CESAR ROBOTICS AND INTELLIGENT SYSTEMS RESEACH FOR NUCLEAR ENVIRONMENTS*

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CESAR Robotics and Intelligent Systems Research for Nuclear Environments

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Presented at:
Specialists Meeting on
Application of Artificial Intelligence and Robotics
to Nuclear Plants (AIR'92)
May 25 - 26, 1992
Oarai, Japan

Agenda

CESAR research and development context

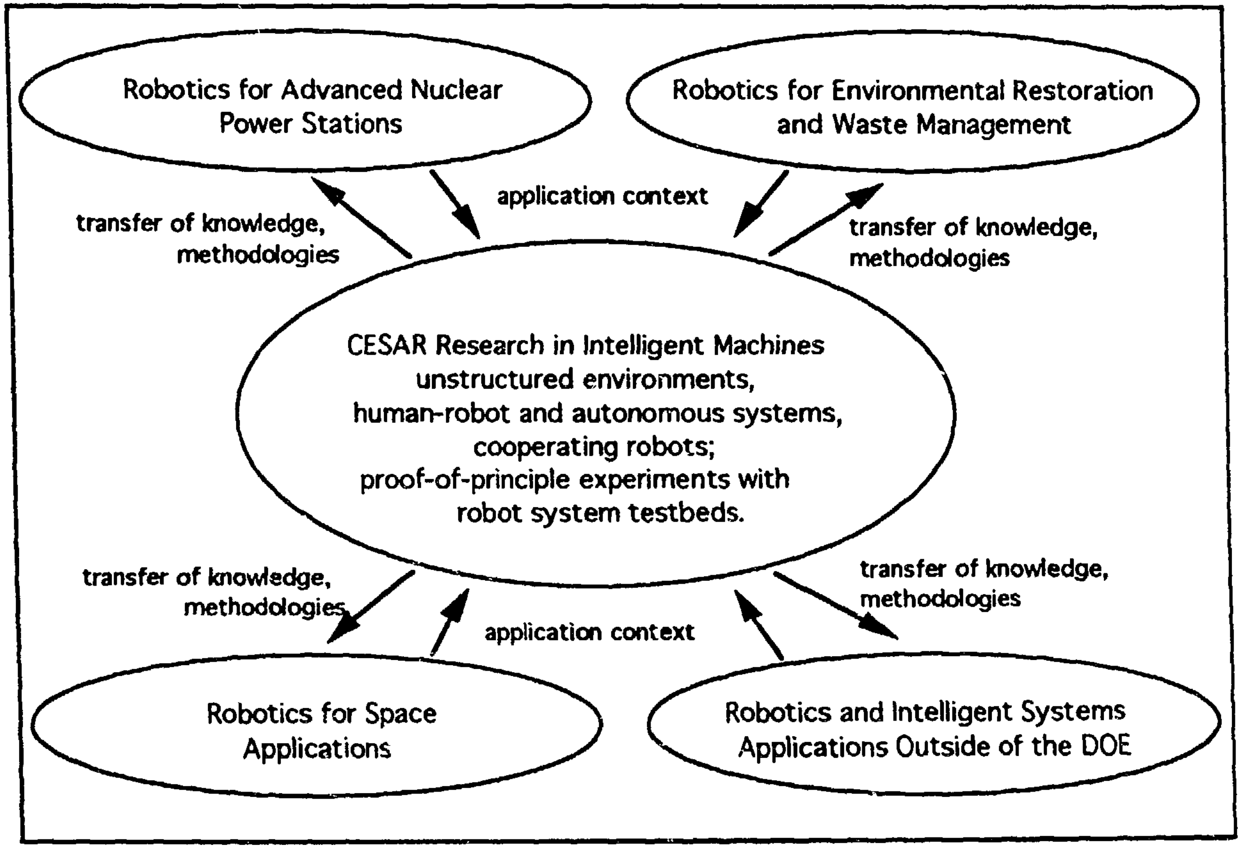
ORNL/University/Industry Consortium

Selected technical highlights:

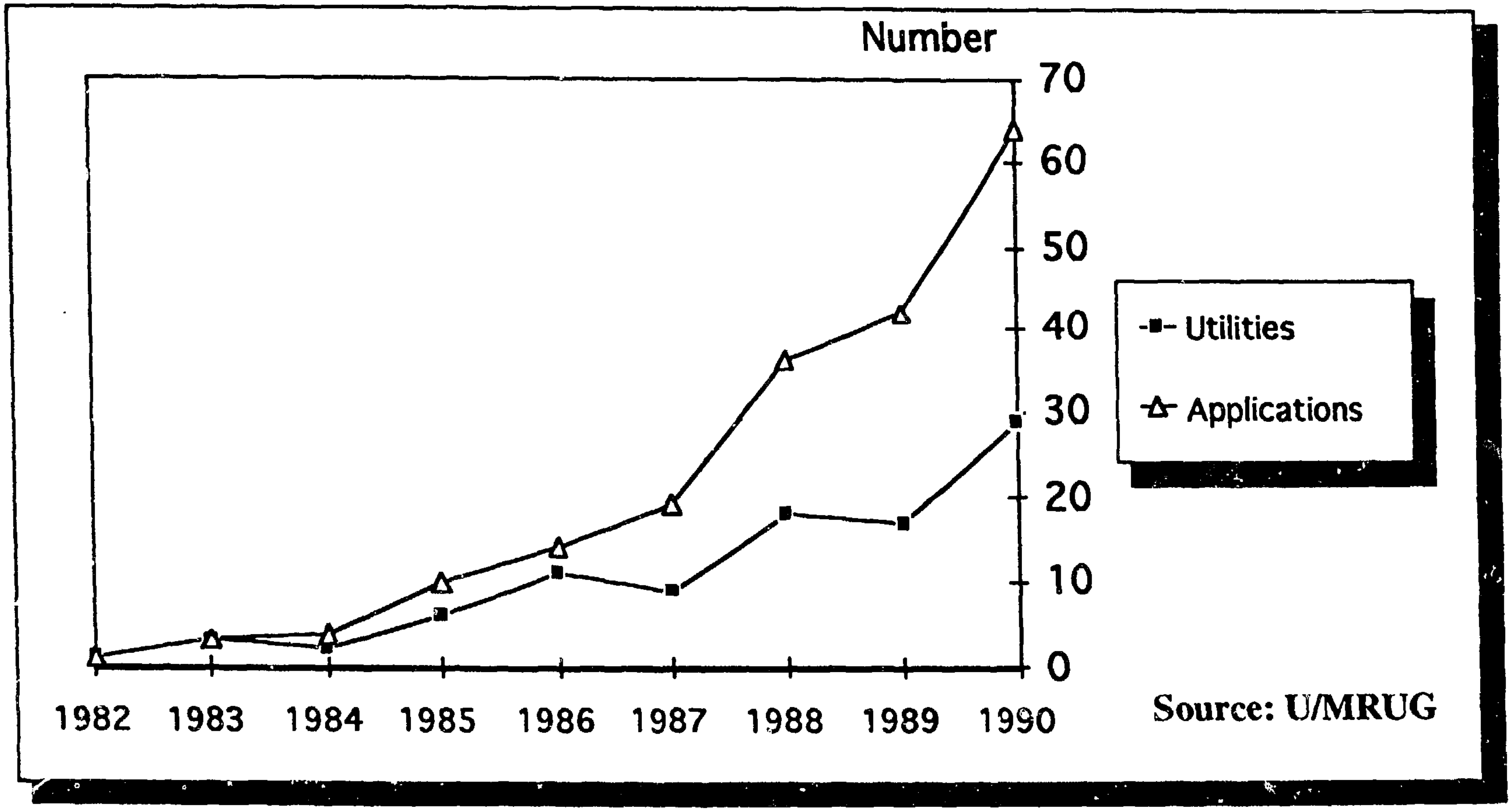
- cooperating manipulators
- path-planning for car-like robots
- real-time qualitative reasoning
- heterogeneous computing environments
- integrated technology demonstrations

