

Robotic Autonomy for Space: Cooperative and Reconfigurable Mobile Surface Systems

P. S. Schenker, T. L. Huntsberger, and P. Pirjanian, Jet Propulsion Laboratory (USA) ¹;
G. T. McKee, University of Reading (UK) ²

1) Jet Propulsion Laboratory, California Institute of Technology
4800 Oak Grove Drive/MS 125-224
Pasadena, California 91109-8099
paul.s.schenker@jpl.nasa.gov

2) University of Reading, Department of Computer Science
Whiteknights Park, Reading, Berkshire, RG6 6AY, England
g.t.mckee@reading.ac.uk

Keywords – mobile robots, multi-robot cooperation, modular robots, planetary mobility, robot control architectures, sensor fusion, Mars rovers, space autonomy

Abstract

We overview some of our recent work on highly autonomous mobile robots for planetary exploration. The work and related system developments address two themes. The first is multi-robot cooperation to perform planetary surface tasks beyond the scope of single robot activity. The second is development of novel mobility architectures and autonomous controls that will enable robotic access to areas of extremely challenging terrain and rich science opportunity. This work is in an early stage; at this time we have demonstrated several research concepts in realistic terrestrial settings. One novel demonstration, the “robot work crew (RWC),” shows two mobile robots cooperating to carry an extended payload over distances of 50 meters on natural terrain. The two robots are visually guided, performing tightly coordinated kinematics and force control for object handling. A second demonstration, the “all terrain explorer (ATE),” shows a reconfigurable wheeled robot that adapts its kinematics configuration and behavior-based controls to perceived changes in the terrain, with ability to ascend and descend steep slopes inaccessible to conventional rover operation. In both these systems perception and control is fully autonomous.

1 Introduction

There is growing international interest in a global exploration of the surface of Mars. Better understanding of Martian surface geology, morphology, geo-chemistry, and atmospheric science will provide

important insights to comparative planetary origins, the potential for past-present life, and capabilities of the Mars environment to sustain a long-term human-robotic colonized presence. Towards this end, there are a numerous ongoing developments of long-range semi-autonomous rovers. We report elsewhere in this meeting on related NASA/JPL FIDO (Field Integrated Design & Operations) rover development and mission simulations [1]. NASA plans an actual 2003 mission using two such flight vehicles. Development of such mobile science laboratories will be ongoing for some time, providing increasing levels of onboard science autonomy, higher science productivity, and capability for an eventual Mars sample return. Accompanying this thrust in Mars surface science exploration are longer range goals to extend science coverage and develop necessary planetary resources for a sustained robotic, and eventually, human-robotic presence.

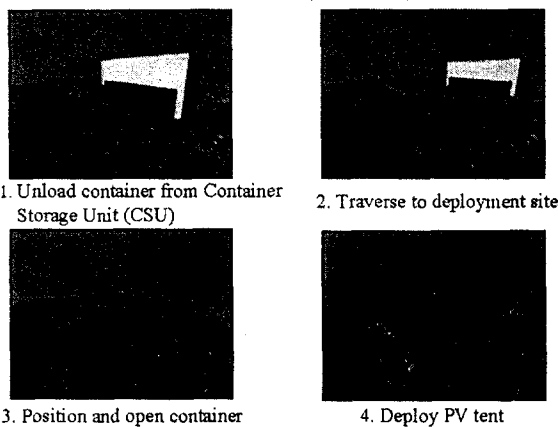


Figure 1: Robots cooperate in deploying a photovoltaic power station on Mars (graphic simulation).

Achieving these longer range goals requires development of new robotic systems and autonomous control paradigms—robots that are more adaptive, intelligent and survivable in navigating diverse Martian terrain, as well as colonies of robots that can work very closely in cooperative physical and scientific tasks. We present some of our initial developments in these directions. We also (McKee and Schenker, Section 4) briefly outline long range issues and architectural precepts of eventual highly networked, intelligent planetary robotic systems. In Section 2 we present our recent work on cooperating rovers and applications to tightly coordinated physical tasks such as extended object transport. In Section 3 we overview our work on reconfigurable robotic surface systems for all terrain exploration, highlighting recent development and demonstration of an agile, rough terrain adaptive wheeled rover. In Section 4 we further discuss networked robots. In Section 5 we conclude.

