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Proposal for Continued Research in Intelligent Machines at the Center for Engineering Systems Advanced Research (CESAR) for FY 1988 to FY 1991

C. R. Weisbin

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CESAR

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Engineering Physics and Mathematics Division

PROPOSAL FOR CONTINUED RESEARCH IN INTELLIGENT MACHINES

AT THE

CENTER FOR ENGINEERING SYSTEMS ADVANCED RESEARCH (CESAR)

FOR

FY 1988 TO FY 1991

C. R. Weisbin

Center for Engineering Systems Advanced Research

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ABSTRACT

This document reviews research accomplishments achieved by the staff of the Center for Engineering Systems Advanced Research (CESAR) during the fiscal years 1984 through 1987. The manuscript also describes future CESAR objectives for the 1988-1991 planning horizon, and beyond. As much as possible, the basic research goals are derived from perceived Department of Energy (DOE) needs for increased safety, productivity, and competitiveness in the United States energy producing and consuming facilities.

PROPOSAL FOR CONTINUED RESEARCH IN INTELLIGENT MACHINES AT THE CENTER FOR ENGINEERING SYSTEMS ADVANCED RESEARCH (CESAR) FOR FY 1988 TO FY 1991

C. R. Weisbin

I. INTRODUCTION AND BACKGROUND

For a few years prior to 1984, there had been a growing awareness and belief that automation related technologies and intelligent machines should play an increasing role in Department of Energy programs. This trend was stimulated by a number of technical studies and conferences which concluded that automation technology can, to a large degree, increase the productivity and safety in the development and operation of DOE sponsored systems. Therefore, DOE management decided in FY 1984 to initiate a research program to extend the body of knowledge underlying current engineering practice and satisfy perceived future requirements in the area of intelligent machine research. In support of these DOE objectives, the Oak Ridge National Laboratory established the Center for Engineering Systems Advanced Research (CESAR) for the purpose of addressing fundamental problems of intelligent machine technologies.

A. Purpose and Objectives

The purpose of this document is to review CESAR research accomplishments in FY 1984 to FY 1987 and to outline our goals for continued research for the FY 1988 to FY 1991 planning horizon, and beyond. As much as possible, the plan is based on anticipated DOE needs in the area of productivity increase and safety to the end of this century.

B. Characteristics of Intelligent Machines

Intelligent machines, as envisioned in this plan, are artificially created operational systems which have capabilities of autonomous decision making and action. These capabilities are derived from their ability to reason based on acquired information and to learn from experience. Intelligent machines are able to govern themselves in accomplishing given objectives, as they manage their own resources and maintain their integrity. At the highest level of abstraction an operating intelligent machine consists of three elements.

1. Sensory System - The sensory system acquires data and information about the internal state of the intelligent machine, about its environment, and about its relationship to its environment.

2. Control Computer System - Based on newly acquired data through sensory input and/or a database (knowledge base) search, the control computer system assesses the current state of the intelligent machine system with respect to the desired goal state, continuously updates the database and existing plans, and performs a planning process which results in a set of decisions for immediate and/or future actions, for control and for recovery from errors and faults.

3. Actuator System - The implementation of the decisions prepared by the control computer system is carried out by the actuator system, resulting in sensible and measurable effects within prescribed and controlled operational limits.

The ultimate setting of goals for, and supervision of, intelligent machines is done by humans. For simple systems this may be done directly by setting a switch or the like. For complex systems, such as an autonomous robot vehicle, the goal setting and supervision may be done by a team of operators with the help of an off-line or integrated computer system. The human operator(s) together with the supporting computer system and other peripheral equipment are collectively referred to as the "supervisory system". In general, one is dealing with a hierarchy of intelligent machines, where the higher level (echelon) elements are the supervisors of collections of elements at the next lower level. By extension, at the highest level in the hierarchy is (are) the human operator(s).

II. SCOPE OF THIS PLAN

The long-range research and development program of CESAR is shaped and directed primarily by prioritized research and available resources. The technical scope of this plan comprises not only the intelligent machine systems with various hierarchical levels, but also the automation of the corresponding supervisory systems, including the behavior of humans within man-machine systems. It also includes those aspects of related systems engineering, systems designs and plant management that can be automated. "Peripheral technologies," such as data processing, power, propulsion, materials, structures, etc., are of concern here only to the extent to which they influence the operation of automated and intelligent machines.

The technology areas selected for research are oriented along lines of perceived requirements for two operational focuses of roughly equal priority, and which provide technical context relevant to the energy industry. The first focus for the development of intelligent machines is "robotic systems for identification, navigation and manipulation in unstructured environments." The concept "robotic system" is interpreted as a system consisting of a remote part and a proximal part, the latter serves as the supervisory system and includes the human operator(s). Applications include work in toxic, radioactive or physically uncomfortable situations such as those for nuclear plant emergencies, off-shore oil exploration, gas exploration, etc. These situations are particularly unique and central to the mission of DOE. Potential benefits include reduced risk to humans in hazardous situations, machine replication of scarce expertise, minimization of human error induced by fear or fatigue, and enhanced capability using high-resolution sensors and powerful computers. There is a clear need for the expansion of the sciences and technology which would permit the exploitation of the capabilities of intelligent machines.

The second focus for the development of intelligent machines is "multi-purpose plant management and maintenance," where plant means an energy producing or consuming facility. The intelligent aspects include simulation, control, design, training, diagnosis, planning, repair and replacement. This system would have a design support subsystem allowing people to design plants, augment their models with feedback, perform simulations to evaluate alternative plant designs, diagnose problems that arise in operations, and set up training for people who are supposed to run the plant. The control portion of this system would utilize results of faster-than-real-time simulations to guide an actual running system which has to deal with real time operations. There would be automatic monitoring of instrumentation so that the system checks its behavior against expectations and audit trails of all control activities taken by the personnel. Faults occurring in the system would be analyzed and diagnosed. Based on such diagnoses, strategies and plans would be prepared for corrective action and would be implemented automatically or with the help of human supervision.

The two overall themes have much in common in terms of technological development, i.e., real-time control, "world" modeling, sensor understanding, reasoning with uncertainty, etc. During the previous period, FY 1984 to FY 1987, only the first theme has been explored.

III. THE CESAR PERSPECTIVE AND ROLE

A. The DOE/ORNL Context

ORNL is a multipurpose laboratory primarily working on energy problems under the auspices of the U.S. Department of Energy. ORNL is operated by Martin Marietta Energy Systems; the technical program is determined by agreements established between ORNL and DOE with concurrence of the Oak Ridge Operations Office and Martin Marietta Energy Systems.

ORNL is a world leader in the development and use of remote operations and handling techniques in hostile environments; the Laboratory has many years of experience in this area. Building on this know-how and strong analytical capability, ORNL developed a research proposal to DOE in the area of "intelligent control systems," which has emerged as part of the Engineering Research Program of the Engineering and Geosciences Division of the Office of Basic Energy Sciences. A peer review committee was formed, and a steering committee (subsequently transformed into a permanent advisory committee) was appointed. In addition, a DOE/ORNL Workshop on Research Goals and Priorities in Intelligent Machines was held on November 2-4, 1983.[1] The outcome of these activities has been the formation of the Center for Engineering Systems Advanced Research (CESAR). In addition to the CESAR Advisory Committee meetings, periodic reviews are held for the DOE Council on Energy Engineering Research. The latest of these reports of the Advisory Committee are provided in Appendix A.

B. The CESAR Charter

The Center for Engineering Systems Advanced Research (CESAR) is established at the Oak Ridge National Laboratory (ORNL) to address long-range energy-related research in intelligent control systems. These systems are intended to plan and perform a variety of tasks in unstructured environments, given only qualitatively specified goals. Building upon extensive experience in remote operations and human engineering, the Center provides a framework for merging concepts from the fields of artificial and machine intelligence with advanced control theory. Emphasis is on interdisciplinary research for large-scale distributed processes applicable to many energy-related technologies. Research objectives stress the optimization of energy efficiency and the minimization of associated risks in its production and utilization.

Potential applications include emergency situations, remote operations, resource exploration, transportation systems, and large-scale power generation systems.

CESAR is intended to be a national resource, and a major objective is to disseminate its accomplishments freely and comprehensively. Accordingly, results and technology are distributed through refereed journal publications, through the organization of specialists' workshops, and through the development of products which demonstrate concepts. CESAR cooperates with universities, laboratories, and industry, serving as a user facility to provide guests with access to modern computers, unique equipment, and a stimulating scientific environment.

C. Technical Discipline Areas of CESAR R&D

Within the scope of the CESAR Charter, various research elements are aggregated along disciplinary lines for program planning. The selected disciplines are those identified in the DOE/ORNL "Final Report on Research Goals and Priorities in Intelligent Machines," by the CESAR Steering Committee.[2] For each discipline its definition, evolution, importance to intelligent machines, and division into sub-disciplines are described. In addition, the nature and importance of research are discussed in relation to the energy industry and associated subareas.

The discipline areas for CESAR's intelligent machines research are:

1. Machine Intelligence and Advanced Computing;
2. Sensors and Vision;
3. Human-Machine Interface;
4. Mechanisms, Dynamics and Control; and
5. Cross-Disciplinary Research.

The first four areas are representative of the major subsystems of intelligent machines. The last area addresses fundamental questions of system modelling and integration. While the work of this research and development program is primarily motivated by fundamental scientific questions, it also aims to satisfy basic development needs of real operating systems of the energy industry.

IV. TECHNOLOGY RESEARCH AND DEVELOPMENT PLAN

It is expected that intelligent machines will play an important role in the development of future energy systems. The CESAR program thus directs its efforts toward assuring that future complex energy related projects are affordable and cost effective, creating and maintaining a competent and vigorous R&D capability in related technical disciplines at ORNL, and assuring the transfer of technology to the applications sector.

A. Programmatic Goals and Objectives

To assure that the stated general directions can be accomplished, the CESAR research and development activities encompass the following programmatic activities.

1. Fundamental research efforts will be sustained at the appropriate level to satisfy future demands and needs in machine intelligence and advanced computing; sensors and vision; human-machine interface; mechanisms, dynamics and control; and cross disciplinary research for intelligent machines.

2. Collaborative efforts in the above areas will be established with academic, industrial and government institutions to foster a free interchange of ideas, talents and capabilities.

3. Efforts will be sustained to understand continuing programmatic and technical needs in intelligent machine systems and technologies in the energy producing industry and to develop new approaches and to meet these needs.

4. Initiatives will be undertaken to identify unique energy related applications of intelligent machines to provide context and effective utilization for methods development at the component, subsystem, and system level.

5. Programmatic initiatives will be undertaken to establish an intelligent machine technology base that will be made available to support the development of new and more cost effective reliable an safe systems.

B. Technological Goals

In establishing the technological goals of this plan, the DOE/ORNL Final Report on Research Goals and Priorities in Intelligent Machines by the CESAR Steering Committee has been reviewed and used as a point of departure. Other considerations are projected availability of research personnel, laboratory space, equipment, funding, etc. Hence, to start with, the technical goals concentrate mainly on areas oriented towards robotic systems for identification, navigation and manipulation in unstructured environments, the first focus identified in Section II. Work on the non-overlapping areas of the second focus, multipurpose plant management and maintenance systems, will be phased into the CESAR program as resources become available.

The broad, long-term technical goals of this plan are to develop, within the next decade, the required science and technology for intelligent machines with capabilities to validate instructions from the supervisor(s) and reject those that would endanger the system's performance. Such machines would perform task planning to select satisfactory or optimal detailed plans for achieving high level goals, particularly in the presence of large environmental or system variations. The specific disciplinary goals are to develop the required technologies which will enable robotic vehicles with manipulators to operate effectively in unstructured environments representative of industrial facilities. Such technology involves the design and implementation of:

1. Machine Intelligence Systems with reasoning and advanced computation capabilities to do autonomous planning of robot operations within a domain of interest, and to solve problems which require a course of unforeseen actions as a result of operational requirements and/or self-diagnosis.

2. Sensors and Vision Systems, which can obtain the necessary data in a suitable fashion to identify and plan a safe path for travel and positioning, to select target objectives of interest, to identify and grasp objects safely, and to perform self-diagnoses.

3. Human-Machine Interface Systems, which make it possible for human operators to assume intimate control of the remote robotic system through realistic sensory feedback displays, proximal computer simulations, and effective control override capabilities.

4. Mechanisms, Dynamics and Control Systems, which allow robotic vehicles to negotiate obstacles such as stairs, doorways and the like, to move obstacles out of the way as required, to perform precisely controlled manipulation of objects, and to do manipulation tasks with high dexterity.

In addition, it is a goal of this program to develop cross-disciplinary techniques as required in support of the major, long range goals in selected areas such as identification and estimation, sensitivity and uncertainty analyses, specialized computer architectures, and theoretical foundations for system integration.

The center's current research objectives[3] include development of methods for real-time planning with sensor feedback, knowledge representation and decision making using neural networks, determination of concurrent algorithms for optimal implementation on advanced parallel computers, formulation of a learning theory for enhanced knowledge acquisition and interpretation, modeling of the dynamics of flexible structures, generation of automated sensitivity analysis for model simplification and parameter identification, formulation and testing of a comprehensive uncertainty analysis methodology, generation of a machine vision system based on principles of human vision, and inclusion of this research within a system integration framework encompassing concept demonstration and feasibility.

V. CESAR RESEARCH: PRESENT AND FUTURE

To provide a context for the subsequent discussion we first describe the particular machine which we are developing as a testing ground for our research results. It is the Hostile Environment Robotic Machine Intelligence Experiment Series (HERMIES).

A. The HERMIES-II Robot: Present

The current experimental focus of the CESAR program is the mobile system HERMIES-II.[4] William R. Hamel and Stephen M. Killough of ORNL's Instrumentation and Controls Division are the principal architects of HERMIES' evolution into a major research facility. HERMIES-II is a low-cost system developed for initial CESAR experimental activities with autonomous sensor-based robotic systems for use in unstructured work environments. Although limited in its basic performance capabilities, HERMIES-II incorporates mobility and manipulation as well as recently improved sensory feedback functions.

1. Description

HERMIES is a self-powered mobile robot system comprising a wheel-driven chassis, dual-manipulator arms, on-board distributed processors, and a directionally controlled sensor platform. HERMIES-II[4] is propelled by a dual set of independent wheels having a common axle alignment and driven by separate direct-current (dc) motors.

The on-board computer and electronic equipment are located in an enclosure mounted above the drive chassis, and the dual-arm manipulator torso is located above the computers and electronics. The manipulators are five-degree-of-freedom (DOF) units manufactured by Zenith/Heathkit and used on the HERO home robot. The torso assembly for the arms also includes a shoulder pitch motion for each arm and a base for single-shoulder rotation. The two-arm shoulder assembly has a total of thirteen DOF, and all axes are driven by stepping motors controlled directly by the Z8 microprocessor dedicated to manipulator control.

Sonar scan data are preprocessed on board HERMIES and then transmitted via a 2400-baud RS-232 radio link to either the NCUBE or LMI Lambda computers for navigation planning. A ring of five sensors, each of which consists of a phased array of four Polaroid transceivers, using sonar allows for a narrow effective beam width and rapid sonar. The original stepping motor drives for the sensor pan-tilt control have been replaced with high-speed dc servodrives to permit the sonar ring to be stepped quickly. Consequently, the time required to scan a 180^{o} region in front of HERMIES has been reduced from 80 to 7 s.

The dc servodrive of the tilt platform has been designed to accommodate not only the sonar array but also an infrared range detector and dual Sony miniature charge-coupled-device (CCD) black-and-white cameras. The CCD cameras are part of an image-processing system obtained to incorporate computer vision into HERMIES' sensor suite. The overall system is an International Robomation/Intelligence P-256 unit, which

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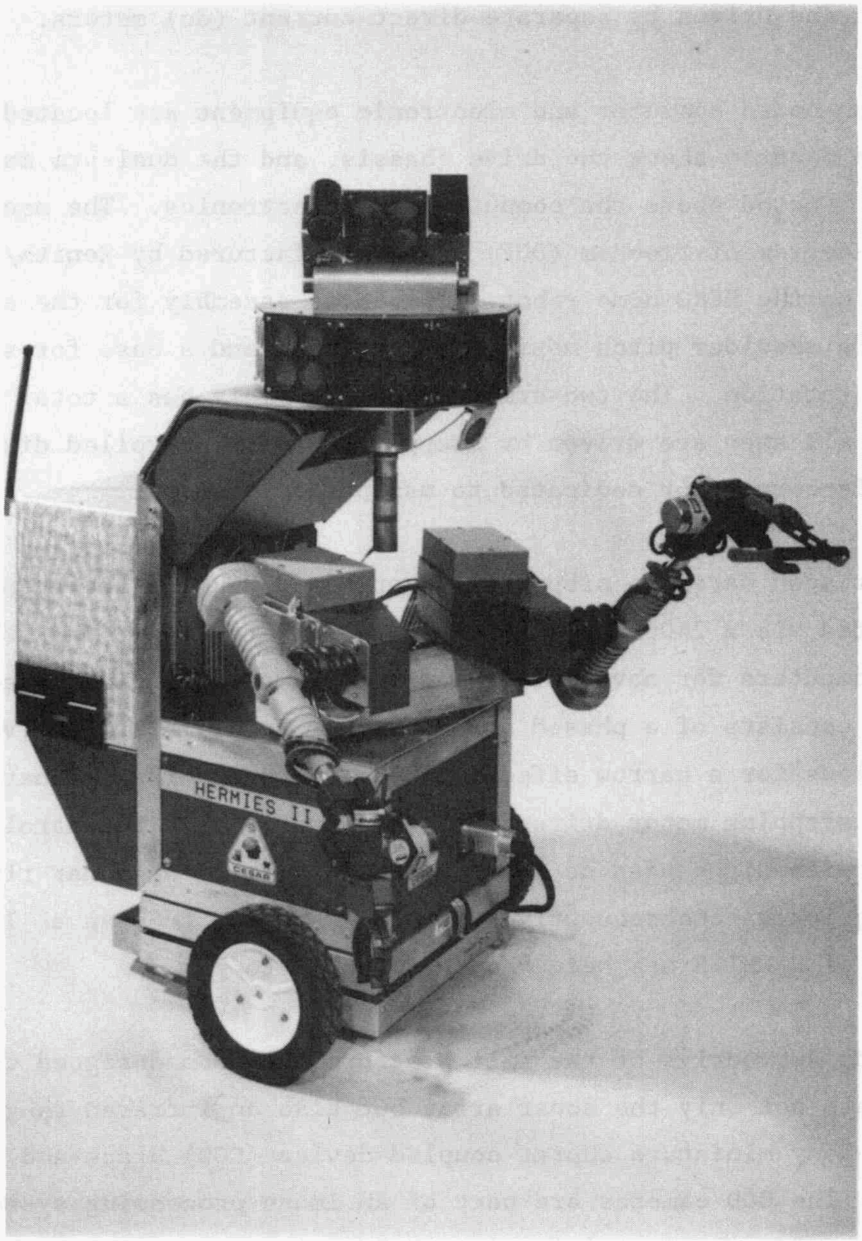

Fig. 1. The HERMIES-II Mobile Robot Developed at CESAR to Test Concepts of Autonomous Navigation, Real-Time Control and Machine Learning.

provides a pixel array of 256 x 256 spatial resolution with 8 bits characterizing possible brightness levels and an integral systolic array processor for reasonably high-speed execution of standard image operations. Much of our current image-processing research is being developed on our 64-node NCUBE hypercube parallel processor, in anticipation of a summer 1987 target by which 16 NCUBE nodes (computational power roughly equivalent to 24 Vax 11/780s) should be mounted on-board HERMIES-II.

2. Control System Architecture

The current HERMIES-II control system consists of a main microcomputer and a satellite microprocessor. The main microcomputer is a single-board computer based on the Intel-8088 microprocessor and the IBM PC backplane. It controls an on-board 320K byte floppy disk drive and passes commands to a Zilog Z8603 single-chip microcontroller, which performs the robot's manipulator control functions. Parameters are passed from the 8088 to the Z8 via a 9600-baud serial link. The dual wheels of the robot are driven independently by two gear-head dc motors that provide a linear speed of 0.154 m/s (0.5 ft/s). HERMIES-II's position is open-loop controlled through the on-board 8088 by real-time monitoring of the wheel encoders and on-off control of the drive motors.

The 8088 microcomputer uses the polyForth operating system and the Forth computer language. Forth is a flexible language designed for control applications, combining the ease of high-level programming with speeds approaching that of an assembly language. Forth word definitions have been used to construct a HERMIES command language for controlling the basic functions of the robot. The radio link is used to issue these commands to the on-board 8088 in a direct ASCII format. As an example, the Forth word command "2 0 FMOVE" causes the robot to move forward 2 ft (0.6 m).

B. HERMIES: Future

HERMIES-II is being upgraded to a new form called HERMIES-IIB. This upgrade will involve improvements to the robot's mobility chassis and on-board computational resources. These modifications will improve reliability as well as increase the degree of "self-contained" autonomy (i.e., dependence on other immobile computers replaced with VME and IBM-AT backplanes in combination). The VME system provides all control and sensor data interfacing and utilizes a Motorola MC-68020 32-bit microprocessor as the basic robot control engine. The VME system also serves as a data gateway to the AT backplane which houses a 4-th order (16 nodes) hypercube parallel computer based upon the NCUBE Corporation 32-bit node processor chip. The on-board hypercube provides the equivalent processing speed of approximately 24 VAX/11-780 processors. The VME system facilitates the on-board integration of a reasonably high-performance computer vision system using DataCube Corporation expansion boards which provide 384 x 512 x 8 color resolution and traditional image processing functions. It is believed that HERMIES-IIB will represent one of the more computationally powerful mobile robots in operation. The system diagram for HERMIES-IIB is shown in Fig. 2.

Initially, HERMIES-IIB will be used to replicate earlier navigation and path-planning experiments with full autonomy. Subsequently, a new set of experiments involving combined manipulation and mobility will be performed. In these experiments, HERMIES-IIB will use on-board vision and an optical guidance/control scheme for manipulator positioning to operate a "simulated" process control panel. The process control panel will consist of two analog readout meters, two slide-type analog input adjustments, and four back-lighted push buttons. The discrete logic and continuous dynamic models which interconnect and drive these inputs and outputs will be implemented with an IBM-PC. Upon finding and establishing position reference with respect to the panel, HERMIES-IIB will "operate" the panel to establish the system output states specified in his original task goals.

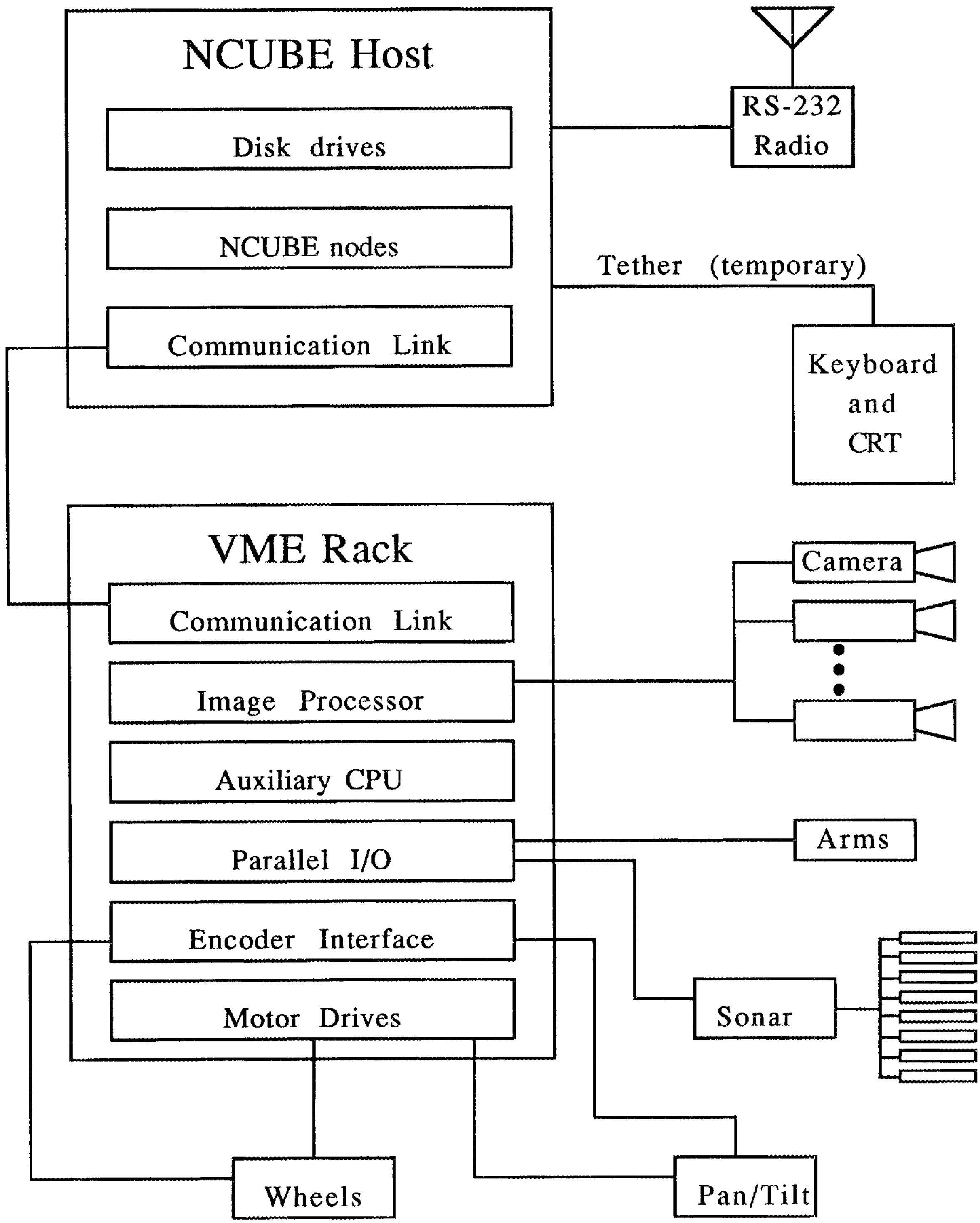

Fig. 2. HERMIES-IIB System Architecture

The mechanical performance specifications set for HERMIES-IIB is given in the following table:

Table I. Mechanical Performance Specifications for HERMIES-IIB

Running Time:	1.8 hour @ 100% Duty Cycle
Speed:	2 ft/sec = 1.36 mph
Acceleration:	2/3 ft/sec^2
Overall Size:	24"W x 24"D x 30.5" to top of turret
Min. Turning Radius:	19.2"

CESAR is actively pursuing the next phase of research in which the scale of operations will be increased into the realm of human sizes in terms of manipulation geometry and loads. To accomplish this the HERMIES-III robot is being designed and fabricated. HERMIES-III will be an electric-powered robot which incorporates the CESAR research manipulator (described later in Section F) and a shoulder/torso mechanism mounted on a modified industrial automatic-guided vehicle (AGV) chassis. Initially, only a single manipulator will be installed, but provisions for adding a second arm at a later date are included. The CESAR research manipulator is a human-scale arm with about a 1.4 m reach, 10-15 Kg load capacity, and no-load tip speeds approaching 200 cm/s. In this configuration, HERMIES-III will be capable of handling relatively large loads from floor level to approximately 2 meters off the floor.

