Experiments with an EVA Assistant Robot

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Abstract

Human missions to the Moon or Mars will likely be accompanied by many useful robots that will assist in all aspects of the mission, from construction to maintenance to surface exploration. Such robots might scout terrain, carry tools, take pictures, curate samples, or provide status information during a traverse. At NASA/JSC, the EVA Robotic Assistant (ERA) project has developed a robot testbed for exploring the issues of astronaut-robot interaction. Together with JSC’s Advanced Spacesuit Lab, the ERA team has been developing robot capabilities and testing them with spacesuited test subjects at planetary surface analog sites. In this paper, we describe the current state of the ERA testbed and two weeks of remote field tests in Arizona in September 2002. A number of teams with a broad range of interests participated in these experiments to explore different aspects of what must be done to develop a program for robotic assistance to surface EVA.

Technologies explored in the field experiments included a fuel cell, new mobility platform and manipulator, novel software and communications infrastructure for multi-agent modeling and planning, a mobile science lab, an “InfoPak” for monitoring the spacesuit, and delayed satellite communication to a remote operations team. In this paper, we will describe this latest round of field tests in detail.

1. Introduction

When humans finally travel again beyond low Earth orbit, they will be accompanied by a variety of robots to help ensure their safety and enhance their capabilities. The exterior of the spacecraft will undoubtedly be routinely inspected and maintained by robots, the life support system of the spacecraft will itself have many robotic characteristics, and when they land on the Moon or Mars, there will be robots to assist in constructing and maintaining the habitat and to help them explore. The work described in this paper is directed toward the last of these genres of robots: those that will assist crewmembers on a planetary surface. Recent studies conducted for NASA emphasize the importance of robotic capabilities for a successful expedition to Mars [6, 7].

Although most will agree that interplanetary human travel is still quite a few years away, it is not too early to begin experiments aimed at discovering the best ways that a robot can assist a spacesuited crewmember and understanding what kinds of tasks can be accomplished best by a robot-astronaut team. Technology will undoubtedly change in unimaginable ways in the next two decades, but if the infrastructure is not in place to provide an avenue for introducing and testing new technology in this context as it becomes available, there will be no hope for incorporating it when it becomes desirable. Not only does the technology need to be verified, but flight-certified hardware (e.g., spacesuit or habitat) may need to be modified to take advantage of it, crewmembers must know how to use it, and flight procedure designers and missions operations personnel need to understand its uses and nuances. One need only look at the technology currently in use in the Space Shuttle and International Space Station programs to get a feel for the time horizon needed to bring technology to full flight readiness for human-rated operations.

For the past four years, the EVA Robotic Assistant (ERA) project in NASA/JSC' s Automation, Robotics, & Simulations Division (AR&SD) has been developing a robotic testbed for this purpose. Working closely with JSC' s Advanced Spacesuit Lab, Exploration Office, and others, this project has emphasized field trials with a suited test subject in representative terrain as a way of understanding the true limitations of the astronaut-robot team, and how the robot and spacesuit can be improved to facilitate this collaboration. The focus of this paper will be field trials held near Flagstaff, AZ, during the first half of September, 2002, and the various partnerships that were able to take advantage of the ERA' s presence there.

The ERA robotic testbed is not meant to be flight hardware. Instead, it is intended to provide a means for testing techniques for interaction between a spacesuited individual and a robot, and discovering what qualities or capabilities the robot and/or spacesuit might possess to improve the effectiveness and safety of the overall team.

In Section 2 we provide some brief background on human-robot, and especially astronaut-robot, collaboration, touching on the more significant previous field trials. In Section 3 we describe the current state of the ERA robotic testbed, including some ideas for future improvements. Section 4 sets the stage by describing the various collaborations that the ERA team has been developing with other groups at JSC, other NASA sites, and with universities. Section 5 describes the 2002 field trials and the various experiments that were performed during the two weeks of tests. Finally, Section 6 summarizes the paper and acknowledges the numerous people from all the various teams who are involved with ERA and have helped to keep the project moving forward.

2. Background

2.1. Human-Robot Interaction

The topic of Human-Robot Interaction (HRI) has attracted a lot of interest in recent years. Many of the complex issues are summarized nicely in the final report of a DARPA/NSF workshop on HRI [13].

