Lunar Avatar – a model-mediated 'store-and-forward' approach to telerobotic operations. C. A. Hibbitts[1] and the APL Lunar Avatar Team, [1]JHUAPL, 11100 Johns Hopkins Rd., Laurel, Md. 20723 (Contact: karl.hibbitts@jhuapl.edu)

Introduction: The Lunar Avatar team at the Johns Hopkins Applied Physics Laboratory has over the past year demonstrated the feasibility of model-mediated, 'store-and-forward' telerobotic operation on the surface of Moon. Instead of using images or video for situational awareness, the operator interfaces with the robot through a 3D model [1]. 'Model-mediated' refers to the interface where an operator controls a virtual representation, and that model sends commands to the robot. Then the model is updated based on sensor feedback from the robot (the mediation). The use of an immersive, mixed-realtiy (XR) model in lieu of still images enables the development of a 3D database allowing interaction with the robot latency free (between updates) in an otherwise latent environment. Also, operation is possible in both 1st and 3rd person for improved efficiency in three areas in particular: Operations & Science Backroom; Interacting with and Manipulating the Environment such as through arms; and directing motion (Mobility). A Boston Dynamics Spot quadruped robot and a commercial off-the-shelf (COTS) point cloud sensor provided interface information for an operator using MRET and Unity software packages. A 3-second uplink and 3-second downlink delay simulated latency as if operating the Lunar Avatar from Earth through a relay satellite.

Operations & Science Backroom. The team utilized Spot as if it were an astronaut. The operator communicated with a "CapCom" that also interfaced with a science backroom (Figure 1), typical of operations during Apollo and again used in simulated astronaut operations such as Desert RATS [e.g., 2]. This proven operational structure results in rapid and efficient operations. With the ability to record and review operations in the XR environment, it is also feasible to verify actions as intended before executing. The concurrent development of the database furthermore enables the operator, or 'other astronauts', to immersively explore the lunar surface that has previously been mapped, such as for identifying areas of science and exploration interests to which the Lunar Avatar can be directed again for a more detailed follow-up. These combinations of capabilities lead to increased operational cadence.

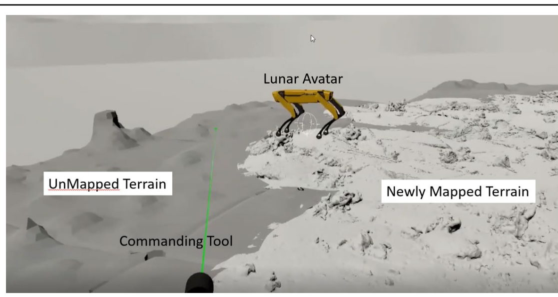

Figure 1. VR headset view of Lunar Avatar Operator.

Mobility & Manipulation of the Environment: We operated Spot in a sandy environment loosely analogous to the lunar surface, demonstrating the ability to direct the robot to a specific location. Spot's on-board low-level autonomy was effective at executing commands in the presence of hazards. Separately, an operator used robotic arms to perform complex tasks such as picking up rocks, rotating them, and positioning a spectrometer to obtain infrared reflectance spectra, all under a comm-delayed environment, demonstrating the value-added of reviewing/playing back the recorded planned motion in the XR environment, for verifying the activity before executing (Figure 2).

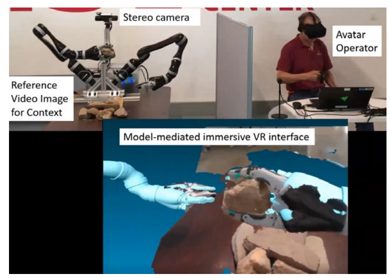

Figure 2. VR model-mediated immersive operation of arms, with a 6-second roundtrip comm latency added.

Summary: The Lunar Avatar project at APL has demonstrated the potential feasibility of model-mediated telerobotic operation of assets on the Moon, controlled from locations where latency would otherwise be prohibitive to telerobotic operations. With further maturation, model-mediated telerobotic operations should be considered as a near-term solution to complex lunar surface operations, enabling such needed capabilities as construction, excavation, and outfitting as well as surface science and exploration.

References: [1] P. Mitra and G. Niemeyer. Intl. J of Robotics Research, 27(2):253-262, 2008.; [2] Bell Jr, E. R., Badillo, et al. (2013). *Acta Astronautica*, *90*(2), 215-223.