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Consolidated Fuel Reprocessing Program

THE STATE-OF-THE-ART MODEL M-2 MAINTENANCE SYSTEM

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J. N. Herndon
Fuel Recycle Division

H. L. Martin and P. E. Satterlee, Jr.
Instrumentation and Controls Division

Oak Ridge National Laboratory*
Oak Ridge, Tennessee

D. G. Jelatis and C. E. Jennrich
Sargent Industries, Incorporated
Central Research Laboratories Division
Red Wing, Minnesota

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ABSTRACT

The Model M-2 Maintenance System is part of an ongoing program within the Consolidated Fuel Reprocessing Program (CFRP) at Oak Ridge National Laboratory (ORNL) to improve remote manipulation technology for future nuclear fuel reprocessing and other remote applications. Techniques, equipment, and guidelines which can improve the efficiency of remote maintenance are being developed. The Model M-2 Maintenance System, installed in the Integrated Equipment Test (IET) Facility at ORNL, provides a complete, integrated remote maintenance system for the demonstration and development of remote maintenance techniques. The system comprises a pair of force-reflecting servomanipulator arms, television viewing, lighting, and auxiliary lifting capabilities, thereby allowing manlike maintenance operations to be executed remotely within the remote cell mockup area in the IET.

The Model M-2 Maintenance System incorporates an upgraded version of the proven Central Research Laboratories' Model M servomanipulator. Included are state-of-the-art brushless dc servomotors for improved performance, remotely removable wrist assemblies, geared azimuth drive, and a distributed microprocessor-based digital control system.

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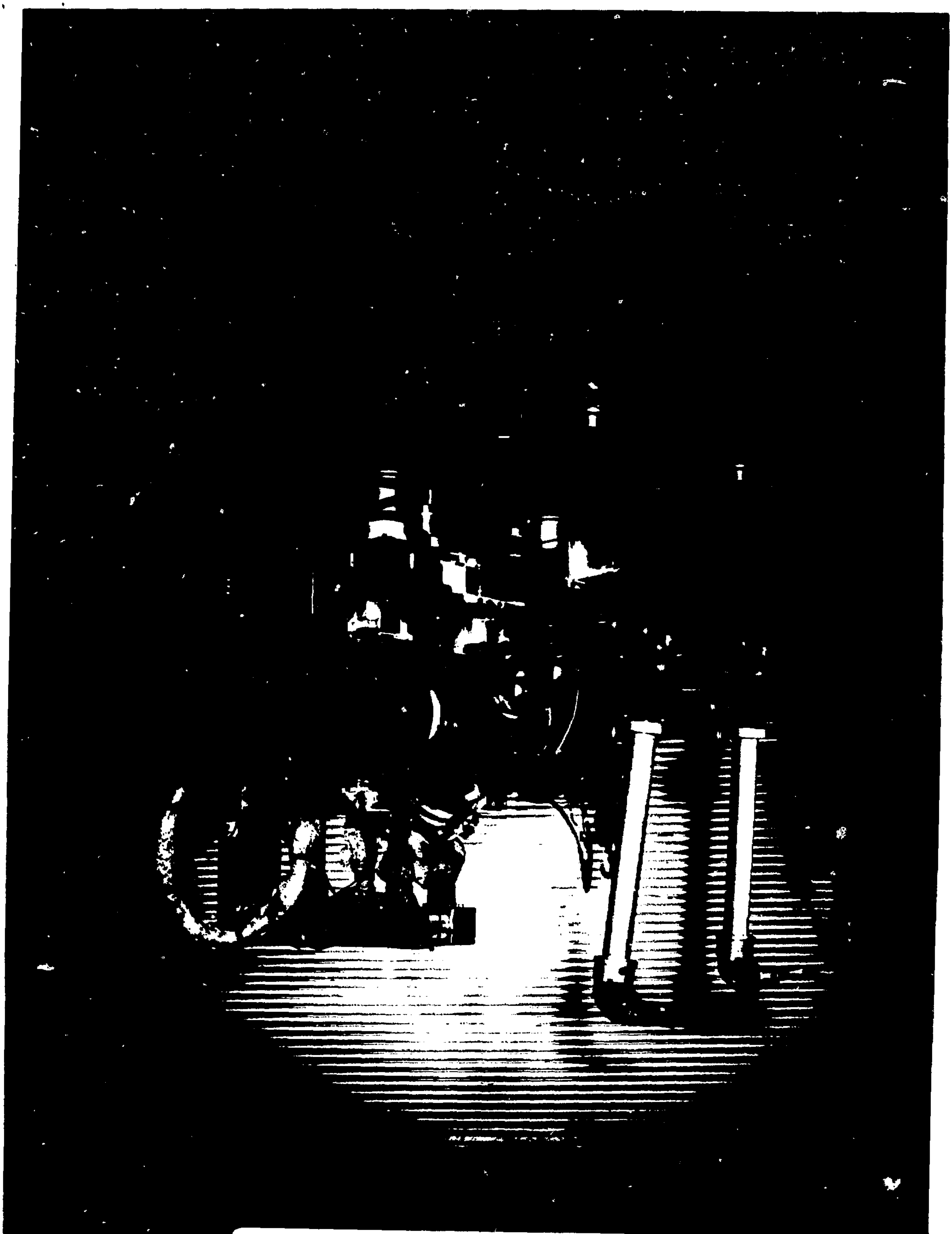
INTRODUCTION

