Autonomous Robots 17, 79–92, 2004

Distributed Control of Multi-Robot Systems Engaged in Tightly Coupled Tasks

TERRY L. HUNTSBERGER, ASHITEY TREBI-OLLENNU, HRAND AGHAZARIAN
AND PAUL S. SCHENKER
Jet Propulsion Laboratory, 4800 Oak Grove Drive, Pasadena, CA 91109, USA
Terry.Huntsberger@jpl.nasa.gov

PAOLO PIRJANIAN
Evolution Robotics, Inc., 130 W. Union St., Pasadena, CA 91103, USA
Paolo@evolution.com

HARI DAS NAYAR
OphirTech, P.O. 6459, Altadena, CA 91003, USA
hari@ophirtech.com

Abstract. NASA mission concepts for the upcoming decades of this century include exploration of sites such as steep cliff faces on Mars, as well as infrastructure deployment for a sustained robotic/manned presence on planetary and/or the lunar surface. Single robotic platforms, such as the Sojourner rover successfully flown in 1997 and the Mars Exploration Rovers (MER) which landed on Mars in January of 2004, have neither the autonomy, mobility, nor manipulation capabilities for such ambitious undertakings. One possible approach to these future missions is the fielding of cooperative multi-robot systems that have the required onboard control algorithms to more or less autonomously perform tightly coordinated tasks. These control algorithms must operate under the constrained mass, volume, processing, and communication conditions that are present on NASA planetary surface rover systems. In this paper, we describe the design and implementation of distributed control algorithms that build on our earlier development of an enabling architecture called CAMPOUT (Control Architecture for Multi-robot Planetary Outposts). We also report on some ongoing physical experiments in tightly coupled distributed control at the Jet Propulsion Lab in Pasadena, CA where in the first study two rovers acquire and carry an extended payload over uneven, natural terrain, and in the second three rovers form a team for cliff access.

Keywords: tight coordination, distributed control architecture, multiple mobile robots

1. Introduction

As NASA fields more sophisticated science payloads with in-situ processing laboratories on the planetary surface rovers, access to "interesting" areas such as cliff faces requires much higher levels of autonomy and mobility than previously flown. Additionally, sustained scientific collection sites on planetary surfaces will be dependent on available onsite assembly, inspection, and maintenance (AIM) capabilities. Examples of these types of operations are shown in Fig. 1 where a rover is traversing a cliff-face while tightly coupled through tethers to two other rovers anchored at the top of the cliff, and in Fig. 2 where two rovers perform a typical infrastructure construction task of solar array deployment. By tightly coupled, we mean continuous coordinated motion with a control cycle time of 10 Hz of multiple robots that are physically linked

Figure 1. Cliff-bot performing active way point navigation on a cliff face with closely coordinated active tether control by two anchor-bots at the top of the cliff.

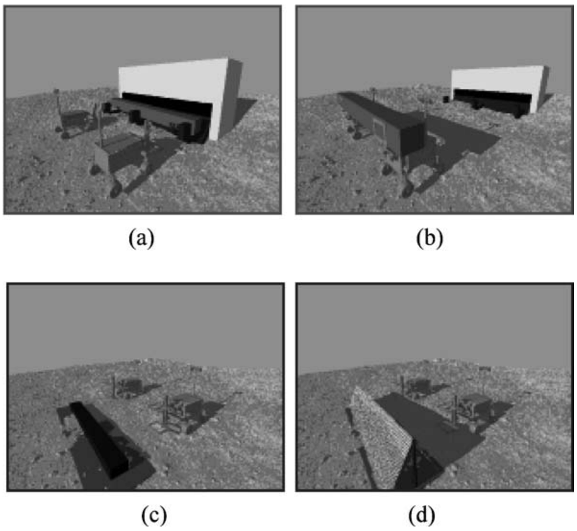

Figure 2. Four step sequence for a PV tent array deployment. PV tent storage container is 5 m in length and is not well handled by a single robot. Steps in sequence are: (a) Unload container from CSU; (b) Traverse to deployment site; (c) Position and open container; (d) Deploy tent.

through a shared payload or tethers. On the one hand, multi-robot systems offer the redundancy needed for long duration mission risk mitigation. However, this is tempered by the increased complexity involved in designing and implementing a suite of control algorithms for such systems. To address these concerns we have developed a control architecture called CAMPOUT (Control Architecture for Multi-robot Planetary Outposts) that is tailored for space-based multi-robot systems.

Recent investigations at various laboratories worldwide (Hara et al., 1999; Khatib et al., 1996; Kurabayashi et al., 1996; Miyata et al., 1997; Osumi et al., 1998; Rus et al., 1995; Sugar and Kumar, 1999; Borenstein, 2000; Wang et al., 2003] and the Jet Propulsion Lab (Huntsberger et al., 2003; Pirjanian et al., 2000, 2001; Schenker et al., 2000, 2001, 2003; Trebi-Ollennu et al., 2002) in Pasadena, CA have started to lay the groundwork for development of algorithms for multi-robot manipulation and transport operations. Our approach is similar to that used in the Omnimate system which uses a compliant linkage platform between two differential-drive mobile platforms (Borenstein, 2000). The Omnimate system drives along a pre-determined path and is able to compensate for uneven floors and moderate wheel-slippage using an internal position error correction (IPEC) technique based on the angular difference between the expected and observed lines of contact between the drive platforms to control wheel velocity. In general, work other than that of Osumi et al. (1998) outside of JPL have concentrated on transport in indoor environments rather than outdoor natural terrain. Outdoor environments tend to have added complexity due to unknown wheel/soil interactions, unpredictable lighting, and sloped terrain.

NASA applications differ in some respects from traditional distributed control regimes in that large swarms of robots will probably not be fielded any time soon due to mass, computational, and power constraints. Also, due to long communication paths (typically ∼40 minutes round-trip), using man-in-the-loop teleoperation to relieve some of the autonomy needs is not really a viable option. This being the case, the most efficient use of small teams of robots is through distributed controlled, tightly coupled cooperative operations. A good review of distributed robotic systems can be found in Parker (2000).

Key capabilities for assembly operations during planetary surface missions include closely coordinated manipulation and movement. Included in the potential suite of behaviors would be grasping, hoisting, winching, and traverse (Huntsberger et al., 2000, 2001). A typical task scenario that includes all of these operations is shown in Fig. 2, which is based on a robotic deployment of photovoltaic (PV) tents onto a planetary surface. This scenario was initially studied by Colozza (1991) using a manned deployment of the tents. The PV tents would be delivered to the planetary surface in a Container Storage Unit (CSU) shown in Fig. 2(a) that may contain up to a dozen 5 meter-long containers. In a four step operation, these containers are unloaded from the CSU (Fig. 2(a)), transported to the deployment site (Fig. 2(b)), positioned and opened (Fig. 2(c)), and the tents are then deployed (Fig. 2(d)). Closely coupled operations involved in the four steps are:

1. grasping and hoisting,
2. ensemble movement, configuration change, possible obstacle avoidance, and load rebalancing,
3. hoisting and precision manipulation, and
4. precision manipulation and winching.

Ideally, this entire sequence would be done autonomously. We will primarily concentrate on the operations involved in step 2 (Fig. 2(b)) of the sequence to illustrate suitable candidates for control of the multi-robot systems.

