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HERMIES-III: A STEP TOWARD AUTONOMOUS MOBILITY, MANIPULATION AND PERCEPTION

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ABSTRACT

HERMIES-III is an autonomous robot comprised of a seven degree-of-freedom (DOF) manipulator designed for human scale tasks, a laser range finder, a sonar array, an omni-directional wheel-driven chassis, multiple cameras, and a dual computer system containing a 16-node hypercube expandable to 128 nodes. The current experimental program involves performance of human-scale tasks (e.g., valve manipulation, use of tools), integration of a dexterous manipulator and platform motion in geometrically complex environments, and effective use of multiple cooperating robots (HERMIES-IIB and HERMIES-III). The environment in which the robots operate has been designed to include multiple valves, pipes, meters, obstacles on the floor, valves occluded from view, and multiple paths of differing navigation complexity. The ongoing research program supports the development of autonomous capability for HERMIES-IIB and III to perform complex navigation and manipulation under time constraints, while dealing with imprecise sensory information.

I. INTRODUCTION

The Center for Engineering Systems Advanced Research (CESAR) at the Oak Ridge National Laboratory (ORNL) focuses its research on the development and experimental validation of intelligent control techniques for autonomous, mobile robots able to plan and perform a variety of assigned tasks in unstructured environments.[1] The assignments originate with the human supervisors in a remote "control station," and the robot then performs detailed implementation planning and executes the tasks. Since the operational environment is generally dynamic, the robot must be in sensory contact with its surroundings to capture and recognize changes which bear on its task objectives and, if necessary, replan its behavior. These capabilities imply that the robot has cognitive capabilities that enable it to form and modify a model of the world around it and relate this world model causally to the task objectives. Research is also conducted to enable the robot to learn from its past experience, and thus improve its performance.

CESAR's principal current objectives are (a) to achieve a level of technological capability which would enable the autonomous performance of classes of navigation and manipulation tasks of human scale in a spatially complex environment; (b) to use these performance tasks as a focus for establishing and conducting its research objectives. In order to achieve these objectives, CESAR is developing a series of mobile autonomous robot vehicles named HERMIES (Hostile Environment Robotic Machine Intelligence Experiment Series) as experimental test beds which enable validation of this research and demonstration of its results.[2-4] Our newest research robot, HERMIES-III,[5,6] includes the functional capabilities which permit research in combined mobility/ manipulation, and allows us to experiment with cooperative control of multiple robots having different capabilities.

II. ROBOT EVOLUTION TO HUMAN-SCALE EXPERIMENTS: HERMIES-III

Although HERMIES-IIB[4] is a powerful and versatile research tool, it has limited manipulative capabilities. In order to approach human-scale performance, CESAR has designed and is assembling a much larger test bed, HERMIES-III,[5,6] to be used in future experiments. This section briefly describes the hardware of HERMIES-III, a proposed software architecture, and a set of experiments which build upon those previously performed with HERMIES-IIB.

A. HERMIES-III Hardware

HERMIES-III is a battery-powered robot currently under construction with operational availability in the spring of 1989 (Fig. 1). It is comprised of:

- A wheel-driven chassis (4' × 5' × 2') with omni-directional steering capability. Two steering wheels and four corner caster wheels are used to distribute the approximately 2700 pounds of vehicle weight over a 10 ft^2 area. A pair of latitudinal and longitudinal hinges enable the vehicle to keep all 6 wheels on the ground even while traversing mildly uneven terrain.