A major goal of the CFRP at ORNL is to improve remote manipulation technology for future nuclear fuel reprocessing and other remote applications. Techniques, equipment, and guidelines that can improve the efficiency of remote maintenance are being developed. This goal is supported by the application of force-reflecting servomanipulators to provide manlike manipulative capabilities for performing maintenance tasks in the remote environment. The Model M-2 Maintenance System, installed in the remote cell mockup area of the Remote Operations and Maintenance Demonstration (ROMD)[1] Facility within the IET at ORNL, is an important demonstration tool for these remote concepts. The M-2 system was developed as a cooperative project between Central Research Laboratories (CRL) and ORNL. The CRL designed the mechanical systems and motor/amplifier components and performed the overall system fabrication; ORNL designed the distributed microprocessor-based control system and all system software.

SYSTEM DESCRIPTION

The Model M-2 Maintenance System consists of two major assemblies: (1) the slave package, which is the "in-cell" working portion of the system and (2) the master station, where the human operator interfaces with the system to execute and monitor maintenance tasks. The slave package, shown in Fig. 1, incorporates a pair of CRL Model M-2 force-reflecting servomanipulator slave arms for performing in-cell dextrous manipulative tasks. Each slave arm has a 23-kg (50-lb) continuous capacity and a 46-kg (100-lb) time-limited (peak) capacity. An auxiliary hoist with a 230-kg (500-lb) capacity is located between the two slave arms to perform the heavier lifts associated with reprocessing plant-type equipment maintenance. These features allow the servomanipulator



arms to be used for "man-like" tasks such as positioning and operating tools, lifting light (~~less than~~ <23-kg) loads, and guiding heavy loads lifted by the auxiliary hoist.

In order to provide operator viewing at the remote task site, one center and two overhead television cameras are provided. Each overhead camera is mounted on a pan-and-tilt mechanism located at the end of a positioning arm with extend/retract and rotate motions. The camera positioning flexibility provided by these four motorized degrees of freedom allows the operator to select orthogonal camera views, thereby optimizing viewing perspective and enhancing depth cues. Each overhead camera also has a motorized zoom lens. The center camera is fixed and equipped with a wide-angle lens to allow general viewing of the manipulator tongs at the task site.

A slave package azimuth drive provides 540° of rotation for orientation of the overall system at the task site. A convenient attach/detach capability enables the slave package to be mounted on different transporter systems.

The master station, shown in Fig. 2, incorporates a pair of CRL Model M-2 force-reflecting servomanipulator master arms for operator input. Each master arm has a 11-kg (25-lb) peak capacity. Switches on the master handles allow for slave tong lock, slave arm lock, master-to-slave "all joint" indexing, tool control, and a unique deadman function. These functions are described in the section on servomotors and controls.

The operator interfaces with the control system primarily through a CRT and touch-screen system. Operating mode selection, force ratio

Fig. 2. Model M-2 master station.

selection, camera/lighting control, and system status diagnostics are provided by this operator interface. This interface is described in depth in the servomotors and controls section.

MECHANICAL SYSTEM

The Model M-2 servomanipulator arms are based on a proven servo-manipulator design that has been upgraded with state-of-the-art motor technology. The master and slave arm designs are based on the CRL Model M servomanipulator developed in the early 1960s at Argonne National Laboratory as the ANL Mark E4A.[2,3] The original Mark E4A kinematics, shown in Figs. 3 and 4, are for the most part retained. The slave and master arms each have the standard seven degrees of freedom (including grasp) arranged in the "over the wall" or "elbows up" configuration as shown in Figs. 1 and 2. The motions at the master and at the slave are in one-to-one correspondence.

