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Research and Development Program Plan for the Center for Engineering Systems Advanced Research (CESAR)

C. R. Weisbin
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Engineering Physics and Mathematics Division

RESEARCH AND DEVELOPMENT PROGRAM PLAN

FOR THE

CENTER FOR ENGINEERING SYSTEMS ADVANCED RESEARCH (CESAR)

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FOREWORD

This document is the first issue of the Research and Development Plan for the Center for Engineering Systems Advanced Research (CESAR) at the Oak Ridge National Laboratory. The document is intended to provide a general framework for more detailed planning on an annual basis, both for DOE and for other sponsoring organizations. It will be examined each year and updated as required.

RESEARCH AND DEVELOPMENT PROGRAM PLAN FOR THE CENTER FOR ENGINEERING SYSTEMS ADVANCED RESEARCH (CESAR)

I. INTRODUCTION AND BACKGROUND

During the last few years, there has 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 to initiate a research program to extend the body of knowledge underlying current engineering practice and satisfy perceived future requirements. In support of these DOE objectives and of requirements by other sponsoring organizations, the Oak Ridge National Laboratory has 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 establish a framework and guidelines for research and development within ORNL's CESAR program in areas pertaining to intelligent machines. The specific objective is to present a CESAR Research and Development Plan for such work with a planning horizon of five to ten years, i.e., FY 1985 to FY 1990 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. Sensor System - The sensor 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 design 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 serving as the supervisory system which 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. To minimize risk to humans and to assure reliable performance in remote environments, 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 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 operation, and set up training for people who are supposed to run the plant. The control portion of this system would translate a simulated and actual running system which has to deal with real time operations. There 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.

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, (Ref. 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.

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 goal. 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 (Ref. 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
2. Mechanisms, Dynamics and Control
3. Sensors and Vision
4. Human-Machine Interface
5. Cross-Disciplinary Research

The first four areas are representative of the major subsystems of intelligent machines and, in particular, robotic systems. 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 objectives.

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

2. Collaborative efforts in the above areas will be established with academic, industrial and other 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 approaches 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 and 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 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. 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.

3. 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 objects of interest, to identify and grasp objects safely, and to perform self-diagnoses.

4. 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.

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.

C. Implementation Plan

1. Objectives and Task Description

The objectives and tasks have been selected in recognition of a number of contraints, such as available funding, talents and laboratory facilities.

A major consideration during the first few years is the development of a laboratory capability in addition to theoretical investigations. It is expected that some aspects of the theoretical research can be tested experimentally in the parallel developing laboratory. The specific objectives and tasks which follow are subdivided in agreement with the disciplinary areas identified in Section III. B.

(a) Machine Intelligence

(1) Design and construct the HERMIES Robot series as experimental devices to test concepts of machine intelligence. This includes the mobile platform, manipulators, computing architecture, sensor array, controls, communications, and man-machine interface.

(2) Study and develop automated planning techniques for robotic systems with real time constraints; develop a HERMIES planner which considers sensor feedback, geometric reasoning, and has capability for automated learning with experience.

(3) Develop and make operational an intelligent machine operating system using specialized computer architectures (hypercube ensemble machine). This includes development of concurrent computation algorithms (e.g., for time dependent planning and robot dynamics).

(b) Mechanisms, Dynamics and Control

(1) Develop and test real-time dynamic models for machines and manipulator systems using computer assisted techniques. These developments include rigid and flexible arms and single and multiple arm linkages.

(2) Develop and test advanced control concepts for intelligent machines including compliant manipulators, and cooperative systems.

(c) Sensors and Vision

(1) Study and develop computer software architectures for the integration of information from multiple sensors including consideration of knowledge bases, associative memories, parallel pattern processing, shell architecture, and multi-level data flow.

(2) Study theoretical problems and techniques related to the interpretation of information from multiple sensors considering contexts in dynamic environments, isomorphic matching of representations, merging of different representations, and automatic generation of higher level representations.

(3) Develop and test new transducers for single and multiple sensors using single and multimodal systems with specialized computers.