2 Rovers that Cooperate

There are a number of surface mission scenarios that could benefit from, and directly motivate distribution of activity across multiple rover platforms [2]. This need goes beyond “passive” cooperation, e.g., where one rover performs precision rendezvous with another rover/robot for purposes of manipulative sample cache pick-up, transfer, etc. As noted above, a predominant driver is future Mars outposts, in which robots will act as precursors to human exploration, and once human presence is achieved, remain essential infrastructure for sustained habitation. There are of course related roles for systems of cooperating surface robots.

Example include groups of closely coordinating robots to handle/integrate large aperture optical instruments, and the deployment of “networked” science systems ranging from local incoherent imaging (long-baseline stereo), to more geographically dispersed structures with some degree of accurate on-line metrology.

We next outline our recent development of a new robotics architecture, “CAMPOUT”—and its experimental demonstration in mobile multi-robot cooperation focused on shared physical tasks [3]. The analogy is the human work crew in construction where two or more crew workers are called upon to carry an extended object over obstructed terrain, performing object acquisition, transport, and deployment (not a piano mover’s problem, but one that does require a high degree of shared state knowledge!). Challenges to this *Robot Work Crew*, as we call it, are major in that achieving a generalized performance requires tight, instantaneous coordination of kinematics and force constraints between the two robots over variable surfaces, subject to pre-emptive behaviors that must manage obstacles and anomalies, all within a non-holonomic space. Most related research has treated the problems of multi-rover cooperation as sequenced interactions, versus closed loop, real-time kinematics coordination under force constraints. Work that does address such “tight coordination” is in most cases is restricted to idealized environments—lab floors. Real terrain operations are significantly different; we have found in simulation and practice that as little as two degrees differential inclination of the rovers/payload can introduce significant control complications.

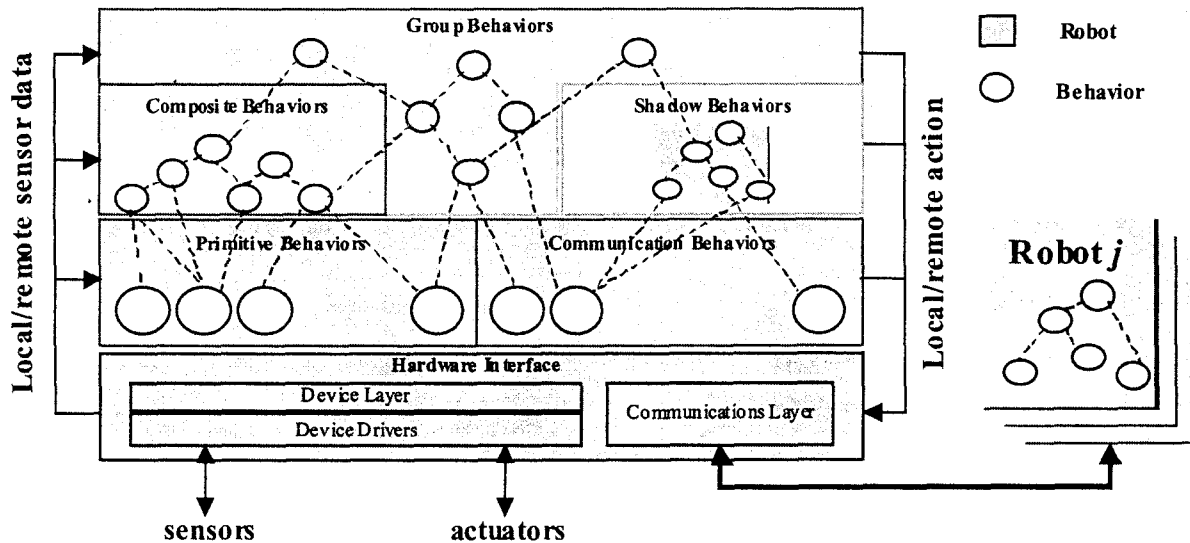


Figure 2: Functional Organization of the JPL Control Architecture for Multi-robot Planetary Outposts (CAMPOUT).

We present our more detailed approach to multi-robot cooperation in [3, 4], including the research priors, and give details of our underlying architecture in [5]. Here, we very briefly sketch our concept, the major architectural features, and one recent significant field experiment in natural terrain.

