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ScienceDirect

Acta Astronautica 62 (2008) 59–65

ACTA ASTRONAUTICA

www.elsevier.com/locate/actaastro

Teleoperation from Mars orbit: A proposal for human exploration☆

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Received 28 October 2005; accepted 11 December 2006
Available online 7 May 2007

Abstract

An effective program for Mars exploration should proceed in steps. The best strategy for the initial human missions to Mars may be to put the humans into Mars orbit and explore the surface by telerobotic operation. This could provide the benefits of human exploration at greatly reduced risk and cost. Telecontrol of Mars surface robots from a Mars-orbital habitat would give human nearly "real time" virtual presence with minimum time delay, allowing high-fidelity virtual exploration of the surface. It is a cheaper, simpler, and safer way to explore, and hence it will be a faster way to investigate a wide variety of locations, from the polar caps to near-equatorial canyon regions. Teleoperation also enhances planetary protection in both directions, protecting Mars from contamination by Earth life and keeping humans from exposure to possible Mars microbes, and has the potential for valuable spin-off technologies.

1. Introduction

An effective program of Mars exploration should proceed in steps. Each step should make progress toward human exploration and settlement, but each step must also be justifiable on its own scientific merits. An outline of such an exploration approach was proposed in earlier papers [1,2]. Here I will further develop the argument that the initial steps of human exploration of Mars should be done without actually landing humans on Mars, but by putting the humans into Mars orbit and operating on the surface using the technology of robotic agents operated by telepresence. This will provide the results of human exploration, but at greatly reduced risk and cost. Teleoperation from a Mars-orbital habitat could allow real time (or nearly real-time) operation on the surface of Mars with minimum time delay, giving a virtual presence on the surface.

It is a cheaper, simpler, and safer way to explore, and hence it will be a faster way to explore. Virtual exploration will have the excitement of being there, at a fraction of the price.

An artist's conception of such a telerobotic system for exploring Mars is visualized in Fig. 1.

2. Rationale

2.1. The Apollo paradigm

If Mars is to be explored, the most reasonable approach is to develop the capability in steps, with each step pushing the envelope of exploration forward incrementally [1]. The first Apollo missions to the moon—Apollo 8 and 10—did not land on the moon, but instead went into lunar orbit without landing.

☆ Paper IAC-04-IAA.3.7.2.05, International Astronautical Federation Congress, Vancouver BC, Oct. 4–8 2004.

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doi:10.1016/j.actaastro.2006.12.049

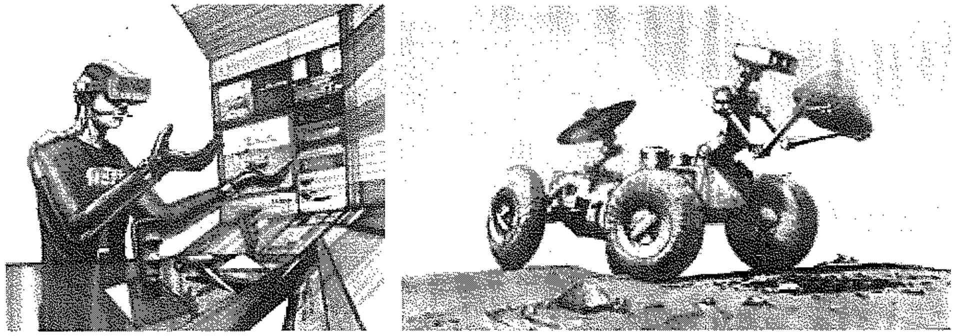

Fig. 1. Telerobotic operations on Mars concept. (Painting by Carter Emmart, courtesy NASA Ames Research Center [9]).

It is quite reasonable that the same approach should be used for Mars missions.

At first thought it may seem unreasonable to send humans all the way to Mars orbit, and then return without going the additional few hundred kilometers to the surface. Nevertheless, this is in fact quite sensible. The actual interplanetary transport is by far the simplest part of a Mars mission. An interplanetary transfer habitat will be similar to habitation modules already demonstrated on the existing space station, and the interplanetary propulsion could be done with technologies already existing.

Landing humans on Mars, on the other hand, is a significant technological challenge. A human-rated entry vehicle must be designed and developed, a soft landing system must be designed and developed, for the landing vehicle, a Mars habitat must be designed and developed, and finally and a Mars Ascent vehicle has to be designed and developed. Each of these are dangerous steps, and of these must be unique vehicles that in many ways will be very dissimilar to any other space vehicles previously made, and will operate in environments far different from those we have been experienced.