- Initially one and later two manipulators; the current manipulator system comprises the CESAR Research Manipulator (CESARm)[7,8] which is a relatively high capacity-to-weight ($\sim 1/10$) manipulator with 7-DOF and a spherical 3-DOF wrist. The arm now contains only a gripper and later will be augmented with a multi-fingered hand. CESARm is mounted about $3\frac{1}{2}$ feet off the floor so that the end effector will reach from the floor to about 8 feet high, and 4 feet beyond the front edge of the vehicle. CESARm's characteristics are being benchmarked, and its control algorithms will be in the public domain;

- A sensor suite including an Odetics laser range camera, two pairs of CCD cameras, an array of 32 sonar transceivers on the chassis sides, and encoders or resolvers on motor shafts and manipulator joints. The laser range camera is mounted on a rotatable mount and provides range and reflectance data for 128 × 128 ray directions within a 60 × 60 degree field of view. All cameras are on pan and tilt platforms; additional pan and tilt platforms and mounting locations will be available for rapid addition of other sensors. Force-feedback and tactile sensors, and wrist mounted cameras for arm control will be mounted on CESARm in the near future;

- A dual computer system comprising IBM PC/AT-NCUBE and VME bus based systems with provisions for up to 128 NCUBE nodes and five Motorola 68020 processors. There

