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# INTEGRATED DIGITAL CONTROL AND MAN-MACHINE INTERFACE FOR COMPLEX REMOTE HANDLING SYSTEMS

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# INTEGRATED DIGITAL CONTROL AND MAN-MACHINE INTERFACE FOR COMPLEX REMOTE HANDLING SYSTEMS*

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ABSTRACT

The Advanced Integrated Maintenance System (AIMS) is part of a continuing effort within the Consolidated Fuel Reprocessing Program at Oak Ridge National Laboratory to develop and extend the capabilities of remote manipulation and maintenance technology. The AIMS is a totally integrated approach to remote handling in hazardous environments. State-of-the-art computer systems connected through a high-speed communication network provide a real-time distributed control system that supports the flexibility and expandability needed for large integrated maintenance applications. A Man-Machine Interface provides high-level human interaction through a powerful color graphics menu-controlled operator console. An auxiliary control system handles the real-time processing needs for a variety of support hardware. A pair of dedicated fiber-optic-linked master/slave computer systems control the Advanced Servomanipulator master/slave arms using powerful distributed digital processing methods. The FORTH language was used as a real-time operating and development environment for the entire system, and all of these components are integrated into a control room concept that represents the latest advancements in the development of remote maintenance facilities for hazardous environments.

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## INTRODUCTION

The Consolidated Fuel Reprocessing Program (CFRP) at the Oak Ridge National Laboratory (ORNL) has been developing advanced techniques for remote maintenance of future fuel reprocessing plants. These efforts are based on the application of force-reflecting servomanipulators for dexterous remote handling and the use of closed-circuit television (CCTV) for viewing in large-volume cell applications. The primary emphasis in the current program is the design, fabrication, and installation of a prototype remote handling system for reprocessing applications, the Advanced Integrated Maintenance System (AIMS).[1,2] It incorporates all the subsystems (Fig. 1) required for large-volume maintenance in a hazardous environment including manipulators, transporters, sensors, signal and power transmission, and human-machine interfaces. In support of these systems, the Robotics and Electromechanics Development Group of the Instrumentation and Controls Division has been developing advanced control techniques and mechanisms.

## CONTROL SYSTEM OVERVIEW

Because of its complexity, control of the AIMS represents a sizable challenge requiring a high degree of hardware and software integration. The difficulties presented have been minimized by partitioning the overall system into a number of satellite computer systems that are more manageable and can be considered separately (Fig. 2). Because each of

