N94- 27360

TELEPRESENCE IN THE HUMAN EXPLORATION OF MARS: FIELD STUDIES IN ANALOG ENVIRONMENTS

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Abstract

This paper describes the role of telepresence in performing exploration of Mars. As part of an effort to develop telepresence to support Mars exploration, NASA is developing telepresence technology and using it to perform exploration in space analog environments. This paper describes experiments to demonstrate telepresence control of an underwater remotely operated vehicle (TROV) to perform scientific field work in isolated and hostile environments. Toward this end, we have developed a telepresence control system and interfaced it to an underwater remotely operated vehicle. This vehicle was used during 1992 to study aquatic ecosystems in Antarctica including a study of the physical and biological environment of permanently ice-covered lake. We also performed a preliminary analysis of the potential for using the TROV to study the benthic ecology under the sea ice in McMurdo sound. These expeditions are opening up new areas of research by using telepresence control of remote vehicles to explore isolated and extreme environments on Earth while also providing an impetus to develop technology which will play a major role in the human exploration of Mars. Antarctic field operations, in particular, provide an excellent analog experience for telepresence operation in space.

Introduction

Human exploration of Mars is a vast undertaking of unprecedented complexity. The scientific potential of Mars exploration is enormous, but the strategy for accomplishing the science has not been worked out in detail. Moreover, there is a real dilemma when one considers how to proceed. One approach to the scientific objectives and strategy for human exploration of Mars is discussed in Stoker et al. (1991). Mars has a surface area comparable to that of the land area of Earth. The most interesting features on this planet are vast by terrestrial standards and, indeed, are planetary in scale. For example, if the Valles Marineris were placed on Earth, it would stretch from the east to the west coast of the north American continent. To understand features on the surface of Mars, it will be necessary to study them over dimensions comparable to the size of the features. Since features of interest are hundreds to thousands of kilometers in size, this is the required spatial scale of exploration. In addition, features of interest are located all across the surface of Mars. Thus, it is clear that achieving a level of exploration accomplishment that would justify the significant expenditure of putting people on Mars requires them to have access to most or all of the martian surface.

This spatial scale of exploration is in stark contrast to the range of mobility which the early Mars explorers are likely to achieve. Here the range is limited by the type of mobility that can be provided, which, in turn, depends on the mass that can be transported from Earth, as well as issues of life support and power sources. We expect that initial human missions will have relatively limited mobility and that later missions will be able to provide increasingly greater capabilities leading eventually to the desired global range. However, this view is based on the assumption of a multi-decade program of human missions which establish considerable infrastructure and capability on the surface of Mars. This, in turn, depends on a philosophy of Mars exploration which involves a continued human presence on Mars, a substantial commitment to build and sustain infrastructure on Mars, and use of Martian resources to support the increased capability of crews on the surface.

Figure 1 shows the expected range of human mobility for the various phases of human exploration. In the earliest human exploration mission or missions, the provision of mobility is likely to be limited to a small low mass rover vehicle. The range of such a vehicle will be limited by the life support capabilities of an astronaut's Personal Life Support System-an integral part of a space suit. During the Apollo moon landings, Astronauts were provided two levels of mobility: (1) the range they could reach walking in their suit, and (2) the range they could reach in an open-air rover similar to a modern dune buggy. However, if the lunar rover broke down, the Astronauts would need to walk back to the base and this limited the range they could travel in the rover vehicle to walking distance from the base. Thus, the suited Astronaut with a rover has a range of approximately 50 km. Given the distance, complexity, and cost of transporting equipment to Mars, an Apollo-type rover is probably the best one can hope for during an initial mission.