HERMIES-III will utilize the combined VME/68020 and hypercube assembly discussed above. The sensor suite will include a five-element sonar ring, a DataCube vision system with two CCD cameras, and a laser range scanning system. HERMIES-III will have 3D optical scanning capability and conventional sonar ranging with additional 2D TV scanning.

C. MACHINE INTELLIGENCE AND ADVANCED COMPUTING

This section first discusses our research in intelligent machine navigation, autonomous learning from earlier traversals, and studies for coping with unanticipated events. Beginning in Section 7, the research in concurrent computation, operating systems, task scheduling, load balancing, and neural networks is discussed.

The CESAR research in intelligent-machine navigation is currently led by Charles Jorgensen and Gerard de Saussure, supported by Ron Fryxell, Donna Jollay, Sitharma Iyengar, Nageswara Rao, Robert Ricks, Deanna Barnett, Moshe Goldstein, and Francois Pin.[5-7] Collision avoidance algorithms fall roughly into two categories: (1) if the position of an obstacle is known, the algorithms mathematically attempt to find optimal paths satisfying obstacle constraints and (2) if the position of an obstacle is unknown, environment-navigation algorithms are usually of the generate-test-move variety in which a tentative path is proposed and tested for potential collisions. The move is executed if no collision is detected; otherwise, a new tentative path is generated.

1. Sensory Feedback

Robot sensors include stereoscopic vision systems; fixed and mobile sonar range finders; laser range finders; touch, stress, and torque sensors; and collision detectors. Particular attention has been given at CESAR to the sonar systems used extensively for HERMIES-II navigation. Low-cost sonar devices function by sending a multifrequency sound pulse outward from a transducer in a cone-shaped wave front. The difference between time of emission and time of return is measured and an estimated distance calculated on the basis of how far the wave could travel in one-half the period measured.

Several well known difficulties occur when a robot uses sonar information to construct spatial distance maps from different scanning positions. First, sonar is sensitive to temperature changes. For example, if a sonar were calibrated at 27^{o}C (80^{o}F) and the actual room temperature were 16^{o}C (60^{o}F) a measured range of 11m (35 ft) would be overestimated by 19.8 cm (7.8 in.) simply because of the temperature difference. Second, sonar is vulnerable to specular reflection and interacts with the texture of materials. The detectability of reflected sonar depends on signal energy and frequency. Frequencies useful in medical imaging are not practical for robotics. An example of this effect occurred in our early experiments using robot manipulators that attempted to grasp polyurethane foam blocks having extremely high sonar absorbency. For all intents and purposes, the blocks become sonar invisible. Other sonar problems result from the typically broad (35^o) conical shape of the sonar beam.

A sonar map made by a robot in the CESAR Laboratory (see Fig. 3) illustrates some of these effects. Current work at CESAR involves exploring the use of edge finding with vision image processing and laser range finding as well as sonar.

2. Navigation Control in Unexplored Terrain

It is not always easy for a robot to recognize a problem situation. Consider a simple maze problem (see Fig. 4) in which the robot is given this control algorithm. When in a new area, first turn toward the goal you wish to reach. Take a sonar reading to see if the path is clear. If a path is clear, move. If it is not clear, take the first open path on either side of the line. Go one-half the distance to the goal. When you arrive at that location, turn toward the goal and repeat the process.

At first glance, such an algorithm would appear usable. The clear path nearest to an ideal straight line is always the one taken. The half-distance criterion also ensures that if the robot is far from the goal, it will move to it rapidly and will make smaller, more careful moves as it gets closer. However, the robot has no memory. As Fig. 4 shows, the robot's goal is directly on the other side of the wall. If the robot follows the initial algorithm, it will scan the corridor and

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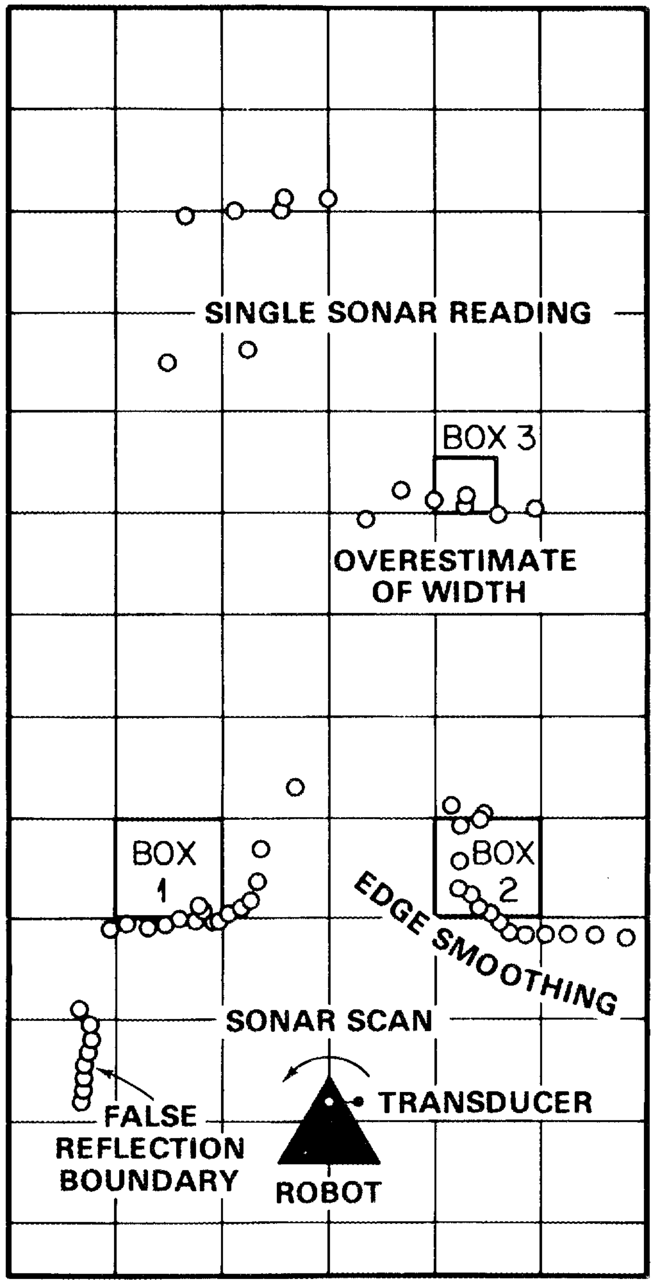

Fig. 3. Sonar Recognition of Simple Obstacles

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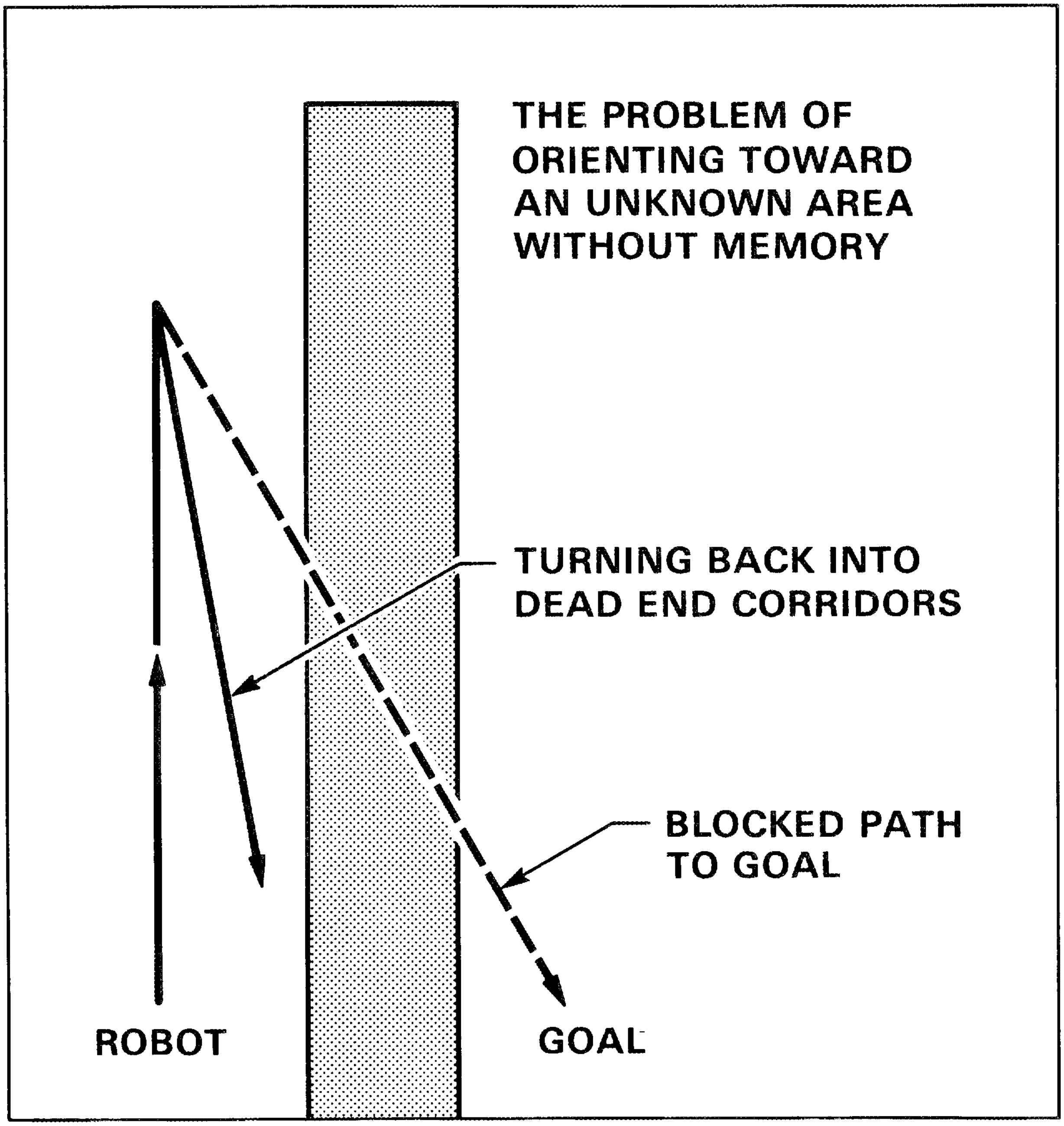

Fig. 4. The Need for Memory

after about a 90^{o} left turn, find the first open path halfway to the goal. The robot will begin to move up the corridor away from the goal. After a short distance, the robot will be far enough so that half the distance can be traveled by making a turn back toward the goal. What happens? The robot again moves into the dead-end corridor. In other words, without memory, the robot would loop recursively and never reach the goal. With a memory, previously blocked areas can be designated "off limits" for a time, gradually squeezing the robot out of dead-end situations. Still other problems occur when navigation environments change quickly over time. Traversal may require continuous creation of new goals because unexpected obstacles invalidate previously formed navigation plans.

3. Learning During Autonomous Navigation

Ideally, an autonomous vehicle should collect information about its local environment and at the same time build or modify a global world model that can be useful for more general purposes. Iyengar[7] et al., have developed a method that enables a mobile robot to select and navigate paths in unexplored terrain while systematically acquiring information about the terrain as it navigates.

Learning begins by classifying information about the space a robot explores. Figure 5 illustrates four independent traversals about obstacles whose locations were unknown to the robot before it begins. Traversals are represented using spatial graphs that map the history or robot obstacle-avoidance movements onto a two-dimensional coordinate system composed of edges (the paths traveled) and nodes (stopping points, turning points, or path intersections). The spatial graph provides a real-time data structure to record past movements; however, it is not efficient for planning future movements because no data are retained about the shapes of obstacles, about areas of the room requiring further sensory analysis, or about regions that are clear for maneuvering. Thus, a second type of graph structure called a Voronoi diagram is used to

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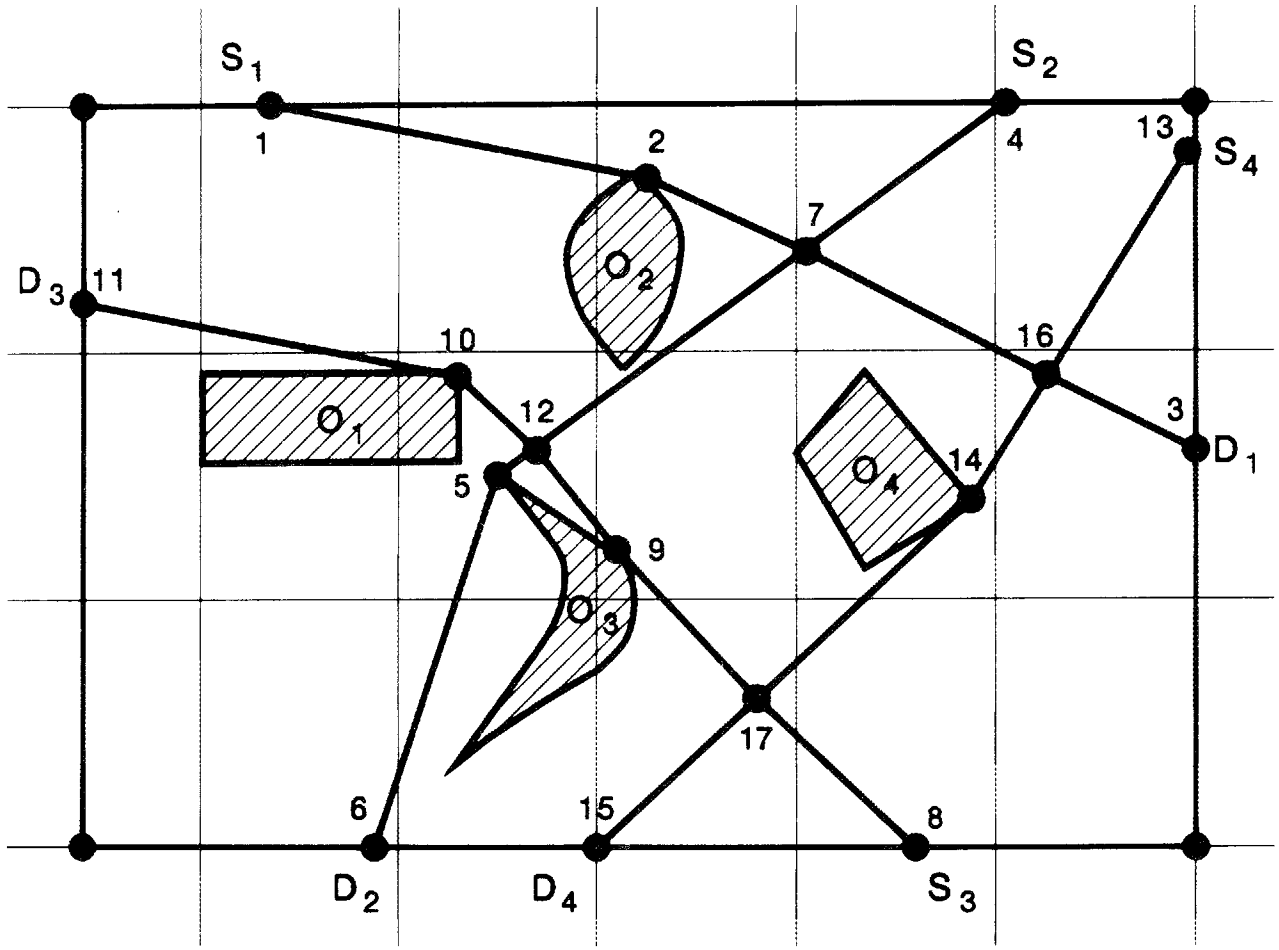

THE TERRAIN

Fig. 5. Four Traversals Completed From Starting Points (S_i) to Destinations (D_i) Around Obstacles (O_i) Using Sensor-Based Navigation.

bound obstacles using polygons that can subsequently be labeled and associated with higher-order learning processes.

Consider determination of a new path from source point S_5 to destination D_5 as in Fig. 6. A virtual source point S_5^1 and destination D_5^1 are found from the Voronoi diagram corresponding to the nearest graph node points from the four previous explorations. The paths from S_5 to S_5^1 and D_5^1 to D_5 are determined using localized sensor-based navigation.

The polygon P_2 contains the source end of the line $S_5^1D_5^1$. The region P_2 is scanned using the sensor, and the polygon P_2 is partitioned into the regions P_2^1, P_2^2, and P_2^3 as in Fig. 7. The regions P_2^1 and P_2^3 are free polygons, and the region P_2^2 is an obstacle polygon with respect to the vertex S_5^1. At this point, the source end of $S_5^1D_5^1$ is contained in the polygon P_2^2. The robot navigates along the obstacle boundary nearest to $S_5^1D_5^1$ arriving at intersection S_5^{11}. Next the path $S_5^{11}D_5^1$ is planned. As illustrated in Fig. 8, the polygon P_3, which was previously unexplored, is partitioned (using sensor data) into the regions P_3^1, P_3^2 and P_3^3. P_3^1 and P_3^3 are free polygons and P_3^2 is an obstacle polygon. At this stage P_3^1 contains the source end of $S_5^{11}D_5^1$; the path $S_5^{11}D_5^1$ is directly traversed. The final leg from D_5^1 to D_5 is traversed using sensor-based obstacle avoidance. The final spatial graph of the terrain is given in Fig. 9. Note that the obstacles O_2 and O_4 are bounded by smaller polygons than shown in Fig. 5. Also, the polygons P_2^1, P_2^3, P_3^1 and P_3^3 are declared to be free polygons. Finally, regions P_2^3 and P_3^3 are combined to form a single free polygon. As more paths are traversed, more and more polygons are explored and the spatial graph is consolidated.

4. Real-Time Expert System Control of Mobile Robots

Ron Fryxell, Robert Ricks, Deanna Barnett, Donna Jollay, and Gerard de Saussure are exploring the feasibility of using the process intelligent control (PICON) package as a basis for decision making and robotic control.[8] This software package was written by LISP Machine,

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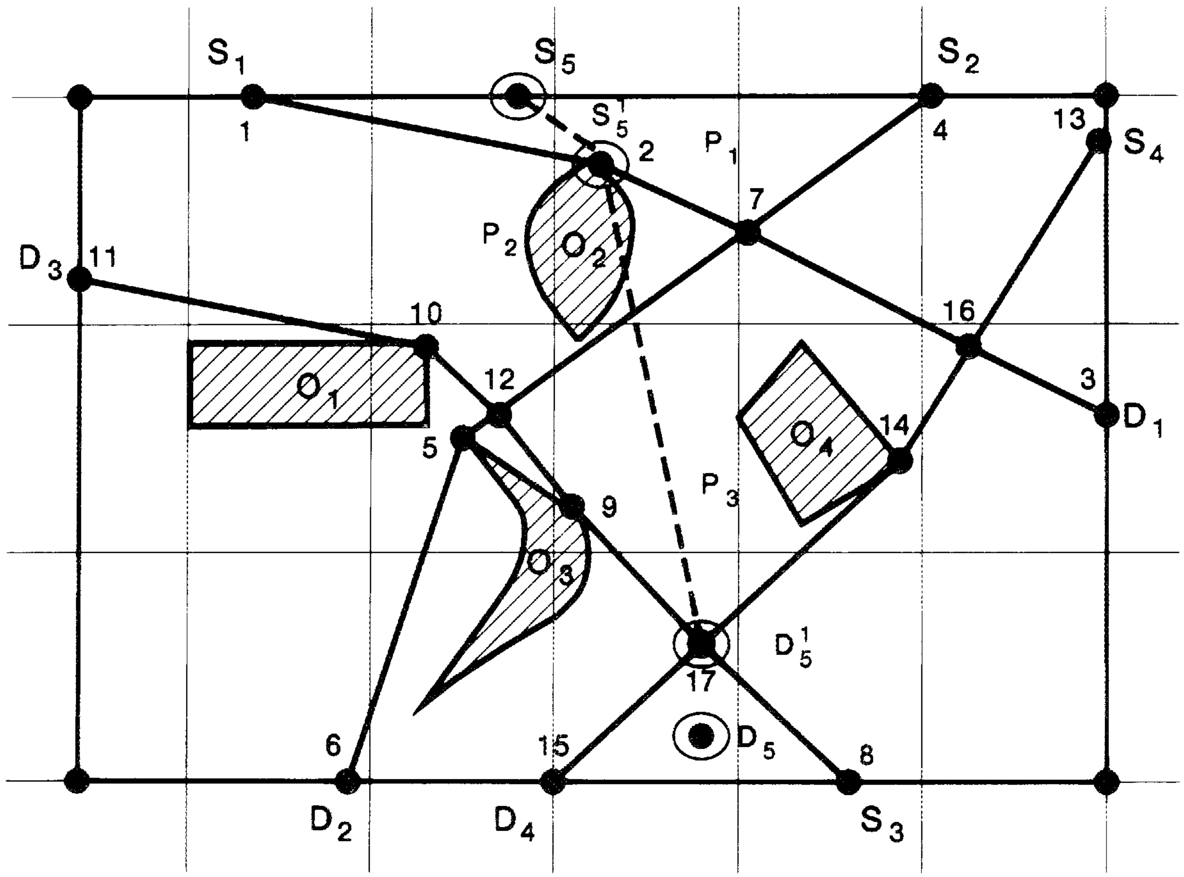

Fig. 6. S_5 Source Point D_5 Destination Point.

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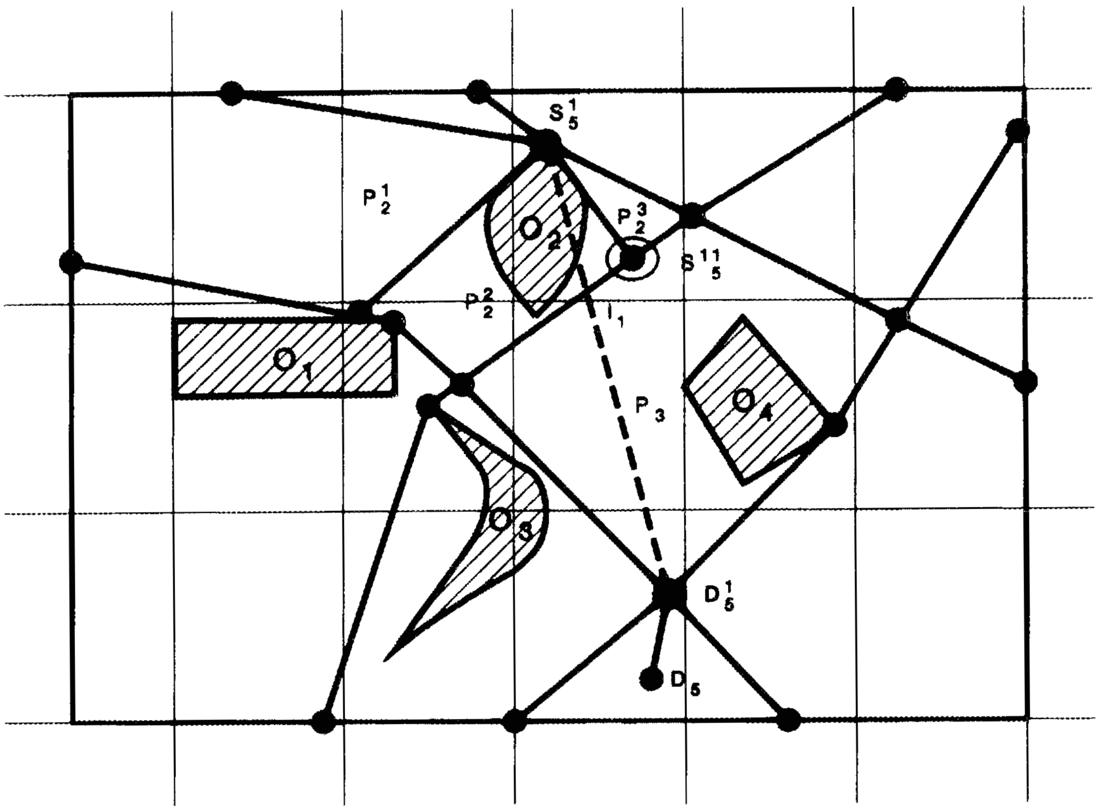

Fig. 7. Exploration of Polygon P_2

Source end of $S_5^1D_5^1$ lies in polygon P_2.

Polygon P_2 is explored.

P_2 is partitioned into polygons P_2^1, P_2^2, P_2^3.

P_2^1, P_2^3 - free-polygons.

P_2^2 - is an obstacle-polygon with respect to S_5^1.

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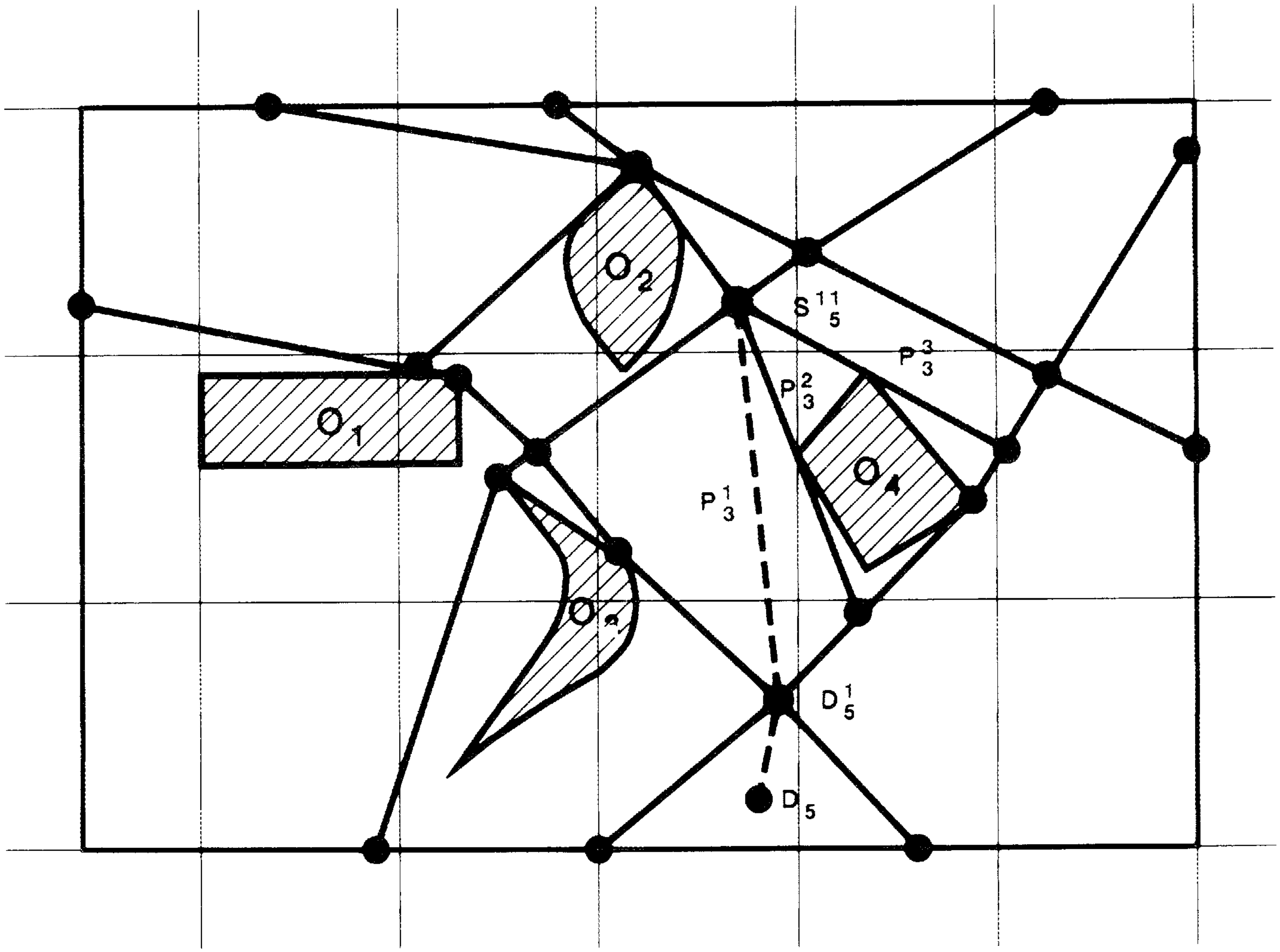

Fig. 8. Exploration of Polygon P_3.

