Submitted Space Operations Communicator
3-14-14

Putting Human Cognition and Awareness on Other Worlds: A Challenge for Human and Robotic Space Exploration

Dan Lester[1]
University of Texas, Austin TX 78712

The goal of space exploration is here considered as instilling human presence on other worlds. That presence is best achieved by establishing real-time human cognition and dexterity on those worlds, in order to maximize situation awareness and immersion in the local environment. This can obviously be done by putting humans on other worlds, but now, with new sensor, communication, and manipulator technologies, can be done telerobotically by just getting humans nearby, in order to reduce communication latency and optimize bandwidth. We describe on-orbit telerobotics and telepresence as a new approach to human-robot collaboration in space operations that can serve to establish human presence in advance of putting humans on planetary surfaces. The latter involves significant expense and risk. This new approach builds on major terrestrial investment for both commercial and defense applications. While the first tests of on-orbit telerobotics are now being done on the International Space Station (ISS), exercising presence on the Earth, we see lunar surface telerobots controlled from near the Moon as a near-term demonstration of value for deep space exploration. The concept of operations of such telerobotics is summarized here. Once established, the concept can be applied to exploration of Mars from martian orbit, perhaps from Phobos or Deimos, offering a huge advantage compared with Earth-controlled robotics. The strategy is a powerful one, essentially expanding the list of solar system destinations for human presence to include places we would otherwise likely not send people.

I. Introduction

Dramatic advances in telerobotic technologies in the last few decades prompt a new way of looking at space exploration. The historical template for exploration is one where humans travel to distant sites to establish their presence. They manipulate local objects with their fingers, see directly with their eyes, and leave bootprints in the dust. That template is increasingly limited, as our technologies have advanced. Our scientific spacecraft continue to explore the entire solar system, giving us at least pictures of distant locales with remarkable fidelity. But the sense of presence they provide, when controlled from Earth, is seriously limited by the speed of light and communication latency. For the Moon, that two way latency is a modest 2.6 seconds, but for Mars it can be tens of minutes. Such time delays interfere with real human cognition at these locales, and these explorations are therefore done largely autonomously, ideally supervised. An autonomous approach is entirely satisfactory for explorations that can be considered mainly reconnaissance. But for explorations that demand a high level of cognitive involvement, where mission planning is tightly coupled to situation awareness and the local impact of such involvement, such supervised autonomy is constrained by the timescale over which that supervision can be applied. For Curiosity on Mars, we have mobility and, with the robotic arm and end effectors, some degree of dexterity. At best, with "real time" communication, light-time delays would make operation highly non-cognitive. But that rover is, in practice, controlled with roughly daily sensor downloads and command uploads that make it even more challenging to process task management cognitively. The human brain is not built to interact efficiently with the environment over latencies that long.

Our scientific spacecraft and solar system science have evolved with the implicit limitation of communication latency. If we cannot send people there, but rely on telerobotic surrogates to impose human presence, then time delays are the cognitive price that we have to pay if we are going to control them from the Earth. In many respects, this has constrained the way we do solar system science. A good example is field geology, where scientists develop a geological understanding of a locale by being on-site, quickly answering questions posed by observations. How

---

[1] Research Fellow, Department of Astronomy, University of Texas, Department of Astronomy, 2515 Speedway, Stop C1400, Austin, TX 78712-1205

does this sedimentary layer fit with that one? Given that, we need to measure thicknesses and stratification, and it looks like we need to better perhaps inspect the fines on this one layer. That kind of science is very hard to do across long time delays. In fact, the way humans do geology on the Earth is quite different than the way they now do it in space, for exactly this reason. Not only for geology, but for any kind of space development, a sense of real high-quality presence will drive progress. Large latencies offer what can be called a low-quality kind of presence.

Our technological advances have led to telepresence, otherwise known as tele-reach, as being a powerful new tool for space exploration. For relatively nearby objects, such as for satellite servicing in Earth orbit, that tool can be hugely enabling. We can be on Earth controlling surrogates aloft that offer precision multi-joint manipulation, microscopic vision, and even haptic feedback, allowing complex tasks to be completed effectively in real-time. For at least these reasons, space telepresence has been considered a "Grand Challenge" for the National Aeronautics and Space Administration (NASA) by the Office of the Chief Technologist [1]. Now for the Moon, several second latency from the Earth is a noticeable but manageable handicap. For slowly driving around, and getting from here to there, that latency is not highly constraining, as demonstrated by the Lunokhod team forty years ago, and most recently, the Yutu rover with Chang'e-3. Even for seamless conversation with their colleagues back on Earth, the Apollo astronauts found that latency unencumbering.

