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TELEROBOTIC MANIPULATOR DEVELOPMENTS FOR GROUND-BASED SPACE RESEARCH*

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ABSTRACT

New opportunities for the application of telerobotic systems to enhance human intelligence and dexterity in the hazardous environment of space are presented by the National Aeronautics and Space Administration (NASA) Space Station Program. Because of the need for significant increases in extravehicular activity and the potential increase in hazards associated with space programs, emphasis is being heightened on telerobotic systems research and development. The Automation Technology Branch at NASA Langley Research Center currently is sponsoring the Laboratory Telerobotic Manipulator (LTM) program at Oak Ridge National Laboratory to develop and demonstrate ground-based telerobotic manipulator system hardware for research and demonstrations aimed at future NASA applications. The LTM incorporates traction drives, modularity, redundant kinematics, and state-of-the-art hierarchical control techniques to form a basis for merging the diverse technological domains of robust, high-dexterity teleoperations and autonomous robotic operation into common hardware to further NASA's research.

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*Research performed at Oak Ridge National Laboratory, operated by Martin Marietta Energy Systems, Inc., for the U.S. Department of Energy under Contract No. DE-AC05-840R21400, and sponsored by the National Aeronautics and Space Administration, Langley Research Center.

INTRODUCTION

New opportunities for the application of telerobotic systems to enhance human intelligence and dexterity in the hazardous environment of space are presented by the National Aeronautics and Space Administration (NASA) Space Station Program. The suited astronaut has been the mainstay of the U.S. space program to date, and this will continue. Nevertheless, with significant increases in extravehicular activity (EVA) likely and potentially increased hazards associated with future programs, heightened emphasis is being placed on telerobotic systems research and development. R&D goals are to improve overall safety and efficiency and provide significant spin-off technology to improve the productivity of the U.S. industrial sector. The Automation Technology Branch at NASA Langley Research Center currently is sponsoring the Laboratory Telerobotic Manipulator (LTM) program at Oak Ridge National Laboratory (ORNL) to develop and demonstrate the ground-based telerobotic manipulator system hardware for research and demonstrations aimed at future NASA applications.

NASA plans indicate the need to rely on teleoperation for control of dexterous telerobotic systems in the construction and initial operation of the Space Station. Evolution into intelligent robotic operations is desirable. Because of present technological limitations, evolution is expected to be gradual. The unique nature of orbital operations demands that this evolution be carefully controlled. A major limitation in implementing the transition is the lack of available telerobotic hardware that can function well as a real-time teleoperator while providing a sound hardware basis for intelligent, autonomous robotic operations. The LTM is being developed as a basis for the merger of these diverse technology domains into common hardware to further NASA research.

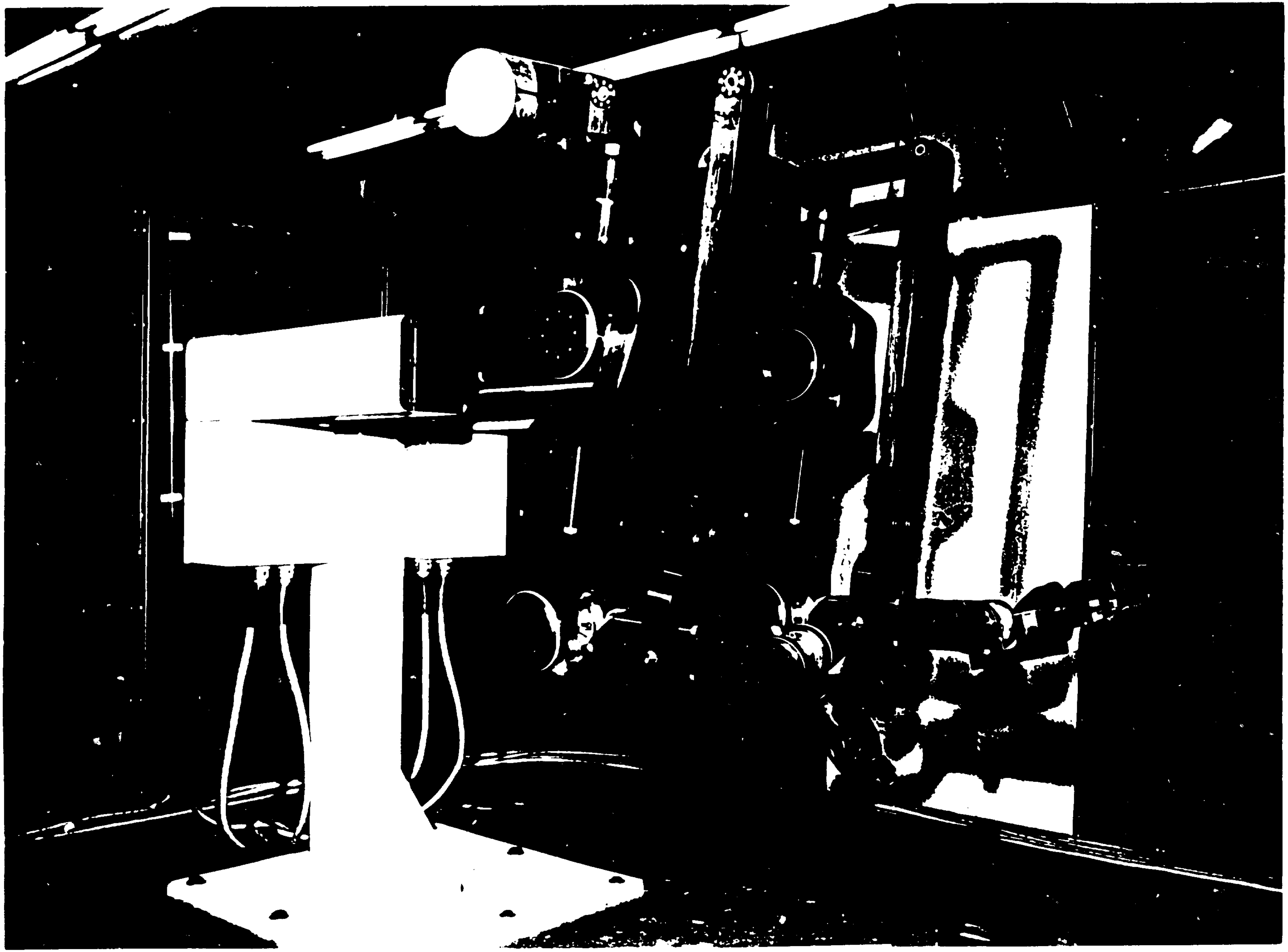
SYSTEM DESIGN FEATURES

Merging the mechanical and control features necessary for a force-reflecting servomanipulator and a robotic positioner into a single system is a particularly difficult task. A good force-reflecting servomanipulator designed for efficient human-in-the-loop control emphasizes end effector speed for good master response to human control input, good slave tracking of the master, high-joint back-drivability for force reflection, and low reflected friction and inertia to minimize operator fatigue. On the other hand, a good robotic positioner emphasizes end effector accuracy, end effector speeds, and mechanical and control stiffness. A major objective of the LTM design is to bridge the gap between these two technologies by providing the most important design and operational parameters of each. The LTM prototype system is composed of two force-reflecting slave arms (Fig. 1) and two force-reflecting master arms (Fig. 2) with a digital-based control system providing bilateral, position-position, force-reflecting control. End effector robotic control with kinematic redundancy resolution is planned.[1] Finally, joint-level robotic control of position and velocity and open-loop joint drives are provided for implementation of robotic control.

