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COOPERATING ROBOTIC SYSTEMS FOR HAZARDOUS
ENVIRONMENTS*

Received by OSTI

JUL 25 1991

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Paper Submitted To:

Space Operations, Applications, and
Research Symposium [SOAR '91]

Gilruth Recreation Center
NASA/Johnson Space Center
Houston, Texas

July 9-11, 1991

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*Research sponsored by the Engineering Research Program of the Office of Basic Energy Sciences, U.S. Department of Energy, under Contract No. DE-AC05-84OR21400 with Martin Marietta Energy Systems, Inc.

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RESEARCH AND DEVELOPMENT AT ORNL/CESAR TOWARDS COOPERATING ROBOTIC SYSTEMS FOR HAZARDOUS ENVIRONMENTS

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ABSTRACT

One of the frontiers in intelligent machine research is the understanding of how constructive cooperation among multiple autonomous agents can be effected. The effort at the Center for Engineering Systems Advanced Research (CESAR) at the Oak Ridge National Laboratory (ORNL) focuses on two problem areas: (1) cooperation by multiple mobile robots in dynamic, incompletely known environments; and (2) cooperating robotic manipulators. Particular emphasis is placed on experimental evaluation of research and developments using the CESAR robot system testbeds, including three mobile robots, and a seven-axis, kinematically redundant mobile manipulator. This paper summarizes initial results of research addressing the decoupling of position and force control for two manipulators holding a common object, and the path planning for multiple robots in a common workspace.

INTRODUCTION

Interest in issues related to achieving effective coordination of multiple robotic devices has been growing over the past few years. There are two main areas of active research related to cooperative robots: (1) path planning and navigation for multiple mobile robots sharing a common workspace, and (2) coordinated or cooperative use of two or more robot manipulators to perform a set of tasks. A useful compilation of representative publications on the topic can be found in [1]. Proceedings of the IEEE International Conferences on Robotics and Automation during the past four years also represent a convenient source of information about recent research efforts. References [2] and [3] contain useful bibliographies covering coordinated robot manipulators and path planning for multiple mobile robots, respectively.

There is a broad spectrum of fundamental problems associated with cooperating multiple robots, ranging from high-level planning to low-level control, and to important architectural and systems issues. Solutions to these problems will have great impact on the safety and productivity of operations in a number of applications including flexible manufacturing, nuclear energy facilities, environmental restoration and waste management, future intelligent transportation systems, as well as space and underwater applications.

CESAR was established during FY-1984 at ORNL for the purpose of addressing fundamental problems and issues arising in the development of intelligent machines. The

approach at CESAR involves concentrating part of the resources on the development of an evolving series of mobile robot prototypes HERMIES (Hostile Environment Robotic Machine Intelligence Experiment Series). These machines serve as testbeds for new methods, and hardware and software developments. They are used in experimental scenarios that provide the necessary quantitative data for testing and validation of new approaches, as well as for performance evaluation of different robot system components in integrated systems. HERMIES-II and -III (see Figure 1) are currently operational mobile robots [4, 5]. HERMIES-III is equipped with the 7 degree-of-freedom CESARm research manipulator. A second redundant manipulator will be available in the near future. A third mobile platform with simultaneous translational and rotational motion capability as well as on-board VLSI fuzzy logic processors [6] is also part of the unique experimental facilities. Among the most recent experiment scenarios for proof-of-principle demonstrations with the HERMIES robots were the autonomous clean-up of simulated chemical spills [7], and autonomous mapping of areas and objects with beta-radiation contamination (manuscript in preparation).

This paper summarizes recent work at CESAR in the areas of decentralized path planning for multiple mobile robots, and control of coordinated manipulators. The current focus of these activities is on multiple agents with heterogeneous capabilities, with respect to sensing, manipulation, mobility, reasoning. Application focus is derived from a number of applied programs that can benefit from this research in several problem areas, including site characterization, construction, remediation of contaminated sites, and decontamination and decommissioning of facilities.

COORDINATION OF MULTIPLE MOBILE ROBOTS

We have been addressing problems associated with global and local motion planning for multiple mobile robots in a common workspace. Previous and on-going work in this area can be broadly characterized into approaches based on centralized or on distributed planning and control. Early references concerning these approaches are [8] and [9].

