CONF-860434--1

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CONVERSION OF A SERVOMANIPULATOR FROM ANALOG TO DIGITAL CONTROL

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CONF-860434--1

DE86 000090

Presented at the
1986 IEEE International Conference on
Robotics and Automation
April 14-17, 1986
San Francisco, California

*Operated by Martin Marietta Energy Systems, Inc., for the U.S. Department of Energy.

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ABSTRACT

Oak Ridge National Laboratory (ORNL) has developed expertise in computer control of force-reflecting master/slave servomanipulators as a result of research for the Consolidated Fuel Reprocessing Program. These computer control capabilities have been applied to a commercially available servomanipulator, the TeleOperator Systems SM-229. All of the servo drive and control circuitry has been replaced with commercially available digital controls and amplifiers, and a customer software package has been developed at ORNL. This conversion to digital computer control resulted in significant improvements in force-reflection characteristics, ease of operation, diagnostic capabilities, indexing features, and potential increased reliability. The system will be used at the Tokamak Fusion Test Reactor at the Princeton Plasma Physics Laboratory (PPPL) for maintenance demonstrations.

Digital computer control offers several advantages over the analog system that it replaced. Long-term drift problems associated with analog electronics have been eliminated, and advanced indexing and scaling features have been added that would have been difficult to implement using analog circuitry. Some of these added features are adjustable force-reflection ratios over a range of 1:1 to 8:1, kinematic scaling ratios of 1:1 or 2:1, position- and drive-signal diagnostics, improved man-machine interface using a CRT touch screen, and indexing

*Research sponsored by the Office of Facilities, Fuel Cycle, and Test Programs, U.S. Department of Energy under Contract No. DE-AC05-84OR21400 with Martin Marietta Energy Systems, Inc.

for all joints. Tests have confirmed that the new control system significantly improved the overall force-reflection quality as judged by the accuracy of the operator's perception of force at the slave manipulators.

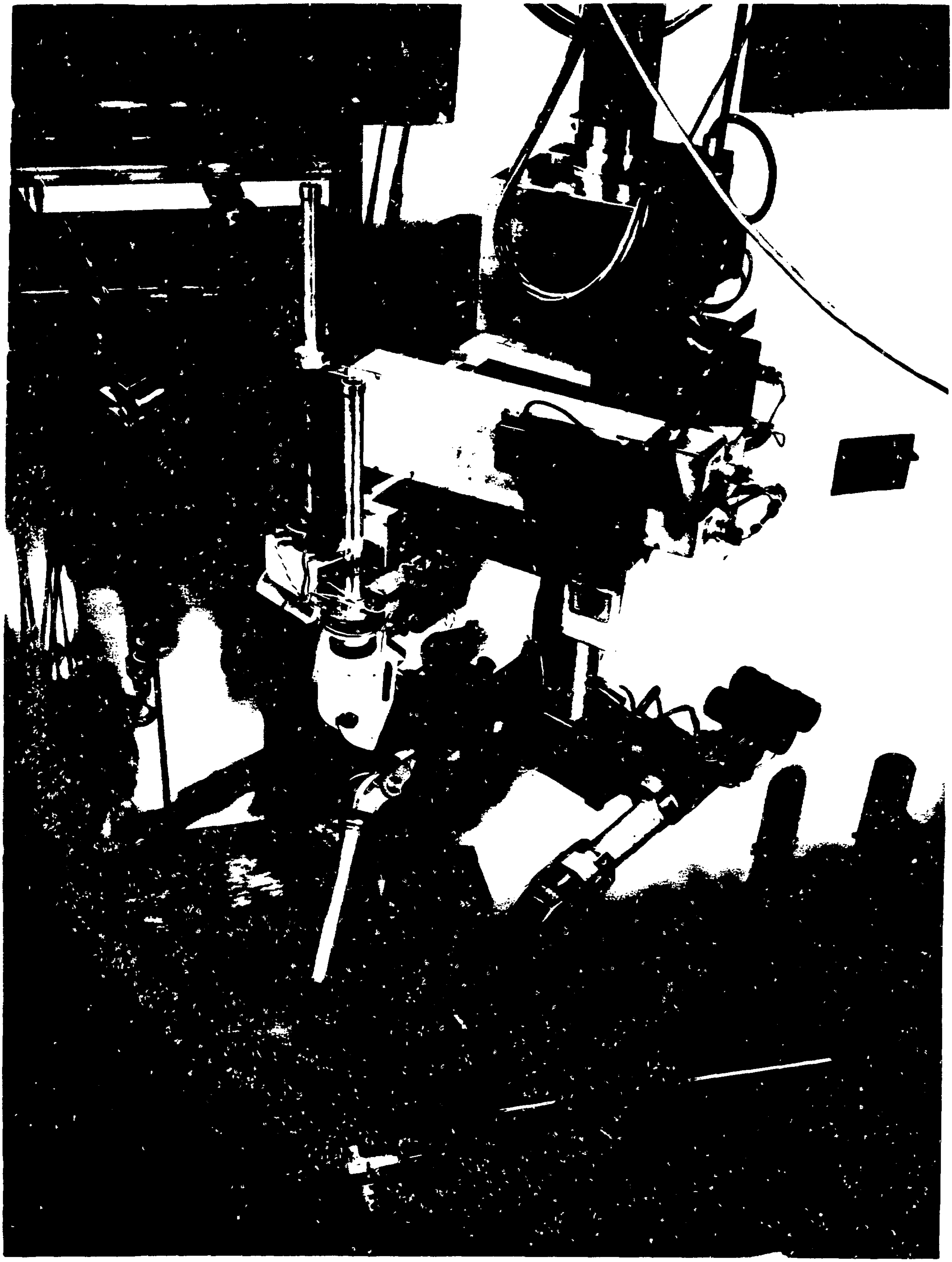
This paper describes the original system, presents details of the digital control hardware implementation, discusses the software controls programmed in the language FORTH, and reviews test results which reveal improvements in force-reflection quality. Related applications of the control system developed at ORNL will also be discussed.