MECHANICAL DESIGN

The LTM design uses a modular approach for joint construction, with common pitch-yaw differential joints implemented for the arm, shoulder, elbow, and wrist. An output roll follows the wrist pitch-yaw differential to give a compact hemispherical wrist positioner. A simple parallel jaw gripper is provided for the slave, and a pistol grip handle is provided on the master. Each pitch-yaw joint mechanism provides these motions about orthogonal axe and each is attached to adjacent joints by four mechanical fasteners that produce a modular mounting arrangement. This arrangement allows the LTM arms to be easily assembled and disassembled. Cabling connections are automatically engaged during mechanical connection. All cabling is routed internally to eliminate external pigtails and connectors. This modularity, shown in Fig. 3, allows the LTM arms to be easily reconfigured for changing requirements and also permits maintenance of the arms simply by replacing the module. Traction drives with variable loading mechanisms were chosen for torque transmission through the LTM differentials. Although traction drives have not been widely used for servocontrol applications, potentially they can provide benefits for space applications, such as zero backlash and minimal lubrication requirements. Redundant LTM kinematics provide good dexterity for work in confined spaces and allow solutions for avoiding kinematic singularities. The overall reach of 55 in. and end effector speed of 36 in./s with any joint were chosen for dexterous performance as a teleoperator. All joints have an unloaded acceleration capability exceeding 1g in all directions.

The LTM has load capacities to accommodate expected requirements for orbital operation while providing counterbalanced operation for 1-g earth demonstrations. Each LTM arm has a peak load capacity of 30 lb and a continuous load capacity of 20 lb. For effective ground operation, the LTM arm is configured from joints with different torque capacities. To reduce fabrication and engineering costs, a large joint with a peak torque capacity of 1650 in.-lb is used at both the slave shoulder and elbow positions. To optimize dexterity and minimize weight, a small joint with peak torque capacity of 435 in.-lb is used as the slave wrist joint. The master arms are composed entirely of small joints due to the reduced requirements for output torque. As shown in Fig. 4, each joint assembly consists of a differential drive mechanism; two dc servomotors with integral reducers, fail-safe brakes, tachometers, and optical encoders; two in-line torque sensors; and two 16-bit



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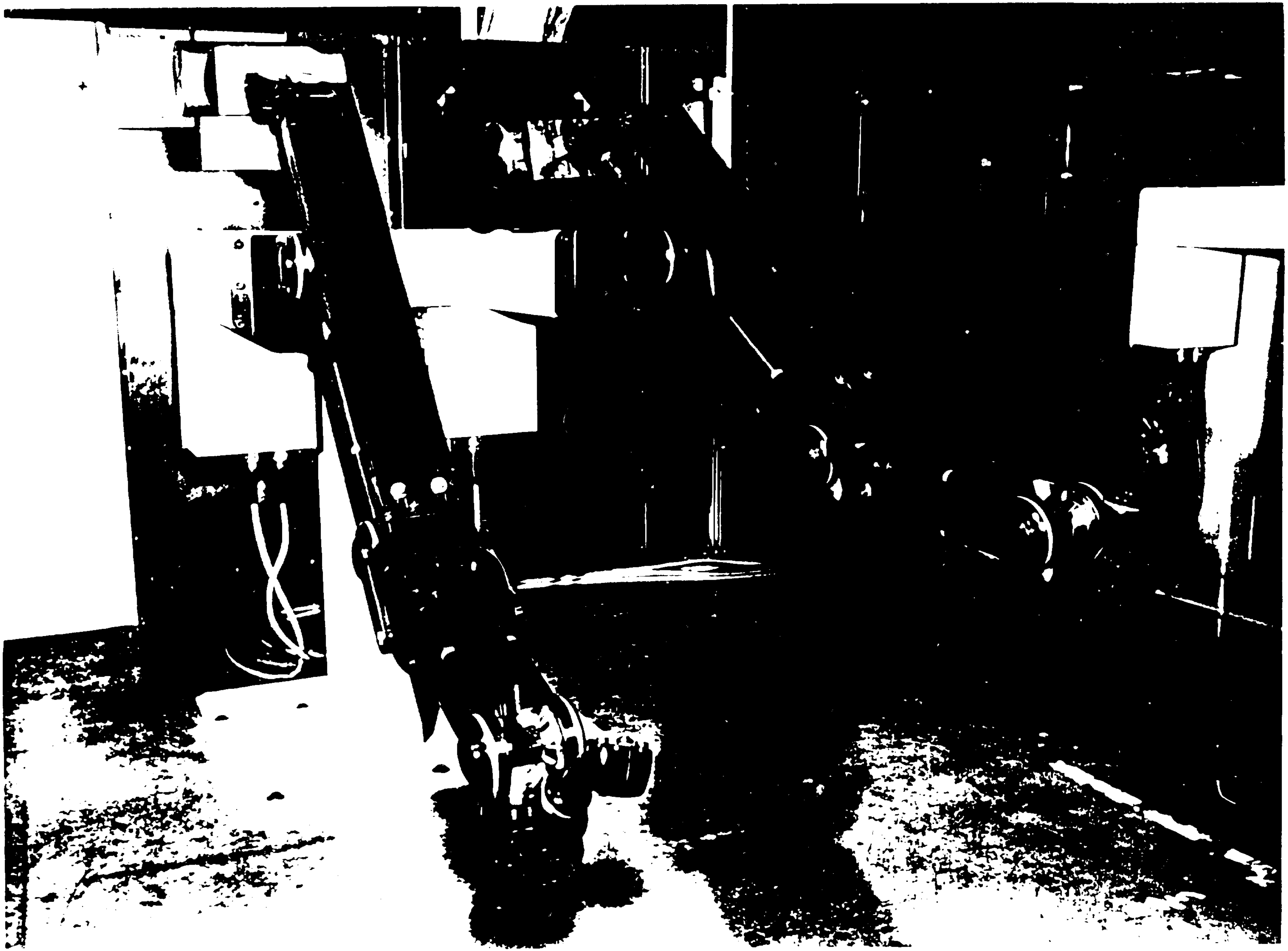

Fig. 2. LTM master arms.