Most centralized approaches assume complete knowledge of the workspace and capabilities of all the robots, and proceed to develop a plan which is then followed by all robots. It was shown that the amount of computation involved is exponential in the number of robots [10].

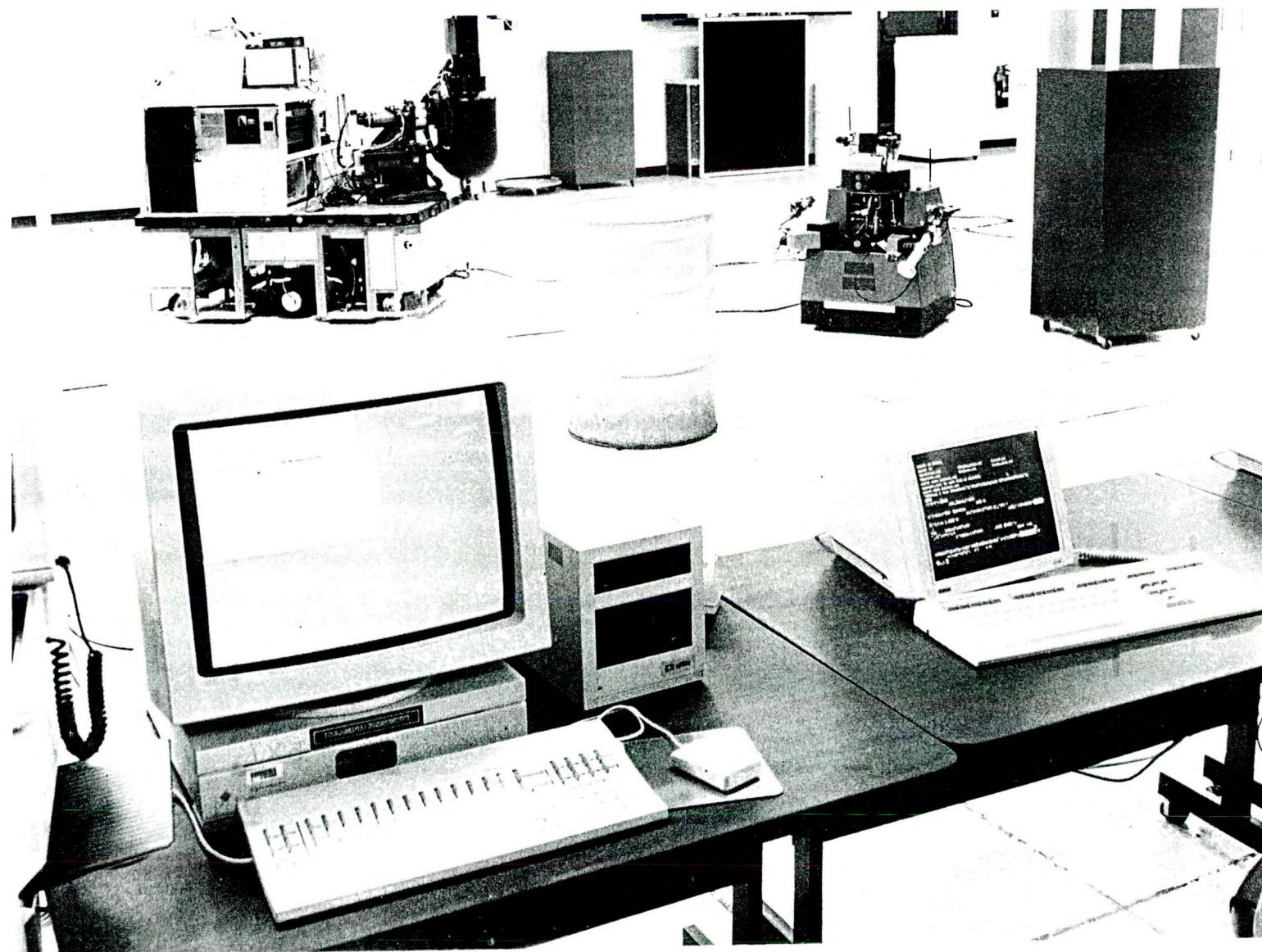


Figure 1: The CESAR mobile robots HERMIES-IIb (right) and HERMIES-III (left).

Central planning for all robots in a prioritized order has been employed [11] to avoid this complexity, at the expense of sub-optimal solutions.