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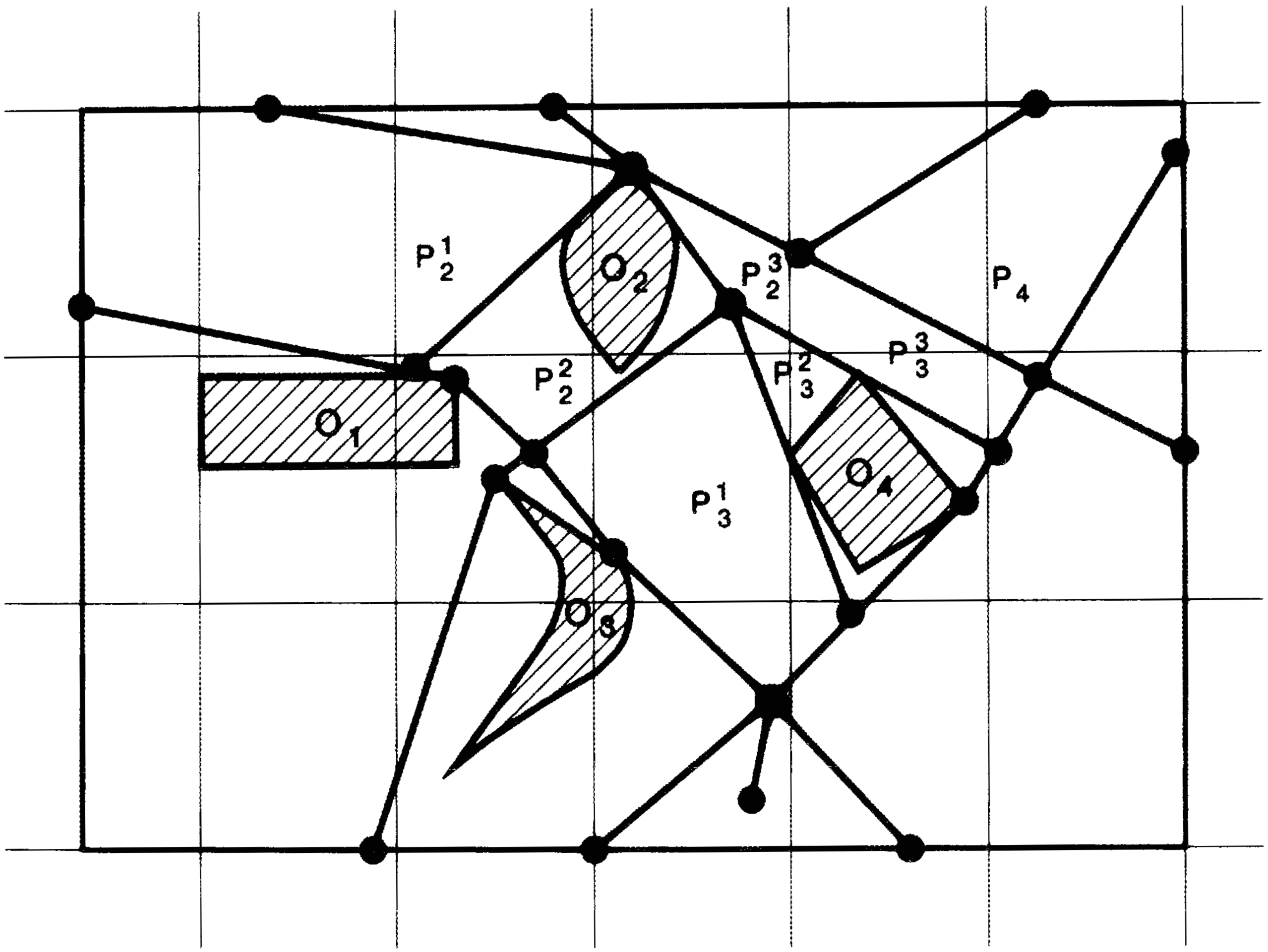

Fig. 9. Terrain Model After the Path from S_5 to D_5 is Consolidated.

Inc., for implementation on its Lambda machine, which includes a dedicated LISP processor running in parallel and asynchronously with a Motorola 68010 processor. The software is partitioned between PICON (the LISP expert system, which operates on the dedicated LISP processor) and RTIME (written in C and running on the 68010.) RTIME handles routine tasks such as communications with the robot, sensor data analysis, path planning, and unusual-condition sensing, and PICON handles the operator interface, status monitoring, operation sequencing, and problem diagnosis. RTIME continuously monitors the communication channels between it and PICON for commands and passes to PICON information on the status of its operations. In addition, RTIME passes information on unexpected occurrences deduced from sensor data to PICON to high-level analysis and waits for commands on how to intelligently react to these events.

An example navigation problem illustrates the use of the system. A navigation module written in C is made available to RTIME to be activated by a message from PICON. The module requests information on the robot's initial position, the goal position, the navigation algorithms to be used, and the command to proceed; these data are passed from PICON to RTIME.

In each forward movement of the robot, the front-fixed sonar is continually activated, and if it indicates an unexpected obstacle within 0.7 m (2 ft), the robot stops and reports the fact to RTIME along with the distance actually moved. RTIME stops the navigation algorithm, reports the situation to PICON, and waits for commands. PICON then requests information from RTIME about the unexpected obstacle: Two front sonar readings are taken at a fixed-time interval followed by a reading at a higher elevation. RTIME then passes this information about obstacle characteristics (for example, size and shape) to PICON. A diagnostic rule base in PICON is used to determine an appropriate action (see Table II).

Table II. Diagnosis and Action on Unexpected Obstacles

Obstacle Characteristic	Action to Take
1. Stationary and >1 m tall	1. Start the navigation algorithm from the current position.
2. Stationary and <1 m tall	2. Move forward to the obstacle, pick it up with the manipulator arms, put it to one side, and proceed to the original destination. Anything shorter than 1 m is guaranteed to be light enough to lift.
3. Has moved out of the way	3. Proceed to the original destination.
4. Is moving away from the robot	4. Wait for the obstacle to clear the path and proceed to the original destination.
5. Is moving toward the robot	5. Check to the left and right with sonar, if clear, move out of the way. If both sides are blocked, go back to starting position and recheck escape routes to left and right.

In this way, the robot can respond not only to a changed environment but a dynamically changing one as well. The system is easily modified to activate various robot responses and to accommodate a larger variety of sensors by simply modifying the diagnostic rule base and adding modules to RTIME. A simple robot navigation problem (and possible solutions using a PICON knowledge base of 32 if-then rules) is illustrated in Fig. 10.

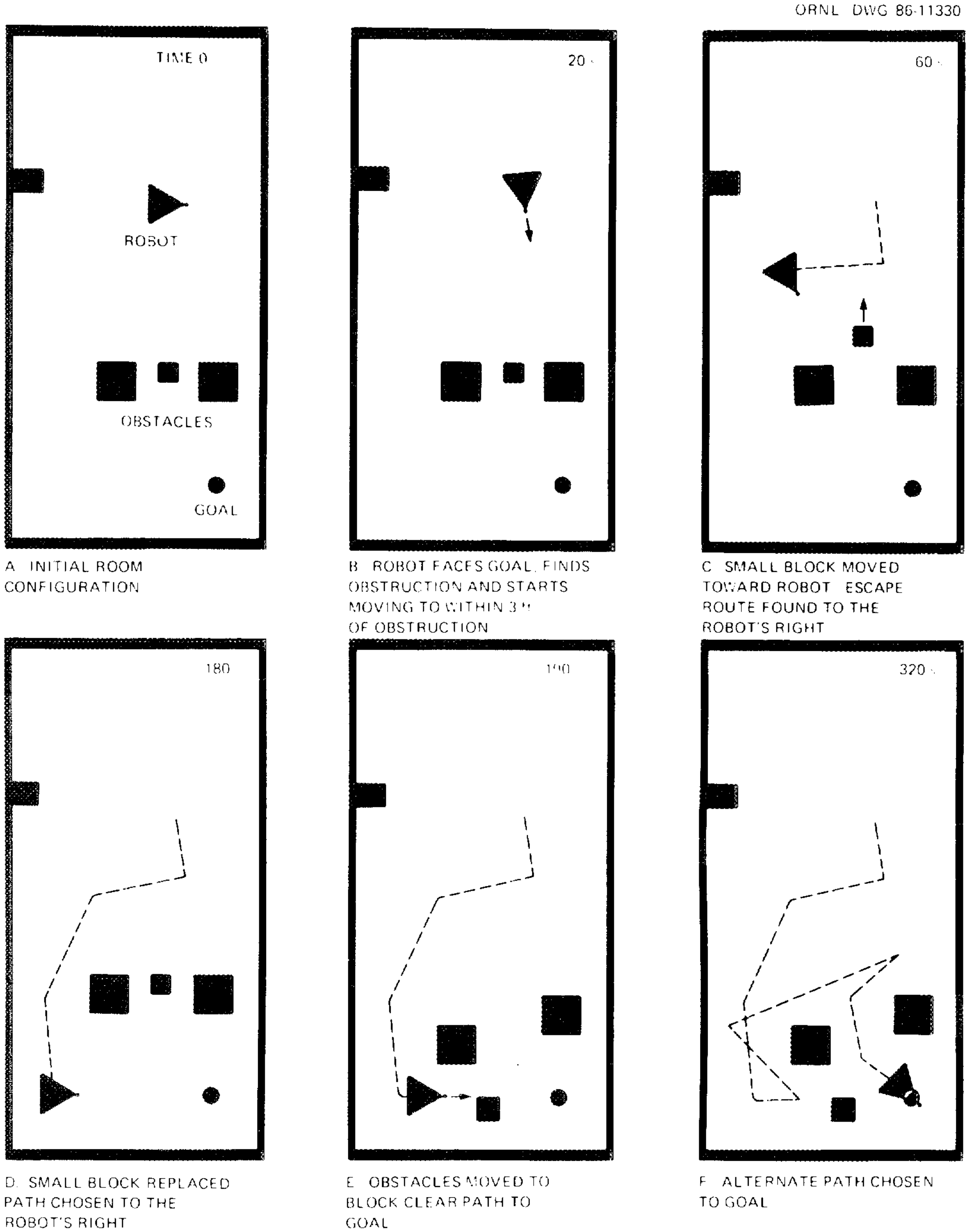

Fig. 10. Sample solution to a navigation problem involving a dynamic environment: (a) initial room configuration; (b) robot faces goal, finds obstruction, and starts moving to within 1 m of obstruction; (c) small block moved toward robot. Escape route found to the robot's right; (d) small block replaced, and path chosen to the robot's right; (e) obstacles moved to block clear path to goal; and (f) alternate path chosen to goal.

5. Robot Navigation Based on Electricity-Conduction Analog

In another CESAR approach toward navigation planning, Matthew Hall, formerly of ORNL's Engineering Physics and Mathematics Division, has used an electricity-conduction analogy. Obstructed squares are regarded as insulators, and clear squares are regarded as conductors. A potential difference is placed between HERMIES' current location and the goal, and HERMIES then proceeds along a path based on the line of maximum current density. When this path encounters an unobserved square, a sonar scan is requested, the world model is updated, and navigation continues. The main computational expense of this approach is incurred in computing the current density, which involves solving the Laplace equation. However, this calculation takes only a few seconds. This approach to path planning offers an alternative to heuristic approaches.

6. Intelligent Autonomous Navigation: Future Research

As was the case in the past few years, research in the next few years will in part be driven by a series of demonstrations where HERMIES performs progressively more difficult and more realistic tasks and increases its domain of competence. Eventually HERMIES must be able to navigate in a partially known, or unknown unstructured environment, search for a given object, such as a valve and perform a useful task such as closing or opening the valve, all autonomously.

For 1988 - 1989 the following scenarios has been defined as a goal-demonstration, as another interim step toward the overall CESAR paradigm problem.

Scenario:

HERMIES begins at one end of the lab area and moves toward a goal at the opposite end. Between HERMIES and the goal are obstacles which must be avoided; they may be either moving (people) or fixed (boxes). The goal will be a control panel. HERMIES finds the control panel, positions himself so that the panel may be read and manipulated and begins a diagnostic task. The task will consist of reading a series of status indicators on the panel (lights or control positions), determining what those positions signify (by examination of a series of pattern matching rules in the PICON database), and moving the manipulators to adjust the system status and correct for any abnormal condition. HERMIES will then return to the starting position. Research must be conducted toward making HERMIES manipulation and obstacle avoidance more robust. Algorithms must also be developed to perform systematic exploration and mapping of a three-dimensional area, and for recognition of an object of complexity equivalent to a control panel.

Modular hierarchical approaches are necessary to perform the tasks required in the demonstrations and to extend HERMIES domain of competence. At the present time some of these routines are tested with the expert system PICON acting as a high level decision maker. Since PICON is too bulky to be placed on board HERMIES and too slow for some requirements, the possibility of transporting some of the advantageous features of PICON to the NCUBE parallel computer will be investigated. This will likely include the development of a complete expert system designed to take full advantage of the parallelism of the NCUBE computer.

Future research will investigate several options for world modeling (see also section on world model development and updating in V-D-2-d). Different sensors such as vision, sonar, laser range finder, etc. provide different types of information about the environment and reflect directly in our robot's ability to characterize his world. Different tasks also require different type of world models: pattern recognition for instance can require a high level feature representation whereas navigation may best be accomplished with a quad-tree or combinatorial geometry world model. It is probably most efficient to construct a hierarchical set of world representations and to maintain some consistency between each representation. This will be one focus of our future research in this area. Much work on sensor fusion and world modeling has been done but much research is still needed to optimize performance in an unstructured environment, with a given set of sensors and a range of desired competence (see V-D-2-c).

Another effort which is underway is the development of an emulator for HERMIES; this software tool directly emulates HERMIES performance in that is receives input commands and sensor data in exactly the same format as the real HERMIES, and projects actions that HERMIES would respond with great fidelity. The tool provides the potential for implementing a faster-than-real-time response for review and supervision prior to execution. Differences between HERMIES actual response, and that of the emulator, invariably leads to better understanding of our intelligent machine.

Another area of continued research will be in studies of machine learning. The algorithms for learning based on spatial graphs and Voronoi diagrams will be tested experimentally, refined, and extended to three dimensions. New techniques based on methods of neural networks (to be elaborated upon below) will be explored. A major theme in the learning research will be to develop suitable approaches for HERMIES to monitor its own performance while attempting to increase the probability of successful task execution. Several methodologies exist which can serve as an initial starting point; these however have really only been successfully applied in structured tutoring which is highly interactive with a human supervisor. Event driven autonomous learning for unstructured environments remains a long-term basic research goal.

7. Advanced Computing

To enable a robotic system to work effectively in real time in an unstructured environment, a variety of highly complex mathematical problems, such as online planning, vision, sensor fusion, navigation, manipulation, dynamics, and control, must be solved. The computational requirements of these problems fall into the "supercomputer" class, but ultimately we need to solve them on board the autonomous robot. Jacob Barhen leads the CESAR effort in advanced computing to exploit concurrent computation,[9-13] including the capability to dynamically balance the computational load among all processors in the system. He is supported in this effort by Ralph Einstein, Edith Halbert, Benjamin Toomerian, Judson Jones, Reinhold Mann, Charles Glover, and Michelle Clinard.

a. Hypercube Ensembles

Hypercube ensembles refer to a multiprocessor design in which N ($= 2^d$) identical microprocessor nodes are connected in a binary d-dimensional cube topology; each processor has its own local memory and is connected to d nearest neighbors directly. Communication is performed by message passing; the furthest communication distance between any two processors in the ensemble is d. For illustrative purposes, a few hypercubes of low-order are shown in Fig. 11. A hypercube looks topologically identical from the point of view of each node: there are no corner-vs-edge or root-vs-leaf nodes as exist in regular grids or trees. This symmetry is particularly attractive for simplifying the dynamic reconfiguration of the system.

b. The CESAR NCUBE Hypercube

The concurrent computation system now being investigated at CESAR was developed by NCUBE Corporation (see Fig. 12). It contains 64 processors (6-d cube) in its initial implementation; the number of processors that can be accommodated is 1024, each designed to run conventional computer programs at about the speed of 1.5 VAX 11/780's. Each processor has 128K bytes of local memory (which can be upgraded to 512K/node) and can communicate directly with ten other processors through direct-memory access channels.

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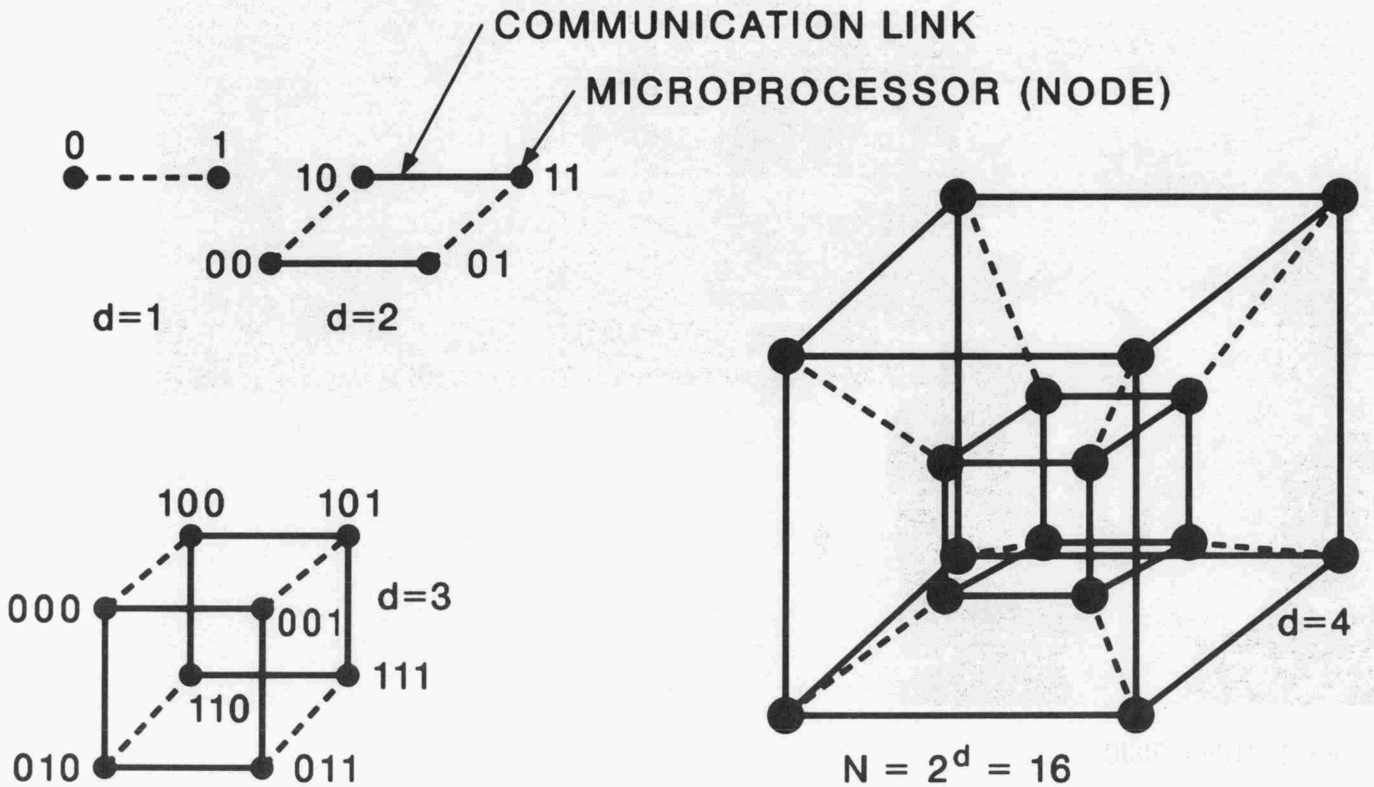

Fig. 11. Hypercube Architecture in d Dimensions. An Order-d Hypercube is Constructed Recursively from Two Order-(d-1) Cubes.

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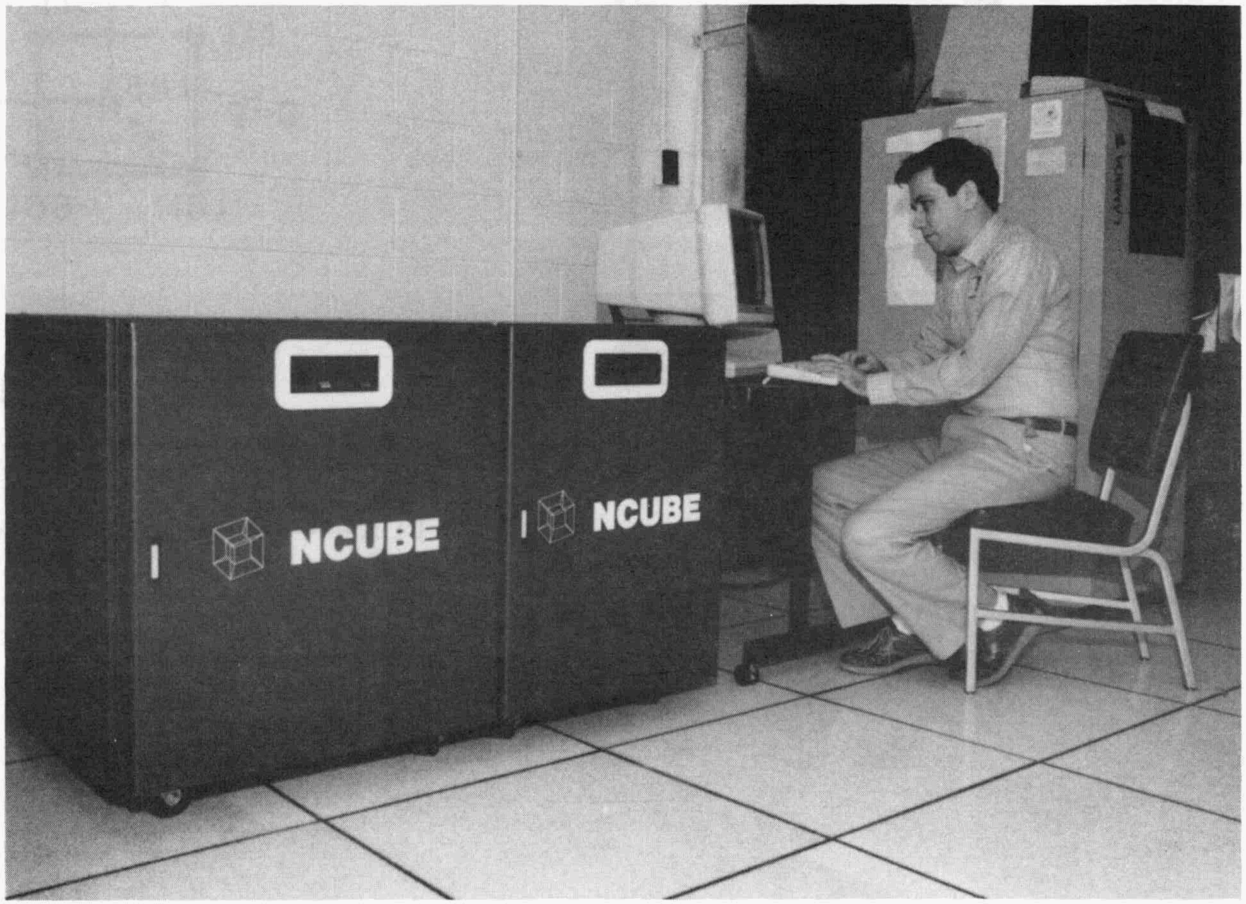

Fig. 12. Operating the NCUBE Concurrent Processor in the CESAR Laboratory for Machine Intelligence. Up to 1024 Processors can be Enclosed in the Left-Hand-Side Box.

The importance of this design for mobile robotics research is that when fully loaded, the hypercube has a capacity of approximately 500 million floating-point operations per second (500 Mflops) contained within a volume less than 1 m^3 (including cooling and power supply) with a power consumption of approximately 8 KW. The system can easily be scaled down for less demanding and compact applications (for example, 8 Mflops in something the size of an IBM PC AT). Compilers for Fortran-77 and C languages are available. The NCUBE node processor (see Fig. 13) is a complex chip of about 160,000 transistors that integrate a memory interface; communication links; and a 32-bit, general-purpose processor, including 32- and 64-bit floating point on chip.

c. Concurrent Algorithms for HERMIES Navigation

Matthew Hall originally developed the NCUBE software for driving HERMIES by partitioning tasks into separate processes. Each process can be executed in a different node on the array board except that processes requiring input-output (I-O) with the outside world must be executed on the controller board. Current HERMIES-II software includes six processes: (1) input of instructions from a terminal, (2) input of data from HERMIES, (3) output of instructions to HERMIES, (4) graphic display of the world model, (5) processing of sensor data and subsequent world modeling, and (6) navigation. Processes 1 through 4 must be on the I-O board, while processes 5 and 6 can be run on the array board. As the complexity of HERMIES sensor data and environment increase, it is anticipated that processes 5 and 6 will be split into many different processes.

d. Advanced Operating Systems with Embedded Reasoning: Future Research

The research in this area is a major long-term endeavor toward implementing machine intelligence through real-time control of a

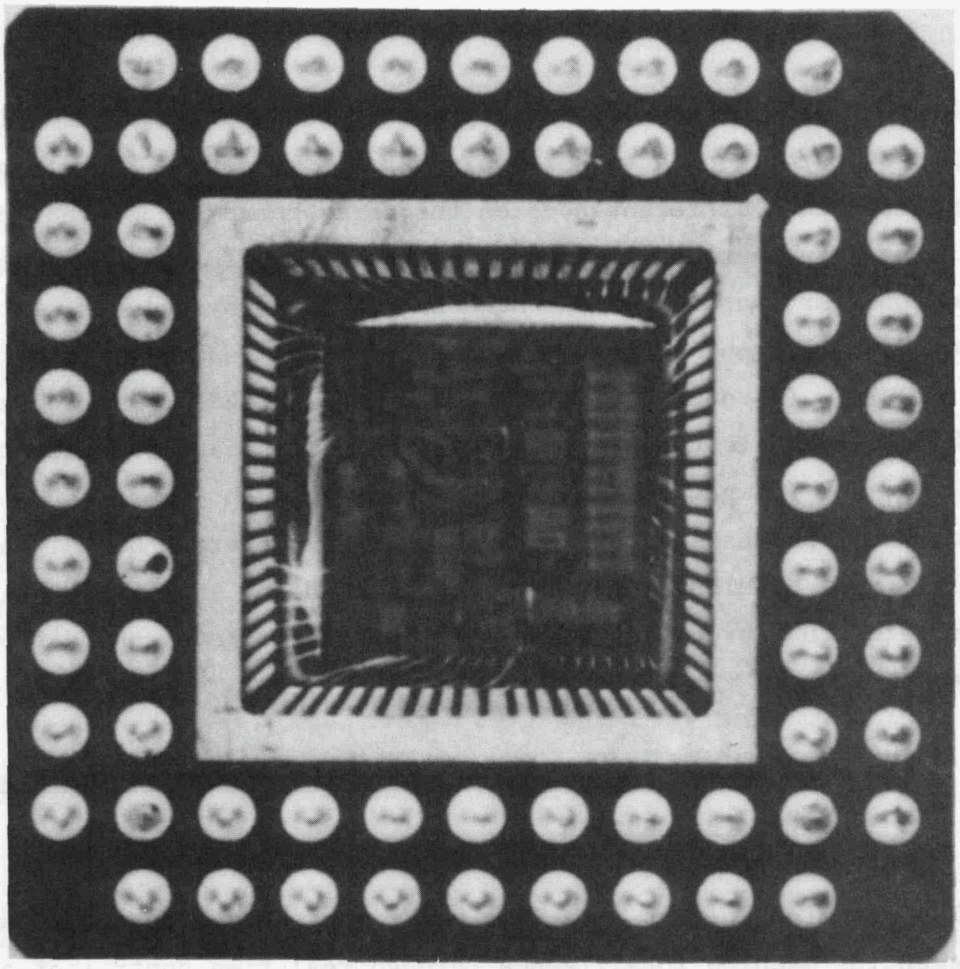

Fig. 13. The NCUBE Node Processor.

dynamically reconfigurable multiprocessor architecture. Reasoning and control functions are intimately associated with an operating system that provides for interrupt capability, priorities, communication, scheduling, and so on. This development includes all research in the four tasks discussed in the following subsections, and is of a long-term continuing nature.