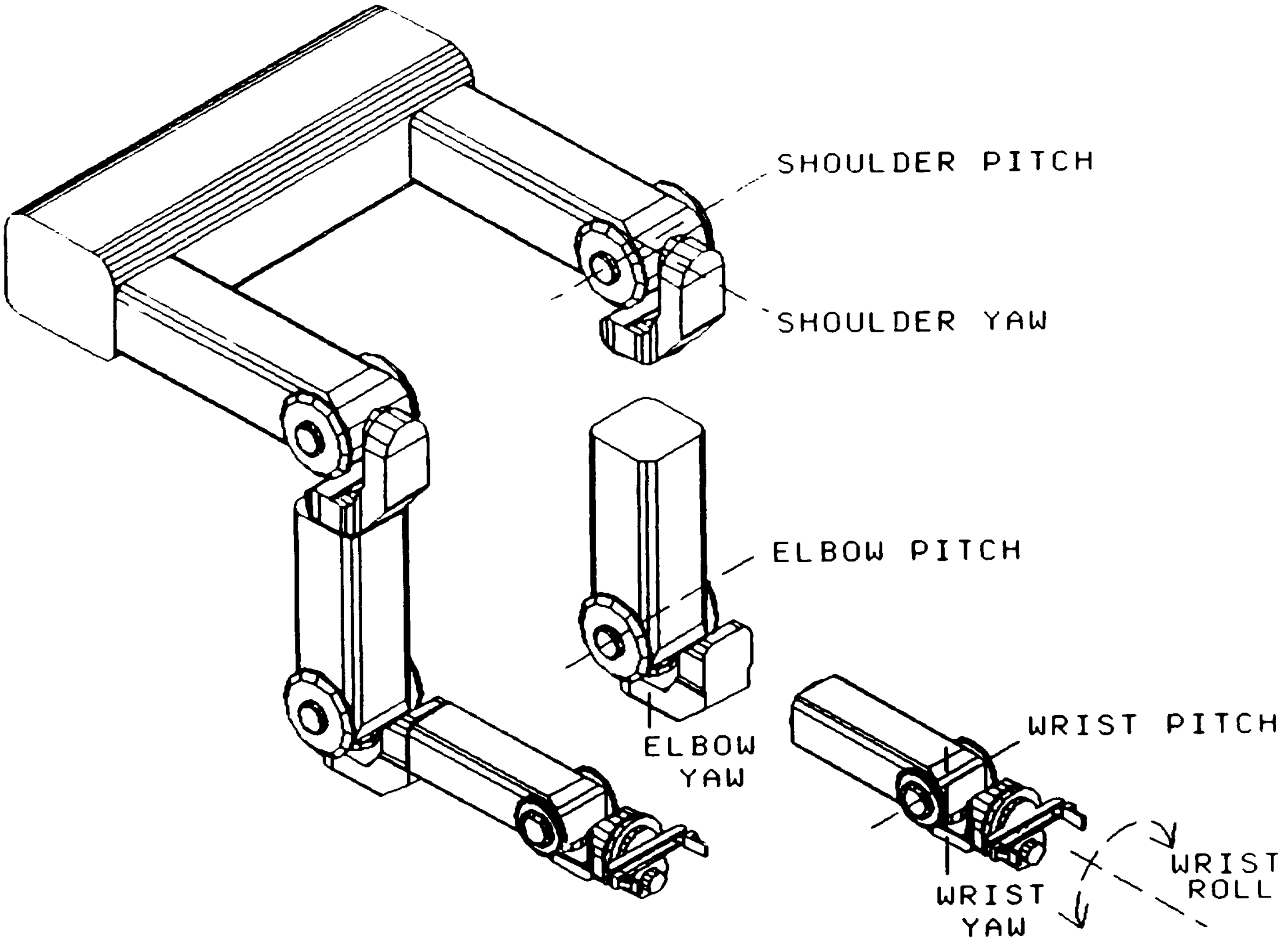

Fig. 3. LTM slave arm modularity.

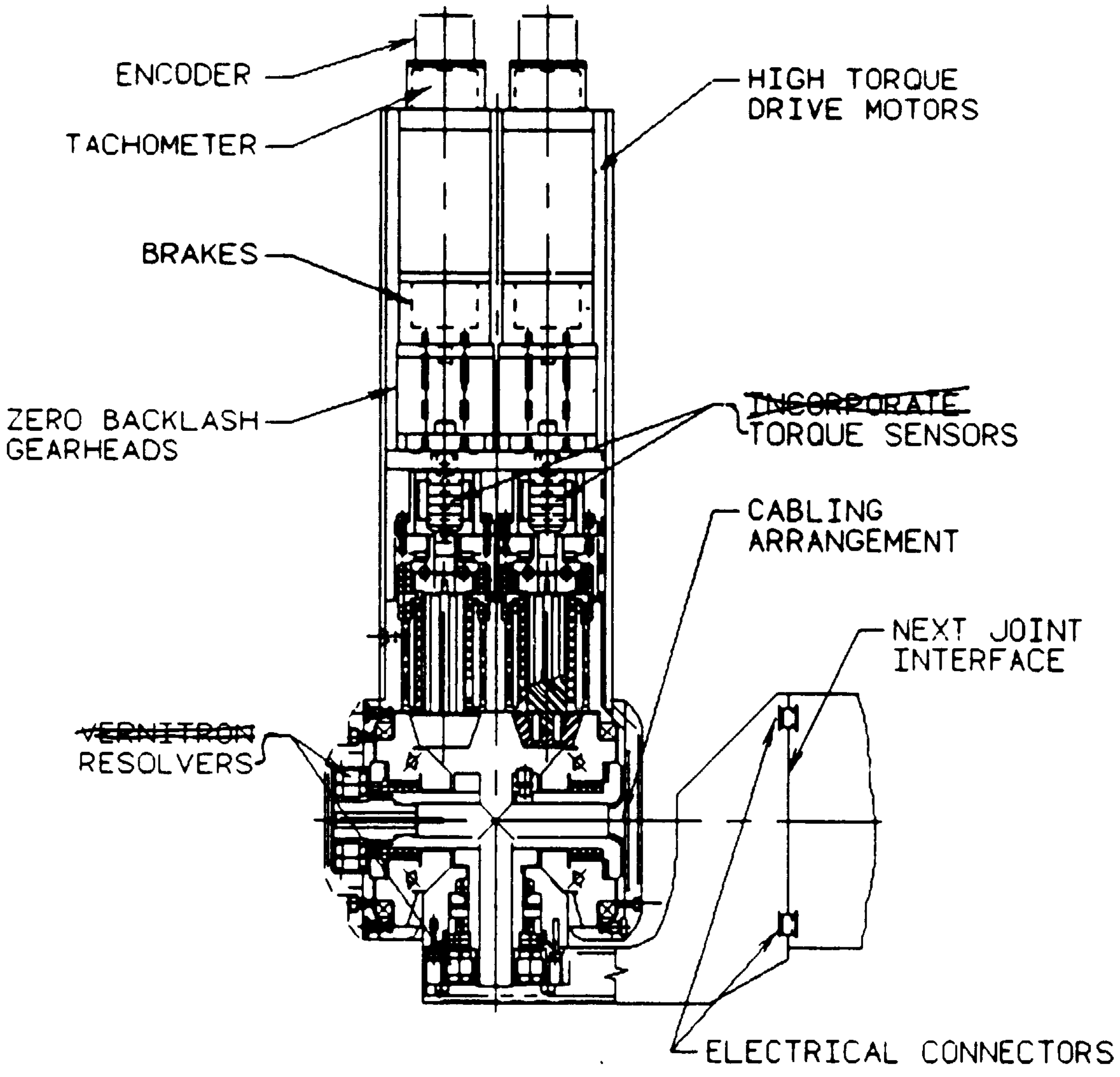

Fig. 4 LTM small pitch/yaw joint assembly.

accuracy single-turn resolvers at the joint output. The speed reduction ratio through the differential is approximately 3.5:1. The reducers were specially designed for LTM and utilize spring-loaded antibacklash gear trains. Commercial in-line torque sensors have been modified and incorporated directly into the joint mechanism to produce a more arrangement. Resolvers at each joint output axis are coupled directly to the axis of rotation. Permanent magnet fail-safe brakes coaxially mounted to each drive motor will safely support loads during power failure and are capable of supporting maximum payloads for extended periods without excessive motor heating. Their advantage is their higher torque-per-unit size and weight compared to spring-set brakes.

