Robotics Challenges for Robotic and Human Mars Exploration

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Abstract

Infrastructure support for robotic colonies, Mars habitat for humans, and/or robotic exploration of planetary surfaces will need to rely on the field deployment of multiple robust robots. This support includes such tasks as the deployment and servicing of power systems and in-situ resource utilization (ISRU) generators, establishing long-life robotic science stations for measurement and communications, construction of beaconed roadways, and the site preparation and deployment of human habitat modules. Precursor robotic missions to Mars that involve teams of multiple cooperating robots to accomplish some of these tasks is a cost effective solution to the possible long timeline necessary for the deployment of a human habitat.

Ongoing work at JPL in the area of robot colonies is investigating many of the technology developments necessary for such an ambitious undertaking. Some of the issues that are being addressed include behavior-based control systems for multiple cooperating robots , development of autonomous robotic systems for the repair of disabled robots, and the design and development of robotic platforms for construction tasks such as material transport and surface clearing. This paper presents the results of an examination of requirements for robotic precursor missions to Mars.

Keywords: Robot colonies, manned Mars habitat, behavior-based control

Introduction

This paper represents, to our knowledge, the first recent attempt to quantify and record the robotics technology needed to deploy and operate a robotic Mars outpost, beyond what is contained in the Mars Reference Mission study [Hoffman & Kaplan (1997), Drake (1998)]. In the Split Mission Plan, such a robotic outpost is envisioned as a precursor to a human mission and would provide a critical link between robotic and human exploration missions to Mars. An illustration of a precursor robotic colony is shown in Figure 1. The robotics requirements identified assume, as a starting point, the scenario of the Reference Mission. However, additional or alternative options to this scenario are also discussed, with the intent of simplifying or streamlining the robotic requirements.

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The robotics requirements that will need to be addressed before the arrival of the human missions include both the precursor tasks as well as the needs for a sustained robotic presence on the planetary surface. Important robotics requirements are (not necessarily exhaustive or in order of importance):

- Load transportation and handling
- Solar power system deployment
- Terrain conditioning and site preparation
- Infrastructure servicing and repair
- Object manipulation and handling
- ISRU plant deployment
- Internal habitat servicing

In this paper, we will cover the first five items, with the last two to be covered in the near future. The next five sections examine each in detail, followed by overall conclusions.

Figure 1: Mars habitat prior to the arrival of the manned missions. Site clearing is ongoing using small autonomous dozers. ISRU plant and habitat are in place and the solar PV tent array has been partially deployed.

Load Transportation and Handling

The transportation requirements are for those operations in which load or cargo is moved from one place to another. The requirements are measured in terms of force to be applied in carrying the weight, the distance to be moved, and the total work to be done. To get a first-order estimate, the main parameters needed are the masses of the

main components or assemblies to be moved, as well as the distance between the initial load location and its destination after the transportation maneuver occurs. The following mass allocation shown in Table 1 is assumed for an illustrative outpost scenario [Hoffman & Kaplan (1997), Drake (1998)].

Table 1: Mass/work assessment for robotic precursor tasks related to a Human Mars habitat

Element of Sub-Assembly	Mass (kg)	Horizontal Load Travel (meters)	Vertical Load Travel (meters)	Total Mechanical Work (Nt-m)
Power System	3,500	200	5	2,810,000
Habitat	1000	100	5	430,000
Science Station	500	100	5	210,000
Communication Station	500	100	5	210,000
Landing Pad Infrastructure	1000	100	5	430,000
Other	2000	100	5	860,000
Total	8,500	700	30	4,950,000

From this table it is possible to conclude that the robotic transportation requirements implied by the Mars Reference Mission [Hoffman & Kaplan (1997), Drake (1998)] would require that the robotic capabilities in load transportation be increased close to three orders of magnitude from those achieved in the Sojourner mission (5800 Nt-m) and a least an order of magnitude over that likely to be achieved for the sample return rover in the Athena 2003,2005 rover mission. Many of the entries in the table are estimated guesses at this time. Nonetheless, they illustrate trends. For instance, total work provides an ultimate "bottom-line" of what the robots must do in transporting and handling major loads from one place to another. The "Other" category in Table 1 represents all of the tasks that are not directly attributable to a specific construction project (e.g. general site cleanup). The power system deployment requirements appear to be by far the most challenging.