Conclusions

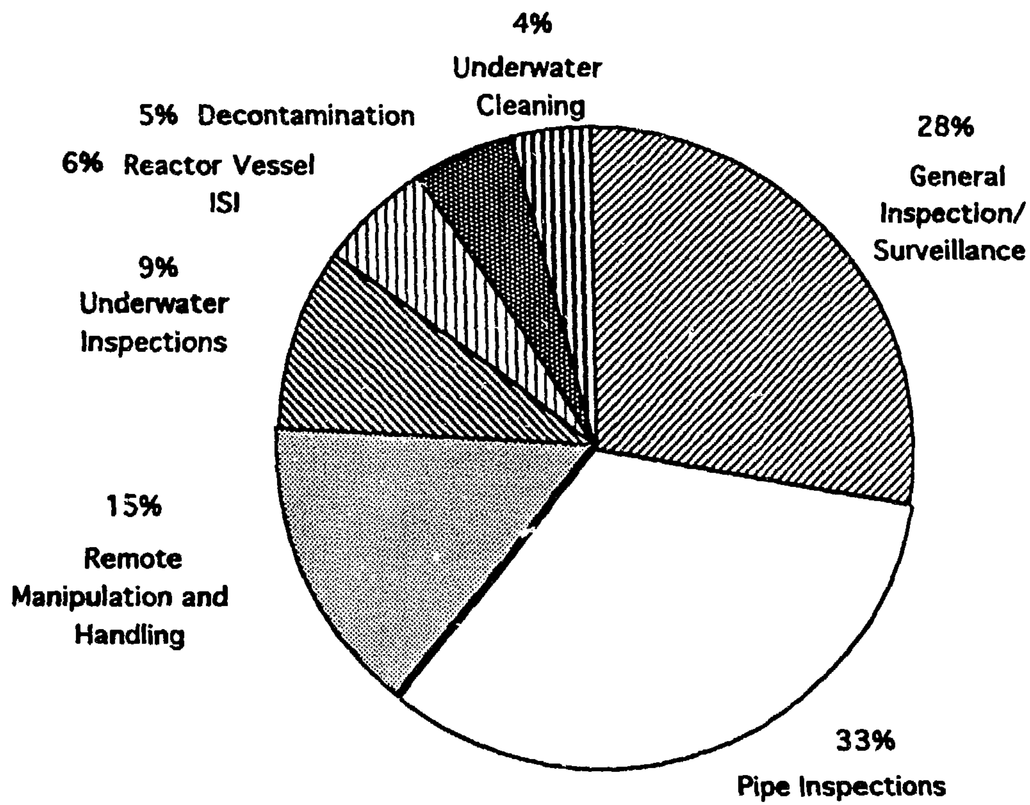
CESAR R&D Context



Robots in Nuclear Power Plants



Robots in Nuclear Power Plants



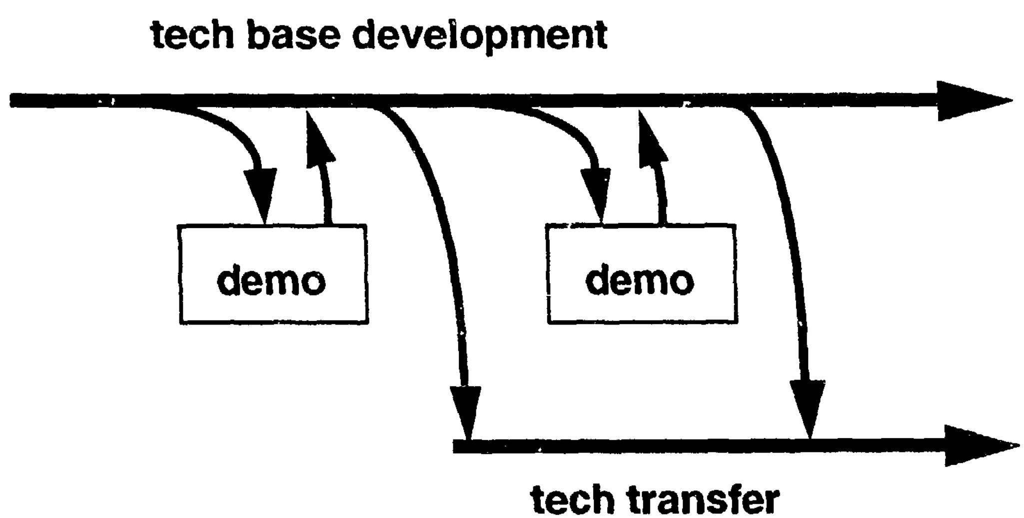
Source: U/MRUG

ORNL/University/Industry Consortium Robotics for Advanced Reactors

Teaming of Universities, Industry, National Laboratory

Produce, in the short-term, results of relevance to the advanced reactor development and to the nuclear industry.

Demonstrate successful systems integration through annual concerted robot experiments.



ORNL/University/Industry Consortium Robotics for Advanced Reactors

Principal Investigators:

- Oak Ridge National Laboratory: Frank Sweeney
- University of Florida: James Tulenko, Carl Crane
- University of Michigan: David Wehe
- University of Tennessee: Mohan Trivedi
- University of Texas: Delbert Tesar

DOE Program Monitor: Harry Alter

Industrial Partners:

- Odetics, Inc.
- Gulf State Utilities
- Florida Power and Light Company
- Remotec
- Telerobotics International

ORNL/University/Industry Consortium Robotics for Advanced Reactors

Integrated Technology Demonstrations:

- 1989: HERMIES-IIB Control Panel Manipulation
- 1989: HERMIES-III Cleanup of a Chemical Spill
- 1990: HERMIES-III Survey of Waste Containers

Other Selected Accomplishments:

- Developed an integrated radiation/temperature on-line component testing facility
- Developed and tested a 2-D radiation imaging camera
- Designed articulated body robot system
- Automated a vision-based manipulation system
- Graduated 36 students with advanced degrees

CESAR Research Agenda

Cooperating robots (M.A. Unseren, A.L. Bangs)

Combined mobility and manipulation systems
(F.G. Pin, D.B. Reister)

Multi-sensor data analysis and fusion
(M. Beckerman, J.E. Baker)

Machine learning (E.M. Oblow, C.W. Glover)

Behavior-based and hybrid robot control
(F.G. Pin, Y. Watanabe)

High performance computing environments
(J.P. Jones)

Cooperating Robot Manipulators

Problem:

Dynamical modeling and control of two structurally dissimilar robot manipulators holding and transporting various types of objects.

Motivation:

Reduce fixturing, enhance dexterity, flexibility; cooperation among multiple heterogeneous robots (mobile manipulators); significant benefits to many applications. Challenging problems: single closed chain mechanism is formed, loss of degrees of freedom occurs, control strategies must account for kinematic and dynamic interactions.

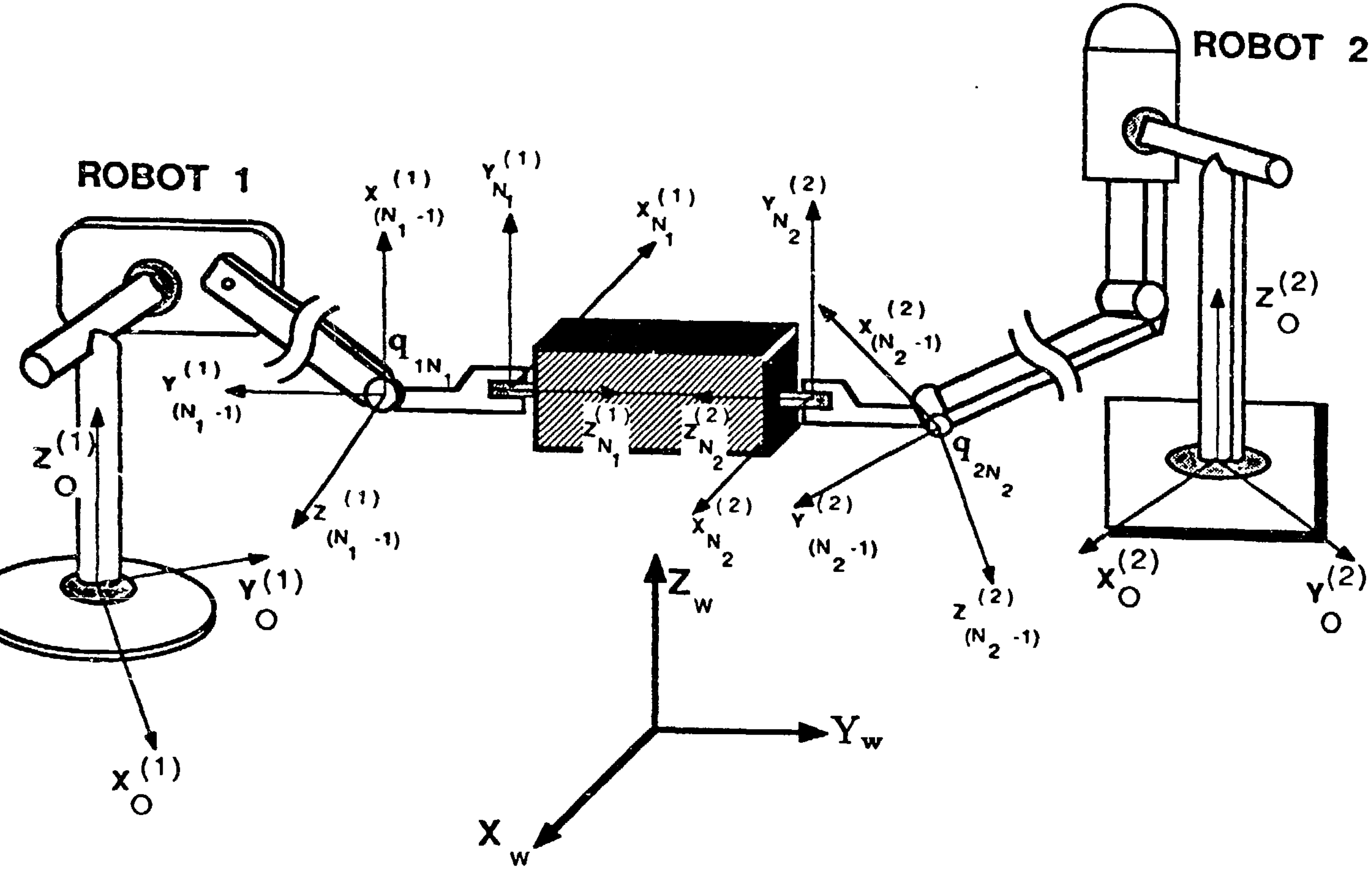


Figure 1. System Configuration and Coordinate System Assignment

Cooperating Robot Manipulators

Accomplishments:

Developed rigid body model and control theoretic architecture for two manipulators holding:

- a rigid, jointless object
- an object containing multi-dof spherical joint
- an object with revolute joints (pliers, scissors)

Control architecture completely decouples:

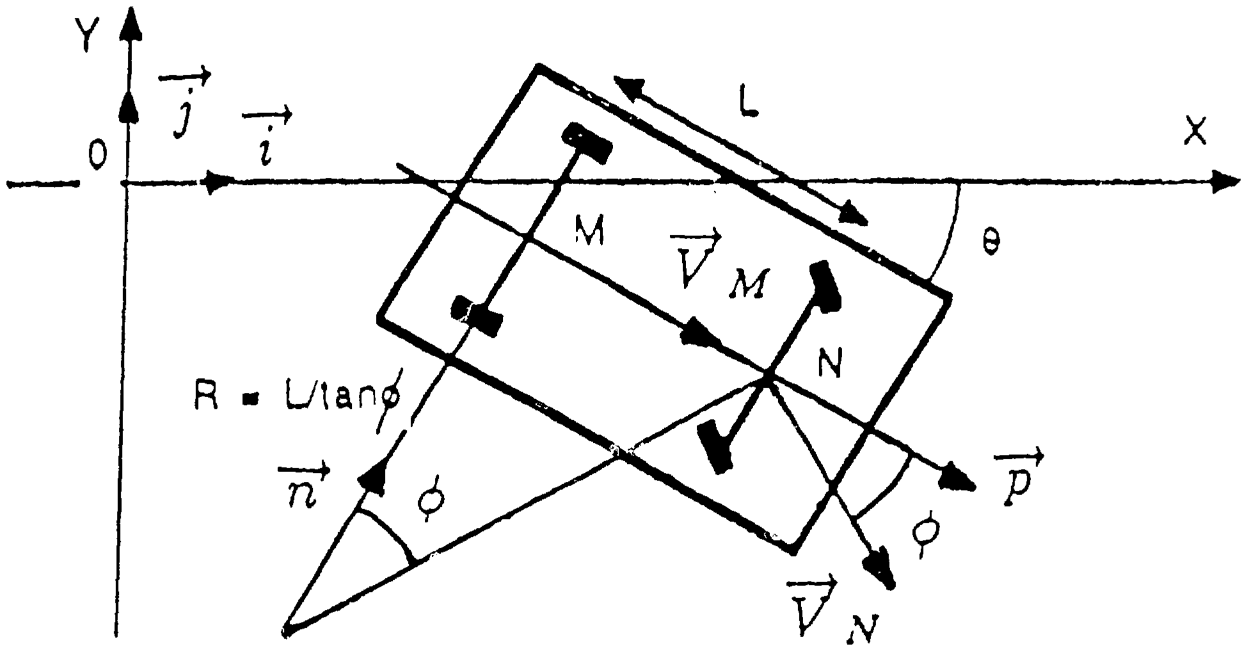
- internal stress and strain force controlled dof
- position controlled dof

Principal Investigator: Michael A. Unseren

Path-Planning for Car-Like Robots

Principal Investigator: Francois G. Pin

KINEMATICS OF A CAR-LIKE ROBOT



- 3 Degrees of Freedom x, y, Θ
- No Slipping of the Wheels
- Limited Steering Angle $|\phi| < \phi_{\max} < \frac{\pi}{2}$

PREVIOUS WORK CONCERNING THIS PROBLEM

- 1986, J. P. Laumond:
  A Car-Like Robot is Controllable.

- 1989, J. Barraquand and J. C. Latombe:
  Discretization of the Environment and of the Configuration Space, and Then Search

  - Non-Holonomic Constraint Applied Using Heuristics

  - Accuracy is of the order of the mesh size, *but*

  - Configuration Space *is* the Space for Path Planning if the Robot is Non-Trivial (i.e., Non-Punctual, Non-Circular, Possibly Deformable, etc.)

- Some Geometric Reasoning Properties Can Be Used to Greatly Improve the Space Representation and Time of Execution.

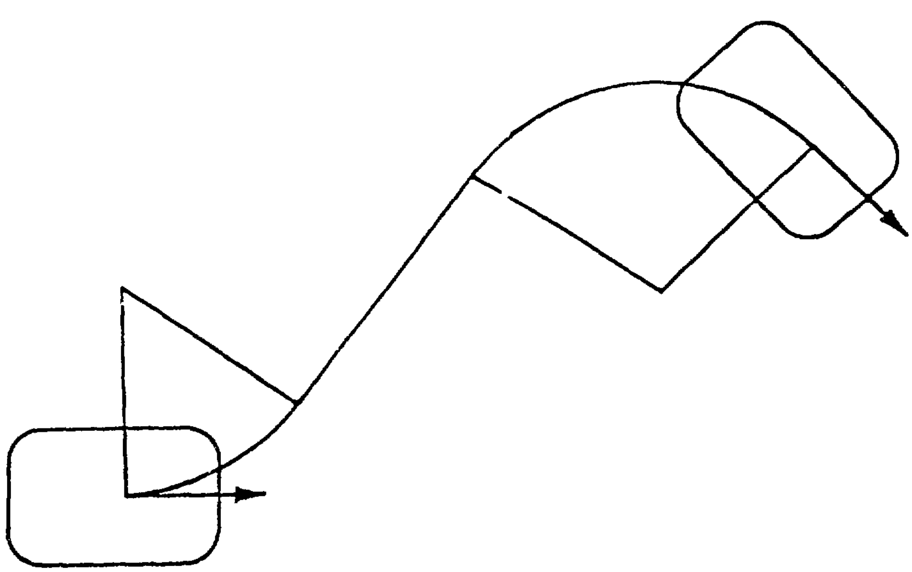
1989 - Jacobs and Canny

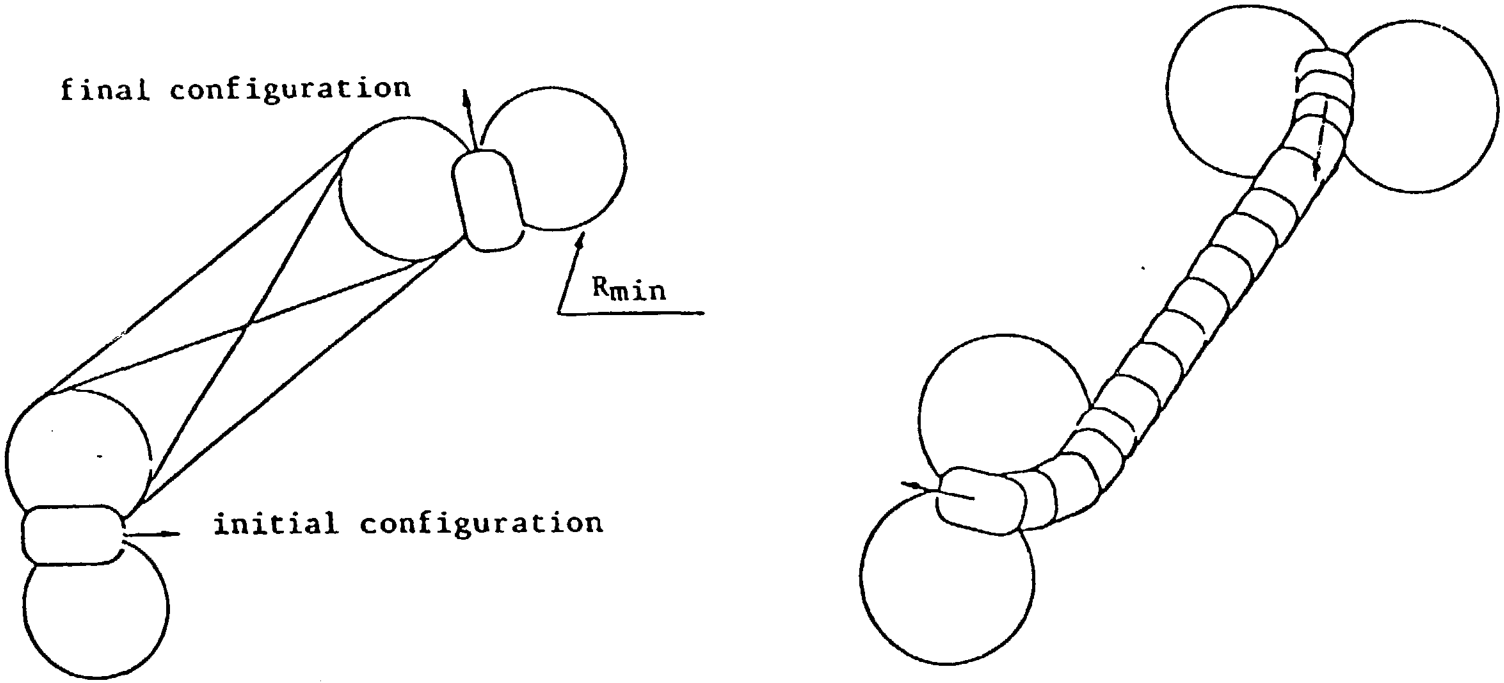
1990 - Laumond, Taix, and Jacobs

1990 - Fraichard, Laugier, and Lievin

1990 - Pin and Vasseur

Utilized and demonstrated the optimality properties of canonical trajectories consisting of a straight line segment, tangent to and connecting two arcs of circle.