During later missions, crews should be able to rely on base facilities which were established on earlier missions and therefor lower the amount of equipment that would have to be transported from Earth simply to stay alive. Thus, extra equipment should be able to be provided to support scientific field work. Clark (1992) has suggested an approach to human mobility over greater distances. This concept is to use a pressurized all-terrain vehicle which incorporates a portable life support system providing a shirt-sleeve environment inside the Rover. Such a vehicle would be capable of several week duration field trips. Depending on the difficulty of the terrain, such a vehicle might allow field trips in a range of up to 1000 km or so before life support or fuel would run out. Still, this is substantially less capability than is desirable for gaining scientific access to the surface of Mars.

Eventually, one can envision the desired capability for human exploration being provided in the form of a suborbital rocket vehicle capable of taking a crew on an expedition of several months to any point on the surface of Mars. Such expeditions would originate at a central Mars base facility and would provide the crew with a similar level of capability obtained by the earliest human expedition to Mars.

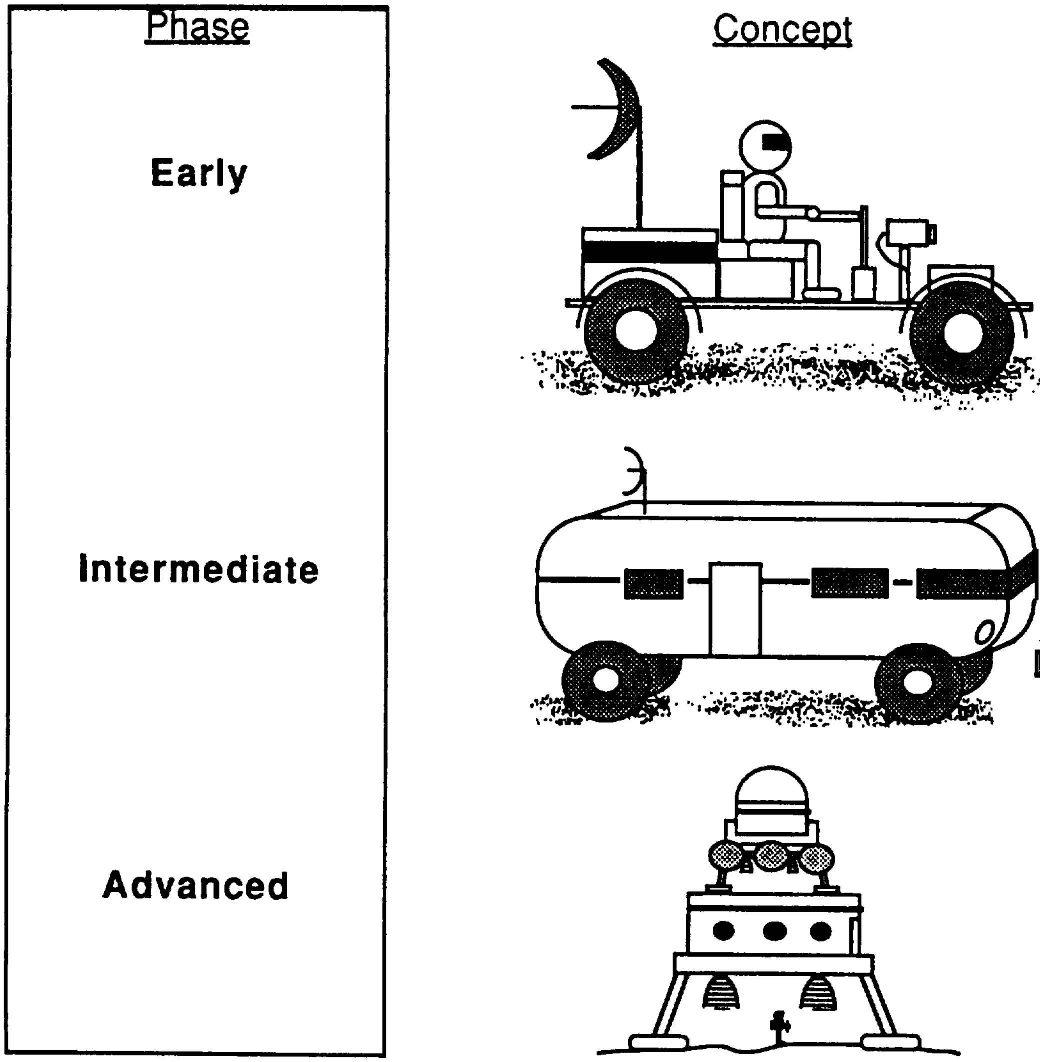

Figure 1. Expected mobility available to human Mars explorers during the earliest (top), intermediate (middle) and advanced (bottom) phases of exploration of that planet.