In addition to the vehicles, a human mission to Mars will require developing life support technologies that will operate reliably in the hostile environment of Mars, subject to dust and chemical hazards as well as the thermal cycling and ultraviolet exposure typical of other space missions. The space suits used for Martian EVA will be used without refurbishment on Earth over surface mission lengths as long as nearly a year, a duration hundreds of times longer than the space suits used in previous orbital or lunar missions, and will have to be designed specifically for the Mars environment. Such Mars space suits do not currently exist.

Without landing, we have no need to develop a human-rated Mars Lander and Mars Ascent Vehicle, and we can send geologists and biologists on the mission; rather than pilots trained to operate VTOL landers. A mission to Mars orbit could, in fact, most likely be done at an order of magnitude lower cost than a mission to land on the Martian surface. It makes sense that the low-cost orbital mission would be done as a logical precursor to any landing.

With that understanding, it is valuable to ask: can useful science be done by an orbital mission, with no human Mars landing?

2.2. *Human factors issues*

Separate from the cost issues, an orbital mission makes sense from the point of view of safety and human factors.

There is some uncertainty about whether astronauts would be able to accomplish useful activities on the surface of Mars after nine months in microgravity on the interplanetary trajectory. A Mars mission might well use the technology of a spacecraft attached to a counterweight by a rotating tether to provide simulated gravity; it would be useful to demonstrate this technique in an interplanetary transport before the first use in a human landing.

There are also significant unknowns about the health hazards of the surface of Mars. Over the course of the landed mission, the space suits will become covered with dust, and EVA operations will bring the Martian dust, along with the space suits, into the habitat. The biological hazard of the extremly fine Martian dust is as-yet unknown [3,4]. Even the size distribution of Mars dust may be a difficulty.

2.3. *Science issues: landing site selection*

Any human landing site will be to some extent a compromise between safety and scientific interest, and many of the most interesting features of Mars may not be suitable for a human landing site. The landing site for robotic missions has typically taken several years of analysis and argument, and the final sites are always selected with mission safety, and not science, as the dominant concern. Such landing site analysis will be even more stringent for human exploration. Landing sites for a human mission are likely to be scientifically "boring" sites, featuring flat surfaces with an absence of boulders, cliffs, channels, craters, or mountains.

Use of telerobots lowers risk, and thereby allows dangerous exploration. Valles Marineris, for example, is a geological section through layers representing many millions of years of Martian geological history, yet the unstable cliff tops and fragile walls mean that human exploration of such canyons would be extremely dangerous.

Tele-exploration from Mars orbit also allows possible investigation of a wide variety of locations. With an orbital base controlling surface telerobotic, human explorers are not stuck with one base location, but can investigate locations all over Mars. They can investigate the polar caps and also near-equatorial canyon regions. This frees the mission from landing site constraints.

With no need to select a "grab bag" site that contains a large number of geologically diverse features at or near a single location; it is now possible to go to all the best sites—paleolake sites, river beds, volcanic calderas, lava tube sites, layered terrain, canyons, possible shoreline features, the North and South poles.

2.4. Science issues: planetary protection

Planetary protection is a significant constraint on human exploration. One of the most significant scientific questions to be answered on Mars is: does Mars have present, or past life? Addressing this question requires exploration of multiple sites to collect biologically pristine samples, with no terrestrial organic contamination. But space suits, and habitats, may very well be leaky. At a minimum, adding a requirement that after donning their spacesuits, each astronaut must then sterilize the entire outside surface of the suit, will greatly increase the complexity (and cost) of the mission. Exploration by telerobotics will allow us to keep the landing site uncontaminated by human habitat effluvia, so when we discover evidence of biological activity, we can have a higher likelihood that it is not the microbes that originated from the human explorers.

Since present day life could exist on Mars, planetary protection is also needed to preserve the (possible) fragile Mars biosphere from competition from ferocious Earth life. Isolated biospheres on Earth have been devastated when they have been exposed to alien life forms introduced—accidentally or deliberately—from another continent. If there is life on Mars, we will wish to protect it from competition by introduced Earth biota.

Reverse planetary protection—protecting the Earth biosphere from exposure to Mars microorganisms—is also a possible consideration. While many biologists would argue that any life that was well adapted to the extreme conditions of Mars could have no possibility of infecting terrestrial life, the "scare factor" of Martian microbiota invading Earth is very real. Despite the unlikelihood of any real risk, from public policy alone, protecting the Earth from Mars is a primary goal. The Apollo astronauts, as an example, were kept in isolation after returning from the moon despite the absurdity of any possible contamination.

Exploring from orbit will reduce biological risk by keeping humans from exposure to possible Mars microbes. A telerobotic mission avoids the difficult human question of how to isolate Mars mission astronauts infected by Martian microorganisms until after a thorough scientific search for such microorganisms has been conducted.

