Cooperative Robot Teams Applied to the Site Preparation Task

Lynne E. Parker, Yi Guo, and David Jung
Center for Engineering Science Advanced Research
Computer Science and Mathematics Division
Oak Ridge National Laboratory, P. O. Box 2008, Oak Ridge, TN 37831-6355 USA
email: [parkerle,guoy,jungdl]@ornl.gov

Abstract

Prior to human missions to Mars, infrastructures on Mars that support human survival must be prepared. Robotic teams can assist in these advance preparations in a number of ways. This paper addresses one of these advance robotic team tasks – the site preparation task – by proposing a control structure that allows robot teams to cooperatively solve this aspect of infrastructure preparation. A key question in this context is determining how robots should make decisions on which aspect of the site preparation task to address throughout the mission, especially while operating in rough terrains. This paper describes a control approach to solving this problem that is based upon the ALLIANCE architecture, combined with performance-based rough terrain navigation that addresses path planning and control of mobile robots in rough terrain environments. We present the site preparation task and our proposed cooperative control approach, followed by some of the results of our initial testing of various aspects of the system.

KEYWORDS: *Multi-robot teams, robot colonies, space applications, site preparation.*

1 Introduction

A primary challenge in the successful deployment of robotic colonies to Mars is the ability to control the distributed team of robots so that they cooperate effectively while ensuring that their entire mission is accomplished, even amidst highly unpredictable and uncertain environments. Robots in these teams need to be able to select the appropriate actions to perform and deal with challenging navigation tasks in rough terrain environments. The combination of potentially heterogeneous robots and decision-making that is based upon the features of the environment make this a particularly challenging task.

Relatively little work to date has addressed cooperative robot tasks that require the interaction with, and alteration of, the planetary surface. One such mission is the site preparation task – an application identified by NASA as an important precursor mission for human exploration of Mars. Due to the limited knowledge of planetary surface conditions and their impacts upon engineered systems (including robots), system designers cannot expect to be able to fully predict the variety of circumstances or fault modes that robot teams may experience. Thus, to build robot teams that are survivable in these harsh environments, system designers must provide robots with the ability to opportunistically select actions based upon the variety of dynamic changes they may experience.

In this paper, we describe the site preparation task and discuss our proposed cooperative control approach to this problem. We present our initial results in implementing various aspects of our proposed solution, and conclude by describing our continuing experimental implementation that will allow further validation of the approach.

2 The Site Preparation Task

We first described the site preparation task in [9]. For completeness, we again briefly describe this application domain that is an important human precursor activity for Mars exploration.

NASA has identified the site preparation task as an important prerequisite for human missions to Mars [4]. This task is also of interest scientifically to the robotics field because it requires teams of robots to work together to physically alter outdoor terrains. As noted by Huntsberger et al. in [3], the site preparation task has many parallels with box pushing – a task that has been studied frequently in multi-robot systems research (e.g., [8, 6, 1, 10, 5]). However, the Martian site preparation task is more challenging, because it also requires the leveling of soil. These previous research efforts did not address this difficult aspect of the site preparation task.

The site preparation task fits within the larger context of the need to deploy PV tent arrays in preparation for human missions to Mars. Figure 1 shows the series of tasks that must be undertaken to solve this complete mission. First, a site must be selected for the PV tent array. This is accomplished through an analysis of satellite images and ground penetrating radar by NASA scientists and engineers to select the site that has a low density of rocks and partially buried rocks, and a relatively level terrain. Once the site has been selected the robotic vehicles are landed nearby,

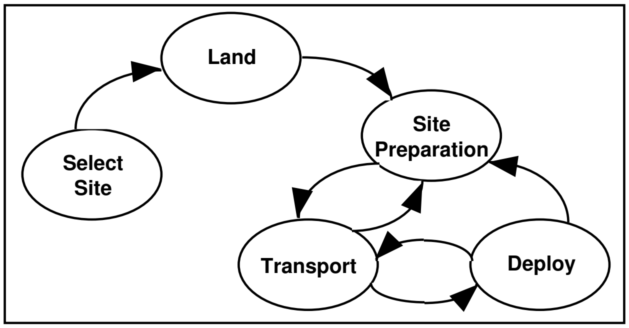

Figure 1: State diagram of complete mission to establish solar PV tent array.

