INTELLIGENCE FOR HUMAN-ASSISTANT PLANETARY SURFACE ROBOTS

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1. INTRODUCTION

Robots will require intelligence to succeed in the uncertain and changing environment on lunar and planetary surfaces. Even with humans directly involved in controlling such robots, individual robotic intelligence is still needed. In fact, robotic intelligence may be even more necessary in human-robot collaborative work than for robots operating alone. In addition to knowledge of terrain and task, human-interacting robots also need knowledge of human needs and the ability to respond to human commands, movements, and dynamics.

Planetary surface robots are necessary to perform the more dangerous tasks and to provide a level of physical capability that space-suited humans cannot provide during an EVA (*E*xtra *V*ehicular *A*ctivity) on a planetary surface. The research goal of the ERA (*E*VA *R*obotic *A*ssistant) Project in the Automation, Robotics, and Simulation Division (ARSD) at NASA's Johnson Space Center (JSC) is to develop robots capable of providing effective and time-saving assistance to astronauts [1]. Our approach is centered on Earth-based field testing with humans and robots working together, in order to best learn what intelligence, capabilities, mechanical design and support systems should be used on future planetary robots. Highly focused remote field tests are combined with continual local subsystem testing, robot hardware and software development, and consultation with exploration scenario experts (i.e. NASA astronauts, scientists, engineers, and university research professors).

The central premise in developing *effective* human-assistant planetary surface robots is that robotic intelligence is needed. The exact type, method, forms and/or quantity of intelligence is an open issue being explored on the ERA project, as well as others. In addition to field testing, theoretical research into this area can help provide answers on how to design future planetary robots. Many fundamental intelligence issues are discussed by Murphy [2], including (a) learning, (b) planning, (c) reasoning, (d) problem solving, (e) knowledge representation, and (f) computer vision (stereo tracking, gestures). The new "social interaction/emotional" form of intelligence that some consider critical to ***H***uman ***R***obot ***I***nteraction (HRI) can also be addressed by human-assistant planetary surface robots, as human operators feel more comfortable working with a robot when the robot is verbally (or even physically) interacting with them. Arkin [3] and Murphy are both proponents of the hybrid deliberative-reasoning/reactive-execution architecture as the best general architecture for fully realizing robot potential, and the robots discussed herein implement a design continuously progressing toward this hybrid philosophy.

The remainder of this chapter will describe the challenges associated with robotic assistance to astronauts, our general research approach, the intelligence incorporated into our robots, and the results and lessons learned from over six years of testing human-assistant mobile robots in field settings relevant to planetary exploration. The chapter concludes with some key considerations for future work in this area.

2. PROBLEM STATEMENT

2.1 The Problem

When humans travel to live and work on the Moon or Mars, they will have many tasks to perform. They will need to transform their base camp into a safe habitat, possibly including the placement, construction, and installation of power sources, communication relays, in-situ resource extraction facilities, greenhouses, and "safe havens" to retreat into during times of intense solar activity. They will need to maintain and repair this entire infrastructure for the duration of their stay – a vital task which will become increasingly difficult with longer duration missions. In addition to these housekeeping tasks, the astronauts will need to pursue their goals of exploration and discovery in the surrounding environment. One of the biggest challenges to this slate of tasks is that humans will be limited to working in spacesuits when outside. Suited astronauts will have limited visibility, dexterity, and strength, as well as limited work durations due to fatigue and limited air and power reserves. Additionally, the astronauts will have a limited ability to carry and use all the tools and instruments required to safely perform their work.

Thus, robots enter the picture to provide much-needed support [4]. The key aspect of our research is HRI, in the context of teaming to perform EVA tasks. Our approach is a top-down holistic strategy involving all salient aspects of realistic scenarios, including analog surface environments, habitats, advanced space suit subjects, remote science teams, and autonomous robots. However, robots also introduce a new host of constraints and challenges, and this is the source of our research topic.

An important aspect of HRI research is understanding and identifying the best compliment of humans and robots for a given task—just as one would want the "best" team for the job, we need to choose the best mix, types and quantities of robots and humans. One approach is to somehow measure the effectiveness of various team compositions on a given set of tasks. Even this is difficult, since tasks must be reduced into primitive actions that can be performed by several candidate teammates, and then performed by the various humans and robots while being able to measure their effectiveness. Task decomposition into primitive actions is discussed in various sources including [5], and potential HRI metrics in [6, 7, 8].

2.2 The Motivation

Robotic intelligence and autonomy are needed to allow *effective* HRI to take place. For robots to work *effectively* with humans on planetary surfaces, they require some level of intelligence in at least four areas: two-way communication with humans, safety awareness, self-maintenance, and self-monitoring. While some aspects of these of these requirements can be accomplished with simple, straight-forward software and hardware, our field research to date has shown that the more intelligence that robots possess, the more effective they will be in their tasks.

To work alongside humans, robots will need to communicate with them in intuitive (and spacesuit compatible) ways. Astronauts will be communicating with each other as well as with robots, so similar language, communication protocols, and voice loop hardware for both human and robot agents will reduce confusion and allow more flexibility. Robots will need to distinguish commands directed toward them from all other communication. Robots will need to respond to various sources of commands, whether from speech, gesture, or direct computer controls, and whether from nearby or distance sources. Space-suited astronauts will need to issue commands with some glove-friendly method, such as voice or gestures. Many commands will require confirmation of some type to prevent execution of misinterpreted commands caused by the noisy environment, echoes, static, or recognition errors. Such confirmation will need to be understandable by the humans, and responsive to the current amount of activity on the voice loop. Some commands may also require or naturally involve gesturing to indicate the subject or object of the command (deictic gestures). All commands need to be succinct and yet still clear, even when detailed instructions are required.

Robots will need to respond to human commands and at the same time, maintain their own safety and prior task assignments. In Figure 1, a robot is shown during field tests in a canyon in Utah, USA. The robot is pulling a trailer and avoiding obstacles, while at the same time following the astronaut and being responsive to new voice commands such as taking snapshots. This situation also introduces another constraint: robots need to be safe for humans to work with side by side, especially when the humans are in spacesuits in a hazardous environment.

Figure 1. Robot performing multiple parallel tasks during an extra-vehicular activity simulation

Other constraints deal with maintenance of the robots. Such maintenance needs to be user-friendly, considering the scarcity and possible lack of any “shirt-sleeve” repair environments. Remote maintenance or even self maintenance is highly useful, especially for minor issues such as power cycling components and restarting subsystems.