2.1 Tight Coordination of Mobile Robots

A long duration mission such as a robotic outpost on a planetary surface has wide ranging needs—from low-level, highly reactive components supporting local navigation and manipulator control, to high-level planning of large-area tasks. *CAMPOUT*, **Figure 2**, is an architecture we have developed that spans a range of tactical-strategic requirements via low-level control drivers directly tied to actuators, commanded in turn by a behavior-based control hierarchy, overseen by a higher deliberative task planning layer. *CAMPOUT* is highly distributed. Advantages of distributed control and coordination (see also Section 4, and related discussions therein on networked robots) include the efficient use of system resources, parallel execution of multiple tasks, reliability and fault-tolerance to failure of individual components (including failure of single robots). Behaviors within a single robot operate in a distributed manner, thus allowing concurrent and/or parallel execution of several tasks. However, each robot can operate on its own, independent of other agents, based on its inherent faculties of perception and action. Cooperation between the multiple robots occurs through active collaboration—there is no centralized planning or decision-making to dictate explicit commands.

Note that *reactive behaviors* facilitate tight perception-action feed-back loops that can promptly address unexpected situations; behaviors are in turn guided by *deliberative plans* for efficient use of global system resources. In effect, in *CAMPOUT*, the role of plans is to guide, not dictate, the control of reactive components. *CAMPOUT* provides a number of so-called coordination mechanisms that are tailored for not only cooperative, but also tightly coordinated tasks. Behaviors are organized in a hierarchy wherein higher level abstract behaviors are built upon less abstract behaviors and so on. Each behavior has an objective that it pursues by coordinating subordinate behaviors. Thus, behaviors can have two roles in an agent: as *actions* and as *action selection mechanisms*. With respect to its subordinates, a behavior is an action selection mechanism; with respect to its superior, a behavior is viewed as an action to be implemented. This approach is attractive for its low computational and communications overhead.

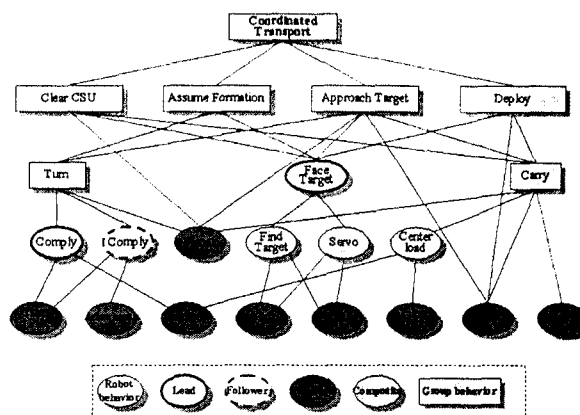


Figure 3: *CAMPOUT* behavior hierarchy describing a coordinated transport task (see *Figure 1*, upper right, example). Bubbles represent single robot behaviors and boxes represent multi-robot “group” coordinated behaviors. High-level actions, themselves behaviors, are composed from yet lower-level behaviors.

2.3 Experimental Example

Objects that many times the length of a single mobile platform are difficult to manipulate and transport. The *Robot Work Crew (RWC)* concept below assumes use of multiple rovers for coordinated operations on such an extended payload.



Figure 4: Coordinated transport of extended payload (2.5 meters) by SRR and SRR2K, performed in the Arroyo Seco near JPL. (Left) row transport formation; (Right): column (leader-follower) transport formation.

These tightly coordinated multi-robot operations are implemented on SRR platforms. The baseline SRR design is reported in [6], wherein it incorporated skid steering and basic functions for stereo-based obstacle detection, continuous motion visual traverse (10-15 cm/sec), visually-servoed manipulation, in-field visual object detection, tracking, rendezvous. More recently, we have augmented the SRR design with 4-wheel steering, improved computational resources, the above described *CAMPOUT* behavioral control architecture, and gimbaled grippers that enable compliant payload

handling (Fully-actuated approaches to transport of extended structures may not always be realistic for planetary surface operations due to mass and power constraints). We initially are investigating a fully instrumented passive gripper design per **Figure 5**.

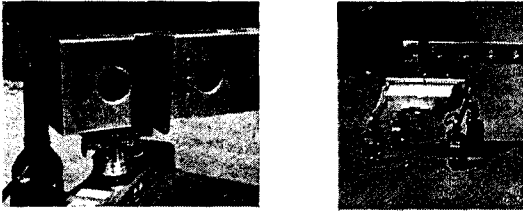


Figure 5: Instrumented gimbal (close-up at left).