Each master and each slave joint are driven by their own individual servomotor drive units. Motions in the X, Y, and Z directions on both master and slave are gear and linkage driven. Eccentric mounts ~~to~~ allow adjustment of backlash and friction. The slave arm azimuth, elevation, twist, and tong motions are driven by a combination of the servomotor drive unit gearboxes and 1/16-in. stainless steel cables. All slave servomotor drive units are located behind the Z-motion axis.

Each servomotor drive unit incorporates a brushless dc servomotor, encoding sensors, brake, cooling fan, and enclosed gearbox. The servomotor drive units are easily removed and replaced as an assembly.

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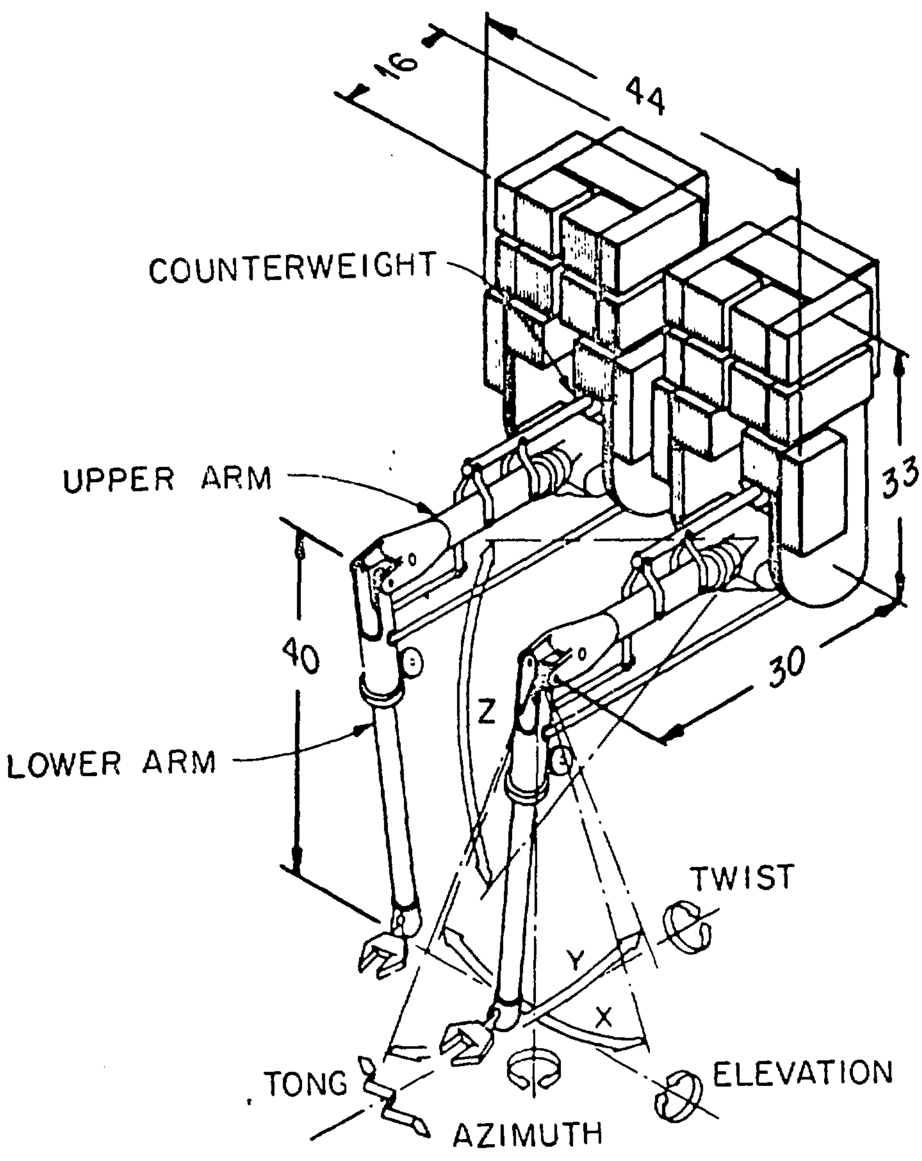

Fig. 3. ARGONNE MARK E4A SLAVE MANIPULATORS.[9]