- Treatment of Precedence Constraints (ROSES)

The robot operating system expert scheduler (ROSES) system[11] is being developed to schedule precedence-constrained tasks for computation by an ensemble of concurrent processors. This endeavor is particularly difficult when the number of tasks required exceeds the number of available processors or when the interconnection topology of the task graph differs from the interconnection topology of the computation ensemble. Multiprocessor scheduling has been studied extensively[14,15]; excellent reviews can be found in the literature. The task of multiprocessor scheduling is to determine the appropriate sequence of tasks for assignment to available resources given a number of tasks and their associated precedence constraints. The ROSES approach seeks near-optimal solutions by combining heuristic techniques to minimize scheduling time as a function of the number and relationship of tasks with data structures in order to meet efficiently use available computer memory and algorithms to control the search process and eliminate dead ends. Further research on ROSES involves development of the capability to permit task preemption and scheduling tasks with stringent execution deadlines.

- Hard-Real-Time Capabilities

Many tasks in intelligent autonomous systems are expected to have stringent execution deadlines. Such tasks are said to induce "hard-real-time" constraints on the system and present major difficulties in the design of the scheduling algorithms for a distributed operating system.

When previously unanticipated tasks, which must be completed prior to some absolute deadline; arrive at a processor node, methods must be developed to guarantee such compliance. The first attempt is to find an open window within the computation schedule already developed for that processor. If this attempt is unsuccessful, task shuffling within the schedule is considered (that is, a check to determine whether already scheduled nonperiodic tasks can be rescheduled at an earlier time to guarantee the newly arriving task is completed prior to its deadline). Finally, internode task bidding is considered for guaranteeing successful task completion. Algorithm development for such scheduling capability is currently under way. The implementation will be carried out within the NCUBE Vertex operating system.

- Virtual Time

The use of distributed memory and message passing makes the hypercube highly scalable, but presents difficulties for rapid responses of the robot to unpredictable events in the environment. In particular, message passing involves significant time delays. Messages, once sent, are out of reach of the sending node and cannot directly be changed by it. Messages sent from various source nodes to a given node may be received out of their intended time sequence for several reasons including task migration, which may be necessary because of hardware failure or desirable for dynamic load balancing.[16]

Such corrections, cancellations, and emergency messages could be handled by the operating system itself. If a correction/cancellation arrives at the input queue of a node while its "mate", the message to be corrected/cancelled, is still in that queue, the operating system can make the necessary changes transparently to the application process. An emergency message must interrupt a running process; this, too, can be a function of the operating system.

When a cancellation/correction message arrives too late -- i.e., its mate has already been processed -- one or more of several possible actions may be taken, depending on the application and the amount of time available before a deadline,

- for a cancellation: emergency trap of any output message(s) at the controller node;
- for a correction: emergency trap of any output message(s) at the controller node, followed by recalculation with the corrected input data;
- for either: a procedure which compensates for the error;
- message notifying the planner.

A virtual-time paradigm is being developed[16] as a synchronization mechanism to cope with this problem. This research builds on a version of the Caltech hypercube simulator made available to CESAR. The Caltech simulator as received by CESAR was such that (1) all nodes executed the same program, (2) message passing was assumed to occur only between nearest neighbors, and (3) all messages were received in the sequence they were sent. Because the CESAR emphasis is on problems characterized by structures irregular in time and space, modifications were made such that (1) nodes can now execute totally different programs, (2) message passing is from any process to any other at any time, and (3) tasks are initiated after the necessary messages have been received. The next phase of research involves the implementation of the virtual-time algorithms (including modification of tentative plans based on new messages from other processors that invalidate previous assumptions) into the NCUBE VERTEX operating system.

- <u>Simulated Annealing</u>

To address the load-balancing problem, Barhen has proposed using a simulated annealing method. Simulated annealing has been proposed as an effective method for determining global minima of combinatorial optimization problems involving many degrees of freedom. In analogy with statistical mechanics, each processor n could correspond to a lattice site in d dimensional space, and each process i would correspond to a particle. The kinetic energy of particle i is identified with the nonmessage-passing portion of the execution time of the corresponding process. A potential energy V_i represents the total time spent by process i for communication. To induce processes to spread out, a repulsive potential is introduced corresponding to the difference between the specific processor computational load and the average. The total energy of the system is then minimized to determine appropriate task allocations among processors.

In the standard simulated annealing methodology, the acceptance of a system configuration is based on the Metropolis criterion which subsumes a canonical distribution, i.e., it is implicitly assumed that the number of "particles" in the system remains constant. In terms of an optimization problem this means that the number of degrees of freedom remains constant in time. This assumption is unreasonable for many event-driven applications, particularly in the area of intelligent autonomous systems, where the process structure (i.e., the interrelationship between the various tasks in the system) may evolve dynamically, e.g., new processes are created, others are annihilated.

The standard methodology also requires equilibrium to be reached at each "temperature". This is a lengthy process and thus a serious obstacle for applications requiring near real-time performance. Furthermore, current formulations have not yet been concerned with implementation on a parallel processor, and the potential ensuing speedup. To handle these problems, our approach will focus on nonequilibrium statistical mechanics techniques, combined with methods for effective selection of new configurations, the determination of appropriate annealing schedules (i.e., selection of annealing temperatures and sample sizes at these temperatures), and the use of the "grand-canonical" distribution for handling the varying number of degrees of freedom.

e. Hypercube Algorithms for Robot Dynamics: An Example

The pioneering work of J. Y. S. Luh and C. S. Lin[17] of Clemson University on scheduling of parallel computations for a computer-controlled mechanical manipulator has served as a benchmark for subsequent R&D of parallel algorithms for robot dynamics. Barhen and Einstein have examined the same problem using a modified version of ROSES, and results for the forward recursion (base-to-tip equations of motion) involving 144 tasks indicate that the speed of computation increases with the increasing number of processors--but only up to a point. Beyond this, adding processors is a waste of computing resources.

Direct running-time comparisons are not appropriate because of the different hardware used by Lin and the CESAR group; the individual NCUBE nodes were designed by NCUBE to be about an order of magnitude faster than previously used microprocessors. Timing studies are under way now to verify these assertions. However, the load balance reported by Barhen and Einstein for the most unbalanced node in this benchmark was about 95% for four processors compared with 5% reported by Luh and Lin in an architecture in which one processor is assigned for each joint.

f. Artificial Neuromorphic Systems

Artificial neuromorphic systems (ANS) are adaptive dynamical systems that can carry out useful information processing by means of their state response to initial or continuous input. The excitement behind ANS is the hope that they can provide practical solutions to some of the problems that have confounded computer science and artificial intelligence for the last 30 years. These include fully parallel search through spatiotemporal information patterns, automated acquisition of knowledge from observation of correlated activity, and real-time control of complex systems through self-organizing associative recall of command sequences and fast adaptive optimization.

The CESAR research in this area[18] is relatively new and focuses on four major themes: (1) simulation of large scale neural networks on a hypercube supercomputer, (2) combinatorial optimization, (3) machine intelligence (for example, expert systems, learning, vision, multisensor integration, and so on), and (4) cross-disciplinary issues such as stability and storage capacity.

D. Sensors and Vision

1. Machine Vision Based on Human Neural Mechanisms

The CESAR team has initiated a research effort[19] to develop a robot vision system based on principles of human vision (for example, massive parallelism, dynamic feedback, and multilayer pattern recognition). During the first year in which the research was led by Charles Jorgensen and Richard Gawronski, the modeling effort concentrated on understanding the electrochemical processes in the retina that follow photochemical conversion of the light impinging on the human eye. Two types of neural models were considered. The first represents neural layers in terms of static 2-D linear equations using a linear matrix and linear feedback. The second considers dynamic 2-D nonlinear processes using matrixes of nonlinear differential equations. The first set of equations was parameterized using psychophysical data from the subjective judgments about the intensity of three visual illusions (see Fig. 14). The experimental results were used in a Fourier solution process, which was then applied to new illusions and compared with human subjective results through dimensional plots of transformed pixel intensities. The second set of equations was studied using a computer simulation operating on digitized picture matrixes.

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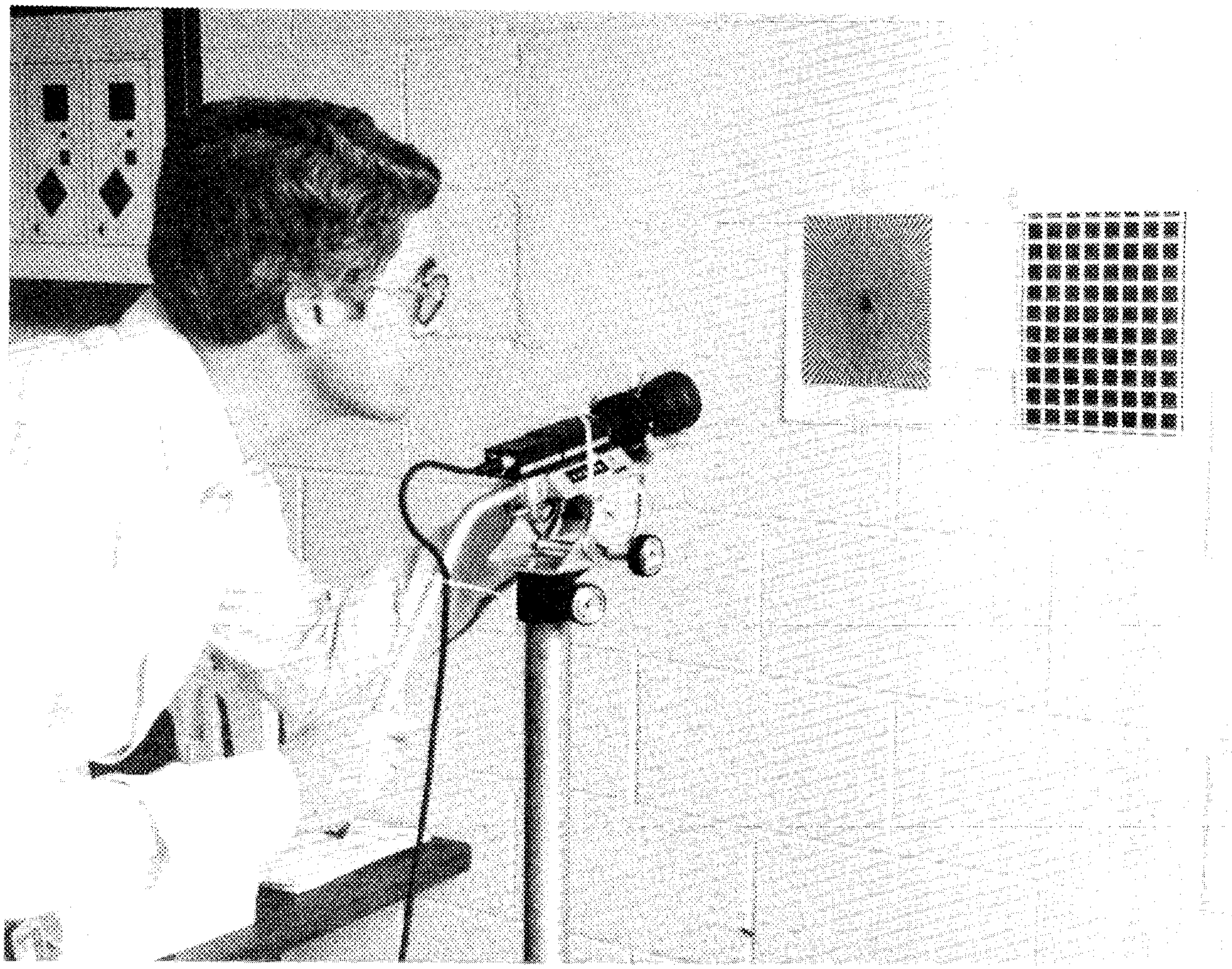

Fig. 14. Capturing Optical Illusions Used to Test Models of the Human Eye.

Although near-term generation of neural-based processors is still out of reach, the development of systems having silicon-based neurons at the front end and pattern-recognition technologies at the higher levels might be feasible. A transition from static to dynamic models and models for higher-level perception remain to be developed.

2. Machine Vision and Multisensor Integration: Future Research

CESAR research in machine vision and multisensor integration using the NCUBE is currently led by Judson Jones and Reinhold Mann. Directly supportive of this effort is research in 3-D world model representation and update led by Moshe Goldstein. Elsie Simpson, Francois Pin, and Gerard de Saussure support one or more of these efforts.

a. Artificial Vision Based on Computational Principles of Biological Vision

In practice, it is impossible to satisfy all requirements for comprehensive perception with a single representation of an image. Instead, the image must undergo a variety of transformations into intermediate representations. Each of these intermediate representations differ in which properties of the image are made explicit, and which are made implicit. For example, one representation might consist of the distance from the observer to each point in the scene (a depth map); another representation might consist of the velocities of all the points in the scene (the optic flow field). Image understanding algorithms must selectively utilize information from each representation as required.

Mammalian visual systems produce multiple image representations. From detailed study of the owl monkey,[20] cat,[21,22] macaque monkey,[23] and other mammals[24] it is now well established that the mammalian visual system constructs multiple retinotopically organized representations of the visual field in physically distinct loci of the cerebral cortex. In the majority of cases, precisely what is made explicit in each representation, and how each representation is computed, is unknown.

The proposition that the striate cortex computes an image representation which makes explicit both the spatial and the spectral content of static images essentially resolves a long-standing "feature/frequency" debate and allows the application of a well developed body of mathematical knowledge to the problem of image processing and its relationship to image understanding. The additional hypothesis that the representation can be computed over a set of elemental signals led to empirically testable predictions, which have since been verified in the doctoral thesis of a CESAR staff member leading this work.[25-27]

It therefore seems reasonable to attempt to solve image segmentation and surface parameter estimation problems using image representations based on simultaneous resolution of image information in space and spatial frequency. We have recently made preliminary progress[28] towards this goal via an implementation of a filtering algorithm on CESAR's NCUBE hypercube multiprocessor. Briefly, we implemented an algorithm which performs frequency domain filtering using sets of 2D Gabor filters, inverse transforms the resulting filtered images, and accumulates the results into a single image plane. This accumulation operation corresponds to a projection of the 4D information space representation onto the two original space axes. This procedure was able to produce images in which segmentation of various image regions becomes highly simplified. Briefly, image periodicities corresponding to texture are eliminated, and the problem is reduced to one of segmenting regions of roughly uniform gray scale.

Although these results are promising, there are some problems with the current implementation which it is our goal to rectify. First, it is likely that a more efficient algorithm for computing the representation exists. Second, only sparse representations were computed. Ideally, one would like to compute dense representations using many filters. Third, the accumulation operation is not universally appropriate. Ideally, one would like to use the full 4 dimensional space as input to reasoning algorithms.

We propose to extend this work with a complete implementation of an algorithm for computing the information space representation of an image using the CESAR hypercube supercomputer, and conduct an investigation into computing image segmentations and surface parameter estimation using the results.

b. Neural Networks for Visual Object Recognition

One cannot expect to recognize objects without the ability to segment an image into a set of discrete objects, or without the ability to estimate some properties of objects prior to recognition. Hence, the research proposed in Section "a" bears a direct relationship to the object recognition problem. However, the ability to segment a scene or estimate surface parameters does not constitute object recognition. In this section we propose research into object recognition using an approach motivated by the study of biological systems and well matched to implementation on massively parallel architectures, the neural network approach.

In brief, a neural network is an abstract non-linear dynamical system composed of a large number of computing elements which interact via "excitatory" and "inhibitory" connections, in analogy to the function of mammalian brains. The input to the neural network is a derived representation of the environment, such as a gray scale digitized image, or a representation computed from an image, such as the one discussed in Section "a".

The connectivity structure and the specific values associated with each connection specify the dynamics of the neural network. An input representation causes the network to assume a specific "state" (defined as the value assumed by all of the computing elements at a given instant of time). The dynamical properties of the network cause the system to follow a trajectory in state space which can be characterized by two terminal properties. If the system reaches some final state and does not thereafter change, it has reached a stable equilibrium point. If the system reaches the same state twice, it will be in a periodic limit cycle. In general, the number of equilibrium points and limit cycles will be much smaller than the number of possible states, or initial configurations. Therefore, each of these terminals can be interpreted as "recognition", since from a large variety of possible initial configurations (i.e., images) a mapping into a small number of final configurations (i.e., object labels) has been achieved.

The appeal of neural network approaches to pattern recognition is based upon three properties possessed by these networks.

Recognition is robust; it occurs for different images and is not prevented by sporadic failure of individual components. This property has important implications for fail-safe operation of a system in the field, operating under adverse conditions. In a practical implementation of neural networks for pattern recognition, the system will be composed of a large number of elements. In ordinary pattern recognition systems the failure of a single element can lead to catastrophic failure of the entire system. Neural networks offer a path toward fail-safe operation which does not involve the redundant replication of components. Fail-safe operation, in the sense of graceful degradation, is a property of the system which is considered from the outset in the theoretical development.

Many different attractors exist for a given system. This allows a single system to recognize a particular object as an instance of multiple classes of objects. Furthermore, the relative "distance" of attractors in the network can be controlled, so that the probability of error can be related to the cost of making errors. The probabilities of misrecognition can be controlled based on the particular costs associated with each.

Learning mechanisms or selection processes exist which allow building a net with attractors corresponding to some features of the outside world, such as patterns presented to the net. This capability allows single hardware and/or software implementations of neural networks to be applied to different recognition tasks. The difference between networks lies in the particular manner in which the networks are "trained" (i.e., the attractors are formed).

There are some problems of practical interest in current approaches to neural network implementation. First, most neural network models do not scale gracefully. The connectivity matrix of a Hopfield network, for instance, grows as the square of the number of computing elements in the net. A realization of the corresponding network is therefore dominated in complexity by the communications structure. A fully connected network of the Hopfield type is not realizable on a scale which solves problems of practical interest. Hence, most demonstrations have been limited to a few neurons processing a small input space.

Second, current neural network models for artificial vision do not take into account the powerful image preprocessing capabilities found in mammalian systems, choosing instead to work directly on the binary or gray scale values. In simple simulations involving only a few neurons preprocessing is not as essential as it would be for complex recognition by large, parallel architectures.

We propose to extend the range of applicability of neural network models for object recognition by investigating reduced connectivity neural networks, and by exploiting the computational power of the hypercube supercomputer. The particular form of the network we plan to investigate is the natural mapping of network architecture onto the hypercube. We anticipate that the same advantages of scalibility will be conferred on the neural network simulation as are conferred on the hypercube computer system itself.

Furthermore, we propose to investigate the application of advanced image preprocessing capabilities of the elementary signal representation described in Section "a" as an input to a neural network architecture.

c. Multisensor Integration (MSI)

One of the prerequisites for intelligent behavior in robotic systems is the ability to generate consistent, system-internal representations of the environment. In general, this is impossible on the basis of any single sensor domain. Hence, robotic systems are being equipped with an increasing number of different sensors that supply partly redundant information. MSI designates the task of combining data and information from these various sensors such that a consistent world model, i.e., a model free of contradiction, can be generated, on the basis of which decisions concerning navigation, manipulation, etc. can be made.

The task is highly complex because of several circumstances related to the diversity of sensors. Depending on the physics underlying a particular sensor, the amount of time required to acquire data varies among different sensors e.g., from on the order of seconds for sonar distance measurements to 1/30 second to digitize a TV image (with US TV frequency). The amount of time needed to perform quantitative analysis of sensor data and extract features also depends on the nature of the sensor. As an example, analysis of digital images is generally more time-consuming than the analysis of one-dimensional signals. This introduces scheduling and synchronization problems in a dynamic environment. The confidence associated with a sensor measurement depends on the situation in the environment, e.g., a sonar sensor tends to underestimate distances to room corridors, and cannot detect open spaces between obstacles whose distance from each other is smaller than the width of the ultrasound beam. It follows that there should be a sensor hierarchy that depends on the environment. Thus, any mechanism for MSI must have access to the knowledge base describing the world model, and flow of information between different sensor domains must be possible at all stages in the data and information processing. Finally, it must be noted that the existence of a consistent representation of the environment on the basis of the available sensors is not guaranteed. A method for MSI must recognize such a situation and be able to deal with this uncertainty.

The scope of research and development falling under the heading MSI, also referred to as sensor fusion, is not well defined. Depending on the level of abstraction, i.e., mathematization, at which the problem is discussed, even results from the seemingly unrelated theory of finite groups (related to graph morphisms) can be of relevance to MSI. In analogy to commonly accepted terminology in image analysis methodology we can distinguish between work in low and high level MSI. The former is concerned with combining the outputs from sensors at the level of the actual data supplied by the sensors, e.g., stereo vision, and the merging of registered reflectance and range data from laser range finders. High level MSI deals with the integration of information extracted from the data collected by different sensors. The combination of object labels obtained from vision, heat, and acoustic sensors probing a scene may be viewed as an example for high level MSI.

Research is proposed at CESAR with the goal to integrate data from vision and range sensors for navigation and manipulation, and to develop a framework for high level MSI. The approach consists of solving consistent labeling problems in each sensor domain in the presence of constraints between labels from different sensor domains. This in turn represents a consistent labeling problem. Conflicts among labelings are resolved by choosing that labeling for which the a posteriori probability P(label/feature) is maximum for all labels and a given feature. These probabilities are computed from the a prior probabilities

P(feature/label) using Bayes' rule. Moreover, the receiver operating characteristics for each sensor are taken into account. This approach results in a self-organizing hierarchy among the sensors as a function of the contents of the scene that is being probed. In addition, feedback can be provided from the inter-sensor labeling to the individual sensor domains, so that the a priori probabilities can be adjusted as the environment is probed, i.e., learning can be accomplished. As an alternative to this probabilistic approach, the application of O-theory (described in Section V-G-1-b) to MSI is being studied.

The computational complexity of the tasks involved is enormous even for moderately complicated environments. Therefore, methods are investigated that appear suitable to accomplish these tasks, such as relaxation labeling, simulated annealing for graph matching, artificial neural networks, in view of the existence of a concurrent hypercube computer at CESAR.

d. 3-D World Modelling With Updating Capability Based on Combinatorial Geometry

In the area of knowledge representation, CESAR staff member Moshe Goldstein has proposed and begun development of a 3-D world modeling capability[29] based on methods of combinatorial geometry (CG), which are used widely in Monte Carlo particle transport calculations. Discrete measurements of range information that quantify the distances from the sensor focal plane to the object surface, are transformed to a surface representation. First, each measured point on the object surface is surrounded by a small sphere with a radius determined by the range to that point. Then, the 3-D shapes of the visible surfaces are obtained by taking the (Boolean) union of all the spheres. The result is an unambiguous representation of the object's boundary surfaces.

Prelearned partial knowledge of the environment can also be represented using the CG method with a relatively small amount of data.

Using the CG type of representation, distances to boundary surfaces of various objects are efficiently calculated. This CG feature is particularly useful for continuously verifying the world model against the data provided by the range finder, and for integrating range data from successive locations of the robot during motion. Early feasibility of the proposed approach has been demonstrated[29] using simulations of a spherical robot in a 3-D room in the presence of moving obstacles and inadequate prelearned partial knowledge of the environment.

Techniques for edge identification, object characterization (i.e., replacement of individual spherical volume elements with a compact combinatorial geometry description and recognition are proposed for future development. It is also vital that this methodology, developed originally on mainframe computers, be ported to the hypercube contained on HERMIES-IIB and tested with actual data. Finally, 3-D world modelling and updating with this range information, must be synthesized with the results obtained in our vision research (i.e., Sections "a" and "b") and incorporated with extending ideas developed in Task "c" on multisensor integration.

E. Human-Machine Interface: Future Research Thrust

As in any project related to intelligent machines, we have spent considerable time developing suitable man-machine interfaces and exploring fertile ground for research (e.g., see discussion in V-C-6 regarding the development of an emulator for HERMIES). With that experience behind us, we are now ready to explore what is likely to be a major CESAR research thrust.

1. Man-Robot Symbiosis

W. R. Hamel is coordinating a new initiative in man-robot cooperative problem solving research supported by Lynn Parker, Francois Pin, Chuck Jorgensen, Tom Burgess and Scott Babcock.

We believe that now is an appropriate time to begin research on the development of a new class of remotely-operated systems which utilize machine intelligence concepts to achieve true man-machine cooperative control and intelligence. In this context, human-machine integration involves optimization of the partnership both electromotively and intellectually. The fundamental goal of man-robot symbiosis is to improve the admissible task range, accuracy, and work efficiency of man robot(s) systems.

The fundamental concept of a man-robot "symbiont" is depicted in Fig. 15. The symbiont structure may be comprised of several basic features integrated into a unit which accomplishes the desired cooperative environment. The slave system of a conventional teleoperator becomes an intelligent robotic system capable of sensor-based control in response to high level commands. The telepresenter is essentially an advanced man-machine interface which incorporates advanced technology such as 3D graphics to increase the human operator's perception of the remote environment and the remote robot. The Symbiosis supervisor is a computer system(s) which facilitates the critical aspects of computer augmentation, learning, and dynamic task allocation necessary to accomplish the dynamic state transitions shown in Fig. 16. The essence of the symbiosis research theme is the real-time implementation of these state transitions in an environment where experience is captured through learning mechanisms and man-machine division of responsibility is optimized.

