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Robotics and Intelligent Systems Program

MANIPULATION HARDWARE FOR MICROGRAVITY RESEARCH*

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ABSTRACT

The establishment of permanent low earth orbit occupation on the Space Station Freedom will present new opportunities for the introduction of productive flexible automation systems into the microgravity environment of space. The need for robust and reliable robotic systems to support experimental activities normally untended by astronauts will assume great importance. Many experimental modules on the space station are expected to require robotic systems for ongoing experimental operations. When implementing these systems, care must be taken not to introduce deleterious effects on the experiments or on the space station itself. It is important to minimize the acceleration effects on the experimental items being handled while also minimizing manipulator base reaction effects on adjacent experiments and on the space station structure. NASA Lewis Research Center has been performing research on these manipulator applications, focusing on improving the basic manipulator hardware, as well as developing improved manipulator control algorithms. By utilizing the modular manipulator concepts developed during the Laboratory Telerobotic Manipulator program, Oak Ridge National Laboratory has developed an experimental testbed system called the Microgravity Manipulator, incorporating two pitch-yaw modular positioners to provide a 4 dof experimental manipulator arm. A key feature in the design for microgravity manipulation research was the use of traction drives for torque transmission in the modular pitch-yaw differentials.

INTRODUCTION

The establishment of permanent low earth orbit occupation on the Space Station Freedom will present new opportunities for the introduction of productive flexible automation systems into the microgravity environment of space. Much attention has been given to the role that the Flight Telerobotic Servicer will play in Space Station assembly and maintenance. Though given less attention, the need for robust and reliable robotic systems to support experimental activities normally untended by astronauts will also assume great importance. Many experimental modules on the space station are expected to require robotic systems for ongoing experimental operations. When implementing these systems, care must be taken not to introduce deleterious effects on the experiments or on the space station itself. It is important to minimize the acceleration effects on the experimental items being handled while also minimizing manipulator base reaction effects on adjacent experiments and on the space station structure. NASA Lewis Research Center (LeRC) has been performing research on these manipulator applications. The LeRC program has focused on improving the basic manipulator hardware, as well as developing improved manipulator control algorithms. Early in the development of the Laboratory Telerobotic Manipulator (LTM)[1] at Oak Ridge National Laboratory (ORNL), it was recognized by LeRC investigators that the LTM design features would also lend themselves very well to the demanding microgravity robotic system application.

By utilizing the modular manipulator concepts developed on the LTM program, ORNL has developed an experimental testbed system called the Microgravity Manipulator (MGM). The MGM system incorporates two pitch-yaw modular positioners to provide a 4 dof experimental manipulator arm. The base positioner has a 1650 in.-lb output torque capacity and the forearm positioner has a 435 in.-lb output torque capacity. The 4 dof arm assembly, shown in Fig. 1, is mounted on a six-axis JR^3 force-torque sensor to provide experimental base reaction data. Each pitch-yaw module incorporates a dual-differential output with intersecting pitch-yaw axes to provide compact positioning. Key to the selection of this approach for microgravity manipulation research was the use of traction drives for torque transmission in the module pitch-yaw differentials. Traction drives are particularly well suited for microgravity application in that they provide zero-backlash torque transmission. Smooth torque transmission is key to this application. These traction drives can have much higher torsional stiffness than equivalently sized gears, when the traction drives are operated at high initial preloads, as will be the case in robotic positioning operations. In addition, traction drives require little lubrication because of the absence of the sliding friction present in gear teeth. As a result, a thin layer of ion-implanted gold provides all the lubrication necessary on the differential drive rollers in the MGM, resulting in a system which should be ideal for vacuum operation over extended periods and minimize the possibility of experimental contamination by lubricants. Other features of the MGM originating with the LTM design include: (1) modularity for ease of reconfiguration and addition of new modules in the kinematic chain at a later date and (2) pitch-yaw modules that are highly instrumented for research purposes. Sufficient motor input and pitch-yaw output sensing is provided such that with the addition of an output force-torque sensor, it is possible to implement virtually all major advanced control algorithm approaches in the literature today.