INTRODUCTION

Electric servomanipulators are an outgrowth of the mechanical master/slave manipulators developed for handling hazardous radioactive materials. These servomanipulators, first pioneered by Ray Goertz of the Argonne National Laboratory [1], had several advantages over mechanical manipulators, the main advantage being the much larger separation distances possible between the master and slave. Servomanipulators also supplied "force feedback" so the operator could estimate the forces at the work site. This restored the "feel" characteristics that the mechanical manipulator had.

One such commercially available servomanipulator, the TeleOperator Systems (TOS) model SM-229, was purchased by the Princeton Plasma Physics Laboratory (PPPL) for use with their Tokamak Fusion Test Reactor (TFTR). Similar servomanipulators are being used at the Los Alamos National Laboratory.

For two years, PPPL's SM-229s were on loan to ORNL for development of remote maintenance techniques. The SM-229s were installed in the Remote Systems Development Facility (RSDF) at ORNL (Fig. 1). The manipulator was complemented by a transporter, viewing system, and man-machine interface for completely remote operations.



The TOS SM-229 provides force feedback for all six arm degrees of freedom and for the tong. The maximum lift capacity is 10 kg. These manipulators use metal tape and pulley power transmissions which provide very low friction. Because the force reflection makes both the slave and master friction appear at the master, friction reduction on both master and slave is very important for improving force reflection and reducing operator fatigue. Both the master and slave arms are designed to be backdriveable, unlike a typical robot, so that weights as low as 1.0 kg can backdrive the system and provide force reflection to the master. Overall mechanical performance of the system is very good.

The original SM-229 control system, developed around 1976, was built entirely from analog electronics. Each degree of freedom had its own servo control loop containing the basic position-position servo loop circuitry in addition to lead and lag compensation circuitry. Thus the system could be thought of as a simple "analog computer." Other features of the original system were logarithmic-tapered force-reflection ratios, current-trip overload safety features, and limited indexing for the shoulder pitch and elbow pitch motions.

Analog control circuitry, unfortunately, limits performance and reliability. Because of the drift characteristics of the potentiometers, capacitors, and resistors, the analog circuitry had to be retuned on the average of once a week when the manipulator was used frequently. At the end of the loan period, ORNL proposed to replace the original analog control system with a microprocessor-based design similar to others developed at ORNL. This would significantly improve the manipulator system performance, maintainability, and reliability. The proposal was accepted and funded by PPPL. A design was developed using techniques refined at ORNL for the Central Research Laboratories Model M-2 servomanipulator [2] and the ORNL Advanced Servomanipulator [3]. The resulting new digital control system has significantly improved force-reflection performance, reliability, routine maintenance, and operational features of the SM-229 system.

Digital Control System

One of the first distributed-digital control servomanipulators built in the United States is the M-2, developed for the ORNL Remote Operations and Maintenance Demonstration (ROMD) of the Consolidated Fuel Reprocessing Program. ROMD is a demonstration facility used to explore concepts of maintaining a sealed, zero-man-access facility for recycling nuclear fuels. The M-2 slave unit is the principal maintenance device for mock-up demonstration and experiments. Since access to the slave and its control electronics is difficult, low-drift digital circuitry was used to minimize calibration and servo tuning requirements. Another advantage brought about by the digital control was the use of serial communication links to greatly reduce the conductor count between master and slave. Other advanced features, such as adjustable force reflection and improved indexing, were easier to achieve using digital electronics.