The gimbal is attached to a cross brace that spans the shoulders of the SRR and has three degree of freedom force sensors and potentiometers for monitoring the container relative to the rover body. Our goal for this experimental study was the transport of an extended container (12.5cm X 12.5cm X 250.0 cm) by two rovers (SRR and SRR2K, the latter being a minimalist mechanization of the first) from a pickup point to a deployment zone that is up to 50 meters away, over un-occluded natural terrain. This was accomplished with the four-phase sequence of **Figure 6**.

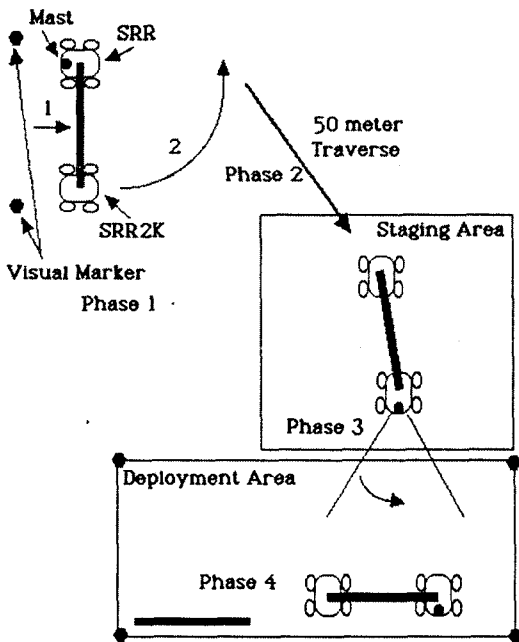


Figure 6: 1) Initiate transport configuration; 2) Move to staging area; 3) Initiate site survey; and, 4) Dock.

We provide a detailed description of the experimental implementation using CAMPOUT in [5], including the specific sensory-control behaviors and their higher

level compositions (see also [7]). As a general operations strategy, we minimize explicit communication between the rovers (as would reflect possible operational constraints during an actual mission). This is facilitated by using the shared container as an implicit means of communication—e.g., relative positions of the rovers are known through the yaw gimbal angle on each rover. Also, we are exploiting natural design constraints of the task where possible to assess useful trades of mechanized cooperation versus explicit control (as one example, the use of passive compliance in both grippers along the beam axis).

4 Rovers for High Risk Access

The logical evolution of science rovers would be to more autonomous *all-terrain capabilities*. There are numerous known and posited areas of the Mars surface that are not currently within safe reach of conventional rover designs, yet promise to be very high in science content. E.g., there have been recent orbital observations suggesting water out-flows and attendant rich mineralogy near cliff edges. Thus, development of robotic mechanization and control architectures that enable roving into adverse, challenging terrain—areas that can change dramatically over short distances—is of considerable importance. We have recently undertaken related work, where the emphasis is having a rover autonomously adapt its real time control and geometry to estimated terrain conditions and observed system state—at behavior level [8]. **Figure 7** sketches the concept and scenarios that motivate it. The general approach is to have the rover image its forward-looking terrain, build from this a 3D map, analyze traversability characteristics relative to kinematic-and-quasistatic maneuverability/stability of progress, and enact compensating behavior that optimizes a rover performance index. The behavior is implemented on a JPL's SRR in terms of reposing its stance and c.g. This is done in two ways: by independent articulation of the rover shoulder strut angles, and repositioning the rover top-mounted robot arm. Per **Figure 8**, the arm is treated as reconfigurable resource to be used in both kinematically unconstrained and closed-loop fashions, e.g., in the latter case, the arm acts as a drive actuator, pivot point, or other element in rover-ground interactions (as might be essential in some de-trapping or operations). No consideration is given as yet to rover dynamics, as they are not a major contributory factor in the 5-to-10 cm/sec operational regime and low mass/volume envelope we are treating. We do however, take into full account static friction-and-slip effects, treating these through kinematics and quasi-statics analysis referenced to surface contact models.



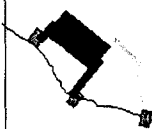



Posture and Mobility Modes →	Center-of-Gravity Rebalance	Shoulder Raise/Lower	Arm Ground Contact	“Belly Down”	“Crabbing”	Join/Split & Tethering
Detectable/Predictable Conditions ↓						
Traction Loss	Visual Odometry & Wheel Current				Roll/Pitch Sensing & Wheel Current	
Steep Slope	Roll/Pitch Sensing & Range Map	Roll/Pitch Sensing & Range Map		Range Map	Roll/Pitch Sensing & Wheel Current	
Wheel Trap			Wheel Current			
Support Loss			Acceleration & Tilt Sensing			Acceleration & Tilt Sensing
Crevasse						Range Map
Tip Over			Roll/Pitch Sensing			

Figure 7: Mobility reconfiguration in response to adverse terrain conditions.