Monitoring of robot status needs to be simple and not time-consuming, as astronauts inside and outside the habitat have little extra time to devote to such monitoring. Astronaut EVA time in particular is very limited and precious. And because of time delays, even an army of humans staffing an Earth-based mission control will not be able to provide the timely responses for missions to remote sites such as Mars. Robot self-monitoring would be best, with the robot able to respond, adjust, or repair itself autonomously, or else to alert humans if functionality is at risk of failing, has failed, or can continue in a degraded mode. Even local monitoring by astronauts in the vicinity may not be consistently available due to the fragility of the newly established, resource-limited infrastructure. Thus, at times, a robot will need to be able to carry out tasks on its own during periods without any external monitoring or control.

Other authors also discuss the need for autonomy and robot intelligence in future planetary exploration missions. An extensive survey determined that key challenges for robots include robustness, human-robot interaction, and the ability for robots to handle mission-level objectives [9] [10]. Common sense reasoning, the understanding of human intentions, and the ability to execute complex plans in uncertain environments are all needed for human-assistant exploration robots. Longer duration missions in which human operational control is minimized will require more knowledge and understanding on the part of the robot. While human supervision and anomaly response will still be needed, systems must be automated more and more in the future in order to reduce the overhead for human crew members [11].

All these constraints and challenges will require intelligence to some degree on the part of the robot. The more intelligence the robot is given, the more efficient and productive such robots will be. Ultimately, robots need to operate on the same level as humans to be the most accepted and utilized during complex, joint human-robot space exploration missions.

3. RESEARCH APPROACH

Aside from knowing the issues and goals described above, we must determine how to begin work in this research area. Without the resources to experiment in space as a first step, we must locate and use effective test-beds here on Earth. The questions which need to be asked include:

- What robotic tasks or capabilities are really useful to astronauts?
- What level and type of interaction is best or most useful?
- What is the best mix of robots and humans to successfully execute a given task?
- If needs vary between individuals, what range of behaviors are expected?

We maintain these questions are best answered using the “practice like you play” approach – by field testing realistic scenarios in space-relevant environments, with experts in the fields of exploration, science, and habitat construction serving as astronaut test subjects (including actual astronauts). Additional guidance comes from continual discussions with exploration scenario developers and astronauts, and researchers in related areas such as advanced spacesuit design, voice and data communications, infrastructure development, human-robot interaction, and logistical and mission support.

3.1 Robotic Capability Requirements

Identification of desirable tasks and capabilities for robotic assistants is coupled with ongoing improvement of already developed capabilities. Robustness and reliability are key components of the overall utility of such robots. Without reliable behavior, humans will not be able to depend on their robotic assistants and will naturally tend to seek out alternative means of support, even if those means are less productive, less efficient, or introduce greater risk to the humans. The reliability needed is not only in hardware, but in software as well. Adaptability is a partner to this type of reliability, as it requires the ability to adapt to subtask failures or plan changes. One of the key advantages of human explorers is their ability to quickly evaluate situations and to change their plans to fit any new facts or issues that arise [4]. Robots assisting humans will need this same ability to adapt.

While robots operating alone can perform tasks at their own rate, human-assistant robots need to perform at a speed or pace matching that of human activity. Just as with reliability, without robots that can keep up, astronauts will seek out other tools to use. Part of our research is developing robots that can provide the needed services at the needed time.

Robot Capabilities Matrix

		ROBOT PLATFORM		
		Boudreaux	Thibodeaux	SCOUT
CAPABILITIES	Teleoperation	√	√	√
	Full autonomy	√	√	√
	Point-to-point navigation	√	√	√
	Human following with stereo vision	X (possible with added HW)		√
	Human following with GPS	√	√	√
	Obstacle avoidance	√	√	√
	Autonomous Scouting and Mapping	√	√	×
	Manipulation (robotic arm, hand)	√	√	×
	Trailer-towing	√	√	√
	Tool carrying	√	√	√
	Passenger Carrying	×	×	√
	Watching	√	√	√
	Natural Language Understanding	√	√	√
	Speech Synthesis	√	√	√
	EVA traversal maps, MET	√	√	√
	Differential (Skid) Steering	√	×	×
	All-Wheel-Drive	√	√	√
	Front-wheel steer	×	√	√
	Rear-wheel steer	×	√	√
	Night-time driving	×	×	√
	Offboard camera control	√	√	√
	Video Feedback	√	√	√
	Wireless connectivity	√	√	√
ONBOARD COMPUTING	Laptop1	1.9GhZ P4M	1.9GhZ P4M	2.4GhZ P4
	Laptop2	1.9GhZ P4M	1.9GhZ P4M	2.4GhZ P4
	Laptop3	Open	Open	3.6Ghz P4
	Laptop4	×	Open	Open
OPERATING SYSTEMS	Linux	√	√	√
	Windows XP	×	×	√
PROGRAMMING LANGUAGES	C++	√	√	√
	Java	√	√	√
COMMUNICATIONS APIs	CORBA (primary)	√	√	√
	NDDS	×	×	√
	Raw Sockets	√	×	√
SENSORS	Differential GPS	√	√	√
	Inertial Navigation Unit	√	√	√
	Voltage/Current/Power	√	√	√
	Velocity	√	√	√
	1394/Firewire Cameras	√	√	√
	Drive motor temperature	×	×	√
	Steering motor temperature		×	×
	Steering limit switches	×	√	√
	Web Camera	×	×	√
ACTUATORS	Pan-tilt cameras	√	√	√
	7DOF Arm+Barrett 3Finger Hand	√ (shared)		×
	Drive motors	√	√	√
	Steering motors		√	√
	Software power control of devices	√	√	×
SPECIFICATIONS	Height (m)	1.9	1.9	2.75
	Width (m)	0.95	1.25	2
	Length (m)	1.25	1.5	2.75
	Weight Ready-To-Roll (kg)	180	180	1150
	Max Velocity (MPH)	2	20	7
	Approximate Available Payload (kg)	45	90	90
	Endurance (hours)	4	TBD	4
	Ground Clearance (cm)	35	25	33
	Onboard Crew Size	0	0	2
	Towing capacity (kg, at ½ max slope)	70	TBD	TBD
	Max obstacle size (cm)	35	35	35
	Max slope (degrees)	40	20	10

Table 1. ERA Robot Capabilities Matrix

Physically and mechanically, ERAs must possess the strength, endurance, speed and traversability that matches or exceeds their human teammates. Table 1 outlines the capabilities of three such robots used in our research.

3.2 Robotic Intelligence Requirements

Robotic intelligence can help in achieving these goals of reliability and maintaining a proper pace. In order for a robot to be reliable in an unknown environment such as on a planetary surface, that robot must have adaptable software which can determine how to respond in unforeseen situations. Such adaptability is a form of intelligence involving reasoning, decision-making and fault tolerance. When humans are involved as well, robotic intelligence often needs to adapt to whatever course of action the humans decide to pursue at any given time. For maintaining a proper pace, intelligence can allow a robot to plan ahead in order to help compensate for any physical limitations. If a robot cannot travel as fast, or along the same obstacle-strewn course as a human astronaut, intelligence can aid the robot in several ways. The robot could predict when it will be needed and arrange its tasks such that it can be where it is needed when it is needed. The robot could plan its own paths, travel at its own rate, and meet up with the human astronauts at a later time without having to be guided directly by the astronauts as they travel. The robot could also plan an alternate, more manageable route, and meet the human astronauts beyond any impassable terrain.