There are two main types of human-robot interaction. The first is tele-operation, where a dedicated human controls a remote robot to perform a task. There must be adequate sensor feedback to the operator for the task, and generally the fastest control loops are closed at the robot. The second is collaboration, where the human and robot work together in the same workspace to perform a task. Ideally, the robot is autonomous, but in some situations it may be tele-operated by a remote operator or controlled through communication with the human collaborator.

There is a vast literature on tele-operation of various sorts, concentrating primarily on the presentation of sensor data to the operator and situational awareness. Although the ERA robot is capable of tele-operation, the emphasis of the research has been on autonomous behaviors for collaboration. There are fewer research groups investigating human-robot collaboration, although researchers at MIT and CMU have developed robots that are expected to interact with people in their space [3, 15]. Generally, however, these robots are not expected to *physically* interact with people or environment. In contrast, an EVA assistant robot may be expected to carry, manipulate, collect, present, and receive objects with humans in its workspace.

2.2. Astronaut-Robot Collaboration

A crewmember in a spacesuit is severely constrained in many ways. Dexterity, stamina, strength, field of view, audition, tactile sensitivity, and range of motion are all limited by the suit. The Portable Life Support System (PLSS) adds considerable mass and bulk. Most importantly, there is a hard time limit by which the crewmember must return to the habitat or risk running out of life support. A robot can assist a suited crewmember in many ways: by scouting terrain and finding paths, carrying tools and samples, acquiring samples, deploying cables, photo and video documenting, providing a presence for remote experts, monitoring the status of the traverse and PLSS, and watching the health of the crewmember. NASA researchers have only recently begun conducting field trials with robots and high-fidelity test spacesuits to explore these possibilities.

The first such field tests were the AStronaut-ROver (ASRO) experiments in California in early 1999. During these tests, the Marsokhod robot was used to assist a suited test subject in several scenarios. The most important lesson learned was that the robot must be able to keep pace with the human it is assisting. Marsokhod, designed for low power, was simply too slow to be useful as an assistant. The ASRO field tests are described in detail in [11, 16].

In the fall of 2000, the ERA team and Advanced Spacesuit Lab conducted two weeks of field tests in Arizona for the first time. Three scenarios were tested: power cable deployment, solar panel deployment, and pack mule. In each of these, the robot used a different autonomous behavior and interacted differently with the test subject. The 2000 field tests are described in detail in [4, 12]. Lessons learned from ASRO and these first ERA field experiments have led to many improvements in the robot and its current capabilities as an EVA assistant, as well as some modifications to the test spacesuit.

3. ERA Robot Description

The ERA robot testbed, nicknamed “Boudreaux”, is always changing as different components and capabilities are added or removed, depending on the state of testing and tailored for the various scenarios. This section describes a core set of hardware and software that has become standard, with some others that were present for the 2002 field trials.

3.1. Hardware

The ERA testbed began as a commercial 4-wheeled base from RWI, Inc. (Now part of iRobot, Inc.). This base was modified for the 2000 field season with the addition of a tower to support a camera platform and a rigid suspension that moved the wheels down and out to add clearance and stability. By the 2002 field tests, only the lower shell and motor and drive mechanism of the original robot remained. All electronics and the entire upper deck had been redesigned to increase robustness. As an indication of the intention to have this robot do real physical work, the ERA base has had a trailer hitch as standard equipment from the beginning.

The new "upper deck" of the robot supports all the processors, sensors, radio equipment, and cameras. The upper deck is designed to be an independent module, with only power coupling it to a mobile base. This allows the ERA team to experiment with new base designs that have different capabilities, such as the one described in Section 4.5.

Current onboard devices include a laser range finder, IMU with built-in compass, stereo camera pair for tracking the astronaut mounted on a 2-DOF platform, stereo camera pair for obstacle detection and terrain mapping, speech synthesizer, Differential RTK GPS (accuracy: 2cm), 802.11b wireless ethernet, wireless audio communications link, three Pentium 4 laptops running Linux, a PC-104 K6-2 (also running Linux), and an ethernet switch.

After the 2000 field trials, it was decided that the resilience of the robot would be improved by replacing the three on-board computers with industry-standard embedded PC-104 canisters with solid-state (compact flash) hard drives. These would save power, take up less space, and be less susceptible to the bumpy terrain. Unfortunately, recent experience has shown that available PC-104 technology is not yet able to meet the integration challenges of this project (heat, interface limitations, throughput limitations, etc.). Instead, the upper deck has been modified to accommodate three laptop computers.