3. Exploring Mars from orbit

3.1. Telerobotic exploration

Telerobotic systems operated on Mars by locally present astronauts have been proposed before [1,2,5–7]. For example, the 2001 Mars Surface Reference Mission design [8] stated that one of the tasks of human astronauts might be to: "Perform teleoperation of robotic sample collection systems such as rovers. Humans on Mars can operate remote systems that extend their field geology capabilities beyond a human's range. This can be done effectively because of the short delay times that can exist on the surface during human missions. While telerobotic systems cannot replace the observational abilities of an astronaut in the field, such systems may be particularly effective at collecting samples under human supervision. These systems could be used to extend astronaut operating range, or could be used in advance of astronaut sorties to provide detailed information about a specific local area or rock type."

This proposal, then, suggests rather expanding the applicability of "extending the field geology capabilities beyond a human's range."

Teleoperation of Mars surface robots from a Mars-orbital habitat will operate near "real time" operation with minimum time delay, giving a virtual presence on the surface. True immersive virtual presence will require human presence at Mars.

Most roboticists make a distinction between teleoperated and remotely operated robots [9,10]. A teleoperated rover, has a real time operator interface, such as the joystick control that is routinely used for operating underwater vehicles. Often, teleoperation is assumed to include an immersive "virtual" environment, so that the human views the scene from the robot's point of view. On Mars, true teleoperation requires humans to be close enough to the robot that the speed-of-light delay is short enough that the human can operate the rover in real time.

In the telerobotic exploration scenario, the humans remain in an orbital habitat, and use teleoperation to rove across the surface of Mars and explore.

This type of exploration will require a high-fidelity, high-bandwidth connection to give the humans a fully detailed virtual presence in the robotic body.

Tools for human telepresence in orbit are already being developed, such as the "Robonaut" [11,12] shown in Fig. 2. The concept uses a humanoid interface, allowing the operator to use the telerobot in the same way that the human body operates. Robonaut, for example, is explicitly designed to mimic a human's viewing and manipulating capabilities. It incorporates human-scale arms (Fig. 3) with dexterous five-fingered hands (Fig. 4), each incorporating a force sensitive glove. This glove serves as the hand's skin, detecting where the hand has made contact with an object. The inset shows a prototype of that glove, with the index finger incorporating force sensors embedded along the inner surfaces [12]. The glove transmits the sensation of holding an object to the operator's hands. Picking up a rock with an advanced version of the force-sensitive hand would feel like picking it up in your own hands.

A bipedal robot body would present the highest fidelity virtual presence. The technology for bipedal robots is being developed by many laboratories, for example, by researchers at Honda, who have developed a bipedal robot "Asimo" that can duplicate much of the flexibility and balance of a human. However, it is not necessary that the robotic body mimic a human in all ways, and arguments for a wheeled transportation system include the simplicity of wheeled locomotion, the stability of the platform, and the multi-thousand-year development history of wheeled transportation, compared to the relatively small number of legged-locomotion designs. A humanlike interface could be used on a mobile body, as shown in the "Teleprospector" concept sketched by Rawlings (Fig. 5), or the "Centaur" concept for robotic exploration proposed by Ambrose et al. [12].

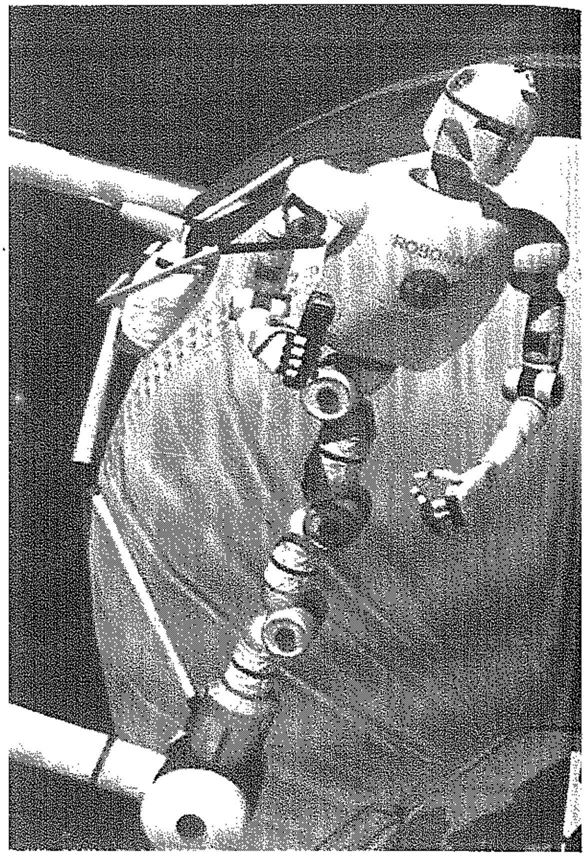

Fig. 2. "Robonaut," a system being developed for astronaut-operated telerobotics for EVA on International Space Station (visualization by John Frassanito and Associates, courtesy NASA).