In summary, we predict the future state of the rover based upon look-ahead stereo range imaging, on-board IMU, and any other derived state information that can be sensed, e.g., stall conditions, inferred slip from accelerometry; etc. This information is used to compute a *tipover-stability and slip-and-traction Locomotion Metric* [9], which determines possible and appropriate reconfigurations of rover geometry and center-of-mass. The algorithmic procedure is:

1. Determine the surface shape of terrain ahead of the rover (model by appropriate spatial representation).
2. Solve the configuration kinematics to predict rover configuration on the modeled terrain, i.e. roll, pitch, yaw, internal angles, and wheel contact points
3. Given a friction coefficient that characterizes wheel-ground interactions, determine if the span of nominal frictional and normal forces at the predicted contact are sufficient to resist the *gravity wrench* (and any other disturbance forces) in both the nominal and reconfigured kinematics/c.g. (Reconfiguration consists of independent left-right shoulder angle changes and center-of-gravity shifts using the manipulator).
4. Determine the minimum coefficient of friction in Step 3. This term is interpreted to be a *Locomotion Metric* indicative of the quality of the given configuration (or reconfiguration).

Step 1 is implemented by stereo imaging—correlating Laplacian left/right images along epi-polar lines to establish image disparity, and consequently the range, via a camera model. Step 2 is computed by means of an iterative Newton Solver. Step 3 involves setting up polyhedral inequality approximations to the friction cone at each rover contact point, and expressing as inequalities the unidirectional constraints on the wheel normal forces and the wheel torque constraints. These linear relationships are then transformed to the vehicle frame using the vehicle *Locomotion Matrix* [9]. An equality constraint characterizes the manifold of contact forces able to resist the applied wrench without regard to constraints. A linear programming solution uses these inequality and equality constraints to determine if a feasible set of friction and normal forces exists to resist the applied wrench. A binary search algorithm then computes the metric by determining the smallest value of friction coefficient that suffices to resist the applied vehicle wrench.

We have implemented approximating approaches to this procedure through which we have achieved some very promising results to date. As an example, the rover has successfully made stable descents of 40-to-50 degree slopes and performed ascents and cross-traverses of 30 degrees or more, per **Figure 8**.

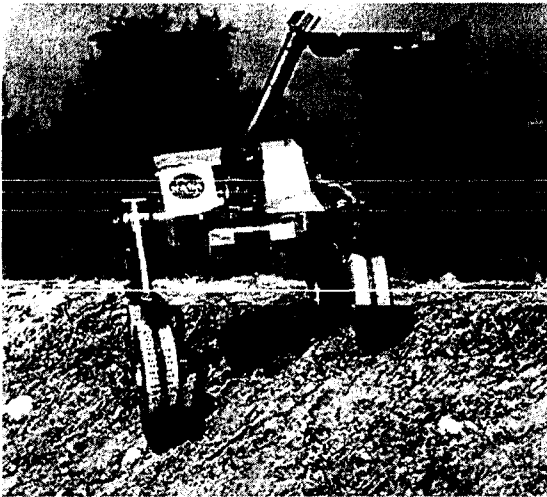


Figure 8: SRR descending steep hill at Arroyo Seco near JPL. By comparison to operations with nominal fixed geometry and c.g. (the arm in stowage position), rover tip-over instability is greatly improved.

4 Toward Networked Robotic Autonomy

CAMPOUT, as was discussed in Section 2, provides the basis for decentralized control and collective state estimation over multiple heterogeneous robotic platforms—with mechanisms for control, communication, behavioral coordination/negotiation, etc., as well as commensurate development tools [4,5]. Few explicit assumptions or limitations exist on the character of the agents involved, their number, or for that matter, their means and rates of communication. In essence, we have presented an extensible framework for *networked robotics*. In this section we look briefly at further issues and prospects for “networked robotics”—the concept and the perceived benefits. It is reasonable to assume, given some terrestrial parallels, that in time our exploration of Mars, the small bodies and related orbits will become just this thing: a cohesive and extensible *interplanetary network of robotic resources*.