This paper will concentrate on the control algorithm development under CAMPOUT, rather than details of the architecture which are reported elsewhere (Huntsberger et al., 2003a; Pirjanian et al., 2000, 2001; Schenker et al., 2003). The next section gives a very brief review of the CAMPOUT framework that is used for development of the control algorithms. This is followed by a detailed discussion of the suite of algorithms, using the PV tent and cliff-bot scenarios as reference. The results of some experimental studies are presented next, and a final section that summarizes the work and current directions.

2. CAMPOUT

CAMPOUT is a behavior-based control architecture that has been under development at JPL over the last three years (Huntsberger et al., 2003a; Pirjanian et al., 2000, 2001; Schenker et al., 2000, 2001, 2003; Trebi-Ollennu et al., 2002). The behavior-based methodology was selected for its ability to span the range of robotic capabilities from purely reactive behaviors such as obstacle avoidance, all the way to highly complex operations such as autonomous assembly tasks (Arkin, 1998). A high level overview of the CAMPOUT framework is shown in Fig. 3. There is currently no planning layer in CAMPOUT and all sequencing is done through Finite State Machines (FSMs) for deterministic control. A planner would interface to CAMPOUT through the *group* and *composite behaviors*. The behavior coordination mechanisms used to manage the *group behaviors* are based on multi-objective decision theory where a weighted combination of behaviors is analyzed for consensus (Pirjanian, 2000). These weights would be adjusted by the higher level planner as the mission unfolds. The lower layer shown in Fig. 3 contains all of the hardware specific interfaces and is based on the software infrastructure developed in support of the JPL FIDO (Field Integrated Design and Operations) rover (Huntsberger et al., 2002). FIDO is a technology prototype rover that was built for development and field testing of algorithms, and for the

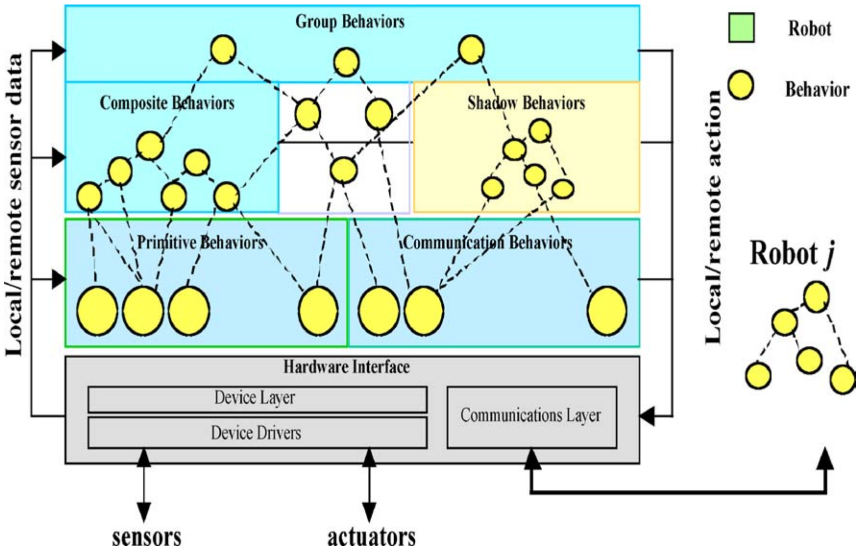

Figure 3. CAMPOUT high-level organization with a behavior layer (primitive, composite, and group behaviors) (Pirjanian et al., 2000a; Huntsberger et al., 2003).

training of the 2003 MER (Mars Exploration Rover) science team.

The behavior layer is built to accommodate the construction of behavior networks with its single robot *primitive behaviors* being used to build more complex *composite behaviors* through behavior composition mechanisms. *Group behaviors* are distributed throughout the robot ensemble and are managed through behavior coordination mechanisms either explicitly using *communication behaviors*, or implicitly using *shadow behaviors*. All communication between the rovers is done using wireless modem within a publish/subscribe protocol (Gerkey and Mataric, 2000). The publish/subscribe communication protocol uses data producers and consumers and message tags with the content of the messages rather than the destination. Any data consumer that is subscribed to a content network will receive the message. The issues of system scaling and heterogeneity are explicitly addressed with the protocol. *Shadow behaviors* rely on shared attributes, such as a beam or tethers, to infer the relative state of the other members of the team. Further details about CAMPOUT can be found in Huntsberger et al. (2003) and references therein). In the following discussions we will underline the group behaviors and italicize the composite behaviors in the text.

3. Distributed Tightly Coupled Control

In this section we will describe the underlying behavior hierarchies for the closely coupled operations of transport (Fig. 2(b)) and cliff traverse (Fig. 1). A CAMPOUT behavior hierarchy for the second phase (Coordinated Transport) of the PV tent deployment scenario (Fig. 2(b)) is shown in Fig. 4. Currently the behavior hierarchies are built by hand. This network was designed for two heterogeneous rovers with non-holonomic constraints such as those shown in Fig. 5. This Robot Work Crew (RWC) is composed of two small technology rovers called SRR and SRR2K (Sample Return Rover) that have been fitted with an instrumented (4 DOF: pitch, roll, yaw, and lateral translate), non-actuated gimbal mechanism (detail shown in Fig. 6) for carrying a half-sized (2.5 meters long) mockup of a PV tent container. The gimbal mechanism

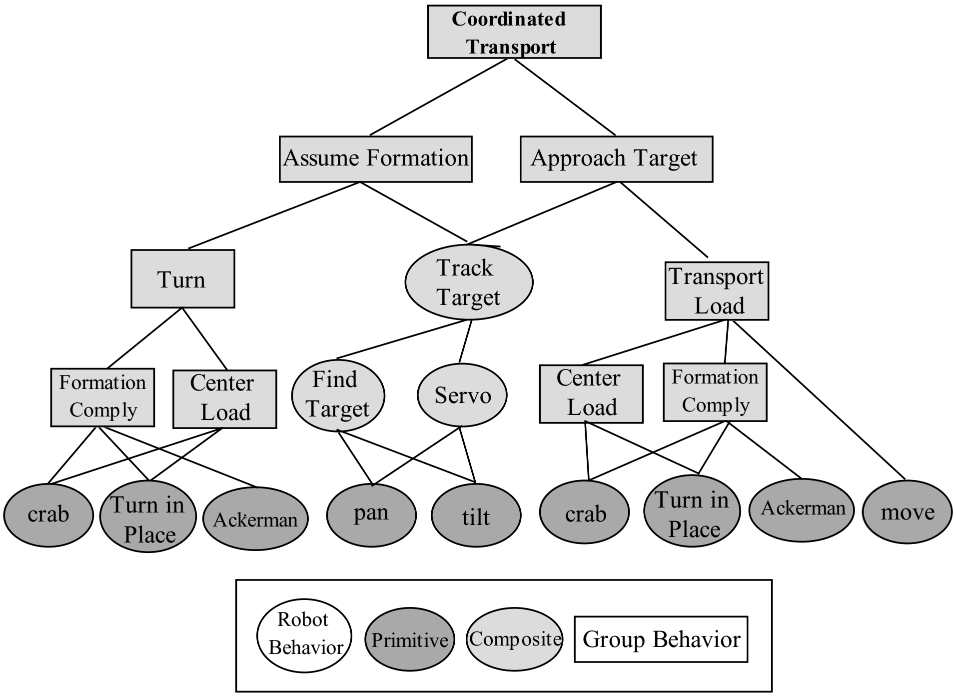

Figure 4. CAMPOUT behavior hierarchy describing a coordinated transport task (see Fig. 2(b)). Bubbles represent single robot behaviors; boxes represent multi-robot "group coordinated behaviors. Higher-level actions, themselves behaviors, are composed from lower-level behaviors (Pirjanian et al., 2000).