The 2000 field tests also revealed the need for the testbed to be able to manipulate its environment. This would enable tasks where the robot interacts physically with the astronaut or environment, through tools or rock samples. A 7-DOF manipulator designed by Metrica Inc., was added, along with a 3-fingered hand made by Barrett Inc. (See Figure 1).

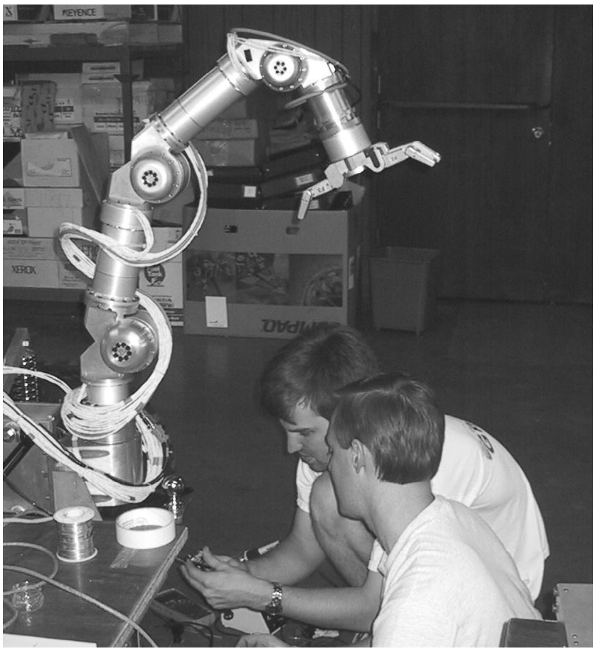

Figure 1: Preparing the 7DOF manipulator and Barrett Hand for field work.

3.2. Software

The software architecture of the ERA testbed is written in C++ and consists of a number of CORBA clients and servers. Due to the modular nature of the hardware, it is critical that the software be modular in a similar way. The CORBA servers are arranged in a functional hierarchy. Thus, at the lowest level, there is a server dedicated to each of the sensors. Next there are servers for each capability that uses the sensors, such as tracking, path planning, speech recognition and generation, and so on. The servers higher up the hierarchy interact at correspondingly more abstract levels.

3.3. Capabilities

The ERA has multiple autonomous capabilities that reduce the physical and cognitive load on the human partner, such as tracking, mapping and science instrument deployment, and monitoring and annunciating situational awareness. Various sensors can be used to track/follow the human subject: stereo cameras, laser rangefinder, or differential GPS. Although the laser was the primary sensor used in the recent field tests (it proved highly reliable and consistent), any of these sensors can provide the human' s position to the robot. The tracking server then uses this position data to direct the robot to follow the human, maintaining a given, user-adjustable, distance from the person. Details on this tracking capability, including a discussion of the different sensor inputs, can be found in a companion paper [9].

The ERA platform is also able to generate a map of the traversed area as the robot progresses. This map includes terrain information as seen by the robot, and can be supplemented by user-defined areas such as a habitat zone. The pose information gathered by the robot (of the astronaut, the robot, waypoints, etc.) can also be combined with this map to allow a remote user to see the layout of the field, and to generate information such as the current distance between astronaut and habitat.

Autonomous science instrument deployment was also implemented for the 2002 field tests. In response to a single command, the robot could ready its arm from the stowed position, grab the geophone sensor from the body of the robot, place the geophone in the ground, and return to the stowed position.

4. Collaborations

The ERA testbed has become an important research tool for several different groups in NASA and in Academia. It is rare to find a field-ready robotic platform capable of handling planetary analog terrain, and even more rare to find a high-fidelity spacesuit in the field. As a result, no fewer than fifteen different groups were associated in some way with the 2002 field season. Although it was difficult to coordinate such an assembly of teams and some efficiency was undoubtedly lost, it seemed better to take this opportunity as it presented itself: budgets being what they are, the next major field expedition may be another two years away.

Since inception, the core of the ERA team has been composed of researchers at NASA/JSC from two branches within the Automation, Robotics and Simulation Division (AR&SD): Intelligent Systems and Robotic Systems Technology. This collaboration has provided the team with expertise from both "camps" of robotics: AI Robotics and ME Robotics.