The essence of networked robotics is the concept of distributed resources providing one or more interactive services [10, 11 and refs. therein]. Sensors (vision, range, position, etc.), effectors (manipulators, mechatronic modules, grippers, mobile platforms) and computational units (fused state estimation, mapping, planning and navigation-control functions) are three basic categories of resource encountered in robotics. In more historical robot architectures, resources were not often distinguished as such. Rather, these robotic sensors, effectors, and computational units are “hard-wired” functional components of a fixed, immutable larger vertically integrative algorithm, the control

architecture. In the networked robotics context these resources become self-descriptive interfaces that make explicit the services they can export and incorporate scope for a range of local and remote connectivity options. The resources, thus encapsulated as modules, provide the basis for flexible, re-configurable robotic architectures mapped across multiple physical robot systems, namely a networked robot. The underlying paradigm is very powerful: Higher-level networked modules that autonomously inherit attributes of lower-level resources—with emergent control and sensing properties, as well as accompanying new module descriptors that themselves become the resources of yet further networked system aggregates.

There are many potential instantiations of this idea that are purely autonomous and robotic, and some yet more classically telerobotic [12, 13]. In addition to work of Section 2 on robot work crew cooperation, we have begun experimental development of modular reconfigurable surface systems (R2S2)—re-taskable multi-robot systems of higher granularity in which the units interact at both low and high levels of temporal and spatial coordination [8]. **Figure 9** is illustrative of this idea. We also are carrying out more theoretical work addressing the above modular system synthesis, aggregation and resource modeling problems [14].

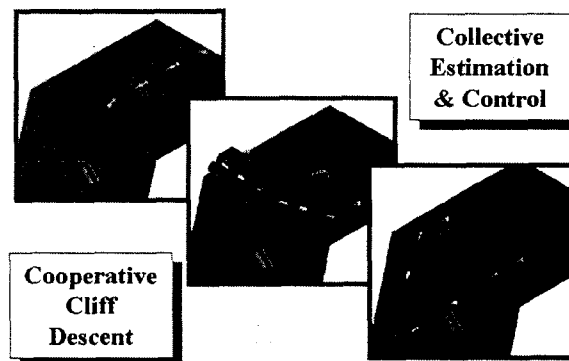


Figure 9: Multiple, modular robots reconfigure and cooperate in a cliff descent for stratigraphy analysis.

5 Conclusion

We have described new concepts for planetary surface mobility. If successful, such robotic & automation designs will enable new classes of planetary science; more robust, survivable operations; and ultimately, a sustaining, colonized robotic presence. Fundamental to these system designs are new architectures that are: highly flexible; distributed in their resources; tightly coordinated in their actions; decentralized in their sensing, control, estimation; and, easily reconfigured and extensible as global priorities and goals change.

Acknowledgment

This work was carried out at Jet Propulsion Laboratory, California Institute of Technology, under contract with National Aeronautics and Space Administration.

