CONF-930264--1

ROBOTICS AND ARTIFICIAL INTELLIGENCE FOR HAZARDOUS ENVIRONMENTS*

CONF-930264--1

DE93 008271

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Invited Keynote Address and Paper for:

XVII Congreso de Investigation Cientifica
Universidad Interamericana de Puerto Rico
Hotel Condado Beach

San Juan, Puerto Rico

February 11-12, 1993

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

Robotics and Artificial Intelligence
for Hazardous Environments
by

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In our technological society, hazardous materials including toxic chemicals, flammable, explosive, and radioactive substances, and biological agents, are used and handled routinely. Each year, many workers who handle these substances are accidently contaminated, in some cases resulting in injury, death, or chronic disabilities. If these hazardous materials could be handled remotely, either with a teleoperated robot (operated by a worker in a safe location) or by an autonomous robot, then human suffering and economic costs of accidental exposures could be dramatically reduced. At present, it is still difficult for commercial robotic technology to completely replace humans involved in performing complex work tasks in hazardous environments. The robotics efforts at the Center for Engineering Systems Advanced Research represent a significant effort at contributing to the advancement of robotics for use in hazardous environments. While this effort is very broad-based, ranging from dextrous manipulation to mobility and integrated sensing, the technical portion of this paper will focus on machine leaarning and the high-level decision making needed for autonomous robotics.

CESAR Robotics Laboratory

The Center for Engineering Systems Advanced Research (CESAR) is sponsored by the Engineering Sciences Program of the Department of Energy (DOE) Office of Basic Energy Sciences. It represents a core long-term basic research program in intelligent machines with a variety of application areas (see Fig. 1). CESAR research includes studies in multiple cooperating robots, multi-sensor data analysis and fusion, control of mobile robots and manipulators, machine learning, and embedded high performance computing.

The outstanding facilities support experimental research in autonomous and human-machine systems, as well as human performance experimental investigations. The CESAR laboratory with its mobile robot prototypes (HERMIES-IIB, HERMIES-III, and a new experimental platform), redundant degrees-of-freedom research manipulators, and computer network

Center for Engineering Systems Advanced Research R&D Context

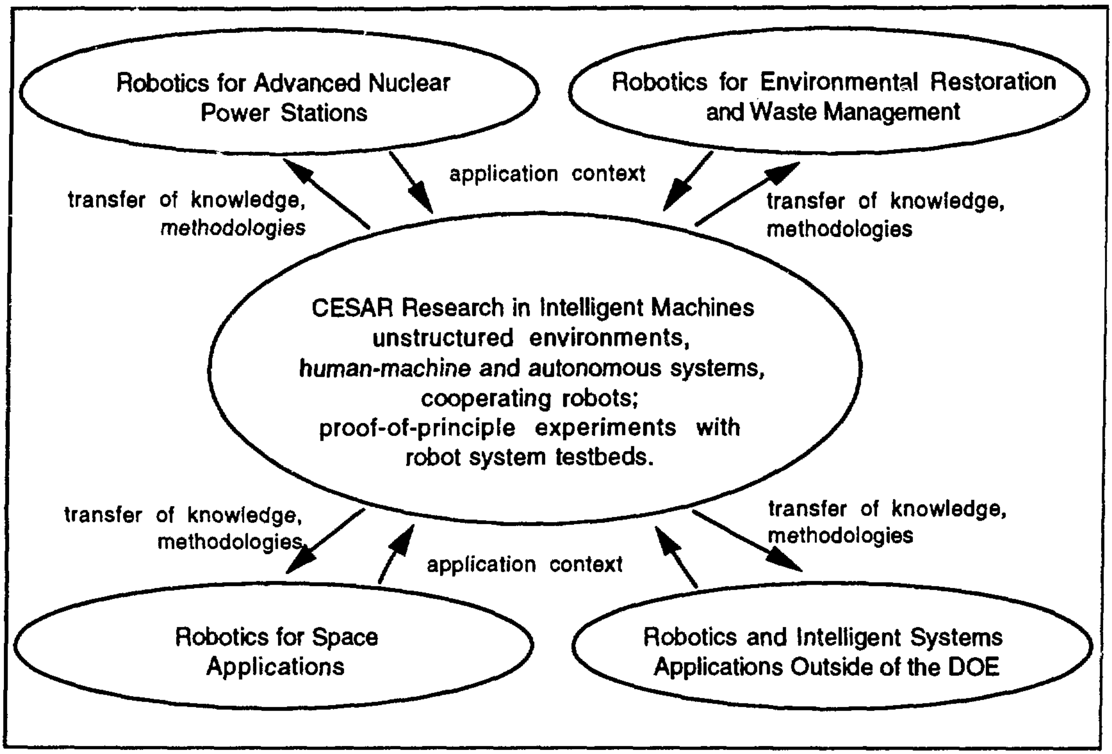

Figure 1. Context for CESAR research and development efforts[9].

including hypercube concurrent processors, parallel systolic arrays, custom-made VLSI fuzzy logic processors, and scientific workstations, continues to be used as a collaborative research facility by numerous guest researchers and students from the U.S. and overseas (Japan, South Korea, France, Germany, Denmark, Norway, Belgium).