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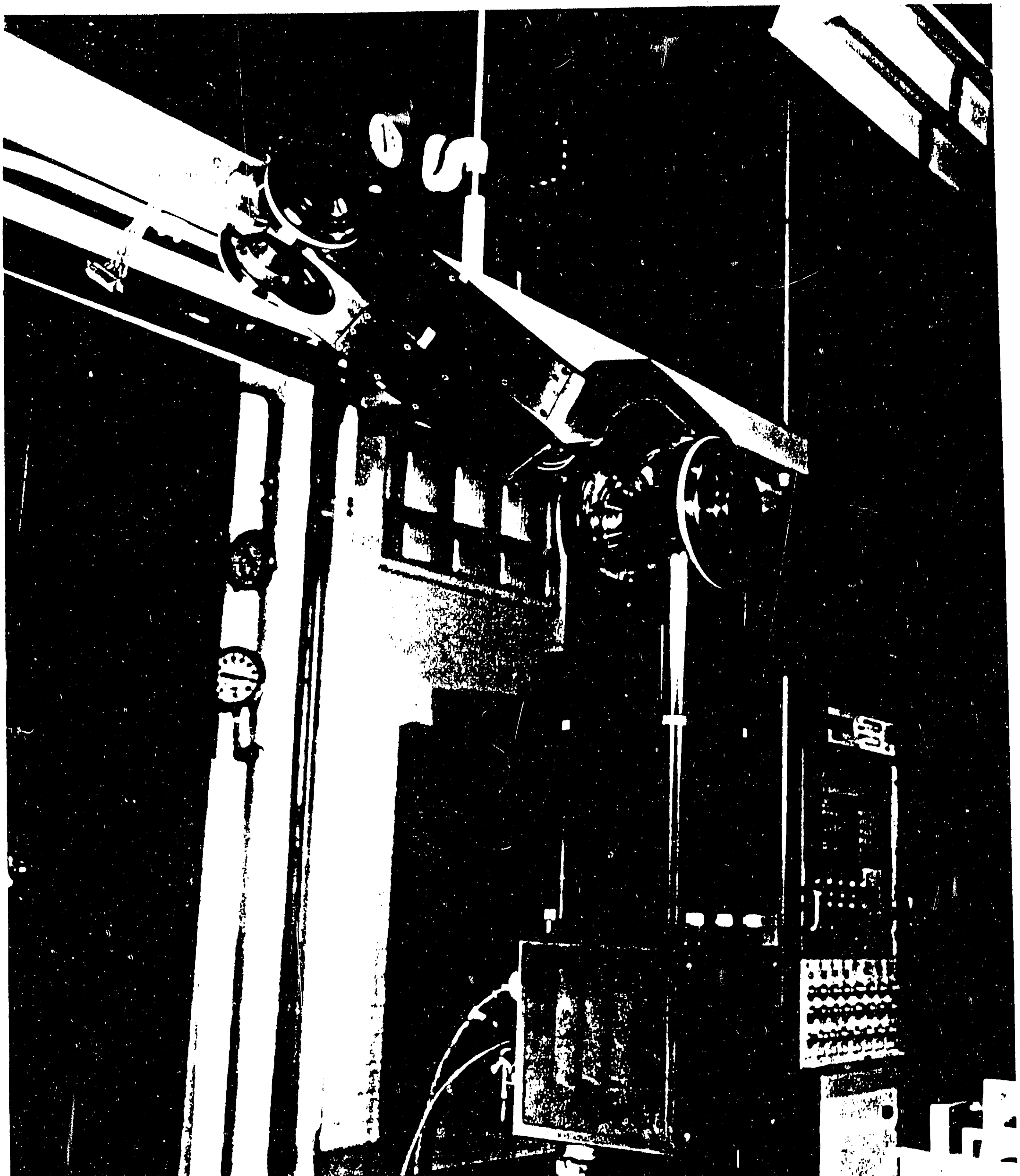

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The control system approach for the MGM is based on sensor data acquisition distributed into the modules and serial data communication to the central control rack, a central control rack based on VMEbus electronics, and a Macintosh II human-machine interface. A compact interface console, shown in Fig. 2, is provided with a joystick to operate the MGM in teleoperated mode with no force reflection. In addition, the human-machine interface approach provides for ease of implementation of new robotic control algorithms and allows collection of data on overall system performance.