The resulting M-2 servomanipulator, jointly designed by Central Research Laboratories and ORNL, consisted of a control system with 32 Intel 8031 microprocessors, one per joint, plus four communication controllers, all tied together by high-speed serial links. An array of television cameras, lights, hoists, and cranes are also built into the system. For a more detailed description of the M-2 system, see ref. 4.

The next progression in servomanipulator development activities at ORNL resulted in the construction of the Advanced Servomanipulator (ASM) and its corresponding control system. Both the mechanical and control aspects of the ASM represent significant advances in the state of the art, making the system more reliable and maintainable for use in the hostile environment of nuclear fuel reprocessing. A unique feature of the ASM is that it can be remotely maintained by another manipulator. This is accomplished by mechanical modularity, which in turn is made possible by all gear and driveshaft power transmission. Advances in electronics simplified the control system design so that four Motorola

68000 microprocessors are used to control the joints rather than the 32 microprocessors used to control the M-2. Furthermore, the distributed-digital system used with the ASM was built from commercially available single-board computers and card cages, thus eliminating most of the custom electrical designs required for the M-2. Cable-handling problems will also be greatly reduced by a new, high-speed microwave serial link being developed for signal transmission between the master and slave.

It was proposed to upgrade the operation and performance of the TOS system for PPPL using a simplified version of the ASM control system as a foundation. In the first simplification, the slave manipulator sensor and motor leads were run with cables directly to the computer system at the master, leaving only one main computer rack (compared with two racks for the ASM). Second, because tachometers are not used on the TOS servos, velocity was derived by software differentiation of the position signal. Finally, the man-machine interface was enhanced by using a CRT touch screen as the system control and display panel.

Hardware

The hardware for the control system is built from general-purpose bus-based microcomputers. The main reason for choosing a bus type architecture was the availability of wide varieties of single-board computers, communications devices, industrial instrumentation, and input/output devices. Bus architectures also provide the simplest interconnection and highest communication bandwidth between the varied devices in the system. Since several of the slots can contain single-board computers, a very powerful system can be assembled using multiprocessing techniques. This type of parallel processing is very applicable to manipulators since most of the joint control processes can be carried out independently for each joint.

The Intel Multibus was selected for the ASM control system because of its good performance and extensive vendor support. Multibus architectures include 16-bit-wide data paths, 20-bit-wide address paths, and built-in logic for bus arbitration. In the TOS conversion, three single-board computers, two communications input/output boards, and seven analog input/output boards were installed in the 15-slot rack, thus leaving three slots left for future expansion.

Motorola 68000s form the heart of the system through single-board computers made by Onmibyte Corporation. Each Onmibyte OB68K1A computer board contains a 68000, two serial ports, and 128 Kbytes of dual-port memory. One of the computers is designated as the controller for the rest of the sites; it is linked to the disk drive and serial communications ports and is linked to the other two computers through their dual-port memories. Up to 16 Mbytes may be addressed through the Multibus by these cards, although most Multibus boards have only one megabyte of address space.

A powerful analog input/output subsystem based on the Data Translation Intelligent Analog Peripheral series handles all of the communication with the manipulator drives and sensors. These analog boards can also be considered intelligent controllers since they contain 8085 microprocessors for sophisticated control of the analog converters. Communication to the Multibus is accomplished by 16-Kbyte, dual-port memories that can be accessed by both the 8085 on the analog board and, via the Multibus, the 68000 single-board computers. Some of the control features implemented by the 8085 are data scaling, safety features such as timeout timers, data collection timing, and motor on/off control. In general, the extra processing in the analog cards performs some of the lower-level data collection tasks that would otherwise have to be performed by the 68000 processors.

The analog portions of the Data Translation boards consist of 32 analog-to-digital and digital-to-analog converters, although only 28 channels are used to control the two master and two slave seven-degrees-of-freedom arms. Sensor feedback from the manipulator potentiometers is digitized by the 14-bit A/D converters at a 100-Hz rate. The drive signals to the servo amplifiers are provided by the 12-bit D/A converters, also at a 100-Hz rate. Digital input/output lines are also provided for servo amplifier on/off control and fault detection.

High performance pulse-width-modulated (PWM), current-loop servo amplifiers made by the Performance Controls Company were used for all the motor drives. PWM amplifiers were chosen because of their high efficiency, resulting in less power consumption and heat buildup. Potential problems caused by PWM noise were prevented by using optical isolation for all connections between the computer and the amplifier. Twisted, shielded pair wiring was also used extensively to prevent noise radiation from the motor leads and to prevent noise pickup on the potentiometer leads.

The upgrade design emphasized improvements in the man-machine interface to make system operation easier and less error prone. Control inputs are provided by a touch screen and by push buttons on the manipulator hand grips. The touch screens communicate with the host computer via an RS232 serial link.

System Performance

The performance of the system improved in three main areas: the control features, the man-machine interface, and the force-reflection quality. In addition, long-term improvements in reliability and reduced electronic drift are anticipated but not yet verified.