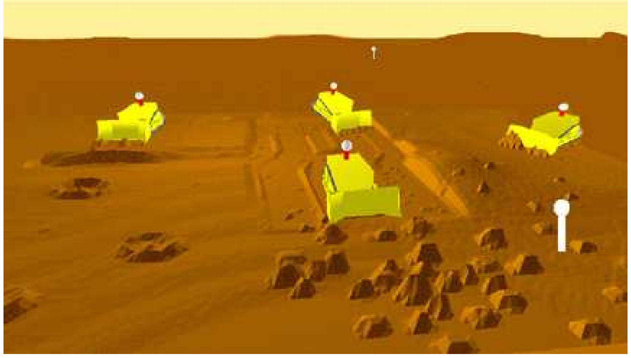

Figure 2: Illustration of site preparation task.

followed by the initiation of site preparation. Once a portion of the site has been cleared, the task of transporting the PV tent arrays to the site can begin, followed by PV tent deployment. Site preparation, transport, and deployment can take place in parallel or serially to incrementally set up working PV tent arrays while further site preparation is ongoing.

The site preparation task, illustrated in Figure 2, requires an area of approximately 50m x 100m to be cleared of rocks and obstructions and to be leveled (e.g., ditches filled in) sufficiently to allow the solar PV tent arrays and the human habitat to be deployed. We assume that a map generated from satellite views and ground penetrating radar is available, along with appropriate analysis software, to enable the robot team to determine the burial depth of rocks in the area. We assume that the area identified for site preparation can be marked by radio beacons, or pseudolites, which the robots can sense for positioning. We further assume that the rocks to be removed from the site can either be pushed outside the area (leaving a suitable path into and out of the area), or can be pushed to a common collection point. A number of constraints on an acceptable solution make the site preparation problem particularly challenging and interesting, and illustrate the need for dynamic action selection. Several of the most important of these constraints include limited team size (only 4-5 robots available), the "iceburg" problem (only portions of rocks visible), limited robot power, limited daylight, and the heterogeneity of robots.

3 Cooperative Control for Site Preparation

A primary control issue in solving the site preparation problem is a continuous determination of which actions individual robots should take throughout their mission to accomplish the site preparation task under the above constraints. Because of the important need to ensure fault tolerance across the robot team in spite of several points of failure, the preference is to design a distributed control approach. A distributed control approach enables robot team members to select their actions individually in response to the high-level goals specified by the (human) mission coordinator and to the dynamic events that occur during the mission. The degree to which the human mission coordinator influences the team can vary from a high degree to only occasional inputs.

The design of our cooperative control approach to the site preparation task is shown in Figure 3. This approach is based upon our previously-developed ALLIANCE framework [7] that enables individual robot team members to efficiently and robustly select their actions throughout their mission, and to adapt to dynamic events as they occur. The ALLIANCE framework is a behavior-based, distributed control technique that has been demonstrated to enable robot team members to automatically select appropriate actions even in the midst of sensor and actuator uncertainties, robot capability drift, and varying team compositions in a potentially dynamic and uncertain environment.

Unlike typical behavior-based approaches, ALLIANCE delineates several behavior sets that are either active as a group or are hibernating. Each behavior set of a robot corresponds to those levels of competence required to perform some high-level task-achieving function. Because of the alternative goals that may be pursued by the robots, the robots must have some means of selecting the appropriate behavior set to activate. This action selection is controlled through the use of motivational behaviors, each of which controls the activation of one behavior set. Due to conflicting goals, only one behavior set is active at any point in time. However, other lower-level competencies such as collision avoidance may be continually active regardless of the high-level goal the robot is currently pursuing.

The motivational behavior mechanism is based upon the use of two mathematically-modeled motivations within each robot – impatience and acquiescence – to achieve adaptive action selection. Using the current rates of impatience and acquiescence, as well as sensory feedback and knowledge of other team member activities, a motivational behavior computes a level of activation for its corresponding behavior set. Once the level of activation has crossed the threshold, the corresponding behavior set is activated, and the robot