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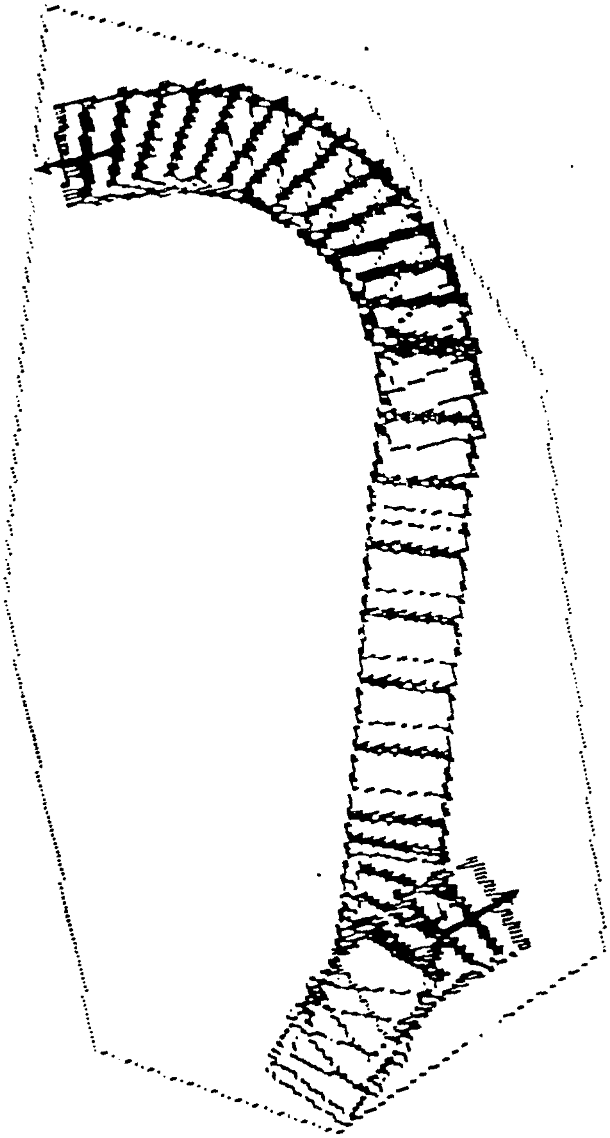
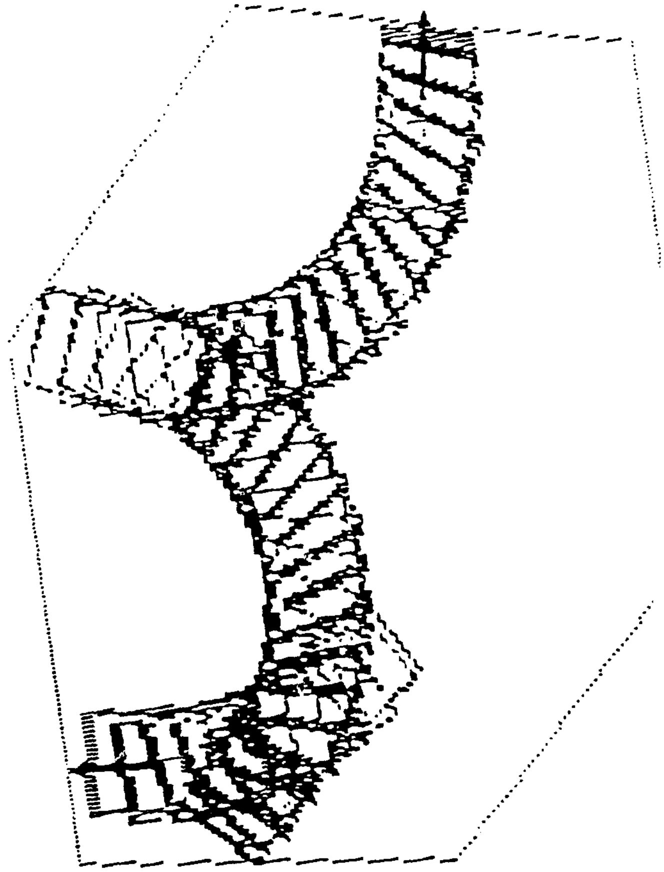
The method for generation of basic trajectories has been extended to take into account:

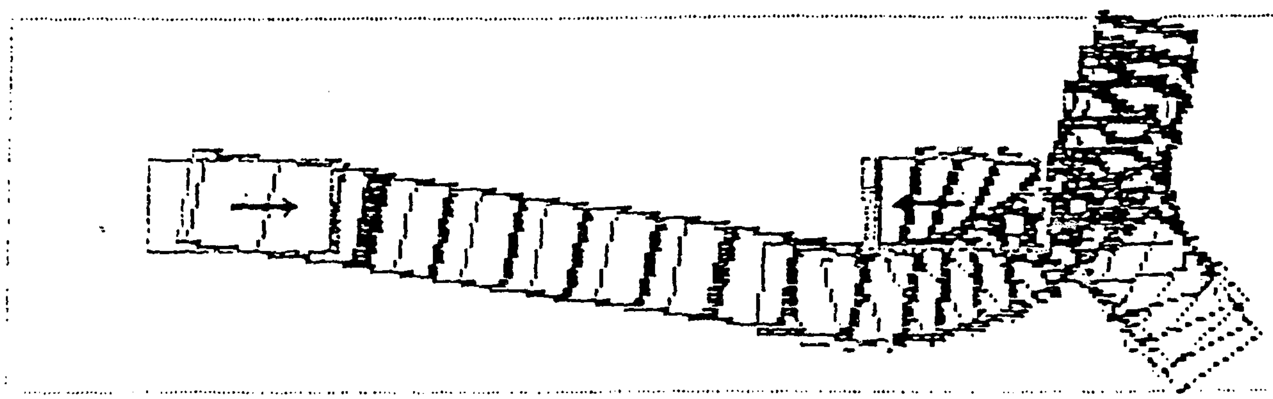
- Limited Steering Rates

- Maneuvering in Restricted Environments

- Integration with Global Planners







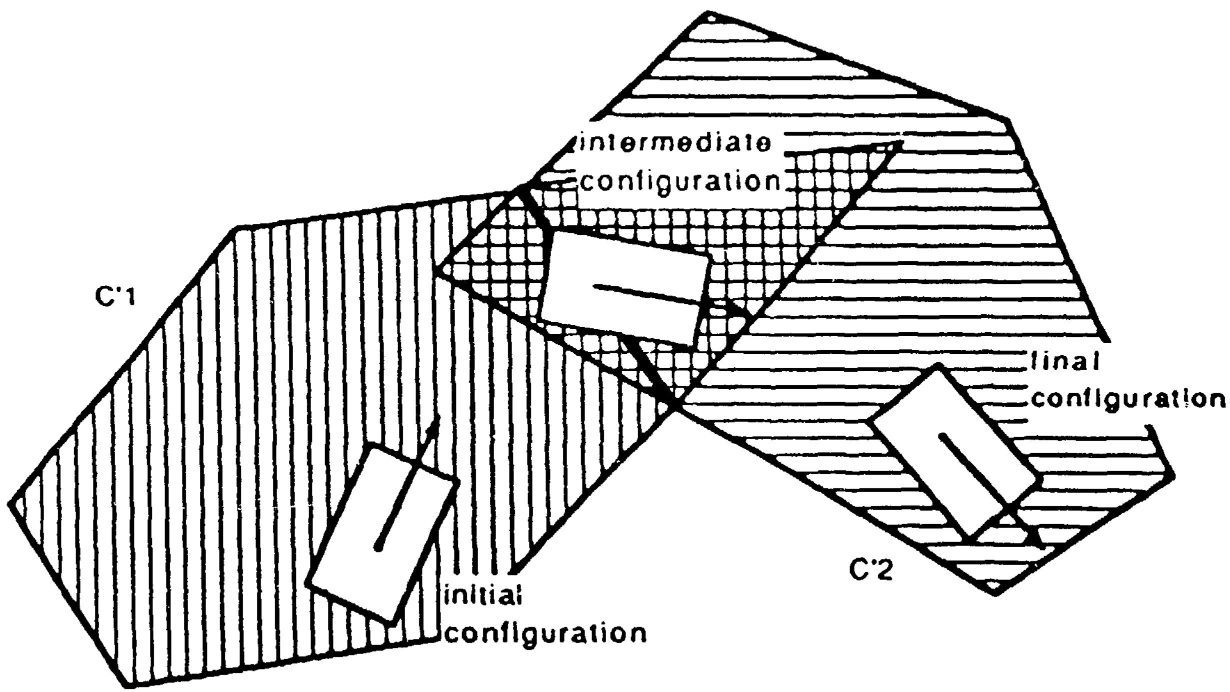
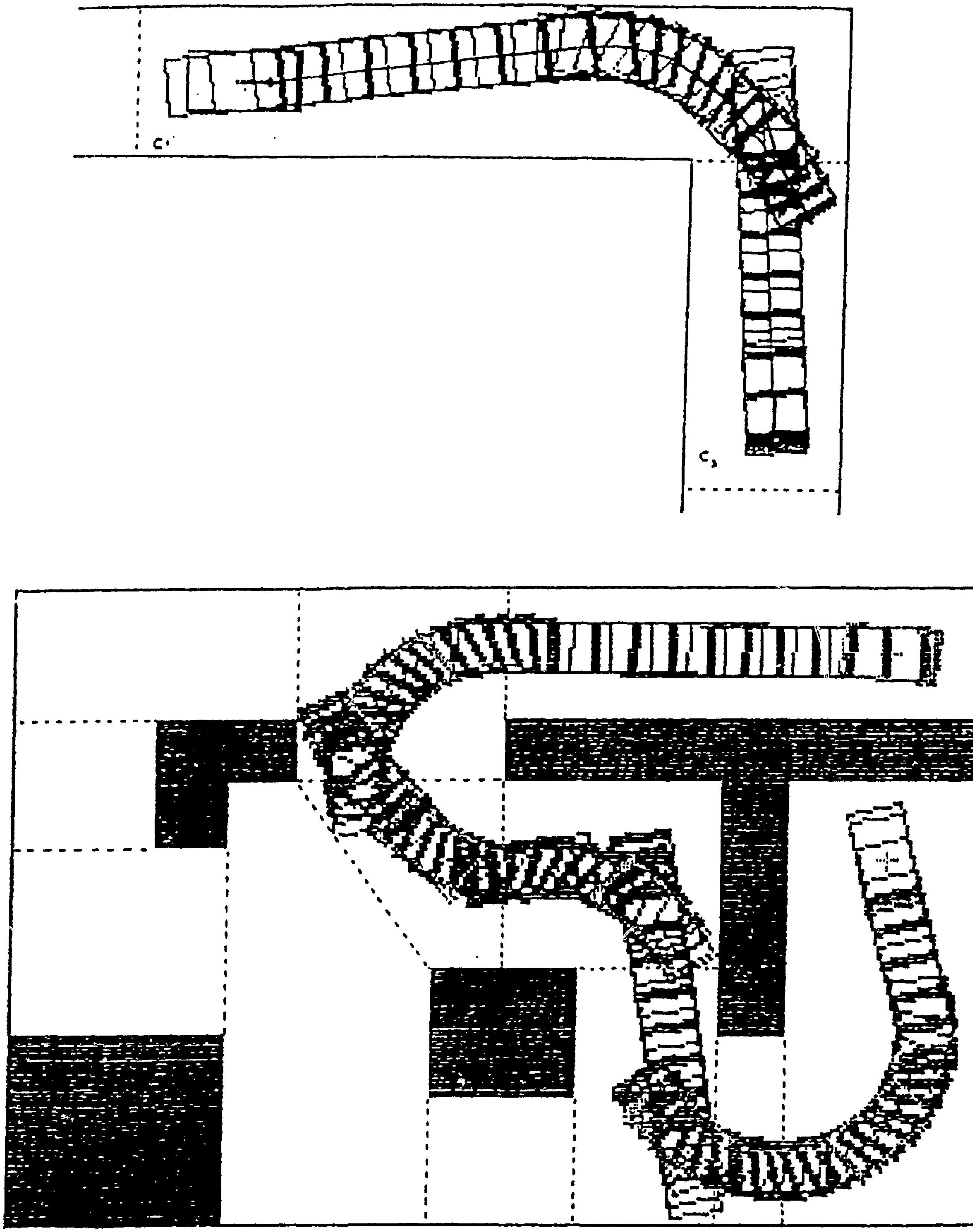
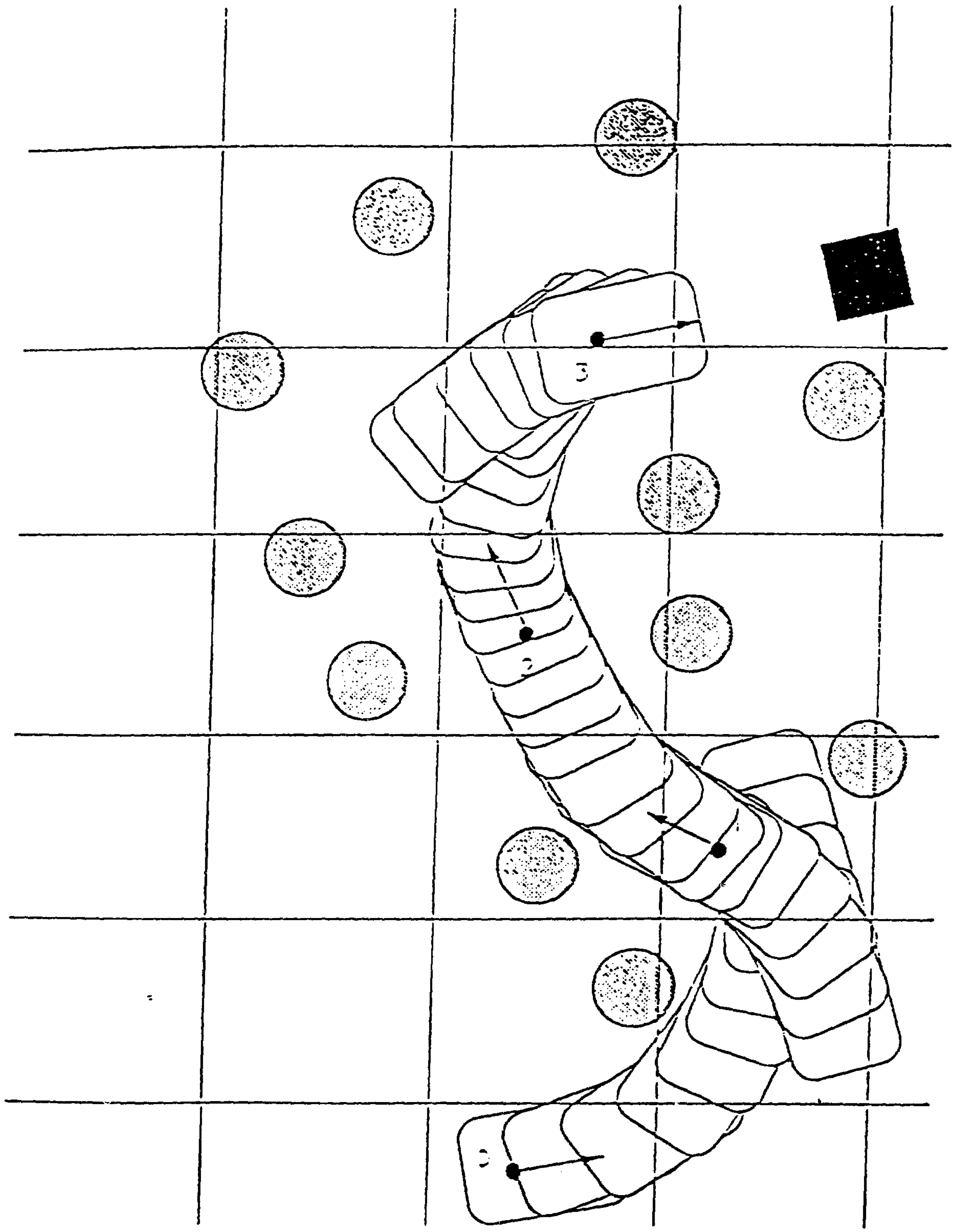


Fig 7: : Intermediate configuration in $C'1 \cap C'2$.



Navigation in constrained environment.



Real-Time Qualitative Reasoning Support for Mobile Robots

Team:

Francois Pin, Yutaka Watanabe, Robert Pattay — CESAR
Hiroyuki Watanabe, Jim Symon — U. of North Carolina

Product:

VME-compatible computer boards with VLSI fuzzy logic chips; allow for full inferences with up to 350 rules and 28 sensor input channels to be executed at a rate of 30kHz.

Applications:

Behavior-based navigation by a mobile robot.
Support for remote driving of a telerobot.
...

Concurrent Computing Environments for Robotics Applications

Principal Investigator: Judson P. Jones

Parallel and Distributed Computing Research at CESAR

Intelligent and Robotic Systems demand

- High performance computing
- Integration of physically distributed resources
- Systematic methods for constructing large-scale systems
- Experimental testing of theoretical principles

Parallel Computing

is a theoretical and experimental discipline which treats issues related to coordinating the activities of interacting processors (or agents) as they cooperate to achieve a common goal.

These issues include existence, complexity, optimality, efficiency, experimental methods, and a host of problems which arise in practical applications.

CESAR has significant experience and expertise in

High Performance Computing

- 1986-92 Ncube B-test site
  1st generation message passing systems
- 1992-> Intel iWarp installation
  1st generation systolic systems

Heterogeneous Distributed Systems & Software Engineering

- 1989-> Hetero Helix shared memory simulation for heterogeneous distributed networks
- 1991-> Automated methods in software engineering for distributed systems

A Scalable Parallel Image Analysis System for Distributed-Memory Message-Passing Multicomputers

A scalable parallel library which presents a reasonably friendly programming environment which permits programmers to exploit the power of parallel processors without necessarily becoming experts.

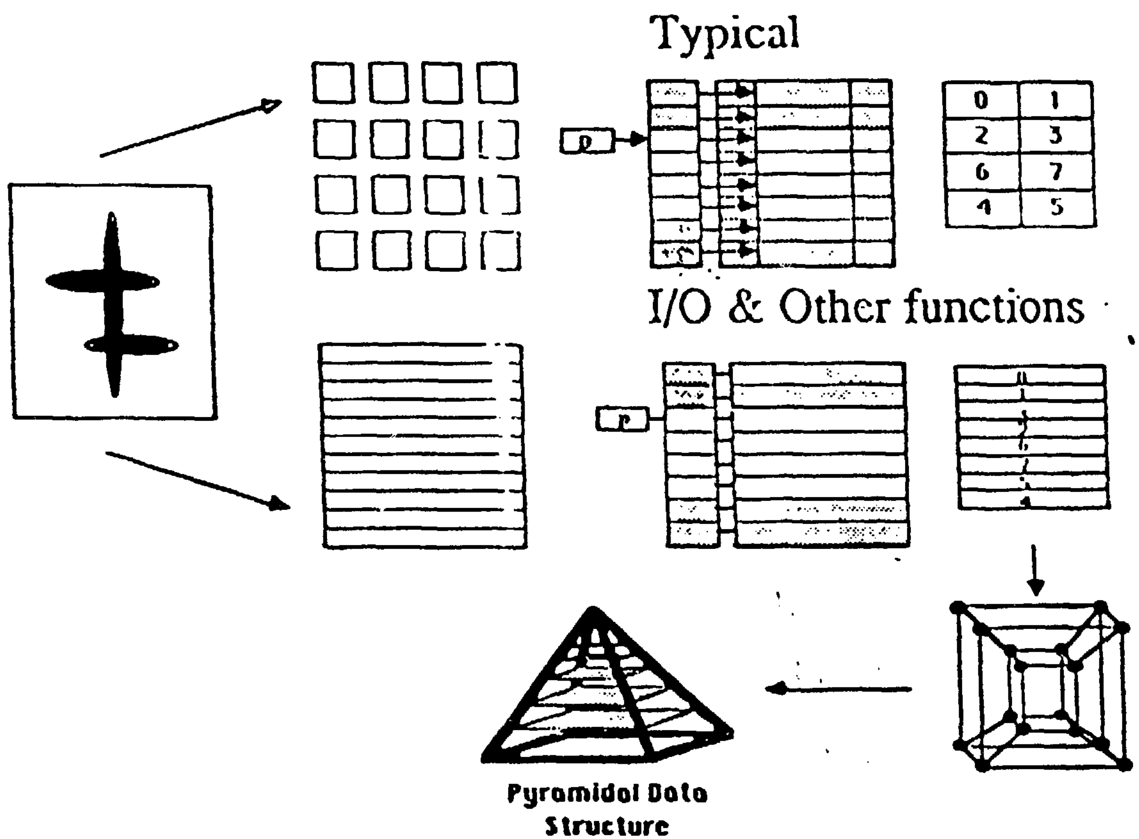
- has demonstrated utility in a variety of applications
- has proven to be scalable to relatively large machines