In distributed approaches, each robot develops a plan based on information available about motions of the other robots in the workspace. This information can be rather limited, and usually depends on the robot's sensory capabilities and/or on the communication bandwidth among the different robots. Solutions can generally not be guaranteed to be globally optimal, and deadlock situations may occur. Recent reports on distributed approaches include [9, 12, 13]. Among the simplifying assumptions made in many of these contributions is the homogeneity of the robots with respect to mobility, sensing and reasoning capabilities.

Motivated by many potential application areas for multiple mobile robots, e.g., nuclear environments, space, environmental restoration and waste management, we have been working on the problem of decentralized motion planning for multiple heterogeneous mobile robots in a common workspace.

A computer simulation system has been developed in which the model for each robot or agent consists of three modules: a planning algorithm, knowledge about the environment, and an action interval. These modules determine how well the agent can navigate to a destination point based on knowledge about the environment, how much the agent knows about the current status of its workspace, and how quickly the agent can react to changes in the workspace. Each robot maintains a local map of its environment. The scope of a robot's sensor(s) is reflected in this map. The planning module generates a path based on the information in the map. The agents are treated as completely independent without direct communication among them. Motion planning is based either on visibility [9] or on accessibility [14]. A robot computes estimated future locations of other robots and moves in one of the directions along which a future collision can be avoided. Collisions are avoided by changing the direction of motion, while moving at a constant speed. Each robot repeats the process of planning, acting (moving), and updating its map at a frequency determined by the action interval.

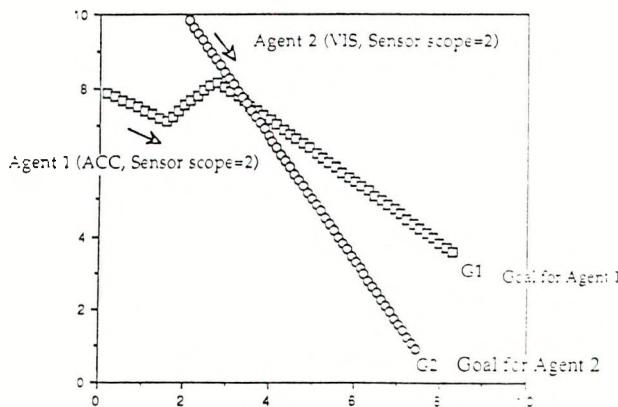


Figure 2. Example of paths followed by two robots with different planning algorithms.

The simulation system was recently described in detail [3]. Among others, our results show that distributed mobile robots can coordinate their motions without deadlocking when appropriately different obstacle avoidance strategies are used by different mobile robots. The simulation system is a useful tool for the investigation of many issues concerning sensing and planning under uncertainty, including reactive and high-level planning for multiple mobile robots.

COOPERATING ROBOT MANIPULATORS

Advancements of our basic understanding of how to accomplish efficient multi-arm manipulation will represent benefits for many application areas for advanced robots in unstructured environments. The effort at CESAR has focused so far on issues arising when two manipulators hold a common object.

Two cooperating manipulators can lift and transport an object whose mass and/or geometry, (e.g., a long, rigid beam) is beyond the carrying capacity of a single manipulator. Two manipulators can directly assemble two parts into a rigid end-product where each part is held by a manipulator. This typically allows for the reduction or even elimination of the expensive, custom-made fixturing often required for a single manipulator to accomplish the same task. Unfortunately, when two manipulators mutually hold an object, the three form a single closed-chain mechanism and a loss of degrees of freedom (DOF) occurs. Strong kinematic and dynamic interactions between the manipulators due to the shared payload result in a constrained system motion. Clearly the manipulators cannot function independently in this closed-chain configuration.

In order to better understand the problems associated with two manipulators lifting and transporting a common object, an adequate process model describing the dynamic behavior of the constrained system is required. In [2], a rigid body dynamical model has been developed for two structurally dissimilar manipulators holding a rigid object in a three-dimensional workspace. The configuration of the system is shown in Figure 3. The final model consists of two sets of equations. One set constitutes the reduced order model which governs the motion of the closed-chain system. The generalized contact forces imparted to the common load by the manipulators are eliminated from the reduced order model but are calculated separately by the other set of model equations. A nonlinear control architecture consisting of the sum of the outputs of two controllers is suggested, which according to the model, leads to the exact decoupling of the position- and force-controlled DOF during motion of the system. The composite controller enables the designer to develop independent, non-interacting control laws for the simultaneous position- and force-control of the closed-chain system.

