INEEL/CON-98-01276
PREPRINT

Mobile Robotic Teams Applied to Precision Agriculture

M. O. Anderson (INEEL)
R. A. Kinoshita (INEEL)
M. D. McKay (INEEL)
W. D. Willis (INEEL)
R. W. Gunderson (Utah State University)
N. S. Flann (Utah State University)

April 1, 1999 – April 1, 1999

8th International Topical Meeting on Robotics and Remote Systems

Mobile Robotic Teams Applied to Precision Agriculture

Matthew O. Anderson, Robert A. Kinoshita, Walter D. Willis, and Mark D. McKay
(Idaho National Engineering and Environmental Laboratory Robotics Group)
Robert W. Gunderson and Nicholas S. Flann
(Utah State University's Center for Self-Organizing and Intelligent Systems)
P.O. Box 1625, Idaho Falls, ID 83415-2220/USA
E-mail: matthew @ inel.gov
Tel: 208-526-4308

ABSTRACT

The Idaho National Engineering and Environmental Laboratory (INEEL) and Utah State University's Center for Self-Organizing and Intelligent Systems (CSOIS) have developed a team of autonomous robotic vehicles applicable to precision agriculture. A unique technique has been developed to plan, coordinate, and optimize missions in large structured environments for these autonomous vehicles in real-time. Two generic tasks are supported: 1) Driving to a precise location, and 2) Sweeping an area while activating on-board equipment. Sensor data and task achievement data is shared among the vehicles enabling them to cooperatively adapt to changing environmental, vehicle, and task conditions. This paper discusses the development of the autonomous robotic team, details of the mission-planning algorithm, and successful field demonstrations at the INEEL.

1. Introduction

Several generations ago farmers relied on tools such as almanacs and the phases of the moon to estimate when to begin planting. Today these tools are supplemented with space age technologies that allow the farmer to raise their crop in more precise and efficient ways. Some of these technologies include global positioning systems, geographic information systems, yield mapping, variable-rate technology, and remote sensors. Precision farming (the art of using these technologies to increase yields and profits while protecting the environment) is becoming more prevalent in farming operations [1]. There is a need in the farming community for tools that provide the farmer easy access to these technologies while avoiding cumbersome data gathering systems, information overload, or burdensome application equipment. The Idaho National Engineering and Environmental Laboratory and Utah State University's Center for Self-Organizing and Intelligent Systems have been performing research to develop a family of intelligent, fully autonomous robotic vehicles capable of individually or cooperatively providing optimal operations in precision agriculture environments.

1.1 Robotic Team Development

In 1996, Utah State University (USU) received a three-year University Research Consortium (URC) grant to develop a family of intelligent fully autonomous robotic vehicles suitable for characterization and remediation operations in hazardous environments. The INEEL received Laboratory Directed Research and Development funding during this same three-year period allowing INEEL and USU to collaborate on this URC goal. During these efforts four robotic vehicles were developed as part of the intelligent fully autonomous family.

1.1.1 Advanced Rover Chassis III

During first year efforts, USU developed a new omni-directional intelligent wheel approach to robotic vehicle drive and steering, which permits ultra-maneuverability and mobility. The omni-directional intelligent wheel, or “Smart Wheel”, is shown in Figure 1 with the tire and hub removed. The Smart Wheel consists of a Motorola 68332 microprocessor that is programmed to control the drive and steering motors housed within the wheel. Eleven Nickel-Cadmium rechargeable batteries provide all the power for this smart wheel assembly and surround the microprocessor and associated circuitry. The wheel also contains a unique “optical slip ring” which provides inter-processor communications without a hard-wire link thus allowing continuous 360-degree rotation of the wheel assembly [2].