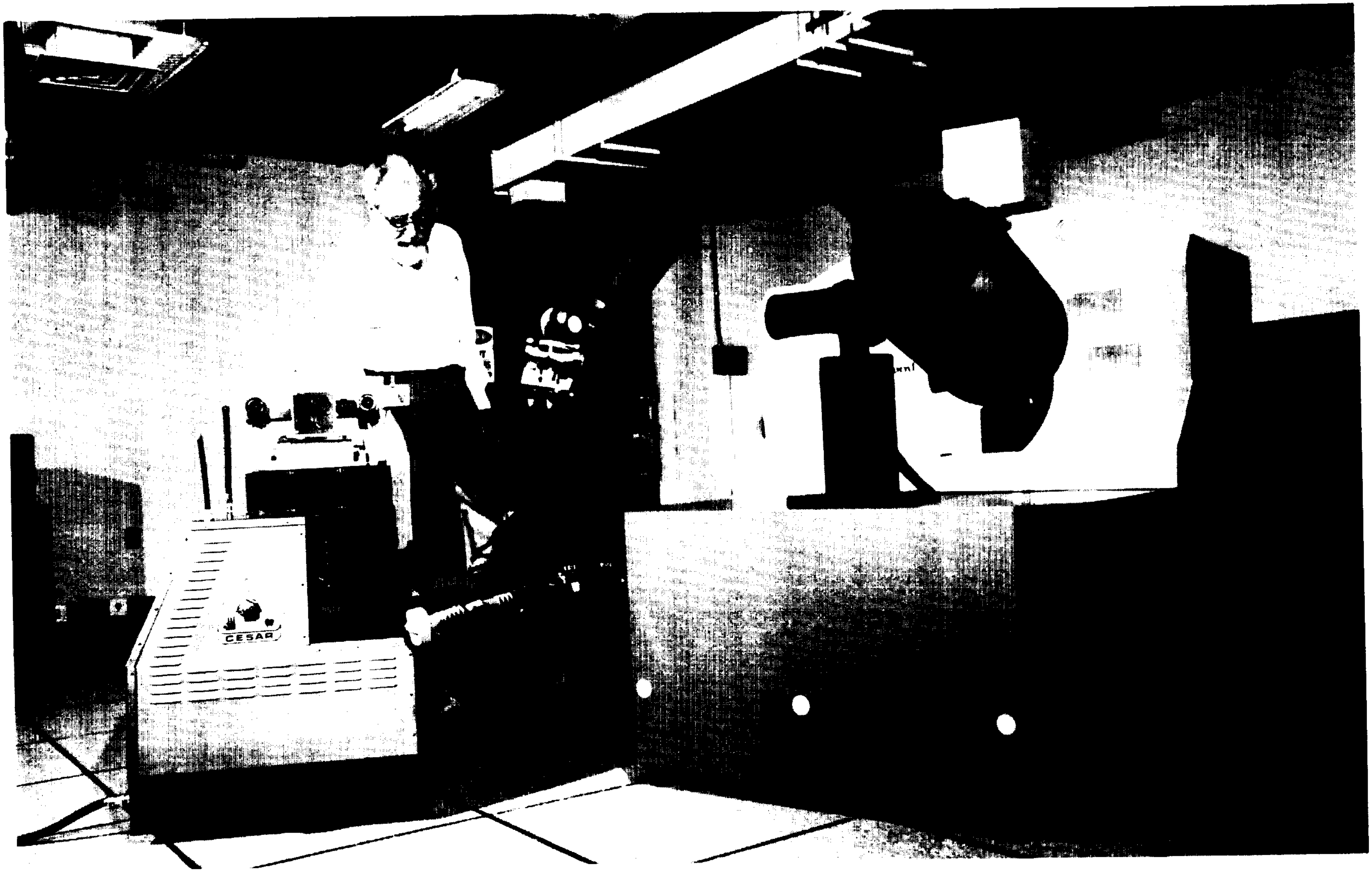

Fig. 1. The HERMIES-III mobile robot full-scale model is pictured alongside the HERMIES-IIB machine.

are 2 Mbytes of RAM and $\frac{1}{2}$ Mbyte for each NCUBE node. Mass storage is provided by two 40 Mbyte hard disks and a 1.2 Mbyte floppy disk.

- An RS-232 wireless model used for communication with the on-board computer system during experiments. The on-board batteries allow 3 to 4 hours' normal operation of all components. The sizes of the platform, batteries, and electronics compartment allow later expansion, including the addition of a second arm, more sensors, and additions to the computer system.

- The specifications for the mechanical design are:

Total weight	1230 kg (2700 lbs.)
Batteries	410 kg (900 lbs.)
	48 V at 110 amp-hours
	24 V at 220 amp-hours
vehicle speed	60 cm/sec (2 ft/sec)
vehicle acceleration	120 cm/sec/sec (4 ft/sec/sec)
arm tip speed	300 cm/sec (10 ft/sec)
arm weight	160 kg (350 lbs.)
arm payload	15 kg (33 lbs.)
arm reach	137 cm (54 in.)

A symbolic layout of the hardware architecture is presented in Fig. 2.

B. Proposed Software Architecture

HERMIES-III has been designed and constructed to provide significant hardware capability for perception, manipulation, mobility and computing; accordingly, the software for control of this vehicle will require a great degree of modularity, standardization, and hierarchy. Figure 3 represents our current view[5] of a suitable logical architecture for HERMIES-III. Before describing the diagram in more detail, three caveats are appropriate. First, this architecture is only now being implemented. The authors clearly recognize that experience will suggest revisions particularly for the data flow paths between modules. Second, the structure must accommodate and facilitate the implementation of a "brain" for HERMIES-III near-term demonstrations as well as a mechanism for the testing of basic research concepts. Demonstrations and basic research sometimes conflict in terms of requirements for standardization. Finally, the figure presents only a coarse look at the overall structure. The specific algorithms to be used in any given module and the data structures and interface specifications have not yet been finalized.

The envisioned structure includes five major components: Human Machine Interaction, Control, Mobility, Perception, and Manipulation. Although there is a Public Knowledge database, the architecture permits private "world" models to be maintained locally within any given task module. There is no single box allocated to Machine Learning. Our current view is that specification of a single learning program independent of local context and need would not be optimal; i.e., machine learning capability is subsumed within each of the modules according to need. The architecture is intended to accommodate a wide range of situations and tasks.