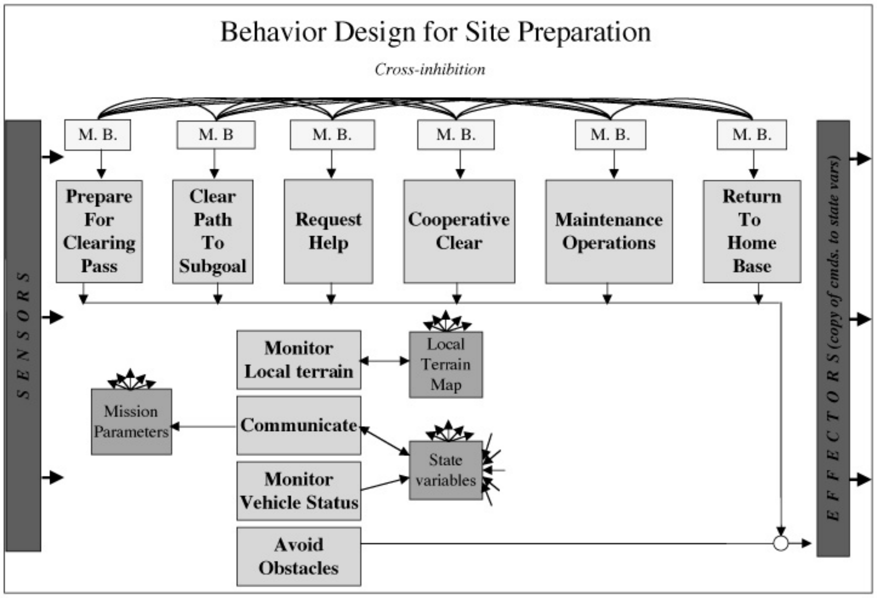

Figure 3: ALLIANCE-based solution to the site preparation cooperative task. This figure shows the control organization within one team member of a cooperative team.

has selected an action. The motivations of impatience and acquiescence allow robots to take over tasks from other team members (i.e., become impatient) if those team members do not demonstrate their ability – through their effect on the world – to accomplish those tasks. Similarly, they allow a robot to give up its own current task (i.e., acquiesce) if its sensory feedback indicates that adequate progress is not being made to accomplish that task.

3.1 Behaviors for Site Preparation

In the specific design for the site preparation task, each robot has 6 high-level behavior sets – Prepare for Clearing Pass, Clear Path to Subgoal, Request Help, Cooperative Clear, Maintenance Operations, and Return to Home Base. A robot only selects to perform one of these high-level behavior sets at a time, based upon its action selection choices determined by the motivational behaviors. In addition, each robot has a number of survival, monitoring, and communication behaviors that are always active, updating appropriate state variables and performing critical tasks, including obstacle avoidance and communication. These lower-level behaviors are shown in Figure 3 as *Monitor Local Terrain*, *Communicate*, *Monitor Vehicle Status*, and *Avoid Obstacles*.

The following subsections describe the six high-level behavior sets of each robot.

3.1.1 *Prepare for Clearing Pass*

The *Prepare for Clearing Pass* behavior set plans the next clearing activity for an individual robot. This behavior set is given the lowest priority of all behavior sets, and thus only becomes active if the robot is not involved in already performing a clearing pass, cooperatively helping another robot (or getting help), performing maintenance operations, or returning to the home base.

Once activated, this behavior set involves selecting the next rock or strip to clear, and then planning the path for moving from the starting point to the rock to be moved (or strip to be cleared), and then to the goal destination across rough terrain. The ultimate goal is that this planning should take into account a variety of issues including available energy, activities of the other robot team members, cost (in terms of time, energy, robot wear-and-tear, etc.), and so forth. At present, an approach to the optimal selection of the next activity selection based upon this variety of issues has not been developed, although Section 4 discusses our ideas on how to proceed in this direction.

At present, this planning step considers a nonholonomic mobile robot driven by two differential wheels, whose kinematics is governed by $\dot{x} = v\cos(\theta)$, $\dot{y} = v\sin(\theta)$, $\dot{\theta} = \omega$, where vector $q = (x, y, \theta) \in \Re^2 \times \mathcal{S}$ is a configuration specifying the horizontal position and heading of the robot in the global frame; v and ω are the translational and angular velocities respectively. The relationship between (v, ω) and the left and right wheel velocities $(\omega_{left}, \omega_{right})$ is described by: $v = \frac{r_\omega}{2}(\omega_{right} + \omega_{left})$ and $\omega = \frac{r_\omega}{d_\omega}(\omega_{right} - \omega_{left})$, where r_w is the radius of the wheels and d_2 is the azimuth length between the wheels. The robot operates in a rough terrain, described by surface patches defined from an elevation map in z associated with a regular grid in (x, y). The navigation problem is to determine wheel velocity inputs $(\omega_{left}, \omega_{right})$ within velocity and acceleration limitations, so that the robot reaches its goal from the starting position. Our approach, described in detail in [2], determines these velocities as a function of safety, distance, time, and energy. The output of this planning activity is a series of waypoints indicating the general path that should be followed.