2. Basic Research in Man-Robot Symbiosis

The purpose of symbiosis research is to explore the issues which currently limit optimal deployment of man-machine systems. The ultimate goal is cooperative problem solving to take advantage of man's recognized capabilities in dealing with new situations, image understanding, physical dexterity, etc. and the machine's inherent strengths in precision, rapid computation, etc. The task allocation mix will evolve

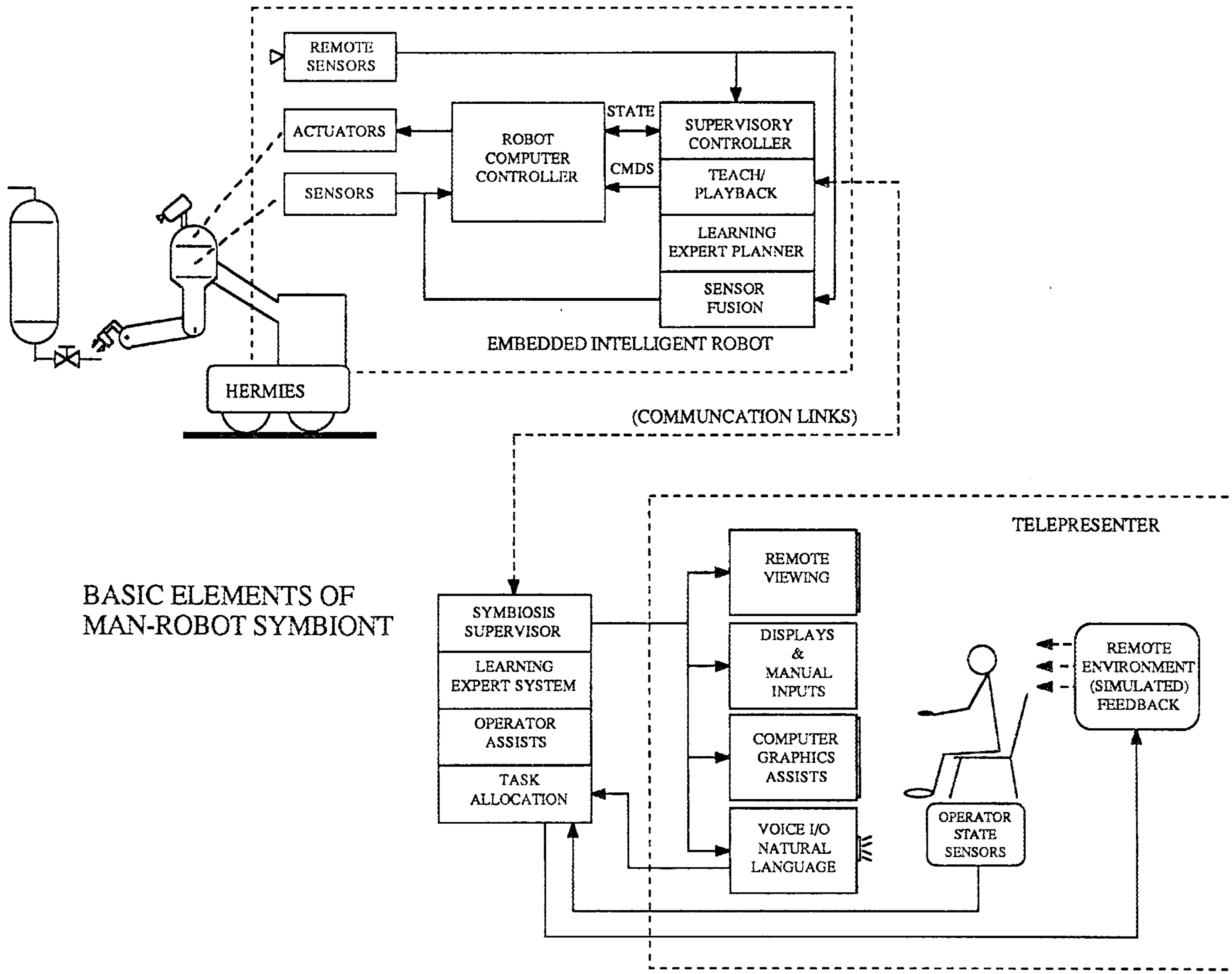

Fig. 15. Basic Elements of Man-Robot Symbiont.

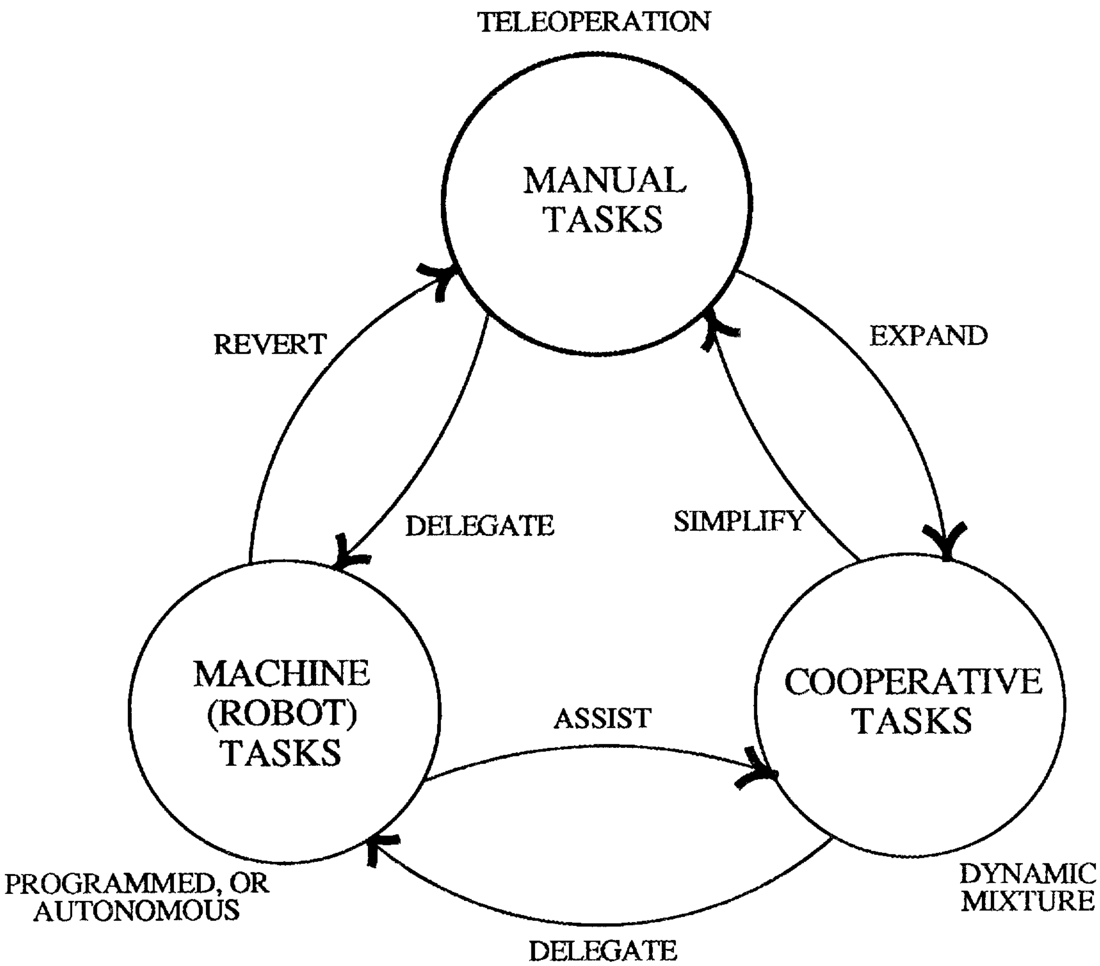

Fig. 16. Man-Robot Symbiosis State Diagram

dynamically in previously unpredictable ways. The human and machine possess overlapping expertise that when integrated should result in better joint system performance than is possible by either man or machine alone. Two basic research areas are described: (1) Dynamic Man-Machine Task Allocation, (2) System Learning.

a. Dynamic Man-Machine Task Allocation

Ultimately, one must develop a real-time, data driven system that deals directly with the problem of time dependent task reconfiguration. This problem is directly analogous to task scheduling and load balancing of parallel computer processors except that these "processors" (man and machine) are heterogeneous. To facilitate the allocation process one can associate the human's skills, knowledge, constraints, and attitudes with the machine's validated software, knowledge base, hardware limitations, and uncertainty handling. Remaining differences can be treated heuristically during the allocation process. We seek to apply recently developed ORNL methods in load balancing to optimize overall system performance.

b. System Learning

It is essential that the combined man-machine system have learning capabilities, and that the improvement of each element (man or machine) be able to benefit from the experience of the other, i.e., the system and each element must be trainable and adaptable. The machine can effectively implement rote learning schemes (pruning selectively the information no longer required) and improve plan generation by synthesizing rule combinations into procedures while insuring that the accomplishment of one event does not violate the preconditions of another. The procedural descriptions (rules) and declarative statements (facts) can be refined automatically as the human instructs the machines to note successful (or unsuccessful) concepts and the machine generalizes (or refines) its existing models accordingly. The current state of the art is such that learning through generalized analogy is best done by man. Research must examine a variety of learning methodologies and examine them with respect to the system element most appropriate for implementation within the current context.

In addition to the above research, complementary efforts in automated speech recognition and advanced telepresence would be particularly germane. We believe that the man-robot(s) symbiosis concept has important basic research components and will serve as an effective bridge between today's state-of-the-art technology, and the autonomous intelligent machine of the twenty-first century.

F. Manipulator Dynamics and Control

Current and proposed research activities in the area of manipulator dynamics and control include model development and parameter identification, advanced control algorithm development, mobile manipulation, dual arm manipulation, and dexterous manipulation using multi-fingered hands.

The proposed research activities in the area of manipulator dynamics and controls follow a natural sequence toward mobile, dexterous manipulation. Initial efforts have and will continue to focus on manipulator research in a fixed base environment. Next, research topics associated with mobility and manipulation will be addressed. The addition of a second arm to the experimental equipment will allow basic research in dual arm manipulation. Finally, research associated with multi-fingered hands will provide the capability for dexterous manipulation.

1. CESAR Research Manipulator (CESARM)

The CESAR Research Manipulator is being developed by Scott Babcock and William Hamel as a test bed for advanced manipulator design and control methodologies suitable for applications in unstructured environments (see Fig. 17.). It embodies several unique features. First, it has a relatively high capacity-to-weight ratio while maintaining a large maximum no-load tip speed. Mobility requires that overall weight and power consumption be minimized; thus, manipulators must be designed with low weight-to-capacity ratios. Second, it has a unique spherical three-degree-of-freedom wrist which has all singularities at the extremities of motion and simple kinematic calculations. Third, the drive train has low friction and is backdrivable, which should enhance force control. Finally, it has a seventh degree of freedom, which is desirable for obstacle avoidance and expanding the range of motion.

As indicated in Fig. 18, the manipulator's seven degrees of freedom are: vertical axis, shoulder pitch, upper arm roll, elbow pitch, wrist pitch, wrist yaw, and wrist roll (not counting the gripper jaws). The offset shoulder design was chosen to allow the addition of a second arm in an anthropomorphic configuration. Having the redundant seventh degree of freedom, the CESAR Research Manipulator can be configured to both place and orient the wrist and to somewhat arbitrarily lower and elevate the elbow. This will allow the arm to reach under, over, or around obstacles in an unstructured environment. Also, the working volume of a manipulator is restricted by the physical limits of the individual joints. Points which would be unreachable in the six-dimensional volume of positions and orientations for a six-degree-of-freedom manipulator, due to joint limits, can be reached given an additional degree of freedom.

The control system for the CESAR Research Manipulator is flexible and expandable, from both a hardware and software viewpoint. The hardware consists of a VMEbus microcomputer system, a custom amplifier and interface electronics package, a 72 VDC power supply for the

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Fig. 17. The CESAR Research Manipulator.

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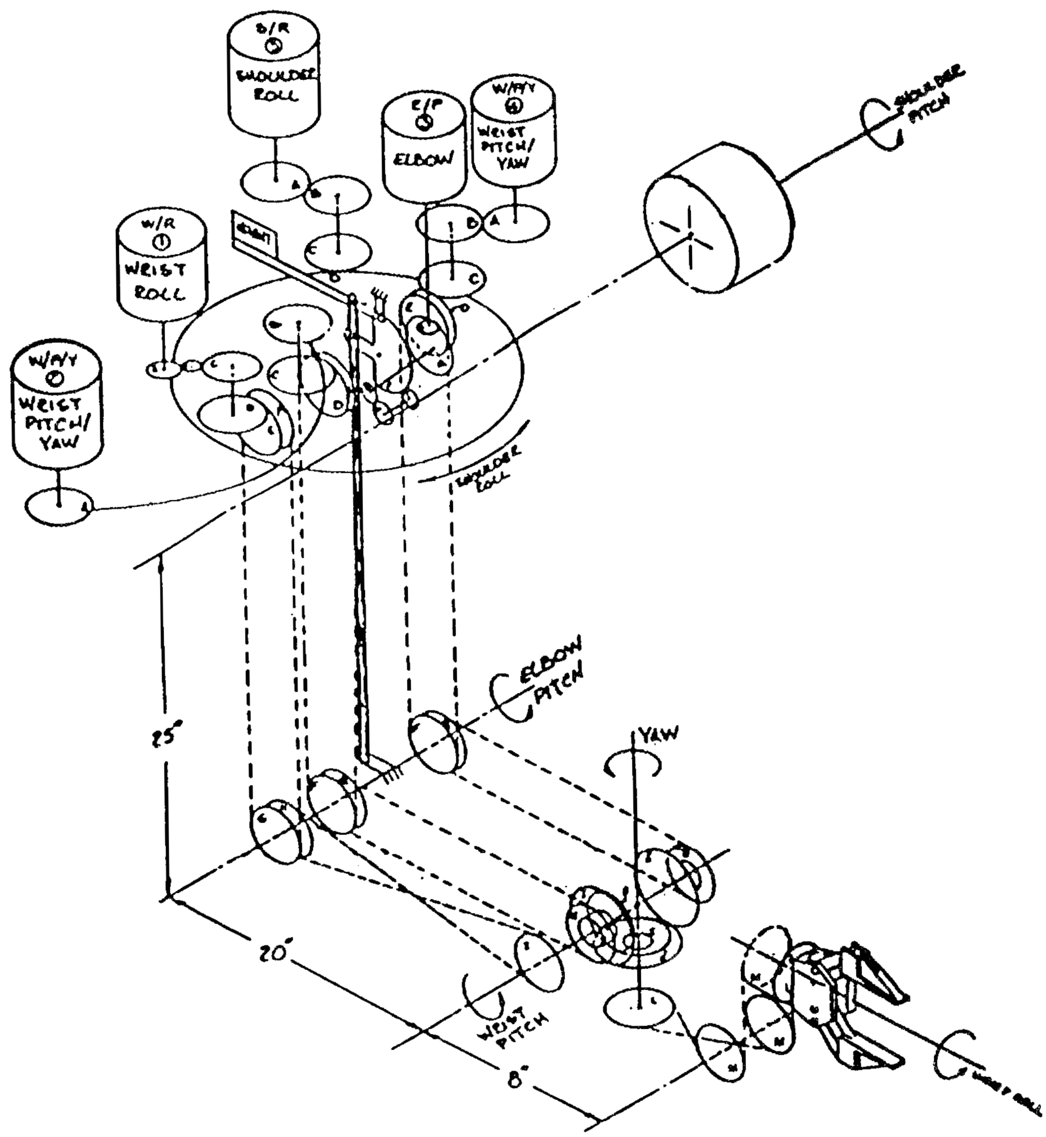

Fig. 18. CESAR Research Manipulator Power Transmission.

amplifiers, and a 24 VDC power supply for the brakes and interface electronics. The CESAR research manipulator will be initially controlled using the VMEbus microcomputer system with two Motorola 68020 microcomputers. The control system software is being implemented in the "C" language. In addition, parallel communication is being established between the VMEbus and an IBM AT which will be used for data analysis and display. Also, a communications link with the NCUBE hypercube computer is underway.

2. CESAR Research in Dynamics and Control: Future

a. Manipulator Modeling and Simulation

One research objective is to develop an experimentally verified dynamic model of CESARM. The model is needed for simulation and advanced control algorithm developed. The model will be more complex than the typical models developed for serial link manipulators with actuators located at the joints. Drive train compliance is significant for the cable driven degrees of freedom and must be included. In addition, the dynamics of the four bar linkage which is used for the elbow drive and associated counterweight must be incorporated.

- Parameter Identification. Use of the manipulator model for simulation and control algorithm development requires a knowledge of the inertial characteristics of the links of an arm. An inertia test stand has been fabricated for experimental determination of the manipulator's inertia tensor. In addition to the experimental determination of the inertia of the elements of the manipulator, a computer aided design approach is being pursued. This will provide an independent verification of experimental results. Other parameters of the manipulator model will be identified from independent tests. For example, motor characteristics such as the torque constant, rotor inertia, and friction will be determined via bench top motor test. A series of tests of the assembled manipulator will be designed to extract missing parameters from dynamic response data and verify the validity of the manipulator model. This effort will hopefully provide a verified model with complete parametric data that could be useful to the entire robotics research community.

• <u>Trajectory Planning</u>. One of the more significant qualities of the CESAR Research Manipulator is its seven degrees of freedom. One vital research effort involves trajectory planning for manipulators with redundant degrees of freedom. To allow initial operation of the manipulator, a polynomial interpolation teach/playback capability was implemented which includes sample point capture of joint angles, polynomial coefficient calculation, and real-time polynomial evaluation for command generation. This is the most fundamental approach to trajectory planning in joint space and relies on previewing joint position and velocity trajectories to assure constraints are satisfied.

Trajectory planning efforts are currently directed toward off-line programming in a cartesian base coordinate system, considering only manipulator kinematic equations of motion. Two approaches are being pursued. In the first, the inverse kinematic relations are obtained from an analytical reduction of the kinematic equations coupled with numerical solution of any resulting transcendental equations. Due to the redundant degree of freedom, an additional constraint or criteria for optimization must be provided to obtain a solution. Two types of equality constraints will be considered: (1) specification of one of the joint angles as a function of time and (2) specification of a functional relationship between joint angles. For example, the elevation of the elbow may be specified to allow reaching over, under, or around an object. As in the teach/playback case, planned trajectories must be previewed to assure that inequality constraints are met, including joint motion range and velocity limits and limits required to avoid collisions between the hand or forearm and the pedestal.

The second approach being considered involves generalized solutions for the joint angle velocity vector given the cartesian velocity vector of the endpoint and criteria for optimization. The initial effort would be to implement a gradient technique which identifies trajectories along which the manipulator tends toward configurations[30] which improve (1) "efficiency", (2) "mechanical advantage", and (3) "flexibility." In the first case, a "manipulator-velocity-ratio" is increased in the direction of motion resulting in lower joint velocities required to obtain a desired end-effector velocity. In the second case, "manipulator-mechanical-advantage" is increased in the direction of applied force and moment along a trajectory resulting in configurations requiring lower joint torques for given end-effector forces and torques. In the third case, the "manipulator-velocity-ratio ellipsoid" is made more uniform along the trajectory, thus improving ability for arbitrary motion and avoiding singular regions. Extensions to this work are planned which include a treatment of inequality constraints for joint angle limits and obstacle avoidance as well as weighted combinations of the above criteria.

b. Control Algorithms for Manipulators with Compliant Drive Trains

Another research objective is the development of advanced control algorithms of manipulators for autonomous mobile applications. Many recently developed algorithms for the control of manipulators contain embedded models of the manipulator to be controlled. For the CESAR Research Manipulator, the compliant wrist drives must be considered in the development of such control algorithms. The implementation of various algorithms will require the addition of appropriate sensors. We propose to develop the following series of control algorithms.

- Full State Feedback Control. The initial efforts are to develop full state feedback control algorithms for the wrist degrees of freedom. A cable drive test stand will be utilized prior to implementation on the manipulator to allow study of the control of one of the three wrist degrees of freedom. Wrist joint position sensors in addition to motor position and velocity sensors will provide a complete state for feedback, assuming derived wrist joint angle velocities. The inherent cross-coupling of the wrist pitch and yaw due to the differential drive, prohibits truly independent joint control when implementing full state feedback. Also, cable tension sensing may be considered, however, a custom cable sensor would have to be developed.

- Inverse Dynamics Position Control. The second type of algorithm to be developed is an inverse dynamics control algorithm. This algorithm will utilize an embedded model of the manipulator to dynamically decouple the various degrees of freedom of the manipulator.

- Position/Force Control Algorithms. The third type of algorithm will provide force control capability. Extensions of hybrid position/force control[31] and impedance control[32] will be considered. The addition of a six-axis, force-torque sensor between the wrist and the parallel jaw gripper has been anticipated in the design of the CESAR Research Manipulator.

c. Longer Range Objectives

In subsequent years, our research will include modelling and control of a mobile platform, control of the manipulator on a non-rigid base (continuing collaboration with MIT), coordinated manipulator/mobile platform control, dual arm modelling and control (following the addition of the second CESARM), and increasing dexterity by the addition of multi-fingered hands. Collaboration with the DARPA robotics program in the area of multi-fingered hand development may be possible.

G. Cross Disciplinary Research

There are a number of important research areas which span one or more of the conventional technological subdisciplines of the field of intelligent control systems. Some of these such as advanced computing architectures and algorithms, and systems integration have been discussed previously as part of other sections. Advanced computing was grouped with machine intelligence (Section V-C) to provide focus in terms of development of the robotic brain. Systems integration and HERMIES development (Section V-A,B) was described early on as the experimental focus for testing concepts. One important focus which has not been discussed earlier, however, is our research in sensitivity and uncertainty analysis which is discussed below.

1. Sensitivity and Uncertainty Analysis

Ed Oblow leads the CESAR effort in developing methods for automated derivative generation and systematic uncertainty analysis. Oblow is currently supported in this effort by Martin Beckerman, Francois Pin, and Brian Worley. First derivatives (sensitivities) are required for model-simplification studies and parameter identification of complex calculations such as robot dynamics. A comprehensive uncertainty analysis is required to handle numerical data uncertainties (such as occur in sensor measurements), rule and heuristic uncertainties (for searches and decision), and structural uncertainties for vision and language problems. Each of these uncertainties must be properly represented and combined for use in different decision-making environments.

a. Sensitivity Analysis: Present

Sensitivity theory has been used in many fields over the past two decades to assess the importance of variations in modeling data and parameters on calculated model results.[33-38] Sensitivity determination based on reruns is usually unwieldy for complex programs having large databases. Statistical methods are not comprehensive enough and require associated a priori engineering judgment of importance for much of the data set. Adjoint methods have required significant code development prior to implementation.

Oblow, Pin and Worley have developed and validated an automated procedure for performing sensitivity analysis. The procedure uses a new Fortran precompiler that has computer calculus capabilities. The new compiler is called the gradient enhanced software system (GRESS); in it each Fortran line corresponding to storage operations is analytically differentiated, and total first derivatives are propagated using the chain rule. The GRESS system[39-42] has now been successfully tested on several major codes. The major advantage of the GRESS language is its ability to process the model source program as data; no special effort is needed to specify the model.

b. Uncertainty Analysis: Present

A new hybrid uncertainty theory, called Operator-uncertainty Theory (OT), has been developed by E. M. Oblow in an attempt to combine the strengths of Dempster-Shafer Theory (DST) and Fuzzy Set Theory (FST) within a probabilistic framework. The belief structures and possibility sets of DST, and the mathematical diversity and rigor of FST form the basis for this effort. The effort is directed at developing a sound theoretical basis for uncertainty analysis which can be used in artificial intelligence domains.

The initial work performed over the last year and a half, has laid a basic foundation for this theory by defining an operator set-algebra. This algebra allows uncertainties from independent sources to be combined and propagated in a manner analogous to the set operations defined in FST. Since OT is probabilistically based, however, these new operators offer combination rules which considerably extend the applicability of conventional Bayesian inference techniques as well as DST to set-theoretic AI problems.

Two publications were produced in this timeframe.[43-44] The first, spelled out the basic OT set operations which currently include dominance and order, union, intersection, complement, and general mappings. The second explored the formal connection between masses in OT and probabilities. This later work suggests that the distinctions between DST and probability theory are far less consequential than previously assumed. The DST conception of uncommitted belief was shown to be compatible with classical probability theory.

2. Sensitivity and Uncertainty Analysis: Future

Our automated sensitivity analysis capability will be tested with respect to model simplification and parameter identification for CESARM.

OT applications currently being explored include problems in logical inference, rule-based expert systems, sensor fusion and learning. Future theoretical work will be directed at the problems of:
(1) correlated combination of information, (2) treatment of conflict as an uncertainty representation, and (3) ways to handle conditional uncertainties. Considerable effort will also be directed toward developing efficient computational algorithms for all applications of OT. Specifically, parallel algorithms in hypercube compatible form will be developed and tested.

The extensions of the theory to cover correlated information and conditional uncertainties will allow applications of OT to cover all areas now treated by classical probability theory and Bayesian inference. These areas include sensor fusion from differing information sources, logical inferencing and rule-based planning and learning. The completion of these tasks will result in a full enhancement of classical probability theory to handle the OT representations of conflict and undecidability. These features are essential to the solution of real-time, real-world robotics problems.

The task related to algorithm development will make heavy use of the theoretical extensions just described. To operate in real time, these algorithms need to be parallel in structure and must operate in an NCUBE environment for realistic application with the HERMIES robot. Since the algorithms will have a probabilistic basis, they can be developed at various levels of approximation to avoid the inherent NP completeness of the power sets used as the basis for OT.

The new OT representations in this computational framework, will be treated in the same manner as conventional probability distributions, so that approximate statistical algorithms (Latin hypercube sampling, star designs, etc.) can be used to efficiently sample and propagate uncertainties. Such methods are ideally suited to parallel computer implementation without major new developments.

VI. CESAR PROGRAM DEVELOPMENT AND INTERACTIONS

CESAR has organized and led two major national workshops. In November 1983 a workshop entitled "Research Needs in Intelligent Machines" was held to develop long-range goals and priorities.[1] In August 1985 CESAR conducted a second workshop, "Planning and Sensing for Autonomous Navigation," in conjunction with the International Joint Conference on Artificial Intelligence.[45]

Based on R&D results to date, other federal agencies have elected to participate in the sponsorship of CESAR. The U.S. Army Human Engineering Laboratory (HEL) is supporting research in soldier-machine system development, which has applications for projects that require dexterous manipulation in hazardous environments, such as explosive ordnance disposal and vehicle refueling and decontamination. HEL is also supporting research that explores the feasibility of applying human neural models to advanced robotic vision systems. The Air Force Wright Aeronautical Laboratories is sponsoring research in concurrent computation that exploits the potential speed, compactness, and versatility offered by the CESAR hypercube ensemble machine with application to multisensor integration in target recognition. The Strategic Defense Initiative program is supporting CESAR research in real time operating system development and neural networks. The Marine Corp has initiated a new program (designated Gaters) which deals with advanced mobility feedback from remotely driven vehicles. Finally, the DOE Office of Nuclear Energy is sponsoring a program coordinated by CESAR, that is intended to lead to the development of a surrogate man operating in nuclear reactor environments. The DOE/BES program is the basic research kernel from which many of the other technology programs seek potential application or specific mission oriented research extensions.