The concept of space telepresence is hardly new. MIT cognitive scientist Marvin Minsky proposed a space station thirty years ago that was entirely telerobotic, such that research tasks there could be managed entirely by scientists on the ground [2,3]. This proposal never went very far, at least because telerobotic technology was in its infancy, but also because the historical template for exploration did not incentivize doing space exploration without humans in situ. Around this time, physicist Fred Singer, who had a fascination with the Martian moons as possibly being artificial in origin, suggested that they not only be staging posts for trips to the surface of Mars, but also used as control venues for Mars surface telerobots. In what started as a small NASA-funded study, Singer developed a concept for martian on-orbit telerobotics that he espoused at many Mars science and development meetings [4,5]. In many respects, Singer was the first to consider the purpose of human spaceflight as a strategy for telerobotic latency mitigation.

Space telepresence and low latency telerobotics were the subjects of a NASA symposium two years ago at Goddard Space Flight Center (GSFC) -- http://telerobotics.gsfc.nasa.gov/ co-organized by this author. The attendees received an overview of terrestrial models for telepresence exploration, considered enabling strategies, and briefed the agency on their findings. The report from that symposium is available that website.

II. Latency, Bandwidth, and the Sense of Presence in Telerobotics

It is useful to quantify what we mean by high-quality presence in exploration [6,7]. Such presence requires low communication latency, which defines the delay or lag that is associated with every human action, and high bandwidth, which is a measure of the situation awareness information returned to the human per unit time, and the specificity with which commands for dexterity and mobility are sent by that human. The simplest way to view these parameters is in terms of the human body, and the connection between the brain, the human sensory organs, and the muscles.

In terms of bandwidth, the useful information flow is certainly dominated by vision. The bandwidth of human vision can be assessed in a number of ways. Biologically, the metric is the number of firings of the ganglion cells in a retina. This was assessed for guinea pig retina, and multiplied by a factor of ten to account for the greater number of ganglions in a human retina. The end result was about 9 Mb/s [8].

Another way to look at this, in a more practical sense, comes out of commercial telepresence applications that are specifically intended to provide situation awareness to remote humans. The Cisco C40 office telepresence system uses a 1920x1080 (1080p) camera, with 3 colors/pixel, 8 bits/color, with a frame rate of 30 fps. This corresponds to 1.5Gb/s of uncompressed data. With a modern compression codec (e.g. H.264), this can be transmitted over a 4 Mb/s line. Now, the need for such high spatial resolution and high frame rate for quality situation awareness is certainly somewhat negotiable. But these two ways of estimating visual bandwidth for high-quality presence are at least roughly consistent. The human visual system can process roughly 10 images per second, with visual image persistence of about 100ms, so a frame rate of 10 fps would probably be sufficient, though without smoothing perhaps would be perceived, as in early silent films, with some jerkiness. We therefore believe that a working number for an imaging sensor that would support real-time high quality telepresence is of order 1 Mb/s.

For command latency, the telepresence requirement is a little more specific. The human visual reaction time is about 200 ms, which is the lag that is experienced in moving, say, a finger, in response to a visual cue. That being said, shorter latencies can still be recognizable, especially with training. Experienced video game players can find communication latencies of more than 100 ms uncomfortable, and 50 ms actually recognizable.

Now, to the extent that things are not happening on that time scale on a planetary surface, such control latencies might be considered to be vastly smaller than needed for real task effectiveness. But mobility introduces such requirements naturally. The need to avoid obstacles suggests that control latencies shorter than the time required for the robot surrogate to move its own scale size would be handy. For a human walking, our visual reaction time corresponds to a scale of movement of about a foot. For a world class sprinter, it would correspond to about six feet, but such runners would not be traversing a path with obstacles that needed to be actively avoided. Also, control latencies shorter than the time required for a field of view to pass by as the visual sensor is being panned are conducive to good situation awareness. Latency is also costly for situation awareness in dexterous manipulation. The penalty of latency on task completion time has been richly considered, though mostly for latencies that are far shorter than what we experience in space exploration, since large latencies have little terrestrial relevance. Even surface point-to-point communication over geosynchronous satellites can produce control latencies of less than a second. Some of the earliest studies, done at MIT, are especially insightful with regard to understanding the impact of these longer latencies on human cognition [9.10.11].

That human reaction time, multiplied by the speed of light, and divided by two (to account for round-trip communication) establishes a spatial scale for high quality telepresence. <200 ms two-way latency can be achieved only across distances of <30,000 km, a distance scale which we have coined the “cognitive horizon”[12]. This distance is nearly that from Earth to GEO, so for satellite servicing at that locale controlled from the surface of the Earth, real-time presence and high-quality cognitive awareness can be assured. Interestingly, the path to LEO might actually be farther, in that access would probably be via such GEO comsats. The Moon is considerably outside that cognitive horizon from the Earth (a factor of 13 or so farther), and Mars is vastly outside of it (a factor of several thousand farther).