Such robots can have expanded senses. A robot can easily have radar, infrared, and gamma-ray eyes, and so in principle a robot can see far more than a human can.

It is a cheaper, simpler, and safer way to explore, and hence it will be a faster way to explore. Indeed, as discussed by Minsky [13], telerobotics has at least as high human engagement factor as direct astronaut exploration: children are excited by video games, robots, and virtual reality. It has all the excitement of being there, at a fraction of the price.

3.2. Exploration scenario

Selecting the orbit for a human habit for telerobotic exploration presents an interesting design exercise.

If interesting landing sites can be found in the near-equatorial regions, then an aerosynchronous orbit would be an obvious choice. With a period of 24 h and

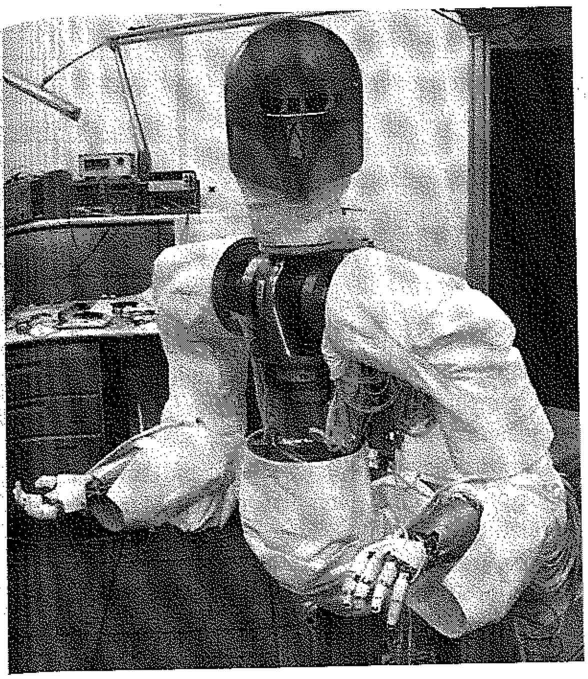

Fig. 3. Robonaut technology developed for hand and arm manipulation [12].

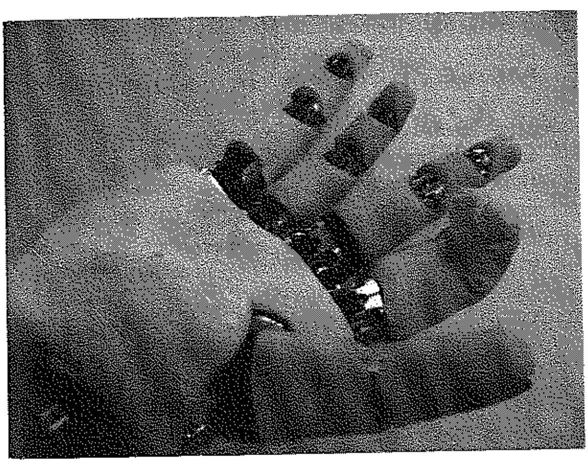

Fig. 4. Dexterous "hand" manipulator developed for Robonaut project [12].

39.5 min., synchronous with the rotation of Mars, an aerosynchronous orbit will stay over a constant spot on the Martian equator. Due to the lower gravity of Mars, aerosynchronous orbit is about three times closer to the Martian surface than the similar geosynchronous orbit is to the Earth's surface. This has the advantage of reducing the round-trip lightspeed delay compared to the nearly quarter-second delay experienced on Earth geosynchronous communications. It has a disadvantage, however, of meaning that the amount of Mars surface viewed from aerosynchronous orbit is slightly less than the comparable view from Earth orbit.