The CESAR program recognizes the vital importance of remaining cognizant and actively participating in other intelligent machine research programs being conducted for different application areas. The Department of Defense, through its Joint Director of Laboratories (JDL) has formed a Joint Technology Panel on Robotics. The purpose of this panel is to recommend research, develop cooperative programs, and exchange resources. Participation includes representatives from the U.S. Army, Air Force, Navy, DARPA, Marines, and NASA. The CESAR Director serves as the DOE representative to this group. Several of the CESAR staff serve as proposal reviewers for the National Science Foundation program aimed at improved manufacturing productivity. CESAR has developed programmatic interfaces through research programs it currently pursues for NASA labs/JPL and Ames) and DOD agencies (U.S. Army Human Engineering Laboratory and the Air Force Wright Aeronautical Laboratories). Interfaces with other DOE offices exist through ORNL support of Nuclear Energy, Fusion Energy, and the Office of Civilian Radioactive Waste Management. Relationships with EPRI programs are currently being pursued.

Relevant research is underway at other leading U.S. Universities (the AI Laboratory at MIT, Boston University, Carnegie Mellon, University of Rhode Island, University of Maryland, Purdue University, Ohio State University, Rensselaer Polytechnic Institute, Stanford University, the University of Southern California, UCLA, Berkeley, Harvard, the

University of Michigan, the University of Texas, Cal Tech, Louisiana State University, the University of Tennessee, the University of Florida, and the University of Illinois) and institutions (the National Bureau of Standards, the Jet Propulsion Laboratory, Stanford Research Institute, Draper Laboratory, and Bell Laboratories).

The Engineering Research Program of DOE/BES also supports related activities. Cal Tech and the University of Wisconsin are studying the development of process design and control strategies. Idaho National Engineering Laboratory is developing an integrated sensor/model for automated welding and expert system aids for analysis codes. The Engineering Research Program hosts periodic workshops to enhance technology transfer among its contractors.

CESAR staff attempt to keep cognizant of as much of this work as possible through study of the literature, society meetings, sponsorship of workshops, site visits, etc. The CESAR emphasis is to bring together meaningfully the resources of the somewhat disparate communities of artificial intelligence, concurrent computation, and advanced control to focus upon fundamental research issues of import to energy related problems.

VII. RESEARCH FOCUS, SCHEDULE AND RESOURCES, AND FACILITY REQUIREMENTS

A. CESAR Paradigm Problem

As framework for gauging the appropriateness of the various CESAR research and development projects, a reference problem has been selected. The reference problem involves the operation, diagnosis and repair of fluid control valves in various environmental settings. The operational requirements for this paradigm problem are deemed to be rich and comprehensive enough to cover most important aspects of autonomous robotic systems.

The overall problem (long-term) can be characterized with the following assumptions:

1. The absolute coordinates and orientation of the valve are uncertain (as-built drawings unavailable or obsolete).

2. The optical properties of the valve site are unknown a priori (valve may be clean or greasy, emergency lighting only).

3. The valve is one of multiple valves of this type located in this vicinity.

4. The current operability of the valve is unknown (may be corroded, slippery, etc.).

5. The robot's mobile platform is at a known initial condition and can move as required. At the valve site, the platform can elevate the manipulator sphere of influence to encompass the valve.

6. The valve access may be partially obstructed (e.g., a pipe may cut across the viewing angle). Only part of the valve can be viewed from any degree, but the degrees of freedom of the manipulator are sufficient to allow operation of the valve with the mobile platform positioned correctly in three dimensions.

7. There are several paths which the mobile platform may follow (through rooms, aisles, etc.), some of which may be obstructed by unanticipated objects.

8. Time is important for successful task completion but mobility and vision are not hampered by the emergency (no fire, smoke, etc.).

9. The total power available to the robot is limited, but may be replenished by returning to the starting point.

10. Communication with the robot can be effectively maintained throughout the plant by existing location of repeaters.

11. A world model exists including

    - a complete description of the valve type (sufficient information to generate a view of the valve from any angle), and

    - piping and other appropriate construction drawing information but not "as built" drawings, to establish the approximate location of the valve (including identification of end points of the line which it is located, such as vessels), and possible paths.

The global (long-term) paradigm problem is then to:

- Locate and approach the valve considering possible paths, obstacles, time, power requirements and monitoring, etc.

- Find the orientation of the valve and the handle position with respect to the robot platform.

- Evaluate the operability of the valve by inspection.

- Develop a strategy for actuation, replacement, repair, etc.

B. Schedule and Resources

Already completed milestones (FY'84-'87) are listed in Appendix B with citation to publication/demonstration(s) which satisfy the objective. The schedule (Fig. 19) covers a four year planning horizon from FY 1988 through FY 1991. The milestones for each subtask indicate deliverable items which take the form of journal papers and/or demonstrations. Currently, the resources, both man years and funding, can reasonably well be estimated through FY 1989. The resources for FY 1990 through FY 1991 are approximate projections. The resources requested from BES/ERP correspond to approximately 40% of the estimated total required effort. The remaining 60% is derived from technology programs which seek to test, validate, or extend the fundamental advances made in the BES/ERP CESAR program.

C. Facility Requirements: In Place

1. HERMIES-II

The current robotic focus of the CESAR program is a mobile system called HERMIES-II (Hostile Environment Robotic Machine Intelligence Experiment: Series II). HERMIES is a self-powered mobile robot system comprising a wheel-driven chassis, dual manipulator arms, on-board distributed processors, and a directionally controlled sensor platform. HERMIES-II is propelled by a dual set of independent wheels with a common axle alignment and driven by separate dc motors that permit a linear speed of 0.154 m/sec (0.5 ft sec). The on-board computer and electronics equipment are located in an enclosure mounted above the drive chassis, and the dual-arm manipulator torso is located above the computers and electronics. The two-arm shoulder assembly has a total of 13 DOF, and all axes are driven with stepping motors controlled directly by the Z8 microprocessor dedicated to manipulator control.

Signals are transmitted via a 2400-baud RS-232 radio link to either the NCUBE or LMI Lambda computers for navigation planning. A ring of five sonar sensing elements, with each element consisting of a phased array of four Polaroid transceivers, allows for a narrow effective beam width and rapid scan. The original stepping motor drives for the sensor

TASK AREAS	FY'88	FY'89	FY'90	FY'91
A. Machine Intelligence and Advanced Computing (a) Planning and Learning (b) Advanced Computing	(35) (3) (32)	(44) (39) (8)	(42) (33) (45)	(31) (43) (46)
Funding ($000) Manyears	450 3.0	480 3.0	680 4.0	720 4.0
B. Mechan. Dyn. and Contr. (a) Dynamic Modelling (b) Control Structures	(11)	(40) (47) (12)	(48) (34)	(50) (52)
Funding ($000) Manyears	195 1.3	240 1.5	323 1.9	435 2.4
C. Sensors and Vision Syst. (a) Human Analog Vision (b) Sensor Integration	(53) (56)	(54) (16)	(55) (57)	(36) (58)
Funding ($000) Manyears	375 2.5	400 2.5	510 3.0	540 3.0
D. Human-Machine Interface (a) H/M Task Allocation (b) Advanced Telepresence	(18)	(59) (62)	(60) (63)	(61) (64)
Funding ($000) Manyears	150 1.0	240 1.5	255 1.5	450 2.5
E. Cross Disciplinary Res. (a) Sensitivity Analysis (b) Uncertainty Analysis (c) Systems Integration	(28)	(22) (25)	(23) (26) (66)	(38) (65)
Funding ($000) Manyears	80 0.54	140 0.9	232 1.4	255 1.4
TOTAL RESOURCE PLAN — FUNDING ($000)	1250	1500	2000	2400
TOTAL RESOURCE PLAN — WORKYEARS	8.3	9.4	11.8	13.3

Estimated costs/manyear FY'88 (150K), FY'89 (160), FY'90 (170), FY'91 (180).

Fig. 19. Schedule and Resources: Circled Numbers Correspond to Milestones Listed on Subsequent Pages.

Journal Paper/Demonstration

Milestone
Number:

(3) Scheduling of robotic tasks under hard-real-time constraints.
(8) Theory of dynamic load balancing using generalized simulated annealing.
(11) New control algorithm for compliant manipulator verified by performance testing.
(12) New control algorithm for coordinated control of a manipulator and mobile platform verified by performance testing.
(16) Integration of laser range finder and vision.
(18) Representation of tasks involving skill.
(22) Simplified robot dynamics application using sensitivity analysis.
(23) Hardware validation of sensitivity tool.
(25) Incorporation in expert system of uncertainty analysis.
(26) Incorporation in planner of uncertainty analysis.
(28) Design and fabrication of HERMIES-III.
(31) CAD based knowledge base.
(32) Theory of cellular automata and neural networks for machine intelligence.
(33) Faster-than-real-time plant simulation.
(34) Control of dual manipulators and a mobile platform.
(35) HERMIES demonstration including task planning, monitoring, replanning, object recognition, and manipulation using on-board NCUBE.
(36) Machine vision system prototype based on principles of human vision.
(38) Hybrid statistical/deterministic uncertainty analysis capability.
(39) Parallel processing version of real-time reasoning system operating on the hypercube.
(40) Analysis of vehicle-manipulator dynamic interaction studies of MIT and technology transfer as appropriate.
(42) Complete emulator for HERMIES-III.
(43) Development of methodologies which allow HERMIES to monitor his own performance.
(44) Algorithms for machine learning based on neural networks tested on HERMIES-IIB.
(45) Implementation of Virtual Time Operating System on HERMIES-III.
(46) Scheduling and load balancing with 512 node hypercube.
(47) Near-real-time graphic simulation of manipulator.
(48) Dynamic model and graphic simulation of manipulator and mobile platform.
(50) Dynamic model and graphic simulation of dual arm manipulator and mobile platform.
(52) Dynamic model and graphic simulation of dual arm manipulator with multi-fingered end effectors.
(53) Implementation of Gabor filter expansion on the hypercube.
(54) Neural network architectures for artificial vision recognition.
(55) Real-time human analog object recognition demonstration.

Journal Paper/Demonstration (cont'd)

(56) 3-D World modelling and update.
(57) Multisensor integration via solution of consistent labelling problem.
(58) Multisensor integration on-board HERMIES NCUBE.
(59) Man-machine task allocation in changing environments.
(60) Synthesis of task allocation with automated planner.
(61) Man-machine symbiosis with feedback learning mechanisms.
(62) 3-D graphical displays.
(63) Computer-aided enhanced sensory feedback.
(64) Context-driven speech recognition for man-machine interaction.
(65) Multi-fingered end effector integrated onto HERMIES-III.
(66) HERMIES upgrade to dual arm manipulation.

arm/tilt control have been replaced with high-speed dc servodrives to permit the sonar ring to be stepped quickly. Consequently, the time required to scan a 180^{o} region in front of HERMIES has been reduced from 80 s to 7 s. The dc servodrive of the tilt platform has been designed to accommodate not only the sonar array, but also an infrared range detector, and dual Sony miniature CCD (charge coupled device) black and white cameras. The CCD cameras are part of a new image processing system obtained to incorporate computer vision within HERMIES' sensor suite. The overall system is an International Robomation/Intelligence P-256 unit, which provides a pixel array of 256 x 256 with 8 bits of gray level and an integral systolic array processor for reasonably high-speed execution of standard image operations.

2. LISP Machine

In the CESAR laboratory, a dedicated LMI LISP machine is used for algorithmic development of high level reasoning in near real time task and path planning. The LISP machine implements task and trajectory plans by returning executable command/control software primitives directly to the on-board distributed digital control system. When this option is used, the LISP machine essentially serves as an immobile fixed nerve center of the HERMIES mobile robotic system. An External Serial Data Link (ESDL) facilitates communication with HERMIES-II and can be operated through a cable, or through a infra-red wireless transceiver.

3. Hypercube Concurrent Processor

The concurrent computation system currently being investigated at CESAR, developed by NCUBE corporation, contains 64 processors (6-D cube) in its initial implementation; the number of processors which can be accommodated potentially is 1024, each capable of running conventional computer programs at about the speed of approximately 2 Vax 11/780's. Each processor has 128 Kbytes of local memory and can communicate directly with up to ten other processors through direct memory access channels. The importance of this design for mobile robotics research is that when full loaded, the hypercube has a capacity of approximately 500 million floating point operations/sec (500 Mflops) contained within a volume < 1 m^3 (including cooling and power supply) with a power consumption of approximately 8 kw. Compilers for Fortran-77 and C are currently available. The NCUBE node processor is a complex chip of about 160,000 transistors that integrates a memory interface, communication links, and 32 bit, general purpose processor. A second NCUBE controller board was acquired to permit up to 16 researchers to simultaneously perform research investigations on the NCUBE machine.

4. CESAR Research Manipulator

The CESARM incorporates several fundamental characteristics important for mobile operation. Mobility requires that overall weight and power consumption be minimized, which implies manipulators designed with low weight-to-capacity ratio. The CESARM manipulator weighs approximately 68 kg (150 lbs.) and can lift approximately 13.6 kg (30 lbs.); a weight-to-capacity ratio of approximately 5, a factor of 4 improvement over typical industrial manipulators. Drive motors for the upper arm roll, elbow pitch, and wrist pitch, jaw, and roll are centralized at the shoulder to minimize the inertia and the actuator size. Note that the 3 degree-of-freedom (DOF) wrist is cable driven.

Complex tasks will require high dexterity. The CESAR research manipulator has 7 DOF plus the parallel jaw gripper to be used as the initial end-effector. The manipulator's low friction drive train, together with the redundant degree-of-freedom, provides an ideal research tool for dexterous manipulation. The manipulator incorporates a unique 3-DOF spherical wrist whose singularities occur only at the extremities of motion. A flange interface between the wrist and the parallel jaw gripper will facilitate research with other end-effectors and multi-fingered hands.

The control system for the CESAR Research Manipulator is a new design based on the VME bus. It utilizes Motorola MC68020 microprocessors and the Microware OS-9 operating system. Amplifier and sensor interface electronics are designed for expansion for a second manipulator and future use in a mobile system.

At present, mass and inertia properties of the manipulator are being determined experimentally for use in a mathematical model, and a simple torsional pendulum has been built for use in determining individual link inertias. The remaining model parameters, such as compliance and friction, will be identified from manipulator test data. This effort will provide a verified model with complete parametric data that should be useful to the entire robotics research community.

5. CESAR Intelligent Machine Laboratory

A new 4200 ft^2 laboratory was constructed for CESAR research in navigation, identification and manipulation. The CESAR team occupied this new laboratory in October 1986.

6. Efficient Data Links and Memory

Additional memory now totalling 8 megabytes was added to our LMI machine to provide a significant upgrade in program execution. In addition, a communications board was procured to permit efficient communication between our LMI machine and HERMIES. Similarly, a DR11W data link was obtained which permits high speed (1 megabyte/second), parallel, bi-directional transfers between the NCUBE computer and a VME bus. The NCUBE is connected, via the VME bus, to (a) the custom computer hardware controlling CESARM, CESAR's experimental manipulator; (b) the Maxvideo vision system for rapid execution and preprocessing of images.

7. NCUBE Medium-Resolution Graphics System

This medium-resolution, medium-speed graphics system comprises an NEC color monitor and a Matrox MSBX-900 Graphics Controller. The controller provides a resolution of 640 x 640 x 8 bits/pixel. It can draw up to 35000 vectors/sec, and can dump two complete-screen images per second. It utilizes a Hitachi HD63484 Advanced CRT Controller which incorporates a large number of graphics drawing commands, split screens, windows, etc. This system is used in algorithm development for image processing, and also for general-purpose computer graphics.

8. HERMIES-IIB

HERMIES-II is being updated to a new form called HERMIES-IIB. This upgrade involves improvements to the robots' basic mobility chassis and on-board computational resources. These modifications will improve reliability and increase the degree of autonomy. A VME system provides all control and sensor data inferencing and utilizes a Motorola MC-68020 32-bit microprocessor. The VME system also serves as a data gateway to an AT backplane which houses a 4th order (16 nodes) hypercube parallel computer based upon the NCUBE Corporation 32-bit node processor chip. The on-board hypercube provides the equivalent processing speed of approximately 24 Vax 11/780 processors. The VME system facilitates the on-board integration of a reasonably high-performance computer vision system using Data Cube Corporation expansion boards which provide 384 x 512 x 8 color resolution and traditional image processing functions. Mass storage is provided by a 20 megabyte hard disk and one high capacity floppy drive. It is believed that HERMIES-IIB will represent one of the most computationally powerful mobile robots in operation.

D. Facility Requirements: Anticipated Acquisitions

1. Laser Range Scanner

Serious research in sensor fusion to achieve realistic 3-D vision sensing requires accurate range measurements (currently we rely on sonar with extremely coarse resolution) be integrated with our existing 2-D vision system.

2. HERMIES-III

CESAR is actively pursuing the next phase of research in which the scale of operations will be increased into the realm of human sizes in terms of manipulation geometry and loads. To accomplish this, the HERMIES-III robot is being designed and fabricated. HERMIES-III will be an electric-powered robot which incorporates the CESAR research manipulator and a shoulder/torso mechanism mounted on a modified industrial automatic-guided vehicle (AGV) chassis. Initially, only a single manipulator will be installed, but provisions for adding a second arm at a later date are included. HERMIES-III will utilize the combined VME/68020 and hypercube computer assembly discussed above. A new faster and more rigid pan/tilt sensor platform has been developed and the sensor suite includes the five-element sonar ring, a Data Cube CCD camera pair, and laser range scanning system. In this configuration, HERMIES-III will be capable of handling relatively large loads from floor level to approximately 2 meters off the floor.

3. Mobile Control System

The control system for the manipulator was initially designed to a great extent for conversion to battery powered operation when moved from the fixed pedestal to HERMIES-III. Amplifiers and interface electronics were packaged separately from power supplies and designed for 24 and 72 VDC operation. However, some repackaging is anticipated to meet

HERMIES-III space constraints and cabling constraints. It is anticipated that HERMIES-III will have a control architecture which includes the VMEbus and the hardware integration of the manipulator's VMEbus control system will be relatively straightforward.

4. 3-D Graphics System

Recent developments in the area of advanced graphics chips will soon find their way into commercial VMEbus products which may provide an alternative to special purpose advanced graphics workstations. The need for a graphic display suitable for real-time or near-real-time solids modeling for research in the area of path planning is particularly significant for manipulators with redundant degrees of freedom such as the CESAR Research Manipulator and will be even more critical with the addition of a second manipulator.

5. Torso/Sensor Package

The basic configuration of the manipulator includes an offset shoulder which is well suited for the addition of a second manipulator. However, the pedestal and shoulder pitch drive assembly must be replaced with a torso/sensor package to allow the addition of the second arm and the integration of TV camera(s), a laser range finder, and possibly other sensors. These sensors will need pan and tilt drives at a minimum. The torso/sensor package may include a multi-degree-of-freedom waist motion to allow motion of the arm pair relative to the HERMIES-III vehicle. The addition of a hoist to the torso/sensor package will be considered. It would allow limited experiments in coordinated manipulation prior to the addition of the second arm and more complex experiments following.

6. Second Manipulator

A second CESAR Research Manipulator will be needed to support research in the coordinated control of multiple manipulators.

Modifications required for the addition of joint, cable tension, and force/torque sensors to the first CESAR Research Manipulator will be included in the second.

7. Multi-Fingered Hands

In keeping with the recommendations of the CESAR Advisory Committee and consistent with the proposed research, multi-fingered hands will be added to the existing CESAR Research Manipulator and to the second manipulator proposed above. Existing multi-fingered hand designs will be considered. However, even if a suitable existing design can be identified, integration of the hand into the CESAR research manipulator will likely be a significant mechanical design effort involving major modifications to or replacement of the forearm and wrist.

8. High-Speed Communication System (microwave or infra-red)

This wireless data communications subsystem is required to allow HERMIES-III to operate with CESAR's support computers (NCUBE, LMI) with no umbilical while permitting transmission of extensive data (i.e., video). Our current RF link is fine with transmission of limited sonar data, but would be overwhelmed in dealing with vision data.

9. Integrated HERMIES-III Man-Machine Station

This subsystem is essential for serious research in the man-machine interface issue, and for research in task allocation as systems evolve from teleoperation to autonomy.

10. Additional NCUBE Processors

As indicated in the text, our NCUBE machine can accommodate up to 1024 processors, for which we only currently have sixty-four. Additional processors are required to effectively deal with real-time requirements for computationally intensive processes such as computer vision, multisensor integration, robot dynamics, etc.

CAPITAL EQUIPMENT NEEDS

	FY'88	FY'89	FY'90	FY'91
• Laser Range Scanner	110			
• HERMIES-III Mobile Platform	65	40		
• Mobile Control System	30			
• 3-D Graphics System		65	40	
• Torso/Sensor Package	35	40	60	
• Second CESAR Manipulator		75	125	
• Multifingered Hands				150
• High-Speed Communications System	30			
• Integrated HERMIES-III Man-Machine Control Station				60
• High Resolution Vision System (1024 x 1024)				150
• Additional NCUBE Processors		100	100	100
TOTALS ($000)	270	320	325	460

VIII. MANAGEMENT STRUCTURE AND RESEARCH STAFF

The CESAR organization is generally structured along disciplinary lines as shown in Fig. 20. Senior staff members and their associated technical interests are listed in Fig. 21; illustrative resumes follow. The cross-disciplinary activities are embedded within the group activities. The permanent advisory committee provides periodic inputs to the annual planning and evaluation process of CESAR.

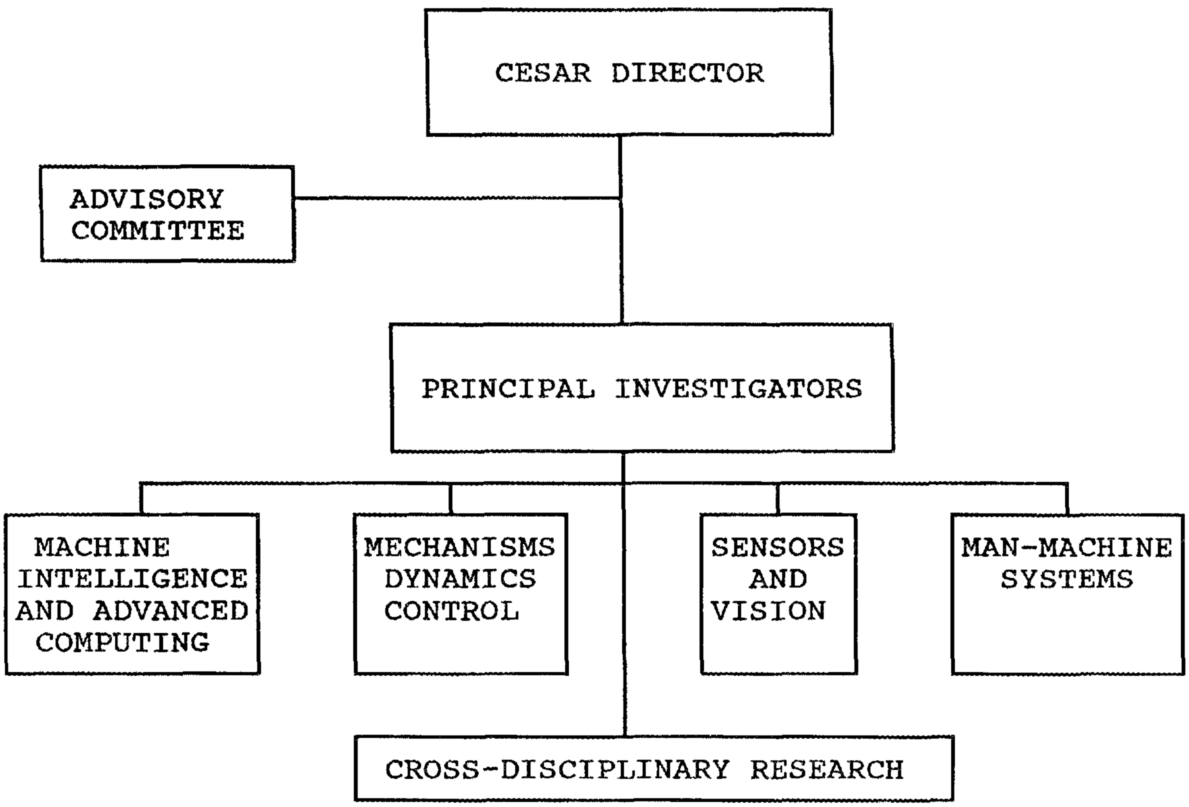

Fig. 20. CESAR Management Structure

C. R. Weisbin
Director

Staff Members	Technical Interests
S. M. Babcock	Dynamic Systems Analysis and Control
J. Barhen, Principal Investigator	Concurrent Systems and Algorithms, Cellular Automata, and Neural Networks
M. Beckerman	Sensitivity and Uncertainty Analysis in Decision Making
B. Burks	Mobile Robot Architecture and Operation
G. de Saussure	Strategy Planning and Machine Intelligence
J. R. Einstein	Concurrent Computation and Real-Time Operating Systems
C. Glover	Concurrent Computation and Multi-Sensor Integration
M. Goldstein	World Modelling and Path Planning
W. R. Hamel Principal Investigator	Dynamic Systems Analysis and Controls, Manipulator Design, and Mechanical Nonlinear Systems Analysis
J. P. Jones	Concurrent Computation and Machine Vision
C. C. Jorgensen	Machine Learning and Neural Network Simulation
R. C. Mann	Concurrent Computation, Machine Vision, Pattern Recognition, Multi-Sensor Integration, and Systems Theory
E. M. Oblow	Sensitivity and Uncertainty Analysis in Decision-Making
F. G. Pin	Man-Machine Cooperative Problem Solving, World Modeling, and Machine Learning

Fig. 21. Ph.D. Staff Members and Their Associated Technical Interests

C. R. Weisbin

- Director, ORNL Robotics and Intelligent Systems Program (RISP). The mission of this laboratory-wide program includes all robotics and related artificial intelligence and parallel computing for the Departments of Energy and Defense, NASA, and other sponsors.

- Director, Center for Engineering Systems Advanced Research. The mission of this center is long-range, energy-related research in intelligent control systems.

- Section Head, Mathematical Modeling and Intelligent Control, Engineering Physics and Mathematics Division, Oak Ridge National Laboratory, Oak Ridge, TN 37831.

- Associate Professor, The University of Tennessee, Knoxville, Computer Science Department, teaching Introduction to Artificial Intelligence.

- Associate Editor, "IEEE Expert: Intelligent Systems and Their Application."

- Associate Editor, Impact, published quarterly by the Society for Machine Intelligence (SMI).

- Martin Marietta Corporation Artificial Intelligence Steering Committee.

- DOE Representative to the Department of Defense, Joint Directors of Laboratories, Robotics Technology Panel reporting to Major General Cercy.

