Prospecting for Lunar Ice Using a Multi-Rover Cooperative Team

Paul Klarer
Sandia National Laboratories
Albuquerque, New Mexico

John Feddema
Sandia National Laboratories
Albuquerque, New Mexico

Chris Lewis
Sandia National Laboratories
Albuquerque, New Mexico

ABSTRACT
A multi-rover cooperative team or 'swarm' developed by Sandia National Laboratories is described, including various control methodologies that have been implemented to date. How the swarm's capabilities could be applied to a lunar ice prospecting mission is briefly explored. Some of the specific major engineering issues that must be addressed to successfully implement the swarm approach to a lunar surface mission are outlined, and potential solutions are proposed.

Keywords: Robots, rover, swarm, cooperative robotics, lunar surface.

INTRODUCTION

With the recent data return from the Lunar Prospector orbital mission hinting that water ice may exist in permanently shadowed areas at the lunar poles [1], it is time to begin considering how to confirm that information using sensors on the lunar surface. Furthermore, rather than simply confirming that water ice exists in measurable quantities, a thorough survey of this important resource should be performed so as to support planning for eventual exploitation of the resource on future lunar surface missions. Surface rover missions to the Moon and Mars have demonstrated the utility of rover technology for remote sensing, and have also pointed out some of the limitations imposed on mission objectives by the use of a single rover. A single rover imposes limitations on how much ground can be covered by its sensors in a given time frame, and restricts which sensors can be deployed for the mission due to limited payload space. A single rover also represents a single-point-of-failure mode for a surface mission that is fraught with hazards and literal pitfalls. Recent work in cooperative mobile robotics points the way to a potentially more effective approach to performing a site survey for lunar surface water ice.

DISCLAIMER

The capability to build robotic vehicles that can navigate over long distances either using teleoperation or autonomous control has been demonstrated by a number of researchers, see for instance [2]. In recent years, this field has expanded to consider large numbers or squads of vehicles [3]. The underlying goal of multi-vehicle systems is expanded capability through cooperation. Methods for controlling groups of vehicles range from distributed autonomy [4] to intelligent squad control and general purpose cooperative mission planning [5]. In simulation, it has been shown that by sharing concurrent sensory information the group can better estimate the shape of a chemical plume and therefore localize its source [6]. Simulation has also shown that enhanced perimeter control for physical security tasks can be achieved by dispersing the group uniformly and by communicating when possible intrusions occur [7].

A cooperative team incorporating a collection of several rovers that share data, make decisions, and provides inherent redundancy has advantages over the more conventional single rover approach to planetary surface exploration. For example, a team of rovers inherently provides redundancy such that the loss of a single rover to a surface hazard or mechanical failure can be tolerated by the overall system. Communications from a lander to the team of rovers can be extended using a data relay technique to allow rovers to explore beyond the horizon if required. Although some degree of homogeneity in the team's make-up is required to provide redundancy, some degree of heterogeneity allows for a variety of sensors to be deployed, and perhaps even for samples to be taken and returned to the lander for detailed analysis. This paper describes how recent developments in cooperative swarm robotics at Sandia National Laboratories can be applied to a site survey mission to the lunar surface in search of water ice or permafrost.

SYSTEM DESCRIPTION

A small swarm of semi-autonomous all terrain vehicles for remote sensing applications has been demonstrated by Sandia National Laboratories [8]. As a test bed to verify communications, control, and sensing strategies, it provides a potential model for a cooperating team of rovers to perform a lunar surface prospecting mission. A base station computer communicates on a common radio data network along with all of the vehicles, so that any vehicle can pass data to other vehicles and to the base station. Several communication strategies for managing this arrangement in real time have been investigated and evaluated to date, primarily the hub-and-spoke and the token-ring network topologies. Each vehicle may be in any of several operating modes, offering a wide variety of overall system architectures and real-time system operation flexibility. Vehicle operating modes include teleoperation, autonomous, and formation.