Force transmission through the differential drive mechanism is by traction drives. Unlike force transfer through gear teeth, which generate torsional oscillation as loads transfer between the teeth, force transfer through traction is inherently smooth and steady, without backlash.[2] The elements of this traction differential drive can be seen in Fig. 5. Two driving rollers provide input into the differential. A significant advantage in this differential setup is that each driving roller is required to transmit only one-half the total torque necessary for a particular motion, thus reducing required motor size and resulting weight. These rollers interface with two intermediate rollers that drive the pitch-yaw output roller about the pitch and yaw axes. The axis about which the pitch-yaw roller rotates depends upon the rotation direction of the driving rollers. The contact surfaces of the traction rollers are gold-plated by an ion plating process developed by NASA Lewis Research Center. This plating serves as a dry lubricant in that it prevents the substrates from making contact. The thin layer of gold is a cost-effective solution for lubrication of these rolling surfaces in space. By using resolvers directly at the output of each joint, any creep experienced through the traction drive differential will not affect positioning characteristics of the arm.

For traction drives to function, there must be a normal force between the mating rollers that transmits torque by friction. As an alternative to the more common constant-loading mechanisms, variable loading mechanisms have been employed on the LTM in an effort to improve differential back-drivability, mechanical efficiency, and fatigue life. Constant loading mechanisms produce a constant normal load between traction drive rollers. This constant normal load must be sized to ensure adequate traction at the joint's maximum torque capacity. The obvious disadvantage of this constant normal load is that traction drive rollers and their supporting bearings are needlessly overloaded during periods of low torque transmission, not only generating extra bearing losses at low torque transmission but, more importantly, shortening the drive systems fatigue life. In order to ensure adequate traction with minimum friction loss, variable loading mechanisms were developed for the LTM. These purely mechanical mechanisms produce varying normal loads between the traction rollers that are proportional to the

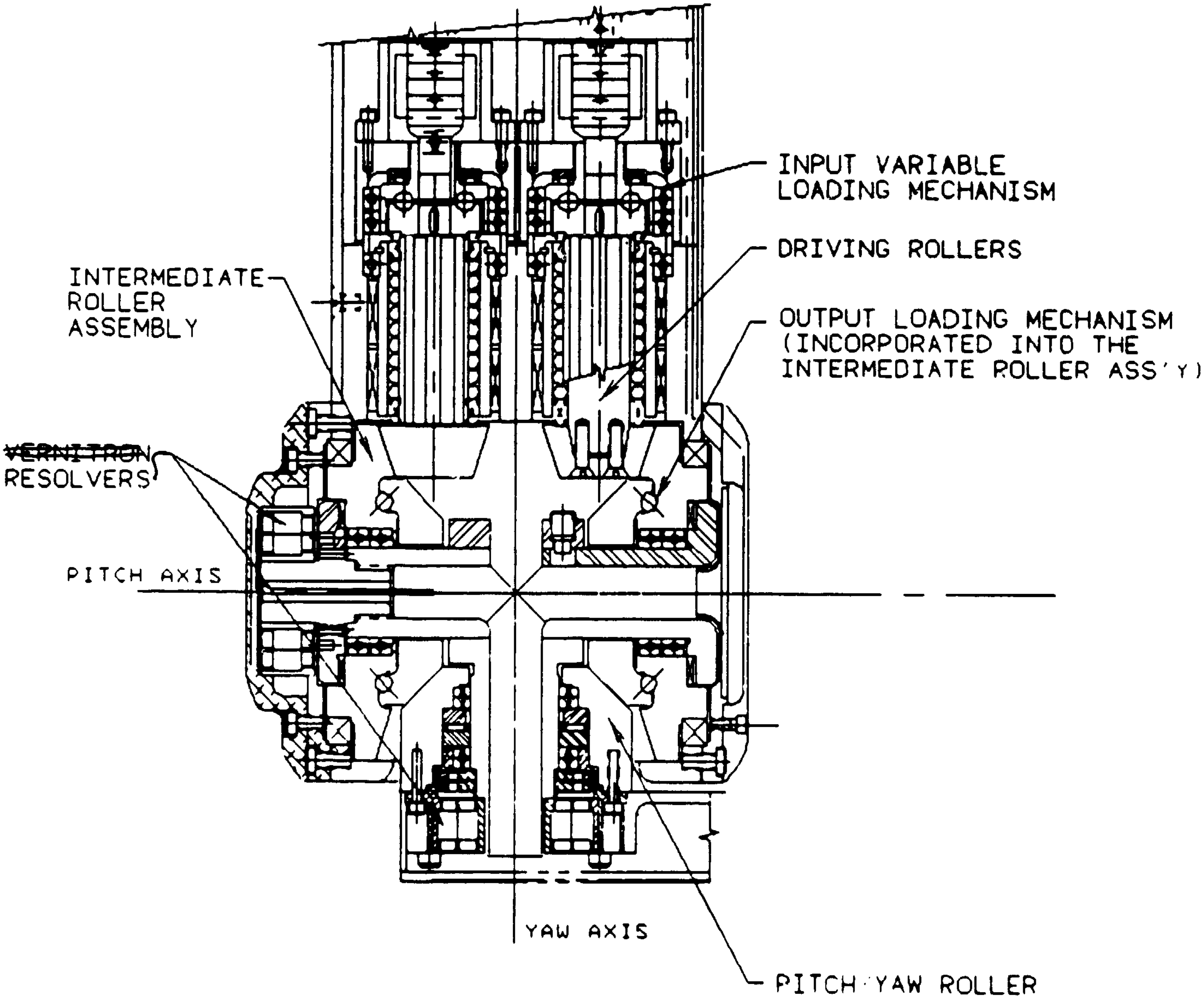

Fig. 5. LTM traction drive differential.

transmitted torque. Variable loading mechanisms have been incorporated into the traction drive differential, one pair at the input rollers and one at the output pitch-yaw roller. These preloading mechanisms are illustrated in Fig. 5.

CONTROL SYSTEM DESIGN

The LTM control system is a modular hierarchical design with expansion capabilities for future enhancements of both the hardware and software. It is based on past ORNL experiences in complex hierarchical manipulator systems[3] and the need to be consistent in the overall space station NASREM approach.[4] A top-level block diagram illustrating the organization of the system hardware is shown in Fig. 6. At this level, the system is composed of two computer systems, one master and one slave, connected by a high-speed serial communication link to allow significant separation between master and slave arms. Each rack controls a pair of LTM arms using data acquired from sensors in the individual joints. Custom embedded computers distributed in the joints provide sensor data acquisition for and data communication to the central computer systems through high-speed fiber optic links. A Macintosh II computer interfaced with the master computer system provides a graphics-based interface for system operation.

A commercial VME bus approach is utilized for the central computer systems and is based on multiple Motorola 68020 single-board computers operating in parallel. One single-board computer coordinates the overall operation of the system, while additional single-board computers complete the control algorithm calculations required for teleoperation, robotics, and electronic counterbalancing. In addition to the single-board computers, the VME systems support digital and analog I/O, distributed communication links, terminal support, and mass storage. PWM amplifiers that provide drive signals to individual joint motors are also located in the central computer racks. The overall hardware arrangement for the master rack is shown schematically in Fig. 7.