MECHANICAL DESIGN

The MGM design utilizes a modular approach for joint construction with common pitch-yaw differential joints implemented for base and forearm positioners. Each pitch-yaw joint mechanism provides these motions about orthogonal axes and is attached to the adjacent joint or base using four mechanical fasteners to produce a modular mounting arrangement. This allows the MGM arm 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 approach would allow space-based arms to be easily reconfigured for changing requirements and would also permit maintenance to be performed by simple module replacement. Traction drives with variable loading mechanisms were chosen for torque transmission through the differentials. Although traction drives have not been used for robotic servocontrol applications prior to the LTM, they potentially can provide many benefits for space applications.

The MGM joints have load capacities to accommodate expected requirements for orbital operation while providing electronically counterbalanced operation for 1-g earth demonstrations. To accomplish this requirement effectively for ground operation, the MGM arm is configured from joints with different torque capacities. A large joint with a peak torque capacity of 186 Nm is used for the base positioner. A smaller joint with peak torque capacity of 49 Nm is used as the forearm positioner. These two joints are direct extrapolations from the LTM design,[1] and each joint has an acceleration capability exceeding 1-g. Both joint assemblies consist 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 accuracy single-turn resolvers located at the joint output as shown in Fig. 3. The speed reduction ratio through the differential is approximately 3.5:1. The integral reducers were specially designed for the LTM application and utilize spring-loaded anti-backlash gear trains. The in-line commercial torque sensors have been modified and incorporated directly into the joint mechanism to produce a more compact arrangement. The resolvers are located at each joint output axis and are coupled directly to the axis of rotation. Permanent magnet fail safe brakes are coaxially mounted to each drive motor. These brakes will safely support loads during power failure and provide the capability of supporting maximum payloads for extended periods without excessive motor heating.

As stated earlier, torque transmission through the differential drive mechanism is accomplished by traction drives. Unlike torque transfer through gear teeth which generates