Figure 5. Transport formations for the Robot Work Crew (SRR in foreground and SRR2K in background): (left) Column formation for transport and obstacle avoidance; (right) Row formation for precision placement.

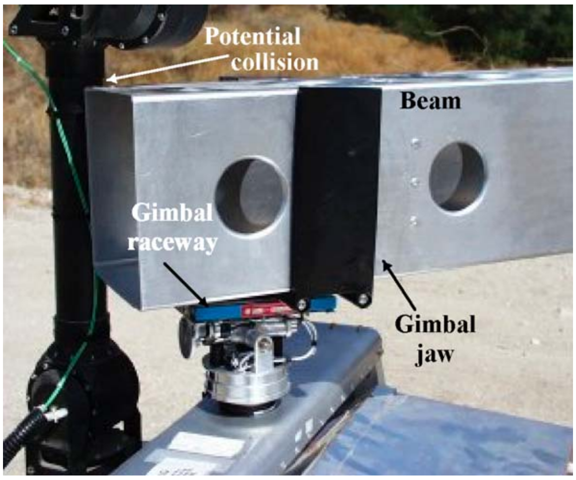

Figure 6. Compliant gimbal instrumented with position, angle, and force feedback sensors used to hold and sense the container. The white arrow shows the potential for collision of the beam with the fixed mast on the rover.

has a rubber contact friction grip that holds the container but will allow it to slip from the gimbal jaws in the event of large lateral movement. This design safeguards the rovers from a tip-over situation due to the container acting like a long lever arm. The gimbal jaws are free to rotate about the vertical axis subject to the collision constraints. Container movement in the z-axis, as would be experienced by the rover ensemble in the event of a large terrain height mismatch, will tend to cause the gimbals to slide to the end of their raceways since the container is held with the friction grip of the gimbal jaws. The Center Load behavior can compensate for this to a certain extent, but the load cells in the base of the gimbal mechanism will alert the system to any overly large loads causing an abort to ensemble motion. Further details of the mechanical design can be found in Trebi-Ollennu et al. (2002).

The unencumbered rovers are holonomic with independent four wheel drive and steering motors, but motion is constrained in order to avoid collisions between the mast and container end (close tolerance indicated by white arrow in Fig. 6). In addition, only one of the rovers (SRR) has a color camera stereo pair on its mast which is used to track a target for heading to a goal location during the transport. SRR was thus designated the Lead rover and executes the *Track Target* composite behavior (shown in the center of the hierarchy in Fig. 4). The *Track Target* behavior is a very simple visual tracking algorithm that locks onto a large color target in the deployment zone. Any other type of heading determination such as a beacon could be used in its place. The *Track Target* composite behavior is a general enough structure that it can be reused by simply supplying the *Find Target* composite behavior that is appropriate for the given task.

The set of primitive behaviors at the bottom of the hierarchy in Fig. 4 are those commonly found on most mobile robotic platforms, such as Turn in Place and Move. The two lowest level group behaviors are Formation Comply used during ensemble reconfiguration, and Center Load used to rebalance the shared container if it has shifted due to terrain variations or during a turn. The Formation Comply and Center Load behaviors are used to build the higher level group behaviors of Turn and Transport Load which are at the core of the distributed control for the ensemble. The high level Coordinated Transport behavior is composed of the Assume Formation and Approach Target behaviors. The *Track Target* behavior is used by both of these to align the ensemble during reconfiguration and transport respectively. Obstacle detection and avoidance are not included in the behavior hierarchy shown in Fig. 4 and will be the topic of a forthcoming paper (Huntsberger and Aghazarian, 2004) In the following subsections we describe the implementation of the main group behaviors under CAMPOUT.

Behavior coordination for the Turn and Transport Load behaviors (composed of the Formation Comply and Center Load behaviors) is done through a priority-based weighting of the recommendations for heading and velocity changes from the individual contributing behaviors. These weights were determined based on simulation studies of the ensemble behavior while adjusting to a variety of different formations. The PD controllers associated with these behaviors use the gimbal yaw error, the deviation from the gimbal center, and the magnitude of the force vector along the payload longitudinal axis as inputs. The set of priority weights for the heading and the set of priority weights for the heading velocity for each of the three controllers add to one. Their values are dependent on the current formation of the rovers: gimbal yaw error being the dominant one for velocity in a row formation, and the deviation from the gimbal center being dominant for velocity and gimbal yaw error for heading in the column formation. Further details of the model and weights can be found in Trebi-Ollennu et al. (2002).

3.1. Assume Formation

The Assume Formation behavior changes the configuration of the rovers between any arbitrary start and end formation. Two example configurations, "column" and "row", are shown in Fig. 5. For grasping and hoisting operations, the row formation is favored due to the need for precision alignment with the container. For transport operations the column formation is favored for ease of obstacle avoidance due to its narrower footprint. The *Track Target* behavior provides the heading to the target then the Turn behavior reconfigures the formation to a desired one. Two constraints make this a challenging task. First, transformation between the current and target formations must ensure that the container is handled safely, i.e., the distance between the robots, d, should always remain within some tolerance margin. The Formation Comply behavior, described later, monitor the state of the load and constrain the movement of the rovers to guarantee this requirement. Second, it is required that the container does not collide with the mast on the lead rover (indicated by arrow in Fig. 5), which could lead to damaging the mast, the gripper/gimbal, or the container, and/or dropping the container. This constraint defines a safety zone around the mast that is not allowed to be entered during the ensemble reconfiguration.

3.1.1. Turn. Figure 7 illustrates the sequence of motions that occur to change formation. In Fig. 7(a) we show a scenario where the rovers are in row formation in the Approach Target behavior when the Assume Formation behavior is invoked. Each rover has a specific role and their actions occur simultaneously. The role of the lead rover is to drive a pre-determined trajectory along an arc with the follow rover acting as a pivot point to change the formation. At the same time, the follow rover wheels are continuously aligned with the load and it simultaneously drives forwards or backwards to ensure that the load is centered in its gimbal and load forces are minimized. The following steps occur in sequence to change the formation:

- *Step 1*: The follow rover aligns its wheels with the load and the lead rover waits (Fig. 7(b)).
- *Step 2*: The lead rover turns its wheels to drive along the pre-determined arc trajectory (Fig. 7(c)). As the lead rover drives along an arc, the follow (pivot) rover continuously aligns its wheels with the load and drives forwards or backwards based on sensory inputs from its gimbal to compensate for the lead rover's deviations from the arc (that inevitably occur due to ground slippage, terrain effects, etc.) (Fig. 7(d)).
- *Step 3*: When the lead rover has traversed the arc, the lead rover steers its wheels into a turn-in-place (point turn) configuration. At the same time, the follow rover straightens its wheels back to its original wheel configuration (Fig. 7(e)).
- *Step 4*: The lead rover turns in place until the load is at the commanded formation angle (Fig. 7(f)).

3.1.2. Formation Comply. In order to avoid losing grip of the container, the Formation Comply behavior performs coordinated turns and straight-line formation motion of the rover pair with minimal explicit communication between the rovers. Utilizing the gimbal sensory information and the known physical constraint between the rovers imposed by the PV tent container, each rover can partially estimate its physical relationship with respect to the other rover. Using this information and knowing its role in achieving the current goal (turn or move in formation in a straight line), each rover can operate independently until the terminal condition indicating goal achievement or an exception condition occurs.