Custom electronics packages were developed to reduce the number of cables required for each arm. Because the LTM utilizes an embedded cabling approach in which all power, control, and communication cables pass through the pitch/yaw joints, it was necessary to minimize the number of cables required. The custom computer packages reduce the cabling by acquiring, processing, and multiplexing the many sensor signals over serial communication links between arm modules and VME bus racks. The electronics packages consist of four individual systems: a joint processor logic board (JPl) in each joint, a joint processor power board (JPp) in each joint, a link processor (LP) board for each joint to interface with the VME bus, and the fiber optic communication system. The joint processor logic board and the

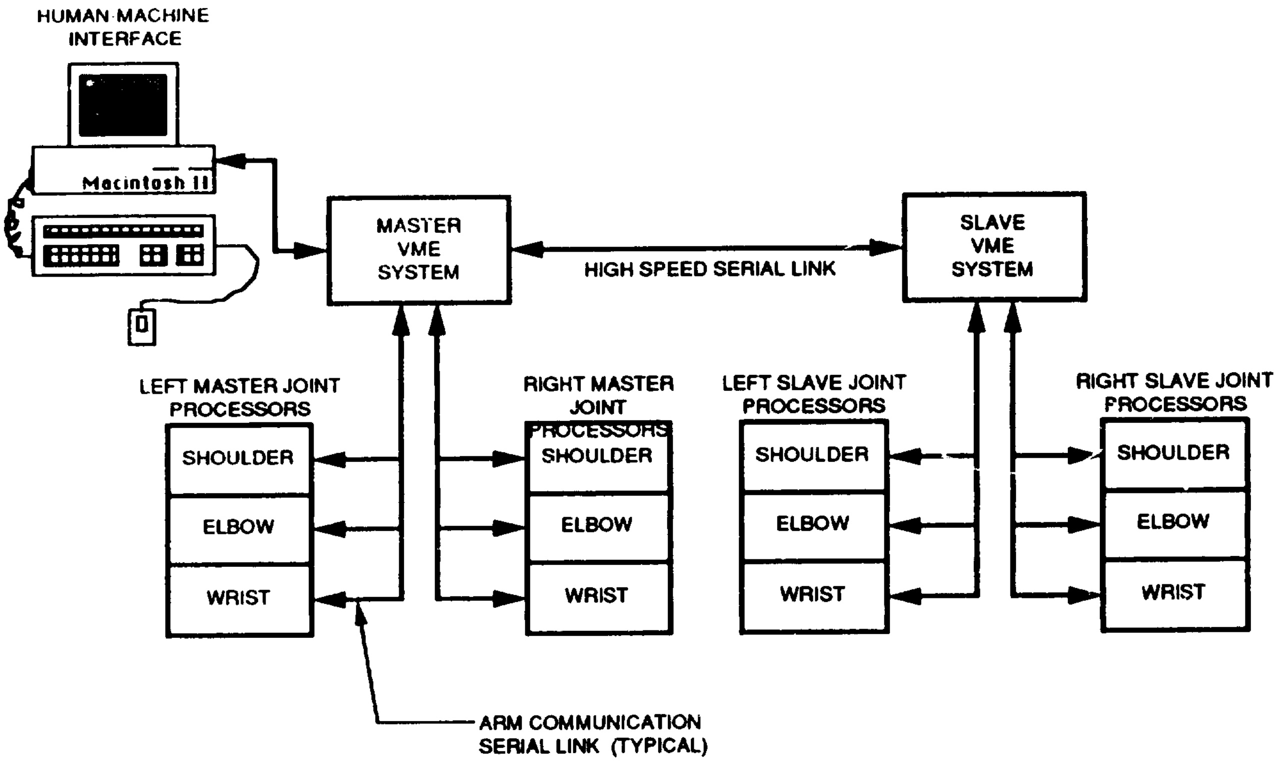

Fig. 6. Block diagram of the LTM control system hardware.

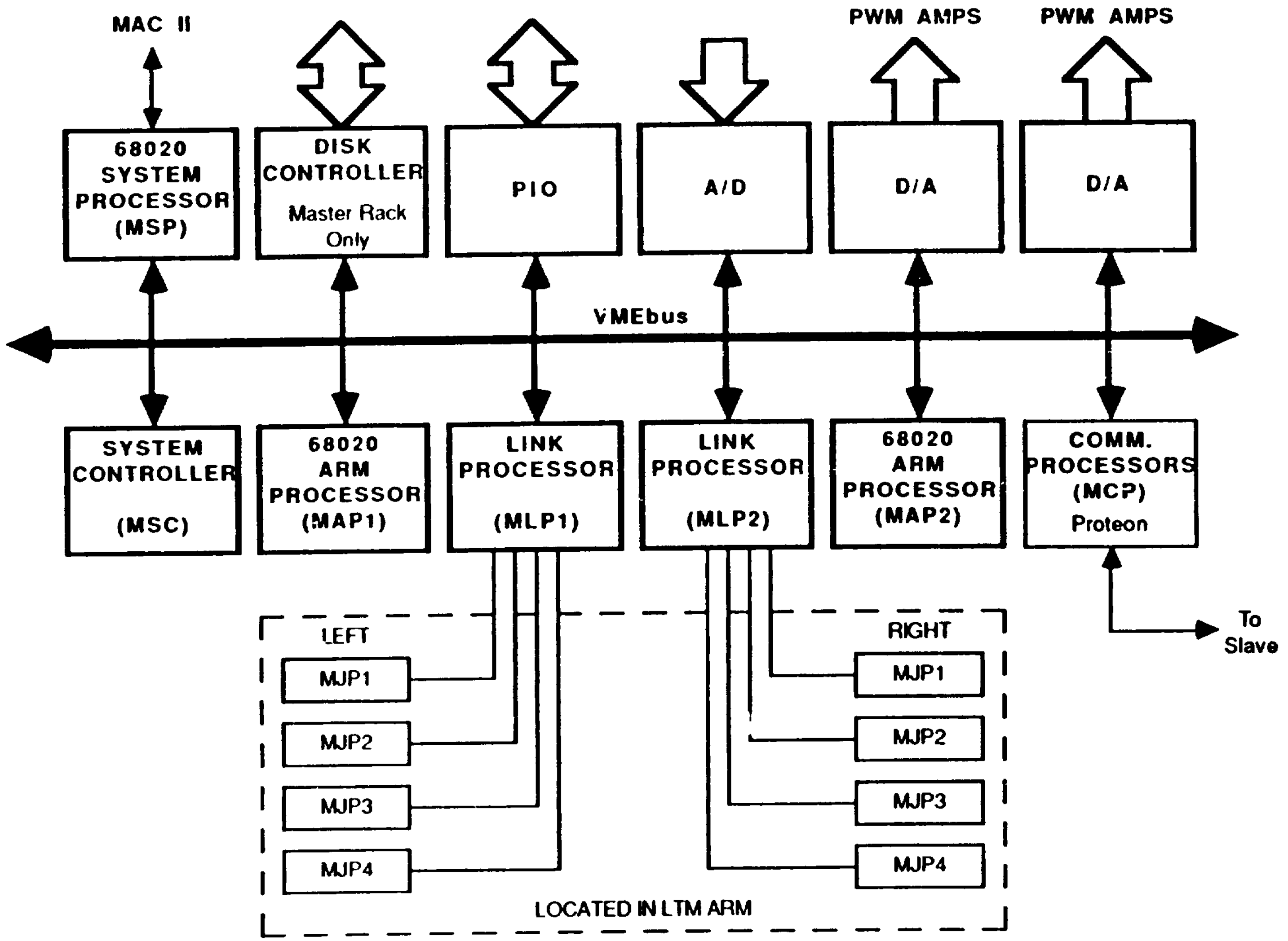

Fig. 7. Schematic of LTM master VME rack.

link processor board are high-density circuit boards using surface mount technology on both sides of a multilayer board. The JPl board is a five-layer board with 40 integrated circuits, all in surface-mount technology. The LP board is a four-layer board. These boards are shown in Fig. 8. Figure 9 illustrates internal cable routing and an onboard JPp board.