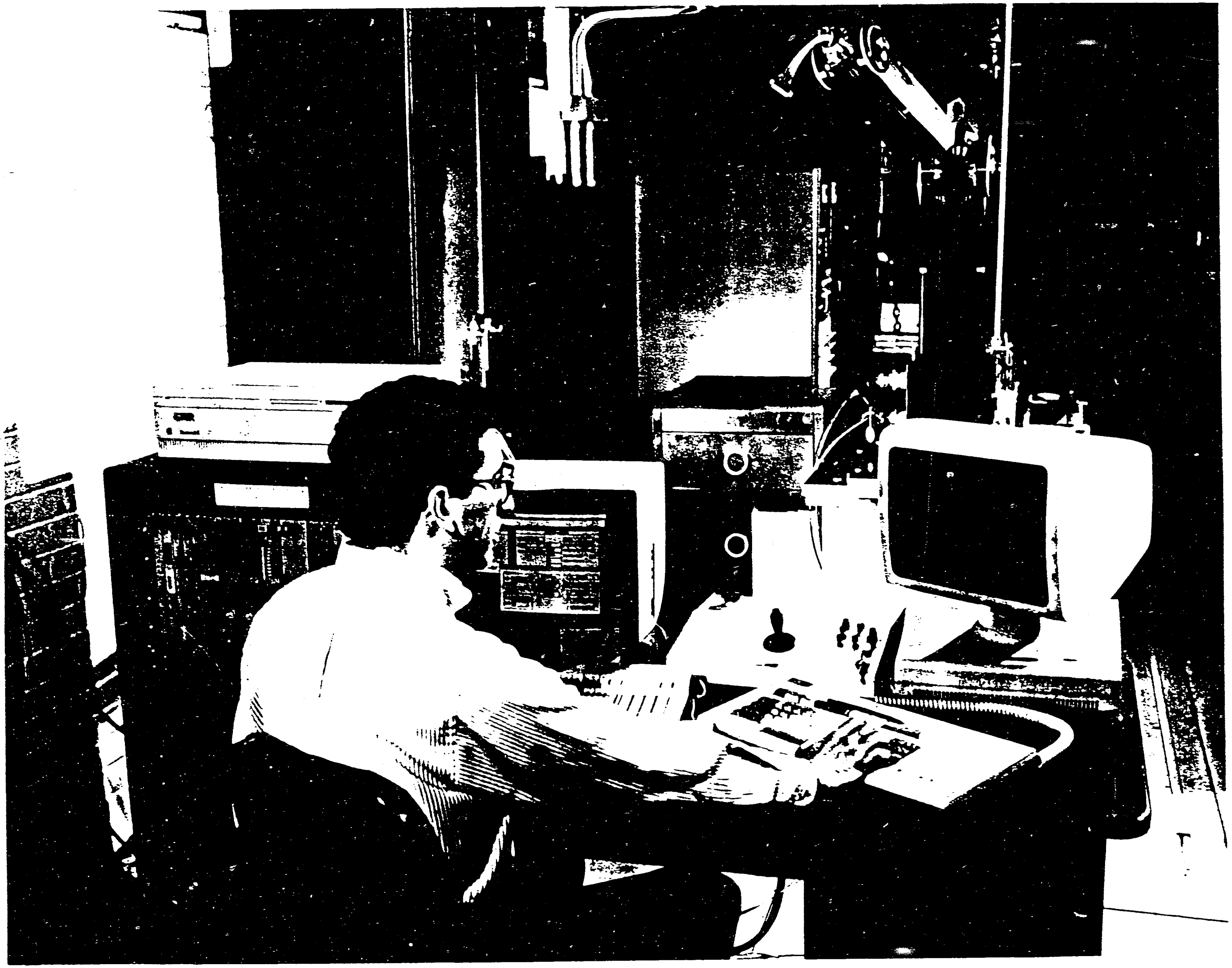

Fig. 2. MGM installation at NASA Lewis Research Center.