Key Properties

- Multi-resolution data structures
- Several domain decompositions
- Transparent & Efficient I/O
- Transparent Typing
  (Indirect Code Generation)

A Concurrent Image Analysis System

Domain Decompositions



A CONCURRENT IMAGE ANALYSIS SYSTEM

APPLICATIONS

On-board mobile robots	Burks, et al. (1987); Weisbin, et al. (1990)
Multi-spectral texture analysis	Huntsberger & Huntsberger (1989)
Dynamic scene analysis	Soh & Huntsberger (1989)
Object recognition for mobile robots	Jones (1988)
Multiresolution image analysis	Christensen & Jones (1989)
Spatio-temporal image analysis	Christensen (1989)
Concurrent algorithm development	J.P. Jones (1988); Bowyer, Jones, &Lake (1989)
Wavelet representations	Huntsberger & Huntsberger (1990)
Multisensor integration	Jones, Beckerman,&Mann (1989)
	Beckerman, et al. (1992?)
Image restoration (mean field annealing)	Hiriyanniah, Bilbro, Snyder, Mann (1989)
Parallel I/O	Embrechts & Jones (1990)

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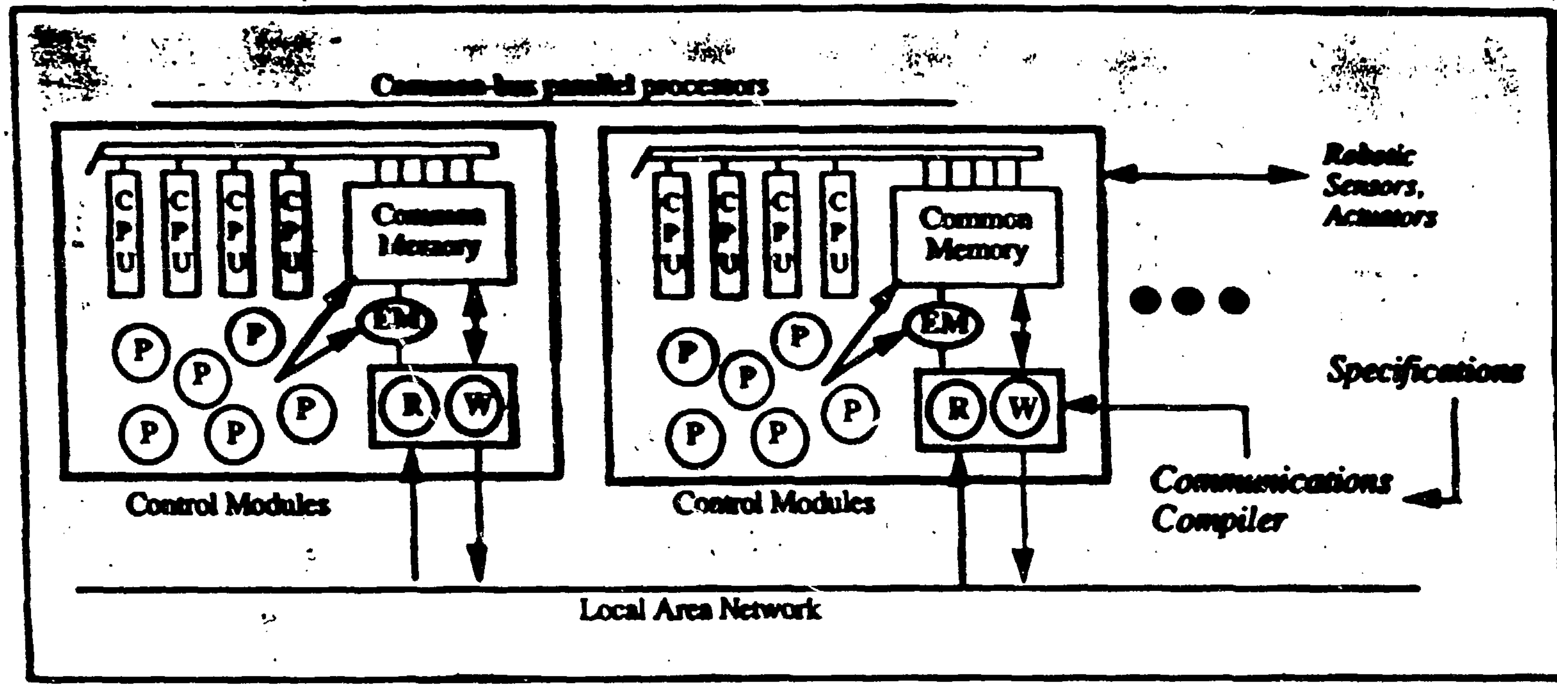
Parallel Computing Environment for Robotics



Scalable, integrated software development and maintenance environment

- reduces time and cost in development, integration, and maintenance
- supports real-time, synchronous and asynchronous control systems
- supports heterogeneous distributed-memory computer networks

Summary

CESAR performs research and development of intelligent machines with particular focus on cross-cutting research issues with high impact on a number of application areas.

Research areas include multiple cooperating robots; multi-sensor fusion; mobile manipulator systems; real-time qualitative reasoning; machine learning; and embedded high performance computing.

CESAR leads a university/industry consortium that addresses specifically the development of robotic systems for nuclear power stations.

Transfer of CESAR R&D products into applications has significant impact.

CESAR Robotics and Intelligent Systems Research for Nuclear Environments*

Reinhold C. Mann**

ABSTRACT

The Center for Engineering Systems Advanced Research (CESAR) at the Oak Ridge National Laboratory (ORNL) encompasses expertise and facilities to perform basic and applied research in robotics and intelligent systems in order to address a broad spectrum of problems related to nuclear and other environments. For nuclear environments, research focus is derived from applications in advanced nuclear power stations, and in environmental restoration and waste management. Several programs at CESAR emphasize the cross-cutting technology issues, and are executed in appropriate cooperation with projects that address specific problem areas. Although the main thrust of the CESAR long-term research is on developing highly automated systems that can cooperate and function reliably in complex environments, the development of advanced human-machine interfaces represents a significant part of our research.

The objective of this paper is to review recent results of research and development at CESAR, with particular emphasis on activities targeted at robots for nuclear environments.

I. INTRODUCTION

The Center for Engineering Systems Advanced Research (CESAR), sponsored by the Engineering Sciences Program of the Department of Energy (DOE) Office of Basic Energy Sciences, represents a unique core long-term basic research program in intelligent machines (Fig. 1). CESAR research includes studies in multiple cooperating robots; multi-sensor data analysis and fusion; control of mobile robots and manipulators, including methodologies that incorporate reactive behaviors; machine learning; and embedded high performance computing.

The CESAR laboratory with its mobile robot prototypes (HERMIES-IIB, HERMIES-III, and a new experimental platform, Figs. 2, 3), robot manipulators, and computer network 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). A number of applied research and development programs support activities at CESAR. These include among others robotics for advanced reactors, a program for which we perform applied robotics research, systems integration, and provide overall coordination and management of a consortium of four university research groups (Florida, Michigan, Tennessee, Texas); and robotics for environmental restoration and waste management.

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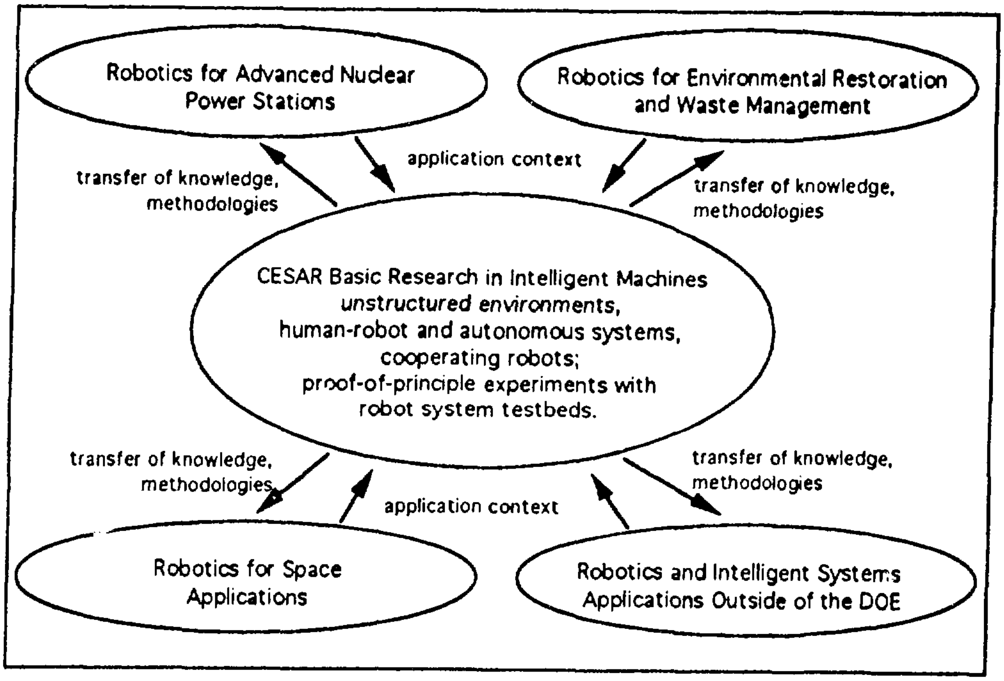

Figure 1: CESAR research and development context.