Independence is another key issue for human-assistant space robots, closely linked to the need for intelligence. As mentioned earlier, astronauts' time is very precious and limited. Earth-based controllers are limited by time delays and often possess inadequate sensor feedback. The more robots can do on their own, the more helpful they will be to astronauts and their exploration goals.

3.3 Practical Issues and Constraints

In order to identify, develop, and test the requirements identified above, appropriate field testing is needed. While initial theoretical and laboratory based testing is necessary and useful, along with discussions with experts in multiple subjects, in order to move robotic assistants into practical use, field testing in relevant environments is required. Space-relevant, or planetary-analog, sites here on Earth are chosen for various reasons. Lists of such sites have been compiled, with pros and cons identified for each [12, 13, 14]. Basically, the terrain and environment should be applicable to the specific tests to be performed. For mobility tests, rough terrain is needed. For communication tests, remote areas with obscuring hills and hidden canyons may provide the desired challenges. For logistical tests of science and exploration goals, areas with interesting science are needed. Some of the most severe or persistent issues that are found in cooperative field testing with humans and robots involve communications, power, dust, and thermal variations. Choosing field test sites that can stress these areas produces more data relevant to and experience in dealing with these issues.

In addition to an applicable environment, remoteness in general can provide an added benefit for field testing: the enforcement of self-sufficiency. Identifying what equipment, communications, and capabilities are really needed for a remote space robot is one of the primary accomplishments of many field tests, often providing surprising results. Challenges are frequently uncovered that would not be found in a laboratory or simulation setting, specifically relating to terrain, logistics, and human interaction needs.

In addition to providing a test environment for robots, field testing provides operational training for humans. For future missions, humans may control robots from a long distance (such as from Earth), from a nearby but still remote location (such as from an orbital station or ground habitat), or from the immediate neighborhood. All three control locations present different needs, and all three can be, and must be, tested in the field with as much fidelity as possible. By participating in field testing, not only can operational crew gain an understanding of what is needed, but researchers can gain an understanding of what interfaces and capabilities will be needed in the future.

Thus, our approach has been to perform as much field testing in planetary-analog sites as possible, interspersed with local subsystem testing in our outdoor Rock Yard as needed (see Figure 2). The field testing provides information about what issues we need to address more closely and what capabilities we need to develop for further testing.

Figure 2. Boudreaux (left) and SCOUT (right) in JSC Rock Yard with suited test subjects

4. IMPLEMENTATION AND RESULTS

4.1 Robots

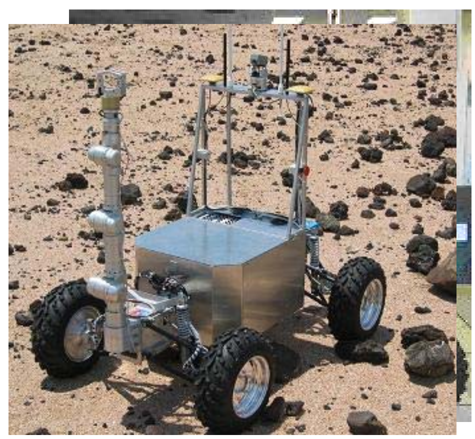


Figure 3. Thibodeaux in the JSC Rock Yard

Our research group in ARSD is currently working with three robotic test beds for planetary surface exploration, named Boudreaux, Thibodeaux, and SCOUT. Boudreaux and SCOUT are shown in Figure 2, and Thibodeaux is shown in Figure 3. Boudreaux and Thibodeaux are four-wheeled, battery powered robots meant to serve as ERAs. They have a range of capabilities meant to assist astronauts as they set up a base camp and explore their surroundings. Both of these robots are approximately the size of a typical ATV (All Terrain Vehicle). Each robot has a suite of sensors, including cameras, lasers, GPS units, and dynamic measurement units for angular pose. A seven degree of freedom manipulator arm and three-fingered Barrett® hand can be mounted to either robot. Either robot can also pull a trailer with supplies and tools. They carry multiple computers on board, have speech synthesizers, and can perform speech recognition.

SCOUT stands for Science, Crew, Operations, and Utility Testbed. This robot is designed to carry two suited crewmembers, and can be operated in multiple modes: manual driving, teleoperated driving, and autonomous driving. During autonomous activity, this robot can perform many of the same tasks that the ERA robots can, though it is, of course, larger in size. SCOUT measures approximately 3 by 2 meters. This robot also has cameras, lasers, GPS units, and an IMU (Inertial Measurement Unit), and carries multiple computers on board. SCOUT also has lights for nighttime operation, for the ease of human drivers. SCOUT is a newer project, and thus has not been involved in remote field testing, other than an initial foray for information gathering only. Some preliminary work has also been done with the Robonaut [40], project dealing with the potential for a mobile, highly dexterous robot for human-robot interaction. Some autonomous abilities also used in the ERA and SCOUT projects have been implemented for use during human interactive tasks with Robonaut, and future plans include much more work in this area [15] [16]. Although much local testing has been carried out with SCOUT and Robonaut, the remainder of this section will concentrate on the remote field testing done with the ERA robots.

4.2 Robotic Assistant Control Architecture

A high-level overview of the ERA robot architecture is shown in Figure 4 to illustrate its basic design and capabilities. The individual objects in the figure are discussed in the following paragraphs. Our system is similar to other multi-layer autonomous robotic architectures (such as Remote Agents [17] or 3T [18]), with the significant difference that we may use the space-suited astronaut (that the robot is assisting) as the highest level of intelligence in our system. The human may command the robot to perform a certain task, and the robot works on that task until finished or receipt of another command from the human interrupts that task.