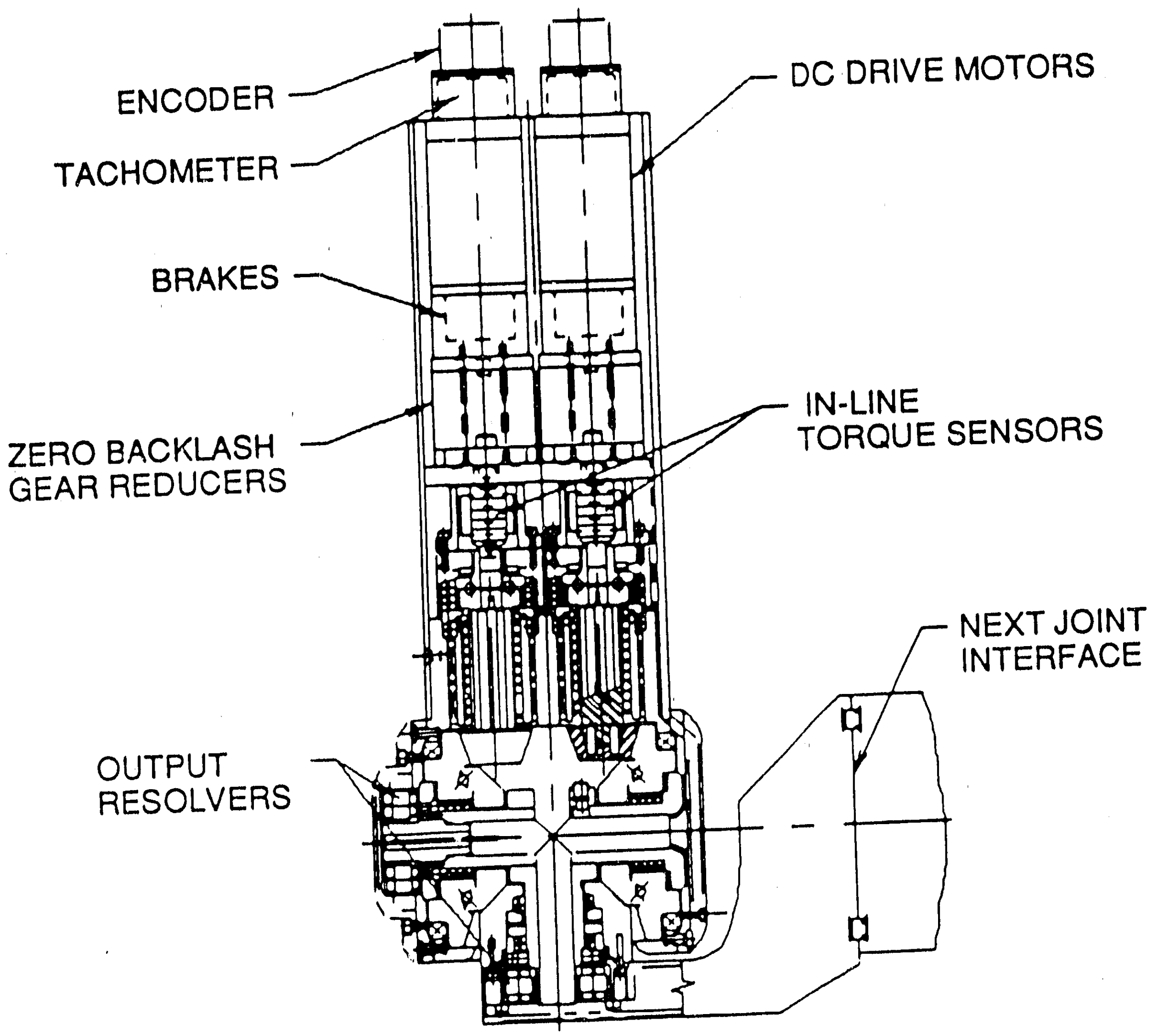

Fig. 3. MGM pitch-yaw joint cross section.

torsional oscillation as the load transfers between teeth, torque transfer through traction is inherently smooth and steady, without backlash.[2] The elements of this traction differential drive can be seen in Fig. 4. Two driving rollers provide input into the differential. These rollers interface with two intermediate rollers which, in turn, drive the pitch-yaw output roller about the pitch and yaw axes. The axis about which the pitch-yaw roller rotates depends upon the direction of rotation of the driving rollers. The rolling surfaces of the differential are gold plated in an ion implanting process developed by NASA LeRC. This plating serves as a dry lubricant in the sense that it prevents the substrates from contacting. By utilizing the output resolvers directly at each joint for positioning, creep experienced through the traction drive differential will not affect the positioning characteristics of the arm.

For traction drives to function, there must be a normal force between the mating rollers in order to transmit torque by friction. Variable loading mechanisms were employed on the LTM design as an alternative to the more common constant loading mechanisms in an effort to improve the differential backdriveability, mechanical efficiency, and fatigue life. These variable loading mechanisms were carried over in the MGM design. Although the MGM operates at a rather high initial preload for robotic positioning accuracy, the ability to vary preloading to assess the effects of various drive train stiffnesses is an important feature. Two variable loading mechanisms have been incorporated into the traction drive differential of the MGM, one pair at the input rollers and one at the output pitch-yaw roller. These preloading mechanisms are illustrated in Fig. 4.

CONTROL SYSTEM DESIGN

The LTM control system is a modular, hierarchical design with flexible expansion capabilities for future enhancements of both the hardware and software. A top level block diagram illustrating the overall organization of the system hardware is shown in Fig. 5. At this level, the system is composed of a central VMEbus computer system rack controlling the two arm joints utilizing data acquired from sensors in the individual joints. Custom embedded computers distributed in the arm joints provide sensor data acquisition and communication of the data to the central computer system through high-speed fiber optic links. The human-machine interface consists of a Macintosh II computer interfaced to the central computer system rack to provide a graphics-based interface for operation of the system. A commercial VMEbus approach is utilized for the central computer system and is based on dual Motorola 68020 single-board computers operating in parallel. One single-board computer coordinates the overall operation of the system while the second single-board computer completes the control algorithm calculations required for teleoperation, robotics, and electronic counterbalancing. In addition to the single board computers, the VME system supports digital and analog I/O, the distributed communication links, terminal support, and mass storage. The PWM amplifiers which provide drive signals to the individual joint motors are also located in the central computer rack.