Teleoperation Control

Teleoperation is useful for navigating complex terrain and for investigating the environment manually. In teleoperation the vehicle is controlled with a joystick at the base station, where the operator has direct control over wheel speeds and direction of rotation. Video from any one of the vehicles can be selected and displayed at the base station to aid in control. Teleoperation of one vehicle does not necessarily affect the behavior of the other vehicles. However, any portion of the swarm can be maneuvered as a unit by specifying a formation relative to one vehicle being teleoperated. This feature is described later in the paper.

Autonomous Control

The ability to automatically navigate from one location to another is a fundamental capability of the swarm system. In autonomous mode, the vehicles rely on a position estimate derived from both dead reckoning and GPS data, as well as the vehicle's current heading and tilt sensor readings. A simple control strategy monitors these sensors as it steers toward desired world coordinate locations and avoids obstacles along the way. A skid-driven vehicle model is used for autonomous control. In this model, the vehicle's linear and angular velocity are related to the right and left wheel velocities as follows:

$$\begin{bmatrix} \dot{x} \\ \dot{y} \\ \dot{\theta} \end{bmatrix} = \frac{1}{2}\begin{bmatrix} r\cos(\theta) & r\cos(\theta) \\ r\sin(\theta) & r\sin(\theta) \\ r/l & -r/l \end{bmatrix}\begin{bmatrix} \omega_r \\ \omega_l \end{bmatrix} = B\begin{bmatrix} \omega_r \\ \omega_l \end{bmatrix} \tag{1}$$

where l is the distance from the center of the vehicle to the wheel, r is the wheel radius, and θ is the heading angle.. The differences between desired and actual location and orientation are used as feedback as follows:

$$\begin{bmatrix} e_x \\ e_y \\ e_\theta \end{bmatrix} = \begin{bmatrix} x_d - x \\ y_d - y \\ k_1(\theta - a\tan 2(y_d - y, x_d - x)) + k_2(\theta - \theta_d) \end{bmatrix} \tag{2}$$

where k_1; and k_2 are gains. The system matrix B is inverted to determine the wheel velocity commands:

$$\begin{bmatrix} \omega_r \\ \omega_l \end{bmatrix} = B^+\begin{bmatrix} e_x \\ e_y \\ e_\theta \end{bmatrix} \tag{3}$$

For relatively large values of k_l, the vehicle will turn first and proceed toward the goal. Smaller values produce an arching trajectory depending on the initial conditions. The value of k_2 is kept small so that its only effect is to orient the vehicle once it achieves the desired final position.

Because the vehicles move relatively slowly and have very high torque capabilities, obstacle avoidance is achieved using the tilt sensors. When the vehicle runs into an obstacle such as a rock, the front wheels will climb until the tilt sensor reaches a cutoff value. At this point the vehicle will reverse direction, turn away from the obstruction, and move forward. At this point automatic control is restarted, and the autonomous control will reorient vehicle before resuming toward the original destination. This simple strategy has proven effective in avoiding most of the obstacles in a natural environment.

Formation Control

The ability to maintain a formation is useful for conducting searches and for moving the swarm from place to place as a group. This capability has been implemented using the base station's Graphical User Interface (GUI) and utilizing the autonomous navigation capability described earlier. To initiate formation control the operator designates a lead vehicle, and then graphically places the other vehicles relative to the leader as shown in Figure 1. When the formation is initiated, the vehicles are automatically commanded to autonomously navigate to their respective locations surrounding the leader. As the leader moves either by autonomous navigation or using teleoperation control the other vehicles maintain the formation. In the current implementation, orientation is not considered so that the vehicles always traverse nominally the same distance as the formation moves along. A formation always remains aligned to the compass frame rather than to the lead vehicle's frame. In the future, we will be implementing a formation control mode in the lead vehicle's frame. In this case, the lead vehicles turning rate will have to be limited to account for the greater distances traveled by vehicles that are farther away. A number of control strategies are being investigated for actively maintaining tight formations regardless of the differences in the terrain and path lengths traversed by each vehicle participating in the formation.