In the coordinated turn of an arbitrary angle one rover acts as the pivot point for the turn and the other rover drives in an arc to rotate the ensemble through the turn angle. Since the length of the container is known, the arc length and its radius to be traversed are precomputed before execution of the turn. During the turn, the rover at the pivot point turns in place to maintain alignment with the container. As the other rover drives in an arc, the rover at the pivot point drives forwards or backwards based on sensory inputs from its gimbal to

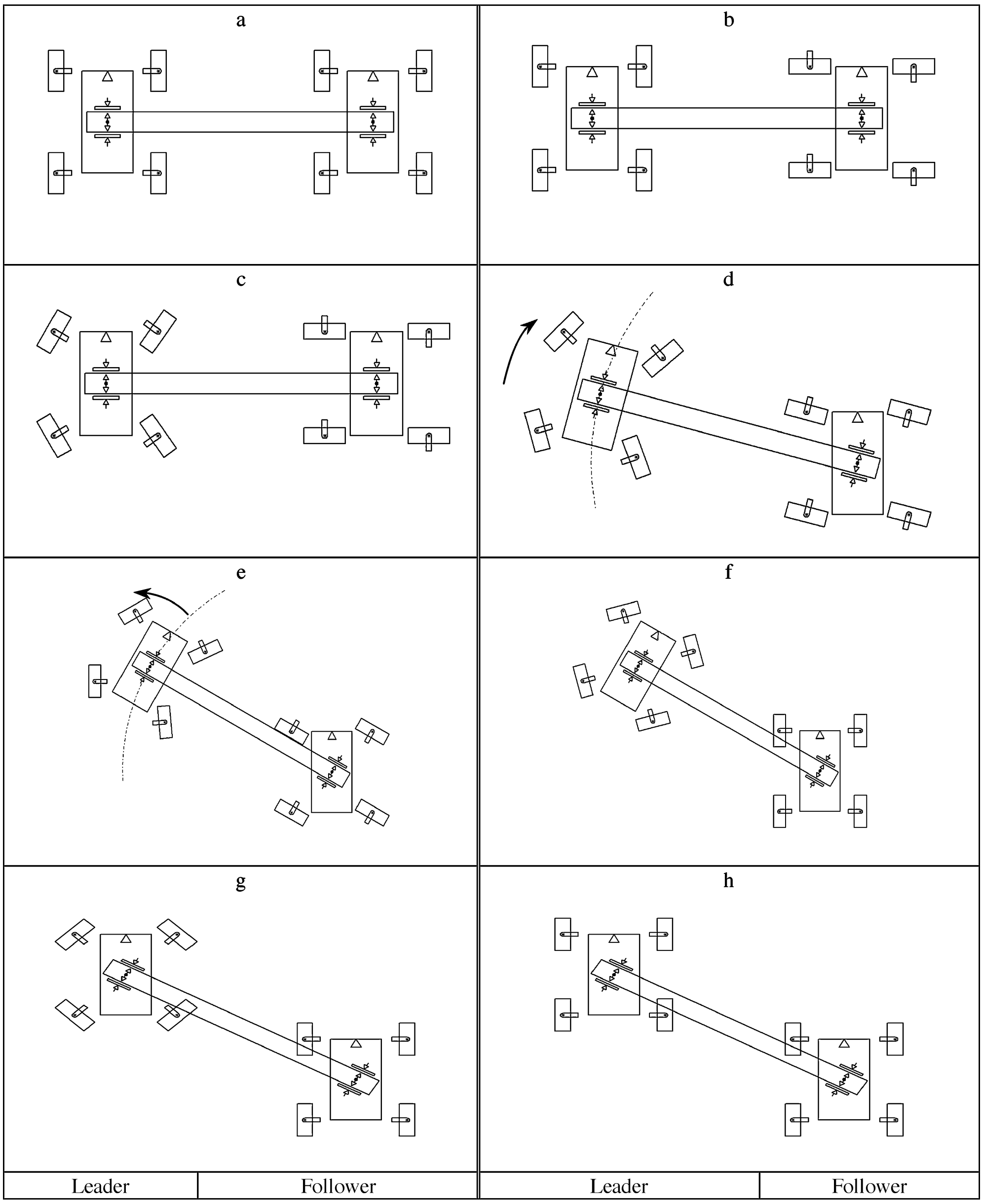

Figure 7. Phases of the Assume Formation group behavior: (a) initial configuration; (b) follow rover aligns its wheels with the load and the lead rover waits; (c–d) lead rover turns its wheels to drive along the pre-determined arc trajectory and the follow (pivot) rover simultaneously aligns its wheels with the load and drives forwards or backwards based on sensory inputs from its gimbal to compensate for the lead rover's deviations from the arc; (e–f) lead rover steers its wheels into a turn-in-place (point turn) configuration and the follow rover simultaneously straightens its wheels back to its original wheel configuration; (g) lead rover turns in place until the load is at the commanded formation angle; (h) rovers are aligned in new formation.

compensate for the other rover's deviations from the arc (that inevitably occur due to ground slippage, terrain effects, etc.). The terminal condition to end this activity is when the rover on the arc has completed driving its arc length and the rover at the pivot has either turned the appropriate angle in place or the time allotted for the turn expires. The exception condition is when the force in the gimbal exceeds a specified threshold. This usually occurs almost simultaneously on both rovers because of reaction forces on the container. Should an exception occur, the rovers stop the activity, synchronize and re-acquire the target to re-initialize their current locations with respect to the target location. This is also done upon successful completion of the turn because the actual angle turned will differ from the desired.

3.1.3. Center Load.

The Center Load behavior is an example of a behavior that is not as tightly coupled as Formation Comply, and is closer to a loosely cooperative manuever. The Center Load behavior is activated when the force in the gimbal on either of the rovers exceeds a specified threshold. A example of a non-centered container is shown in Fig. 6 and further illustrated in Fig. 8(a), where the gimbal has traveled