Telepresence - a Shortcut to Surface Mobility

An alternative to providing mobility to take Astronauts to the information would be to bring the information to them at high enough fidelity that it is very close to being there. We propose that telepresence systems represent a significant augmentation and alternative to human mobility. In fact, the provision of telepresence as an exploration tool is potentially so powerful that it could establish a new paradigm of exploration where humans and robots interact synergistically to achieve exploration goals.

What is telepresence? It is a high fidelity form of remote control which projects the senses of the human operator into a robot at a distant work site. Telepresence represents the marriage of technology which has been developed for Virtual Reality uses and the technology of advanced robotics. In the telepresent operation of a robot, the images from the robot cameras would be directly projected into the eyes of the operator. The humans body movements would control the motions of the robot, and the human would make the decisions. Telepresent operation of robots is an alternative to Artificial Intelligence because human intelligence is used instead. Thus, the level of automation (and the complexity of the computer control and software involved) is much lower. In effect, the human operator servo-controls the remote vehicle with the natural motions of her (or his) body.

The obvious advantage of telepresent operation of remote vehicles is that they could be landed anywhere on the surface of Mars and then operated from a distant location, such as the site of a Mars base. Thus, the range that humans can explore using telepresence depends on the communication range and the practicality of deploying the remote vehicles.

Telepresence operation of remote vehicles also offers the potential for substantially leveraging crew time. Telepresence-controlled rovers could be designed so that they could function and be controlled in a variety of ways. For example, one need only consider the stages of a normal geology field trip to see how to partition the work in a telepresent field trip. Any geology field trip on Earth starts out by driving a car or truck over relatively uninteresting terrain to reach the study site. One then surveys the study sight, perhaps with the aid of areal photographs, or climbs to the highest spot to get the overview of the area. After surveying the region on a broad scale, various areas are picked out for intensive investigation which is carried out in an intensive way. The field geologist at this stage is on hands and knees, touching and tasting, breaking off fresh rock faces and examining them with a hand lense, and of course, collecting samples for later analysis. All of this requires extensive documentation with field notes.

A telepresence/robotic field trip might function as follows. The rover might be given a ground command set of instructions to go to a location of interest. It could have enough AI to get to that location, perhaps with occasional supervisory control from Earth, and avoid obstacles, and danger. Once the robot reached the area of interest, it could walk around surveying the region. Again, this activity could be controlled from Earth since it would be tolerant of long time delays (the round trip light time between Mars and Earth is up to 20 minutes depending on the relative positions of the two planets). This information could be stored and sent back to the Mars base location and could be accessed and explored in a virtual reality data base by the martian explorers so that they could use it to select the locations of greatest interest. At the stage where the geological rubber meets the road, the scientist/Mars explorer would use the telepresence mode of operation of the rover to perform detailed scientific field work in selected sites. This mode would use the full range of telepresence capability to give the scientist a strong sense of presence in the remote environment.

Telepresence offers other advantages for exploration besides increasing the range of access to the martian surface. Because the telerobot can record and transmit all the information it collects, it frees the explorer from the drudgery of keeping field notes. The explorer can instead keep a running verbal record of what s/he is thinking while operating the telerobot. The entire experience is recorded and so it can be replayed. Another obvious advantage of having this high fidelity record is that the community of access to the exploration experience can be vastly expanded. One can have the exploration experience second hand in one of two ways. The actual experience could be replayed by putting on a head-mounted display and watching the entire experience. One could literally hear and see everything the original explorer did. Thus, other scientists could access the information in this way, as well as could the general public. The power of this technological capability for education is stupendous. Students at every level could have the thrill of participating in the exploration experience while learning in a very first hand way the mental processes and techniques used in field science.