Technology demonstrations at CESAR include the results of research efforts in a number of areas, ranging from sensor fusion to manipulator control. Specifically, present research focuses on: (1) planning and control of combined mobility and manipulation systems ("mobile manipulation")[1]; (2) robot control using custom-built fuzzy logic processors[2]; (3) path planning and navigation for car-like robots[3]; (4) control of hard-contact motion of two interacting dissimilar manipulators[4]; (5) fusion of data from multiple sensor domains[5]; (6) embedded high performance computing environments[6]; and (7) machine learning[7].

Nuclear Energy Robotics for Advanced Reactors Program

The United States' social and economic well being are heavily dependent upon its energy supplies. The increasing concerns over global warming due to fossil fuel emissions, air and water pollution, acid rain, and the instability of oil supplies from the middle east have led to research in the development of advanced nuclear power plants by the U.S. Department of Energy (DOE). Important criteria for this new generation of nuclear plants are that they be safe for both the public and the workers who operate them, and be economic with respect to other forms of electrical generation.

In order to meet the dual needs of both safe and efficient operation of these advanced reactors the DOE Office of Nuclear Energy has provided support to four universities (the Universities of Florida, Michigan, Tennessee, and Texas) and the Oak Ridge National Laboratory (ORNL) in order to pursue research leading to the development and deployment of advanced robotic systems[8] (see Fig. 2). These robotic systems must be capable of performing tasks that are hazardous to humans, that generate significant occupational radiation exposure, and/or whose execution times can be reduced if performed by an automated system. The goal is to develop a generation of advanced robotic systems capable of performing complex surveillance, maintenance, and repair tasks in nuclear energy facilities and in other hazardous environments.

The strategy adopted by this team to achieve these goals consists of utilizing, and advancing state-of-the-art robotics technology through close interaction between universities, national laboratories, commercial robot producers, and the manufacturers and operators of nuclear power plants. The approach to achieving the program objective is a transition from teleoperation to the capability of autonomous operation within three successive generations of research robotic systems and a recently acquired commercial robotic platform. The robotic system will always have the capability of requesting human assistance.

