SPACE ROBOTS

Exploration telepresence: A strategy for optimizing scientific research at remote space destinations

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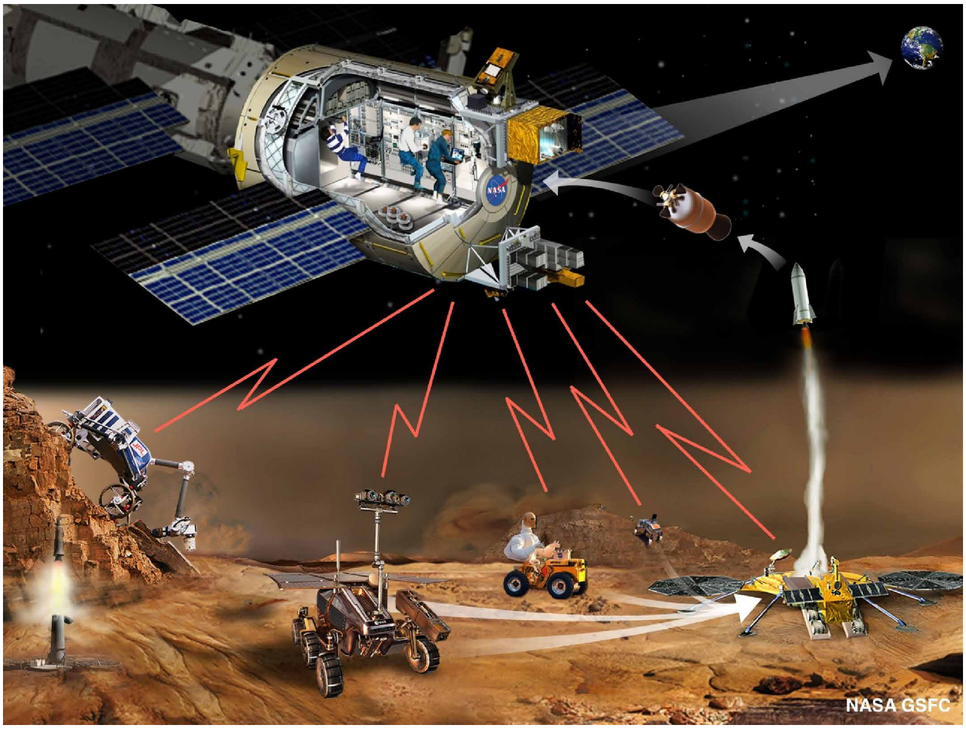
Modern telerobotic technologies offer astronaut scientists real-time presence on planetary surfaces without the risk and cost of putting them all the way there.



Concept for exploration telepresence on Mars from a habitat in orbit. Astronaut scientists safely in orbit over Mars control telerobotic surrogates on the surface. These surrogates give the scientists real-time vision, dexterity, and mobility. They can operate a diverse suite of surface tools at many different locations on the surface, providing real-time electronically mediated presence.

We assert that space exploration is the practice of extraterrestrial human presence and understanding. It focuses on getting senses, dexterity, mobility, and perception to sites beyond Earth. Scientific research on planetary surfaces relies on human awareness and decision-making. Robotic tools such as Curiosity on Mars transmit data to Earth, where scientists examine and interpret. However, the large transmission distances carry a penalty: no opportunity for real-time scientific observation and interaction with the research target. The two-way radio latency to the Moon is 2.6 s, just 10 times that of human reaction time. At more distant destinations, the delay is more constraining: For Mars, two-way radio latency is between 5 and 40 min.

To the extent that much of scientific research is an iterative process, where awareness drives action, the communication latency between humans on Earth and planetary exploration sites is limiting (*1*). One strategy is to keep latencies within the cognitive window of the human reaction time. This sort of telerobotic manifestation of human awareness is called telepresence. Telepresence is widely used on Earth for commercial and defense activities. Teleoperators remotely control undersea, mining, and agricultural vehicles. Surgeons routinely do their work physically removed from the patient. Unmanned aerial vehicles provide front-line reconnaissance and combat capability with pilots who are safely removed from danger. Telepresence in the office makes for productive "real-time" meetings of a distributed work force.