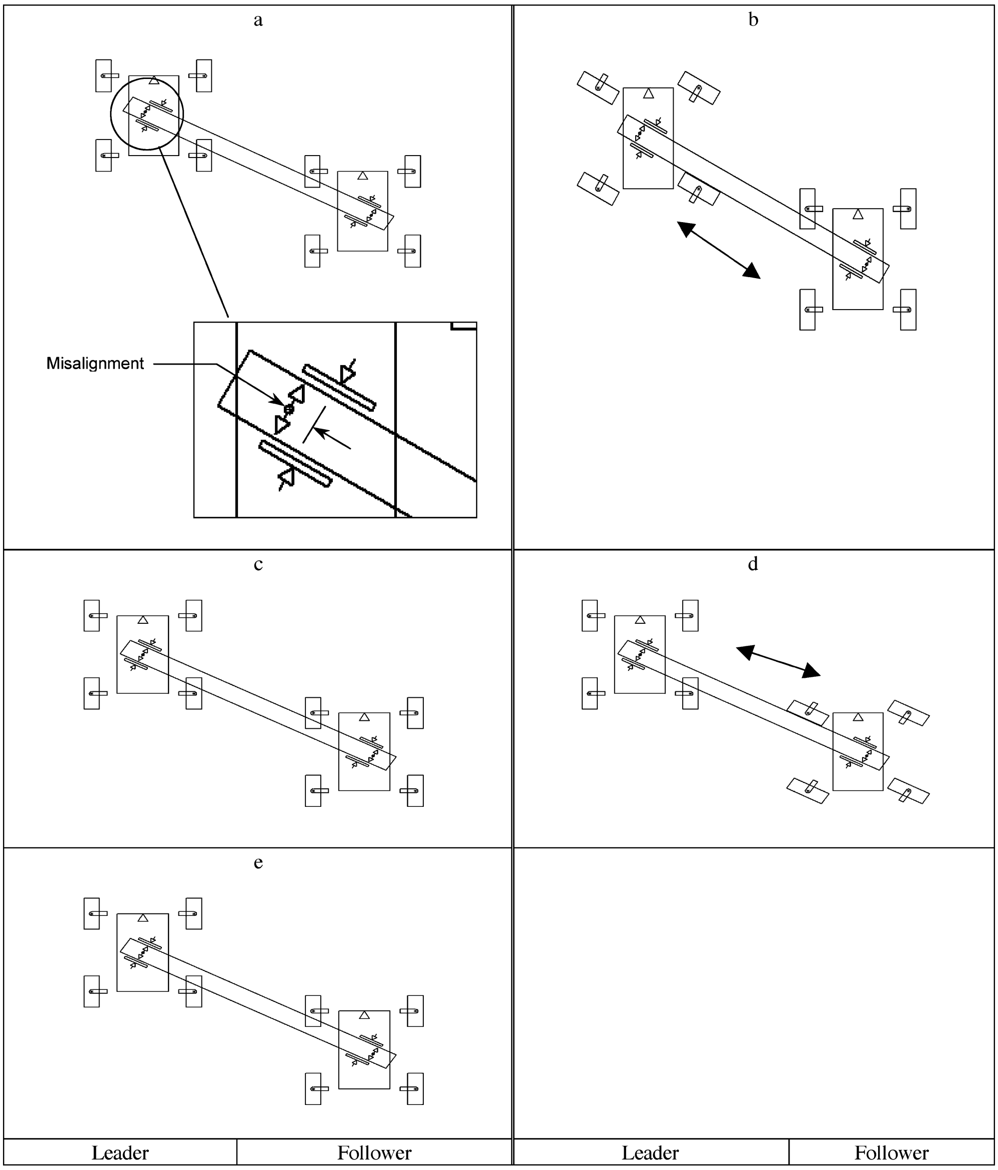

Figure 8. Phases in the Center Load group behavior: (a) synchronization occurs between the rovers to indicate triggering of the behavior and both rovers then halt; (b) lead rover turns its wheels to align them with the load; (c) lead rover drives the appropriate distance to correct for the misalignment, and upon completion of the correction, the lead rover straightens its wheels; (d–e) rovers reverse roles and the follow rover also performs (b) and (c).

the full lateral extent of the raceway to the right and further movement in that direction would cause the container to be dropped. Figure 8 illustrates the sequence of motions that occur to center the load on both rovers and reset the force. In Fig. 8 we assume a scenario where the rovers are in a column formation in the Transport Load behavior when the Center Load behavior is triggered. The corrective procedure is for each rover to center the load with respect to the center of its gimbal raceway. The misalignment is illustrated by the arrows on Fig. 8(a). In the corrective procedure, the lead rover performs its correction while the follow rover waits. When the lead rover has completed its correction, the rovers reverse roles and the follow rover performs its correction. The following steps occur in sequence during the center load behavior:

- *Step 1*: A synchronization occurs between the rovers to indicate triggering of the *Center Load* behavior. Both rovers then halt (Fig. 8(a) illustrates the rovers in this configuration)
- *Step 2*: The lead rover turns its wheels to align them with the load (as illustrated in Fig. 8(b)). The distance to drive to correct the misalignment is determined by reading the displacement from the gimbal translate sensor (the sign indicates the direction to drive in).
- *Step 3*: The lead rover then drives the appropriate distance to correct for the misalignment, and upon completion of the correction, the lead rover straightens its wheels (as shown on Fig. 8(c)).
- *Step 4*: The rovers reverse roles. The follow rover also performs Steps 2 and 3 as shown on Fig. 8(d) and (e) and respectively.

During the course of the Center Load behavior, the configuration may have gotten out of alignment. The Formation Comply behavior is then invoked to realign the ensemble, with a subsequent Center Load if needed.

3.2. *Approach Target*

The Approach Target behavior's objective is to safely carry the container towards the deployment area. It is composed of the Transport Load and *Track Target* behaviors (see Fig. 4). The main challenge of the Transport Load behavior is to prevent the container from falling from the gimbals, which is achieved by active compliance. The Transport Load behavior must comply to any external and internal disturbances caused by the rovers or the uneven terrain.

3.2.1. Transport Load. The Transport Load behavior coordinates the motion of the two rovers in a desired formation. During a traverse, both rovers continuously modify their heading (i.e. steering trajectories) and velocity trajectory profiles to ensure that the formation is maintained, the load is centered in their gimbals, and gimbal forces do not exceed a specified threshold. These operations are executed through the Center Load and Formation Comply behaviors. Each rover attempts to maintain its orientation with respect to the container (and so its orientation with respect to the other rover) using local sensory data from its gimbal. Depending on the formation (column, row or something in between), each rover uses its speed and its heading to compensate for deviations from the formation and for force build-up (compression or extension) of the container. The terminal condition for this activity is the achievement of the distance traversed as determined by relative distance to the target as returned by the *Track Target* behavior. Thresholds on force and formation angle error trigger exceptions that abort the activity. The following steps occur in sequence during Transport Load:

- *Step 1*: The rovers synchronize to initiate driving.
- *Step 2*: During driving, the state information (force, torque, and translation) from the gimbal on each rover is used to continuously modify velocity and heading of the rovers.
- *Step 3*: During transport, excessive force in the load on either rover may trigger a Center Load behavior. The rovers perform the Center Load behavior, and upon completion, recheck the ensemble alignment and trigger the Formation Comply behavior if necessary. Then, the Transport Load behavior resumes (Steps 1 and 2) until the transport distance is completed as indicated by the *Track Target* behavior.

3.3. *Cliff Traverse*

We next turn to the cliff traverse scenario which can be characterized as tightly coupled in that system stability is directly tied to coordinated tether movement with respect to the cliff-bot traverse on the cliff face. The behavior hierarchy for the cliff traverse scenario (rover configuration of Fig. 1) is shown in Fig. 9. This hierarchy reuses the entire *Track Goal* composite behavior to determine sequence success with appropriate modifications for this task. In this scenario, the goal or target is selected by scientists using remote imagery of the cliff face, as would be done in a mission context. The goal