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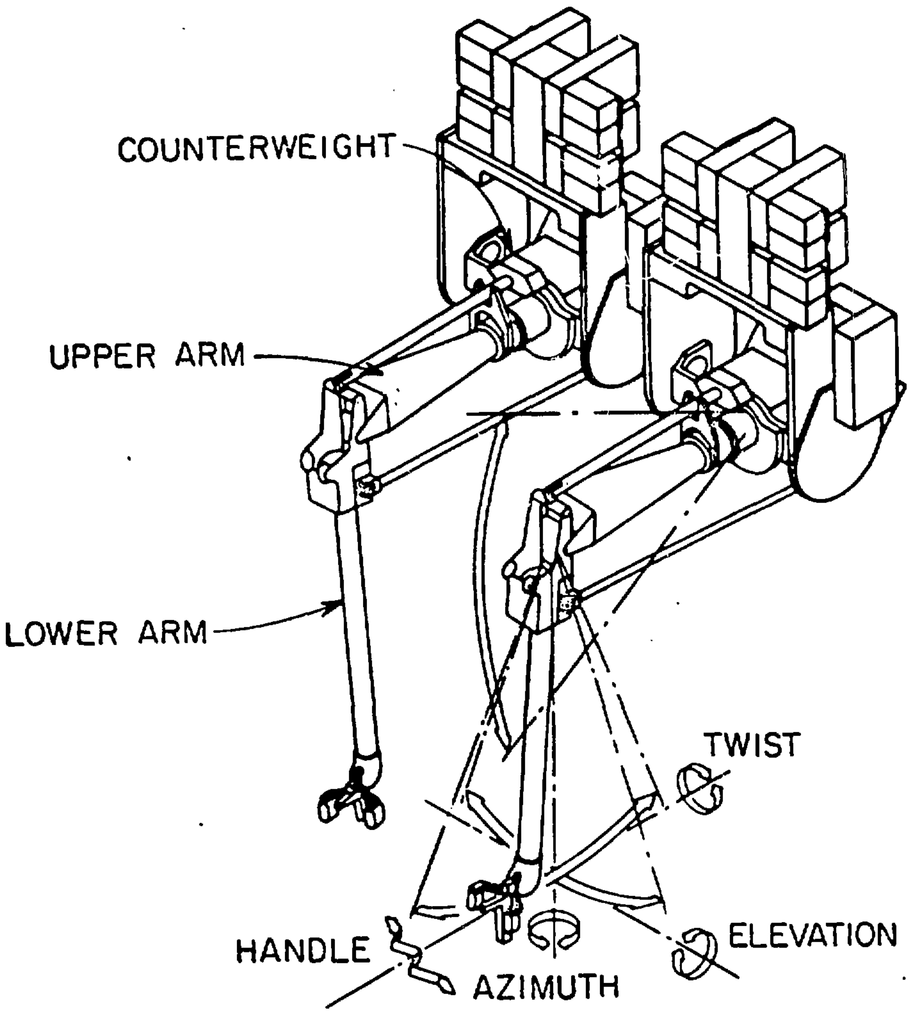

Fig. 4. ARGONNE MARK E4A MASTER MANIPULATORS.

The slave cable-driven motion gearbox drums are located outside of the shoulder assembly (as shown in Fig. 5), which allows ease of maintenance for the cable drives. The cables are routed down the outside of the shoulder, through the center of the Z-motion axis, and then down the center of the slave arm.

In order to upgrade to the peak 46-kg capacity, the slave arm azimuth drive has been modified. The former azimuth cable drum, which attached directly to the lower arm tube, has been replaced with a cable drum and pinion assembly mounted external to the lower arm tube driving a gear attached to the lower arm tube. The standard mechanical master/slave roll-pitch-roll wrist motions are provided. The heavy-duty, remotely detachable wrist joint and gear-driven tongs, available on the CRL system 50 manipulators, have been incorporated on the Model M-2 slave. This remotely detachable wrist joint assembly allows removal of the wrist joint and tong (the portion of the slave arm most vulnerable to mechanical damage and contamination) without disturbing the slave cable drives. The slave drive cables terminate in drums near the bottom of the lower arm tube.

The Model M-2 master arms, shown in Fig. 2, were originally designed with very light structures to minimize effective inertia.[2] This feature has been retained. The X, Y, and Z motions, as indicated earlier, use gear and linkage drives for force transmission. The master arm wrist azimuth, elevation, twist, and squeeze motion force transmission is accomplished using steel tapes. Tapes are used to reduce friction for better sensitivity.