We will not cover, in this paper, the specific opportunities that high quality telepresence enables. Suffice it to say that telerobotically putting high quality human presence and dexterity on another world should in principle offer many of the same opportunities that a human in situ would provide there. Rather, we will concentrate on the implementation strategies to put it there.

III. Terrestrial Telerobotics, and Its Lessons for Space Exploration

The rapidly increasing importance of telerobotics for terrestrial applications is a big advantage to space exploration. With large commercial, industrial, and defense related investments in low latency telerobotic control, the technology and operational experience that it can bring to space exploration is profound. See Figure 1.

To the extent that regolith moving will be important in extraterrestrial development, efforts in the commercial telerobotic mining industry are of great interest [13]. Telerobotic mining is routinely done in Canada and Australia, controlled at sites thousands of kilometers away. Two way control latencies of order half a second are common for this application, largely determined by internet switching facilities rather than speed of light. Though mines deep underground are not naturally conducive for local area wifi networks, strategies for network layout along shafts have been successfully developed. Telerobotic mining has proven to be cost effective for industry, greatly lowering risk to mine workers.

Telerobotic control is regularly used for deep-sea operations – oil, gas, and cable management, as well as science. While acoustic modems are used for low bandwidth control to small depths, deep sea telerobotic operations are done via cable. Done this way, with a control station on the ship directly above, latency is minimal, and very high data rates are possible [14]. Unlike for telerobotic mining, much of this work involves maintenance and repair, which requires a significant amount of dexterity.

Drones/UAVs are becoming standard tools for surveillance and warfare. The tasks served by these include high resolution imaging and targeting, as well as flying with takeoff and landing. In this case, the dexterity is applied to aircraft control surfaces and camera pointing, and in the case of targeting, a high degree of cognition and real-time decision making is needed. For this work, control latencies up to a second are managed, again determined by switching circuits.

Figure 1. Examples of terrestrial low-latency telerobotics. At upper left, the Predator undersea manipulator arm (Kraft Technologies). At upper right, a new concept telerobotic mining control node (Penguin Automated Systems). At bottom, the da Vinci commercial telerobotic surgical system (Intuitive Surgical Inc.)

Perhaps the most impressive demonstration of telerobotic dexterity and situation awareness is telerobotic surgery. The electromechanical separation of surgeon and patient is done more for augmenting the precision with which a surgeon can manipulate tools than to enable surgery at remote sites. But whether the operating table is across the room from the surgeon, as it is currently in thousands of hospitals, or on the other side of the world, the telerobotic requirements are similar. The effect of latency on telerobotic surgery has been well researched and is of great interest for space telerobotics involving significant dexterity. It is found that the precision cutting, stitching, and knot tying a surgeon needs to do cannot tolerate latencies of much over 500 ms [15]. The potential of such remote surgery for space medicine has been considered as well [16].

However, space exploration efforts controlled from Earth are, in many respects, independent of technologies that have terrestrial value. That is because such efforts at great distance invariably involve large control latencies that are simply not encountered on the Earth. High latency, largely autonomous telerobotics has few markets on Earth, mainly because the control distances are much shorter than for space.

IV. On-Orbit Telerobotics and Exploration of the Moon

While the Moon is well outside the cognitive horizon of the Earth, low-quality telepresence can be achieved there. The Lunokhod program in the early 1970s was a masterful demonstration of Earth-based humans-in-the-loop driving (if very slowly) a rover across the lunar surface. While the two-way light time latency is 2.6 seconds, the Lunokhod team endured latencies 5 times larger than this, because of relatively primitive networking technologies. The technology that will come to bear with the Google Lunar X-Prize rovers will presumably allow a more responsive connection. Although the Chang'E-3 Yutu rover provides video in real time, it is not clear whether humans are in the loop for actual driving.

One goal of low latency lunar surface telepresence is field geology. A rover with some dexterity, that can reach out and grasp and manipulate irregularly sized rocks for inspection, and develop situation awareness about rock formations, would allow science to be done efficiently. Lower latency would also allow the rover to be driven at higher speeds, covering more ground on which to do the science. It is important to understand that a high dexterity rover with advanced imaging systems could offer more capability than an astronaut there, who peers at rocks through a helmet, with limited spectral information, and whose dexterity is highly limited by extravehicular activity (EVA) gloves. To the extent we can achieve high bandwidth, low latency telepresence on the lunar surface, at least science will benefit strongly.