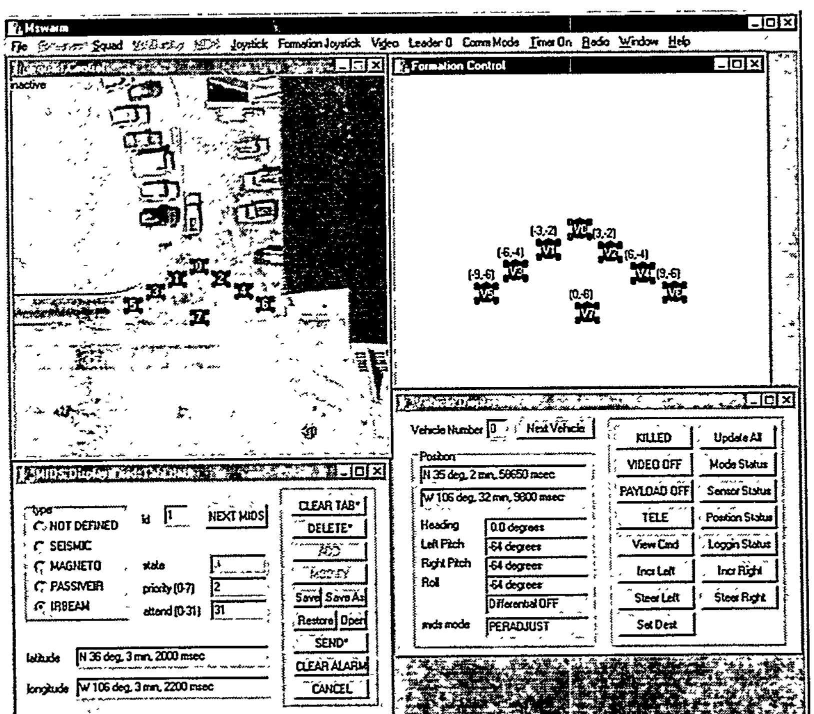

Figure 1. Graphical User Interface showing Formation Control mode.

Lunar Prospecting Application

In the lunar prospecting mission scenario, the objective is to cover as much ground as possible with sensors appropriate to detect the presence of water ice in the soil. Working from a centrally located lunar lander vehicle from which the swarm of rovers is deployed, several control strategies may be employed to perform the mission. Although not the most efficient method, a simple random method has been shown in simulation to provide some advantages for both searching and marking regions [9]. Making use of the formation mode as described above, subsets of the swarm could be employed in various formations to deterministically explore a defined region, covering very wide swaths of ground with each pass. An alternative would be to allow each rover to spiral out from the lander in phases such that the resulting coverage pattern would resemble a pinwheel. A combination of the above methods would result in a small number of wide pinwheel swaths originating at the lander. By overlapping the "leaves" of the pinwheel and employing a suite of sensors spread out and duplicated over the entire swarm for redundancy, a multi-spectral image of the overall site can be obtained at extremely high spatial resolution compared with similar surveys done from orbit. In any case, as craters and boulder fields are encountered by individual rovers the location and extent of those obstruction hazards can easily be shared with the remainder of the swarm via the common communications network described earlier. In this way both a very detailed hazard map as well as a resource map of the search area can be built quickly and used by the swarm to avoid getting into trouble. In the almost inevitable case where a rover is lost due to an accident with a terrain hazard (such as a steep crater wall), the advantage of having multiple rovers deployed becomes evident.

Applying the system described above to a mission on the lunar surface to prospect for water ice is hardly trivial, however the essential capabilities are present to perform the most important tasks. The missing pieces include some lunar equivalent to GPS for accurate position estimation, an appropriate suite of sensors for water ice assay, and a small to medium sized rover design intended to operate in the envisioned environment and appropriately sized for launch in swarm quantities on available launchers.