(d) Human-Machine Interface

(1) Develop techniques of planning for skill related operations considering human analogs; determine criteria for optimal human-machine task allocation.

(2) Design an experimental work station (control station) for remote control of robotic devices.

(e) Cross-Disciplinary Research

(1) Develop and validate a methodology for the automated generation of sensitivity coefficients to enable systematic model simplification and parameter identification.

(2) Develop theory for planning under uncertainty incorporating the advantages of the Dempster-Shafer methods, Fuzzy Sets, and Bayesian techniques.

(3) Conduct system integration studies and develop a test bed for robot technology demonstrations, human-machine performance research, and fundamental contributions to system design methodology and implementation.

2. Research Context

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. A sequence of three phases of increasingly more complex valve-related system operation tasks has been developed, and corresponding subsystem characteristics have been derived as summarized in Fig. I.

	Phase 1	Phase 2	Phase 3
System Demonstrations	Operate Manual Valve 1988	.Remove/Install Flanged .Valve 1990	. Locate, Diagnose, and . Operate Valve 1992
Cognition and Planning	Non-Realtime Plan/Execute Known Simple Task	.Non-Realtime .Plan/Execute Known .Task	. Realtime . Human Supervisory Mode
Sensory Perception	Position Force-Reflection 2D Computer Vision	.Multiple 2D Computer- .Vision .Tactile Sensing	. Acoustic . Infrared . Radar
Manipulation	Single-Arm	.Coordinated Arms .Advanced End-Effectors .Simple Tools .Auxilliary Lift Capacity.	. Multiple End-Effectors . Adaptive Position/Force . Control
Mobility	Localized Navigation	.Localized (Navigation . in Unstructured . Environment)	. General World . Radio Link, On-Board . Power

Fig. I. Phased Reference Problem in Terms of System Operations and the Related Subsystem Characteristics*

*Each successive phase assumes capability of previous phases.

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

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

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

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

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

E. 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.

F. 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 angle, 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.

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

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

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

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

K. 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:

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

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

3. Evaluate the operability of the valve by inspection.

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

3. Schedule and Resources

The research schedule given in Fig. II has been developed based on the Objectives and Task Descriptions of Section 1, while considering the Research Context of Section 2.

The schedule covers a five year planning horizon from FY 1985 through FY 1989. It includes work sponsored by DOE and relevant work sponsored by other organizations. The milestones for each subtask indicate deliverable items which are called out at the end of this paragraph. They include capability demonstrations, pieces of hardware, or publications. The state of accomplishments as of February 1986 is presented in Ref. 3. Currently, the resources, both man years and funding, can be reasonably well estimated through FY 1986. The resources for FY 1987 through FY 1989 are approximate projections.

Milestones:

(1) => Capability to navigate in unstructured environment.
(2) => Capability to do rudimentary machine learning.
(3) => Scheduling of robotic tasks under hard-real-time constraints.
(4) => Integration of sensor data structures for learning about the environment.
(5) => Hypercube with 64 nodes operational.
(6) => Theory of static load balancing of hypercube multiprocessors using simulated annealing.
(7) => Virtual time distributed operating system with application to robotics.
(8) => Theory of dynamic load balancing using generalized simulated annealing.
(9) => Model for rigid manipulator with compliant joints.
(10) => Model and identify parameters of CESAR research manipulator.
(11) => New control algorithm for compliant manipulator verified by performance testing.
(12) => Control of one manipulator and mobile platform.
(13) => Theory of human retinal models.
(14) => Algorithms for vision guided manipulation.
(15) => Human analog vision recognition using concurrent computing.
(16) => Integration of laser range finder and vision.

(17) => Concepts for optimum task allocation.
(18) => Representation of tasks involving skill.
(19) => Advanced teleoperated dexterous manipulation.
(20) => Optimized work station design.
(21) => Sensitivity analysis software validation.
(22) => Simplified robot dynamics application using sensitivity analysis.
(23) => Hardware validation of sensitivity tool.
(24) => Uncertainty theory established.
(25) => Incorporation in expert system of uncertainty analysis.
(26) => Incorporation in planner of uncertainty analysis.
(27) => Complete fabrication and assembly of CESAR research manipulator.
(28) => Completion of testbed system.
(29) => Upgraded testbed system.