An second way that other communities could examine the data is through the use of virtual reality to explore Mars using high fidelity models of field sites created with the aid of the data from telerobotic exploration. Thus, in virtual reality, one could roam around in the model terrain at will and each person could have a unique experience of the data. Thus, telepresence offers a tremendous enhancement of the capabilities available to perform field science on Mars.

Telepresence with Undersea ROV's

Operations in the undersea environment is a good training ground for developing technology to be used in space exploration. Exploration of the undersea environment faces many of the same constraints as exploration on a planetary surface. Extra-vehicular Activity on a planetary surface is conceptually similar to SCUBA diving where the capabilities of life support limit the range of human explorers. Teleoperation of Remotely Operated Vehicles (ROV's) is already widely used in the undersea environment, both for scientific exploration and for operational applications such as the inspection and repair of offshore oil rigs. Sophisticated underwater ROV's can be obtained "off the shelf" for relatively low cost. The level of teleoperation of such vehicles can be quite sophisticated and they are frequently equipped with multi-function manipulator arms and sampling devices as well as cameras.

We have developed a telepresence control interface for an underwater ROV and are using the Telepresence-controlled ROV (or TROV) to perform scientific field work in undersea environments. This vehicle and telepresence system is described in Gwynne et al. (1992) and is briefly summarized here.

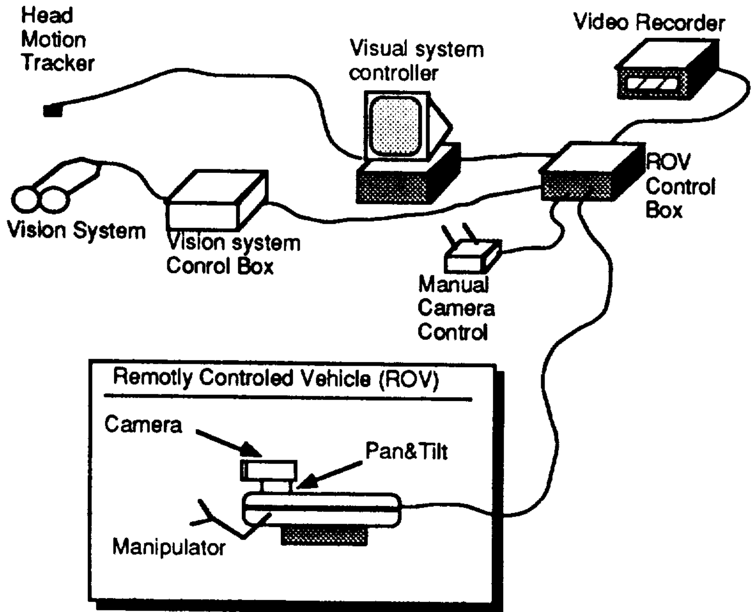

Figure 2. Conceptual layout of TROV system.

The TROV is based on an off the shelf underwater ROV SuperPhantom 2 built by Deep Ocean Engineering in San Leandro California. The ROV is capable of movement in four axes and can operate at depths up to 450 m. It weighs 68 kg has an operating underwater speed of 3 knots (1.54 m/s).The ROV is equipped with a 1,100 foot cable to provide power and communications from the surface to the ROV.

The thrusters which control the motion of the TROV are driven using a vehicle controller based on control-sticks. Mounted on the vehicle is a camera platform which can pan and tilt. A single video camera is mounted on that platform. The image from the video camera is sent to the surface via the electrical cable where it can be displayed on a variety of image display devices and is video recorded.