- Eng.Sc.D. in 1969 from Columbia University, New York, NY, Nuclear Engineering - Post doctoral year at Columbia University, 1970.

- 1973-Present - Engineering Physics and Mathematics Division, Oak Ridge National Laboratory, Oak Ridge, TN.

- Contributed to and edited a book, "Sensitivity and Uncertainty Analysis of Reactor Performance Parameters," Vol. 14, Advances in Nuclear Science and Technology 1982. (Co-authors at ORNL, General Electric, Argonne National Laboratory, Israel).

- Program Chairman, Second International Conference on Artificial Intelligence Applications, 1985.

- Program Committee, 1987 IEEE International Conference on Robotics and Automation.

- Research interests in robotics, concurrent computation, machine intelligence, decision making, sensitivity and uncertainty analysis.

Jacob Barhen

- Head, Machine Intelligence and Advanced Computer Systems Group, Engineering Physics and Mathematics Division.

- Associate Professor, Department of Computer Science, University of Tennessee, Knoxville; teach graduate courses: Introduction to Concurrent Supercomputers; Introduction to Artificial Neurocomputers.

- Principal Investigator (recent projects)

  - Hypercube VLSI Supercomputers in Ballistic Missile Defense: Advanced Methodologies for Sensor-Based Kinetic Energy Weapons Fire Control; source: DOD/AFWAL, FY'87-89, $1500K.
  - Neuromorphic Systems and Hypercube Methodologies for SDI Applications; source: Joint SDIO/DOE Innovative Concepts Program, FY'87-89, $1300K.
  - Intelligent Control Systems (Center for Engineering Systems Advanced Research); source: DOE/BES/ERP, FY'83-87, $4M

- Recent Professional Activities

  - U.S.-Japan Human Frontier Science Project (Sixth Generation Intelligent Computers); invited as U.S. representative; the Panel's first meeting will be in 1987.
  - JASON: Invited to participate in the 1986 meeting of the President's Advisory Panel; lectured on hypercube supercomputing.
  - National Science Foundation Select Panel on research issues in dynamical systems; co-chaired committee on supercomputing.
  - Chairman and organizer for the 1987 IEEE Symposium on Advanced Computer Architectures for Robotics and Machine Intelligence: "Neural Networks and Neurocomputers," Raleigh, NC (4/3/87).
  - Program Chairman (Supercomputing), 1987 International Computers in Engineering Conference, New York, NY (8/8-13/87).
  - Member, program committee, IEEE Second Annual Conference on Artificial Intelligence Applications, Miami-Beach, FL (12/87).

- Sc.D in 1978 from the Technion-Israel Institute of Technology, Nuclear Engineering. Since 1978 with Oak Ridge National Laboratory.

- Author of over 70 publications. Referee NSF and DOE/BES.

- Current research interests include artificial neuromorphic systems (neurocomputers and nonlinear dynamical systems), machine intelligence, advanced operating systems for hypercube concurrent supercomputers, and fast optimization methodologies for combinatorially complex problems (e.g., simulated annealing).

- Member: AAAI, ACM, ADPA, IEEE.

William R. Hamel

William R. Hamel has a BS degree in mechanical engineering from West Virginia University, a MSME from Oklahoma State University, and a PhD from the University of Tennessee. He is a member of the Sigma Xi, Tau Beta Pi, and Phi Kappa Phi honoraries.

His professional experience began at TRW Systems in Houston where he worked as control systems analyst on the Apollo Lunar Module digital autopilot software during Apollo missions 8 through 13. Subsequent experience was with the Measurement and Controls Technology Department of Union Carbide Corporation's South Charleston Technical Center where he developed computer simulations of chemical process control systems.

Since 1972, Dr. Hamel has been a member of the research staff at the Oak Ridge National Laboratory where he is assigned to the Instrumentation and Controls Division. At ORNL, he has worked in measurements and control development including distributed digital process control systems for highly radioactive environments.

Recently Dr. Hamel has been concentrating on the development of robotics systems for radioactive and unstructured work environments. He has studied remote technology as a method for reducing occupational radiation exposure in the maintenance of nuclear power plants. As leader of the Robotics and Electromechanics Group, he directs a research team with expertise in robot systems controls, electronics, and sensing. This group is a major contributor to the development of an advanced telerobotic systems involving a new modularized force-reflecting servomanipulator concept which utilizes a multi-processor digital control system. The group is performing robotics research and development for NASA, DOD, and other facilities in the Oak Ridge area. As a principal investigator in the Center for Engineering Systems Advanced Research (CESAR), he is performing basic research in autonomous intelligent robotic systems for hazardous unstructured environments. His research interests are in high performance manipulator design, manipulator dynamics and control, and robot sensor integration.

Dr. Hamel has written numerous reports and papers in the area of nuclear remote technology and its relationship to the advancing field of robotics. He maintains memberships in the ASME, IEEE Society of Systems, Man and Cybernetics, and Robotics International.

Charles C. Jorgensen

- Ph.D. Quantitative Psychology, University of Colorado, 1973
- Research Fellow AI, Carnegie-Mellon University, 1974
- Chief Combat Developments Team, U.S. Army Research Institute, 1974-1983
- Senior Scientist, Reliability and Human Factors Group, ORNL, 1984
- Senior Scientist, Machine Intelligence and Advanced Computation Group, CESAR 1984 - Present
- Chairman, Department of Defense Technical Advisory Group on Manned Systems Simulation
- Member, National Academy of Sciences Panel on Human Operating Modelling
- Advisor, National Security Industry Association on Training
- Member, Sigma XI, Psi Chi, Who's Who in Science and Technology, 1986
- Winner, Most Innovative Technology Award. American National Society International Topical on Human Factors, 1985
- Nominated, RIST Prize in Operations Research, 1982
- Over 50 technical publications in the areas of machine learning, simulated neural networks, human modelling, and robotics

IX. ACKNOWLEDGEMENTS

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APPENDIX A

1986 REPORT OF THE CESAR ADVISORY COMMITTEE

CENTER FOR ENGINEERING SYSTEMS ADVANCED RESEARCH
AT THE OAK RIDGE NATIONAL LABORATORY
(CESAR/ORNL)

Advisory Committee Report
of October 15-17, 1986
Site Visit

Advisory Committee Members

Wayne Book

Eward Heer

John Palmer

Harry Pople

Michael Rabins (Chairman)

Karl Reid

CENTER FOR ENGINEERING SYSTEMS ADVANCED RESEARCH

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CENTER FOR ENGINEERING SYSTEMS ADVANCED RESEARCH AT THE OAK RIDGE NATIONAL LABORATORY (CESAR/ORNL)

Advisory Committee Report of October 15-17, 1986 Site Visit

INTRODUCTION

During October 15-17, 1986, the CESAR Advisory Committee met at the Oak Ridge National Laboratory. A copy of the agenda for that meeting is appended as ATTACHMENT 1. Prior to the meeting, each Committee member was sent relevant papers and background material. Each Committee member was also asked to come prepared to lead the review discussions of one or two of the scheduled subject presentations. This arrangement worked well with only minor modifications.

The meeting covered all items of the agenda. The new visit format involving sub-group meetings with intensive detailed discussions permitted greater in-depth review than heretofore. At the outset of the meeting the Committee was given a list of four questions (ATTACHMENT 2) which the CESAR program director requested the Committee to consider. These questions are addressed throughout the report as relevant to each section and also in the report summary.

At the 1985 visit the Committee discussed in some detail with the program director the charge under which it should be operating. As a result of those discussions, the "Charter for the CESAR Advisory Committee" was rewritten and sent to the Committee on February 5, 1986 (ATTACHMENT 3). At its October 15-17, 1986 meeting the CESAR Advisory Committee members unanimously concurred in this new Charter.

Since Dr. Oscar Manley from the U.S. Department of Energy (Basic Energy Sciences Program) was present at the meeting, there was some discussion about the future renewal funding proposal that will be submitted by ORNL to DOE prior to our next Advisory Committee meeting. It was agreed that individual Committee members will assist in the proposal drafting on only an informal and as-requested basis. However several general observations were made in regard to this proposal that will be included in the final summary section of this report.

On the first day of the visit the Committee spent almost two hours in the new CESAR Intelligent Machine Laboratory facility at ORNL and observed several important demonstrations. The successful demonstrations of actual robot navigation in a changing environment (moving obstacles) and vision controlled manipulation impressed the Committee, as did the computer demonstrations of image segmentation using the NCUBE machine and a pattern seeking algorithm. The progress on the CESARM assembly was also observed.

The report which follows is organized, in no special order, into six sections and a summary as follows:

Task Scheduling & Load Balancing	-	J. Palmer
Expert System Control of Robots & Learning	-	E. Heer
Characterization of CESARM & Soldier Robot Interface Project (SRIP)	-	K. Reid
Uncertainty Analysis	-	H. Pople
Vision	-	W. Book
Review of Program Plan & Summary	-	M. Rabins

TASK SCHEDULING AND LOAD BALANCING (J. Palmer)

Summary

The progress in scheduling seems to go from Roses to Simulated Annealing to Neuron Networks. These approaches are characterized by the following:

1) Roses: slow, static scheduling, simplified model, non optimal.
2) Simulated Annealing: faster, more realistic, more optimal.
3) Neuron Networks: fast (real-time), dynamic, new and untried.

Both Roses and Simulated Annealing have been implemented (I think) and have provided good results and future directions. There have been papers written on both efforts. Using Neuron Networks for scheduling, as far as I know, is a new idea and the work is just beginning.

In the area of load balancing, the major work has been the implementation of the Virtual Time Kernel on the hypercube. The initial implementation was on a simulator and the porting of the Kernel to the NCUBE has just begun. This is a major project and, if successful, will show the implementors to be quite adept at both parallel programming and operating system principles.

Evaluation

The progress since the last review is very impressive. A large amount of software has been produced; several papers have been written; and some new ideas have sprung up which appear to have support from several agencies. Both the quantity and the quality of the work has been very high. Many of the concerns I had at the last review have been more than adequately answered. For example, the Oak Ridge group has been collaborating with both Dr. Jefferson of UCLA and Steve Colley of NCUBE. Both are very well qualified in these areas and I know that Steve has been impressed with the abilities and progress of the Oak Ridge group.

Recommendations

In conclusion, I have two concerns and one recommendation. The first concern is that there seems to be a very large commitment to Neuron Networks. In the past these concepts have not proven very useful. However, times and technologies change, and perhaps this is the right time to readdress the issues. I think I would want to know why they might be a good idea now. A second concern, which is related to the first, is that it is easy to get fragmented by attempting to please too many bosses. New research contracts should be accepted with some care. It is almost always possible to define new research as contributing to the overall goals of the project, but sometimes the necessary stretch is too strong. My primary recommendation is that work on scheduling and load balancing be published in a seriously refereed journal. I think the work is good, and should command universal recognition; it must also be published.

EXPERT SYSTEM CONTROL OF ROBOTS AND LEARNING (E. Heer)

Summary

During the past year CESAR has made several valuable contributions in the area of robot learning and expert system control. The papers "Robots Navigation Algorithms Using Learned Spatial Graphs" and "A Real-Time Expert System for Control of an Autonomous Mobile Robot Including Diagnosis of Unexpected Occurrences" are representative of these contributions. The first investigates the problem of navigating in completely new or partially explored terrain and uses a learning technique based on spatial graphs and Voronoi diagrams. Using acquired sensor data, navigation planning in an unchanging environment is gradually accelerated with experience. The latter capitalizes on several attractive features of expert systems with rule-based knowledge representation to deal with continuously sensed, changing environments. The explicitness and homogeneity of the knowledge representation facilitates explaining, verifying and modifying the rules which determine the robot's behavior.

Evaluation

Both pieces of work that are summarized above and their future extensions are pioneering the field of expert system control of robots and learning. To date very little in terms of demonstrable work has been done in these areas. The fact that the results of this work were demonstrated, at least in principle, using HERMIES, puts these investigations at the forefront of current intelligent robotics research. The work is progressing in the right direction.

Recommendations

We believe that future work should extend the learning concepts to more complex navigation problems. To use the expert systems approach for higher level controls of robots appears to be a good and novel choice. While initially it is probably appropriate to use a commercially available expert system shell (as is being done now by using PICON), we believe that in the future it will become necessary to decide on the development of an expert system tailored to the peculiar requirements of the CESAR objectives. This is especially the case if the expert system will be put on the NCUBE. In this connection it might be worthwhile to investigate the use of the expert system shell ART which is also under consideration for Space Station applications.

Personnel

The individuals involved in this research have the required background and have acquired the necessary experience to do first class work. The incorporation of additional, appropriately trained, more junior talents should be taken under consideration to expand the overall efforts in expert system control of robots and learning.

CHARACTERIZATION OF CESAR RESEARCH ARM MANIPULATOR (CESARM) AND SOLDIER ROBOT INTERFACE PROJECT (SRIP) (K. REID)

Summary

The CESARM Program has completed Milestone (27) of the 5 year CESAR Research Plan - fabrication and assembly of the CESAR research manipulator. Substantial investments are evident from BES and ORNL internal funds to date in hardware and software development for CESARM. The opportunity now exists for directing primary efforts of research personnel to research issues in mechanisms, dynamics and controls.

The SRIP effort is a mobile telerobot testbed development under contract with the U.S. Army Human Engineering Laboratory (HEL) and in cooperation with Odetics, Inc. The telerobot test bed is to be used to evaluate opportunities for manpower amplification, hazard reduction, and threat reduction -- e.g., explosive ordnance disposal, combat vehicle NBC support, etc. The ORNL responsibility is for:

- Systems Integration,
- Controls/Electronics/Wrist Mechanisms, and
- Soldier Machine Interface and Remote Viewing.

The relationships with the CESAR/BES Program include:

- PI common to both CESAR & SRIP (Hamel).
- Some design experience (e.g., 3 DOF wrist) may be transferable to hardware development under the BES program.

- Some control algorithm development may be transferable (HEL to BES or vice versa).
- BES will have limited access to the Army's mobile telerobot to evaluate navigation strategies and advanced manipulator control algorithms which are being developed under BES support. The Army has a long-term interest in extending the telerobot to an advanced autonomous vehicle with dexterous manipulation capability.
- Another HEL subcontractor (MIT-Dubowsky) will provide a theoretical basis for the vehicle-manipulator dynamic interaction that will be of value in BES developments.

The discussion in the remaining portion of this section pertains only to the CESARM Project.

Evaluation

The high quality of the CESARM hardware design effort is apparent. The thorough and excellent job done will greatly facilitate future research which depends on the CESARM testbed. The experience gained by the engineering staff from previous ORNL technology development activities has greatly benefited the BES program.

This subgroup has established research goals that are consistent with the recommendations from the Leesburg workshop. Accomplishment of these goals will be fully supportive of other CESAR/BES program goals, and will result in fundamental contributions. Availability of a unique seven degree of freedom arm with compliant drives and high back drivability will allow work on, research issues previously not addressed, involving highly dexterous, highly mobile, and fast acting manipulators. Planned research on precision force control should be enhanced by the high back drivability feature. In addition, the arm has been appropriately designed to facilitate the long-term goal of development of a two-arm mobile robot testbed.

Recommendations

A new milestone should be considered to account for potential transferability of results from an HEL subcontractor's (MIT-Dubowsky) work on vehicle-manipulator dynamic interaction.

A new milestone should be considered which addresses the need for an integrated multi-fingered end effector on the CESARM to achieve the goal of high dexterity.

Personnel

There is a pressing need to add one full-time Ph.D. level staff members with a background in system dynamics and control theory. Milestones presently forecasted and those which should be considered cannot be achieved within the required timeframe otherwise.

UNCERTAINTY THEORY (H. Pople)

Summary

The work on uncertainty theory ("O-Theory-A Hybrid Uncertainty Theory" by E.M. Oblow) is aimed at a unification of several disparate theories of evidential reasoning, including Bayesian inference, Demster-Shafer theory, and Zadeh's theory of fuzzy sets. There are several motivations for this work ranging from the pragmatic goal of providing an improved framework for judgmental decision-making in expert systems, to the theoretical goal of obtaining a derivation of the new theory, working from first principles of group theory.

Evaluation

It is difficult for members of this committee to gauge the degree to which Oblow's theory has attained, or has the potential to attain the various goals that have been set. For this reason, we find it particularly important that this work be subjected to the peer review process inherent in publication in good refereed journals. We are encouraged that this external review process appears to be well underway. However, to date the publications seem oriented towards definition and algebraic results obtained using the O-theory operators, and give little insight with respect to either the pragmatic or deeper theoretic goals.

Oblow claims that O-theory can, by virtue of its probabilistic tolerance of contradictory assertions, enable sound judgments to be obtained in the face of a self contradictory set of hypotheses. If this can be shown to be true, a working "inference engine" that employs O-theory constructs may ultimately be shown to be superior to current methods for combining evidence used in expert systems. What we have yet to see, however, is a realistic example -- an approximation at least to a real-world decision scenario -- that unequivocally makes this case. We are not alone in arguing the need for concentration on the analyses of realistic test cases that demonstrate the pragmatic benefits of the proposed theory. Even Zadeh, we are told, has deferred judgment with respect to the real potential of O-theory pending demonstration of its ability to handle certain test cases that present a challenge to Zadeh's theory of fuzzy sets.

Recommendations

While we applaud the effort to obtain significant theoretical results, we recommend that the major short-term thrust of this project be development of convincing examples of usefulness of this approach. The reason for this immediate concern is that in other activities of the CESAR center, decisions are being made with respect to the framework to be adopted for implementing a variety of expert systems. If the emergence of O-theory is to impact these decisions appropriately, its true potential must be illustrated, tested, and proved without delay.

Personnel

The Committee believes that it will be important for E.M. Oblow to have increased future planned opportunities to interact with the CESAR staff working on other aspects of the overall CESAR program. Through these interactions, for example with the navigation or vision or expert system control of robots efforts, the future real world tests of the proposed O-theory are more likely to emerge.

VISION (W. Book)

Summary

This review of vision research at CESAR is based on one technical report, "Modelling Early Stages of Human Vision" (CESAR-86/05), provided to the committee in advance of the presentations, a presentation, a demonstration and personal discussion.

The vision research underway was presented by Reinhold Mann and Judd Jones. The work is based on a paradigm of vision as decomposed into low, intermediate, and high level sections. The lowest level of vision interfaces directly with the sensing transducers. The highest level provides a description of the scene in aggregate conceptual levels in terms suitable for decision making by an intelligent machine. Dr. Jones is concentrating on the lower levels of processing with techniques based primarily on filtering and related signal processing techniques, especially those with a biological basis. Various filters are under consideration to provide an alternative image which will emphasize features of the image. The premises on which the research is based include the following:

1. Much conventional research converts the two dimensional image to a symbolic form almost immediately. A contribution can be made by considering an approach which keeps the image representation at the intermediate level.
2. Local and global features cannot be detected by the same filtering approaches.
3. Sensor fusion can be pursued at either low or high levels of vision.

Dr. Mann is interested in the high levels of processing. His presentation was very brief and involved his work from more than 5 years ago in the detection of motion. This work seems quite relevant to the CESAR mission and complementary to the work of Dr. Jones. Their work as a team is very desirable.

A demonstration of the effect of filters on simulated images was made and a conventional approach of vision for HERMIES was used in its demonstration.

The research described in the technical report provided for background reading was authored by a totally different set of people. This report by Jorgensen, et.al. was quite lengthy and to the greatest extent was tutorial in nature. This was partially an effort to incorporate the ideas of Prof. Gawronski, a Polish immigrant at the University of West Florida. The experiments correlating the performance of algorithms and humans in response to standard illusions was interesting and apparently a contribution to the field. Dr. Jorgensen's interests seem to have shifted completely out of this area of research. It is important to the CESAR Program and, one would suppose, to Dr. Jorgensen that this work be published, or at least submitted to an archival journal in the form of a paper significantly distilled from the report. The IEEE Transactions on Systems, Man and Cybernetics would be a suitable forum. This is the stated intention and one would hope that the change in interests of Dr. Jorgensen will not prevent this from happening. These concepts will be implemented by Mann and Jones in the hardware for HERMIES. The implementation is also being carried forward by the contracted work at Louisiana State University in graph theory.

Dr. Moshe Goldstein is also undertaking work in combinatorial geometry which has a basic importance to the missions of CESAR. The effort will be the modeling of the visual scene in terms of primitives that can be used for the calculation of geometric properties which would be useful to an intelligent machine operating in the environment being observed. An example is the distance between two obstacles in the path of navigation. He has just begun his work with CESAR and will be present for one year as a visiting researcher.

Collaboration with the University of Michigan (Prof. Wehe) and the University of Tennessee (Prof. Gonzales) under sponsorship of DOE Nuclear Energy is expected in the coming year. CESAR may also be the system integrator for the efforts of these and two other universities similarly supported. The details of this expected collaboration are not yet known.

Some additional vision related equipment is expected in the near future. A faster data link to HERMIES and the on board NCUBE will improve the experimental capabilities.

<u>Evaluation</u>

The research in vision is moving rapidly forward in spite of some disruption in staffing and modification of approach.

Although Dr. Jones and Dr. Mann have only recently joined the staff of CESAR they seem to have a good sense of direction and training very appropriate for the tasks being undertaken.

Work by Mann, Jones and Goldstein is not yet at the point that results are available for evaluation. The directions and approaches seem sound, however.

Work by Jorgensen seems to have included a substantial amount of effort in background work and collaboration with Dr. Gawronski which could go "down the tubes" due to a change in his research emphasis unless strong advisory leadership is provided. Results obtained to date should be put in a publishable form if possible by Dr. Jorgensen. This somewhat inconsistent attitude to a research area, or at least its approach, could give ample future ammunition to a critic of CESAR. Overall work by Dr. Jorgensen is of high quality and he has been very productive in the past year by the usual measures. His new work in neural networks is more consistent with his long term interests and the vision researchers now active are committed to vision research that will support the CESAR objectives.

Contracts with specialists in graph theory and computer science serve the objectives of the program well.

The collaboration with U. of Tennessee and U. of Michigan is a positive step to accelerating the progress in the important and difficult area of vision.

Recommendations

1. The latest vision team seems very well qualified and should be encouraged to collaborate with each other and with the overall CESAR team as they are doing in the case of HERMIES. Connections with "O-Theory" (i.e., text cases) would complement both efforts as well.

2. Stability in the research team on vision must be improved over that observed during the past year. It appears that steps have been taken to adequately accomplish this.

3. Responsibility to carry through to journal publication the research undertaken needs to be encouraged. This will help reduce the adverse effect of the abrupt switching of topics or approaches on the long term reputation of CESAR and progress of the research.

4. The effort in combinatorial geometry seems closely related to work in computer aided design and graphics. The rich literature in this area should be explored to avoid wasted effort in rediscovery.

5. The vision capabilities of HERMIES at this point are not state-of the-art. Implementation of the research progress on the HERMIES test bed will enhance the integrated value of the CESAR research and image.

REVIEW OF PROGRAM PLAN & SUMMARY (M. Rabins)

At the time of the October, 1986 visit the CESAR Advisory Committee members were provided a 34 page copy of a "Research and Development Program Plan for CESAR" dated November, 1986. While there was no opportunity for a detailed review of this draft plan as a group, individual members of the Committee did have an opportunity to discuss it with the program director and all of the members had a chance to read it and informally discuss it.

The Committee reiterates all of the general positive statements about the research planning process and the previous plan itself that appeared in the October 15, 1985 Site Visit Report. Further, it appears to the Committee that all four of the questions raised (on page 3 of the previous report) about the 1985 plan have been satisfactorily addressed in the 1986 plan. The format of the 1986 plan is well-suited to easy understanding and is particularly well-structured for easy updating and modification each year.

The issue of near-term and long-range research planning takes on added significance in view of the recently announced "Robots and Intelligent Systems Program" (RISP) at ORNL under the management of the CESAR program director. It is clear that there will be complementarity between the RISP and CESAR program efforts. The expanded responsibilities associated with RISP will require careful planning of the kind evidenced in the CESAR 1986 Research Plan.

It was noted in the introduction that there was brief general discussion during the 1986 site visit of the forthcoming proposal from ORNL to DOE for funding renewal. The five original DOE criteria for judging the quality of basic research proposals remain in force:

1. Is it a good idea?
2. Is it something new?
3. Is the proposer capable of conducting the work?
4. Can it be done at the place proposed?
5. It is within the definition of Engineering Research and within the mission of the Department of Energy?

The Committee believes that the ongoing CESAR research summarized and evaluated in the previous sections of this report meet these 5 criteria.

Further, in regard to the issue of recruitment of a senior staff member (see the 5 points made on page 2 of the 1985 Committee report), the Committee believes that this matter is no longer at issue. The CESAR research program has made impressive progress, and is well-managed. The addition of a senior research staff member is no longer viewed as a sine qua non to successful growth of the program. However, if the opportunity presents itself for the CESAR program to hire a well-known and highly-regarded researcher in one of its key program areas, then the Committee believes the program should take advantage of such an opportunity.

Finally, by way of summarizing some of the key points made in this report the four questions posed by the program director (see attachment) will be addressed next.

SUMMARY

1. In general, the CESAR program research activity appears to be addressing the appropriate problems with the correct research approaches and with high overall potential value for real future contributions. There were some mild cautionary concerns voiced about continuity in staffing and research approaches in the vision program, real-world testing of O-Theory and monitoring the viability of the neuron network research approaches as they develop. Overall, however, the Committee was very favorably impressed by the research approaches and research results reported.

2. While time did not permit discussion of specific candidates for potential new staff positions, there was general concurrence on needs. First, there is the need for a new controls staff member to support the work of and interact with Drs. Hamel and Babcock; and second, there is need for new expert systems staff to work with G. de Saussure et al. It is recommended that CESAR staff call upon the Committee members in a one-on-one mode to solicit names of candidates as staff positions become open.

3. The initiation of a second focus of the CESAR program on plant management and maintenance is still viewed by the Committee as premature based on present CESAR program objectives and staff levels, and not appropriate for inclusion in an ORNL proposal to DOE for funding renewal. However, this judgement could change as the new RISP program grows and as relevant basic research issues emerge relating to plant management and maintenance.

4. The Committee fully concurs with the current draft of the CESAR Program Plan. The only general modification that might be considered is the addition of flexibility into the planning process so that new research initiatives (e.g., neuron networks) or relatively sudden shifts in research approaches (e.g., vision) can be accommodated. Alternately, the planning process could introduce checks and balances on the review of such major shifts when they are first introduced.

In conclusion, the Committee is very favorably impressed by the management of and the rapid growth of the CESAR program and the program's truly noteworthy research accomplishments. The Committee is proud of its modest role in helping the CESAR program attain its present stature and level of accomplishments.