We have considered optimal orbits for a telerobotic control station near the Moon. Low lunar orbits have the advantage of extremely small latencies (of order several milliseconds) but are otherwise handicapped. One handicap is that the surface facilities being controlled rise and set quickly, so contact times are brief. Another is that low lunar orbits are generally unstable, because of gravitational irregularities, so an orbiting habitat there needs a lot of propellant for stationkeeping. Highly elliptical Molniya-type orbits have been considered, as there are some that require little station-keeping propulsion, but these orbits too have limited connection times, and present communication latencies that change drastically. We view Earth-Moon L1 and L2 orbits as being enabling in this regard [17, 18]. Those orbits (see Figure 2) stay over the lunar near- and far-sides respectively. Halo-type orbits, as shown, revolve around the Earth-Moon line in a roughly two-week period, keeping roughly the same distance to the surface. Even for L2, with a large enough halo orbit, the line-of-sight to the Earth can be continuous, over the lunar limb. While these Lagrange point orbits are not entirely stable, it takes little propulsion for stationkeeping -- of order 100 m/s/year.

Because these orbits remain over one side of the Moon, a large fraction of that hemisphere is visible continuously. While the lunar poles are in the line of sight for only half of the orbit, one can envision work being done at each pole at different times. For lower latitudes, not only is the line-of-sight continuous but, unlike for a lunar surface outpost, contact with many sites across the hemisphere is possible at any one time. Both L1 and L2 orbits are almost continually illuminated by the Sun, so power management at the orbiting control station is simplified, compared with a low lunar orbit which endures regular shadowing.

The choice of L1 versus L2 would depend, of course, on in which hemisphere work needs to be done. Although it used to be thought that L2 was propulsively easiest to get to, it is now understood (19) that low altitude lunar swingbys can offer a similarly economical entry into L1. Of special interest is that a habitat, or space station, placed at L1 or L2 can be moved to the other Lagrange point with little propellant, over a period of a month or so, as demonstrated by the Artemis mission [20]. So these two Lagrange points should be treated as a system that can be targeted by a single habitat and mission design. The L1 and L2 orbits offer two-way control latencies to the lunar surface of about 400 ms. Not quite real time, but close, and far better than from the Earth.

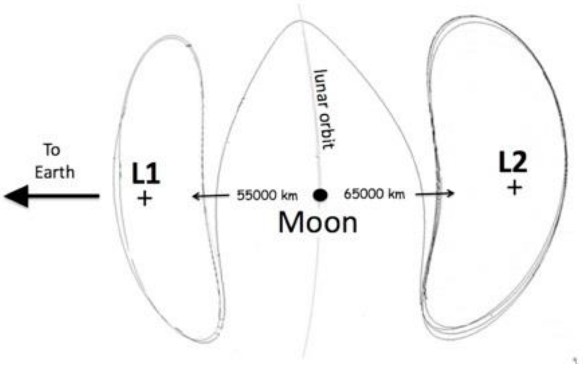


Figure 2. The Earth-Moon Lagrange points are shown relative to the Earth and Moon. Also shown are parts of the orbit of the Artemis P1 spacecraft, which did several recent orbits of L2 before being directed, via a low-energy maneuver, around to L1 [20].

Lunar surface communications from L1 or L2 need to be considered carefully, especially if the mission concept adheres to a high-quality telepresence-enabling communication bandwidth uplink of >1 Mb/s over a distance of 60,000 km. That kind of bandwidth and range is achieved from Earth to GEO, but with large pointed antennas that are not well suited to a highly mobile robotic surrogate that is bouncing over the regolith. It is noteworthy, for example, that MSL/Curiosity on Mars uses a relatively compact and omnidirectional UHF low gain antenna that permits up to ~0.2 Mb/s uplinks to MRO, which is only several hundred kilometers overhead. That strategy would clearly not be applicable here. One advantage of Earth-Moon L1 and L2 for on-orbit telerobotic control on the lunar surface is that the control station will move only very slowly in the sky overhead. So unlike with MRO on Mars, a conveniently sized high gain antenna (HGA) on the surface unit (e.g. a ~10º FOV, 25 dBi Curiosity heritage 30 cm "patch" Ka/X band antenna) would not need to be rapidly slewed to follow it. But it would need to be slewed to compensate for motion of the rover, and might need significant power. In order to transmit 1Mb/s successfully, it would, in addition, require a 1 m-class receiving antenna if the transmitter were powered with 20W, like the

Curiosity HGA. Optical communication is a strategy that is potentially enabling here, in terms of achievable bandwidth, but with typical laser beam divergences of 10-100 µrad the challenges of pointing are much more severe.