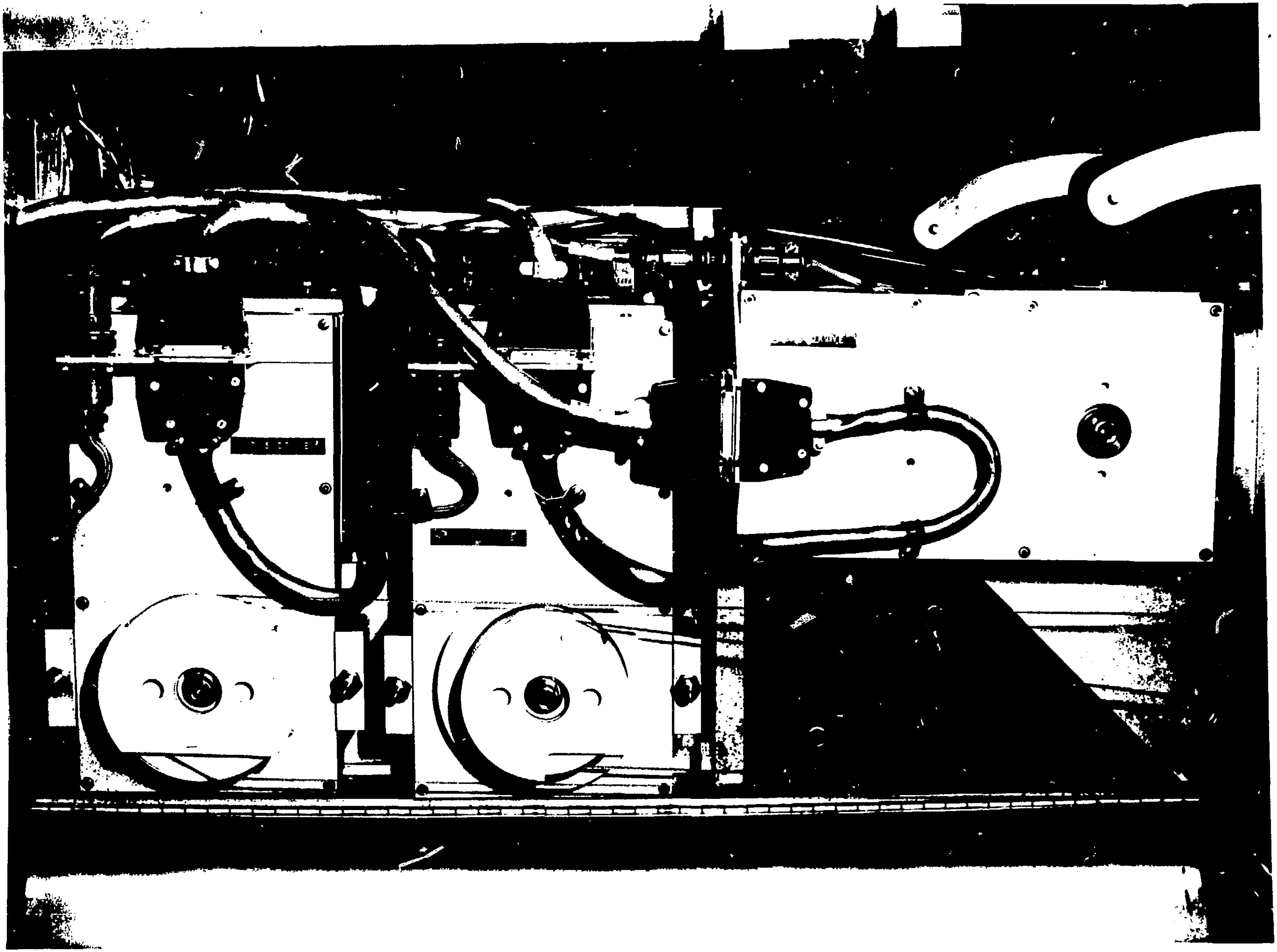

Fig. 5. Model M-2 slave servomotor drive units.

SERVOMOTORS AND CONTROLS

The original design for the Model M servomanipulator[2,3] incorporated two-phase, ac servomotors. Four motors were used for each slave servomotor drive unit, and two motors were used for each master servomotor drive unit. A synchro mounted on one motor and a tachometer on a second motor provided joint encoding. The Model M-2 servomanipulator arms have been upgraded by the application of modern motor technology. Brushless dc servomotors with rare-earth samarium-cobalt permanent magnets, manufactured by Inland Motor Division, Kollmorgen Corporation, are used. The higher torque capacities of the master and slave motors allow the servomotor drive units to be packaged with one motor each. In addition, an 11% increase in continuous capacity and a 100% increase in peak capacity have been attained over the original design. The X, Y, and Z motion maximum velocities are more than double those of the earlier design. The velocity signal for the servomotor drive unit is provided by a tachometer, and position is provided by a digital encoding technique. Table 1 summarizes the dynamic performance characteristics of the Model M-2 servomanipulator arms.