The improved control features of the new system consist of improved indexing, adjustable force-reflection ratios, and kinematic motion scaling. Indexing involves placing the slave unit at the work site and then moving the master to a position that is comfortable to the operator. The resulting index is then retained so that the operator can use the manipulator in a comfortable position. This feature is available for all degrees of freedom. Another useful feature is adjustable force-reflection ratios. The ratios available are 1:1, 2:1, and so on up to 8:1, and infinite to 1 (no force reflection at all). These selectable ratios are useful when the slave is handling heavy loads; then the force reflection can be reduced to prevent operator fatigue. Finally, the motion-scaling feature reduces the slave motions relative to the master by a factor of 2:1 (e.g., the slave moves 1 cm for every 2 cm of the master). It is anticipated that this will increase work efficiency for certain fine-motion tasks.

After converting the system to computer control and adding these new features, extra effort in making the system easy to operate was the next objective. This was necessary because not only are there more features to choose from, but now separate features are selectable for each individual joint, resulting in a complex array of possibilities. Furthermore, the typical manipulator operator has little computer experience. These problems were solved by implementing an easy-to-use man-machine interface activated with hand grip push buttons and menu-based touch screens. Operator error checking is also provided to prevent operator mistakes from damaging the equipment. If something does go wrong with the system, online diagnostics are available to assist in correcting problems.

The main touch screen shown in Fig. 2 displays possible menu selections, present mode status, and present force-reflection status. This menu contains information and control capabilities to cover the majority of operations for a typical manipulator session. From this screen, the operator can change the operation mode or force-reflection ratio for the upper arm (shoulder and elbow), wrist, or tong for the left or right arm. The available modes are OFF, IDLE, RELATIVE MASTER/SLAVE, SCALED MASTER/SLAVE, and ABSOLUTE MASTER/SLAVE. OFF obviously means turn the joint off, while IDLE turns the joint on but holds it in the present position. RELATIVE master/slave automatically indexes the master and slave and enters a master/slave mode which