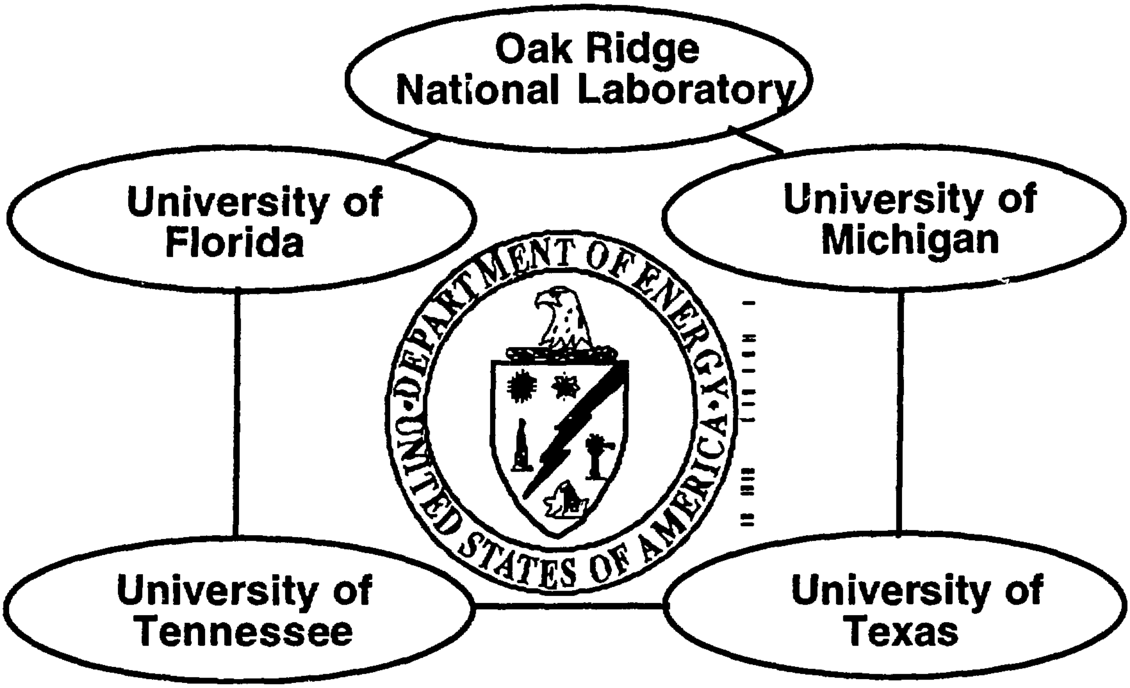

Figure 2. Participants in the DOE NE Robotics for Advanced Reactors Program

Progress of work by the team members towards the common goal has been demonstrated during the project through coordinated experiments, or demonstrations. For these experiments, equipment and software developed at the different institutions were assembled in order to test the planned interaction between components, and to perform tasks of increasing complexity as the project progresses. ORNL coordinated the integration of university efforts and the demonstrations were done in the CESAR laboratory. This program is designed to take full advantage of existing substantial resources at the participating institutions and various industrial partners. The overall progress of the program is overseen by a Board of Governors, which also establishes contacts with other institutions in the public and private sector that may serve to enhance the strength of this program, and to facilitate technology transfer to the private sector.

It is generally recognized that development and implementation of robotics, and related intelligent systems, can have a significant impact on the productivity and safety of advanced nuclear reactor plants. Minimization of personnel radiation exposure and reduction of plant outages are among the potential benefits[9]. While some routine surveillance jobs may be amenable to existing commercial robot technology, most maintenance and repair tasks require more advanced technology. Remote maintenance and surveillance requirements for new plants should be considered early in the plant design process to minimize technology requirements. For example, clear pathways and direct access to vital equipment will significantly reduce the current need for legged vehicles which must operate in congested and generally inaccessible environments inside containments. Robotics research is required for capabilities that go well beyond today's current commercial products. Redundant degrees of freedom in manipulator design are necessary to permit an arm to conveniently reach around an obstruction. Path planning and control of such systems remain research issues. There is also an important need to increase the strength-to-weight ratio of the robot. Most available commercial robots today can only lift approximately 4% of their weight. Lighter weight manipulators introduce research issues dealing with modeling and control of flexible structures. Robotic systems must be made more compact, and effectively hardened against adverse environmental conditions, e.g., high radiation fields.

Most sophisticated industrial robots today rely heavily on video cameras and light sources, radiation sensors, and temperature sensors, drawing on the human interface for the interpretation of sensor measurements. As we strive towards man-robot systems in which man is used more in a supervisory capacity, and the robot autonomously carries out desired functions, major issues of three-dimensional world modeling, scene understanding, and multi-sensor integration must be dealt with in real time, including the concomitant need for parallel computing architectures and algorithm development. Systems which today rely exclusively on the human operator for fault assessment and contingencies, must be made robust in order to meet the demands of increasingly complex remote operations.

The NE robotics team has formulated a division of technical responsibilities and assigned leadership roles for different R&D areas in this project to the various universities and to ORNL. These assignments were made so as to more fully take advantage of the expertise of the staff at the participating institutions and to ensure the high level of collaboration and communication necessary to accomplish successful integration of R&D products.

The major responsibilities of University of Florida are in the areas of locomotion and navigation, 3-D world modeling based on geometric databases available for nuclear power plants, robot component hardening against environmental conditions, and robot intelligence as it pertains to navigation.

The group at the University of Michigan has the lead in developing vision algorithms for robot navigation, in supporting the team effort in the area of robot reasoning and decision making, and is developing a new gamma radiation imaging sensor.

Responsibilities at the University of Tennessee are in the areas of robot vision and sensing for manipulation, the integration of different sensors for manipulation, and the planning of trajectories for robot manipulators.

University of Texas has the lead in developing manipulator technology for this program. This includes the design of robot manipulators with redundant degrees of freedom, analyzing their dynamics, developing and implementing appropriate control algorithms, and fabrication of these manipulators. In addition, the group leads the effort in force feedback systems for kinesthetic control.

ORNL, through its Center for Engineering Systems Advanced Research, fulfills a dual role in this program. The ORNL group is responsible for R&D in the areas of range sensor-based 3-D world modeling, fusion of information from different sensors to support robot decision making, and concurrent computing. ORNL also handles the integration of different robot modules developed at the participating institutions into operational prototypes. The latter activity is part of ORNL's role as program coordinator and integrator. It involves the use of unique facilities at ORNL, including the mobile robot series, HERMIES, and mockup nuclear environments to perform concerted experiments with the robot prototypes developed by the team.

Artificial Intelligence and Machine Learning

Intelligent machines must learn from and adapt to their environments. For environments with little pre-defined structure, learning is a most difficult, yet essential, task. Information must be sensor-based, and active sensing is needed to create and continuously update the robot's internal model of its surroundings. A major issue in machine learning is the development of appropriate representations for the information the robot is to learn and remember.

An early application of machine learning was done using the HERMIES-IIB platform. The robot's task was to navigate through an environment with initially unknown obstacles to find a control panel which needed adjustment[12,13].