The Model M-2 Maintenance System incorporates a distributed, microprocessor-based digital control system. This system represents the first successful implementation of an entirely digitally controlled servomanipulator and is a significant advance in servomanipulator technology. This control system is described in depth in refs. 4 and 5. Many benefits are derived from use of digital control techniques. First, hardwired analog control designs for the M-2 maintenance system

Table 1. Performance and operating characteristics of ~~for the~~ Model M-2 servomanipulators

	X (Shoulder Roll)	Y (Elbow Pitch)	Z (Shoulder Pitch)	AZ (yaw)	Elevation (pitch)	Twist (roll)	Tong
Maximum master torque or force	~~25 lb~~ 111 N	~~25 lb~~ 111 N	~~25 lb~~ 111 N	~~150 lb in.~~ 17 N.m	~~130 lb in.~~ 15 N.m	~~110 lb in.~~ 12 N.m	~~25 lb~~ 111 N
Maximum slave continuous operating torque or force	~~50 lb~~ 222 N	~~50 lb~~ 222 N	~~50 lb~~ 222 N	~~500 lb in.~~ 56 N.m	~~412 lb in.~~ 47 N.m	~~350 lb in.~~ 40 N.m	~~100 lb~~ 445 N squeeze
Peak slave torque or force ~~capacity~~	~~100 lb~~ 445 N	~~100 lb~~ 445 N	~~100 lb~~ 445 N	~~960 lb in.~~ 108 N.m	~~800 lb in.~~ 90 N.m	~~680 lb in.~~ 77 N.m	~~250 lb~~ 667 N squeeze
Maximum no-load linear or angular velocity	>1.5 m/s	>1.5 m/s	>1.5 m/s	>344 deg/s	>400 deg/s	>344 deg/s	>1.0 m/s
~~Typical motion range~~ of slave arm motion range	± 45° ~~degrees~~	± 45° ~~degrees~~	± 45° ~~degrees~~, with indexing 255° ~~degrees~~ total	+210° ~~degrees~~	+ 40°; −125° ~~degrees~~	±180° ~~degrees~~	Tong 0.08 m; Handle 0.07 m

would have resulted in a cable bundle requiring approximately 300 conductors between masters and slaves. Cable handling for a bundle of this size over a large-volume remote application such as a reprocessing plant would be very difficult at best. Using a digital serial link reduces the signal transmission requirements of the M-2 system to four coaxial cables for control and three coaxial cables for television signals.

Second, the digital control system is inherently flexibile by virtue of its software implementation. In addition to the standard master/slave mode, the M-2 servomanipulator has the capabilities for:

- selective robotic operations;
- multiple slave-to-master force ratios with individual joint tuning for each force ratio;
- unique "all-joint" index of master relative to slave, which allows a position offset between master and slave arms for reduced operator fatigue when operating near extremes in the slave coverage range;
- unique controlled low-power and low-velocity synchronization of master arm to slave prior to entering master/slave mode; and
- deadman switch on master grips which removes power from the master arms when the operator removes his hand.

Third, digital electronics designs are generally less susceptible to drift and thermal stability problems than are analog systems and so have reliable, enhanced performance. Finally, real-time diagnostics that report to the operator the occurrence and location of faults are incorporated in the Model M-2 Maintenance System. This allows the operator to modify his actions to prevent a full system shutdown and aids in the location of failures when they occur.

An additional benefit of the digital control system is the ability to implement a menu-driven, touch-screen/CRT operator interface[9] (The operator console is shown in Fig. 6). All operating mode selections, force ratio selection, camera/lighting power, automated slave position calibration, and system status reporting are controlled through the touch-screen interface. The menu-driven system reduces operator training time and panel requirements. Experienced mechanical master/slave operators can learn to execute very complex maintenance tasks with little initial training on the M-2 system. Camera positioning is controlled with a four degrees-of-freedom joystick. Lens zoom, focus, and iris are controlled with rotary potentiometers.

IET INSTALLATION

The Model M-2 slave package is installed on an overhead three degrees-of-freedom positioning telescoping tube trolley in the ROMD remote cell mockup area within the IET facility, as shown in Fig. 7. This portion of the IET facility contains prototypical reprocessing equipment and systems designed to be operated and maintained remotely, and it is here that servomanipulator-based remote maintenance can be demonstrated and evaluated. Remote handling features of prototypical reprocessing equipment can be tested, and equipment mean-time-to-repair data for plant design applications can be acquired. The evaluation of these features and capabilities can be used to design future maintenance systems.