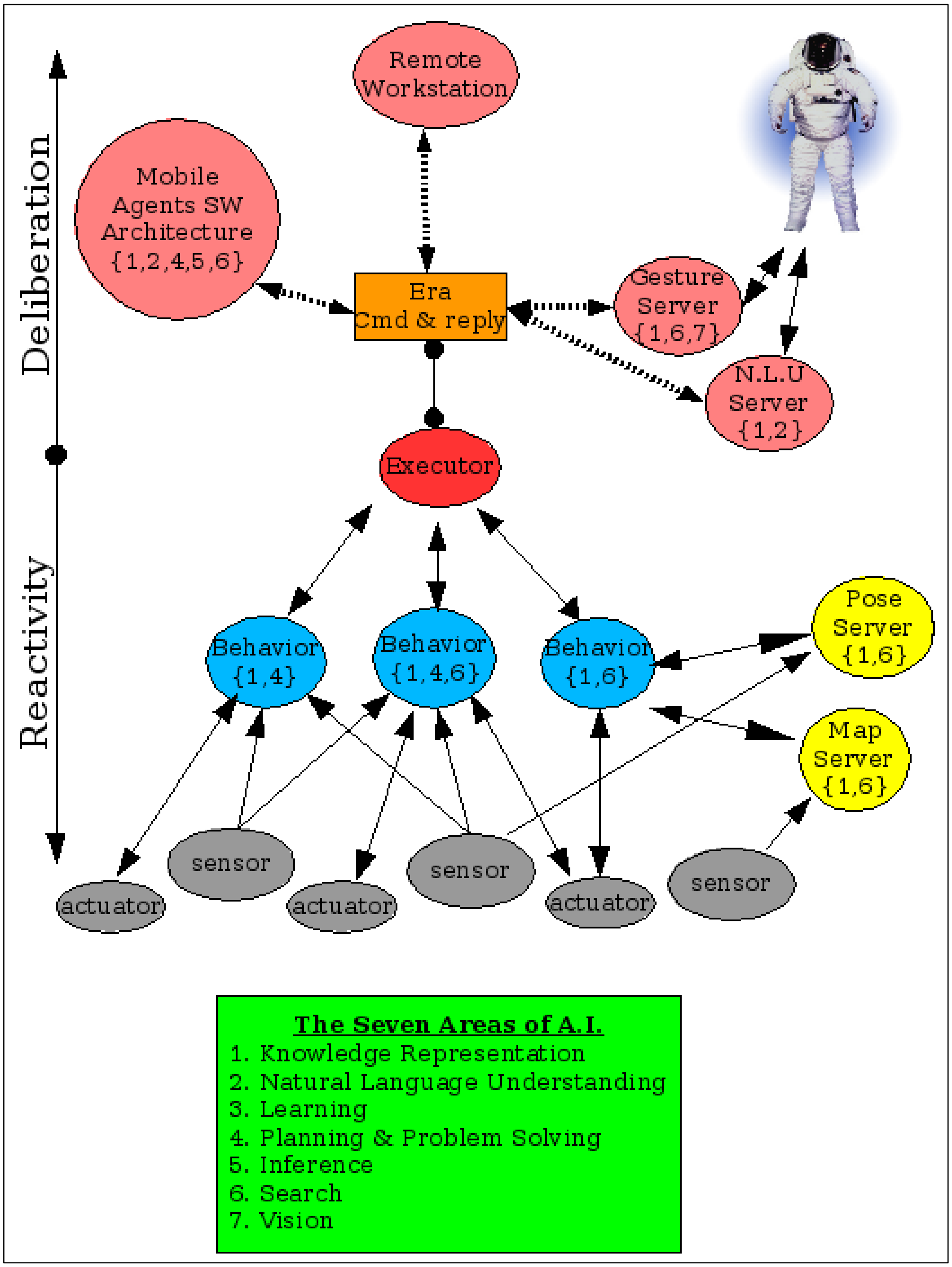
The software processes (servers) that interface with actuators/sensors (the grey ovals at the bottom of the figure) represent the lowest layer of the architecture. These servers actually communicate with robot hardware to read sensors and/or command actuators. Low-level actuator servers are designed to control a physical actuator (such as the drive motors, pan tilt units, computerized on/off control, etc). Generally, these servers take a myopic view of the world, and simply try to safely control their device as they are directed, without reasoning why the action was requested. Because these servers are connected to physical devices, they should be commanded by only one behavior at a time to prevent contention. Low-level sensor/data servers obtain and process data such as GPS location, temperatures, laser range measurements, battery status, power usage, etc., and make it available to other servers upon request. These types of servers can simultaneously communicate with all the servers who desire data from the particular sensor (i.e., no resource contention issues).

The servers which talk to multiple sensors/actuators to perform more sophisticated actions (which we call behaviors) are indicated by the blue ovals. Some behaviors currently in the ERA architecture are (1) deploy, (2) follow, (3) photograph, (4) sample, (5) say, (6) scout, and (7) watch. Note: other architectures frequently have a separate obstacle avoidance behavior, but in the ERA architecture this functionality is a modular, configurable component used by other move behaviors such as follow or scout.

As an example of a behavior from our architecture, consider (3) from the list above. When this behavior is activated, the robot is being told to take a photograph of a particular location. This behavior must find the current robot and target locations, and then calculate the pan/tilt values to "point" the camera toward that specified location. The behavior must then command the pan/tilt unit to the specified angles, and then wait for that movement to finish. Finally, the behavior must obtain the resulting image from the camera (now that it is pointed in the right direction), and return that image to whoever initiated that behavior request (most likely another behavior or the Executor). Note that multiple behaviors can receive data from the same sensor without contention, but when multiple behaviors utilize the same actuator, contention will exist when both behaviors are simultaneously active.

This contention between simultaneously active behaviors is resolved in the Executor process (red oval), which monitors and arbitrates resource contention using a priority scheme. Each requested action is received in a command structure also containing a desired priority (possibly originating from a human or external agent). The command maps to a set of behaviors to produce the desired result. If other behaviors are active, are in resource contention or behavioral conflict, and have lower priority, the Executor suspends them in favor of the higher-priority command and its behavior set. Besides behavioral commands, commands to handle reporting and mode switching are defined. The ERA robots may be configured into "safe","teleoperated", or "autonomous" modes.

In addition to conflict resolution and mode changing, the Executor also serves as the single point for interfacing with external influencing agents such as space-suited humans and software systems. A well-defined set of commands and replies is used by these external entities to command or monitor the autonomous robots. This interface and command set has been used successfully over several years of field tests and is evolving as the robot capabilities and scenario



complexities increase.

Figure 4. Control Architecture used in the ERA and SCOUT projects. The Seven areas of AI are from Barr [31]. The location of these types of AI within our architecture is called out in the individual process ovals in {braces}.

The ERA architecture currently lacks its own high-level planner and cannot coordinate a team of humans and robots nor provide procedure tracking or mission-data dissemination to the outside world. These critical functionalities and their requisite intelligence methods are currently provided by the external software system known as Mobile Agents software Architecture (or MAA), currently under development at NASA Ames Research Center. We will briefly describe the MAA here; for a detailed overview of the Mobile Agents project and MAA we point the reader to Clancey, et al [19].