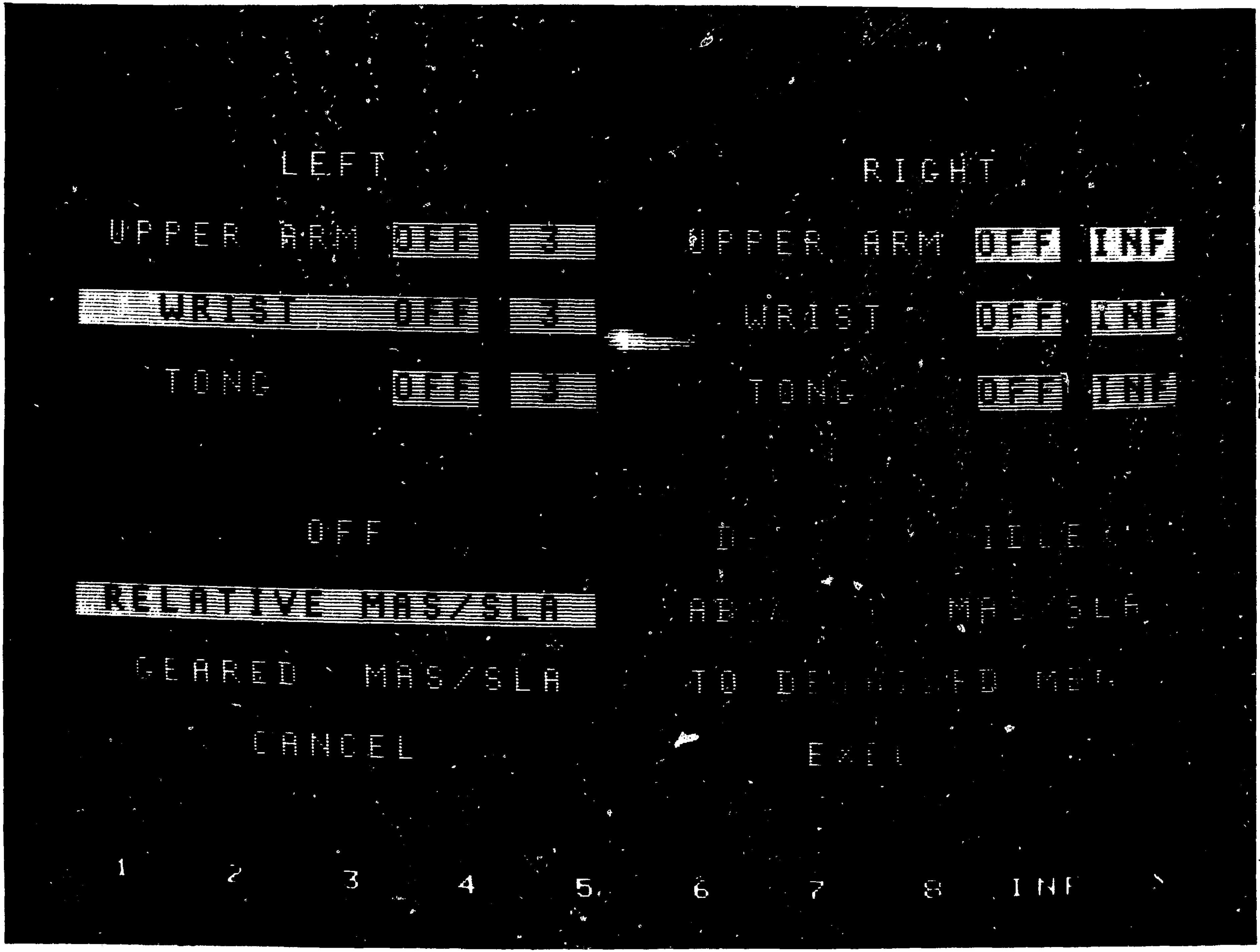


Fig. 2. Main touch screen.

retains the index that was present when the mode was entered. SCALED master/slave is like that of the RELATIVE master/slave mode except that the slave motions are scaled to one-half the motions of the master. ABSOLUTE master/slave first removes any indexing between the master and slave by pulling the master to the slave's absolute position and then entering the master/slave mode.

Operating the touch screen simply involves touching the label for the desired operation. When the label is touched, the label is highlighted as shown for the left WRIST label and RELATIVE MAS/SLA label in Fig. 2. The selection can then be executed by touching the EXECUTE label or abandoned by touching the CANCEL label.

For some of the less typical operations, the detailed menu is selected to analyze and control individual joints. The operator selects the joint to be analyzed from an intermediate touch-screen menu. Then the the touch screen displays a detailed menu as depicted in Fig. 3, shows additional status of the joint along with extra control options. These status indications consist of raw position, current, brake, and servo amplifier status as well as the mode and force-reflection status that are shown on the main screen. These indications are useful for diagnosing wiring or computer problems. The extra control options consist of changing the position and current limits as well as controlling the slave brakes independent of the control mode.

The handgrip buttons are the most convenient control input since they can be operated without the operator having to remove his hands from the manipulator grip. They operate similarly to the touch screen in that the three master/slave modes can be selected, except that when using the handgrip buttons the entire arm is activated at once. A separate button is provided for turning the tong on and off.