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~~THE ADVANCED INTEGRATED MAINTENANCE SYSTEM~~

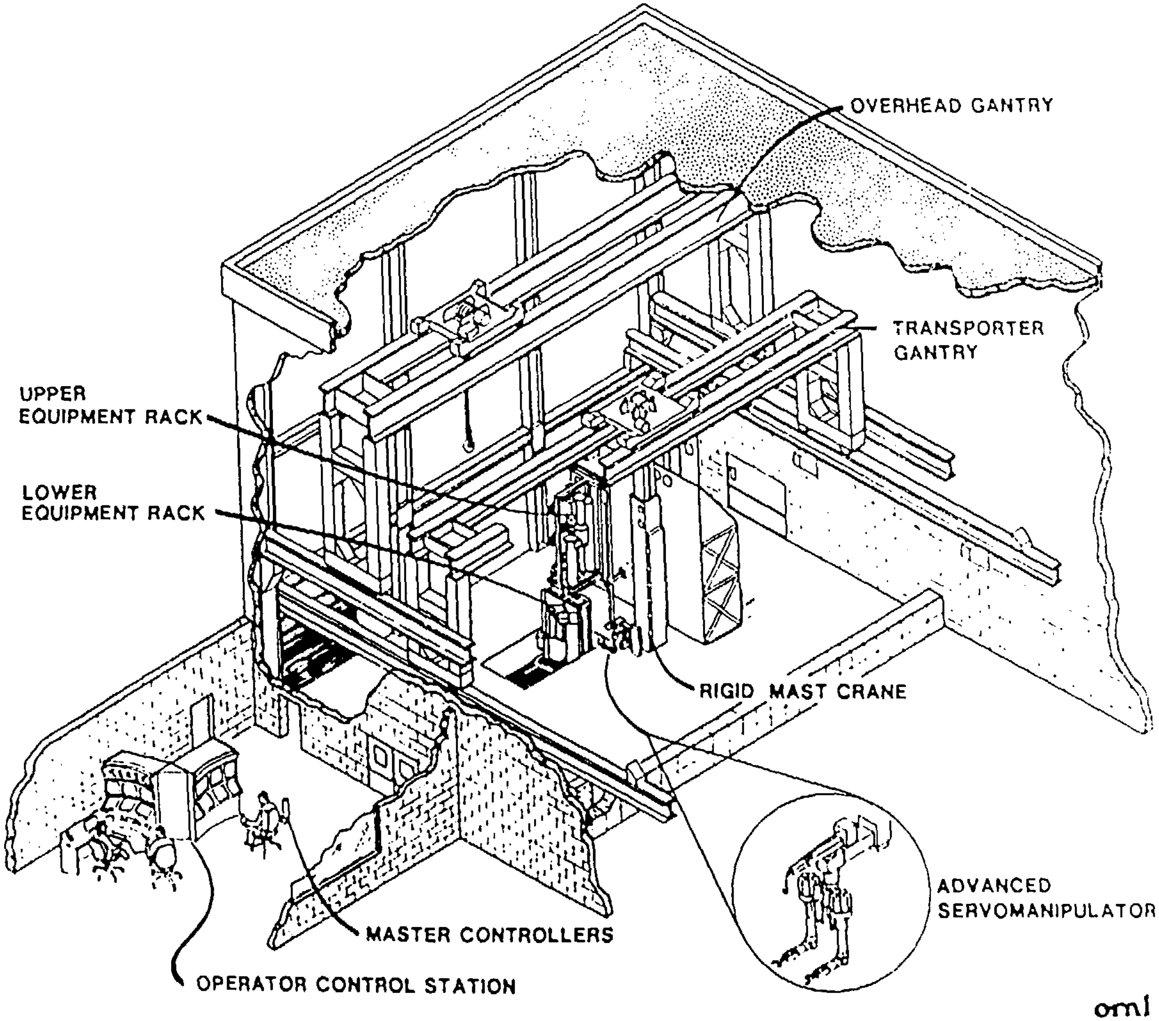


Fig. 1. The Advanced Integrated Maintenance System.

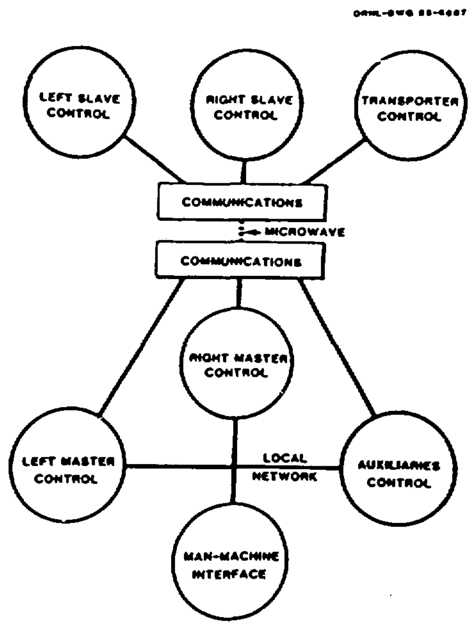


Fig. 2. AIMS control system block diagram.

the satellite computer systems is responsible for the control of a separate subsystem of the overall AIMS hardware, each is a stand-alone application in itself. By distributing the interface and control requirements among the different computer systems, the overall computational burden, hardware complexity, and software complexity are reduced. A communications network then ties the various modules together into a unified system which is both powerful and flexible.

The complexity of the overall control system is best illustrated by the fact that it must provide control of 26 bilateral, force-reflecting servos that require updating at a 100-Hz rate, 58 non-force-reflecting drives, 6 graphics displays, 21 television displays, and 2 operator control stations. This is accomplished through a system of 7 Multibus computers containing 15 Motorola 68010 CPUs, 372 analog input/output (I/O) channels, 1080 digital I/O points, 64 RS-232 serial channels, and 4 graphics processors. The number of listed I/O channels also includes the installed capacity of the system that is available for future expansion.

All the AIMS computer hardware is based on the industry-standard Multibus (IEEE-796) backplane. At the time the control system designs were being finalized, it provided the best combination of performance and support that was available. The large base of Multibus hardware that is commercially available provided a maximum of flexibility both in selecting current hardware and in obtaining expandability for future enhancements. The Omnibyte single-board computers used throughout the control system are based on Motorola 68010 microprocessors operating at 10 MHz. Input/output and special purpose boards were chosen to meet individual subsystem requirements. All the software modules in the system were written in the language FORTH because of its adaptability and the ease of implementation for real-time hardware control.

Before describing the individual subsystems in more detail, a description of the overall control architecture will help to place each individual subsystem in its proper relationship to the other subsystems. Each circle shown in Fig. 2 represents one of the seven separate Multibus computer systems controlling the AIMS. The out-of-cell systems, consisting of the left master controls, right master controls, auxiliary control system, and man-machine interface are located in the control room area and are linked through a local area control network that ties the individual modules into a unified system. The other three Multibus systems, including the left slave controls, right slave controls, and transporter controls are located in-cell or remote from the control room. The remote systems interface with equipment in the maintenance area and are tied to an individual out-of-cell control computer through a high-speed dedicated communications link.

The following discussion will be divided into six sections, each of which will describe one or more of the AIMS subsystems. The sections are as follows: the man-machine interface (MMI), the auxiliary control system (ACS), the advanced servomanipulator (ASM) system, the local area control network (LAcN), the remote communications link, and the control software. Because they are directly linked, the transporter control computer will be covered with the auxiliary control system. Likewise, the left and right arm controls, master and slave, are best described together in the ASM section.

## MAN-MACHINE INTERFACE

The MMI computer provides the highest level of control in the AIMS control hierarchy. As such, the MMI handles much of the operator interaction with the rest of the system, accepting input through the operator control station, passing commands to the other subsystems, and reporting back status to the operator. The MMI also has the only disk drive in the system and provides mass storage facilities for the entire system through the local area control network.