Determining the rover's position to a high degree of accuracy on the lunar surface is not trivial, even when humans are making direct measurements in-situ. The Apollo missions provide anecdotal evidence of this [10]. The use of passive laser retroreflectors on the rovers would allow an Earth-based laser ranging system to pinpoint the vehicle's locations in a global sense, sufficient to allow the system described above to function correctly [9]. An alternative would be an RF beacon system deployed at the lander and via teleoperation to at least one other location away from the lander. Including a retroreflector with the beacon would allow its position to be surveyed from Earth.

The lunar region of interest for hunting potential water ice is the permanently shadowed polar regions, therefore the environment will be perpetually dark, cold, and likely non-line-of-sight with Earth. As a result communications, energy storage, and thermal design will be major issues but are not within the scope of this paper. Likewise, specifying the sensors appropriate for assaying the lunar soil's volatiles content is also beyond the scope of this paper, however it is possible that recent advances in microchip-based detectors could provide solutions to detecting hydrogen, water, ammonia, and other volatile compounds at or just below the lunar surface.

SUMMARY

An existing, demonstrated system for the cooperative control of a swarm of mobile robots has been described. This system provides a capability that could be extended to use on the lunar surface for a prospecting mission, provided that technical issues specifically related to operating in the lunar environment are addressed. Those issues include sensing payload, communications, power storage, thermal management, and accurate global position estimation.

REFERENCES

1. Feldman, W., et.al.; "Deposits of Hydrogen on the Moon", *Workshop on New Views of the Moon: Integrated Remotely Sensed, Geophysical, and Sample Datasets*, (January, 1998), pg. 29
2. Bapna, D., et.al.; "The Atacama Desert Trek: Outcomes", *Proceedings of the 1998 Conference on Robotics & Automation"*, Leuven, Belgium, May 1998, 597-604
3. Cao, Y., Fukunaga, A., Kahng, A.; "Cooperative Mobile Robotics: Antecendents and Directions", *Proceedings of the 1995 IEEE/RSJ IROS Conference*, 226-234
4. Fukuda, T., et.al.; "Evaluation on Flexibility of Swarm Intelligent System", *Proceedings of the 1998 Conference on Robotics & Automation"*, Leuven, Belgium, May 1998, 3210-3215
5. Brummitt, B., Stentz, A.; "GRAMMPS: A Generalized Mission Planner for Multiple Mobile Robots in Unstructured Environments", *Proceedings of the 1998 Conference on Robotics & Automation"*, Leuven, Belgium, May *1998, 1564-1571*
6. Hurtado, J., Robinett, R., Dohrman, C., Goldsmith, S.; "Distributed Sensing and Cooperating Control for Swarms of Robotic Vehicles", *IASTED International Conference on Control & Applications, Aug 12-14, 1998, Honolulu, Hawaii*
7. Lewis, C., Feddema, J., Klarer, P.; "Robotic Perimeter Detection System", *SPIE International Symposium on Enabling Technologies for Law Enforcement and Security, Proceedings of Sensors, C3I, Information, and Training Technologies for Law Enforcement and Security, Boston, November 3-5, 1998*
8. Lewis, C., Feddema, J., Klarer, P.; "Cooperative Control of a Squad of Mobile Vehicles", *IASTED International Conference on Control & Applications, Aug 12-14, 1998, Honolulu, Hawaii*
9. Klarer, P., "Small-Scale Intelligence for Lunar Exploration", *International Federation of Automation and Control (IFAC) World Congress 1996, June 30 – July 5, 1996, San Francisco, California*
10. Heiken, G., Vanniman, D., French, B.; ed., *Lunar Sourcebook, a User's Guide to the Moon,* Cambridge University Press 1991, ISBN 0-521-33444-6, pp. 28-29

Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy under contract DE-AC04-94AL85000.