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]

Facilities that support experimentation and proof-of-principle demonstrations with robotics equipment include three mobile robot prototypes, a redundant degrees-of-freedom robot manipulator mounted on a mobile robot, multiple CCD cameras, a laser range camera, additional robot sensors, such as tactile and proximity sensors, a graphics and other high performance computer workstations, as well as several multi-processors, including hypercubes, and one iWarp mesh-connected parallel processor. Human-machine interface research makes use of our Cognitive Engineering Research Laboratory which is equipped with eye-gaze tracking hardware and appropriate tools to analyze eye-gaze data collected with human subjects who are requested to perform various cognitive and process control tasks.

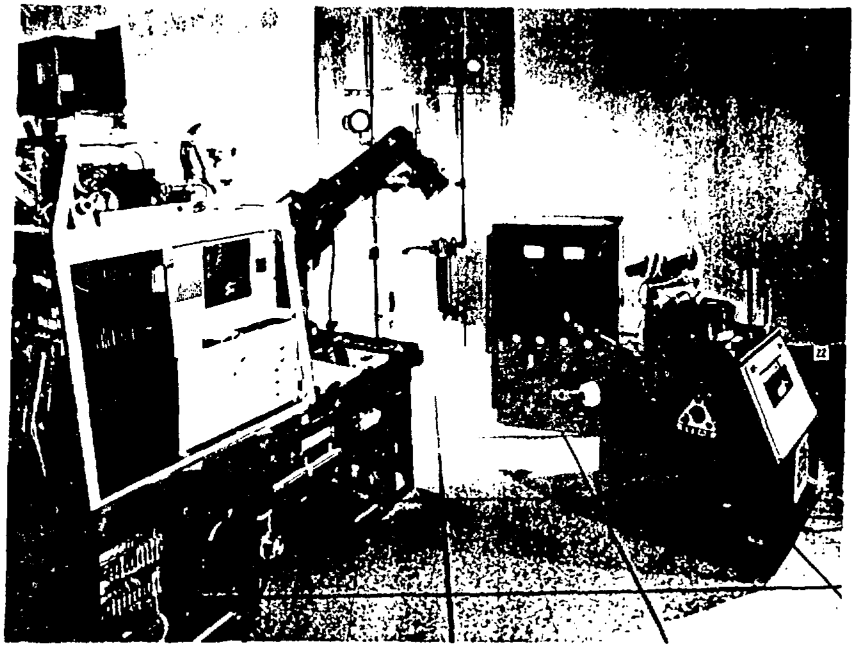

Figure 2: Two CESAR mobile robots, HERMIES-IIB (right) and HERMIES-III (left).

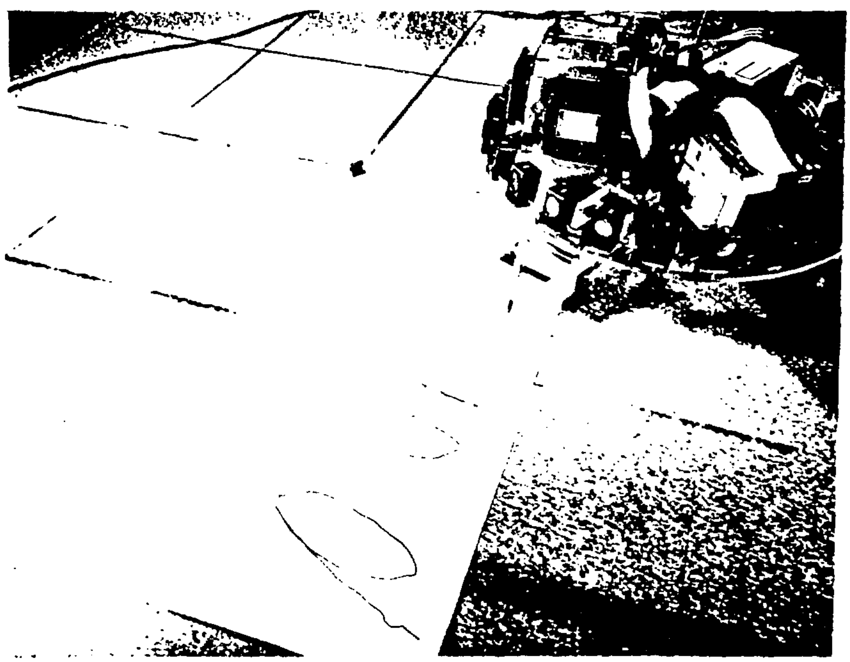

Figure 3: New fully omni-directional mobile platform[8].

The use of robots in existing nuclear power stations is on the rise. Recent data[9] show that in 1990 about 30 utility companies used robots for more than 60 different routine tasks in nuclear power stations in the U.S.A. These systems are all tele-operated with only limited levels of automation. A closer look at the nature of tasks performed by these robots shows that they are used predominantly (more than 75%) for surveillances and inspections that do not require any manipulation that involves hard-contact motion control. Clearly, many priority maintenance tasks that have great potential for reducing worker exposure when executed tele-robotically, require the capability to manipulate tools and devices through hard-contact motion. The technology required to accomplish these goals is being developed and demonstrated at CESAR and other laboratories. Accelerated transfer of this work into fieldable systems is being pursued.

The purpose of this paper is to summarize selected CESAR research results, previously reported in the open literature. Some of the material is excerpted, often verbatim, from the referenced publications.

II. CONTROL OF COOPERATING MANIPULATORS

For robots to be able to perform maintenance tasks they have to be able to effectively control hard-contact motions. It is also necessary to make effective use of more than one manipulator in order to provide an alternative to often expensive fixturing or special tooling, especially in facilities that were not originally designed for the use of robotic devices.

A rigid body dynamical model an control architecture were developed for the closed chain motion of two manipulators holding a rigid object in a three-dimensional workspace[4].The manipulators can be structurally dissimilar, including different numbers of joints. Dynamic and kinematic constraints were determined and combined with the equations of motion of the manipulators to obtain a dynamical model for the entire system in joint space. A functional relation for the generalized contact forces exerted on the shared load was developed and included in the model. An in-depth analysis of the model led to the development of a new control architecture that allows to decouple the force- and position-controlled degrees of freedom during motion of the system. The proposed composite controller enables the designer to develop independent, non-interacting control laws for the force and position control of the complex closed chain system.

III. MOBILE MANIPULATION

Mobile robots equipped with manipulators are of increasing interest to a number of applications arising in hazardous environments; e.g., nuclear power stations, environmental restoration and waste management; and in other areas, such as space exploration applications. These mobile manipulation systems can significantly improve productivity and safety of important material handling and other manipulation tasks.

The combination and coordination of the mobility of an autonomous platform with the robotic motion of a manipulator represent challenging analytical and practical problems. Among those is the resolution of the kinematic redundancy associated with practical mobile manipulators.

CESAR researchers have developed and tested new methods for redundancy resolution that optimize the robotic system's position and configuration when changes occur in task requirements and constraints[1]. Optimization criteria include obstacle avoidance, maneuverability, manipulability, and several torque functions. Extensive testing of the methodologies using our HERMIES-III robot is underway.

IV. NAVIGATION OF CAR-LIKE ROBOTS

For many practical robots it is not realistic to assume that they can move unconstrained as if they were point objects in two-dimensional space. Car-like robots, for example, cannot follow arbitrary paths due to their kinematics. In addition to obstacle avoidance and other criteria, path planning for such robots has to satisfy two constraints: a lower bound on the radius of turn, and a non-holonomic constraint. When the robot is not circular in shape, precise maneuvering implies working in the configuration space of the vehicle. The complexity of the problem has led to compute-intensive methods, and hardly allows for real-time applications.

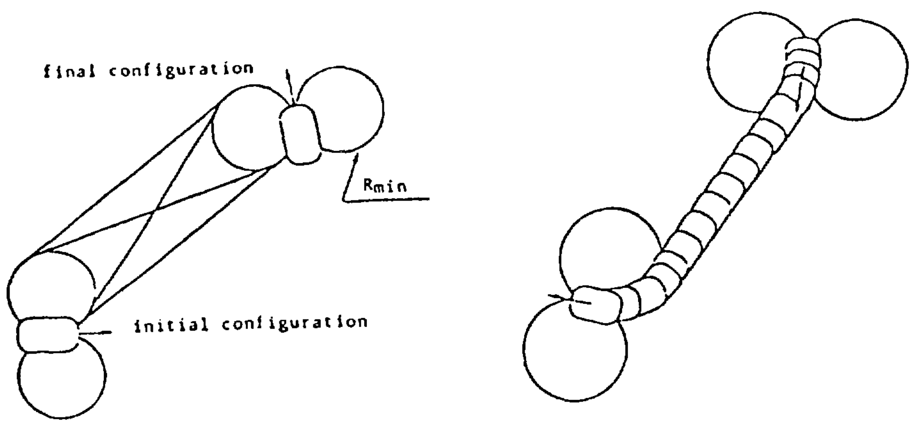

Figure 4: Path planning for car-like mobile robots.

CESAR researchers have developed a method for rapidly computing the possible maneuvers of car-like robots operating within convex polygonal workcells[3]. In such cells, maneuvering can be handled with geometric reasoning. The method allows for precise computation of the maneuvers using the whole configuration space, since only a few boundary configurations have to be checked to avoid collision. More general workspaces can be handled by means of a graph connecting adjacent convex cells. The graph is searched in order to determine the cells that have to be traversed to find a path to the goal. Intermediate configurations are then computed inside the intersection of each pair of adjacent cells. Finally, the trajectories generated inside each cell are assembled to produce a collision-free path.