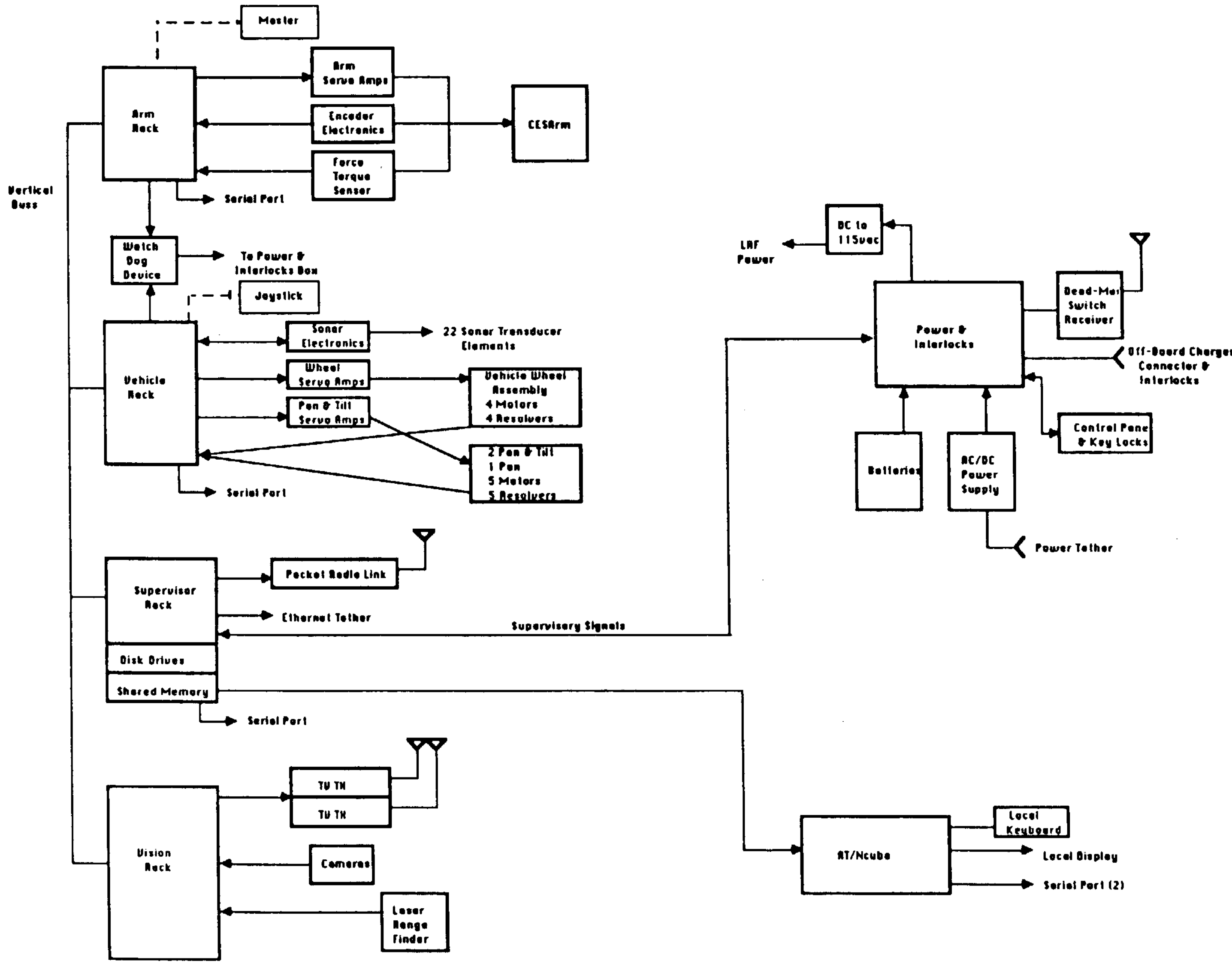

Fig. 2. The HERMIES-III initial hardware architecture.

We begin our discussion of Fig. 3 with the Human-Machine Interaction component. A goal is specified by the user through a suitable Human-Machine Interface which can be either keyboard or voice command. The next module, Job Decomposition Among Resources, is intended to divide the overall goal appropriately among the potential resources according to capability, availability, etc. For example, HERMIES-IIB might find, read, and monitor a control panel while HERMIES-III is attempting to suitably manipulate related valve(s).