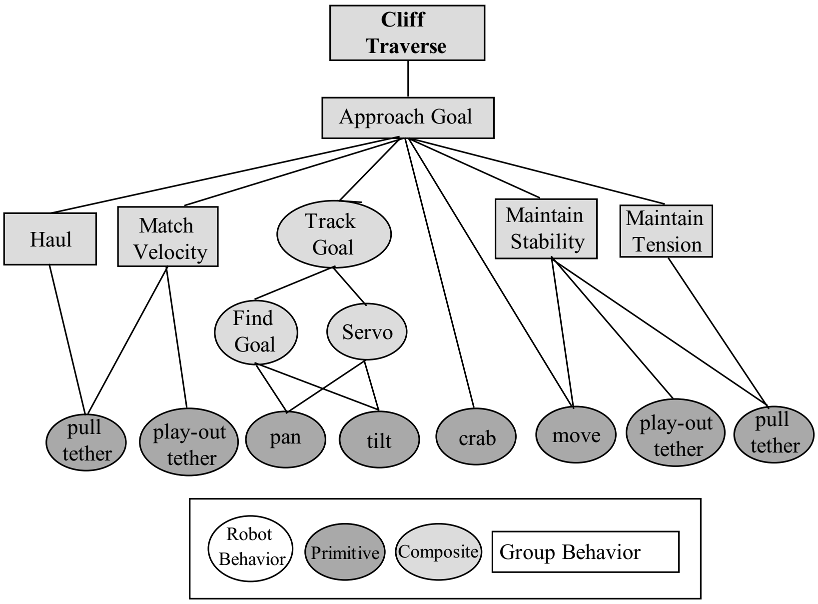

Figure 9. CAMPOUT behavior hierarchy describing a coordinated cliff traverse task (see Fig. 1). Bubbles represent single robot behaviors; boxes represent multi-robot "group coordinated behaviors. Higher-level actions, themselves behaviors, are composed from lower-level behaviors (Pirjanian et al., 2000).

is then tracked (see Huntsberger et al., 2002a) using visual servoing of the mast on the cliff-bot rover. The cliff-bot ensemble shown in Fig. 1 did not have the mast in place during our studies, so a position on the cliff face was selected manually and passed to the rovers through a wireless link. Further details can be found in Pirjanian et al. (2002). Communication between the fixed anchor-bots at the top of the cliff and the cliff-bot on the face is done through the publish and subscribe communication protocol (Gerkey and Mataric, 2000) discussed in Section 1. Further details of the cliff-bot ensemble can be found in Pirjanian et al. (2002).

The crab and move primitive behaviors are also reused from the Coordinated Transport behavior hierarchy. The two new primitive behaviors of pull tether and play-out tether both have to do with tether management. These are used to build the Haul, Match Velocity, Maintain Stability, and Maintain Tension group behaviors, that are then coordinated through the Approach Goal group behavior. The Maintain Stability behavior minimizes the risk of tip-over, the Maintain Tension behavior keeps a constant tension on the tethers, the Match Velocity behavior controls the tether play-out rates to match those of the active agent on the cliff face, and the Haul behavior gives the active agent a pull if it has insufficient torque to get moving at the start of a traverse. A detailed view of the Approach Goal group behavior from the anchor-bot1 standpoint is shown in Fig. 10. This figure does not explicitly include the *Track Goal* composite behavior, but instead treats it as one of the Perception inputs for the module.

The Approach Goal group behavior uses sensory inputs from the encoders on both of the anchor-bots to monitor tether play-out velocity, resolvers at the cliff-bot tether anchor point to measure the angles of the two tethers relative to the cliff-bot body, and load cells at the cliff-bot tether anchor point to monitor tension on the tethers. The group behaviors are prioritized based on mission risk, with Maintain Stability, Haul, and Match Velocity (from highest to lowest) being combined using a priority-based arbitration mechanism (Pirjanian, 2000).

4. Experimental Studies

We have run some preliminary experimental studies in the Arroyo Seco at JPL. These were done using the rover ensemble shown in Fig. 5 running under CAMPOUT. The entire deployment sequence shown in Fig. 1 has been examined throughout all of our studies, but we will only report on the results for the transport step of the operation shown in Fig. 2(b). The two rovers are mechanically coupled through a 2.5 meter long hollow

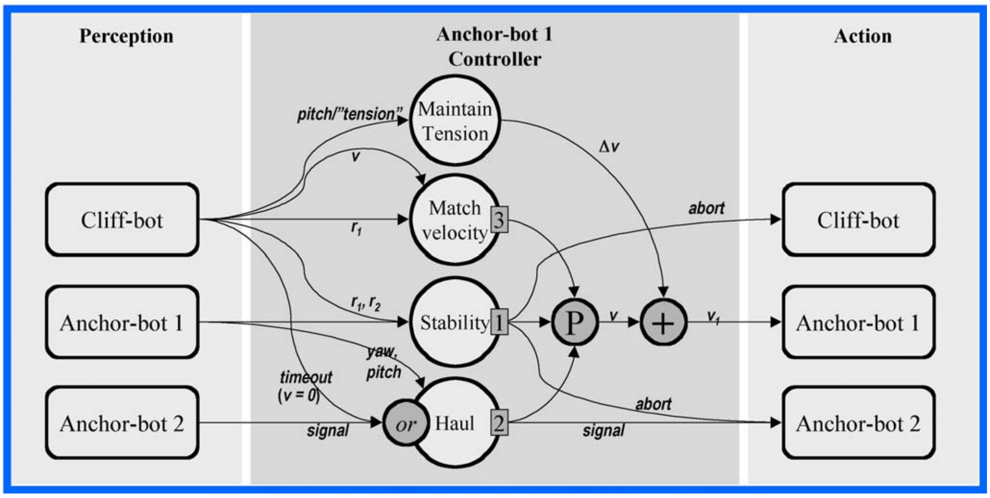

Figure 10. A subset of the Approach Goal group behavior for collective cliff-descent illustrating sub-system for controlling the velocity of anchor-bot 1. The arrows represent data links between local blocks as well as remote components (behaviors, sensors, actuators).

beam with a 0.25 meter by 0.25 meter square cross-section (half-size mockup of a PV tent). The slider on the gimbal had a full range of plus or minus 0.02 meters.

The average results of the first experimental studies with ten runs of the system using the control structure shown in Fig. 4 demonstrated:

1. 40-to-50 meter autonomous traverses of outdoor irregular terrain (maximal slope of 9°) by two rovers (SRR/SRR2k) in the tightly coupled transport of an extended container,
2. autonomous approach to the CSU and coordinated grasping of the payload container in outdoor irregular terrain (maximal slope of 2°) by two rovers (SRR/SRR2K),
3. autonomous change of formation by two rovers carrying an extended container under compliant control, and
4. continuous, autonomous visual guidance to a designated deployment site from 50 m, with a heading error $<1°$; and a distance error $<5\%$ by use of a visual template.

The second set of experimental studies were done with the cliff-bot ensemble on a mesa overlooking JPL. We ran five studies on natural, challenging hill-sides on slopes greater than 70 degrees and over distances of 10–15 meters. Way-points were designated manually along an axis aligned with the slope (straight driving) and also cross-axis (crab motion). Quantitative distance errors were measured from a videotape of the studies, and the average errors over the five runs was 25 cm down-slope and 35 cm cross-slope.

5. Summary and Conclusions

We have described our recent work on distributed control for tightly coupled robotic systems. The implementation of the algorithms was done under the behavior-based framework of CAMPOUT and fielded on JPL technology rovers. The mechanical construction of the rovers and their computational capabilities mimic those of flight rovers and so can serve as terrestrial analogs. Our preliminary experimental studies in the field have demonstrated that the distributed control algorithms are robust enough to autonomously perform relatively complex, tightly coupled transport and cliff traverse operations. These types of operations are common to planetary surface construction and exploration tasks. The localization errors experienced by the rover ensembles can be traced to the tracking of a relatively large target for the transport task and the reliance on wheel odometry without visual servoing on a goal for the cliff traverse task. We are currently examining distributed localization methods such as Howard et al. (2002), Kurazume and Hirose (2000), Leonard and Durrant-Whyte (1991), Rekleitis et al. (1997), and Roumeliotis and Bekey (2000) to address this problem. Localization is most important for robotic construction tasks, since precision placement of components after a traverse is essential. In addition, we are investigating extensions to the cliff-bot behavior hierarchy that include effects such as tether hang-up on obstacles and drop-offs from over-hangs.