4. Facilities Plan

The research facilities for CESAR are undergoing a period of change. Reference 3 gives an overview of current facility and equipment developments. The major existing and planned facilities with accessories include:

(1) Two LISP Machines with LISP Upgrade (FY-85)

(2) General Access to ORNL Common Facilities (FY-85)

(3) Hypercube Parallel Processor (FY-85)

(4) HERMIES-I Robot (FY-85)

(5) HERMIES-II Robot Upgrade (FY-86)

- Vision System
- Servo Sensory Platform
- Multiple Sensory Array
- Hypercube Interface

(6) CESAR Research Manipulator (CESARM-I) (FY-85, 86)

(7) HERMIES-III Robot (FY-86, '87)

- High Speed Communication System
- Mobile Platform with Manipulator Torso
- Sensor Platform
  - Phased array sonar

TASK AREAS	FY '85	FY '86	FY '87	FY '88	FY '89
a Machine Intelligence					
(A) Automated planning	1	2	3	4	
(B) Hypercube Oper. Systems	5	6	7		8
Funding ($000)	630	700	1000	1400	1800
Manyears	4.5	4.7	6.3	8.2	10
b Mechan. Dyn. and Contr.					
(A) Dynamic modeling	9				
(B) Control structures			10	11	12
Funding ($000)	210	250	280	310	350
Manyears	1.5	1.7	1.8	1.8	1.9
c Sensors and Vision Syst.					
(A) Human Analog Vision		13		15	
(B) Sensor Guided Control			14		
(C) Sensor Integration					16
Funding ($000)	30	250	500	700	1000
Manyears	0.2	1.7	3.1	4.1	5.6
d Human-Machine Interface					
(A) H/M Task allocation			17		18
(B) Work station design				19	20
Funding ($000)	50	285	480	510	720
Manyears	0.3	1.9	3	3	4
e Cross-Disciplinary Res.					
(A) Sensitivity analysis		21	22		23
(B) Uncertainty analysis		24	25		26
(C) Systems integration *		27	28		29
Funding ($000)	500	470	785	985	1270
Manyears	1.0	2	2	2.5	3.5
TOTAL RESOURCE PLAN FUNDING ($000)	1420	1955	3045	3905	5140
TOTAL RESOURCE PLAN WORKYEARS	7.5	12.0	16.2	19.6	25

*This item includes capital equipment and operating costs. Estimated costs/manyear '85 (140 K), '86 (150 K), '87 (160 K), '88 (170 K), '89 (180 K).

Fig. II. Schedule and Resources: Circled Numbers Correspond to Milestones Listed on the Previous Pages

(8) Second Hypercube Controller Board for Multiple Access (FY '86)

(9) CESARM-II (FY '87)

(10) Laser Range Scanner (FY '87)

(11) Utah/MIT Multifingered Hand (FY '87)

(12) Integrated Man-Machine Control Station (FY '88)

For future development, ORNL has designated a space of ~4200 sq. ft. to house the CESAR Laboratory which will include facilities and equipment for robot navigation experiments, manipulator development, advanced computing, sensor and signal transmission equipment, maintenance shops, etc. The space will contain standard features including electric power and air conditioning, and will be constructed as a second floor addition to Building 6010 at ORNL. A rough layout of the Laboratory is given in the following page, Fig. IV. The installation of this Laboratory is expected to be completed in July 1986. Finally, a large mobile manipulator robitics testbed is being assembled in behalf of the Human Engineering Laboratory of the U.S. Army.

5. Management Structure

The CESAR organization is generally structured along disciplinary lines as shown in Fig. V. The cross-disciplinary activities are embedded within the the group activities. The permanent advisory committee provides periodic inputs to the annual planning and evaluation process of CESAR.