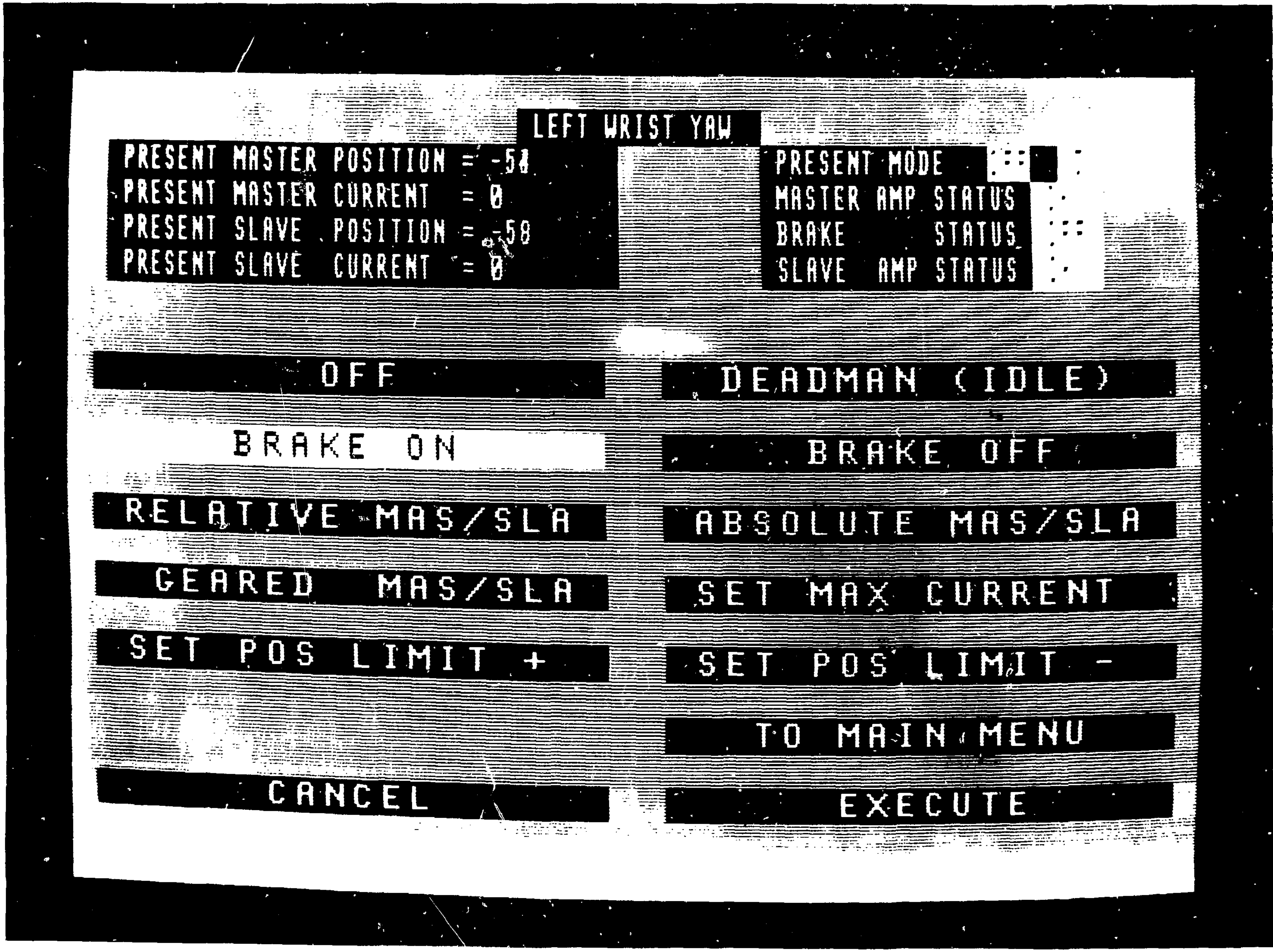


Fig. 3. Detailed touch screen.

Software

As expected with a computer-based application, much of the effort and creativity of this system lies in its software. Most of the software is written in the language FORTH, except for speed critical areas which use assembly language. A large effort was also put into making the software tasks modular, resulting in more reliable and understandable code.

FORTH is a unique language that has several characteristics that make it useful for manipulator control. Speed is very important for stability, and FORTH is one of the fastest high-level languages available, being only about three times slower than an equivalent machine language program. Another advantage is that low-level bit manipulation and memory-addressing commands are part of the language, making access easy to the many input/output devices in the bus rack. Finally, FORTH is a very interactive language that enables trial-and-error experimentation. Because of the many human interaction aspects of the system, many trials were required to satisfy the subjective "feel" requirements.

The modularity of the software architecture is shown in Fig. 4. The modules range from the analog board, low-level routines to the top-level, man-machine interface routines. The analog input/output routines are written in 8085 machine language and are programmed in a read-only memory, which is placed on the board with the 8085 microprocessor. These routines perform functions such as analog conversion at specified rates, data scaling, timeout timers, and amplifier on/off control. Data from these boards are then processed by the joint-control routines, which are FORTH routines running in the 68000s. The tasks for the 68000s are divided as follows: the first 68000 computer board controls the right arm joint routines, the second 68000 board controls the left arm joint routines, and the third 68000 board controls the man-machine interface. The third 68000 board also generally controls the whole system through its link with the terminals,