The Model M-2 master station is installed in the ROMD control room adjacent to, but separate from, the cell mockup area. The manipulator operator can view remote maintenance tasks on three color television

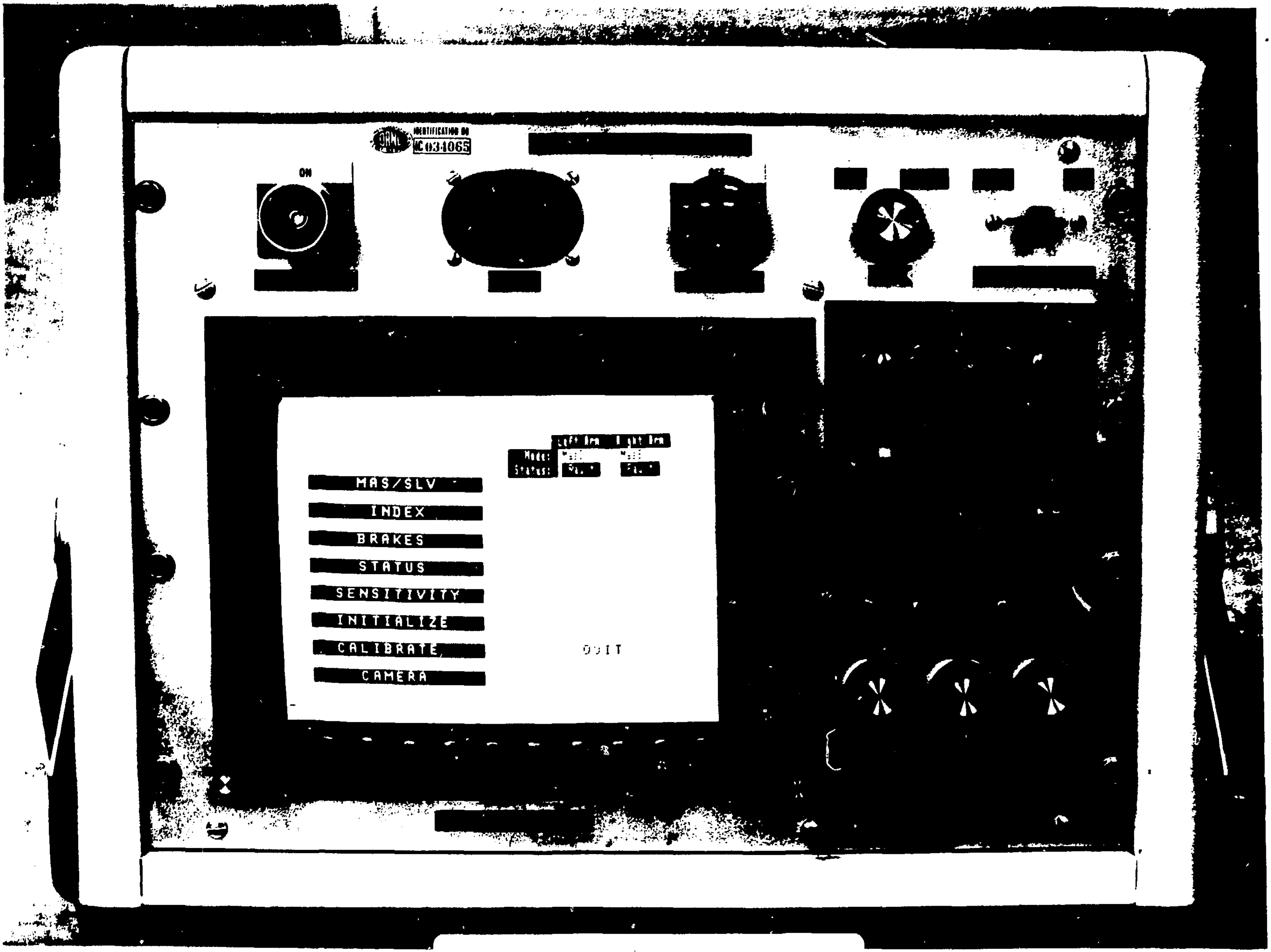

Fig. 6. Model M-2 operator console.