The MMI directly controls the operator control stations shown in Fig. 3. It is felt that operator efficiency is enhanced through the use of a two-operator team approach for control of operations.[3] The manipulator, or primary, operator (see Fig. 3) is responsible for performing dexterous maintenance operations using the manipulator arms and television viewing. The secondary operator (see Fig. 3) is responsible for control of the transporter, a large 20-ton overhead crane, television camera positioning, control station displays, and overall maintenance supervision.

As shown in Fig. 3, the primary operator has a number of displays in front of him to assist him. There are three 19-in. black and white television monitors across the bottom. These monitors provide the working views of the task site. Across the top are six smaller black and white televisions that provide a selection of alternative views currently available from the remote site. These smaller views can be moved to the larger 19-in. monitors as required by a computer-controlled video matrix switcher. Across the center of the console are three 19-in. color graphics monitors on which can be displayed control menus, data, status, operating procedures, and other information used by the

Fig. 3. The AIMS control room is designed for a two-person team, with the primary operator console on the right and the secondary operator console on the left.

operator. Using a miniature, thumb-actuated joystick to control a cursor on the color graphics displays, the primary operator can interact with the system; make menu selections; and, in general, control any of the equipment in the system. Although it is possible for the operator to control any of the equipment, it is intended that he concentrate on dexterous manipulation and allow the secondary operator to assist him or her in controlling the balance of the equipment.

The secondary operator consoles provide similar views to those at the primary station. The six smaller televisions at the top and three 19-in. televisions at the bottom provide identical views. The three color graphics monitors have been moved to a lower console, and in their place are an additional set of three 19-in. televisions. The secondary operator requires these additional views because this operator is responsible for moving the transporter and crane and for overall supervision, and thus requires a wider perspective than the primary operator. The color monitors have been moved closer to the secondary operator because he or she interacts with the system through touch screens on those monitors. The secondary operator controls the equipment through the same menu system as the primary operator but makes selections by touching control pads displayed on the monitors (Fig. 4) or by manipulating a mouse-controlled cursor on the screen.

The MMI control system handles most of the operator interaction with the overall system through the flexible, graphics-based control interfaces, thus eliminating hard-wired buttons and knobs. This not only provides an operator interface which is very flexible and can be

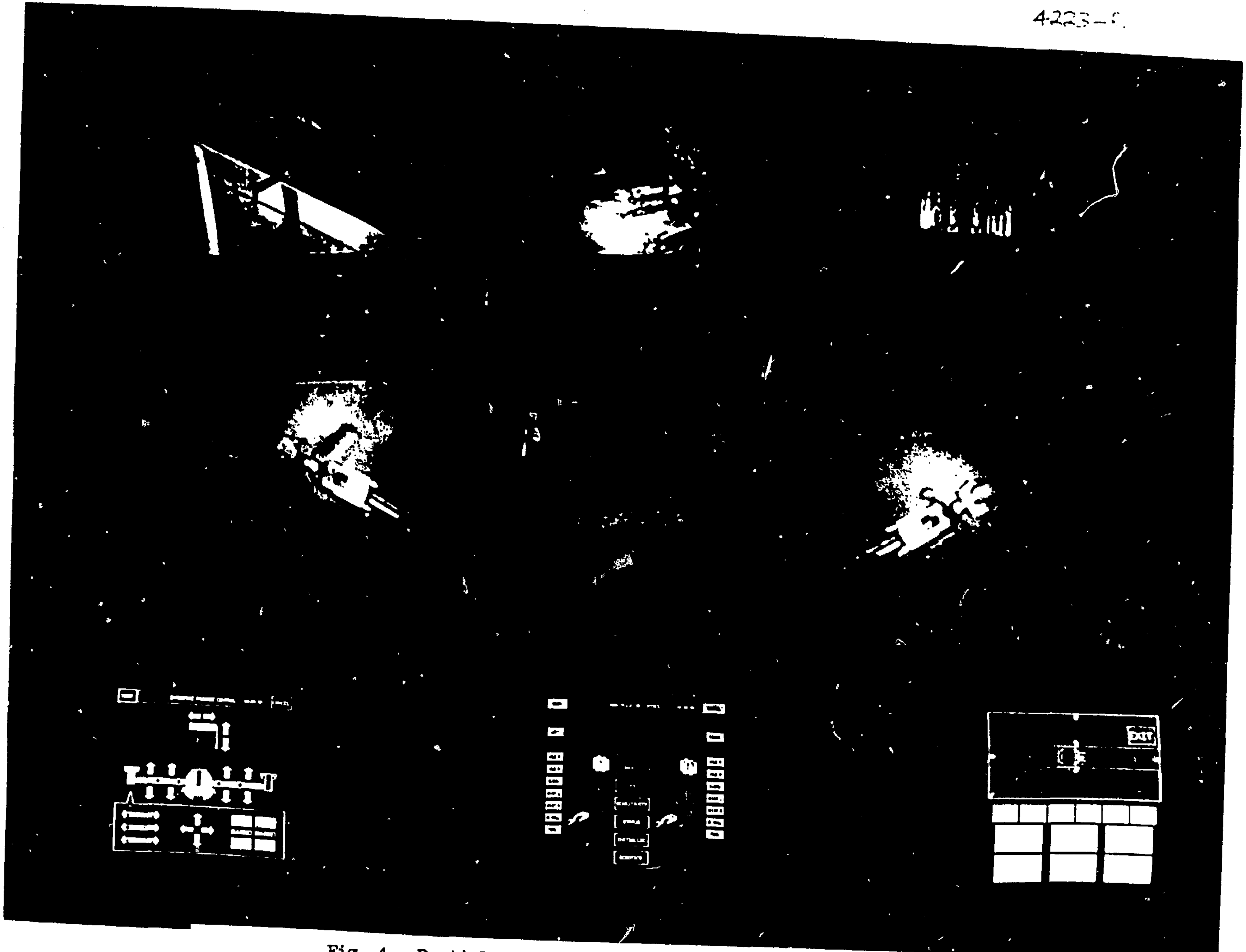


Fig. 4. Partial view from the secondary operator control station with three control menus displayed.