An Expert System was written in the 'C' Language Integrated Production System (CLIPS) shell, developed at NASA Johnson Space Center. This expert system was capable of learning about how to properly manipulate a simulated control panel to adjust the system and shut off a danger light. The expert system consists of three components: a Response-Sequence Learning segment, an Inferencing unit, and a Hypothesis Generating section. The Response-Sequence Learning unit enables the robot to experiment with the environment (control panel) to learn sequences of responses associated with particular panel states to solve a problem. The Inferencing unit generalizes from the self-generated examples to infer categories of control panel problems. The Hypothesis

Generating portion of the expert system permits the robot to produce intelligent hypotheses about correct solutions, including those for particular problems not yet categorizable, but which are similar to previously solved problems. Thus, the learning system aboard HERMIES-IIB learns in a hierarchical manner -- concepts are derived from information gained from manipulating the environment. Hypotheses derived from those concepts are used to solve new problems by manipulating the environment, which, in turn, leads to more knowledge from which new concepts may be inferred. The cycle repeats as long as new information permits forming new concepts.

In a non-robot-based machine learning effort, CESAR researchers are investigating the use of random set representations for probabilistically approximately correct (PAC) learning. Results to date show significant improvements in speed of learning. They have also studied the performance characteristics of a system consisting of N learners combined by an algorithm that can integrate knowledge from the individual learners[11].

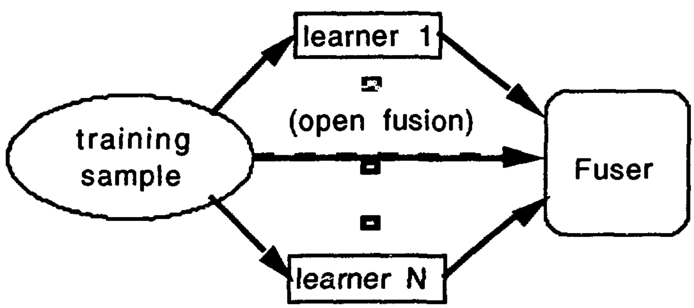

Figure 3. N-learner knowledge fuser[10].

Given a system of N PAC learners, a method has been developed that allows the system to perform better than any of the individual learners. The important new element is the knowledge fuser, as illustrated in Fig. 3. The faster learning can be accomplished under certain conditions on the learners and the fuser, which have been analytically determined. The research presents benefits for many applications of machine learning, including identification of parameters that govern complex processes, adaptive pattern recognition systems, and so on. This research is also expected to contribute significantly to efforts to design a system of multiple simple robots working cooperatively to solve problems of realistic complexity.

Another research effort at CESAR has investigated an architecture which combines Artificial Neural Networks (ANNs) and an Expert System (ES) into a hybrid, self-improving artificial intelligence (AI) system[14,15]. The purpose of this project is to explore methods of combining multiple AI technologies into a hybrid intelligent diagnostic and advisory system. ANNs and ESs have different strengths and weaknesses, which can be exploited in such a way that they are complementary to each other: Strengths in one system make up for weaknesses in the other, and vice versa. There is presently considerable interest in the AI community in ways to exploit the strengths of these methodologies to produce an intelligent system which is more robust and flexible than one using either technology alone.

Any process which involves both data-driven (bottom-up) and concept-driven (top-down) processing is especially well-suited to displaying the capabilities of such a hybrid system. The system can take an incoming pattern of signals, as from various points in an automated manufacturing process, and make intelligent process control decisions on the basis of the pattern as preprocessed by the ANNs, with rule-based heuristic help or corroboration from the ES. Patterns of data from the environment which can be classified by either the ES or a human consultant can result in a high-level ANN being created and trained to recognize that pattern on future occurrences. In subsequent cases in which the ANNs and the ES fail to agree on a decision concerning the environmental situation, the system can resolve those differences and retrain the networks and/or modify the models of the environment stored in the ES. Work on a hybrid system for perception in machine vision was funded by an Oak Ridge National Laboratory seed grant, and the system components ran in a parallel distributed computer environment. Subsequently, the hybrid AI architecture has been adapted to process control for an advanced nuclear power plant.

Summary and Conclusions

This paper has summarized a variety of research and development efforts undertaken at the Center for Engineering Systems Advanced Research at Oak Ridge National Laboratory. The projects reported here, as well as others either completed or just beginning, represent long-term research programs in intelligent machines, for application in a number of areas in which there can be anticipated to be harm to humans working in the area. These research areas include multiple cooperating robots, multi-sensor data fusion; combined mobility and manipulation; machine learning; and embedded high-performance computing. CESAR is also a user facility, which welcomes visiting scientists, faculty, and both undergraduate and graduate students on internships and cooperative education programs.

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