V. BEHAVIOR-BASED CONTROL OF ROBOTS

CESAR research in control architectures has been directed recently at investigating combined or hybrid approaches that include both high-level and behavior-based control methods. In the process, a real-time qualitative reasoning capability to support robotic operations of mobile platforms[2] was developed.

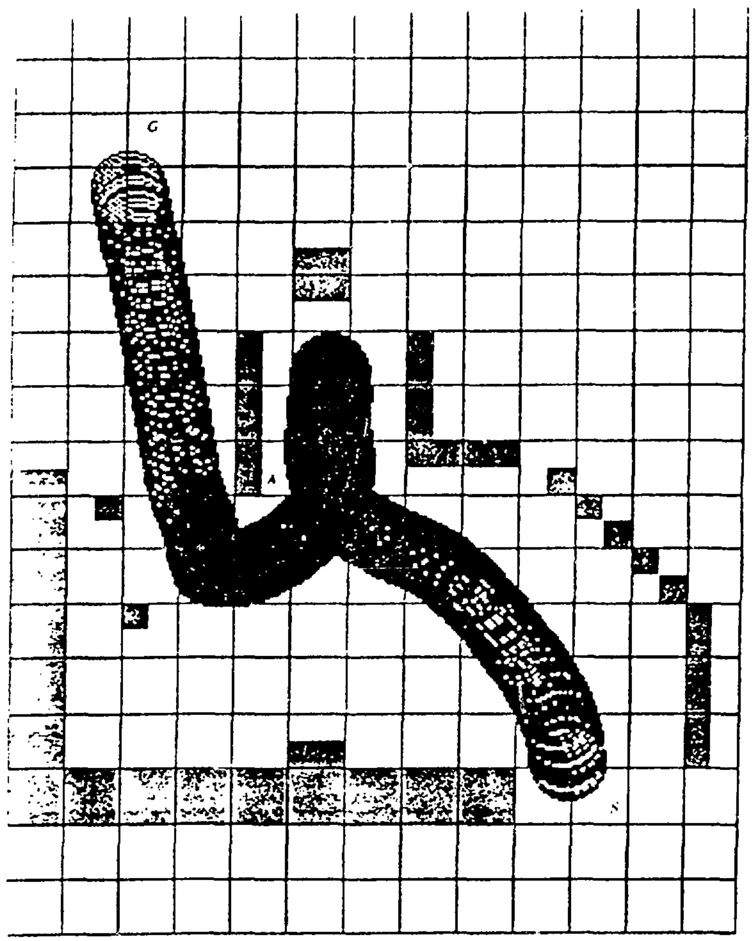

Figure 5: Sample run of the platform illustrating obstacle avoidance and the capability to exit potential traps.

In collaboration with researchers at the University of North Carolina, VME-compatible computer boards were developed including VLSI fuzzy logic chips. The boards allow full inferences with up to 350 rules and 28 sensor input channels to be executed at a rate of 30 kHz. The boards were installed in a VME-based computer system on-board the new CESAR mobile platform (Figure 3) and was used to demonstrate behavior-based navigation with as few as 13 rules in an unknown environment (see Figure 5).

VI. MACHINE LEARNING

Intelligent machines must learn from and adapt to their environment. For environments with little pre-defined structure, learning is a most difficult, yet essential, task. Most information is sensor-based and active sensing must be possible in order to create and continuously update a model of the robot's surroundings. One major issue in this machine learning task is the development of appropriate representations for the concepts to be learned.

CESAR researchers have investigated the use of random set representations for probabilistically approximately correct (PAC) learning, and reported significant improvements in learning speed[7]. In addition, they investigated the performance characteristics of a system consisting of N learners combined by an algorithm that can integrate the knowledge generated by the individual learners[10].

Given a system of N probably approximately correct (PAC) learners, a method was developed that allows for the design of a fuser such that the composite system performs better than the best of the individual learners (Figure 6).

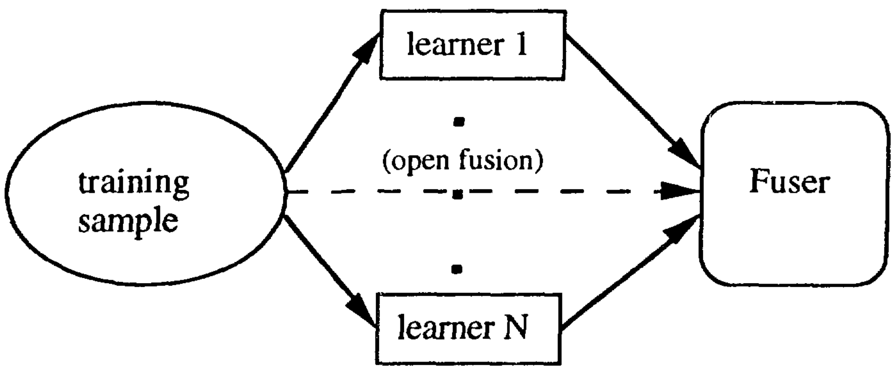

Figure 6: N-learner fusion of knowledge.

This can be accomplished under certain conditions on the individual learners and the fuser as well as on the hypothesis space. These conditions have been determined analytically. This work represents a development that benefits many applications of machine learning, e.g, identification of parameters that govern complex processes, adaptive pattern recognition systems, and others. The results are expected to have considerable impact on the important problem of designing systems consisting of multiple, relatively simple agents that cooperate in some way in order to solve problems of realistic complexity. Examples include crews of multiple mobile robots, each capable of executing relatively simple behaviors or other control algorithms and some form of adapting their behavior through learning.

VII. INTEGRATED TECHNOLOGY DEMONSTRATIONS

Part of the CESAR research is addressing issues that arise when the technologies developed in our programs are integrated in robot testbeds and prototypes in order to demonstrate increasingly complex capabilities.

We have recently demonstrated the application of the highly automated mobile robot HERMIES-III to perform surface contamination surveys of waste storage containers[11], as part of reducing hazards to humans involved in waste facilities operations (see Figure 7). For this experiment the robot was controlled in tele-robotic mode under supervision of a human operator. Many functions, such as path planning, navigation with local obstacle avoidance, range image analysis to locate the waste storage containers, control of the seven degree of freedom CESAR manipulator on-board HERMIES-III, positioning of the platform so that the robot end-effector holding the beta-radiation detector could scan the container surface, were executed automatically.

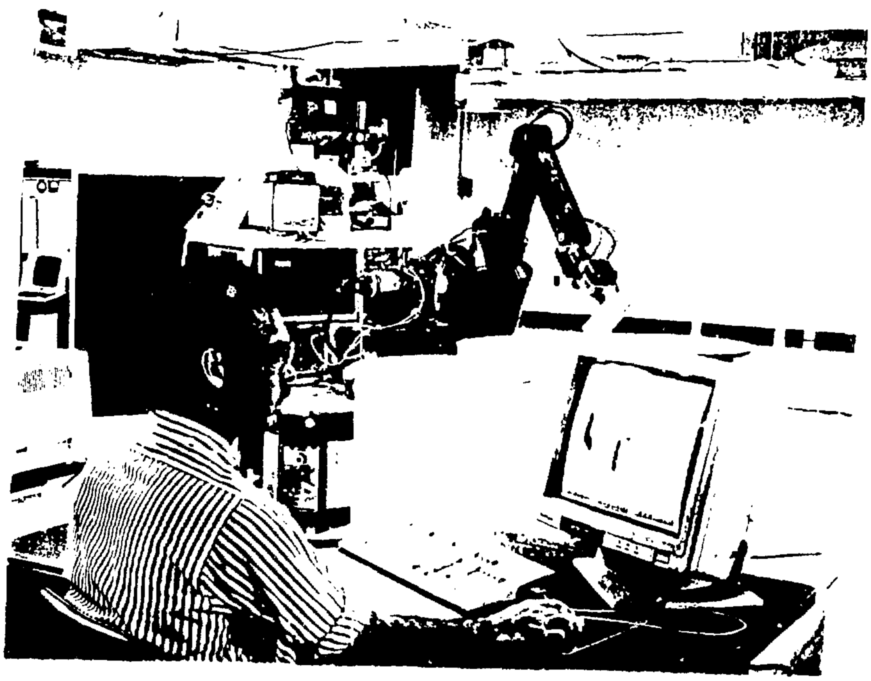

Figure 7: HERMIES-III performs contamination survey of waste storage containers.

This experiment was the result of collaborative research with four university teams (the universities of Florida, Michigan, Tennessee, and Texas). It involved the integration of over 100,000 lines of software running on a total of 27 CPUs on- and off-board HERMIES-III in a heterogeneous network. The integration was made possible by the Helix programming environment developed at CESAR[6]. Helix simulates shared memory on a heterogeneous network of computers. The machines in the network can vary with respect to their native operating systems and internal representation of numbers. Helix was designed to present a simple programming model to developers, and also considers the needs of designers, system integrators, and maintainers.

VIII. SUMMARY

This paper summarized previously published research and development results obtained by a number of activities underway at ORNL Center for Engineering Systems Advanced Research. The Center encompasses long-term research in intelligent machines with particular focus on cross-cutting research issues with high impact on a number of application areas. Research areas include multiple cooperating robots; multi-sensor data analysis and fusion; control of mobile robots and manipulators, including methodologies that incorporate reactive behaviors; machine learning; and embedded high performance computing. The Center also includes applied research and development that benefits from the ability to rapidly transfer results from the basic research program.

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