The approach given in [2] has been generalized to the case of two manipulators holding two types of complex payloads: (i) a spherically jointed object and (ii) a part containing a revolute joint. In [15], the problems of dynamically distributing the jointed loads and of quantifying and controlling the internal stress, strain, and torsion component of the generalized contact forces which were not addressed in [2] are discussed. The problem of solving the rigid body system model for the forward dynamics (i.e., to determine the output response to given applied inputs) is demonstrated to be well-specified,

whereas the solution of the model for the inverse dynamics (i.e., to determine the required inputs when the desired output response of the system is given) is underspecified. It is shown that the number of configuration DOF lost due to the imposition of the kinematic constraints is the same as the number of DOF gained for controlling the internal stress contact forces which do not induce motion in the shared, jointed payload. The composite control architecture proposed in [15] completely decouples the position- and internal stress force-controlled DOF.

CONCLUSIONS

This report provides a brief synopsis of research at ORNL/CESAR in the area of cooperating multiple robots. Initial efforts have been focusing on decentralized path planning for multiple mobile robots, and on controlling two robot manipulators holding a common object. A simulation system was developed that allows for investigations of different planning strategies for multiple mobile robots that differ with respect to their sensing, mobility, and reasoning capabilities. The system supports the study of different reactive behaviors as well as high-level control approaches. A rigid body dynamical model was developed for two structurally dissimilar manipulators holding a rigid object in a three-dimensional workspace. A nonlinear control architecture was suggested, which according to the model, leads to the exact decoupling of the position- and force-controlled DOF during motion of the system. This approach has been generalized to the case of two manipulators holding two types of complex payloads: (i) a spherically jointed object and (ii) a part containing a revolute joint.

Results and lessons learned from these initial studies are now being transferred into efforts that are more experimentally oriented and are making use of the CESAR mobile robots and manipulator(s) for proof-of-principle demonstrations that are relevant to a number of applied programs.

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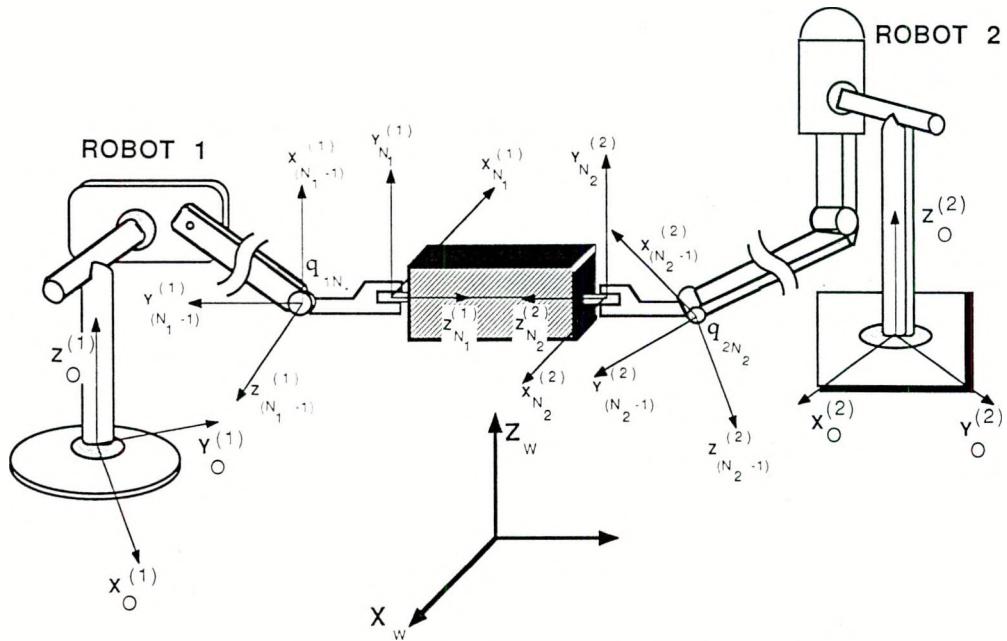


Figure 3. System configuration and coordinate system assignment.

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