Figure 1. The Smart Wheel with the tire and hub removed

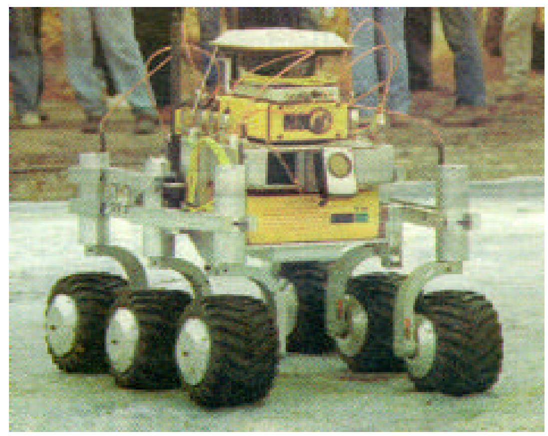

Figure 2. The Advanced Rover Chassis III

The Smart Wheel is modular in design, which allows a vehicle to be assembled in a variety of configurations depending upon the payload and the terrain. Figure 2 illustrates the Advanced Rover Chassis (ARC) III, a robotic vehicle assembled using six Smart Wheels with an instrumentation bay that houses additional microprocessors for sensor integration and overall vehicle control. A Trimble 7400msi real-time kinematic (RTK) differential global positioning system (DGPS) is being deployed on this particular ARC III. The vehicle is approximately 24” (61.0 cm) high, has a width of 18” (45.7 cm) and length of 18” (45.7 cm). The six-wheeled configuration provides ultra-maneuverability making it ideal for movement within difficult terrain and surroundings. Placing the rechargeable power supply for each wheel in the lower half of its wheel hub provides a very low center of gravity and excellent stability even with an 11 pound (5.0 kg) payload mounted in the chassis instrumentation bay. A differential chassis suspension system helps to mechanically self-level the instrumentation bay. Two ARC III vehicles have been developed for use as part of the cooperative robotic team applicable to precision agriculture.

1.1.2 Robotic All-Terrain Vehicle

The small-scale ARC III possesses many characteristics that are highly desirable in vehicles suited for deploying large precision agriculture implements. For example, the mobility and maneuverability characteristics allow for precise positioning in confined environments. In the second year, the combined INEEL-USU team began an industrial survey looking for a commercially available all-terrain vehicle (ATV) with capabilities similar to the ARC III. The Triton Predator ATV, shown in Figure 3, best satisfied all of the criteria and specifications. The Predator is an eight-wheel drive amphibious vehicle featuring a hydrostatic drive system. It is fairly large, with length 114.5" (290.8 cm), width 60" (152.4 cm), and height 84" (213.4 cm). It has a very stable design and can climb a 45-degree slope. It is powered by a 25 hp Kohler 90 degree V twin cylinder overhead valve engine, and weighs 1000 pounds (450 kg) unloaded with a gross weight capacity of 2000 pounds (900 kg). Maximum speed on a level surface is 22 mph (35.4 kph). During the industry search it was determined that the Predator was currently the only commercially available ATV which possessed a hydrostatic drive system. This drive system, and the ability to execute an on-the-spot 360-degree turn, were considered essential features.

Figure 3. Triton Predator - RATV

Two Predators were converted to allow the capability of manual, RF, or fully autonomous computer control suitable for individual or cooperative missions. Three Motorola 68332 microprocessors are used to provide closed loop low-level motor control, integration of obstacle avoidance and positioning sensors, and an interface to the control station. A Trimble 7400msi or Ag132 DGPS system is used for position information. Obstacle avoidance is accomplished using both ultrasonic transducers and an infrared scanning laser [3]. Details of the conversion of the Triton Predator to a Robotic All-Terrain Vehicle (RATV) can be found in Jacob, et al [4].

1.1.3 Precision Farming Implements

To demonstrate the suitability of the RATV to characterization and remediation operations as well as precision agriculture, each was fitted with soil sampling and spraying implements. A Geophyta Mobile Soil Sampler (sold by Concord Environmental Equipment as a 2000 series precision auger soil sampler) provides motorized 1" (2.5 cm) diameter auger sampling at depths of up to 12" (30.5 cm). To use the Geophyta system, an operator sits in the back of the RATV as seen in Figure 4. Since the vehicle is positioned autonomously, the operator can concentrate on running the sampling equipment rather than driving the system to a precise location. When the RATV arrives at the precise position, a light signals the operator that a sample needs to be taken. Once sampling operations are complete for this sample site, the operator presses a button signaling the control system to move to the next location. Figure 5 shows a RATV with a 100 gallon (378.5 L) tank and 18' (5.5 m) boom spraying system, which was used to demonstrate automated variable rate chemical applications. The spraying system can be activated either remotely or manually allowing manual or unmanned operations.

Figure 4. RATV with a Geophyta Soil Sampler

Figure 5. RATV with a 100-gallon sprayer

1.2 Optimal Mission Execution and Planning System

The family of autonomous robotic vehicles is designed to participate in individual or multi-agent missions. Applications include strategic sampling and spraying, topographical mapping, and site analysis and cleanup. The system consists of a team of autonomous vehicles, equipped with location detectors (DGPS) and environment sensors (sonar and laser), connected together via a radio link. The team is controlled by a distributed Mission Execution and Planning System (MEPS) that takes high-level tasks from human managers via a graphical interface and produces an optimized stream of instructions for each vehicle.