The link processor is based on the Intel N80C196KA 16-bit microcontroller. The system has 16 kbytes of ROM to contain the startup and communication code, 4 kbytes of dual-port RAM, and 16 kbytes of SRAM to hold the application code after it is downloaded from the VME system through the DPRAM. The LP communicates with the VME system through 4 kbytes of dual-port RAM that is memory-mapped to 4-kbyte blocks in the VME memory. Communication with the JPls via the fiber optic links is controlled by an Intel N82588 2-Mbaud LAN controller. A link processor sends commands to an individual joint processor to acquire joint data and, after receiving the joint data, places the data in a portion of shared global memory containing the current world model. During operations, the LP sends data requests every millisecond independent from and asynchronous to the VME system. The LPs also pass commands and code to the joint processors from the VME system.

The joint processor logic board, like the link processor, is based on the Intel N80C196KA 16-bit microcontroller. The system also has 16 kbytes of ROM to hold the startup and communication code and 16 kbytes of SRAM to hold application code that is downloaded through the LP after startup. The JPl also utilizes the same N82588 LAN controller for communications. A joint processor acquires data from the numerous sensors in a pitch/yaw joint upon demand and returns them over the fiber optic link to a paired link processor. The data consist of pitch and yaw velocity, pitch and yaw position, motor positions, motor velocities, joint torques, and joint temperatures. In addition, the JPl on the wrist joint acquires data for wrist roll and master grip commands for controlling the end effector, man-machine interface cursor, and various mode selection buttons.

The joint processor power board converts the 24-V dc power distributed through the arms to the +5-V dc and ±12-V dc needed by the joint processor boards. The power board also supplies power to the joint torque sensors, supplies the resolver reference drives, and contains the motor brake relays. The fiber optic system consists of two full-duplex bidirectional transceivers and a single high-strength fiber for each link and joint processor pair. The link processor transceiver is in the rack with the VME computer system, and the joint processor transceiver is on the JPp board in each joint. The transceivers use two different wavelengths of light to receive and transmit, thus providing full-duplex operation on a single fiber. A multidrop link approach could have been implemented, but the overall speed would have been significantly reduced.

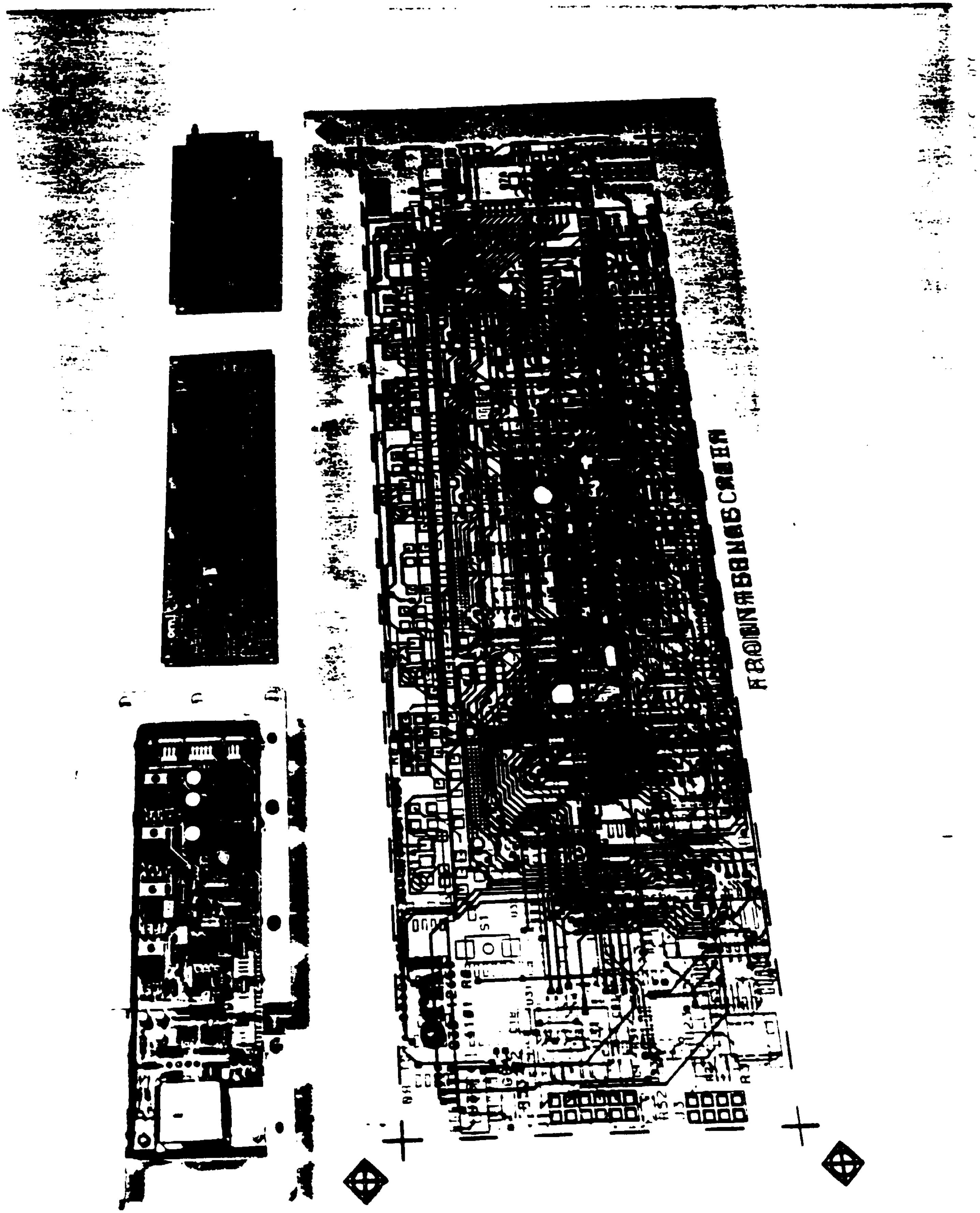

Fig. 8. LTM custom electronics packages.