The challenge of high bandwidth uplinks from a mobile surrogate to a L1 or L2 habitat can be relieved somewhat if the surface units are part of a local WLAN (e.g. 802.xx). With a central fixed communication hub hosting a large directional antenna that slews slowly to follow the control station across the sky, much higher bandwidths can be accommodated with an omnidirectional antenna on the nearby rover. In fact, the Lunar Communications Terminal (LCT) proposed for a Constellation outpost was conceived in exactly this way [21]. The disadvantage of a central communication hub, however, is that horizon limits the range, and the rover must, in any case, maintain a line-of-sight to that hub.

The promise of on-orbit lunar telerobotics has only recently considered a completely different class of orbits – selenographic distant retrograde orbits (SDROs). These orbits are roughly circular about the Moon, and the retrograde motion renders them highly stable, unlike the quasi-stability of Lagrange point orbits. This stability has been considered an attractive advantage to the new Asteroid Redirect Mission concept, where a small asteroid would be brought into cis-lunar space as a target for human exploration. Once such an asteroid is brought into cis-lunar space, it is imperative that it reside in a safely stable orbit, and an SDRO with a mean lunar distance of 70,000 km has been chosen in order to minimize the capture delta V. This is slightly further from the Moon than Lagrange point orbits. But while a 70,000 km SDRO is near the periphery of what is known as the "Hill sphere" around the Moon, such that larger orbits would no longer be bound to the Moon, much smaller SDROs are possible, at least down to an orbital radius of a few thousand kilometers, where non-uniform lunar gravity introduces instabilities.

These smaller SDROs have been termed “moderately distant SDROs” by Adamo et al. [22], who explore their potential benefits. They may offer important opportunities for lunar telerobotics. They can be much closer to the lunar surface, offering reduced control latency compared to the Lagrange point orbits and, to the extent considered necessary, offer line-of-sight access to both lunar hemispheres in the course of one orbit. While the selenographic orbit of a 70,000 km SDRO is about 12 days, that for a 10,000 km SDRO is about one day, offering continuous line-of-sight control to an individual surface telerobot for a full workshift. The relative advantages of Lagrange point orbits and moderately distant SDROs are only now being considered, and both classes of orbits will no doubt contribute to the usefulness of on-orbit lunar telerobotics.

V. Lagrange Point Architecture

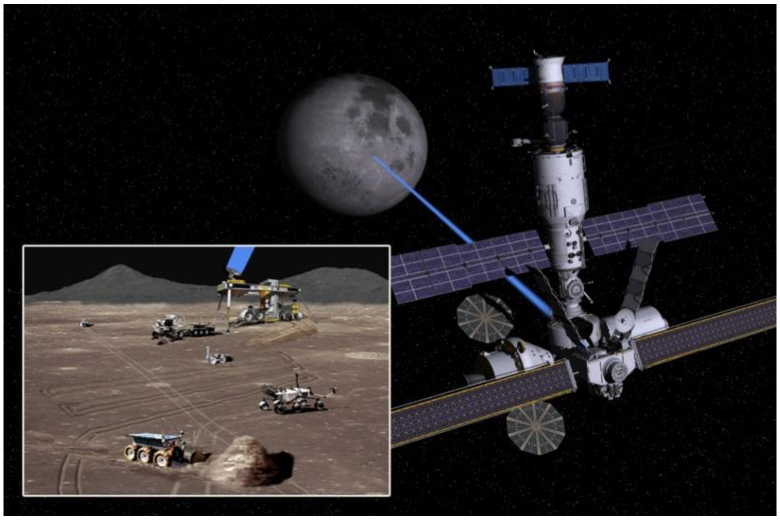
I would like to briefly review, in particular, concepts for Lagrange point habitat architecture that would serve the purposes of a lunar surface telerobotic control station. The architecture for such habitats, while designed specifically for Lagrange point orbits, would cleanly apply to SDROs as well. First of all, it should be noted that, at minimum, a simple multipurpose crew vehicle (MPCV) could suffice. Lockheed has proposed a “Farside” exploration strategy that would host on-orbit telerobotics from an Orion MPCV at Earth-Moon L2 [23]. Assuming that an Orion could be outfitted to remain at L2 for perhaps a week or two, this would be a good proof-of-concept for more extensive Lagrange point telerobotic control, accomplishing limited tasks. Such a capsule might not, however, easily have room for large telepresence immersion displays. The communication architecture for high bandwidth communications, ideally with a sizeable directional antenna, might also be challenging to attach to an Orion.