Custom electronics packages were developed in the LTM design[1] and carried over in the MGM system to reduce the number of cables required for the manipulator arm. Since the

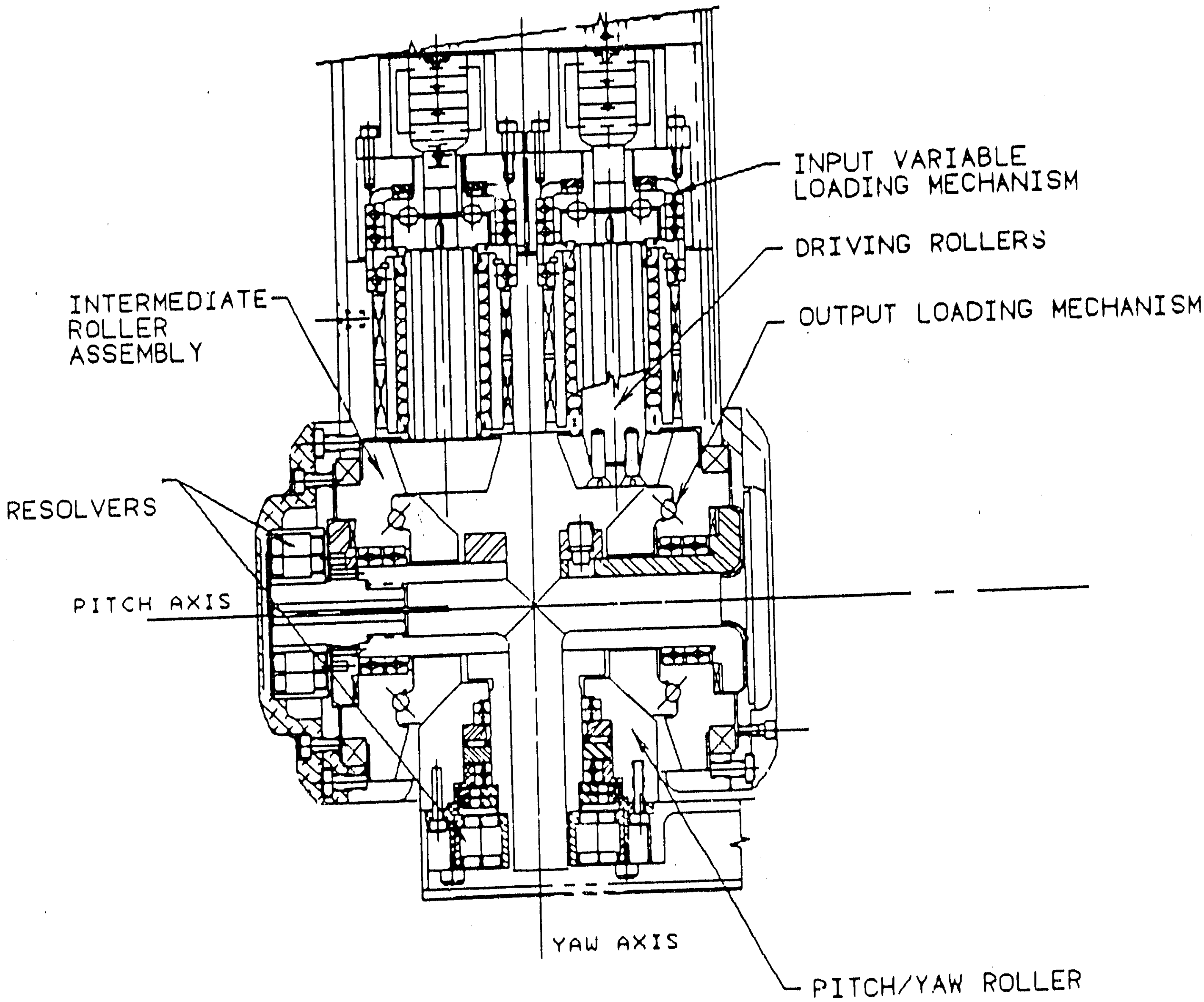

Fig. 4. MGM differential drive cross section.