3.1.2 *Clear Path to Subgoal*

This behavior is responsible for generating and tracking the trajectory along the path waypoints planned by the *Prepare for Clearing Pass* behavior set. The precondition for activating this behavior set is that a current set of path waypoints has been planned for the next clearing pass, and that no other high level activity is currently ongoing (i.e., cooperatively helping another robot (or being helped), performing maintenance operations, or returning to home base).

Once activated, this behavior set involves a planning step to generate a reference trajectory as a function of time, followed by an execution step that tracks the reference trajectory using feedback control. The details of this trajectory generation and tracking are given in [2]. In short, the trajectory generator smooths the path from the waypoints created by the *Prepare for Clearing Pass* behavior set and generates reference velocity profiles for the robot to follow along the rough terrain. The trajectory tracking step calculates the wheel velocities needed to follow the generated trajectory, which are then executed.

3.1.3 *Request Help*

This behavior requests cooperative clearing help from another robot in order to successfully move a particular rock to a goal destination. This behavior will be activated if the robot is not already involved in (1) helping another robot, (2) maintenance activities, or (3) returning to home base, and also if (4) the plan output by the *Prepare for Clearing Pass* behavior set involves the movement of a rock too heavy for one robot to move alone.

To request help, a robot communicates a message indicating its own identity, the location of the help request, and the type of help needed. The robot then waits a period of time for help to be granted by some other robot. If no other robot is available to help within a sufficient period of time, the robot cancels its help request and goes on to some other activity. Determining exactly when to go on to some other activity is an optimal cooperative control decision, which we are just beginning to address; see Section 4.

3.1.4 *Cooperative Clear*

After a robot has successfully recruited help for a cooperative clearing task, this behavior performs the cooperative clearing in conjunction with another robot (or robots). This task is inherently cooperative, meaning that the actions of robots performing the cooperative clearing task have to be closely coordinated with each other. This behavior also disables the obstacle avoidance behavior, since the robots will be very close to each other and the rock(s) that they are moving. The exact method for performing the cooperative clearing task is dependent upon the characteristics of the robots being used, and is not addressed here.

3.1.5 *Maintenance Operations*

Periodically, a robot must perform various health maintenance operations, such as battery recharging, component replacement, etc., that extend the useful life of the robot. The *Monitor Vehicle Status* behavior that is always active will update the state variables that are important for the robot's health. When these state variables reach certain settings, the robot will become motivated to initiate the *Maintenance Operations* behavior set. Typically, the motivation to perform maintenance operations will have the highest priority over other robot activities, to some extent dependent upon the urgency of the maintenance requirements.

3.1.6 *Return to Home Base*

When certain predefined conditions are met, such as a particular time of day, length of vehicle operations, or command of the human commander, the robot will initiate the *Return to Home Base* behavior set to complete the work day and perform other end-of-day activities, such as uploading data, receiving the next day's instructions, and so forth.

3.2 Human Interface to Multi-Robot Teams

While the cooperative control approach described thus far assumes the multi-robot team is acting autonomously, it is also possible to enable a human mission controller on Earth to interface with the multi-robot team when needed, through an interface to the ALLIANCE control architecture. Of course, these interactions by the operator must be at a level of detail that is practical, considering the time delays between Earth and Mars. Low-level cooperative pushing tasks, for instance, cannot be teleoperated by the human. However, the human can specify specific tasks for a robot to do, such as to move a particular rock to a specified location.

Ideally, the robots should be able to perform highly autonomous actions while at the same time responding to human commands when needed that alter their behavior. The operator can select a specific task/behavior for a robot to engage in, or to prohibit a robot from performing a particular task/behavior, etc. The interface from the human operator to ALLIANCE involves straightforward extensions that convert the human operator commands into the "language" of ALLIANCE – i.e., preconditions, motivations, communicated messages, and world state. All other automated functions that are not affected by the human operator commands continue as before. The consequence of this approach is that the autonomous vehicle does not need to distinguish between effects caused by the world (or other robot interactions), and those caused by the influence of the operator. Of course, if it is important that a robot "know" when it is being influenced by the operator, that capability can be provided.