4.1. Advanced Spacesuit

The Advanced Spacesuit Lab (EC5, within JSC’s Crew and Thermal Systems Division) provided the spacesuit (and test subject) for the ASRO field trials described in Section 2. The ERA project was started to address some of the shortcomings of the Marsokhod robot for this line of research, and the ERA team continues to work closely with EC5. The teams meet regularly to discuss, specify, and implement modifications or improvements to each other’s hardware that could facilitate the interaction between suited crewmember and robot.

4.2. Communications

After the 2000 field season, a collaboration was formed with researchers at Glenn Research Center (GRC) and Kennedy Space Center (KSC) to improve the communications systems used by the spacesuit team for safety and for spacesuit-robot communication. The primary task was to replace the radio network used for voice communication between the test subject, robot, safety crews, and command crews. At the same time, custom DSP and audio hardware was developed to improve the quality of the voice signal coming from the suit to a level where the robot’s voice recognition software could operate successfully. This partnership also led to the involvement of GRC’s satellite communications group, and field experiments in delayed communication with a remote operations group (see Section 5.7). Although they played a relatively minor role in the 2002 field tests, follow-on field experiments are currently being planned, and eventually it is hoped that JSC’s ExPOC (Exploration Planning and Operations Center) will take an active role in introducing the Mission Operations community to the issues of significantly delayed communications and dealing with multiple autonomous robots as members of an EVA team. The ExPOC research team has previously studied delayed mission operations as part of the Haughton-Mars Project [8, 10].

4.3. Mobile Agents

The ERA testbed is one of several technologies being integrated in Ames Research Center’s (ARC) Mobile Agents project. This project seeks to use the Brahms multi-agent modeling and planning system to provide software agents that can facilitate communication between people and system components distributed across a network. The Mobile Agents Architecture (MAA) pulls together the ERA testbed, Brahms, the Mobile Exploration (MEX) communications architecture, the RIALIST spoken dialog interface, and Stanford’s spacesuit Biovest. The Mobile Agents project provided partial funding support to the ERA project, and all of the groups mentioned above were present and active during the 2002 field tests (See Section 5). The MAA is described in [5, 14].

4.4 Fuel Cell

One limitation of the current robot configuration has been the short battery life of the system. During the field trials in 2000, the usable battery life was roughly 90 to 120 minutes. The ERA project welcomed the opportunity to collaborate with a group from JSC's Power Systems Division (EP) to incorporate a fuel cell into the testbed. The IHOPP (ISRU Hydrogen/Oxygen Power Plant) is the first stage in a research effort to develop fuel cells that can operate using Martian in-situ resources. The current hydrogen/oxygen fuel cell design can supply 2kW for over 11 hours, greatly improving the stamina of the robot. In return, the IHOPP team gained experience with remote field-testing, as will be described in Section 5.4. The EP team has presented the IHOPP results in [1].

4.5. New Mobility Base

Despite improvements that had been made to the mobility and clearance of ERA's commercial base for the 2000 field trials (see Section 3), it was decided that the only way to address its traction, steerability, and suspension limitations would be to redesign it. This led to collaboration with the Special Projects branch of AR&SD. The new base was designed to accommodate the IHOPP, with a low center of mass, support the ERA's modular upper deck without modification, and used off-the-shelf suspension and steering linkages from the ATV industry. The result has 4-wheel independent suspension and drive with independent forward and rear steering. Field-testing of this new base is described in Section 5.5.

4.6. Exploration Office and NExT

JSC's Exploration Office (EX) has played an active role in designing experiments and scenarios and collecting quantitative data during the field tests. EX established contact with the geologists at UTEP who provided the geophone science instruments (and a graduate student with expertise in operating them) for the geophone deployment task (See Section 5.1).

The NASA Exploration Team (NExT) has helped guide this effort, and has fostered discussion with researchers at JPL regarding the fundamental tradeoffs of human/robot collaboration in space exploration.

5. Field Tests: Arizona, September 2002

Having described in the previous section many of the teams that participated in the 2002 field season, it is now possible to describe the field tests and the experiments that were performed. As mentioned in Section 4, there were a lot of people to coordinate.

5.1. Geophone Deployment

The primary experiment of the 2002 field tests was the Geophone Deployment. This experiment was conducted under several different conditions: astronaut alone, astronaut with robot assistance, and robot alone.

