMD Teleoperation Interfaces: To fully examine the full capabilities that HMD technologies afford; follow-up experiments will examine the impact of more feature-rich MR HMD interface designs in various teleoperation tasks. In these experiments, VR technology, outlined above, will be integrated with AR technology that overlays and anchors virtual imagery to the real world. An interface featuring augmented virtuality such as this [4], could provide additional assistive data to the user, such as navigational assistance or instructional information for assembly tasks.

Multiple additional features are also possible for this type of interface, including: integration of Lidar point clouds that allow the user to "step out" of the robot and physically explore a generated world mesh as well as "seeing-through" the robot when occluding the camera's view; head and hand motion controls for more natural and intuitive control of the robot.

MR Interfaces for the Artemis Program: MR HMD interfaces hold many benefits over our traditional, outdated interfaces on 2D displays. In turn, Artemis should consider a robust surface-to-orbit network infrastructure able to manage the bandwidth requirements of transmitting high resolution sensor data. Studies have shown that humans have a cognitive threshold for perceiving video as occurring in real-time for round-trip latency values of 0.3-0.4 seconds or less [3], which would be possible to achieve if teleoperating surface robots from an orbital platform (such as the lunar Gateway).

Autonomous systems may be improving by the day, but many of which are still untested or at a nascent stage of development. Manual control or close monitoring of these autonomous systems will still be required for: tasks that require low-level manual teleoperation for unexpected, complex tasks; 2) failsafe measures if/when autonomous components fail; and 3) for supervisory or shared control systems. This type of research also compliments space habitats on the Moon and Mars and paves the way for the next generation of human-robot teaming. Allow humans to safely transport their consciousness to dangerous and fascinating places, since robots have the physical capability to explore where humans cannot.

With the development and utilization of advanced teleoperation methods and systems, scientists will be better equipped to leverage the full capabilities of their robots and learn more about both the lunar environment and the early universe without the need of a physical human presence.

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References:

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