Solar Power System Deployment

The power needs for human surface operations are substantial. Power source requirements of the order of (100+ kWe) are anticipated. Of this, about 30 kW are needed for habitation, 30-60 kW are needed for regenerative life support, and 50 kW are needed for ISRU. A nuclear power generator of about 5-7 tonnes may be needed. Alternatively, solar power arrays of about 5000 square meters would suffice with present technology. The advantages of solar PV tent arrays include modularity, relatively low overall mass (3.5 tonne), low political volatility, and environmental safety.

We have recently started an investigation into the robotic needs for the deployment of a modular solar PV tent array such as that specified by Colozza [Colozza (1991)]. Colozza's study demonstrated that a nearly constant power profile is realized by a tent array using a blanket of standard silicon PV cells. In addition, atmospheric dust deposition is minimized due to the steep angle of repose (60 degrees) of the PV blankets. The study also included an examination of the relevant wind force

Table 2: Multistep sequence for robotic deployment of PV tent array capable of supplying 100 kWe with Martian solar parameters.

SEQUENCE	MASS/MOVEMENT	REQUIREMENTS
Unload boxes	25 X 83 kg 5 meters	Stereo cameras Manipulator arm
Traverse to deployment site	25 X 83 kg 200 meters	Stereo cameras Coupled navigation
Placement of boxes	25 X 83 kg 50 meters	Stereo cameras Manipulator arm
Unfolding of boxes	None 50 meters	Stereo cameras Manipulator arm
Opening of initial valves	None	Remote control
Visual inspection at semi-deployed state	50 meters	Stereo cameras
Opening of secondary valves	None	Remote control
Visual inspection at fully deployed state	50 meters	Stereo cameras
Securing of guy wires	50 meters	Stereo cameras Manipulator arm
Securing array to surface	50 meters	Stereo cameras Manipulator arm

upon the array. Such a PV tent array would be difficult to deploy using a solitary robot, since the modules are 5 meters long and would represent a considerable challenge for precision placement. Keeping in mind the mass and power constraints consistent for a mobile robotic platform on the Martian surface, two cooperating robots can perform the task using the sequence of steps given below in Table 2.

The main robotics requirements for this task include coordinated grasping and navigation over open terrain by two or more cooperating robots. Sugar and Kumar recently investigated cooperative transport of large objects in a 2-D environment [Sugar & Kumar (1999)]. Although obstacles were allowed in their study, navigation over unconstrained terrain will prove to be a significant challenge. It is expected that a two robot system for container unloading and deployment will be field tested in the arroyo at JPL during January, 2000.

Terrain Conditioning and Site Preparation

Methods and equipment for site preparation for a lunar colony was previously studied by Iwata (1988) and Brazell and Smith (1991). Their studies included precursor robotic surveillance of the proposed site, coupled with construction robots for site clearing. Site clearing can be accomplished by a solitary robot if all of the significant rocks are within the size and mass constraints that the robot is able to handle. Rocks that are outside these limits will need to be cleared using a cooperative multiple robot strategy. Terrain conditioning shares many of the elements of the cooperative box-pushing task [Huntsberger, Mataric, & Pirjanian (1999)]. Cooperative robotic box-pushing has been the subject of numerous recent research studies [Kube & Bonabeau (1999) and references therein].

A biologically motivated strategy based on food transport mechanisms in ants was done at JPL in software simulation studies of the terrain conditioning task under planetary surface conditions. A series of 250 simulations were performed using the behavior-based control system BISMARC. The area to be cleared was 5000 square meters, which is about the area needed by the solar PV tent array system. The results using from two to six rover platforms are plotted in Figure 2, where the average total mission time is plotted versus the number of dozers. The performance was not linear, indicating that there is significant interference between the dozers as the total number

Figure 2: Average total mission time for 48 simulation trials versus the number of dozers in each trial. Time is in arbitrary simulation units with an average time of 3 weeks, 4 days for two dozers.
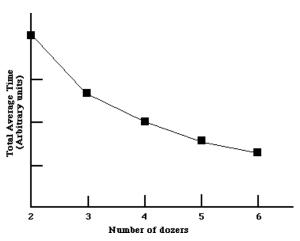
increases. This behavior manifested itself through more complicated repositioning operations due to the "avoid other robots" behavior, and travel time delays due to the need to maintain a safe distance during the recruitment phase.