With regard to more spacious, long-term habitats, the Decadal Planning Team (DPT) in 1999-2000 envisioned L1 as the site for a “Gateway”, providing a logistics node for trips to the lunar surface as well as trips outside of cis-lunar space [24]. While the DPT did not specifically consider on-orbit telerobotic control of lunar surface facilities, their habitat design can be seen as useful for such purposes. More recently, Boeing has considered an long-duration habitat for L1 and L2 based on ISS architecture, perhaps even using components of ISS as that facility is retired [25]. See Figure 3. This would provide a relatively expansive living space that could support extended telerobotic activities across several generations of crew, as well as acting as a depot facility for human trips to the lunar surface. While this “ISS Exploration Platform” (ISS-EP) could, like ISS, increase gradually in size to accomplish many cis-lunar goals, on-orbit telerobotics requires rather little capability (no EVA/airlock, minimal docking ports), such that an early version in the evolution of such a platform would likely be a viable hosting site.

VI. The ISS as a Site for Proving On-Orbit Telerobotics?

The ISS has already been used regularly as a venue for telerobotic control. While a number of efforts have concentrated on telerobots on board controlled from either the ISS or from the ground, the appropriate comparison for is with ground telerobots controlled from ISS. Several such experiments have been carried out.

Figure 3. Notional image of a suite of lunar surface telerobots controlled over an optical communication link from a long-duration habitat at Earth-Moon L1. The main surface communication element is shown at center, and forms a local area network within which a number of surface vehicles are working. The habitat concept shown – ISS-EP, is one based on ISS component heritage.



The European Space Agency Multipurpose End-To-End Robotic Operations Network (METERON) experiment [26] has a surface android robot being controlled by an astronaut on board ISS, exploring not only dexterity, but haptic and force-reflex teleoperation. While this experiment could be carried out with moderate latency over the Tracking and Data Relay Satellite System (TDRSS), the METERON team is assembling a set of S-band ground stations that would allow continuous line-of-sight connection with ISS for periods of tens of minutes during an ISS pass-over. This would mimic, for short periods of time, the real-time access (with milliseconds of latency) that astronauts could have with an off-world surface telerobot, such as on the Moon from a low orbit, or a Lagrange point. Also, the surface telerobotics part of the NASA Human Exploration Telerobotics (HET) effort has had ISS astronauts driving a K10 rover across a simulated moonscape [27]. While done over TDRSS, and not quite real-time, sub-second latency was achieved by using the ISS system network, which is IP-based, and routed through Mission Control in Houston. The generic "Payload LAN" on ISS can potentially serve much larger amounts of data, but with many seconds of delay. These efforts with ISS clearly illustrate the concept of on-orbit telerobotics, and the potential for control of surface facilities without landing humans in a gravity well.

It is important to consider the ways in which ISS on-orbit telerobotics can provide unique information that is relevant to planning future off-world efforts. The Goddard Space Flight Center recently held a Technical Interchange Meeting to explore the potential of ISS for this purpose [28], following the May, 2012 *Exploration Telerobotics Symposium* at GSFC, which was co-organized by this author [29]. Certainly, at least for exploring the penalties of communication latency and bandwidth restrictions on, say, field geology, experiments wholly on Earth are probably more useful, if just that latency and bandwidth restrictions are easily simulated without ISS, and the control time that can be committed to such work is vastly greater on the ground than what astronauts on ISS can afford. This work could be done with controllers in a habitat adjacent to the field site. In understanding the tasks that need to be achieved, current state-of-the art field science capabilities (i.e., high latency telerobotics for science as conducted on the Mars Science Laboratory (MSL) or Mars Exploration Rovers (MERs), on Mars with supervised autonomy) should be carefully evaluated as a point of departure.

Clearly, for ISS-to-ground, the communication network is a major challenge, requiring modest latency at useful bandwidths. While on-orbit telerobotics at the Moon or Mars would, unlike with ISS, be designed with orbits that provide low control latencies with extended duration line-of-sight connection, and would enjoy complete ownership of the network, many of the delay-tolerant network challenges that might still be of concern can be met through exercising the ISS telecom system. Such challenges include situations where continuous links are impractical, because of shadowing or noise. One particular concern is the manual control of remote telerobots by astronauts in microgravity, especially if the telerobot is active in a significant gravity field. This could lead to a cognitive disconnect, where the astronaut is conditioned to ignore gravity. With regard to an astronaut visually monitoring the progress of a remote facility on a monitor, and responding with the action of fingers and limbs, the efficacy of eye-hand coordination in microgravity becomes especially important as well. A number of studies of perceptual motor deficits in microgravity have been carried out on ISS, most recently work funded by the Canadian Space Agency for joystick control of aiming tasks [28]. Impairments have been noted, and those impairments can probably be mitigated by proper controller design. But work of a decidedly human-factors variety needs to be done with tasks that are specific to the particular science that is to be carried out. In this context, other factors of an orbiting habitat environment, such as mental load and distraction, on both astronauts and in ground control, are difficult to simulate in a wholly ground based experiment.