reconfigured as necessary in software, but which is simple to learn and easy to use. Figure 4 provides a partial view of the secondary operator console which illustrates the graphics-based menu concepts.

## AUXILIARY CONTROL SYSTEM

The auxiliary control system (Fig. 5) interfaces to all the peripheral systems not controlled directly by the MMI and ASM computers. These include facility cameras, transporter controls, and a 20-ton overhead crane. Within a larger facility, the ACS would also have responsibility for communications with the facility supervisory computer system. The ACS is linked directly to the transporter control module in a remote area through the remote communication link, making up a master/slave pair. A similar link will connect the ACS and 20-ton overhead crane. Facility wall cameras are controlled directly by the ACS, while the transporter cameras are controlled through the transporter computer via the remote communication link.

Some devices controlled by the ACS require variable analog inputs for rate control which cannot be conveniently provided through touch screen inputs. Therefore, the menu interface system on the MMI is complemented by pendant controller inputs to the ACS. The pendant controller (Fig. 6) is a light-weight, hand-held device, which, through a joystick and three rotary potentiometers, provides five axes of analog input. This small device provides a versatile method for secondary operator control of transporter, crane, and camera motions.

In addition to the analog controls, the pendant has a 12-function keypad for mode and device selection, and a four-line liquid-crystal

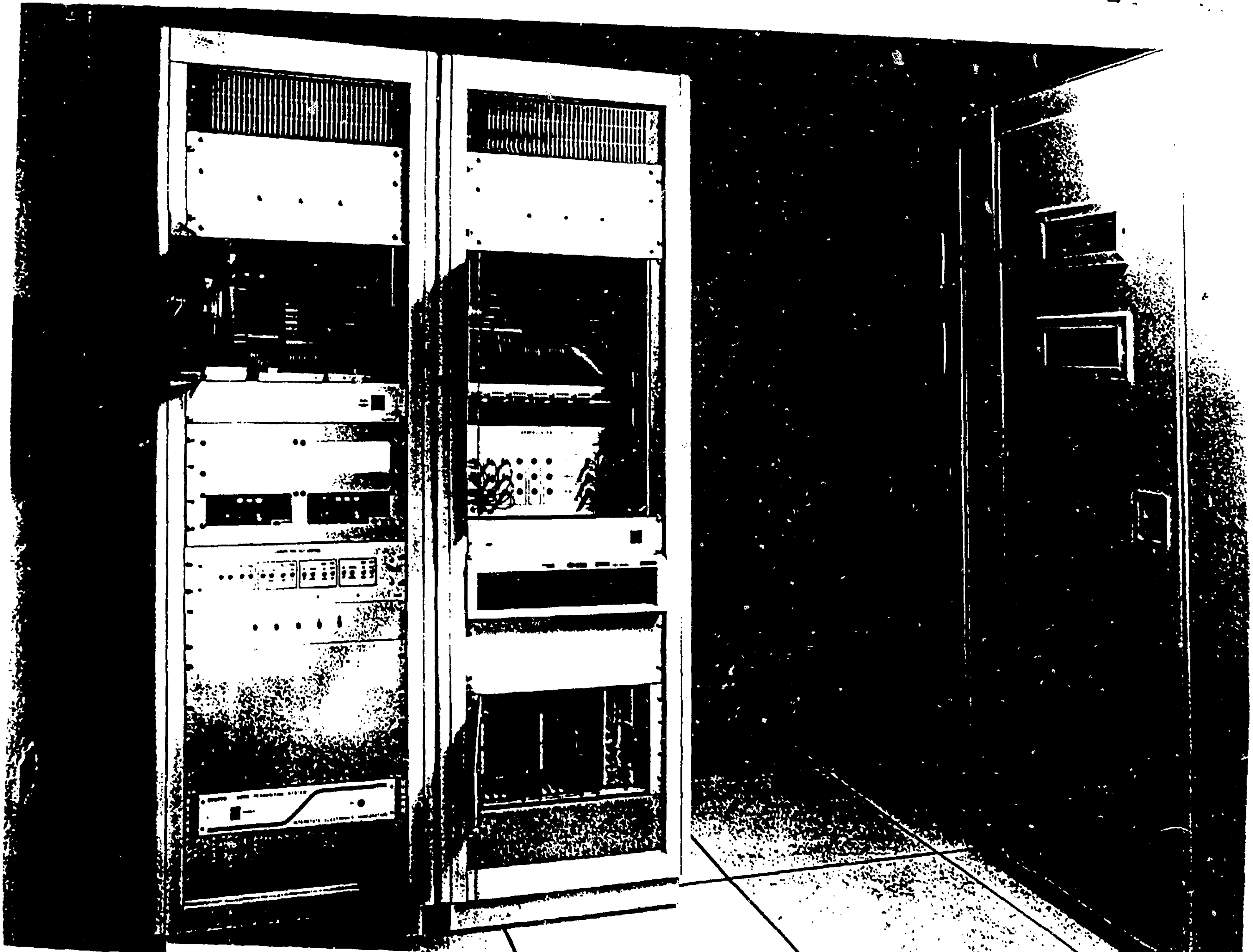

Fig. 5. The Auxiliary Control System (left rack) and the man-machine interface controls (right rack).