A geophone consists of a cylindrical housing for electronics and an attached spike. The spike is placed in the ground and the electronics record seismic data for later download to a computer. In our experiment, twelve geophones were deployed in a straight line – one every 20 feet. Next, a geologist created a ground percussion by striking a plate with a mallet, thus producing a signal for the sensors to read. Geophone retrieval was not part of the experiments.

Separate deployments were conducted by a shirt-sleeved human, a space-suited human, and the robot. During the human runs, the geophones were carried on a trailer that was pulled either by a human in an ATV or by the robot (see Figure 2). The objective was to measure the performance of each of these "agents" to help determine the optimal mix of humans and robots on a team.

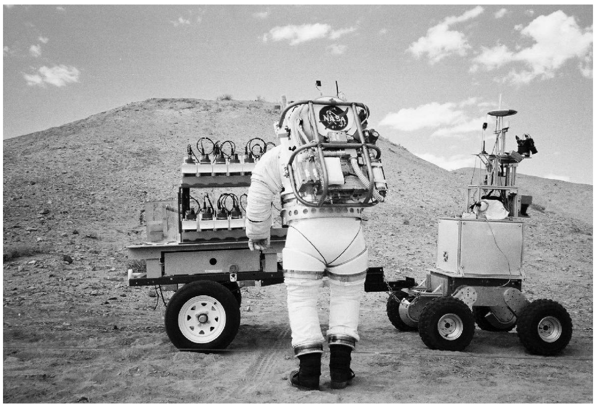

Figure 2: The suited test subject retrieves a geophone from the trailer, pulled by ERA.

The robotic assistance consisted of the robot tracking and following the human while pulling a trailer with the geophones. In the autonomous robot case, the robot followed a human while carrying a single geophone. Upon command, the geophone was grasped and placed in the ground with the manipulator using open loop control. A human then loaded a new geophone onto the robot before the next placement. (This was necessary because the project did not have the resources to engineer a geophone-dispensing caddy.) Unfortunately, the open-loop nature of the geophone placement rarely got the height right on the rough terrain, often causing the robot's hand to stall because it was pressing too hard. One of the lessons learned from the autonomous robot tests is that we need a force sensor in the arm if we want to perform tasks such as science instrument deployment. Due to various difficulties in the field, numerical data were only collected on five runs, none of which had the ERA operating autonomously. Since this is not enough for statistical significance, the data are not presented here.

5.2. Geology Traverse

A second series of tests, performed at Meteor Crater in Arizona, consisted of a suited human subject traversing difficult terrain and being assisted by an autonomous robot. The robot followed the human using the laser range finder (tracking using GPS has been demonstrated in limited field tests, and vision-based tracking was used extensively in the 2000 field tests). The traverses lasted about 20 minutes and the robot was autonomous about 90% of the time (it was controlled remotely via virtual joystick during small parts of the traverse (primarily because the tracking software did not have obstacle avoidance or inertial sensors functioning). The robot carried tools and samples during the traverse to assist the suited subject. Also, the robot performed excellently in a first-ever nighttime traverse conducted to test the ability of robot and suit subject when visibility was low.

One interesting enhancement to the Geology Traverse scenario was the "Mobile Science Lab". A number of science instruments, including a rock crusher, microscope, and computer were mounted on a trailer, which was pulled by either by the robot or the ATV. The science trailer is described in [2].

5.3. Mobile Agents and Taking a Picture

Ames Research Center's Mobile Agents (MA) project is an ambitious multi-year effort to integrate a number of technologies into a complex mission scenario. The goal of the first year, which culminated at the 2002 field trials, was to test integration of all the systems by having the space-suited crewmember ask the robot to take his picture. Although this initially sounds simple, it exercises all of the components of the Mobile Agents Architecture and several major components of the robot, and is a very good first step toward the final goals of the MA project.

For the robot's part, stereo vision, target tracking, pose determination, persistent logging of imagery, resource arbitration, and interfacing with the Brahms external software agents are all exercised. The "take a picture of me" scenario requires Brahm's voice recognition of the spoken command, event coordination, state maintenance and interaction among its various agents and proxy agents. Integration testing between ERA and Brahms went well in the laboratory and outside at JSC's Simulated Planetary Surface (Mars Yard). During the field trials however, radio frequency interference and software configuration issues prevented successful execution.