Once the subgoals for each resource have been established a Task Planner is invoked to determine the steps needed to achieve that subgoal. At this level of planning, the tasks are phrased symbolically (e.g., avoid the obstacle). The symbolic tasks must be transformed to numerical procedures and ultimately to robot primitive operations (e.g., one turn of the wheel). These transformations are implemented through the Symbolic/Numeric Coordinator which mediates where appropriate between the Symbolic Task Planner and the more numerically intensive Mobility, Perception, and Manipulation modules. It should be noted that the overall software architecture is intended to allow for both vertical and horizontal communication. The vertical hierarchy represents task decomposition while the horizontal communications facilitate joint tasking (e.g., simultaneous arm and platform motion) and "reflex" action.

The Human-Machine Interaction, Task Planner, Mobility, Perception and Manipulation modules follow the three level Organization, Coordination and Execution hierarchy suggested by Saridis.[9] The addition of horizontal communication facilitates interactive tasks following the structure suggested by Albus.[10] The overall structure is intended to allow for decentralized control and asynchronous operation. The Mobility module considers global route planning at the highest level with increasing resolution in local navigation and obstacle avoidance at the lower levels. The Perception module integrates information from multiple sensors (e.g., sonar, vision, laser, force, tactile) at different levels with varying resolution following processing and interpretation of data from a single sensor. Similarly, the Manipulation module allows for multi-arm coordination at the highest level with manipulator motion planning and obstacle avoidance at an increasing amount of detail at the lower levels. The broad connectivity (bus structure) within the Mobility, Perception and Manipulation modules allows for at least two levels of representation, i.e., hard-wired or reflex response (e.g., the global route planner can directly control the wheel motion without passing through the Local Navigation and Obstacle Avoidance routines) and problem solving/classification higher level symbolic reasoning (e.g., scene interpretation). In fact, this two level description is arbitrary and corresponds to a continuum of representations for problem solving.

Within their own domain, the Mobility, Perception, and Manipulation modules proceed asynchronously reading from and writing to a Public Knowledge repository when appropriate. Recommended commands to the robot primitives are sequenced temporally and monitored by the Automated Monitor within the overall control module.

The architecture proposed in Fig. 3 is intended to provide capability toward performance which would customarily be deemed "intelligent". It was not conceived as an attempt to parallel the operation of the human brain; thus, the research envisioned strives more toward autonomous robotics and artificial intelligence rather than cognitive science.