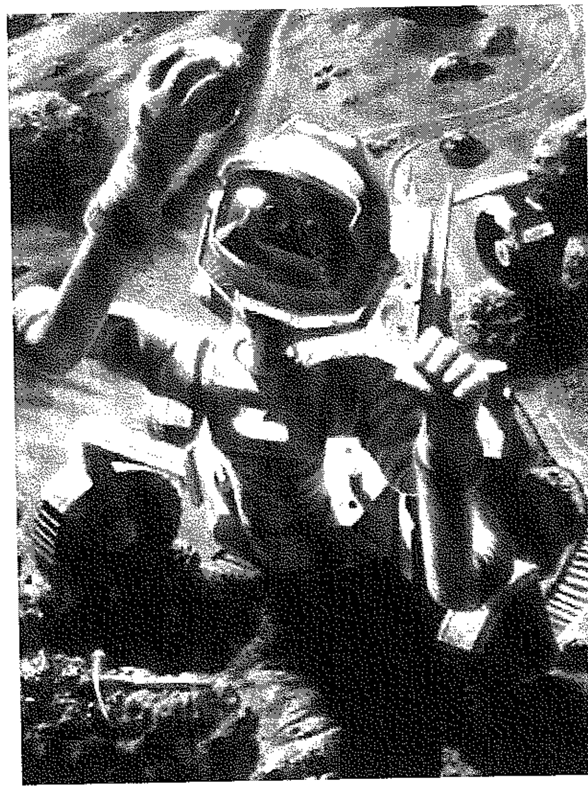

Fig. 5. "Teleprospector" concept, as visualized for NASA by Pat Rawlings.

Such a stationary orbit has the advantage that it would be in constant line of site communications with the landing site, allowing direct telerobotic control at all times.

The Meridian landing site of the Mars Exploration Rover "Opportunity," for example, is an exciting location with a plethora of water-related features. The Valles Marineris canyon system is also located close enough to the equator to be viewed from stationary orbit, as are many other sites of interest.

An inclined synchronous orbit has some advantages for exploring sites off of the equator. Such an orbit would have a ground track of a Figure 8, dipping above and below the equator, and would cross the same point on the ground time at the same local time. This ground track could be synchronized to the crew's work schedule.

Near-polar exploration sites will need to be operated from a nearly Mars-polar orbit to allow direct line-of-sight communications for surface teleoperation. A near-polar inclination synchronous Mars orbit, for example, will put the orbital station in line-of-sight of a given region for about 8 h per day—one teleoperation shift.

An alternative would be to put the habit into a lower orbit with a period of exactly half a Mars day. A habitat in a half-synchronous orbit will result in the habitat moving over different points on Mars, but returning to the same ground location at the same time each Mars day, allowing a telerobotic operator to return to the same site at the same time of day for a work shift.

If relay satellites are used, a synchronous or subsynchronous orbit is not necessary. Relay satellites increase the complexity of the system, and slightly increase the speed of light delay, but the gain in flexibility is likely to be more than the added cost of the relay satellites.

A final possible choice of orbit is to choose the habitat to be on, or near, one of the Martian moons Deimos or Phobos. It may be desirable to use regolith from one of the moons as shielding against cosmic ray and solar proton radiation. In any case, a mission to Deimos or Phobos would result in a human landing on an extraterrestrial body beyond Earth orbit, a body which may be of scientific interest in its own right [1,14,15], and which would be of significant public interest.

3.3. Robotic exploration: spin-off rationale

A final benefit of telerobotic exploration from orbit is the spin-off development of technology.

Telerobotic technology is widely discussed, but a high-fidelity human-capable robot has not yet been developed. Likewise, the high-bandwidth detailed virtual-reality simulation of a planetary surface, that would be used to immerse the operator in the robot's point of view, has yet to be fully developed.

Development of such technology would be a worthy goal for NASA, and one that would enrich missions to other planets beyond Mars. It would also be a valuable technology for applications on Earth, and one in which the cross-fertilization of ideas and technologies between commercial and space applications could be leveraged to the great advantage of both.

One of the often heard reasons for exploring space is that technology development for space also results in technology development for the Earth. A more self-serving version of this rationalization is that pushing the limits of technology enhances the economic strength of the country developing the technology.

By choosing telerobotics as the technology to develop, applications (many of them not yet thought up) will be developed. The economic benefits of this are likely to be far greater than the cost.

4. Conclusions

To be successful, a Mars exploration program should proceed in steps, with each step developing technology toward an eventual human mission to the surface of Mars, and also each step being both scientifically justifiable and also interesting to the public. One such step in the exploration of Mars should be the exploration of Mars by telerobotic agents operated by humans in Mars orbit.

An argument might be made that, once humans travel all the distance to Mars orbit, it would be a major disappointment not to travel the remaining few thousand kilometers down to the surface. However, a human landing on Mars is an endeavor significantly more difficult and expensive than a mission to orbit Mars. In a real-world future of limited budgets and difficult political choices, it may not be a choice between a human mission to orbit Mars or a mission to land on Mars, but instead a choice between a mission to orbit Mars now, or a postponement of any exploration to a distant and indefinite future.

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