One additional interface with the human can involve mixed-initiative activities, where not only does the human supply goals to the robot team, but also the robot team members can take the initiative (in a limited sense) by suggesting new activities that they might undertake as a result of new information gathered by the robots, which the human operator may not yet be aware of. The robots can thus suggest to the operator new activities that the robot team should begin, dependent upon approval by the human controller (when required).

4 Towards Optimal Cooperative Solutions

In [9], we proposed a global optimization function that, if it could be practically optimized, should provide the ideal solution to the site preparation task. However, since complete global information for the entire task will never be known (due to unexpected events in the future, uncertainty in sensing and action, and imprecise information regarding the terrain), an optimal solution for the entire mission cannot be generated. Perhaps it might be possible to find optimal solutions for the next time window, Δt, during which we assume that the current conditions remain constant. Thus, we obtain the following function that should be minimized at time t over the next Δt time window:

$$f(t, \Delta t) = \sum_i (w_1 \times e_{r_i}(a[l,s,p]) + w_2(t) \times 1/c(t))$$

for all functioning robots r_i , where:

$a[l,s,p]$ = motions of robot during time window Δt, having integrated length l, slope s, and pushing effort p

$e_{r_i}(a[l,s,p])$ = energy required for robot r_i to perform motions $a[l,s,p]$

$c(t)$ = cumulative contiguous area cleared at time t (defined as the area such that (1) the densities of rocks above certain heights in that area are less than predefined amounts, and (2) the variation in the area's terrain slope is less than a predefined angle)

w_1 = weight on energy term

$w_2(t)$ = weight on cumulative area term (grows monotonically as t increases)

This optimization function ensures that an increased emphasis is placed on growing contiguous cleared areas and that robots select tasks that increase the cleared areas while still minimizing energy usage (e.g., avoiding pushing rocks up hills, if possible). Note that the energy function is unique for each robot, to allow for heterogeneous robot capabilities. This function takes into account all the problem constraints identified in the previous section except the current battery life of the robot. The recharging behavior of the robot can easily be made a separate behavior (as we have done), when assuming that it is better to have a robot perform productive site preparation tasks whenever its battery is charged.

To minimize this function, a series of tasks must be selected for each robot such that the combined energy usage for each robot to move along a path of a given integrated length and slope, and using a given integrated pushing effort is as small as possible. The selection of tasks for each robot, however, is not a trivial decision, and must opportunistically adapt over time. This selection must take into account a number of issues, such as (1) the tradeoffs between continuing a current task and stopping to help another vehicle, (2) the need to manage battery reserve, (3) proximity to other vehicles, (4) giving up a task if you need help that is not provided, (5) determining the next best rock to move, (6) determining tradeoffs between rock pushing and soil leveling, and so forth. The computation of the energy function must take all of these issues into account. In ongoing research, we are studying the design of the motivational behaviors of the cooperative control approach (see Figure 3) to determine if these optimization criteria can be incorporated in a distributed fashion into the task selection choices of the robots.

5 Experimental Results

While we have not yet fully implemented and integrated these cooperative control concepts, we have implemented several individual components of the system, and are conducting experimentation of these concepts both in simulation and on our five "Emperor" robots. The components that we have implemented include the individual robot path planning, trajectory generation, and trajectory tracking for making individual clearing passes; the basic ALLIANCE control framework for cooperative site preparation; some of the high level behavior sets, as well as some of the lower-level behaviors that are always active; and a user interface to ALLIANCE that enables the operator to specify specific actions for robots to take, as opposed to fully autonomous decision-making.

5.1 Simulation Studies

Figure 2 shows a site preparation example in the simulation environment we are using, which is a 3D environment en-