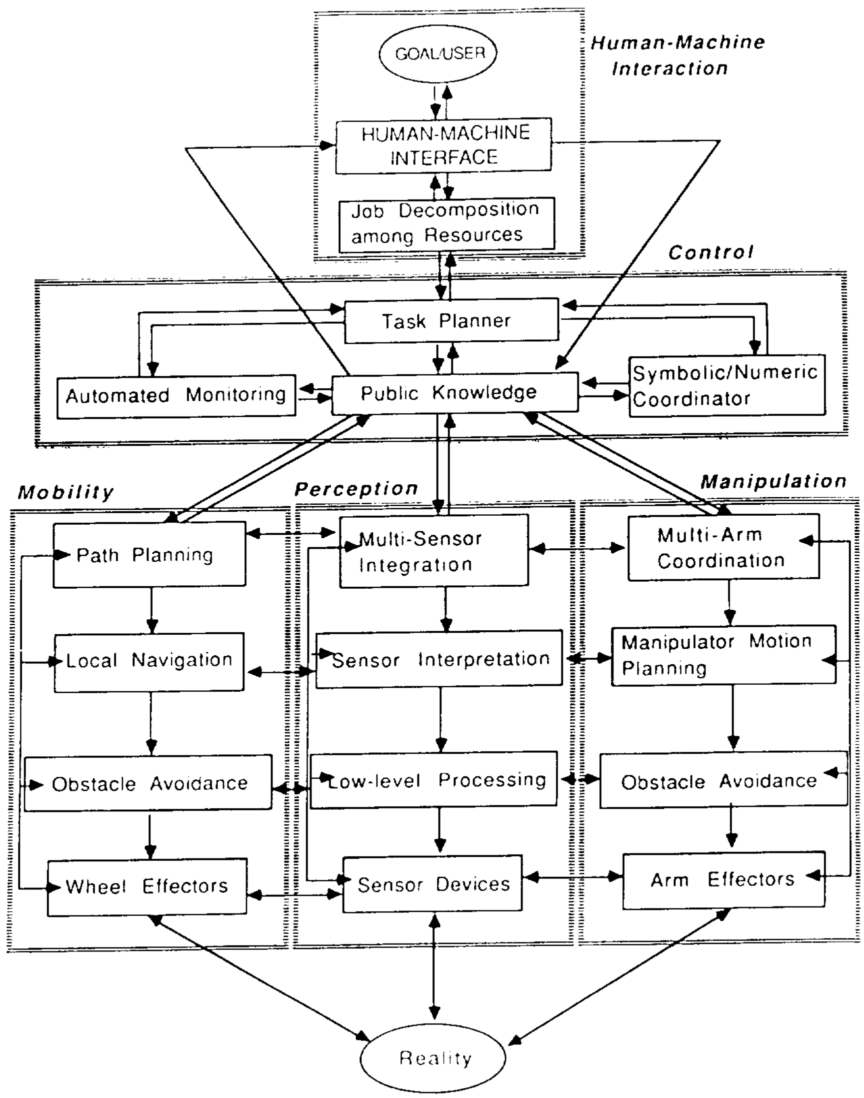

Fig. 3. An initial characterization of the HERMIES-III Software Architecture.

The architecture enables us to investigate a number of fundamental issues including the relative exploitation of algorithms vs. heuristics, the degree of generalized problem solving and learning vs. the specialized knowledge intensive domain approach, the degree of high-level reasoning vs. "wired" reflex, and the issues of long-term vs. short-term and decentralized vs. centralized memory. We anticipate that the HERMIES-III robot studies will lead to contributions to the understanding of these important issues.

C. Experiments with HERMIES-III

A paradigm problem has been chosen involving the operation, replacement and repair of valves, such as are encountered in an industrial environment. These tasks were deemed generic in nature, involving capabilities directly applicable to many other tasks. Some examples follow.

- Radiation monitoring – Mobile robot moves a monitoring device across surfaces to be surveyed.
- Decontamination – Brushing or spraying objects of various sizes and shapes.
- Erecting shielding – Stacking lead bricks.
- Changing an inserted module (filter, etc.) – Disassembly and assembly of dissimilar component parts. Many such tasks require two arms.
- Operation, replacement and repair of valves – Important tasks in industrial environments.

HERMIES-III is (a) instructed to navigate in an unstructured (a priori unspecified) environment, (b) find a control panel, (c) diagnose the problem(s) by reading meters and observing status of buttons that can be illuminated, (d) navigate through a complex piping network to location of valve(s), (e) adjust position of valve(s) to alleviate the problem, (f) return to the control panel to verify that the problem has been solved, and (g) return to the initial location.

An example of such an environment is illustrated in Fig. 4 in which HERMIES-III is shown performing manipulations.

Experimental features include the following:

- Multiple valves, pipes, meters; control panel; obstacles on floor;
- Exact world model (as-built drawings) not given, only information equivalent to preliminary drawings;
- Valves occluded from view and obstructed;
- Current operability of valves unknown;
- Multiple navigation paths of differing complexity;