The basic mission execution and planning problem solved by MEPS is as follows:

Given:

- A map of the area in Arc-info format describing the terrain types and road and trail network.
- A set of autonomous vehicles fitted with DGPS, local controller and interface, obstacle detectors, and a set of task dependent sensors and actuators.
- A set of initial tasks.

Find:

An assignment of tasks and routes for each vehicle;

Such that:

The tasks are achieved near optimally (with respect to cost, energy consumed, crop damage, etc.).

The MEPS performs some planning before the mission begins. After the vehicles get underway, this plan is updated to reflect vehicle discoveries (obstacles, etc.), equipment breakdowns, or mission changes by human operators [5].

The operator station that serves as MEPS is run on a single computer networked to all available vehicles. As tasks are entered and vehicles are commanded, the computer continually runs an "anytime-algorithm" that searches the space of possible schedules for each vehicle. This algorithm rapidly finds a set of adequate solutions and then incrementally improves and adapts these solutions during mission execution. To determine optimal schedules, the system computes the cost of routes through the environment with an incremental shortest-path algorithm. This algorithm enables the scheduling system to rapidly determine the estimated optimal cost for a route from any location to a task location, based on what is currently known about the environment. These costs are updated as new sensor information is received from vehicles during mission execution. This enables maximal cooperation since sensor information gathered by one vehicle is immediately incorporated into the overall mission and hence the behaviors of all the vehicles.

Human managers control and monitor the system via a graphical display that shows the current mission status overlaid on the map of the environment. To enable complex missions to be easily entered and executed, human managers interact with the system at a high level. Managers need only specify the tasks that must be performed by selecting task types and locations. There is no need to denote how the tasks are to be performed and by which vehicle. Details of vehicle assignment and task order are left to MEPS. Figure 6 shows the graphical user interface of MEPS during a cooperative precision agriculture mission.

The interface between MEPS and the vehicles is generic in that a protocol has been defined that can be utilized by a variety of vehicle types. For example, the same protocol that is used to control the ARC III is also used to control the RATV. The protocol has been designed to provide an ideal ``division of labor'' between the vehicles and MEPS. To travel through the environment, the vehicles are given flexible corridors and location points along the route. The vehicles are responsible for working out the best way to navigate these routes, based on local conditions and vehicle capabilities. To perform specialized functions, the vehicles are instructed to activate on-board equipment (such as the described soil sampler or sprayer) or perform known operations.

Figure 6. The graphical user interface component of MEPS

The overall system provides the tools needed for a variety of missions. Two basic tasks are 1) "go-to" a given location and perform some operation; and 2) ``sweep" a given region while performing some operation. In precision agriculture go-to tasks are employed to perform strategic soil sampling, while sweep tasks are employed to perform strategic spraying. In waste site remediation a dynamic combination of the two tasks is used. Detection vehicles apply sweeping tasks to identify possible contamination then generate go-to tasks during mission execution for sampling and cleanup vehicles to perform further testing and treatment of suspected locations. Topological mapping requires a dynamic mix of the two tasks during mission execution. First, one or more vehicles execute broad sweeps to develop a "rough" map, which is then refined by recursively performing more detailed sweeps within areas of high variability.

2. Technology Demonstrations

During the course of the collaborative research between INEEL and USU, several demonstrations were conducted to illustrate the capabilities of the autonomous family of robots. Early in the project, the dual-use nature of the technology was identified allowing different demonstrations encompassing hazardous environment remediation and precision agriculture to be conducted. Demonstrations consisted of simulated radiological characterization and clean-up, high-resolution topographical mapping, strategic soil sampling, and variable spraying. Following is a discussion of three field days conducted at the INEEL.

2.1 INEEL 1996 Site-Specific Technologies for Agriculture (SST4AG) field day

The INEEL SST4AG program invited the INEEL-USU research team to demonstrate their initial research accomplishments during the 1996 SST4AG field day at Hess farms in Ashton, Idaho. The USU URC funded research had just begun six months prior to the SST4AG field day and only early research and investigation milestones had been reached. Original URC milestones and deliverables did not provide for hardware demonstrations this early as only MEPS computer simulations were required as a six month deliverable. However, INEEL and USU researchers capitalized on the potential of this field demonstration by illustrating to both the Environmental Management and Agriculture communities the dual-use capabilities of this emerging technology. To provide a better presentation of the technology, Utah State University built two of the ARC III vehicles ahead of schedule to show both the MEPS software performing optimal simulations as well as real-time vehicle control. Each ARC III vehicle was fitted with a Trimble 7400msi DGPS with ±5-cm accuracy, ultrasonic obstacle avoidance sensors, a compass, and a radio link to MEPS.