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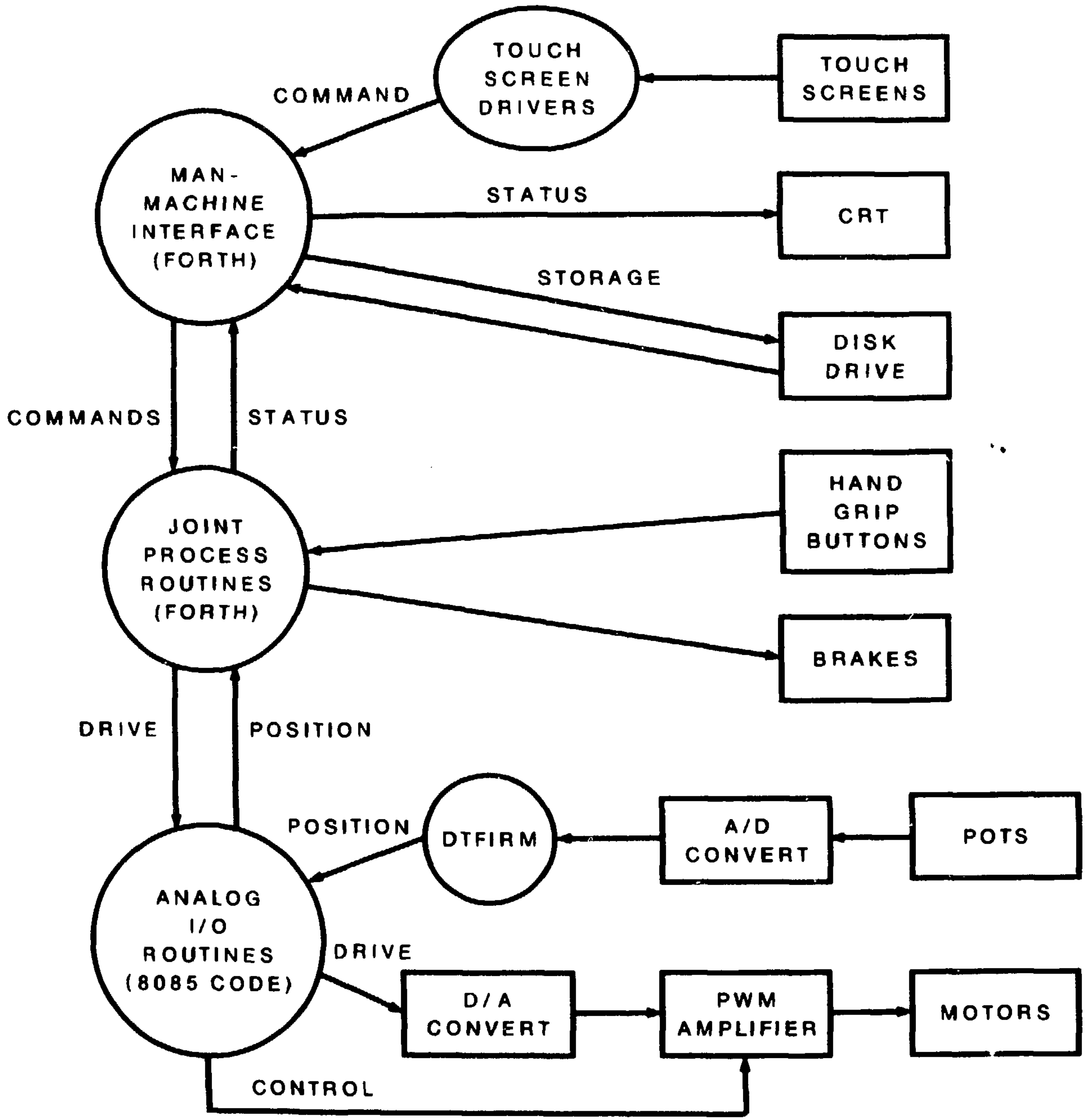

Fig. 4. Software architecture.

touch screens, keyboards, and disk drives. It also downloads and supervises operation of the other 68000s via the man-machine interface program.

The actual servo control algorithm is depicted in Fig. 5. Since the master and slave units except for the end effector are identical, all of the joint mathematics can be calculated for each joint independent of the other joints. Unlike the loosely-coupled computer architecture of the M-2 [3], calculation of the cross coupling among the joints is possible with this computer system. Since the SM-229 was designed for independent joint analog controls, independent joint control algorithms were found to be adequate in this system.

The servo loop is basically a position-control loop using position data directly from the potentiometers and velocity information calculated by software differentiation of the position signal. Velocity is used for damping and stability improvement; furthermore, a velocity signal is coupled between the slave and master to provide a velocity feed-forward term. This feed forward not only speeds up the response time but also nulls out the damping effect such that the velocity feedback does not impede steady-state velocities. A lead network was also added to help improve stability.

One of the improvements in the quality of work possible with the new system is the improved force-reflection characteristics. An experiment performed by the remote control engineering staff has indicated that the perception by the operator of the forces being manipulated by the slave appears to be more accurate with the new computer control system than the previous analog control system. The test consisted of placing several unknown weights in the slave gripper, and then the manipulator operator estimating the weight of the object using only the forces felt at the master. Figure 6 shows the test results for the new digital system. The numbers in the boxes represent how many times a given weight, denoted by the column, was perceived to be the weight denoted by the row. Note how the data for the new system