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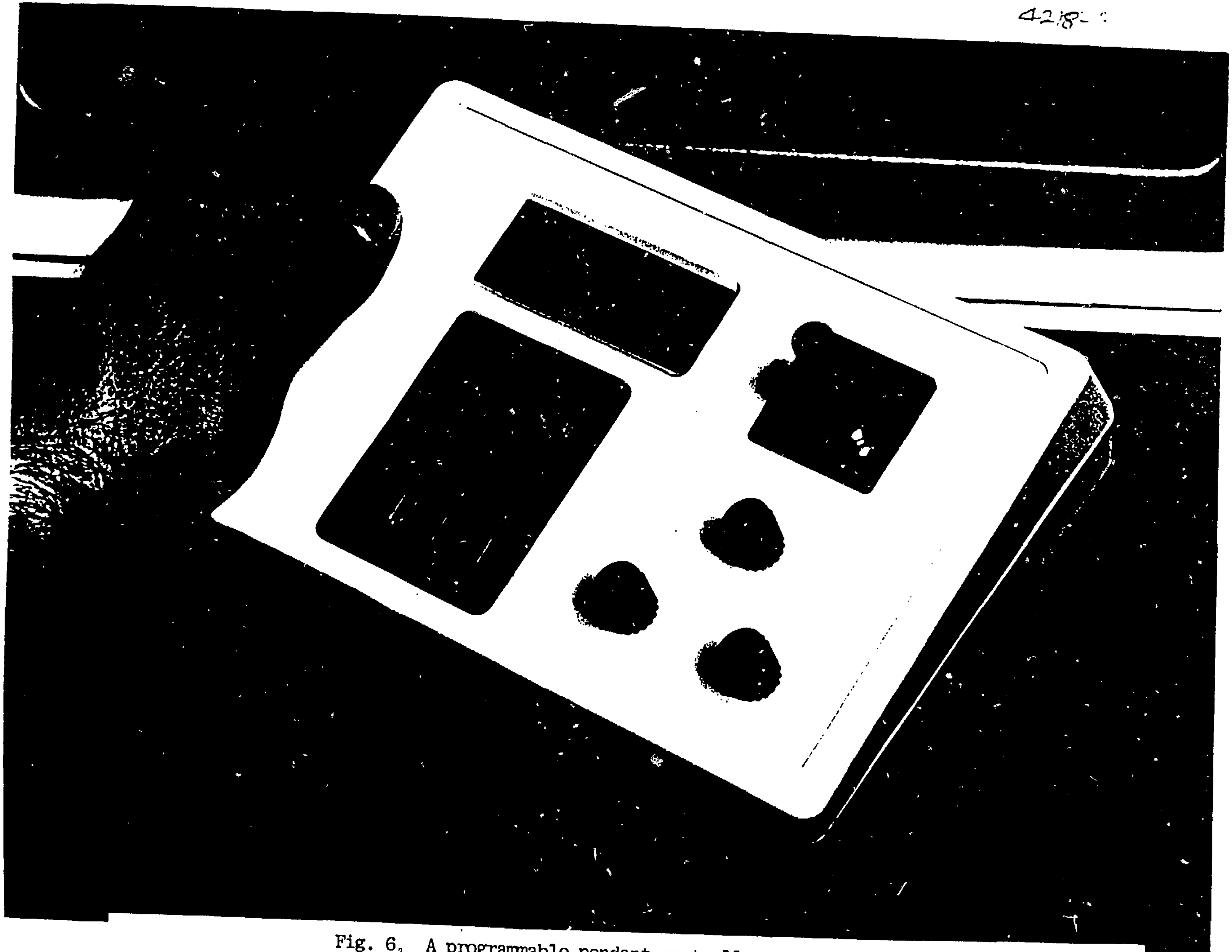
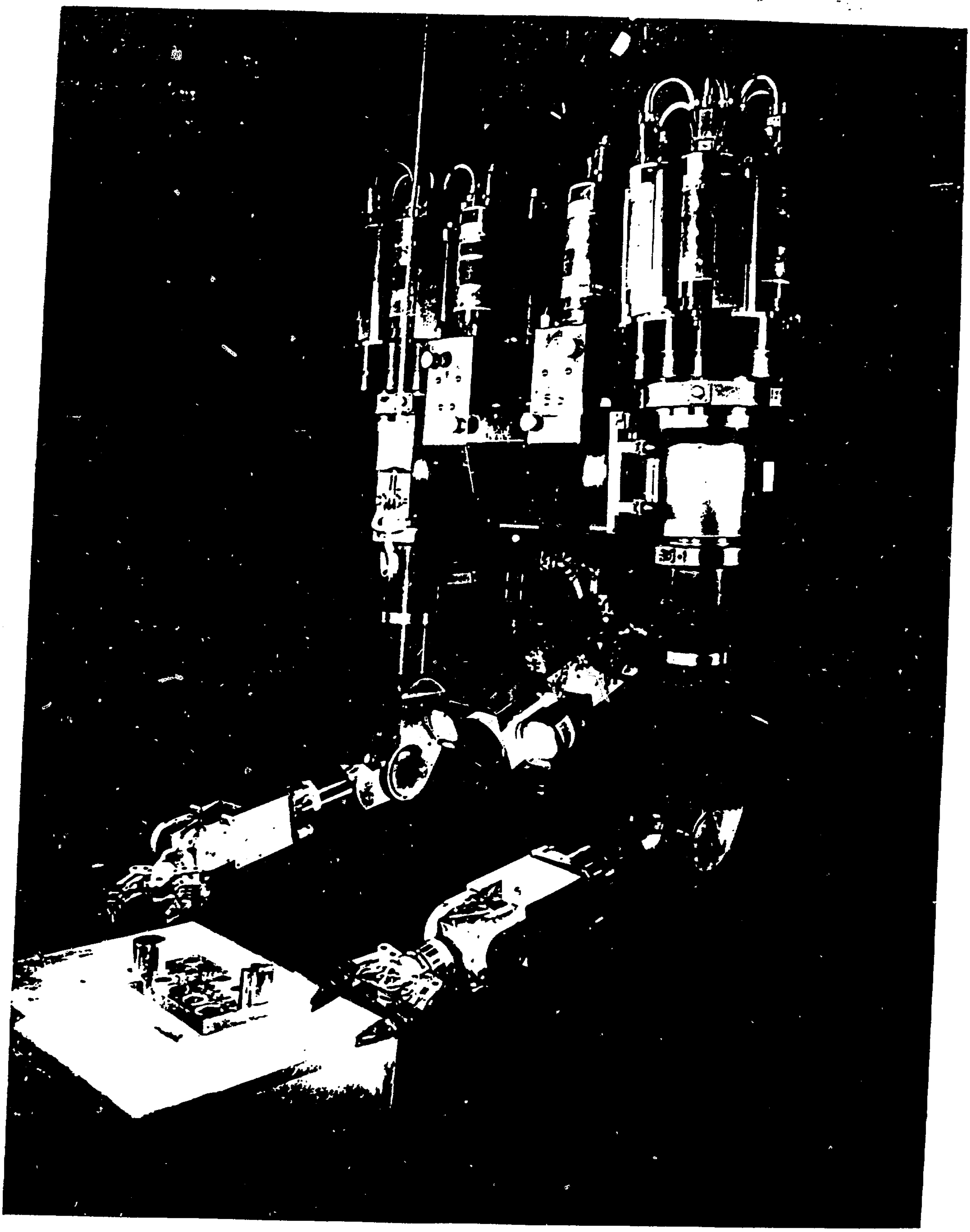