Infrastructure Servicing & Repair

Infrastructure servicing and repair will not only include the habitat, ISRU, and solar power generation structures, but also the robotic rover platforms themselves. The harsh nature of planetary surfaces and finite lifetime of rover components both lead to shorter potential mission duration. Of primary importance for robotic survivability is the need for repair capabilities. The nature of the repair task is such that explicit state information must not only be known by the agents, but must also be shared and updated between the agents.

Autonomous repair of mobile robotic platforms extends their operational lifetime. A simulated wheel repair task is shown in Figure 3. Such skills can also be leveraged for the repair of other units on planetary surfaces. The traditional assembly/disassembly approach geometrically scales with the complexity of the task. Exploiting the geometry and force constraints culls the number of possible states [Lee & Moradi (1999)]. For the repair sub-task, we are currently investigating the integration of an adaptive directional force graph (ADFG) method into BISMARC (Biologically Inspired System for Map-based Autonomous Rover Control) [Huntsberger & Rose (1998)].
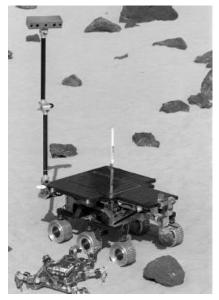

Figure 3: Simulated wheel repair of science rover by hexabot using front manipulators.

Object Manipulation and Handling

There are a number of manipulation requirements for both solitary as well as multiple cooperating mobile robots involved in precursor missions. We have detailed these in Tables 3 and 4 that follow. Of primary importance is the characterization of the types of movements and grasping/ungrasping control issues. Numerous algorithms have been developed both at JPL and outside for the coordinated movement of multiple robots such as those enumerated in Table 3 [Parker (1994), Mataric (1997), Robot Colonies (1998), Huntsberger & Rose (1998)]. A formal study of the grasping/ungrasping problems of Table 4 using a spatial-operator algebra was done at JPL [Rodriguez, Kreutz, & Jain (1992)]. This framework provides a set of linear operators for the solution of complicated control problems such as multirobot cooperative manipulation of structures. Problems that can be addressed by the method include the automation of work/force allocation to each of the cooperating robots during a grasp/transfer/ungrasp sequence of operations. The abstract description of these tasks in the spatial-operator algebra framework enables a much cleaner generation of the necessary control parameters.

Table 3: Geometric and kinematic behaviors associated with a robot colony architecture

COMMANDS	GEOMETRIC CENTER MOVEMENT	ENSEMBLE SHAPE MOVEMENT
SHORT MOVE	Small Translation	Small Dispersion Growth or Controlled Dispersion
LARGE MOVE	Large Translation	Controlled Shape Dispersion
PATH FOLLOW	Follows Prescribed 2-D Path	Controlled to Prescribed Bounds
TRAJECTORY FOLLOW	Follows Prescribed 2-D Trajectory	Controlled to Prescribed Bounds
RE-CONFIGURE COMMAND	Goes to Prescribed 2-D Location	Goes to Commanded Configuration
ROTATE COMMAND	Remains Stationary	Rotates About Fixed Vertical Axis

Table 4: Movement and coordinated force applied to commonly held load

COMMANDS	CONFIGURATION MOVEMENT	CONTACT FORCES
COORDINATED LOAD GRASP	Radial Direction Toward a Load	Transition from none to non-zero in grasped configuration
COORDINATED LOAD UNGRASP	Radial Direction Away from Load	Become zero upon load release

Conclusions

A manned habitat on Mars is a NASA mission being considered for the early decades of the next century. This paper has examined the necessary robotics

requirements for precursor missions within the next ten years. Current control, strength, and survivability of NASA planetary rovers precludes their use for such missions. On the control issue, we have described recent work at JPL in the area of behavior-based systems. In particular, the use of BISMARC for power system deployment, site preparation, and rescue/repair operations was described. A spatial-operator algebra for analysis of manipulator control on multiple cooperating robots was also briefly described. We are currently implementing behavior-based control coupled the enhanced control descriptions of the spatial-operator algebra on mobile robotic platforms at JPL under the Mars Outpost Program.

Acknowledgments

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