As noted, it seems evident that while the ISS offers learning opportunities that would benefit this work, important terrestrial work, which is much more economical than ISS work, is required. Such work might be with an analog methodology, in which field geology, for example, is done telerobotically from the ground at sites that are geologically relevant to the planetary destination. Except perhaps for deep undersea geology, virtually no such work has been done, especially in exploring the penalties of latency and bandwidth. It is probably simplistic to assume that this on-orbit telerobotic work requires a single real-time operator. In view of the other likely job commitments of an astronaut in a distant on-orbit habitat, we should carefully examine the operational protocols for efficient task sharing between real-time operators on-orbit and more distant ones on Earth with higher latency.

One lesson from ISS is the success of international collaboration. Considering that human visits to other worlds are almost certainly going to depend on international collaboration, it is reasonable to consider the extent to which on-orbit telerobotics is a strategy that maps well onto such collaboration. It appears that it does. It is unlikely that the first such human trips will involve more than a few astronauts, and that being the case, crew members will represent only a few nations. But on-orbit telerobotics presents the opportunity for local astronauts to achieve surface presence through surrogates that may come from many different countries. That is, astronauts may see, manipulate, and travel across other worlds with surrogates manufactured by other nations. This offers opportunities for "buy-in" by nations whose astronauts aren't on the crew.

VII. Summary

In the near term, on-orbit telerobotics may be the way that human presence is first returned to the Moon, and first put on Mars. One Mars exploration architecture based on on-orbit telerobotics has been detailed by the “Human Exploration using Real-time Robotic Operations” (HERRO) team at NASA Glenn Research Center [30]. The strategy was incorporated in the recent Mars-X concept developed by students at the International Space University [31]. This on-orbit telerobotics strategy depends on sensor technologies, and technologies for dexterity and mobility that are becoming highly refined, thanks to applications on Earth. Such a strategy might move forward with a minimal habitat at Earth-Moon L1 or L2, or perhaps in an SDRO. This might be implemented with an MPCV, but the full impact will come with the development of a real long-duration habitat. Work now being done on ISS can at least illustrate many of the technological and operational concepts that we need in order to proceed. ISS has had a long history of experiments along these lines, e.g. ROTEX, ROKVISS, and ETS-VII, though all of these older experiments either work over TDRSS (2-7 second "payload" latency), or brief (5-10 minutes per orbit) direct ground connection.

While analog work on the ground and from ISS are in the interest of this greater strategy, the long-term prospects and high level strategic planning should depend on the way that telerobotic systems are likely to evolve. This is the expansion of capabilities that we might be able to expect over the next few decades. It may be simplistic to say that in the next forty years, telerobotic capabilities will advance tremendously like they have in the last forty. While the speed of light will not change, and control latencies will not get any better, to what extent can this trajectory of progress be expected to continue? Assuming we can get people close enough, what will real-time telepresence look like a few decades from now? To what degree will human awareness and dexterity be completely achieved remotely? For that matter, autonomous robotic intelligence is getting sophisticated enough that one might ask to what degree human awareness will even be necessary. These are questions that will guide the future of space exploration, and they should not be answered with naïve extrapolation.

Of great interest is the fact that on-orbit telerobotics provides methodology to put human presence in places that we would never think of putting humans. While this paper has been about near-term applications of on-orbit telerobotics, the longer term potential is quite stunning, This strategy could put human presence on the surface of Venus, or under the methane oceans of Titan. In this way, the list of possible destinations for human presence in the solar system is vastly expanded, putting human presence where we would never want to put humans. This strategy thus represents an entirely new paradigm for human-robot collaboration.

Acknowledgments

I thank Kurt Klaus, Kip Hodges, Cameron Ower, George Schmidt, Dan Adamo, Brent Barbee, and Harley Thronson for useful insights. I appreciate the careful review from an anonymous referee.