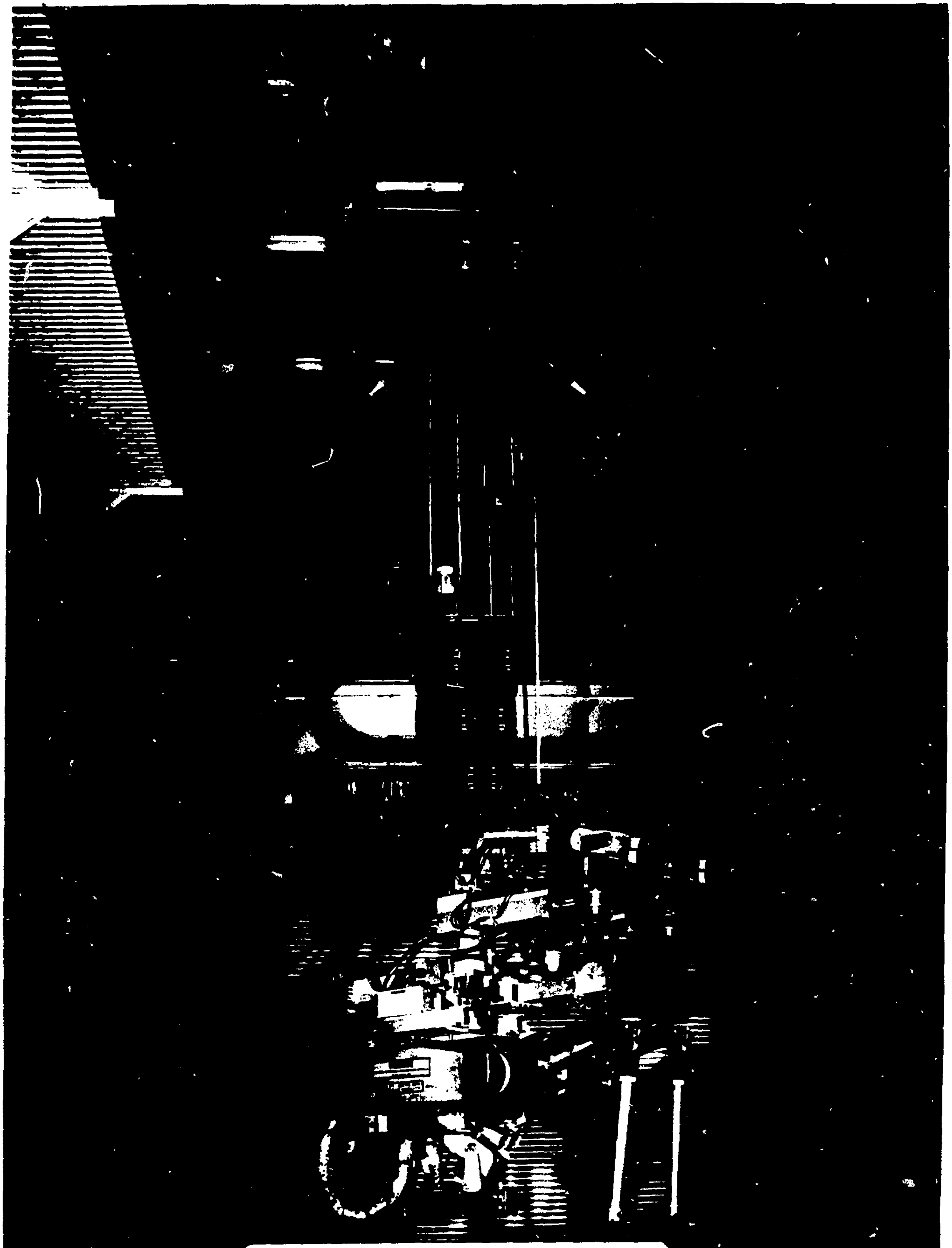

Fig. 7. ROMD transporter system.

monitors (Fig. 2). The operating team consists of two operators, as shown in Fig. 8. The primary operator is responsible for performing the dextrous maintenance tasks with the servomanipulators, and the secondary operator is responsible for controlling the telescoping tube transporter, overhead 10-ton cranes, and television monitor matrix switching. Either operator can control camera position and the auxiliary hoist.

OPERATING EXPERIENCE

The Model M-2 Maintenance System in the IET facility has performed very successfully. Servomanipulator-based remote maintenance has been demonstrated as practical for very complex remote operations. The remote maintenance capabilities and flexibility of servomanipulators have been demonstrated in successful maintenance campaigns on a solvent extraction centrifugal contactor module and on a mechanically complex automated remote sampler vehicle. Experienced mechanical master/slave operators can successfully execute these very complex tasks after only minimal training.

A technically revealing Model M-2 activity was the successful implementation of a finite-difference approximation of joint velocity from position data. This allowed elimination of the tachometer velocity signal from the control loops. The replacement of the noisy tachometer velocity signal with the estimated velocity signal permitted larger control loop gains, which in turn significantly increased the overall manipulator force sensitivity, and eliminated problems with thermal-related tachometer drift.

Fig. 8. ROMD control room.

Future plans for the Model M-2 Maintenance System include (1) additional maintenance campaigns on prototypical reprocessing equipment; (2) software development and refinement including selective robotic slave operations and automatic camera tracking routines, to enhance operator performance; and (3) various evaluations of the operating characteristics and features of the servomanipulator and their effects on the human operator.

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