Two separate demonstrations were given. The first demonstration was designed to illustrate the ARC III team as a useful tool for radiation control technicians tasked with surveying and cleaning up a hazardous environment. One ARC III was identified as the radiation-surveying unit and the other was identified as the radiation-cleaning unit. The purpose of the research was not to develop radiation detection or clean-up sensors, therefore only simulated radiation and clean up activities were given. Figure 7 shows the two ARC III vehicles on the simulated Idaho Nuclear Technology and Engineering Complex (INTEC) radiation area and the MEPS interface. The demonstration consisted of having a human designate a region requiring surveillance and clean up. MEPS performed appropriate task assignments, pre-mission planning, and mission initiation. As the surveying robot performed its sweeping task, when a simulated hazard was identified, MEPS was updated and a mission automatically planned for the clean up robot. Each robot performed its task and returned to a "home depot".

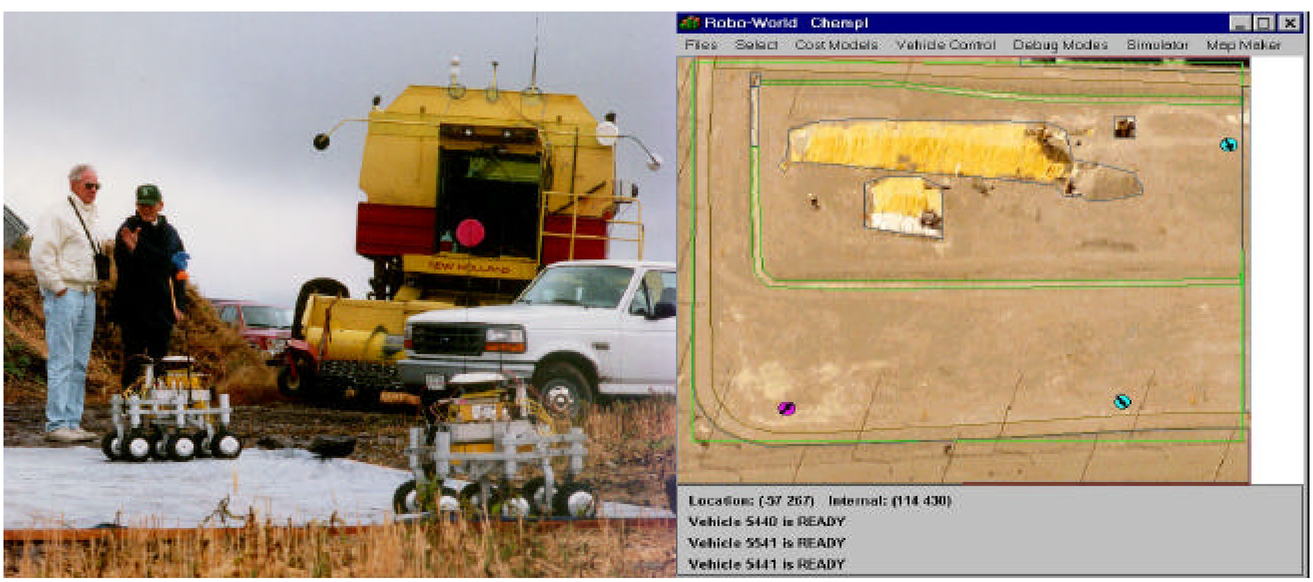

Figure 7. Simulated INTEC radiation area and associated MEPS interface

The second demonstration was aimed at illustrating the ARC III team applied to the task of performing precision agriculture topographical mapping. Without making any modifications to the hardware, the ARC IIIs were placed in a grain field adjacent to the simulated INTEC radiation area as seen in Figure 8. The MEPS interface shown in Figure 6 was used to specify human mission requirements. Once pre-mission task assignment and paths were performed, each ARC III was commanded to perform its assignment. A very interesting event occurred while each ARC III was attempting to complete the given task. A photographer inadvertently stepped in front of one of the ARC III vehicles causing an obstacle to be identified on the MEPS. MEPS took the appropriate action of re-planning mission assignments based upon the new information and subsequently changed the blocked vehicle's task. Observers in the field (away from the MEPS interface and unaware of the mission changes) thought one of the ARC III vehicles had failed or was confused. Later it was pointed out that the entire system had performed exactly as designed by reallocating tasks dynamically.