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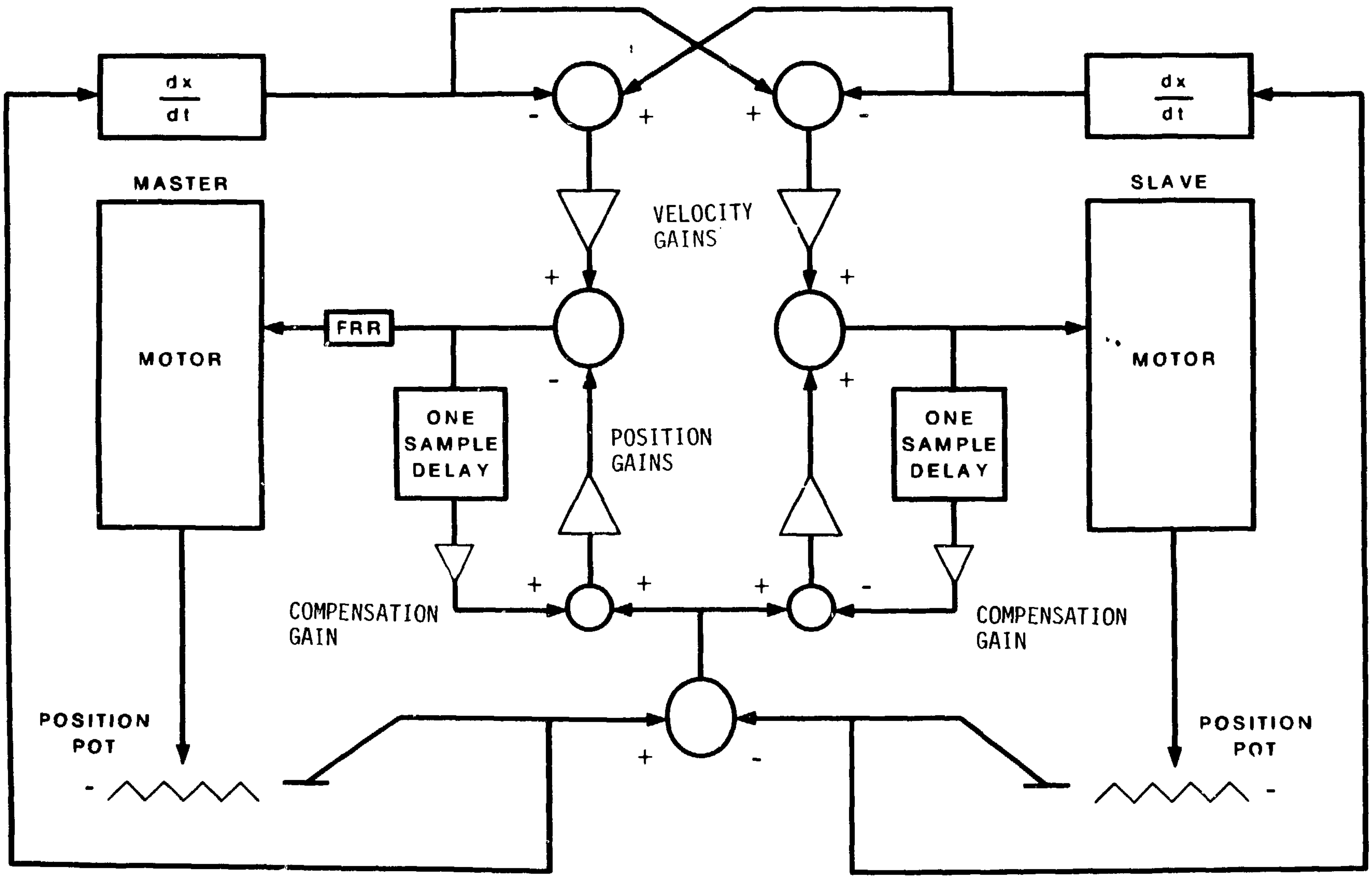

Fig. 5. Servo control algorithm.

Actual Weight (Kg)

Perceived Weight (Kg)	1	2	3	4	5	6	7	8
1	6	7	5	2				
2	8	4	5	3	1			
3	1	2	5	8				
4	1	2		2	2			
5					9	2	1	
6					3	9	3	
7						4	9	5
8							1	10

Figure 6
Actual Versus Perceived Weight

follows the ideal diagonal line closely, thus denoting accurate force perception.

Conclusions

In conclusion, the retrofit has shown that digital computers are powerful and flexible enough to be designed in, or retrofitted to, almost any manipulator application. In this particular application, digital control has proven to be superior to the analog system it replaced with respect to performance, features, and reliability. Tests have also shown that its key feature, providing accurate force reflection, has been significantly improved. In addition, the system does not require frequent retuning to maintain performance due to the low-drift digital system.

Acknowledgments

We at ORNL would like to thank the Princeton Plasma Physics Laboratory for loaning the manipulator to us and for funding the control system conversion. Thanks are also due to Carl Flatu of TeleOperator Systems and to the staff at the Los Alamos National Laboratory Clinton P. Anderson Meson Physics Facility for their suggestions on the conversion.

References

1. Goertz, R., "Some Work on Manipulator Systems at ANL; Past, Present, and a Look at the Future," Proc. 1969 Seminars on Remotely Operated Special Equipment, USAEC Report CONF-641120, May 1964.

2. Martin, H. L., Satterlee, P. E., and Bolfing, B. J., "Distributed Digital Processing for Servomanipulator Control," Transactions American Nuclear Society, Vol. 43, pp. 758-759, 1982.

3. Martin, H. L. et al., "Control and Electrical Subsystems for the Advanced Servomanipulator," Proceedings of the 1984 Topical Meeting on Robotics and Remote Handling in Hostile Environments, pp. 417-424, 1984.

4. Herndon, J. N. et al., "The State of the Art Model M-2 Maintenance System," Proceedings of the 1984 Topical Meeting on Robotics and Remote Handling in Hostile Environments, pp. 147-154, 1984.