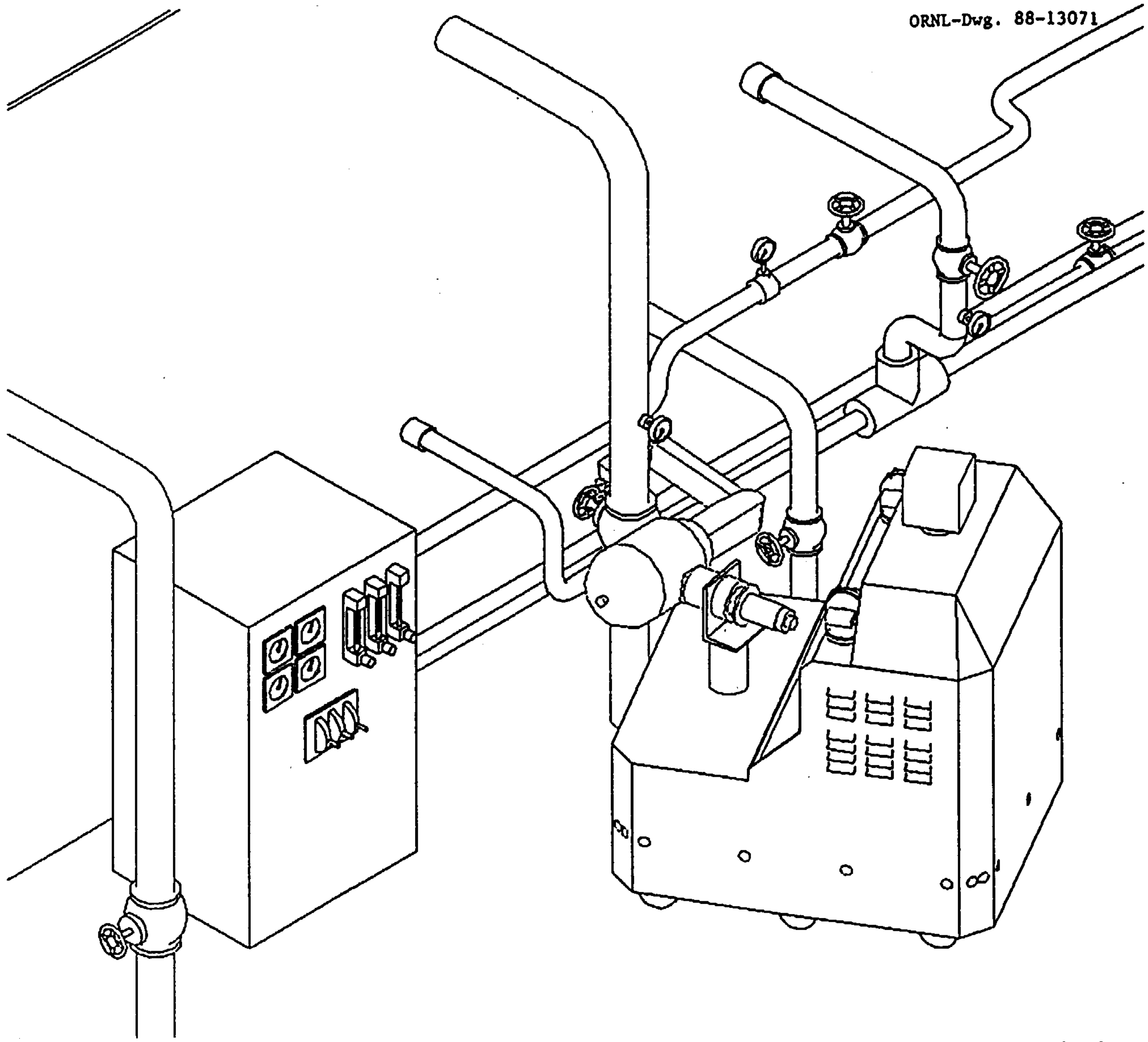

Fig. 4. HERMIES-III operates a valve, access to which is obstructed both by the pipe on which the valve is mounted and another pipe to the left. Visual location of the valve must be provided either by use of the body-mounted cameras from another position of the robot, or by a wrist-mounted camera (not shown).

- Completion of some tasks subject to time constraints.

The environment (network of pipes, etc.) described above will have a number of variable parameters so that not one but a whole range of experiments may be done. The equipment will be constructed so that its parameters can easily be varied. It will be possible to vary the orientations of the valves so that they point up, down, horizontally, or at any other angle, and so that their axes are not necessarily perfectly perpendicular to those of the pipes to which they are attached. Where a valve is obstructed or occluded by another object such as a pipe, the relative positions and orientations of the valve and the obstructing object will be variable. If a valve is behind an access window, its position and orientation relative to that window will be variable.