Fig. 6, A programmable pendant controller.

display (LCD) for operator feedback. The pendant is based on the Intel 8096 microcontroller and provides programmable control inputs to the ACS. Therefore, it can be adapted to control any of the current AIMS hardware or any future hardware. This again supports the flexible, expandable nature of the overall AIMS system. Because the pendant controllers interface to the ACS through a simple serial link, sockets similar to telephone outlets can be provided at several locations and the pendants plugged in as required.

## ADVANCED SERVOMANIPULATOR SYSTEM

The advanced servomanipulator system,[4,5,6] including the dual arm masters,[7] is one of the most complex of the AIMS control subsystems. Four of the seven satellite computers are devoted to it. It represents the latest advance in remote handling technology, mimicking the motions of human arms and hands to repair or replace equipment in hazardous areas. In contrast to stationary industrial robots that perform repetitive tasks, the ASM is mobile and is primarily controlled by a human operator in the control room, although some capability for robotic operations is provided. To perform tasks, an operator maneuvers a "master" control manipulator (Fig. 3) linked electronically through the remote communications link to the "slave" manipulator arms (Fig. 7). Through bilateral force feedback, the operator "feels" the weight of objects and other forces exerted on the slave arms while the CCTV and microphones allow him or her to see and hear the remote task.



The ASM is the first remotely maintainable force-reflecting servomanipulator. The modularized design is accomplished through the use of precision gear and shaft drives which results in higher levels of friction, inertia, and cross-coupling of torques than would normally be present. Special software compensation methods allow the digital control system to offset these adverse effects. In addition, electronic counterbalancing of the slave arms to offset gravitational forces has been achieved without significant adverse effects on force-reflection sensitivity.

The controls for each master/slave pair are provided by a system of six single-board computers in conjunction with various input/output boards (Fig. 8). All the control calculations are completed out-of-cell in the left and right master computers to reduce the in-cell hardware and, therefore, to improve reliability and maintainability and to simplify future radiation hardening of the slave system. Furthermore, the calculations are completed in real time to allow all the servoloops to be updated at a 100-Hz rate with a local velocity loop being updated at a 400-Hz rate. Each master and slave computer pair is tied together through the remote communications link.