The MAA is a multi-agent software architecture developed using the Brahms multi-agent modeling language and the Java programming language [20, 21, 22]. The Brahms language incorporates theories of activities [23, 24], situated cognition [25], situated action [26], work practice modeling [21], and distributed AI and multi-agent systems [27, 28]. Belief-based agents use situated-action and production rules to act and reason in the world. Agents can communicate with each other through a communicative act, in which beliefs are transferred to receiver agents. Agents communicate with each other using speech acts. Speech acts are represented as objects with a well-defined communication protocol. The meaning and intention of the speech act objects are represented as beliefs in the agents. By communicating these beliefs, agents can communicate their intentions and state to one another. The MAA defines a number of speech act types, based on the FIPA Communicative Act Library [29]. Currently the MAA supports the message types: subscribe, inform, request, accept, and failure.

The MAA consists of distributed agents that serve external entities, such as astronauts, ERA robots and mission operation systems. Each external entity has its own Personal Agent (PA) that enables the entity to cooperate with the other entities in the architecture, by communicating speech acts to their respective PA's. The PA's for each entity can be seen as a) the teamwork coordinator and for the non-human entities b) the deliberator and plan executor. People interact with their PA via a speech dialog system [30]. In other words, the MAA enables the coordination of the work of people, robots and mission operation systems during a mission. From a functional perspective the MAA enables the ERAs to work together in a team of astronauts and other robots on a surface exploration mission through:

1) Use of Activity models (an EVA plan) to establish context for data records and expectations for location and duration of astronaut work. Future iterations of the architecture this will lead to a representation of meaning of activity, e.g., "survey," to establish expectations about astronaut actions.
2) Distributed agent architecture allows flexible configuration for managing and automating aspects of the workflow (e.g., storing data in a database with appropriately generated descriptors -- combining data about astronaut location, activity in process, etc. -- and sending e-mail notification to relevant remote participants, e.g., a remote science team).
3) Heuristic interpretation of telemetry information (e.g., biosensors) to generate alerts (again stored, forwarded, broadcast as necessary) -- along with contextual interpretations (e.g., heart rate expectation depending on astronaut actions, such as climbing a hill) as described in #1.
4) Contextual disambiguation of voice commands (e.g. "[Robot name] join me", "Stop working with me", "[Robot name] come here", "What is the next activity").
5) Automated association of data records (e.g., voice annotations and photos) based on context (e.g. "Take a panorama and label it picture at work site four")
6) Integration of external systems (e.g., cameras, database) through "communication agents" that mediate command and data flow between people and their tools (including robots).
7) Integration of diverse data sources (e.g., GPS, agent registry, inter-agent communication protocols) that enables continuous assignment of resources to astronauts (e.g., following or tracking an astronaut).

In Figure 4 the various forms of Artificial Intelligence [31] are mapped onto the processes in the software architectures for ERA and MAA. As both continue evolving, we expect to improve the existing intelligence methods and implement new ones into the overall architecture, leading to more possibilities in the field.

4.3 Field Tests

The ERA robots have participated in multiple remote field tests to date, in several locations in the USA. Most notably, including Arizona (Meteor Crater, Joseph City, Cinder Lake, and SP Mountain), and Utah (at the Mars Desert Research Station near Hanksville). Most of these field tests last for two weeks and involve partners from other research groups. The participants from NASA Johnson Space Center, in addition to ARSD, include the Advanced Suit group from the Crew and Thermal Systems Division, personnel from the Mission Operations Directorate, the Exploration Systems Engineering Division, and the Astronaut Office. NASA Ames Research Center participants include Mobile Agents, Brahms multi-agent simulation environment, Mobile Exploration (MEX) wireless communication system [32], RIALIST spoken dialogue, and Science Organizer [41] groups. Communications experts from NASA Glenn Research Center and NASA Kennedy Space Center often participate in these field tests. Finally, various universities have been involved with a range of contributions: crew member biosensors, science sensor deployments, and suited crew member test subjects. An overview of this field testing is given in Table 2.

4.3.1 Arizona

Our field tests in Arizona usually take place in early September, and have been occurring regularly since 2000. The Meteor Crater area was also used during the Apollo era for astronaut training in lunar driving and geology work. The type of terrain here varies from flat, hard ground to sloping, dusty, sometimes rocky ground. The terrain is generally mild in the areas in which we operate, with few obstructions to line of sight operations. The large open areas do allow greatly extended test runs compared to the limited area we have available for local testing near Johnson Space Center. This allows us to focus on human-robot interactions during nearly hour-long scenarios with suited crewmembers, and multi-hour tests with shirtsleeve crewmembers.

The ERA field tests at Meteor Crater involve human crew members with high-fidelity spacesuits. This has allowed us to understand constraints dealing with pressurized suits, such as the inherent noise from air handling equipment, the human dexterity and strength limitations imposed by the bulky, pressurized suit, and the limited amount of time the human crew member has for conducting activities.

Scenarios have included logistical construction tasks, such as deploying power cables (Figure 5a) and flexible solar panels. These tasks are carried out with both human and robot team members. Humans have provided route guidance for cable deployment and secured the solar panels to the ground after deployment. Boudreaux provided the strength to carry all the material, and provided a fixed heading for precise deployment of the solar panel.

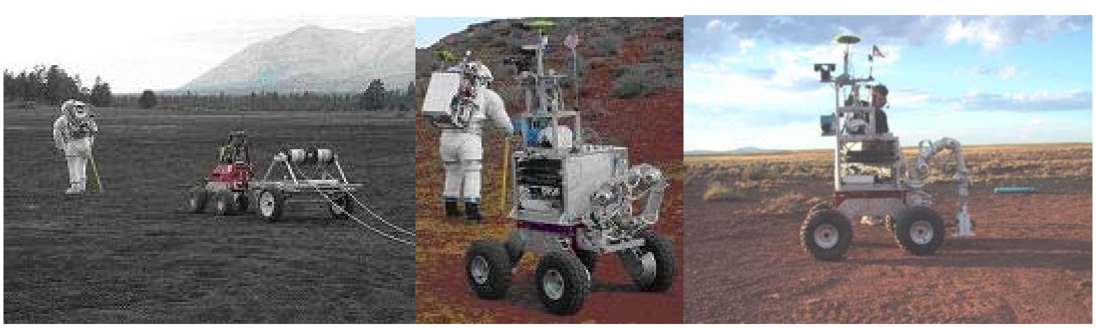


Figure 5. ERA Field Testing: (a) power cable deploy, (b) geology traverse, (c) science instrument (geophone) deploy

Science experiments have also been enacted in these field tests. The ERA has pulled a science trailer with various tools, autonomously following behind an astronaut in order to provide access to equipment needed for analysis of samples in the field. Tools for geology investigations have also been carried by the robot. A science sensor (a field spectroradiometer) was pulled along behind the robot as it performed a search pattern, automatically gathering data for further analysis of the soil [33]. Geophones, which help to determine ground composition, have been deployed by Boudreaux using several methods: cooperatively by carrying the sensors for the astronaut to use as they progress along a straight line, or individually by deploying the sensors itself using its manipulator arm (Figure 5c).