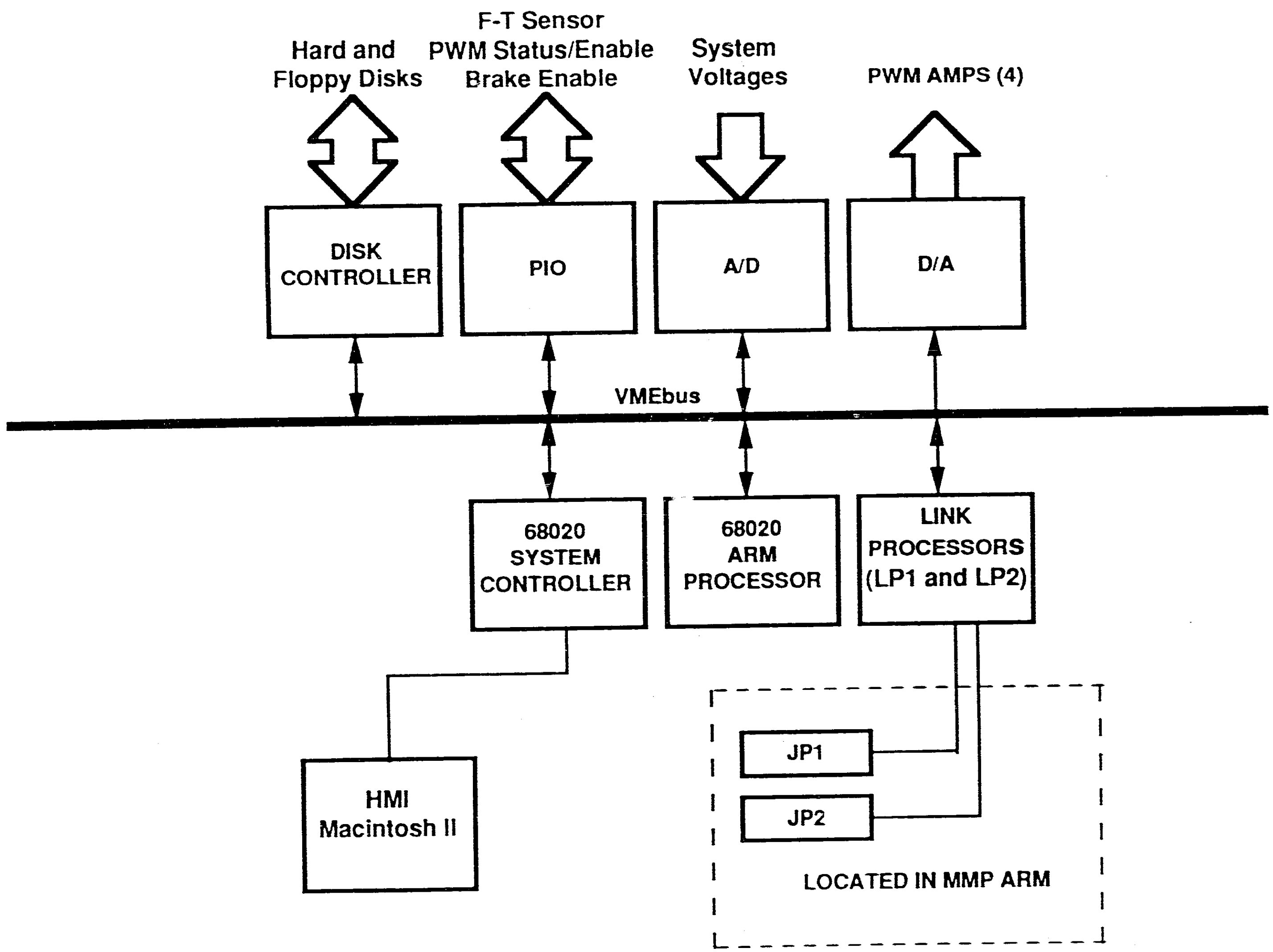

Fig. 5. MGM control system block diagram.