Figure 8. ARC III team in a grain field at 1996 SST4AG field day

2.2 INEEL1997 Decision Makers Conference

During May 1997, another invitation was extended by INEEL to the INEEL-USU research team to demonstrate the current state of the autonomous robotic family at a Decision Makers Conference. By this time in the project significant milestones had been met including developing the two RATV robots and retrofitting them with the described soil sampling and spraying equipment (see Figures 4 and 5 above). At this demonstration MEPS was used to identify sampling locations within approximately a one-acre area. After the locations were sampled, a spraying mission was identified on MEPS and the RATV with the spraying equipment visited the designated areas. This particular demonstration was repeated numerous times during various sessions of the conference.

The RATV outfitted with the soil sampling equipment proved to be of particular interest. At the conclusion of the conference the soil-sampling locations were inspected. At each location the numerous samples holes were typically within a few centimeters of one another. Figure 9 shows INEEL Robotics manager Ron Lujan covering multiple samples points with a single hand. The capability of the autonomous computer controlled system to precisely and repeatedly maneuver the large-scale RATV robots had been demonstrated.

Figure 9. Precise Soil Samples

2.3 INEEL 1997 SST4AG field day

A second invitation was received from the INEEL SST4AG group in October 1997 to demonstrate the family of intelligent fully autonomous robotic vehicles. This field day was once again held on the Hess farms in Ashton, Idaho. The major emphasis of this demonstration was the cooperative aspect of the research applied to precision agriculture. It was decided that the two RATV robots would be used to demonstrate soil sampling and spraying activities in a similar manner to the Decision Makers Conference, only on a much larger scale. In addition to these tasks, the RATV robots were tasked with cooperatively performing topographical mapping in a 300-acre area.

Once both systems were successfully deployed in the field, large area soil sampling and spraying was demonstrated under control of MEPS. The topographical mapping task used the real-time sensor recording capability of MEPS to log the RATV robots' DGPS readings at 5 Hz. Each RATV traveled through the field at approximately 10 mph (16.1 kph) to cover the 300-acre area. Figure 10 shows a small portion of the topographical map gathered during the day. Farmers from the area were especially impressed by this capability, as their current methods of performing topographical mapping were much slower and more tedious.