The position of the underwater camera is controlled by the motions of the operators head. The position of the operators head is tracked using a Polhemus 3SpaceTracker™. Signals from the tracker are fed into a computer and translated into commands to operate the underwater pan and tilt camera platform.

The images from the underwater camera are projected into a video display device which is worn in close proximity to the operators eyes and fills her/his entire field of view. Because camera pointing is controlled by head motions in real time, the result is spatially correspondent vision which gives the operator a strong sense of being present in the underwater environment.

We have experimented with a variety of head-mounted displays for use with the TROV. Relatively low cost head-mounted displays have been developed for the Virtual Reality (VR) market. Such systems are either based on Cathode Ray Tube technology or liquid crystal technology. Both have disadvantages and advantages for the telepresence application. In both cases, the fundamental limitation is the resolution available. Since the image is of a real scene projected close to the operator's eyes, it is important to have a very high resolution display. This is less important for the Virtual Reality application since the resolution of the Virtual image can be matched to the capabilities of the display. CRT's are relatively large and this can be a significant problem when the application calls for mounting the CRT on something that can be worn on the head . Very small CRT's have been developed for use in hand-held camcorders but they are black and white. Similarly small color CRT's are not available. LCD based systems are small and lightweight but have much less dynamic range than do CRT's. While low resolution LCD systems are available in the low cost range, their resolution is not adequate for our application.

We have developed a simple and low cost head-mounted display based on small black and white CRT's of the type used in camcorders. This system is capable of 200 lines of resolution and provides a 25° FOV. The main disadvantage of this system for doing field science is that it is black and white. A color image display system has also been developed by Bill Polhemus, a private inventor, working in close collaboration with our project staff. This system uses a fiber optic cable to project images onto a screen mounted in front of the operator's eyes. This system is thus capable of up to 1000 lines of color video and a 56° FOV.

In the current TROV configuration, an Amiga 2000 computer is used to supply heads-up display and video overlay of key information into the head-mounted display. The Amiga computer is also used to interface the Polhemus head tracker to point the underwater pan and tilt camera.

Antarctica: Field Operations in a Mars Analog Environment

The Telepresence project, and the TROV capability, was selected as a pilot project for a new program jointly sponsored by NASA and the National Science Foundation, to use the Antarctic as an analog environment to help develop and test systems for use in future space exploration. The goal of this project, held in the 1992 Austral Summer, was to perform an integrated demonstration of telepresence, advanced power systems, and satellite communications/data link to Antarctica.

The Antarctic field dates were October 15 - December 7, 1992. There were two distinct field phases, involving different operating conditions and crew. In the first field phase (held Oct. 22 - Nov. 21, 1992) the TROV was used to study the environment beneath the ice in permanently ice-covered Lake Hoare in the Taylor Valley on the Antarctic continent. In the second phase, (Nov. 23-Dec. 7) the TROV was operated under the sea ice in McMurdo Sound a few hundred meters off shore from McMurdo station, the main United States Research Base in Antarctica. During this phase, the principal objective was to demonstrate the capabilities of sending live video images from the TROV to Ames Research Center in Moffett Field, California via satellite. Each of these two phases will be described next.

Lake Hoare Study

Lake Hoare is a permanently ice covered lake located in the Taylor Valley, one of the dry valleys near the edge of the Antarctic continent. The dry valleys have been described as the most Mars-like environment on Earth. These environments are cold and dry, having less than 10 cm of precipitation per year and a mean annual temperature of -17C. Field teams spend up to several months at a time on scientific expeditions into the dry valleys. During these expeditions, the field teams must be self sufficient and are completely isolated from other groups and from any outside contract other than periodic radio communication with the central base. Thus, scientific exploration from a remote camp in the dry valleys of Antarctica is a strong analog to scientific exploration of Mars.