Acknowledgment

This work was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration. We would like to thank the anonymous reviewers of the first draft of the manuscript for their comments, which have made the paper more complete. The work involves important contributions from many colleagues at both JPL and collaborating institutions. We gratefully acknowledge these interactions and note many of the specific developments in references that follow.

References

Arkin, R.C. 1998. *Behavior-Based Robotics*. The MIT Press (Intelligent Robotics and Autonomous Agents series).

Borenstein, J. 2000. The Omnimate: A guidewire- and beacon-free AGV for highly reconfigurable applications. *Intern. J. of Production Research*, 38(9):1993–2010.

Colozza, A. 1991. Design and optimization of a self-deploying PV tent array. NASA CR187119, Lewis Research Center Group, Brook Park, OH.

Gerkey, B.P. and Mataric, M.J. 2000. Principled communication for dynamic multi-robot task allocation. In *Proc. International Symposium on Experimental Robotics (ISER 2000)*, Waikiki, Hawaii, pp. 341–352.

Hara, M., Fukuda, M., Nishibashi, H., Aiyama, Y., Ota, J., and Arai, T. 1999. Motion control of cooperative transportation system by quadruped robots based on vibration model walking. In *Proc. IEEE/RSJ Int. Conf. on Intelligent Robots and Systems (IROS'99)*, pp. 1651–1656.

Howard, A., Mataric, M.J., and Sukhatme, G.S. 2002. Localization for mobile robot teams using maximum likelihood estimation. In *Proc. IEEE/RSJ Int. Conf. on Intelligent Robots and Systems (IROS2002)*, pp. 434–439.

Huntsberger, T.L. and Aghazarian, H. 2004. Obstacle avoidance behavior for tightly coupled rover ensembles, in preparation.

Huntsberger, T.L., Rodriguez, G., and Schenker, P.S. 2000. Robotics challenges for robotic and human Mars exploration. In *Proc. ROBOTICS2000,* Albuquerque, NM, pp. 340–346.

Huntsberger, T.L., Pirjanian, P., and Schenker, P.S. 2001. Robotic outposts as precursors to a manned Mars habitat. In *Proc. Space Technology and Applications International Forum (STAIF-2001)*, Albuquerque, NM, pp. 46–51.

Huntsberger, T., Aghazarian, H., Cheng, Y., Baumgartner, E.T., Tunstel, E., Leger, C., Trebi-Ollennu, A., and Schenker, P. 2002. Rover autonomy for long range navigation and science data acquisition on planetary surfaces. In *Proc. 2002 IEEE International* Conf. on Robotics and Automation (ICRA2002), Washington, DC, pp. 3161–3168.

Huntsberger, T.L., Pirjanian, P., Trebi-Ollennu, A., Nayar, H.D., Aghazarian, H., Ganino, A.J., Garrett, M.S., Joshi, S.S., and Schenker, P.S. 2003a. CAMPOUT: A control architecture for tightly coupled coordination of multi-robot systems for planetary surface exploration. *IEEE Transactions on Systems, Man, & Cybernetics: Special Issue on Collective Intelligence*, 33:550–559.

Huntsberger, T.L., Sujan, V.A., Dubowsky, S., and Schenker, P.S. 2003b. Integrated system for sensing and traverse of cliff faces. In *Proc. SPIE AeroSense'03: Unmanned Ground Vehicle Technology V*, 5083, Orlando, FL, in press.

Khatib, O., Yokoi, K., Chang, K., Ruspini, D., Holmberg, R., and Casal, A. 1996. Vehicle/arm coordination and multiple mobile manipulator decentralized cooperation. In *Proc. IEEE/RSJ Int. Conf. on Intelligent Robots and Systems (IROS'96)*, pp. 546–553.

Kimura, H. and Kajiura, G. 1997. Motion recognition based cooperation between human operating robot and autonomous assistant robot. In *Proc. IEEE Intl. Conf. on Robotics and Automation (ICRA'97)*, pp. 297–303.

Kurabayashi, D., Sasaki, J., and Aiyama, Y. 1996. Cooperative transport with regrasping of torque-limited mobile robots. In *Proc. IEEE/RSJ Int. Conf. on Intelligent Robots and Systems (IROS'96)*, pp. 304–309.

Kurazume, R. and Hirose, S. 2000. An experimental study of a cooperative positioning system. *Autonomous Robots*, 8(1):43–52.

Leonard, J.J. and Durrant-Whyte, H.F. 1991. Mobile robot localization by tracking geometric beacons. *IEEE Trans. on Robotics and Automation*, 7(3):376–382.

Miyata, N., Ota, J., Aiyama, Y., Sasaki, J., and Arai, T. 1997. Cooperative transportation system with regrasping car-like mobile robots." In *Proc. IEEE/RSJ Int. Conf. on Intelligent Robots and Systems (IROS'97)*, pp. 1754–1761.

Osumi, H., Terasawa, M., and Nojiri, H. 1998. Cooperative control of multiple mobile manipulators on uneven ground. In *Proc. IEEE Int. Conf. on Robotics and Automation (ICRA'98)*, Leuven, Belgium, pp. 3198–3203.

Parker, L.E. 2000. Current state of the art in distributed robot systems. In *Distributed Autonomous Robotic Systems 4,* Lynne E. Parker, George Bekey, and Jacob Barhen (Eds.), Springer, pp. 3–12.

Pirjanian, P. 2000. Multiple objective behavior-based control. *Robotics and Autonomous Systems* 31(1/2):53–60.

Pirjanian, P., Huntsberger, T.L., Trebi-Ollennu, A., Aghazarian, H., Das, H., Joshi, S., and Schenker, P.S. 2000. CAMPOUT: A control architecture for multi-robot planetary outposts. In *Proc. SPIE Sensor Fusion and Decentralized Control in Robotic Systems III*, 4196, Boston, MA.

Pirjanian, P., Huntsberger, T.L., and Schenker, P.S. 2001. Development of CAMPOUT and its further applications to planetary rover operations: A multirobot control architecture. In *Proc. SPIE Sensor Fusion and Decentralized Control in Robotic Systems IV*, 4571, Newton, MA.

Pirjanian, P., Leger, C., Mumm, E., Kennedy, B., Garrett, M., Aghazarian, H., Schenker, P.S., and Farritor, S. 2002. Distributed control for a modular, reconfigurable cliff robot. In *Proc. 2002 IEEE International Conf. on Robotics and Automation (ICRA2002)*, Washington, DC, pp. 4083–4088.

Rekleitis, I.M., Dudek, G., and Milios, E. 1997. Multirobot exploration of an unknown environment: Efficiently reducing the odometry error. In *Proc. International Joint Conf. on Artificial Intelligence (IJCAI'97)*, pp. 1340–1345.

Roumeliotis, S.I. and Bekey, G.A. 2000. Collective localization: A distributed Kalman filter approach. In *Proc. 2000 IEEE International Conf. on Robotics and Automation (ICRA2000)*, San Francisco, CA, pp. 2958–2965.

