ON-ORBIT CONTROL OF LUNAR SURFACE TELEROBOTS FROM EARTH-MOON LAGRANGE POINTS.

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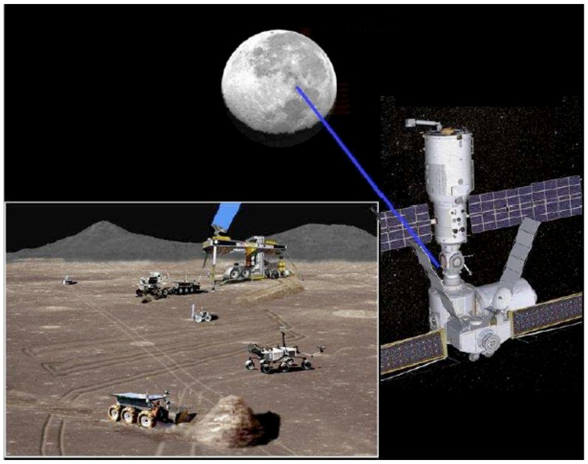
Introduction: We propose a novel approach to operation of future lunar surface telerobots at least as a precursor to return of humans to the lunar surface. This approach builds on current interest in the human space flight community (e.g. HDU/DSH, HEFT, HAT) for a habitat facility at an Earth-Moon Lagrange point (EM L1 or L2), perhaps in the very near-term, and ideally using technologies validated on the International Space Station [1].

The Latency Advantage: These locations, about 50000-60000 km over the near- and far-sides of the Moon, provide light-time two-way control latencies to the lunar surface of order 400 ms, *six times smaller than the control latency from the Earth*. Such small latencies allow for near-telepresence in command and control of surface assets. This allows for a high degree of cognitive coupling with lunar surface activities and likely enables complex tasks that would otherwise require in situ humans [2]. The approach has potential value for lunar science, resource assessment, and site development. In the former case, with an appropriately capable telerobot, an astronaut-scientist at EM L1/2 could do high-productivity field geology without actually being on the surface, where he or she would be operationally limited by a constraining space suit. While some of this work could be done from a Multipurpose Crew Vehicle (MPCV) crew transport, we consider a long-duration habitat as offering more potential for longer-duration exploration sorties by the telerobot.



EM L1 and L2 as Enabling Destinations for Lunar Science: Such an L1/L2 habitat promises many advantages as a base station for science operations on the lunar surface. For projects that require long-distance or long-duration surface operations, such habitats can also be used as depot facilities, with equal opportunity access to and from anywhere on the lunar surface. Many exploration architectures have envisioned EM L1/2 as “high-camps” for human travels to the lunar surface, where reusable landers could be based on-orbit. These locations offer significant advantages for travels outside of cis-lunar space as well. Both because of the “interplanetary superhighway” that connects such solar system Lagrange points with economical trajectories, and the prospect of using lunar ISRU for such deep space travels, EM L1 and L2 have been proposed as jumping off points for voyages to Mars and beyond [3], [4]. These same economical trajectories connect these Earth-Moon Lagrange points with much more distant Earth-Sun Lagrange points that are of increasing value to astronomy and heliophysics. Servicing of science spacecraft that normally operate at those much further locations can thus be achieved at a more convenient job-site in the Earth-Moon system.

Orbital Trades: Orbits around EM L1 and L2 are optimal for such telerobotic control operations. While low lunar orbits offer smaller time delays, those orbits are not highly stable, and even in stability optimized orbits (e.g., for LRO), a habitat would require several hundred m/s of propulsion per year for stationkeeping. In such orbits, target sites would regularly rise and set, such that telerobotic control would be frequently be asynchronous. In both of these respects, EM L1/ L2 orbits provide distinct advantages. Stationkeeping strategies for such orbits require only about 100 m/s/yr propulsion, and much of one entire lunar hemisphere is continuously in the line-of-sight. This would offer telerobotic control to sunlit sites on the lunar surface at all times [5]. The recently successful Artemis mission demonstrates that orbital maintenance at these Lagrange points is straightforward. A habitat at EM L1/2 is in almost continuous sunlight, greatly simplifying power management and, even for EM L2 over the far-side, a halo orbit can assure continuous communication line-of-sight with the Earth. It should be understood that shifting the habitat between EM L1 (for near side access) and L2 (for far-side access) is a relatively low propulsion proposition, as shown with Artemis. Thus, the same habitat could be used for tasks on different sides at different times.

Low Latency Functionality: Controlling a rover that has more dexterous capabilities – and more intuitive user interfaces – than current robotic reconnaissance rover designs, astronauts at EM L1/2 could approach complicated lunar surface tasks with a much higher degree of cognition, awareness, and control than could operators on the Earth. Low-latency teleoperations with cutting-edge technologies could revolutionize our approach to lunar field geology, providing virtual experiences that closely approximate "boots on the ground" field geology while retiring considerable human risk that would normally accompany astronaut sorties. As we invent a new era of planetary field geology that involve coordinated astronaut and robotic activities [6], telepresence could play an important role in the development of sustainable, multi-year research programs on the lunar surface.

Heritage and Extensibility: Terrestrial commercial telerobots are in rapidly increasing use for mining and undersea science, as well as for oil/gas and cable operations. Transcontinental surgery, and military surveillance and munitions (drones) as well. These all use control latencies of a few hundred milliseconds, so on-orbit telerobotic control can take advantage of terrestrial technology investment and operations expertise. On-orbit telerobotic control is also highly extensible, offering huge advantages in latency mitigation to work in other settings, such as Martian moons, asteroids, Mars (e.g. Human Exploration using Real-time Robotic Operations - HERRO [7]), and even at exploration destinations that pose special environmental risks for human exploration (e.g. Venus). Of course, such telerobotic control is also of high value in minimizing the need for EVA for near Earth asteroid visits, and for servicing/depoting/construction projects in the locale of the habitat itself. In many respects, on-orbit control of surface telerobots is not much different from local control of those robots from a surface habitat.

Telerobotic capability has been identified as an important policy mandate, and telepresence capabilities are considered by the agency to be one of several "grand challenges" for space technology [8]. We invite the lunar science community to consider the priority scientific tasks that such on-orbit operations might enable. While human visits to the lunar surface provide optimal opportunities for field geologic research, on-orbit telerobotics may provide attractive alternatives at lower cost and with less human risk in the short term. Telerobotic geology of this sort would be especially valuable precursor activities in advance of human exploration campaigns.

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