The main scientific interest in Lake Hoare is a microbial mat which lives in the bottom of the lake (Wharton et al, 1989 a,b). The environments in these lakes are thought to be similar to ice-covered lakes which existed on Mars in the ancient past. Wharton et al. (1989b) has discussed the potential that the biological activity found in these lakes could be analogous to biological activity in ice-covered lakes on Ancient Mars. Thus, studies of the environment in these lakes provide relevant information which points the way to a scientific approach for the future human exploration of Mars.

Lake Hoare had been previously studied by scientists using SCUBA but, due to the extremely hazardous conditions, the range that a diver can swim in the lake is limited to about 30 meters. The major obstacle to overcome in the exploration of these lakes is putting a dive hole through the three-meter-thick permanent ice cover. Typically scientist make very few dive holes during an expedition. The limited number of these dive holes severely limits the diver/scientists access to the lake.

On October 22, 1992, our six member crew was flown in by helicopter to Lake Hoare. In addition to the crew, helicopters delivered all equipment, food, fuel and supplies for a month-long stay. A solar power system, built by NASA Lewis Research Center, was also delivered to the field camp which supplied 5 Kw of clean, quiet electrical power to the field camp.

The Lake Hoare camp facilities include a small portable jamesway hut which serves as a central meeting area and place for food preparation. The hut is heated and provides a shirt-sleeve environment. The hut was equipped with electrical power (from the solar power system), and had a telephone line equipped with access to electronic mail. The only other camp facilities were a small plywood shed that serves as a laboratory, and an outhouse. The field crew slept in mountaineering tents near the hut.

The first order of business to enable scientific operations on the lake was to melt a hole through the 3 m thick ice cover for the TROV and SCUBA divers to gain access to the lake. A second portable jamesway hut was set up on the lake to serve as a warm operating environment for computers and electronics associated with the TROV, and a dive hole was melted near this hut. Equipment was moved around on the lake surface by loading it on sleds and man-hauling it across the lake ice. The surface of the lake ice is extremely rough due to differential melting of ice in the top meter of the surface. As a result, moving heavy equipment around on the lake ice is extremely laborious and time consuming. Because of this, and the amount of equipment involved, the TROV operations were confined to a single dive hole. In addition to this central hole, three more dive holes were melted at other locations on the lake to allow access by SCUBA divers.

The TROV was used to explore the lake within a 330 m radius of the operations hut on the lake surface. The range of exploration was set by the length of the tether which provided communications and power lines between the TROV and the surface.

The primary purpose of TROV operations was "telepresent" visual exploration of the lake environment, particularly the morphology of the algal mat and the geology of the lake bed. Lake Hoare is bordered on one end by the Canada glacier which extends to the bottom of the lake. The TROV was also used to explore and study the Canada glacier at the ice-water interface . The TROV was not equipped with a manipulator and so could not obtain samples of the sediments or algal mat at the lake bottom. Obtaining these samples was the primary purpose of SCUBA diving operations.

Each of the six team members spent some time operating the TROV with and without the head tracking and head-mounted display capability. Typical time spent exploring the lake environment with the TROV was 6 hours at a time. The lake depth in the accessible area varied from 10 m to 40 m. Thus TROV operations favorably compared with a SCUBA dive which is limited to less than an hour due to depth and air supply limitations. The capability to look around using the pan and tilt camera platform, having slew rates that matched head motions, was found to help maintain spatial orientation for navigating the TROV and for developing a mental map of the terrain. The resolution, contrast, and color capabilities of the vision display was found to be the key requirement for performance. The vision display system we used, and vision display systems in general, will need considerable improvement before they will be satisfactory for scientific work with telepresence.

TROV Operation in McMurdo Sound

After a month of TROV operations at Lake Hoare, all remaining food, fuel and equipment was repacked and transported back to McMurdo station on Ross Island. The TROV was then deployed at a dive hole located on the sea ice several hundred meters from the edge of McMurdo station. Electronic equipment was housed in a mobile trailer. Facilities for TROV operations in McMurdo were far more comfortable than the spartan conditions at Lake Hoare. McMurdo Station, the main US Antarctic research station, is a town with a population of 1500 people during the summer season. McMurdo contains most of the the amenities of civilized college life including dormatory-style housing, cafeteria-style meals, and a variety of organized recreational activities. Since the central purpose of the McMurdo facility is to support scientific operations in Antarctica, the station is very well equipped and staffed for doing so.