4.3.2 Utah

The Mars Society's Mars Desert Research Station, near Hanksville, Utah, provides an excellent field test site for human-robot interaction. The terrain here varies from flat, hard ground, to rolling hills with loose gravel, to rocky ground and deep canyons. Many obstructions to line of sight can be found, and the varied terrain provides nearly every type of testing ground desired.

ERA tests here focus on the integration of robots with the human crew. A cylindrical, two-story habitat allows the human crew to live and work in the environment. The robots can be sent out by themselves to scout around and provide imagery for the human crew in the habitat to use in identifying prime exploration spots. EVAs with humans and robots then take place for further exploration. The robots serve as pack mules, safety monitors, information providers (such as location and distance from habitat), data gatherers (such as panoramic imagery), and communication relays.

Figure 6. ERA Field Testing in Utah.

4.4 Lessons Learned

Lessons learned during our field testing fall into logistical, operational, and functional categories. Logistical lessons include such practical considerations as having radios for voice communication, tents for sheltering support crews, adequate work environment, and spare robot parts. Operational lessons include performing pre-deployment check lists (e.g. check for loose wiring, fasteners, and connectors, and having all spare batteries fully-charged in case they are needed during a test) and continuous monitoring the robot (e.g. temperature, remaining battery life, and power usage) during all tests. Also to prevent electrical damage to components, every device should have a properly rated fuse specific to that device to prevent damage should electrical problems arise. Functional lessons include the requirements for performance and capability, relating both to the physical characteristics of the robots and to the onboard intelligence they possess.

Robotic intelligence is involved in some form in most of the field test scenarios described in section 4.3. This section will concentrate on the functional lessons learned with regard to robotic intelligence requirements for human-assistant planetary activities. The main categories of intelligence include: directional knowledge, task knowledge, physical interaction with humans, and verbal interaction with humans.

Date/Location	Challenge	Scenarios	Robot	Results	Lessons Learned	Resulting Improvement
Febuary 1999 Silver Lake, CA	Initial field test with robot and suited test subject in analog environment. Robot following using stereo-vision	Teleoperated rover as scout, videographer, field science assistant	Ames' Marsokhod	Astronaut spent a great amount of time waiting for robot to catch up	Robot too slow. Ground clearance severely limits robot mobility in tested terrain: need minimum of 10 inch clearance	Purchase new mobile robotic platform. Increase ground clearance
September 2000. Cinder Lake, Meteor Crater, and SP Mountain, AZ	Construction tasks	Solar Panel Deploy. Power cable deploy. Geology assistant. Stereo-vision tracking	Boudreaux	Major success in all scenarios	Need alternative methods of tracking astronaut. Need absolute localization method. Need better battery management. Need better voice and data comm. Need to replace Mobility Software since cannot change it as required.Robotic base needs improving: shock mounting, more speed, better traction, stronger. Need arm+hand manipulator to improve HRI.	Differential GPS on robot. Infopak with dpgs for astronaut. Begain new robot architecture based on CORBA, C++, Linux. Start Thibodeaux
September, 2002. Meteor crater and Joseph City, AZ	Science Collection tasks. Initial testing of Thibodeaux. Five minute comm delay over satellite. Fuel cell testing. Interface testing with Mobile Agents infrastructure	Geophone Deploy/Assistance. Geology Assistant.	Boudreaux, Thibodeaux	Failed to pull heavy geology trailer uphill	Need a single-point of interaction with robots instead of exposing many lower-level processos to external collaborators. Need improved arm hardware and kinematics. Need better speech recognition and natural language understanding	Created interface spec and a single-threaded "executor" to handle interfacing with external agents. Arm hw & sw upgraded, 6axis force-torque sensor acquired. Replaced ViaVoice with Nuance and collaborated with experts on more powerful and flexible grammar
April 2003. Hanksville (MDRS), UT	Integration with Mobile Agents Infrastructure. Terrain with hills and canyons, distance, wireless communications	Geology assistant. Comm Relay. Still imagery	Boudreaux	Periodic COMM outages temporarily prevented remote commanding, heading estimate was not accurate enough for tracking	COMM outages require robot autonomy to recover, many Hardware issues required a power cycle to fix, "hot swap" of batteries would allow for longer missions.	Added second GPS unit to obtain heading estimate, added a "power box" to allow computer control of power to several devices, modified power bus to allow 2 strings of batteries to be used in parallel (allowing for hot swaps)
September, 2003. Meteor crater, AZ	Science Collection tasks. Interface testing with Mobile Agents infrastructure. Initial testing of a SCOUT vehicle	Geology Assistant. Spectrograph data collection	Boudreaux, Thibodeaux	Failed to pull heavy geology trailer uphill, several hardware failures due to poor voltage regulation of motor "noise".	Need better power regulation/monitoring of power bus.	Improved power buss to eliminate power spikes from the motors from reaching other devices
May 2004. Hanksville (MDRS), UT	Conquer Lith Canyon. Involve Remote Science teams	Geology assistant. Comm Relay. Video Survellience, Panoramic Image Generation, situational awareness	Boudreaux	Major success in all scenarios.	Need more field spares. Need better e-kill. Need global information distributed to each robot. Robots need to be able to perform multiple parallel behaviors. Need better power information. Need better data comm. Obstacle Avoidance must not count tracked astronaut	Acquired more field spares. Purchased improved e-kill. Added data distribution functionality to architecture. Refactored/multi-threaded executor and high-level behaviors to allow pause,resume.stop, prioritized execution of multiple simultaneous behaviors. Added battery meter. Replaced wireless comm system with more powerful mesh-technology
April 2005. Hanksville (MDRS), UT	Mult-robot cooperation. Teamwork model. Multiple simultaneous behaviors	Deployment of COMM Repeater, Still/Panorama Image capture, Autonomous scouting, Geology assistant	Boudreaux, Thibodeaux	Significant hardware and software issues. Arm broken prior to RDR deploy. Thibodeaux unused. Significant effort required to debug and test refactored high-level interface to mobile agents. Used many field spares	Funding and schedule must generously allow for robotic development and field test preparedness (i.e. don't plan on development in the field). Flexibility and contingency plans are required for continuing field tests in the face of failures and weather.	Modified the motor controller interface for Thibodeaux to be simpler and more reliable.
May 2005. JSC Sites	Test SCOUT vehicle with space-suited, onboard crew on long-distance trek.	Stereo-vision tracking, autonomous point-to-point navigation, obstacle avoidance, suit ingress/egress, teleoperation	SCOUT	Suited Astronut tracking using stereo vsion, obstacle avoidance was confused by vegitation, velocity control was not properly tuned	Startup/Shutdown proceedures need to be more simple (and always followed). Antenna height is very important to maintaining COMM coverage	Reworked velocity control loop to better maintain speed

Table 2. ERA Field Test History

4.4.1 Directional Knowledge

Directional knowledge can be simple (following a compass heading from its sensor) or complex (following a human). Human following may not require any prior terrain knowledge on the part of the robot, but takes advantage of the human capability of picking out a navigable trail quickly and easily, even in new terrain. The robot's job is just to follow the human. Stereo vision and laser sensors have been used to perform human following, and robotic intelligence is needed to process the raw data to filter out the background and identify the human. This can be accomplished by any number of vision systems/techniques, but whichever vision system is selected needs to be reliable and operate in all conditions. This means that the system should work in low and high light conditions, for astronauts of varying heights, and suits of various colors (since dirt will change the suits appearance over time). Additionally, the human tracking system needs to track the human in cluttered environments, not just in open areas.