As indicated in Fig. 8, five computer boards operating in parallel are used in each master computer to complete the real-time calculations. These computers communicate through a common block of memory. Each computer board reads the data it requires from predefined locations in the common block and, when its calculations are complete, writes the results to the appropriate locations, again in the common block. Thus, the entire system status is continuously available to all five of the computers. The major tasks of the five computers are:

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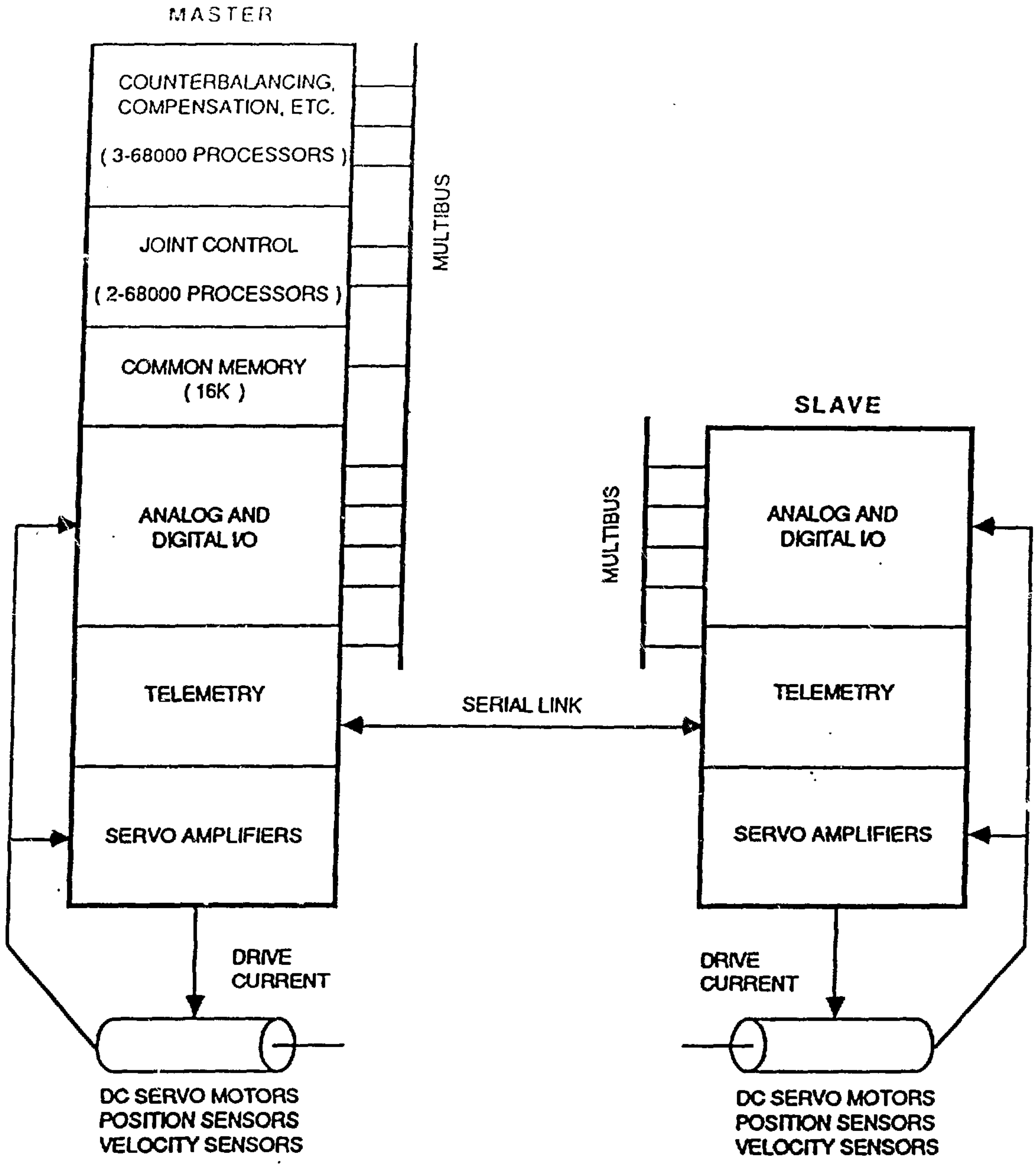


Fig. 8. Block diagram of the Advanced Servomanipulator (ASM) Controls.

1. force-reflecting master-slave joint control,
2. electronic counterbalancing calculations,
3. special control algorithm calculations,
4. data input and output,
5. communications, and
6. interface package control.

The interface package[1] is a mechanical system that connects the ASM to the transporter. It includes camera-positioning arms, cameras, lights, and a hoist, all of which must be controlled by the ASM computers.

## LOCAL AREA CONTROL NETWORK (LAcN)

The purpose of the local area control network is to tie together the separate out-of-cell computer racks into a unified system. It must provide a completely integrated control environment so that each computer can communicate with all the other computers on the network in a real-time control mode. This allows the MMI, for example, to control the facility cameras which are hardwired to the ACS computer. The LAcN derives its name from the fact that it is a local area network with the added capability to pass continuous control data at a minimum specified rate. In this case, the minimum specified rate is 10 Hz.