The main scientific objective for operating the TROV from McMurdo Sound was to evaluate whether the TROV technology would be a useful science tool for studying the organisms living on the sea bottom beneath the ice. The key technology objective was to test a newly installed capability to send live video from the TROV via satellite to the Continental United States (CONUS). A third objective, which was originally planned for a subsequent field season but which we were able to achieve, was to control some functions of the TROV from Ames Research Center via a satellite link.

The remote operation of the TROV from Ames involved the coordination of several different groups and projects. A telecommunications network to Antarctica had been set up by NASA Science Internet which involved the capability to send live video, in addition to the provision of telephone lines and internet access, all linked to CONUS via satellite. The TROV was driven using the local control console stationed on the McMurdo sea ice. The video image was patched by cable to a laser transmitter which sent the image to a receiving station in the center of McMurdo. The image was digitized, compressed, and sent via satellite to CONUS. Once received at Ames, the image was decompressed and broadcast where it appeared on the local NASA select television station. The pan and tilt camera platform on the TROV was operated by an operator at Ames. Control signals for the camera pointing were generated by using a head tracker to sense the head motions of an operator wearing a head mounted display receiving the images from the underwater camera. Coded head tracker position information was transmitted to Antarctica via modem line where it was fed into the controller computer and used to control the pointing of the underwater camera. The total time delay in the control of the underwater camera was 1 second.

Future Plans with TROV

Using the TROV to perform field science will influence the development and improvement of capabilities for this purpose and drive forward telepresence technology into greater maturity. We are continuing to upgrade the system and improve its capability for performing field work. We plan to perform a second Antarctic expedition in 1993 using the TROV with improved capabilities. In this next field season, the central focus will be to perform the bulk of the scientific exploration using telepresence control of the TROV from Ames Research Center. Figure 3 shows an artists concept of the planned TROV operations. The TROV will be equipped with stereo cameras and a manipulator arm. All functions of the TROV including control of its motion though the water will be operated from Ames. To eliminate the effects of time delay on control of the TROV, and to utilize the capabilities of Virtual Reality, the TROV will be first used to survey an area at high resolution. This information will then be used to construct a world model which will form an operating environment. Thus, the

Ames operator of the TROV will be able to explore in the virtual environment, while using this virtual environment exploration to send control signals to the TROV. The TROV will also be continuously sending the real time video signals back to Ames. Thus, the operator will be able to see both the virtual environment view and the real time view while operating the TROV.