Autonomous obstacle avoidance can be performed by the robot, if desired, to make certain that the ground the astronaut chooses is also safe for the robot. This not only allows the robot to ensure its own safety, but also allows the human to act more freely, without considering the terrain limitations of the robot. This enables the human to concentrate on his or her own work, limiting the amount of time the crew needs to focus on the robot. By preventing robots from hindering or burdening human crew members, robots can provide added capability and efficiency rather than added work. Indeed, some of the strongest feedback we received from our first field test with a suited astronaut concerned the speed of the robot. Because the robot traveled so slowly compared to the human, the human frequently had to wait for the robot to catch up. Making robots an asset, and not a liability, on planetary missions will be of utmost importance for astronauts to accept them as team members.

Current obstacle avoidance capabilities require slower motion on the part of the robot, and are not guaranteed in all terrain situations. Though still a work in progress, obstacle avoidance has been successfully used in our Utah testing, and has made apparent the desirability of a more autonomous, intelligent robot during joint human-robot activities. Again, the obstacle avoidance system needs to be reliable, since an error could lead to the loss of the robot. During our field tests, we have a human safety officer watching the robot at all times who has the ability to remotely halt the robot at any time if the robot makes an error in path selection. This "safety net" will obviously not be available to a real planetary robot, so planetary robots will need to operate in a manner that ensures safe behavior at all times.

4.4.2 Task Knowledge

Task knowledge can require many different types of intelligence. For the geophone deployment by the manipulator arm, the robot needed to know how to grasp and move the sensor in order to securely place it in the ground. For the science sensor pulled along in a trailer, the robot needed to know how to perform the search pattern. These are typical robotic activities, but they do require intelligence, especially when working in outdoor, unstructured terrain. For instance, performing a search pattern requires knowledge of the capabilities of the robot, such as how precisely it is able to maneuver. Exact following of a path is often impossible due to small rocks or other terrain features which push the robot off course, or cause it to lose traction. Some level of intelligence is needed to enable the robot to decide when to proceed onward to the next leg of the pattern. This decision point includes knowledge of the robot's location relative to the path as well as the time it has taken to reach its current location. Robotic intelligence enables the robot to decide whether to continue along the current portion of the search pattern, to proceed on to the next leg despite not having finished the current leg, or to abort the pattern completely.

4.4.3 Human Interaction

Physical and verbal interaction with humans is a key component of our research. Field tests have shown what humans expect from a robot, and what they require in order to work together effectively with a robot. Safety is a primary concern, and so human following includes a buffer zone around the robot. If the human moves too close, the robot will back away. Due to a lack of verbal communication with the robot, this behavior produced frustration on the part of the human crewmember during one field test. The robot was pulling a trailer with tools, and when the astronaut needed to use one of those tools, he approached the robot, but without telling the robot to stop following him first. So the robot continually backed away from the astronaut when he tried to approach.

Proper verbal interaction would have prevented this situation. The robot needed the intelligence to respond to any of several phrases which meant "stop," instead of only responding to one particular word. The robot might also need to express its current task or behavior mode more frequently in order to let the human know what the robot thought it was doing. On the other side, though, continual utterances of the robot's thought processes would annoy the human crew members so much that they would turn off their radios and not listen to the robot anymore. Additional intelligence is needed to enable the robot to behave in a more human manner when interacting with humans. Awareness of the current situation and desires of the human would help the robot in adapting its behavior to the moment. This is one of the goals of the Utah test participants.

Communication dropouts during Utah field testing have shown the need for more autonomy and intelligence on the part of the robots. A robot must be able to carry out its currently assigned task, such as traveling to a given waypoint, without having a communication link to the habitat or anywhere else. Often, short or even long term communication dropouts have occurred in our field tests while the robot was in transit. The robot must be able to continue either to its goal, or to return to its original location in order to regain communication. Thus, we have developed our software architecture to provide onboard all the information the robot needs to complete its traverse to a given goal point: self-localization, goal location, navigation, and obstacle avoidance. In the future, the goal point itself can be determined by the robot when needed. Preliminary work has been done to enable the robot to determine a new goal point based on communication signal strength.

When performing a communication relay function between the habitat and the EVA crew members, the robot also must possess enough intelligence to maintain a link with both sides. Onboard intelligence is obviously needed in this case, as the crucial decisions must be made when the robot is in communication with any humans. The benefit of using a robot for this task instead of a fixed relay is that the robot can maneuver as needed when the astronauts change position. The winding canyons of Utah have shown that a single relay is not sufficient for covering all the areas the astronaut-geologists wish to explore. A robot provides a more reasonable solution than having innumerable fixed relays to cover every angle. The goal of such an autonomous capability is that communication between remote field teams and a habitat is seamless and unnoticed – the humans do not have to worry or think about this task, but just allow the robots to perform their duty.

Finally, interaction between robots and humans is a primary area of research in the Utah field tests. The robots need to act as a member of the crew, responding to verbal commands, providing feedback, and not annoying or interfering with the human crew so much that the robots prove more of a hindrance than a help [34]. It is clear that individual humans prefer to hear different amounts of communication from a robot during EVA's. Some want to know every move the robot is going to make, and some want to hear only high level data. Allowing a robot to be configured (or even better, to learn and predict) to communicate in a mode that is preferred by each astronaut will allow the robot interact more successfully with humans. To aid in this goal, intelligence is needed in the form of a better understanding of human interaction, and even human motivation, etiquette, and goals. The NASA Ames Mobile Agents group has been doing research in this area for some time ([35, 36]), and our joint field tests have been a proving ground for much of this work.