ATTACHMENT 1

AGENDA
FOR CESAR ADVISORY COMMITTEE MEETING
October 15, 16, 17, 1986

OCTOBER 15

8:30 - 10:00	CESAR Overview - Building 6010		C.R. Weisbin
10:00 - 10:15	Coffee Break		
10:15 - 11:45	Task Scheduling (Roses)	Expert System Control of Robots	Explosive Ordnance Disposal
	J. Barhen 6010 Conf. Room	G. deSaussure 6025 Conf. Room	W.R. Hamel Trailer Conf.
	(Palmer & Rabins)	(Pople & Heer)	(Book & Reid)
11:45 - 1:00	Laboratory Tour and Demonstrations (New Lab. Navigation with Moving Obstacles, CESARM, Vision)		W.R. Hamel
12:00 - 12:20	Image Segmentation Using the NCUBE		J.P. Jones R.C. Mann
12:20 - 12:30	Vision Controlled Manipulation		S.M. Killough
12:30 - 12:40	Robot Navigation		G. deSaussure
12:40 - 1:00	Pattern Seeking		Bob Glassman
1:00 - 2:15	Lunch (Brough In)		
	(Informal discussion with CESAR Staff - 6010 Conf. Room)		
2:15 - 3:45	Load Balancing	Uncertainty Analysis	Vision
	J. Barhen 6010 Conf. Room	E.M. Oblow 6025 Conf. Room	J.P. Jones Trailer Conf.
	(Palmer & Book)	(Pople & Heer)	(Reid & Rabins)
3:45 - 5:00	Characterization of CESARM	Learning	Review of Program Plan and FY-87 CESAR Demonstration
	S. Babcock 6010 Conf. Room	C.C. Jorgensen 6025 Conf. Room	C.R. Weisbin Trailer Conf.
	(Palmer & Reid)	(Pople & Heer)	(Book & Rabins)

ATTACHMENT 1 (cont'd)

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OCTOBER 16, 1986

8:30 - 100	Explosive Ordnance Disposal	Task Scheduling (ROSES)	Expert System Control of Robots
	W.R. Hamel Trailer Conf.	J. Barhen 6010 Conf. Room	G. deSaussure 6025 Conf. Room
	(Heer & Palmer)	(Pople & Book)	(Rabins & Reid)
10:00 - 10:45	Coffee Break		
10:45 - 11:45	Vision	Load Balancing	Uncertainty Analysis
	J.P. Jones Trailer Conf.	J. Barhen 6010 Conf. Room	E.M. Oblow 6025 Conf. Room
	(Book & Palmer)	(Pople & Heer)	(Rabins & Reid)
11:45 - 1:00	Lunch (Brought In)		
	(Informal discussion with CESAR Staff - 6010 Conf. Room)		
1:00 - 2:15	Review of Program Plan and FY-87 Demo	Characterization of CESARM	Learning
	C.R. Weisbin Trailer Conf.	S. Babcock 6010 Conf. Room	C.C. Jorgensen 6025 Conf. Room
	(Heer & Palmer)	(Book & Pople)	(Rabins & Reid)
2:15 - 5:00	Advisory Committee Executive Session Building 6025 Conference Room		

ATTACHMENT 1 (cont'd)

Page 3

OCTOBER 17, 1986

8:30 - 9:30	Discussion between Advisory Committee and CESAR Team Members as required Buildling 6010 - Conference Room
9:30 - 11:00	Advisory Committee Executive Session Building 6025 - Conference Room
11:00 - 12:00	Advisory Committee and C.R. Weisbin
12:00 - 1:30	Exit Interview with ORNL Management Lunch - Conference Room Building 6025
	Adjourn

ATTACHMENT 2

QUESTIONS FOR THE CESAR ADVISORY COMMITTEE
OCTOBER 15-17, 1986

1. Please comment on the CESAR research activity in terms of the problems addressed, the approach taken, and the overall potential value for real contribution.

2. Can you identify potential new staff members with whom we can initiate contact in the fields of control theory, operation systems, artificial intelligence, concurrent computation, and/or machine vision.

3. Has the time come for CESAR to begin consideration of our second major focus, i.e., plant management and maintenance, or would this dilute our effort too strongly in light of a constrained DOE budget?

4. Do you concur with the current draft of the CESAR Program Plan? Are there any modifications you would suggest?

Attachment 3

NATIONAL LABORATORY
RTIN MARIETTA ENERGY SYSTEMS INC

POST OFFICE BOX X
OAK RIDGE, TENNESSEE 37831

February 5, 1986

CESAR Advisory Committee

Charter for the CESAR Advisory Committee

Based on discussions during our last meeting, as summarized in your report, I have modified the CESAR Program Plan. You should receive it by early March. I also reviewed and finalized the Charter for the CESAR Advisory Committee; the current version of it appears below:

"The goal of this Advisory Committee is to offer advice intended to help CESAR make decisons which enable it to reach its long-term objective of becoming a world-class center in the study of intelligent machines. The Committee reports to the CESAR Director who, in turn, may circulate advice from the Committee to ORNL Senior Management and CESAR sponsors. Anticipated advice from the Committee includes review of the technical quality of the CESAR research, suggestions of appropriate forums for publication and society participation, recognition of important emerging technical problem areas, recommendation of potential sponsorship consistent with our overall mission, identification of potential candidates for employment, and examination of CESAR progress relative to the CESAR Program Plan. It is fully recognized that the relative emphasis and nature of this advice will vary as CESAR matures."

Sincerely,

Chuck

C. R. Weisbin, Director
Center for Engineering
Systems Advanced Research

cc: F. C. Maienschein
O. P. Manley, DOE/HQ
A. Zucker

FEB 12 1986

APPENDIX B

ALREADY COMPLETED MILESTONES (FY'84 - FY'87)

Publication/Demonstration

Milestone Number

1. Capability to navigate in unstructured environment

   C. C. Jorgensen, W. R. Hamel and C. R. Weisbin, "Exploring Autonomous Robot Navigation," published in BYTE, January 1986, pp. 223-235. CESAR-86/04.

   C. R. Weisbin, G. de Saussure and D. W. Kammer, "Self-Controlled: A Real-Time Expert System for an Autonomous Mobile Robot," Computers in Mechanical Engineering, Vol. 5, 2, pp. 12-19 (September 1986). CESAR-86/25.

2. Capability to do rudimentary machine learning

   S. S. Iyengar, C. C. Jorgensen, S. V. N. Rao and C. R. Weisbin, "Robot Navigation Algorithms Using Learned Spatial Graphs," published in ROBOTICA, Vol. 4, pp. 93-100 (1986).

   S. V. N. Rao, S. S. Iyengar, C. C. Jorgensen and C. R. Weisbin, "Robot Navigation in an Unexplored Terrain," Journal of Robotic Systems, Vol. 3, 4, pp. 389-408 (December 1986). CESAR-86/28.

   J. Barhen, "Concurrent Algorithms for Asymmetric Neural Networks," to be submitted to Hypercube Multiprocessors, '87. CESAR-86/32.

   C. C. Jorgensen, "Neural Network Recognition of Robot Sensor Graphs Using Hypercube Computers," to be submitted to Hypercube Multiprocessors, '87. CESAR-86/33.

5. Hypercube with 64 nodes operational

   J. Barhen and J. F. Palmer, "The Hypercube in Robotics and Machine Intelligence," published in Computers in Mechanical Engineering, Vol. 4, No. 5, pp. 30-38 (March 1986). CESAR-86/03.

J. Barhen, "Hypercube Ensembles: An Architecture for Intelligent Robots," J. Graham, Editor, chapter 8 in Special Computer Architectures for Robotics and Automation, Gordon and Breach, New York (February 1987). CESAR-86/11.

J. Barhen and E. C. Halbert, "ROSES: An Efficient Scheduler for Precedence - Constrained Tasks on Concurrent Multiprocessors," chapter 11, pp. 123-148, M. T. Heath, ed., Hypercube Multiprocessors, '86, SIAM Publishers, Philadelphia, PA, (1986). CESAR-86/21.

6. Theory of static load balancing of hypercube multiprocessors using simulated annealing

J. Barhen, "Combinatorial Optimization of the Computational Load-Balance for a Hypercube Supercomputer," Proceedings, Fourth Symposium on Energy - Engineering Science, pp. 71-80, DOE/CONF/8605122, Argonne National Laboratory (May 1986).

9. Model for rigid manipulator with compliant joints

M. G. Forest-Barlach and S. M. Babcock, "Inverse Dynamics Position Control of a Compliant Manipulator," IEEE Journal of Robotics and Automation (February 1987).

13. Theory of human retinal models

C. C. Jorgensen, R. Gawronski and F. Holly, "Modelling Early Stages of Human Vision," ORNL/TM-10031, CESAR-86/05.

21. Sensitivity analysis software validation

E. M. Oblow, F. G. Pin and R. Q. Wright, "Sensitivity Analysis Using Computer Calculus: A Nuclear Waste Isolation Application," published in Nuclear Science and Engineering, Vol. 94-1, pp. 46-65 (September 1986). CESAR-86/19.

24. Uncertainty theory established

E. M. Oblow, "O-Theory: A Hybrid Uncertainty Theory," Accepted for publication to the International Journal of General Systems. (October 1985) ORNL/TM-9759, CESAR-86/02.

E. M. Oblow, "Foundations of O-Theory I: The Intersection Rule," submitted for publication to the International Journal of General Systems (March 1986) CESAR-86/10.

27. Complete fabrication and assembly of CESAR research arm

W. R. Hamel, "Manipulator Technology: The Critical Element of Useful Autonomous 'Working' Machines," Intelligent Autonomous Systems, An International Conference, Amsterdam, The Netherlands (December 8-11, 1986). CESAR-86/43.

APPENDIX C

CENTER FOR ENGINEERING SYSTEMS ADVANCED RESEARCH PUBLICATIONS LIST - March 1987

I. BOOKS AND REFEREED JOURNALS

I.1. S. S. Iyengar, C. C. Jorgensen, S. V. N. Rao and C. R. Weisbin, "Robot Navigation Algorithms Using Learned Spatial Graphs," published in ROBOTICA, Vol. 4, pp. 93-100 (1986).

I.2. E. M. Oblow, "O-Theory: A Hybrid Uncertainty Theory," International Journal of General Systems, 13, 2, p.95. CESAR-86/02.

I.3. J. Barhen and J. F. Palmer, "The Hypercube in Robotics and Machine Intelligence," Computers in Mechanical Engineering, 4, No. 5, pp. 30-38 (March 1986). CESAR-86/03.

I.4. C. C. Jorgensen, W. R. Hamel and C. R. Weisbin, "Exploring Autonomous Robot Navigation," BYTE, pp. 223-235 (January 1986). CESAR-86/04.

I.5. E. M. Oblow, "Foundations of O-Theory: The Intersection Rule," International Journal of General Systems, 13, 4. CESAR-86/10.

I.6. J. Barhen, "Hypercube Ensembles: An Architecture for Intelligent Robots," J. Graham, Editor, chapter 8 in Special Computer Architectures for Robotics and Automation, Gordon and Breach, New York (February 1987). CESAR-86/11.

I.7. E. M. Oblow, F. G. Pin and R. Q. Wright, "Sensitivity Analysis Using Computer Calculus: A Nuclear Waste Isolation Application," Nuclear Science and Engineering, Vol. 94-1, pp. 46-65 (September 1986). CESAR-86/19.

I.8. J. Barhen and E. C. Halbert, "ROSES: An Efficient Scheduler for Precedence - Constrained Tasks on Concurrent Multiprocessors," chapter 11, pp. 123-148, M. T. Heath, ed., Hypercube Multiprocessors, '86, SIAM Publishers, Philadelphia, PA, (1986). CESAR-86/21.

I.9. C. R. Weisbin, G. de Saussure and D. W. Kammer, "Self-Controlled: A Real-Time Expert System for an Autonomous Mobile Robot," Computers in Mechanical Engineering, Vol. 5, 2, pp. 12-19 (September 1986). CESAR-86/25.

I. BOOKS AND REFEREED JOURNALS (cont'd)

I.10. S. V. N. Rao, S. S. Iyengar, C. C. Jorgensen and C. R. Weisbin, "Robot Navigation in an Unexplored Terrain," Journal of Robotic Systems, Vol. 3, 4, pp. 389-408 (December 1986). CESAR-86/28.

I.11. J. R. Einstein and J. Barhen, "Virtual-Time Operating-System Functions for Robotics Applications on a Hypercube," submitted to Hypercube Multiprocessors, '87. CESAR-86/34.

I.12. M. G. Forest-Barlach and S. M. Babcock, "Inverse Dynamics Position Control of a Compliant Manipulator," IEEE Journal of Robotics and Automation (February 1987).

I.13. J. Barhen, "On the Stability, Capacity Storage, and Design of Nonlinear Continuous Network," submitted to IEEE Trans. on Systems Man & Cybernetics (1986). CESAR-86/49.

I.14. R. C. Mann, "A Comparison of Algorithms for the Analysis of Images Generated by Two-Dimensional Electrophoresis," submitted to Electrophoresis (1987). CESAR-87/01.

1.15. N. S. V. Rao, S. S. Iyengar, C. C. Jorgensen and "Terrain Model Acquisition by a Finite-Sized Mobile Robot in Plane," submitted for publication in Journal of Robotics Research (1987). CESAR-86/60.

II. PROCEEDINGS OF CONFERENCES - FULL PAPER REVIEWED

II.1. J. Barhen, S. M. Babcock, W. R. Hamel, E. M. Oblow, G. N. Saridis, G. de Saussure, A. D. Solomon and C. R. Weisbin, "Basic Research on Intelligent Robotic Systems Operating in Hostile Environments: New Developments at ORNL," Proceedings of the 1984 National Topical Meeting on Robotics and Remote Handling in Hostile Environments, pp. 105-116 (April 1984).

II.2. S. M. Babcock and J. Barhen, "Real-Time Algorithms for Robotics Control of Teleoperators," Robots-8 Conference, Detroit, MI, pp. 1972-1987 (June 4-7, 1984).

II.3. C. R. Weisbin, G. de Saussure, J. Barhen, E. M. Oblow and J. C. White, "Minimal Cut-Set Methodology for Artificial Intelligence Applications," The First Conference on Artificial Applications, sponsored by the IEEE Computer Society in Cooperation with American Association for Artificial Intelligence, pp. 465-469 (December 5-7, 1984).

II.4. C. R. Weisbin, J. Barhen, T. E. Swift, G. de Saussure, C. C. Jorgensen and E. M. Oblow, "HERMIES-I: A Mobile Robot for Navigation and Manipulation Experiments," Proceedings of the Robots-9 Conference, Detroit, MI, Vol. 1, pp. 1-41 (June 3-6, 1985).

II.5. M. G. Forrest and S. M. Babcock, "Control of a Single Link, Two-Degree-of-Freedom Manipulator with Joint Compliance and Actuator Dynamics," Proceedings of the 1985 International Computers in Engineering Conference, Boston, MA, pp. 189-197 (August 4-8, 1985).

II.6. J. Barhen, "Robot Inverse Dynamics on a Concurrent Computation Ensemble," Proceedings of 1985 International Computers in Engineering Conference, Boston, MA, pp. 415-429 (August 4-8, 1985).

II.7. S. S. Iyengar, C. C. Jorgensen, S. V. N. Rao and C. R. Weisbin, "Learned Navigation Paths for a Robot in Unexplored Terrain," Proceedings of the Second Conference on Artificial Intelligence Applications, Miami Beach, FL, pp. 148-155 (December 11-13, 1985).

II.8. M. G. Forrest-Barlach and S. M. Babcock, "Inverse Dynamics Position Control of a Compliant Manipulator," Proceedings of the 1986 IEEE International Conference on Robotics and Automation, San Francisco, CA, Vol. 1, pp. 196-205 (April 8-10, 1986). CESAR-86/08.

II. PROCEEDINGS OF CONFERENCES - FULL PAPER REVIEWED (cont'd)

II.9. S. V. N. Rao, S. S. Iyengar, C. C. Jorgensen and C. R. Weisbin, "Concurrent Algorithms for Autonomous Robot Navigation in an Unexplored Terrain," Proceedings of the 1986 IEEE International Conference on Robotics and Automation, San Francisco, CA, Vol. 1, pp. 1137-1144 (April 8-10, 1986).

II.10. C. R. Weisbin, "CESAR Research in Intelligent Machines," to appear in the August 1986 issue of ORNL Review, Proceedings of The Second World Conference on Robotics Research, MS86-772, Scottsdale, Arizona (August 19-21, 1986). CESAR-86/12.

II.11. J. Barhen, E. C. Halbert and J. R. Einstein, "Advances in Concurrent Computers for Autonomous Robots," Proceedings of The Second World Conference on Robotics Research, MS86-771, Scottsdale, Arizona (August 19-21, 1986). CESAR-86/14.

II.12. C. R. Weisbin, G. de Saussure and D. W. Kammer, "A Real-Time Expert System for Monitoring the Performance of an Intelligent Robot and Diagnosing Unexpected Occurrences," SPIE's 1986 Cambridge Symposium on Advances in Intelligent Robotics Systems, October 26-31, 1986, Hyatt Regency Cambridge, Cambridge, MA. CESAR-86/44.

II.13. C. C. Jorgensen, "Neural Network Modeling of Early Retina Vision Processes," presented to Neurcom, San Jose, CESAR-86/48.

II.14. M. Goldstein, F. G. Pin, G. de Saussure and C. R. Weisbin, "3-D World Modeling Based on Combinatorial Geometry for Autonomous Robot Navigation," 1987 IEEE International Conference on Robotics and Automation. CESAR-86/51.

II.15. S. M. Babcock, W. R. Hamel and S. M. Killough, "Advanced Manipulation for Autonomous Mobile Robots," International Topical Meeting on Remote Systems and Robotics, Pasco, WA (March 29-April 2, 1987). CESAR-86/52.

II.16. N. S. V. Rao, S. S. Iyengar and C. R. Weisbin, "On Autonomous Terrain Model Acquisition by a Mobile Robot," JPL (NASA) Conference on Telerobotics (1987). CESAR-86/59.

II.17. N. S. V. Rao, S. S. Iyengar, C. C. Jorgensen and C. R. Weisbin, "On Terrain Acquisition by a Finite-Sized Mobile Robot in Plane," 1987 IEEE Robotics and Automation Conference, Raleigh, NC. CESAR-86/60.

II. PROCEEDINGS OF CONFERENCES - FULL PAPER REVIEWED (cont'd)

II.18. M. Goldstein, F. G. Pin, G. de Saussure and C. R. Weisbin, "3-D World Modeling with Updating Capability Based On Combinatorial Geometry," JPL (NASA) Conference on Telerobotics (1987). CESAR-87/02.

II.19. J. R. Einstein, J. Barhen and D. Jefferson (UCLA), "A Virtual-Time Operating System Shell for a Hypercube in Robotics Applications," Paper, SPIE Cambrige on Optical and Optoelectronic Engineering, Cambridge, Massachusetts, October 21-31, 1986. Proceedings, Vol. 726, Society of Photo-Optical Instrumentation Engineers. CESAR-86/61.

III. PROCEEDINGS OF CONFERENCES - SUMMARY REVIEWED

III.1. C. R. Weisbin, G. de Saussure and J. Barhen, "Automated Planning for Intelligent Machines in Energy-Related Applications," Proceedings of the Conference on Intelligent Systems and Machines, pp. 13-15, Oakland University, Rochester, MI (April 24-25, 1984).

III.2. J. Barhen, C. R. Weisbin and G. de Saussure, "Real-Time Planning by an Intelligent Robot," ASME Conference on Computers in Engineering, pp. 358-360 (August 1984).

III.3. C. R. Weisbin, G. de Saussure, J. Barhen, T. E. Swift and J. C. White, "Strategy Planning by an Intelligent Machine," First World Conference on Robotics Research: The Next Five Years and Beyond, LeHigh University, PA, MS84-501 (August 14-16, 1984).

III.4. J. Barhen and S. M. Babcock, "Parallel Algorithms for Robot Dynamics," First World Conference on Robotics Research: The Next Five Years and Beyond, LeHigh University, PA MS84-499 (August 14-19, 1984).

III.5. C. R. Weisbin, J. Barhen, G. de Saussure, W. R. Hamel, C. C. Jorgensen, J. L. Lucius, E. M. Oblow and T. E. Swift, "Machine Intelligence for Robotics Applications," 1985 Proceedings of the Conference on Intelligent Machines, Oakland University, Rochester, MI, pp. 47-57 (April 23, 1985).

III.6. E. M. Oblow, "A Hybrid Uncertainty Theory," Proceedings of the Fifth International Workshop: Expert Systems and Their Applications, Avigon, France, pp. 1193-1201 (May 13-15, 1985).

III.7. W. R. Hamel, S. M. Babcock, M. C. G. Hall, C. C. Jorgensen, S. M. Killough and C. R. Weisbin, "Autonomous Robots for Hazardous and Unstructured Environments," Proceedings of the Robots-10 Conference, Chicago, IL, pp. 5-9 through 5-29 (April 20-24, 1986).

III.8. D. W. Kammer, G. de Saussure and C. R. Weisbin, "A Real-Time Expert System for Robotic Task Planning, Monitoring and Diagnosis of Unexpected Occurrences," Proceedings of 1986 Conference on Intelligent Systems and Machines, (April 29-30, 1986). CESAR-86/20.

III. PROCEEDINGS OF CONFERENCES - SUMMARY REVIEWED (cont'd)

III.9. E. M. Oblow, "O-Theory: A Hybrid Uncertainty Theory," will appear in the Proceedings of the International Conference on Information Processing and Management of Uncertainty on Knowledge-Based Systems held in Paris, France (June 3-July 4, 1986).

III.10. J. R. Einstein, J. Barhen and D. Jefferson, "Intelligent Operating System for Autonomous Robots: Real-Time Capabilities on a Hypercube Supercomputer," Proceedings of the International Topical Meeting on Remote Systems and Robotics in Hostile Environments, American Nuclear Society, LaGrange, IL (March 1987). CESAR-86/57.

III.11. G. de Saussure, D. W. Kammer and C. R. Weisbin, "A Real-Time Expert System for the Control of Autonomous Robot Navigation in the Presence of Moving Obstacles," Pasco, WA (1987). CESAR-86/50.

IV. INVITED TALKS

IV.1. C. R. Weisbin, J. Barhen, G. de Saussure, W. R. Hamel, C. C. Jorgensen, J. L. Lucius, E. M. Oblow and T. E. Swift, "Artificial Intelligence for Energy-Related Applications," 1985 WATTEC Conference, Knoxville, TN (February 12, 1985).

IV.2. C. R. Weisbin, J. Barhen, G. de Saussure, W. R. Hamel, C. C. Jorgensen, J. L. Lucius, E. M. Oblow and T. E. Swift, "Artificial Intelligence for Concurrent Computation for Robotic Applications," Transactions of American Nuclear Society Annual Meeting, Boston, MA, Vol. 49, pp. 310-311 (June 9-14, 1985).

IV.3. J. P. Jones and M. A. Scudieri, "Image Processing on a Hypercube Concurrent Multiprocessor," presented at RIMSIG Symposium, Santa Fe, New Mexico (October 22-23, 1986). CESAR-86/39.

IV.4. J. R. Einstein and J. Barhen, "Robot Control with a Hypercube: Virtual-Time Functions for the Node's Operating System," presented at RIMSIG Symposium, Santa Fe, New Mexico (October 22-23, 1986). CESAR-86/41.

IV.5. R. C. Mann, "Quantitative Analysis of Two-Dimensional Protein Patterns Using an NCUBE Hypercube," presented at RIMSIG Symposium, Santa Fe, New Mexico (October 22-23, 1986). CESAR-86/42.

IV.6. R. C. Mann, "Multi-Sensor Integration for a Mobile Robot Using Concurrent Computing," to be presented in the Federal Republic of Germany (May 11-13, 1987). CESAR-86/53.

IV.7. W. R. Hamel and C. R. Weisbin, "Human Scale Experiment in Mobile Autonomous Robotics," to be presented in Germany in (May 1987). CESAR-86/58.

V. INVITED PAPERS

V.1. J. Barhen, "Hypercube Concurrent Computation and Virtual Time for Robotic Applications," IEEE Workshop on Special Computer Architectures for Robotics and Automation, pp. 5.1-5.30. International Conference on Robotics Research, St. Louis, MO (March 25, 1985).

V.2. W. R. Hamel, "Manipulators in Teleoperation," American Nuclear Society Conference on Remote Operations and Robotics in the Nuclear Industry, Pine Mountain, GA (April 21-24, 1985).

V.3. J. Barhen, M. C. G. Hall and J. R. Einstein, "Robotics Applications on an Advanced Hypercube Multiprocessor: Initial Developments," IEEE Workshop on Special Computer Architectures for Robot Control, 1986 International Conference on Robotics and Automation, San Francisco, CA (April 7-10, 1986). CESAR-86/13.

V.4. C. C. Jorgensen, "Control Algorithms for Autonomous Robot Navigation," Proceedings of the International Topical on Advances in Human Factors in Nuclear Power Systems, Knoxville, TN (April 21-24, 1986), pp. 100-106 (April 1986).

V.5. J. Barhen, "Combinatorial Optimization of the Computational Load Balance for a Hypercube Supercomputer," Proceedings of the Fourth Symposium on Energy Engineering Sciences, Argonne National Laboratory, Argonne, IL CONF-86-05122, pp. 71-80 (1986). CESAR-86/30.

V.6. W. R. Hamel, "Manipulator Technology: The Critical Element of Useful Autonomous 'Working' Machines," Intelligent Autonomous Systems, An International Conference, Amsterdam, The Netherlands (December 8-11, 1986). CESAR-86/43.

VI. <u>WORKSHOP PROCEEDINGS AND ORNL REPORTS</u>

VI.1. Select Panel on Research Goals and Priorities in Intelligent Machines, Proceedings of a Workshop (November 1984).

VI.2. ORNL/TM-9923, <u>CESAR-86/01</u>. Proceedings of a Workshop: Planning and Sensing for Autonomous Navigation, Edited by E. S. Howe and C. R. Weisbin, held Los Angeles, CA, August 17-18, 1985 (February 1986).

VI.3. ORNL/TM-9759, <u>CESAR-86/02</u>. "O-Theory - A Hybrid Uncertainty Theory," E. M. Oblow (October 1985).

VI.4. ORNL/TM-10031, <u>CESAR-86/05</u>. "Modelling Early Stages of Human Vision," C. C. Jorgensen, R. Gawronski and F. Holly (August 1986).

VI.5. ORNL/TM-9732, <u>CESAR-86/06</u>. "Research and Development Program Plan for the Center for Engineering Systems Advanced Research (CESAR)," C. R. Weisbin, W. R. Hamel, J. Barhen and M. C. G. Hall (February 1986).

VI.6. ORNL/TM-9782, <u>CESAR-86/07</u>. "Robot Navigation Algorithms Using Learned Spatial Graphs," S. S. Iyengar, C. C. Jorgensen, S. V. N. Rao and C. R. Weisbin (December 1985).

VI.7. ORNL/TM-9987, <u>CESAR-86/09</u>. "ROSES: Robot Operating System Expert Scheduler," J. Barhen, P. C. Chen and E. Halbert (February 1986).

VI.8. ORNL/TM-9983, <u>CESAR-86/10</u>. "Foundations of O-Theory I: The Intersection Rule," E. M. Oblow (March 1986). (NOTE: see I.6)

VI.9. ORNL/TM-10232, <u>CESAR-86/47</u>. "Research and Development Program Plan for the Center for Engineering Systems Advanced Research," C. R. Weisbin, W. R. Hamel and J. Barhen.

VI.10. ORNL/TM-10329, <u>CESAR-86/49</u>. "On the Stability, Storage Capacity and Design of Nonlinear Continuous Neural Networks," A. Guez, V. Protopopescu and J. Barhen.

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