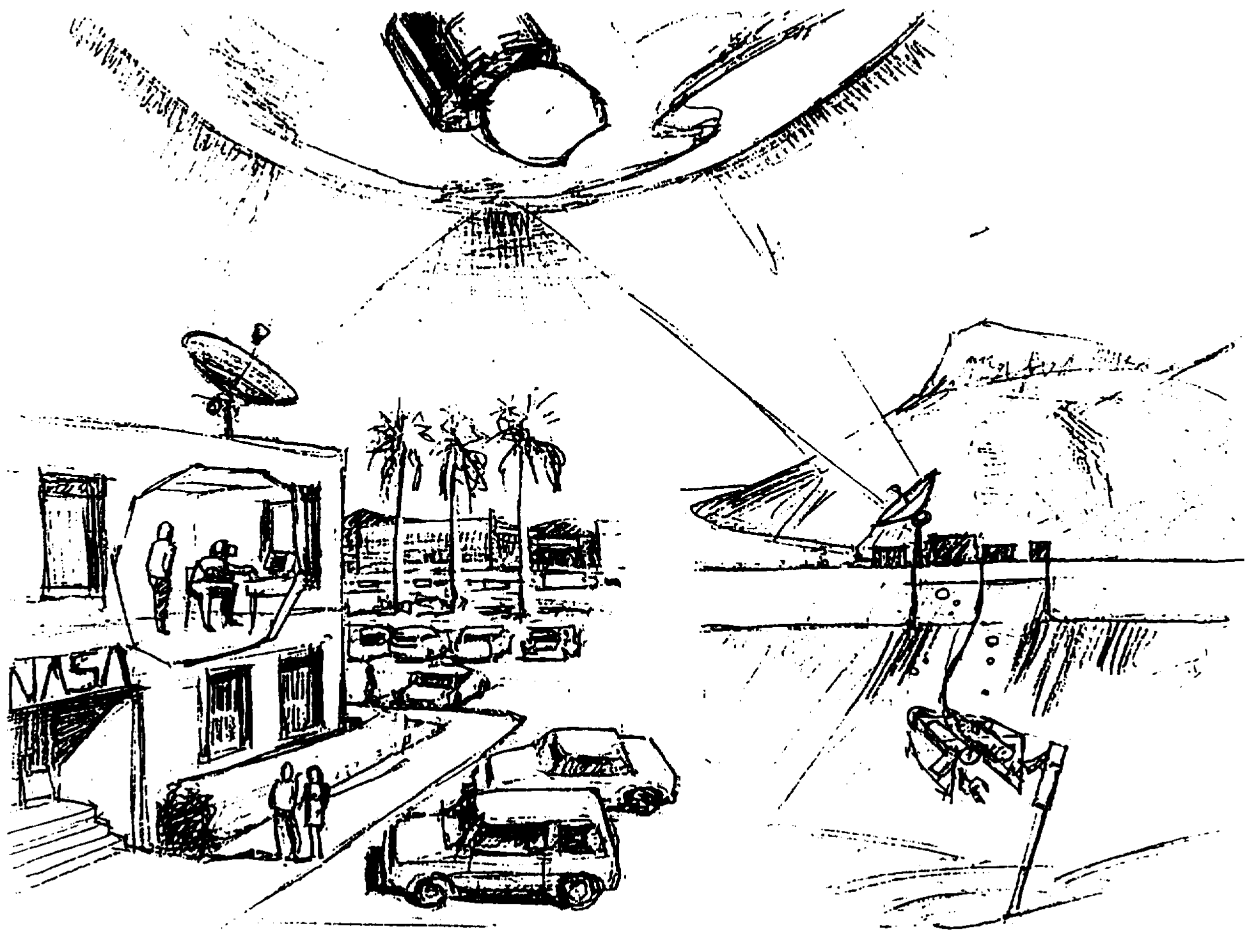

Figure 3. Artists concept illustrating the control of TROV in Antarctica from Ames Research Center

The 1993 Antarctic field experiment will be the first time that a virtual environment world model was developed and used in real time to perform a science task. There are many advantages to this approach. The requirements for sending data are reduced since, once a world model is developed, redundant images need not be repeatedly transmitted. The world model may also help to compensate for time delays. The operator working in the model environment will not experience a time delay in performing a task, but the actual task in the real environment may take place at a later time. In addition, sensor data other than vision may be overlaid on the visual record in the world model, thus provided correlated scientific information.

The strategy for telepresent field work planned for the next Antarctic field season closely approximates the strategy for operation of a remote vehicle at a distant location on Mars, either from a Mars base site or from Earth. Thus, the Antarctic field work is providing a valuable test bed for technology to be used in future Mars exploration.

Conclusions

Using telepresence to operate remote vehicles could lead to a revolution in the ability to perform science in hostile and extreme environments on Earth and could be an enabling technology for performing field science on Mars. Using telepresence now will lead to near-term scientific benefits as well as providing scientific drivers for the development of new and improved technologies for telepresent exploration. In addition, these field studies will lead to a better understanding of how to do field operations using telerobotics on Mars.

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