6. Reporting Structure

The operation of CESAR consists of a formal and an informal reporting process. The formal process requires annual submissions of DOE Form 5120.2, "Field Task Proposal/Agreement" including task descriptions, staffing, requested funding, milestone schedules, facility requirements, prior year publications and other detailed planning information necessary to allocate funding for the particular fiscal year. For other sponsoring organizations, formal proposals are prepared based on the particular requirements of the proposed work. Beginning in FY '87, annual reports will be prepared abstracting the CESAR activities and accomplishments during the previous year.

The informal reporting consists primarily of publications in the open literature including books, refereed journals, conference proceedings and lectures, as well as a peer review process performed by the CESAR Advisory Committee and the Council on Energy Engineering Research.

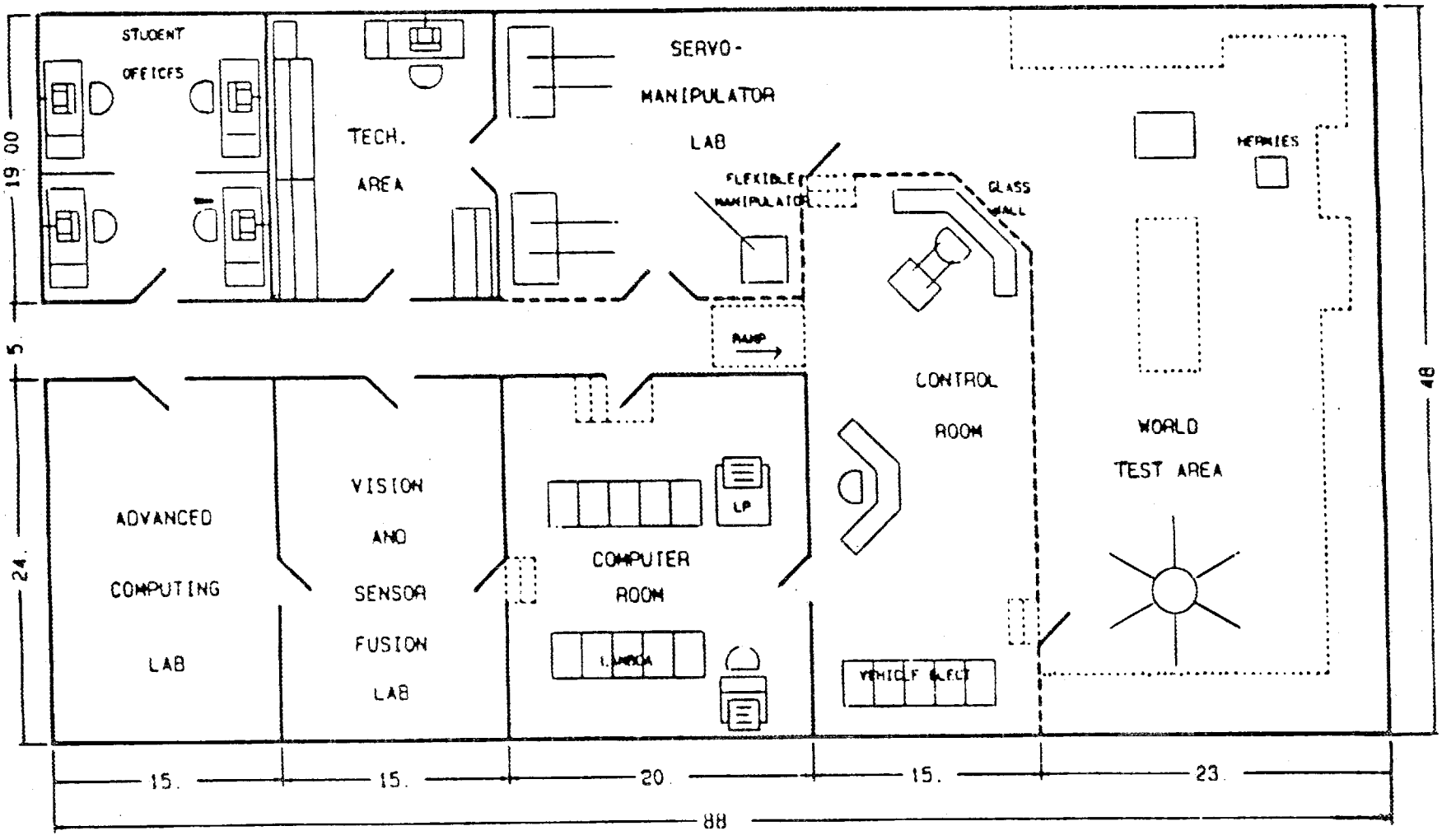

Fig. IV. CESAR Machine Intelligence Laboratory

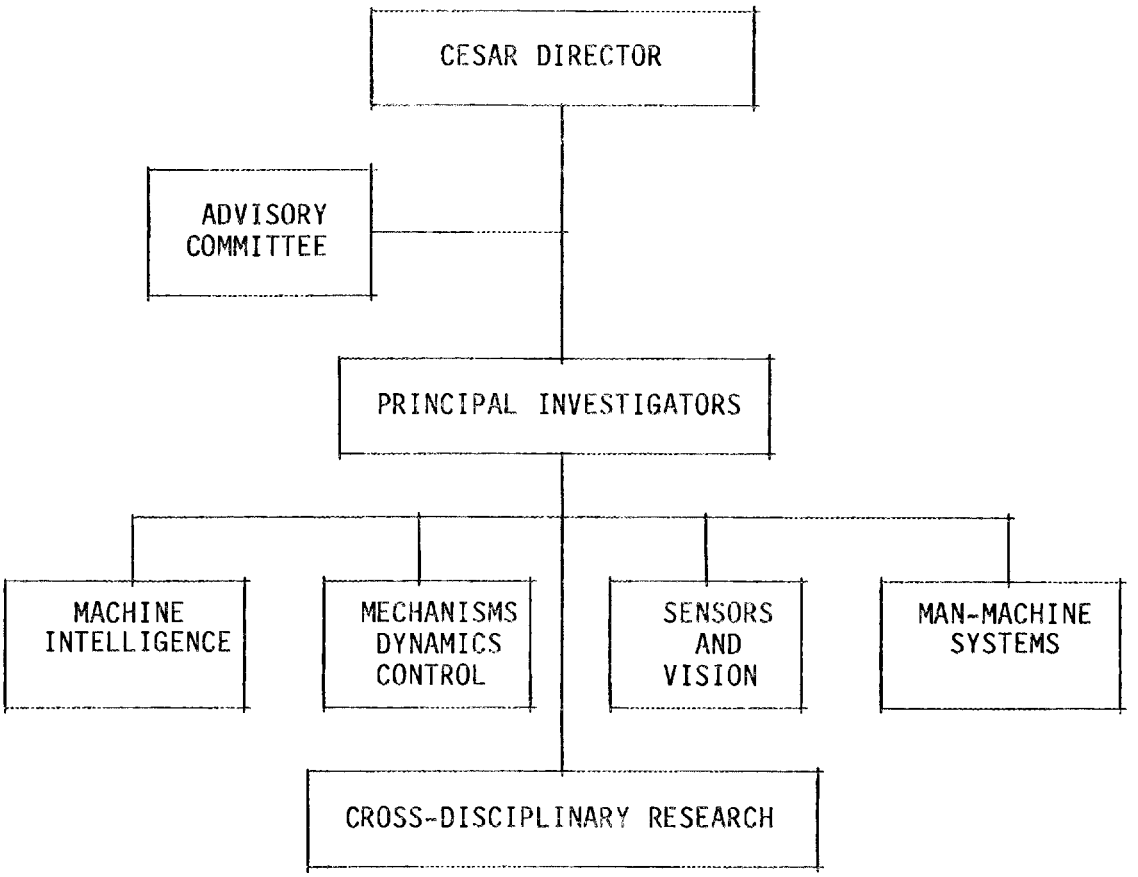

Fig. V. Organization Chart

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