Figure 3: ERA pulls IHOPP, which provides all power to the robot.

5.4. Fuel Cell

The IHOPP was demonstrated powering the new base (see Section 5.5), but problems with the new base software initially prevented its use in the field. Instead, the fuel cell was used in the field on a trailer pulled by the ERA testbed and supplying all of the robot's power (see Figure 3). Unfortunately, a crimped hose led to a fatal leak in the system that terminated the field tests for the IHOPP team. However, they did collect enough data to be satisfied with the performance of the fuel cell, and were able to demonstrate it powering both of the ERA mobility bases.

5.5. New Base

Although the new base was not demonstrated in the field with the fuel cell, it performed well with sealed lead-acid batteries. In fact, it was able to transport two people at decent speeds (for a robot) over rough terrain. In one geology traverse experiment (see Figure 4), the shirt-sleeved human with InfoPak was followed autonomously by the ERA testbed (old base), which was followed by the new base under tele-operation (there was only one upper deck, so both robots could not track targets). The success of the new base in the field has led to new interest at JSC in a testbed unpressurized transport rover in the context of further exploring HRI.

Figure 4: Shirt-sleeved human wearing InfoPak is tracked by ERA, which is followed by the new mobility base.

5.6. InfoPak

The InfoPak is an add-on to the spacesuit's PLSS backpack, and contains a PC-104 computer connected to the wireless 802.11b network. It also has a GPS antenna and connections to sensors on the suit. It relays the GPS location and vital health info of the suit subject to the ERA, improving situational awareness. The ERA is capable of annunciating vital suit status (such as remaining life support), performance data including various temperatures, pressures and heart rate, and alarms signaling events such as time to return to habitat. During (or after) the EVA traverse, the GPS locations can be plotted to provide a detailed map of path taken by the suit subject. Additionally, the PC-104 Computer in the InfoPak can process the voice commands from the Astronaut directly via a hardwire connection to the suit microphones, and eliminate any noise that would be introduced by wirelessly transmitting the voice to be interpreted at a remote location. This improves the reliability and quality of voice commanding, which is a very important part of HRI.

5.7. Remote Communication and Satellite link

Twice during the course of the experiments a satellite link was established between the field site and the JSC's ExPOC by way of GRC (see Section 4.2). Researchers at GRC inserted varying delays of up to five minutes into the audio link to test the ability of a remote science team to communicate meaningfully with an expedition. In one experiment, they were communicating with the suited test subject during a geology traverse. In the other, the robot was conducting an autonomous geophone deployment (see above). Although no hard data were collected by ExPOC, these experiments should provide the mission operations specialists with insight into the issues of dealing with delays and a remote autonomous robot and help them design future quantitative experiments.

6. Summary

Many teams participated in the 2002 field tests. Despite some failures, most teams were able to collect enough data on their subsystem to consider it a success. This is shown by the number of publications that are based to some degree on results obtained during these tests [1, 2, 5, 9, 14, and several others still in the works].

Perhaps the most important lesson learned during the 2002 field tests is one of process: that the more subsystems there are, the more conservative and flexible the overall schedule needs to be. At the same time, however, each team needs to adopt and follow strict procedures for the maintenance and deployment of their equipment. Together, these strategies should minimize avoidable problems while providing the overall group the best opportunity to mitigate the unavoidable problems. The likelihood of something failing and the possibility of unintended interaction between disparate systems both increase drastically with the number of teams. This problem is compounded when hardware development schedules and project budgets preclude much prior integration testing. For instance, despite the best advance efforts by the appointed "Frequency Manager", nearly two days at the start of the field tests were lost to RF issues. This, combined with bad weather and an ambitious but rigid agenda, led to a sense of being behind during the remainder of the experiments.

It is virtually impossible to name everyone who ought to be acknowledged for their assistance on the ERA project, but the complete author lists of [1,2, and 5] provide a start. [5] includes a good list of those who assisted the Mobile Agents effort. At JSC, Ken Baker and Genevieve Johnson were members of the core team for several years. The ERA project has been supported by internal JSC (CDDF) seed funding, CETDP Thinking Systems and Surface Systems, Code R discretionary funding, The NASA Exploration Team (NExT), and the Mobile Agents project. The USGS provided facilities in Flagstaff as a base and staging area for the JSC teams, which was greatly appreciated.

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