We presently use a kind of high-latency telepresence on Mars, where rovers such as Curiosity reach out to manipulate surfaces and inspect landscapes. However, field geology done there remotely is different than what would be conducted on Earth (*2*). Every choice, decision, command, uplink, and downlink is limited by time delay that, in the case of the Mars rovers, is determined by both the lack of relay satellites orbiting Mars and distance from Earth. In practice, it amounts to about a day.

A historical "boots on the ground" approach to realizing human presence at faraway destinations would be accomplished by physically putting astronauts there. However, rapid technology development in the past few decades allows for a new and different approach. Telepresence technologies allow humans near planetary bodies to have real-time exploration awareness without actually being on the surface. Putting astronauts on the surface of Mars is difficult and dangerous. However, putting astronauts in orbit around Mars, with control latency to the surface within the human reaction time, is more tractable and assuredly less expensive. We call this modern approach exploration telepresence (*3*). Exploration telepresence still requires astronauts, but they voyage specifically to minimize latency. This strategy would allow astronaut scientists to feel like they were there. It has been considered in space exploration history (*4*), but only now does the technology support realizable mission concepts (*5*).

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Scientific opportunities provided by exploration telepresence are now being evaluated by a Keck Institute for Space Studies study group (www.kiss.caltech.edu/new_website/workshops/telepresence/telepresence.html). An astronaut scientist in orbit can have real-time vision, dexterity, and mobility on the planet below. This is in many ways superior to an astronaut on the surface in a bulky pressurized space suit with limited consumables. Mars exploration involving decision-making and iteration can be achieved much faster by nearby scientists than by time-delayed scientists on Earth.

Unlike humans at one place on the surface of Mars, humans in orbit can control surrogates in real time at many different sites on the planet. From the perspective of not contaminating Mars with terrestrial biology, exploration telepresence from orbit also offers advantages over in situ humans. This exploration telepresence strategy is not intended to substitute for putting humans on planetary surfaces. Rather, it is the least expensive first step to put real-time human presence at these places, ideally leading to on-site human visits in the future, perhaps to colonize and settle. Once humans are physically present at these places, exploration telepresence will remain a productive tool for exploring their surroundings.

The cost of latency in completion time depends on the task. The first pertinent experiments determined that, for iterative tasks requiring control updates within human reaction times, task completion time cost was roughly the ratio of latency to human reaction time (*6*). From this research, we can see that detailed activity on the Moon controlled from Earth would take about 10 times longer than if someone was actually there and a thousand times longer for Mars. This cost has been researched in assessing the viability of telesurgery over commercial networks. It has been found, for example, that in cutting and stitching compliant tissue, control latencies of >0.5 s are intolerable (*7*). The cost of latency can be minimized with the use of supervised autonomy, where the telerobot can be instructed to autonomously accomplish well-defined tasks: insert this screw in this hole, for example. Although autonomy can be constructive, it may not provide the insight and the discovery, perhaps from surprises, that real-time presence would offer. What tasks to relegate to supervised autonomy and what tasks to relegate to real-time presence will be an important mission planning exercise. Experiments on the effects of latency in planetary field science should be a high priority, given a renewed worldwide interest in human exploration of the solar system.

Astronauts on the International Space Station already control telerobots on Earth. They exercise communication strategies as well as user interfaces that could be applied to more distant sites (*8*, *9*). Such experiments provide a useful degree of human vision and mobility for a bandwidth of about 1 megabyte/s. With respect to planetary science, future analog experiments, in which scientists at a distance from a terrestrial field site do studies there, could be of great value (*10*).

Low-latency exploration telepresence is a new way to think about human-robot partnership for space exploration. It is where humans use robots not as automatons but as extensions of their senses and perception in real time. It is a strategy that can be enabling for use at exploration sites that are dangerous and expensive for human visits, greatly expanding the number of destinations where humans can put their presence.

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