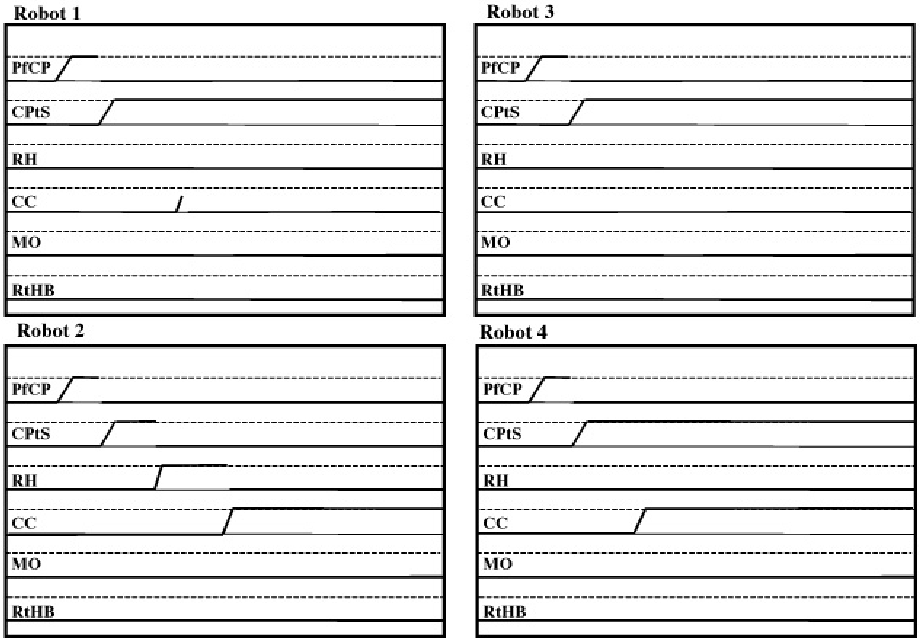

Figure 4: Sample motivation trace results of 4 robots performing the site preparation task. The dashed lines indicate the threshold of activation of each high-level behavior set. The six behavior sets correspond to those shown in Figure 3.

abling dynamic interactions with and alteration of the terrain. While the ultimate goal of this research is to demonstrate site preparation on space-relevant robotic hardware, the practical realities of physical robot equipment limit the extent of investigations that are possible. For most applications, time constraints, battery limitations, and hardware problems prevent a large number of experimental runs. More extensive experimentation is possible through the use of simulation. While simulation does not substitute for the physical robot experiments, it can contribute to the variety of situations and robot control designs that can be explored.

We have extended a 3D simulation system that enables multiple robots to cooperatively push and carry soil in their environment. This simulation is implemented on a dual-processor Silicon Graphics Octane machine. We are using this environment for testing of cooperative control in the site preparation task. This environment allows us to develop, validate, and refine our proposed cooperative control techniques in this application domain.

Figure 4 shows behavior selection traces of four robots during part of one of these simulation runs. In this example, all four robots begin in the *Prepare for Clearing Pass (PfCP)* behavior set, followed by the *Clear Path to Subgoal (CPtS)* behavior set. However, Robot 2 soon discovers that it is not able to push the rock to the goal alone, and therefore needs help. It thus enters the *Request Help (RH)* behavior set to try to recruit another robot's assistance. Both Robots 1 and 4 begin to get motivated to help, but Robot 4 becomes motivated first, and then enters the *Cooperative Clear (CC)* behavior set. Since Robot 2 now has assistance, it also initiates the *Cooperative Clear* behavior set. Robots 1 and 3 continue performing their own path clearing activities.

5.2 Physical Robot Studies

To validate our simulation studies on physical robots, we are in the process of building up the behaviors needed to perform tasks such as site preparation on our CESAR Emperor robots. The Emperor robots, shown in Figure 5, are a team of ATRV-mini and Transit robots that are able to operate in outdoor terrains for proof-of-principle site preparation applications. These robots have a variety of sensors and sensor combinations that make the robots heterogeneous.

Figure 5: The Emperor robots of ORNL's CESAR Laboratory, named Augustus, Constantine, Hadrian, Theodosius, and Vespasian.

All four ATRV-mini robots have 24 sonar sensors, differential GPS, absolute orientation sensors, tactile bumpers, and radio Ethernet. Additionally, two of the ATRV-mini robots have SICK laser scanners, while the other two have a pan-tilt-zoom camera unit. All ATRV-mini robots have onboard computers (Pentium- IIs) and battery power.

The Transit robot has sonar, a SICK laser scanner, a pan-tilt-zoom camera unit, differential GPS, and radio Ethernet, as well as an onboard Pentium-II and battery power.

6 Summary

In this paper, we have examined the site preparation task for robot colonies and have formulated our cooperative control solution to this application. We have described the behaviors of the robots, along with a formulation of the problem in terms of an optimization function and a discussion of how a human controller can interact with the multi-robot team. We have presented some of our initial results of implementing this approach in simulation, showing some of the action selection choices of the robots when performing this application. Our ongoing research is aimed at completing the integration and implementation of the various modules of the system, and at performing extensive experimentation both in simulation and on the physical robots. We are also studying methods for incorporating the optimal control goals into the motivational behaviors of the robot team members.

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