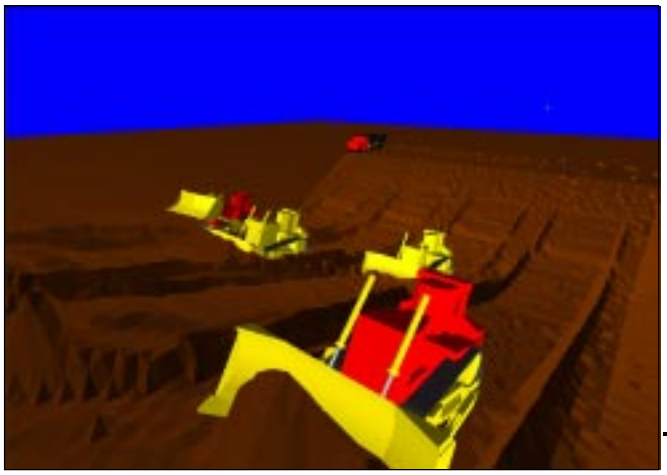


A DOE SUCCESS: Characterization of Underground Structures Through Distributed Planning and Control for Teams of Cooperating Mobile Robots

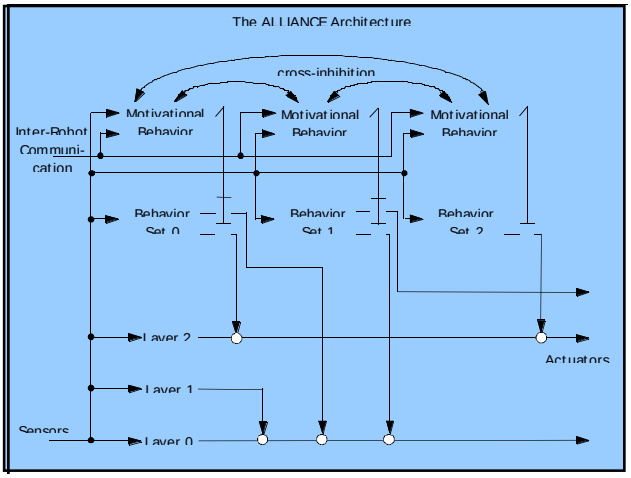
The Project: The long-term vision of robotics and intelligent machines (RIM) applied to DOE hazardous waste cleanup is for teams of robots to work together autonomously, or with minimal human intervention, to remediate challenging hazardous waste sites. To address the realistic size of these cleanup tasks, several vehicles will need to be able to work together in cooperation. By having multiple autonomous vehicles work together, advantages can be realized in the speedup of task completion and in the distribution of key capabilities across multiple robots. Successful automation would enable significant benefits in worker safety and productivity for critical DOE applications.

Over the past several years, Oak Ridge National Laboratory's Center for Engineering Science Advanced Research (ORNL/CESAR), as part of the Engineering Research Program of the Office of Science (SC/ERP) at the Department of Energy, has been developing basic research methodologies that enable this type of autonomous robot cooperation in challenging work environments. As a real world proof-of-principle implementation of these advances, ORNL/CESAR teamed with Caterpillar in November 1998 to apply these fundamental advances in *Distributed Planning and Control for Teams of Cooperating Mobile Robots* to the fully autonomous cooperative control of vehicles performing a production bulldozing task in a surface coal-mining application. Caterpillar provides the application-oriented funding for the project. This project is significant because it addresses key research needs for achieving the multi-robot team cooperation needed for critical DOE applications. Additionally, it addresses the top research goal identified by the DOE Mining Industry Roadmap—the development of autonomous mining equipment. To date, no other research project has successfully developed cooperative autonomous control technologies applied to real-world mining applications.

Novel cooperative control mechanisms for the surfacing mining application are based upon earlier successes in SC/ERP's program at ORNL/CESAR in developing fault-tolerant, adaptive action selection among multiple vehicle team members. The approach involves the use of ORNL/CESAR's ALLIANCE software architecture (illustrated on the following page) that facilitates the fault-tolerant cooperative control of teams of heterogeneous mobile robots. ALLIANCE allows teams of robots, each of which possesses a variety of high-level functions, to individually select appropriate actions throughout the mission. ALLIANCE is a fully distributed, behavior-based control technique that incorporates the use of mathematically-modeled motivations within each robot to achieve adaptive action selection. Since cooperative robot teams usually work in dynamic and unpredictable environments, this software architecture allows the robot team members to respond robustly, reliably, flexibly, and coherently to unexpected environmental changes and modifications in the robot team, even in the midst of sensor and actuator uncertainties.

The Impact: This project has successfully demonstrated the ALLIANCE-based technologies on a team of simulated robots performing the production bulldozing task. This success was based upon the extension of an existing simulation system to enable multi-robot interactions, and the development of the ALLIANCE software for this application domain. A snapshot of this simulation system in operation is illustrated on the front page of this summary. This project provides a significant proof-of-principle demonstration of the capabilities of automated robotic technology in real-world applications of interest to DOE and U.S. industry. This project is an excellent demonstration of how basic research investments supported by DOE can lead to solutions to difficult government and industrial problems. This project has laid the foundation for transitioning the basic research to physical vehicles, leading to new solutions in the field.

Further Advances through a RIM Initiative: The current project is a very important, yet limited, step toward the development of fully autonomous equipment for infrastructure applications such as mining and hazardous waste clean-up. Much more research remains before fully autonomous cooperative vehicles can be fielded in real applications. The availability of fully automated equipment for government and industrial applications would result in a number of significant benefits. The most obvious benefits are the elimination of the need to place workers in dangerous conditions, lower operating costs, reduced downtime, and improved productivity that would lead to a better overall return on assets. The use of more efficient automated vehicles would yield benefits in energy savings and reduced environmental impact. A number of economic benefits would be achieved, including reduced fuel costs, reduced fleet sizes, reduced manpower costs, reduced health risks, and reduced maintenance costs. DOE's RIM investment and collaboration with industry would also greatly benefit the economic competitiveness of U.S. industry. A significant portion of the United States' GNP is accounted for in the building, maintaining, and rebuilding of the Nation's infrastructure. Industries such as mining, earthmoving, agriculture, waste disposal, aggregates and quarry, forestry, and building construction industries play a role in almost all economic activities. There are numerous motivations for using innovative RIM technologies for cooperating vehicles in these infrastructure industries. Cost and efficiency are the most critical drivers, where savings of fractions of a second in cycle time can accumulate to millions of dollars of additional production. Cooperating machine systems that are able to self-organize to most efficiently execute a task can greatly increase the ability of an operator to oversee more than one piece of equipment in its operation—a capability of great significance for the mining industry and hazardous cleanup projects, in which the shortage of skilled workers can lead to project delays. The RIM program thus has significant potential for revolutionizing the mining, infrastructure, and clean-up industries across the Nation.



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