5. DISCUSSION

There are many issues raised by including human-robot teams in the exploration of planetary surfaces. The safety of the crew must be considered above all other concerns. While robotic intelligence can add to the safety of robot operations, the complexity involved also introduces additional risks, due to incomplete testing of all possible situations and due to the inherent fact that the robots will be operating more on their own. The safe operation of the robot can be ensured (as much as is possible) by performing extensive testing and development of the robots here on Earth, and by having multiple levels of safety built into the robots. As an example, we have both hardware and software "kill" capabilities on our robots. The software can tell the robots to stop moving, but if for some reason the software malfunctions or is unable to command a stop, the hardware can physically remove electrical power from the motors. "Kill buttons," usually large red buttons, can be pressed even by space suited personnel, and provide an additional path to stop the robot in case any primary control mechanisms should fail. Having redundant methods for commanding (or stopping) a robot will be a requirement for all planetary robotic assistants.

The robots discussed in this chapter are all designed to be robotic testbeds, and as such are not intended to be actual flight units. These robots replicate the functionality of actual flight units, but avoid the added cost and time involved with building an actual flight unit. This is a fundamental design decision, and one that we feel allows our research to move forward in a more productive manner. Since we are testing new robotic technologies, we are helping to determine which techniques are useful and feasible, and which are not. By determining which functions are most promising, we can help to ensure that when the final flight units are constructed, they will be as capable as possible.

6. CONCLUSIONS AND FUTURE WORK

We have acquired a basic understanding of the types and functionalities of robots needed to successfully assist astronauts in the exploration of planetary surfaces. However, much work remains to be done in successfully utilizing human robot teams effectively [39]. Additional field testing needs to be performed on Earth, with increasingly realistic scenarios, environments, and robots. As plans for actual future missions solidify, analog field tests must simulate those missions. Test participation will be required from all types of personnel expected to take part in those missions. ERA-type robots must continue their iterative improvement, evolving from Earth-based test platforms into space-qualified hardware.

Our near-term plans include both hardware and software related improvements. In terms of hardware, we plan to integrate an improved seven degree-of-freedom manipulator arm, enabling additional mission scenarios. We will also utilize two complete robots in cooperative and parallel field test activities.

In terms of software and intelligence, we will be integrating gestures as an additional form of HRI. We will also be developing a Vehicle Health Management system to improve robustness and allow for operation in degraded modes. We will be adding more deliberative processes, such as a sequencer and a planner. We will be improving behaviors and algorithms for functionalities such as obstacle avoidance. Finally, we will be developing and recording more detailed metrics, both for HRI and autonomy evaluation. Some simple examples of HRI metrics include:

- number of commands given (True Positives, True Negatives, False Positives, False Negatives)
- number of confirmations required
- number of gestures given and/or recognized
- distance humans are tracked
- number of scenarios accomplished

We are aware of the current research of Goodrich [6], Fong [7], Scholtz [8], and Rodriquez [37], and we would like to include their HRI metrics as well. To facilitate the collection of HRI metrics, composite (complex) ERA commands and behaviors will be decomposed into more elemental "primitive" forms, then layered and instrumented to facilitate the collection of metrics.

Examples of autonomy metrics include:
- distance traveled autonomously
- number of waypoints traversed
- number of human interventions required
- number of hardware failures
- number of battery swaps
- number of device upsets/resets
- number of software upsets/resets
- number of times the robot is remotely disabled by the safety officer (E-stops)

As our robotic development continues with an eye toward lunar and Martian missions [38], several key points need to be kept in mind:

1. *Reliability*
   Robots must be reliable to be useful on the moon or Mars. A robot that is not operational might as well not be on the surface, because it will not help complete any mission goals. We need to ensure the robots are dependable team members, or else humans will be forced to operate without them. Reliable robots will also have the added benefit of lower overhead associated with their maintenance.
2. *KISS Principle* (Keep It Simple, Stupid*)*
   Keep the robots simple. Don't try to make them do everything. A concerted effort is needed to ensure that "requirements creep" does not make individual robots too complicated, too fragile, or too expensive.
3. *Modularity*
   The ability to share components, software, and procedures between robots will greatly decrease cost and training requirements, as well as allow robots to share spare parts. With such modularity, astronauts will be able to control and maintain all the various robots with a minimum of training.
4. *Human Safety*
   Robots working side by side with humans, or performing mission critical operations, will need to have their software and hardware verified to be safe and fault tolerant. Additionally, if these robots provide functionality to humans such as carrying them, providing recharging of space suit consumables, or acting as a communications relay, then the mission plans will need to include contingency plans in case of robot failures.
5. *High Level Autonomy*
   Higher levels of autonomy will help avoid low-level and highly monotonous human control of robots. This is especially important when communication time delays are present.
6. *Spiral Development*
   Future robotic missions can always learn from prior missions. Just as we learn from Earth-based field testing, lunar missions should not be viewed as only an end unto themselves. They are also as a way of learning more about the true usefulness and capability of robots to be sent to Mars.

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Field Testing of Intelligent Planetary Surface Robots

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Robots will require intelligence to succeed in the uncertain and changing environment on lunar and planetary surfaces. Even with humans directly involved in controlling such robots, intelligence is still needed. Field testing here on Earth has demonstrated this need, and this chapter will describe the results and lessons learned from over six years of testing human-assistant mobile robots in field settings relevant to planetary exploration.

Planetary-analog sites here on Earth are chosen for various reasons. Basically, the terrain and environment should be applicable to the tests to be performed. For mobility tests, rough terrain is needed. For communication tests, remote areas with obscuring hills and hidden canyons may provide the desired challenges. For logistical tests of science and exploration goals, areas with interesting science are needed.

In addition to an applicable environment, remoteness in general can provide an added benefit for field testing: the enforcement of self-sufficiency. Identifying what equipment, communications, and capabilities are needed for a remote space robot is one of the primary accomplishments of many field tests, often providing surprising results. Challenges are frequently uncovered that would not be found in a laboratory or simulation setting, particularly relating to terrain, logistics, and human interaction needs. Often, robot intelligence provides a solution to these challenges.

Aside from providing a testing environment for robots, field testing provides operational training for humans. For future missions, humans may control robots from a long distance (such as from Earth), from a nearby but still remote location (such as from an orbital station or ground habitat), or from the immediate neighborhood. All three control locations present different requirements, and all three need to be tested in the field. By participating in field testing, not only can operational crew can gain an understanding of what is needed, but researchers can gain an understanding of what interfaces and intelligent capabilities will be needed in the future.

Specific case studies of field testing performed by the Extravehicular Activity (EVA) Robotic Assistant, or ERA project, will be described, including tests in Arizona and Utah. The types of tasks performed include construction and habitat-related logistics, science and exploration, interaction with high-fidelity space-suited personnel, human crew integration, safety monitoring, communication studies, and others. The lessons learned from these field tests will be detailed, focusing on the need for robotic intelligence. Finally, future field testing needs will be identified, with the goal of developing intelligent robots which will enable and enhance the human exploration of space.