The intent of these experiments is to highlight research achievements including, (1) multiple cooperative autonomous robots, (2) multi-tasking including smooth continuous motion and simultaneous sensor data processing, (3) ability to deal with real-time asynchronous unexpected events within the framework of a parallel expert system, (4) multi-sensor integration for 3-D navigation and manipulation, and (5) human scale manipulation using CESARm.

III. SAFETY

Because of the size and complexity of HERMIES-III, safety considerations have played an important role in its design. These fall into several categories as follows.

A. Mechanical Safety

The CESAR Laboratory has restricted access in the operating region of HERMIES-III. On-board strobe lights indicate the availability of motor power, i.e., that HERMIES-III is capable of motion. Possible causes for collision accidents involving the chassis or manipulator include errors in computer programs and malfunctions of the computer or motor-drive hardware. Safety measures include the following, some of which are implemented through hardware interlocks for the main motor power.

- A key-switch interlock prevents all but authorized experimenters from operating the vehicle.

- Operation of the robot is conducted with a minimum of two persons, one of whom has the sole duty of keeping depressed a radio-linked "dead man's" switch while closely observing all robot motion. Loss of radio contact terminates motor power.

- There is a large, red, easily accessible kill switch on each of the vehicle's four corners.

- A computer-actuated signal is used to cause a power-down of all motors in the event of a computer crash, which could lead to a loss of control.

- Computer programs involved in motion are exhaustively checked and tested, and control parameters (e.g., velocities) are tested to ensure that they are within acceptable bounds.

- The sonar transceivers mounted around the entire periphery of the vehicle's base sense objects at distances greater than 3 feet. HERMIES-III is programmed to avoid collision with any sensed object.
- CESARm's joints have brakes which are automatically actuated when the joints are not in motion.

B. Laser Range Finder

The Odetics Laser Rangefinder (LRF), which operates at 820 nm in the invisible infrared, is interlocked so that the laser is inactivated unless the scanner mirrors are operating. The LRF is then eye safe (Class I) at distances greater than 0.5m. A flashing red light above the LRF alerts experimenters, and restriction of the work area prevents non-experimenters from approaching.

C. Battery Charging

The lead-acid batteries on-board the vehicle, (equivalent to about 20 automobile batteries) are periodically charged. Hydrogen evolved during charging is removed to the outside through hoses connected to the battery compartments, which are equipped with fans. Air-flow switches are used as interlocks for the battery chargers.

In summary, the safety considerations involved with a vehicle of this complexity are a vital part of conducting our research in autonomous mobility, manipulation and perception. Our experiments will be carefully phased to assure the required level of reliability and safety.

IV. CONCLUSIONS

HERMIES-III is an important testbed for research in autonomous mobility, manipulation and perception. It is comprised of a seven degree-of-freedom manipulator designed for human scale tasks, a laser range finder, a sonar array, an omni-directional wheel driven chassis, multiple cameras, and a dual computer system containing a 16-node hypercube (expandable to 128 nodes) and Motorola 68020 processors. On-board batteries allow for 3-4 hours normal operation. A software architecture which serves as HERMIES-III's "brain" is described with emphasis upon modularity, standardization, and hierarchy.

The current experimental program involves performance of human-scale tasks (e.g., valve manipulation, use of tools), integration of a dexterous manipulator and platform motion in geometrically complex environments, and effective use of multiple cooperating robots (HERMIES-IIB and HERMIES-III). The environment in which the robots operate has been designed to include multiple valves, pipes, meters, obstacles on the floor, valves occluded from view, and multiple paths of differing navigation complexity. The equipment includes a number of variable parameters (e.g., valve orientation, position) so that an entire range of experiments can be accommodated.

The ongoing research program highlights (1) multiple cooperating autonomous robots, (2) multi-tasking including smooth continuous motion and simultaneous sensor data processing, (3) ability to deal with real-time asynchronous unexpected events within the framework of a parallel expert system, (4) multi-sensor integration for 3-D navigation and manipulation, and (5) human-scale manipulation using CESARm.

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