The data passed between systems on the LAcN is divided into three types. The first is disk data. Through the MMI computer, the LAcN provides virtual disk access to all of the computers on the LAcN. This data is transferred in 1-kbyte blocks. The second type of data is command data, which provides a link between computers similar to the direct serial link between a computer and terminal. This provides a convenient channel for transmitting high-level commands between computers. The third type of data is control data, which is made up of positions, set-points, velocities, and other information needed to close control loops. With the LAcN, all three data types can be transferred continuously between all of the racks at the minimum specified rate.

The desired data rates for the LAcN necessitate the use of a very high bandwidth communication link. The hardware that was used to implement it is the MEGALINK model 11-0080 communication board. It is a Multibus board which permits direct memory access (DMA) block transfers between Multibus systems at a 1-mega-bit per second data rate. The board provides high-level data link control (HDLC) communications protocol implemented in hardware and on-board EPROM. Message synchronization, address check, and error calculations are also implemented in hardware, relieving the Multibus host of much of the overhead involved in a transfer.

The AIMS local area control network is configured in a star network in which each of the computer subsystems is connected to a central node (or star) by a fiber-optic transmitter/receiver pair and a plastic duplex fiber-optic cable. The plastic fiber used has a guaranteed baseband transmission bandwidth of 5 mega-bits per second for cable lengths up to about 50 ft. All the out-of-cell control racks in the control room are located within this distance. The star network box acts as a repeater in that a transmission from any of the computers on the network is regenerated and transmitted to all of the computers.

Fiber optics was chosen for this application because of its high bandwidth and freedom from crosstalk due to electromagnetic induced interference. Low transmission loss as compared to twisted pair or coaxial cable allows much greater separation between components, and because they do not conduct current, the separate computer systems are completely isolated from one another. In addition, optical fibers are smaller, lighter, and cheaper than metallic cables of the same capacity.

The communication protocol used in the LAcN resembles a token passing network in many respects. To ensure that no bandwidth-reducing data collisions occur on the link, a distributed polling scheme was devised. Access to the link is controlled by a network controller, in this case the MMI, which controls the total link update rate. The controller synchronizes the data transfers and provides timeout checks in the event that one or more of the satellite systems is not responding. Each of the satellite MEGALINK boards remains in the idle or receive mode until required. When a data block is received, the Multibus host is interrupted. The host then determines whether the transmission was from a peer or from the network controller. If the data was from a peer, it is moved into a control data buffer for that peer. If the transmission came from the network monitor, the satellite rack is not only receiving data, but it is being given the token to take the link for a specified amount of time. During this time, the satellite rack transmits a data block to each of the other satellite racks. The last transmission is a reply to the link controller, letting him know that the link is free. If the controller does not receive a reply within the required time, a hardware timeout is generated, and the controller continues to poll the satellite racks in a round-robin fashion. This allows the control data transfer rate to remain constant when one or more racks are not responding, thus providing some fault tolerance.

## REMOTE COMMUNICATION LINK

The remote communications link provides all of the data communications between the control room and the remote maintenance equipment. It utilizes the same hardware as the LAcN and actually consists of three 1-megaband duplexed data channels linking the out-of-cell computers to the in-cell computers. All the control information required to close the control loops between the master and slave manipulator arms and to control the cameras, camera manipulator arms, and transporter is transferred serially over the link.

Currently, the data link consists of three fiber-optic channels, but wireless transmission methods are considered very important for simplifying the cable handling on a remotely maintained transporter. Therefore, a directed-beam microwave signal transmission system is being developed for this application. The system will utilize a bidirectional link operating in the 10-GHz frequency range, allowing it to carry not only the three 1.0-megabaud data channels, but also five television channels and two radio channels.

## CONTROL SOFTWARE

All the AIMS system software was written in the language FORTH, specifically polyFORTH II. It was selected because of its enhanced capability for real-time hardware control. Although it is a high-level language, it allows one to work closely at the hardware level, when necessary, and to interactively test both hardware and software. Because it is also modular reentrant code running in a multitasking environment, all of the tasks running in the system can share the same code, thus reducing memory requirements. An additional advantage is the capability to create custom application languages and data structures to fit the application needs, features which were utilized a great deal in the AIMS system.

A commercial version of FORTH was utilized for all of the single-board computer software, but a new FORTH kernel was written specifically for the pendant controller application. The new FORTH was developed for the Intel 8096 microcontroller and resides in less than 8 kbytes of EPROM, thus providing the ability to put the FORTH application completely on the Intel 8796 EPROM version.

The current control software exceed 400 blocks of FORTH code and has approximately 2600 FORTH words in the active dictionaries. As a comparison, it has been estimated that this is equivalent to about 50,000 lines of FORTRAN. The code is accessible by many tasks running on the computer systems. For example, the MMI computer has a total of 22 tasks defined, 11 of which are active control tasks and the rest of which are tasks supporting system development.

## CONCLUSION

The AIMS system has been installed and operational for several months now, and by early 1987, the system is expected to be turned over to operations for maintenance demonstrations and testing. Development of the AIMS control system was a sizable effort which has been made manageable and efficient by segmenting the tasks within a network of real-time computers. In conclusion, the AIMS provides a successful approach to the application of hardware, software, and system concepts for the control of complex remote handling systems.

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