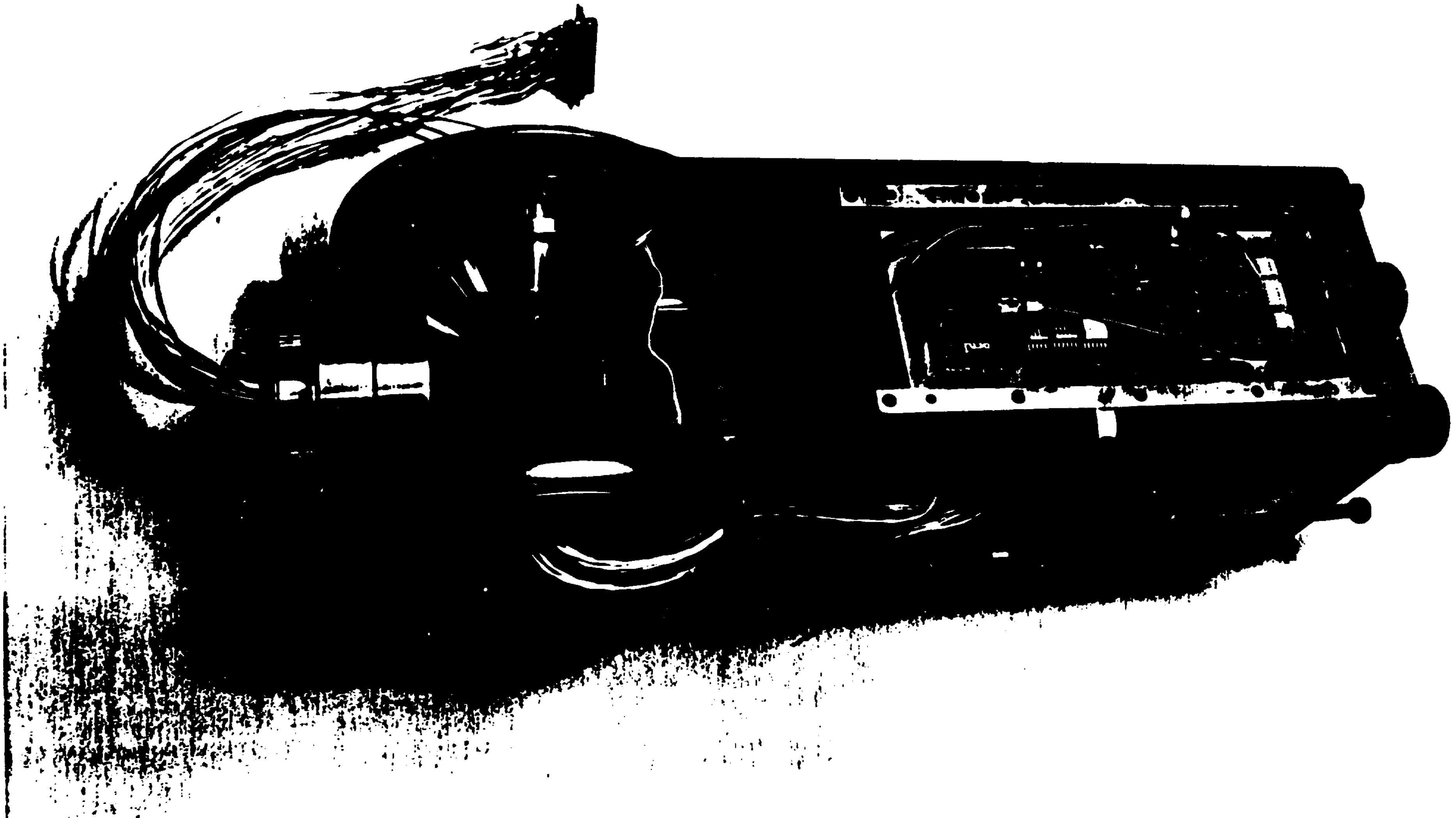

Fig. 9. LTM joint internal wiring and JPp board.

LTM software architecture, shown in Fig. 10, supports a modular hierarchical design with expansion capability for future enhancements to the system. In addition, interfaces have been defined to allow layering into hierarchical control implementations such as NASREM.[4] The operating system for the central VME computers is OS-9, a multiprogramming, multitasking, modular system that provides for position-independent code in real-time applications. Both C and FORTH are currently used for programming. In addition, FORTRAN 77, PASCAL, and BASIC are also supported if required for future developments. FORTH was chosen as the development language for the data acquisition processors distributed in the arms because it allows a minimal system to have powerful debug capabilities, an important consideration with the limited ROM and RAM of link and joint processors. In addition, the FORTH kernel is open, allowing modifications to the operating environment. FORTH has its own assembler and compiler, thus eliminating the need for a cross compiler on the VME system to generate code for the custom modules. A need for user modification in this code is not expected. All higher-level code in the LTM in which future user modification can be expected is written in C because C is much more widely used than FORTH in the robotics research community, and code maintenance should be easier.

The joint level control scheme for the LTM must perform well in two diverse operating modes, a robotic mode and a bilateral, force-reflecting master-slave mode. Performance in either of these modes can be compromised by significant nonlinearities associated with the traction drive pitch-yaw joints, as well as load variations due to changes in arm configuration or payload. The basic approach for addressing these effects in the LTM is to close a torque control loop around the motor drive portion of the drive train using the in-line torque transducer. For the robotic control mode, a proportional-integral control loop for each pitch-yaw joint with decoupled input commands has been implemented, as shown in Fig. 11. For the bilateral, force-reflecting master-slave mode, the pitch-yaw joint control loop minus the integral term has been implemented in classic bilateral, position-position control fashion, as illustrated in Fig.12.

STATUS

Mechanical and control system fabrication and assembly of the LTM system are complete, and initial operation is in progress. The performance of this first LTM prototype is expected to confirm the expectation that a manipulator system bridging the gap between classic teleoperated manipulators and robotic systems can be built.