Rus, D., Donald, B., and Jennings, J. 1995. Moving furniture with teams of autonomous robots. In *Proc. of IEEE/RSJ Int. Conf. on Intelligent Robots and Systems (IROS'95)*, pp. 235–242.

Schenker, P.S., Huntsberger, T.L., Pirjanian, P., Trebi-Ollennu, A., Das, H., Joshi, S., Aghazarian, H., Ganino, A.J., Kennedy, B.A., and Garrett, M.S. 2000. Robot work crews for planetary outposts: close cooperation and coordination of multiple mobile robots. In *Proc. Sensor Fusion and Decentralized Control in Robotic Systems III*, SPIE vol. 4196, Boston, MA.

Schenker, P.S., Huntsberger, T.L., Pirjanian, P., McKee, G.T. 2001. Robotic autonomy for space: Closely coordinated control of networked robots. In *Proc. 6th International Symposium on Artificial Intelligence, Robotics and Automation in Space (i-SAIRAS-'01),* Montreal, Canada.

Schenker, P.S., Huntsberger, T.L., Pirjanian, P., Baumgartner, E.T., and Tunstel, E. 2003. Planetary rover developments supporting Mars exploration, sample return and future human-robotic colonization. *Autonomous Robots*, 14:103–126.

Sugar, T. and Kumar, V. 1999. Multiple cooperating mobile manipulators. In *Proc. IEEE Int. Conf. on Robotics and Automation (ICRA'99)*, pp. 1538–1543.

Trebi-Ollennu, A., Das, H., Aghazarian, H., Ganino, A., Pirjanian, P., Huntsberger, T., and Schenker, P. 2002. Mars rover pair cooperatively transporting a long payload. In *Proc. 2002 IEEE International Conf. on Robotics and Automation (ICRA2002)*, Washington, DC, pp. 3136–3141.

Wang, Z.D., Nakano, E., and Takahashi, T. 2003. Solving function distribution and behavior design problem for cooperative object handling by multiple mobile robots. *IEEE Trans. on Systems, Man, & Cybernetics: Special Issue on Collective Intelligence*, 33(5):537–549.

Terry Huntsberger is a Senior Member of the Technical Staff in the Mechanical and Robotics Technologies Group at the Jet Propulsion Laboratory in Pasadena, CA, where he is the Manager for numerous tasks in the areas of multi-robot control systems, rover systems for access to high risk terrain, and long range traverse algorithms for rovers. He is a member of the planning teams for the Mars Science Laboratory (MSL) mission planned for launch in 2009. He is an Adjunct Professor and former Director of the Intelligent Systems Laboratory in the Department of Computer Science at the University of South Carolina. His research interests include behavior-based control, computer vision, neural networks, wavelets, and biologically inspired system design. Dr. Huntsberger has published over 120 technical articles in these and associated areas. He received his PhD in Physics in 1978 from the University of South Carolina. He is a member of SPIE, ACM, IEEE Computer Society, and INNS.

Ashitey Trebi-Ollennu is a Member of Engineering Staff at the Jet Proportion Laboratory in Pasadena, CA, where he serves as a Control Systems, Operations and Test Engineer for the Field Integrated Design and Operations Rover (FIDO), Robot Work Crews and Mars Exploration Rover (MER) 2003 projects. He is a multidisciplinary engineer with a broad background and extensive experience in Planetary Rover Operations, Distributed Mobile Robotics, System Architectures, Dynamic Modelling and Control Systems design for Aerospace and Mechatronics Systems. His current research at JPL focuses on Planetary Rovers, Multiple Mobile Robots (Planetary Outpost), Reconfigurable Robots and Man-machine Interaction. Dr. Trebi-Ollennu's research has resulted in more than 50 journal articles, conference papers and book chapters. He earned his B.Eng. (Hons) in Avionics Engineering from Queen Mary College, University of London and a Ph.D. in Aerospace Engineering at the Royal Military College of Science, Cranfield University, U.K in 1991 and 1996 respectively. He was a Research Scholar at, Institute for Complex Engineered Systems, Carnegie Mellon University, were he helped develop a system of All Terrain Vehicles (ATVs) for distributed tactical surveillance for DARPA.

Hrand Aghazarian is a Senior Member of the Engineering Staff in the Mechanical sand Robotics Technologies Group at the Jet Propulsion Laboratory in Pasadena, CA. He has extensive work experience in the design and development of real-time embedded software for a variety of avionics systems. Currently he is involved in providing software solutions in the area of software architecture, low-level drivers, motor control, user interfaces for commanding planetary rovers, and navigation algorithm for SRR and FIDO rovers. His research interests are Rover Navigation/Control and Real-Time Embedded software Design and Development. He received a dual B.S. degree in Applied Math and Computer Science and a M.S. degree in Computer Science from California

State University in Northridge. He is a member of ACM and INNS.

Paul S. Schenker is Manager, Mobility Systems Concept Development Section, Jet Propulsion Laboratory (JPL), California Institute of Technology, Pasadena, and as such, is responsible for JPL R&D in planetary mobility and robotics. His published research includes topics in robotic perception, robot control architectures, telerobotics and teleoperation, multi-sensor fusion, and most recently, multi-robot cooperation. He has led the development of robotic systems that include the Field Integrated Design & Operations Rover (FIDO), Planetary Dexterous Manipulator (MarsArm, microArm), Robot Assisted Microsurgery System (RAMS), Robotic Work Crew (RWC), and All Terrain Explorer (ATE/Cliff-bot), with resulting technology contributions to NASA missions. Dr. Schenker is active in the IEEE, Optical Society of America, and SPIE. He has served as an elected Board member and 1999 President of the last; and he currently serves as an elected member of the NAS/United States Advisory Committee to the International Commission for Optics.

Paolo Pirjanian was formerly a Member of the Engineering Staff in the Mechanical and Robotics Technologies Group at the Jet Propulsion Laboratory in Pasadena, CA, and he is currently the Chief Scientist for Evolution Robotics in Pasadena, CA. During his tenure at JPL, he was the System Engineer for the Reconfigurable Robotic Surface Systems/All Terrain Explorer and a System Architect for the Robot Work Crews tasks. He was the primary developer of CAMPOUT, and is working towards the development of new, sustainable, and aggressive mobility systems for autonomous access to highly variable terrain, cliffs etc. using state-of-the-art multi-functional, modular, and reconfigurable sensing, controls, hardware and robotic systems. He received the M.Sc.CS. and the Ph.D. degrees in 1994 and 1998, respectively, both from Aalborg University, Denmark. Until December 1998 he held an assistant research professor position at the Laboratory of Image Analysis, Aalborg University. From January 1999 until November 1999 he was a postdoctoral research associate at the USC Robotics Research lab. working on multiple robot coordination with Maja Mataric. He has over 30 technical publications in the fields of robotics, control, and computer vision. Dr. Pirjanian serves as a part-time lecturer at the Computer Science department of University of Southern California.

Hari Das Nayar received his B.S. (1984), M.S. (1984) and Sc. D. (1989) degrees from the Department of Mechanical Engineering at the Massachusetts Institute of Technology. He worked at Systemantics, Inc. from 1989 until 1990 and at the Jet Propulsion Laboratory, California Institute of Technology from 1990 until 2002. He was also a Visiting Lecturer at the University of California at Los Angeles. Dr. Nayar founded OphirTech in 2002 to develop and commercialize robotics, engineering analysis and educational products.