References

- [1] P. S. Schenker, E. T. Baumgartner, P. G. Backes, H. Aghazarian, L. I. Dorsky, J. S. Norris, T. L. Huntsberger, Y. Cheng, A. Trebi-Ollennu, M. S. Garrett, B. A. Kennedy and A. J. Ganino, Jet Propulsion Lab.; R. E. Arvidson, Washington Univ.; S. W. Squyres, Cornell Univ., "FIDO: a Field Integrated Design & Operations rover for Mars surface exploration," in Proc. 6th Intl. Symposium on Artificial Intelligence, Robotics and Automation in Space (i-SAIRAS'01), Montreal, Canada, June 18-21, 2001.
- [2] *Robot Colonies*, Special Issue of Autonomous Robots (Eds. R. C. Arkin and G. A. Bekey), Vol. 4, No. 5, 1997; also, C. R. Weisbin, P. S. Schenker, R. Easter and G. Rodriguez, "Space AI and Robotics--Robotic Colonies," in Academic Press Encyclopedia of Physical Science and Technology (3rd Edition), in press (2001).
- [3] P. S. Schenker, T. L. Huntsberger, P. Pirjanian, A. Trebi-Ollennu, H. Das, S. Joshi, H. Aghazarian, A. J. Ganino, B. A. Kennedy, and M. S. Garrett, "Robot work crews for planetary outposts: close cooperation and coordination of multiple mobile robots," Proc. SPIE Vol. 4196, Sensor Fusion and Decentralized Control in Robotic Systems III, Boston, MA, Nov. 5-8, 2000.
- [4] P. Pirjanian, T.L. Huntsberger, A. Trebi-Ollennu, H. Aghazarian, H. Das, S. Joshi, and P.S. Schenker, "CAMPOUT: A control architecture for multi-robot planetary outposts," Proc. SPIE Vol. 4196, *ibid*.
- [5] T. Huntsberger, P. Pirjanian, A. Trebi-Ollennu, H. Das, H. Aghazarian, A. Ganino, M. Garrett, Sanjay S. Joshi, and P. S. Schenker, "Tightly-coupled coordination of multi-robot systems for Mars exploration," submitted to IEEE Trans. on Robotics and Automation (Special Issue on Multi-Robot Systems).
- [6] P. S. Schenker, E. T. Baumgartner, R. A. Lindemann, H. Aghazarian, D. Q. Zhu, A. J. Ganino, L. F. Sword, M. S. Garrett, B. A. Kennedy, G. S. Hickey, A. S. Lai, and L. H. Matthies; Jet Propulsion Lab.; B. D. Hoffman, Massachusetts Inst. Technology; T. L. Huntsberger, Univ. So. Carolina, "New planetary rovers for long range Mars science and sample return," Proc. SPIE Vol. 3522, Intelligent Robotics and Computer Vision XVII, Boston, MA, Nov. 1-5, 1998; also, T. L. Huntsberger, E. T. Baumgartner, H. Aghazarian, Y. Cheng, P. S. Schenker, P. C. Leger, K. D. Iagnemma, and S. Dubowsky, "Sensor-fused autonomous guidance of a mobile robot and applications to Mars sample return operations," Proc. SPIE Vol. 3839, Sensor Fusion and Decentralized Control in Robotic Systems II, Boston, MA, pp. 2-8, Sep. 19-22, 1999.
- [7] P. Pirjanian, "Multiple objective behavior-based control," Jnl. Of Robotics and Autonomous Systems, Vol. 31, Iss. 1-2, pp. 53-60, April, 2000.
- [8] P. S. Schenker, P. Pirjanian, B. Balaram, K. S. Ali, A. Trebi-Ollennu, T. L. Huntsberger, H. Aghazarian, B. A. Kennedy and E. T. Baumgartner, Jet Propulsion Laboratory; K. Iagnemma, A. Rzepniewski, and S. Dubowsky, Massachusetts Institute of Technology; P. C. Leger and D. Apostolopoulos, Carnegie Mellon University; G. T. McKee, University of Reading (UK), "Reconfigurable robots for all terrain exploration," Proc. SPIE Vol. 4196, *ibid*.
- [9] J. Balaram, "Kinematic state estimation for a Mars rover," *Robotica*, Vol. 18, 251-262, 2000.
- [10] G. T. McKee and P. S. Schenker, "Networked robotics," Proc. SPIE Vol. 4196, *ibid*.
- [11] G. T. McKee and B. Brooks, "Resource management for networked robotic systems," Proc. IEEE/RSJ Intl. Conf. on Intelligent Robots and Systems (IROS '97), Vol. 3, pp. 1363-1368, 1997.
- [12] P. S. Schenker, "Intelligent robots for space applications," in *Intelligent Robotic Systems: Analysis, Design, and Programming* (S. Tzafestas, Ed.), pp. 545-591, Marcel Dekker: New York City, 1991.
- [13] P. S. Schenker and G. T. McKee, "Man-machine interaction in telerobotic systems and issues in the architecture of intelligent and cooperative control," in Proc. IEEE Intl. Symp. Intelligent Control (Workshop: Architectures for Semiotic Modeling and Situation Analysis in Large Complex Systems, Orgs.: J. Albus, A. Meystel, D. Pospelov, T. Reader), Monterey, CA, August, 1995 (12 pp).
- [14] G. T. McKee, J. A. Fryer and P. S. Schenker, "Object-oriented concepts for modular robotics systems", submitted to IEEE Trans. Robotics and Automation; J.A. Fryer, G. T. McKee, and P. S. Schenker, "Configuring robots from modules: an object oriented Approach, Proc. 8th IEEE Intl. Conference on Advanced Robotics (ICAR'97), Monterey, CA, July, pp. 907-912, 1997.