References

1. http://www.nasa.gov/offices/oct/strategic_integration/grand_challenges_detail.html [4/29/12]
2. Minsky, M. “Proposal for a Remotely Manned Space Station” in *Vision-21: Space Travel for the Next Millennium*, 2003 NASA Conference Proceedings 654, 1193.
3. Minsky, M. “Telepresence”, *OMNI Magazine*, June 1980.
4. Singer, F. “To Mars by Way of its Moons”, *Scientific American*, March 2000.
5. Singer, F. “The PhD Project: Manned Expedition to the Moons of Mars” in *Space Technology and Applications International Forum—2000* (M.S. El-Genk, ed).
6. Lester, D. “Achieving Human Presence in Space Exploration” 2013 *Presence: Teleoperators and Virtual Environments*, in press.
7. Lester, D. “Putting Human Awareness and Cognition on Other Worlds” September-October 2012 *Space Times*, 4.
8. Koch, K., et al. “How Much the Eye Tells the Brain”, 2006 *Current Biology*, 16, 1428.
9. Ferrell, W.R. “Remote Manipulation with Transmission Delay”, 1965 *IEEE Transactions in Human Factors in Electronics*, 6, 24.
10. Sheridan, T. “Space Teleoperation Through Time Delay: Review and Prognosis”, 1993 *IEEE Transactions on Robotics and Automation* 9, 592.
11. Lane, J. Corde, Carignan, C, and Akin, D. “Time Delay and Communication Bandwidth Limitation on Telerobotic Control”, 2001 *Proc. SPIE* 4195, 405.
12. Lester, D., and Thronson, H. “Human Space Exploration and Human Spaceflight: Latency and the Cognitive Scale of the Universe” 2011 *Space Policy* 27, 89-93.
13. Baiden, G., “A Study of Underground Mine Automation”, 1993 Ph.D. Thesis, Department of Mining and Metallurgical Engineering, McGill University.
14. Bulich, C., Klein, A., Watson, R., and Kitts, C. “Characterization of Delay Induced Piloting Instability for the Triton Undersea Robot,” in *Proc. 2004 IEEE Aerospace Conf.*,1, 423.
15. Anvari, M. et al. “The Impact of Latency on Surgical Precision and Task Completion During Robotic-Assisted Remote Telepresence Surgery” 2005, *Computer Aided Surgery* 10, 93.
16. Haidegger, T., Sandor, J., Benyo, Z. “Surgery in Space: the Future of Robotic Telesurgery”, 2011 *Surgical Endoscopy* 25, 681.
17. Farquhar, R. “A Halo Orbit Lunar Station” 1972 *Astronautics & Aeronautics* 10, 59.
18. Lester, D., and Thronson H. “Low-Latency Lunar Surface Telerobotics from Earth-Moon Libration Points,” AIAA Space 2011 Conference & Exposition 2011-7341.
19. Folta, D. "Maintaining a Safe, Stable, and Human Accessible Parking Orbit," in Target NEO Workshop, July 9, 2013. http://targetneo.jhuapl.edu/pdfs/2013_Presentations/session4/NEA_Presentation_final.pdf.
20. Angelopoulos, V. “The ARTEMIS Mission” 2011 *Space Science Reviews* 165, 3.
21. Schier, J.S. “NASA’s Lunar Space Communication and Navigation Architecture” 26th International Communications Satellite Systems Conference (ICSSC), AIAA-2008-5476.
22. Adamo, D., Lester, D., Barbee, B., and Thronson, H. “Moderately Distant Retrograde Orbits Applied to Selenographic Human Operations” 2014 AIAA Space 2014, in preparation.
23. Kwong, J. et al., “Stepping Stones: Exploring a Series of Increasingly Challenging Destinations on the Way to Mars” 2011 AIAA Space 2011, 2011-7216.
24. Decadal Planning Team archives, 2000, http://history.nasa.gov/DPT/DPT.htm .
25. Raftery, M., and Derechin, A. “Exploration Platform in the Earth-Moon Libration System Based on ISS”, 2012 63rd International Astronautical Congress, IAC-12-B3.1.
26. A. Schiele, "METERON – Validating Orbit-to-Ground Telerobotics Operations Technologies", *Proceedings of 11th Symposium on Advanced Space Technologies for Robotics and Automation (ASTRA)*, April 2011
27. T. Fong et al. “The Human Eexploration Telerobotics Project”, 2012 Global Space Exploration Conference, Washington, DC., GLEX-2012.01.2.4x12180.
28. GSFC "Telepresence for Science on ISS" workshop report, http://telerobotics.gsfc.nasa.gov/papers/ISS_LLT_Science.pdf
29. B. Fowler, S. Meehan, A. Singhal, “Perceptual-Motor Performance and Associated Kinematics in Space” 2008, *Human Factors: The Journal of the Human Factors and Ergonomics Society* 50: 879.
30. Schmidt, G., Landis, G., and Oleson, S. “HERRO Missions to Mars and Venus Using Telerobotic Surface Exploration from Orbit” 2011 62nd International Astronautical Congress, IAC-11.D3.1.4.
31. Mars-X Team, "Mars-X Final Report" International Space University, http://www.project-marsx.com/MarsxFinalReport.pdf , 2013.