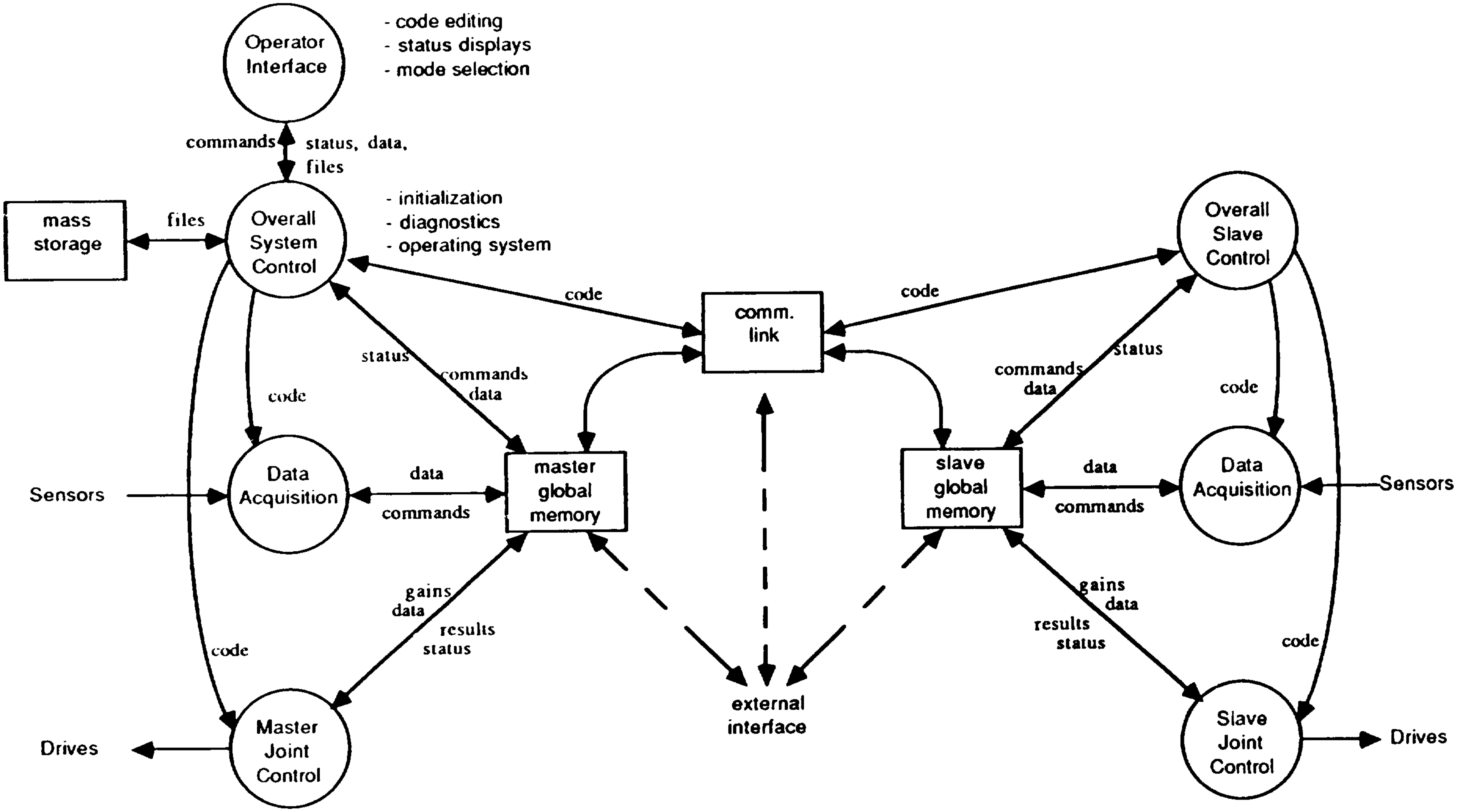

Fig. 10. LTM software architecture.

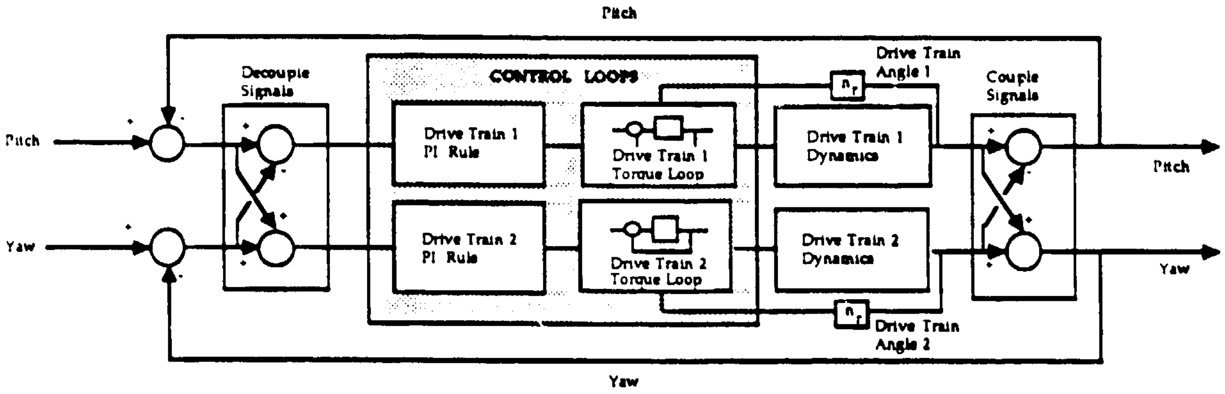

Fig. 11. Block diagram of robotic control loop.

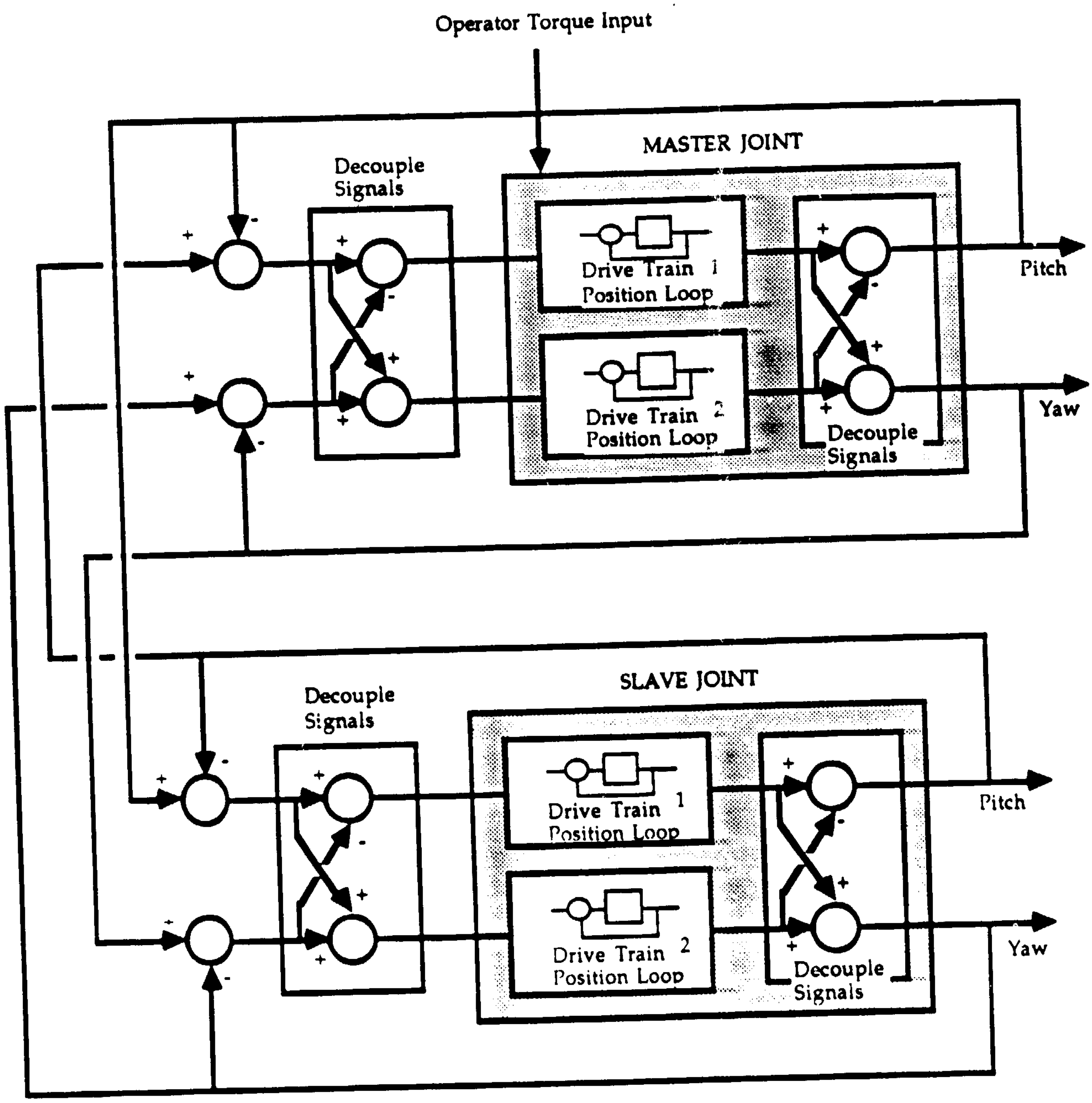

Fig. 12. Bock diagram of the force-reflecting master-slave control loop.

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