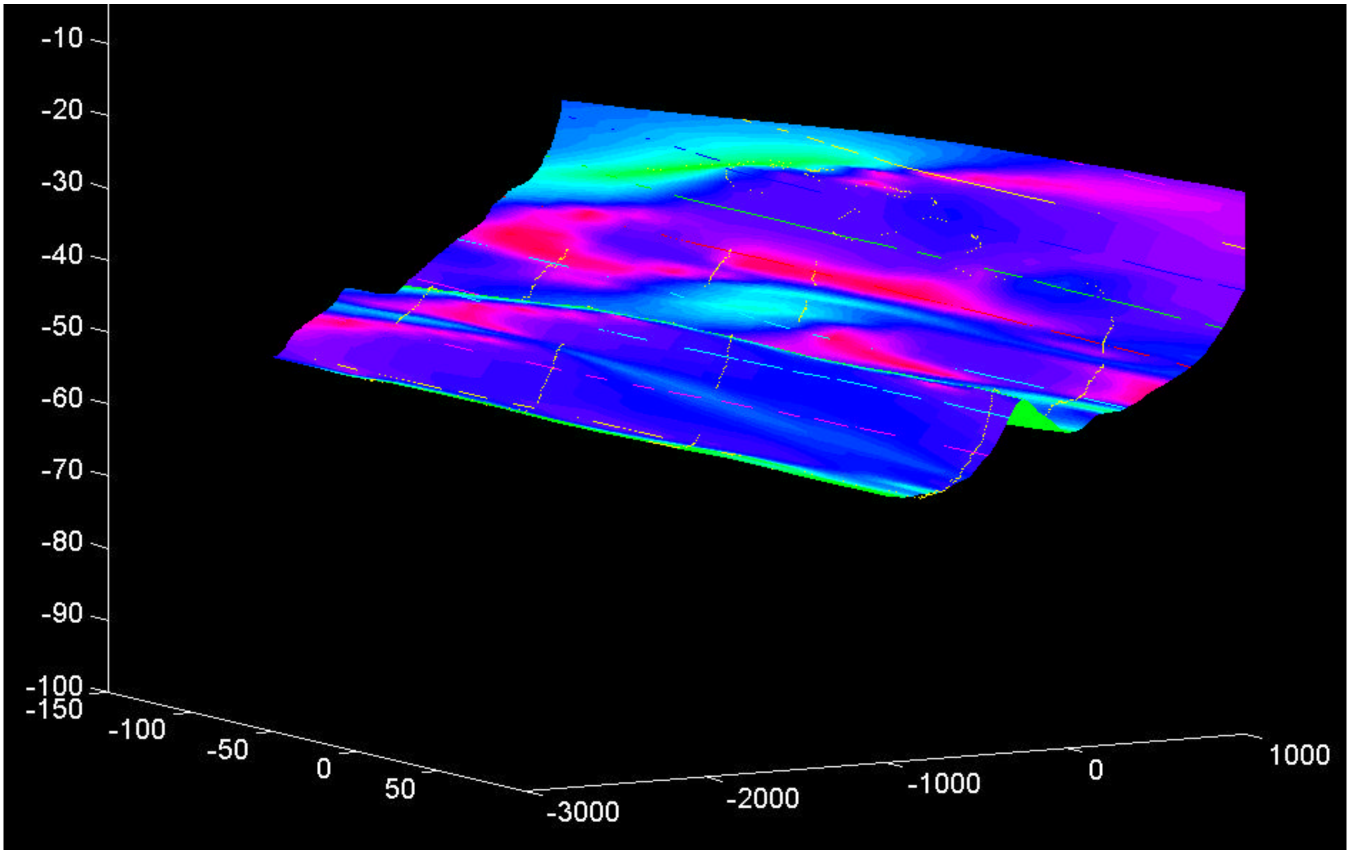

Figure 10. Sample Topographical Map from 1997SST4AG field day

4. Conclusions

The INEEL robotics group and USU's Center for Self-Organizing and Intelligent Systems have successfully developed a family of intelligent autonomous robotic vehicles capable of individual or cooperative operations in a precision agriculture environment. Several demonstrations have been given by the INEEL-USU research team to illustrate various methods of providing the precision farmer easy access to space age technology while avoiding information overload or burdensome application equipment. Additional steps need to be taken to reduce the cost of components of the autonomous family and precise positioning equipment. Cooperative intelligent navigation schemes to augment or reduce DGPS cost is one means of meeting this need and is a worthy research topic.

ACKNOWLEDGEMENTS

INEEL's Academic and Professional Affairs Department provided research funding for this project through manager Debonny Shoaf with University Research Consortium staff Radean Wilcox and Laboratory Directed Research and Development staff Diana Skoy and Steven Piet. The authors would like to recognize the contributions of other participants in this effort including Monte Frandsen, Mel Torrie, Eric Poulsen, Gordon Olsen, Major Peter Van Wirt, Bret Hancy, Marc Oliver, Don Cripps, and John Jacobs. A special thanks to Steve Smith of Trimble Navigation Limited for the loan of DGPS equipment.

REFERENCES

1. Curt Anderson, "Satellites, computers mean new precision for farmers" *Idaho Falls Post Register,* Sunday, December 7, 1997 Section B7.

2. Eric A. Poulson, John S. Jacob, Robert W. Gunderson, Ben Abbot, "Design of a robotic vehicle with self-contained intelligent wheels", proceedings of the SPIE Conference on Robotic and Semi-Robotic Ground Vehicle Technology, Orlando, Florida, April 1998, pp.68-73.

3. Mel W. Torrie, Sriharsha Veeramachaneni, Ben Abbot, "Laser-based Obstacle Detection and Avoidance System", proceedings of the SPIE Conference on Robotic and Semi-Robotic Ground Vehicle Technology, Orlando, Florida, April 1998, pp.2-7.

4. John S. Jacob, Robert W. Gunderson, R. Rees Fullmer, "Conversion and control of an all-terrain vehicle for use as an autonomous mobile robot", proceedings of the SPIE Conference on Robotic and Semi-Robotic Ground Vehicle Technology, Orlando, Florida, April 1998, pp.83-92.

5. Nicholas S. Flann, Kevin Saunders, Larry Pells, "Cooperative Mission Execution and Planning", proceedings of the SPIE Conference on Robotic and Semi-Robotic Ground Vehicle Technology, Orlando, Florida, April 1998, pp.147-154.