MGM utilizes an embedded cabling approach with all of the power, control, and communication cables passing through the pitch/yaw joints, it is necessary to minimize the number of cables required. The custom computer packages reduce the required cabling by acquiring, processing, and muliplexing the many sensor signals over serial communication links between arm modules and the VMEbus rack. 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 VMEbus, and the fiber optic communication system. The JPl board and the LP board are both high-density circuit boards utilizing 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. Figure 6 illustrates a JPl board and a JPp board installed in the MGM arm.

The Link Processor is based on the Intel 80C196 16-bit micro-controller. The system has 16K of ROM containing the startup and communication code, 4K of dual-port RAM, and 16K of SRAM that holds the application code after it is downloaded from the VMEbus system. The LP communicates with the VMEbus system through the 4K of dual-port RAM that is memory-mapped to 4K blocks in the VMEbus memory. Communication with the JPls via the fiber optic links is controlled by an Intel N82588 2-Mbaud LAN controller. A LP board sends commands to an individual JPl board 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 board sends data requests every millisecond independent of and asynchronous to the VMEbus system. The LP boards also pass commands and code to the JPl boards from the VMEbus system. The JPl board, like the LP board, is based on the Intel 80C196 16-bit micro-controller. The system also has 16K of ROM to hold the startup and communication code and 16K of SRAM to hold application code that is downloaded through the LP board after startup. The JPl board also utilizes the same N82588 LAN controller for communications. A JPl acquires data from the numerous sensors in a pitch/yaw joint upon demand and returns it over the fiber optic link to a paired LP board. The data consists of pitch and yaw velocity, pitch and yaw position, motor positions, motor velocities, joint torques, and joint temperatures. In addition, the JPl board on the wrist joint acquires data for wrist roll and master grip commands for controlling the end effector, human-machine interface cursor, and various mode selection buttons.

The JPp board converts the 24 VDC power distributed through the arms to the +5 VDC and ±12 VDC 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, bi-directional transceivers and a single high strength fiber for each Link and Joint Processor pair. The LP board's transceiver is located in the rack with the VMEbus computer system and the transceiver is located on the JPp board in each joint. The transceivers utilize two different wavelengths of light for receive and transmit thus providing full duplex operation on a single fiber. A multi-drop link approach could have been implemented, but the overall speed would have been significantly reduced.

6. JP1 and JPp boards installed.

The MGM software architecture supports a modular, hierarchical design with expansion capability for future enhancements to the system. The operating system for the central VMEbus computer system is OS-9, a multiprogramming, multitasking, modular operating system that provides for position independent code in real-time applications. Both C and FORTH are currently utilized for programming. In addition, FORTRAN 77, PASCAL, and BASIC are also supported by OS-9 if required for future developments. FORTH was chosen as the development language for the data acquisition processors distributed in the arms. FORTH allows a minimal system to have powerful debug capabilities, which is important considering the limited ROM and RAM on the link and joint processors. In addition, the FORTH kernal is open, allowing modifications to the operating environment, and has its own assembler and compiler, thus eliminating the need for a cross compiler on the VMEbus computer system to generate code for the custom modules. All higher-level code in the MGM, where extensive future user modification can be expected, is written in C. C is much more widely used in the robotics research community (compared to FORTH), and the MGM has been configured to provide for ease of importing and testing of code from other research efforts.

Implementation of robust, high-performance robotic position control for the MGM was based on the significant innovations contained in the joint controller for the LTM.[3] These pitch-yaw differential joints with traction drives and variable preloading mechanisms introduce very challenging nonlinear effects for the control design. The overall approach is based on the use of a proportional-differential controller with high-gain positive torque feedback. For robotic operation of the MGM, lead-lag compensation of the torque loops is not required.

STATUS

The MGM system is presently installed and operational in a laboratory testing environment at NASA LeRC, as shown in Fig. 2. Initial testing and refinement of the operation at the individual joint level as a robotic positioner have been completed and initial arm level operational testing has begun. Early testing will examine advanced control techniques for minimized base reactions. An additional large capacity joint for the MGM is being developed under a NASA Small Business Innovative Research program. Incorporating a hybrid differential drive approach, this joint is planned for installation as a third joint in the MGM system at the base location. This new base joint, combined with the addition of an output roll, will bring the MGM system to a full seven dof redundant robotic positioner for more advanced robotic control studies.

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