CONF-860487-- 2

Consolidated Fuel Reprocessing Program

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DE86 004802

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Paper for Presentation at the Robots '86 Conference
Robotics International of SME
Chicago, Illinois

April 20-24, 1986

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

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ABSTRACT

The Remote Control Engineering Task of the Consolidated Fuel Reprocessing Program at Oak Ridge National Laboratory has been developing advanced techniques for remote maintenance of future U.S. fuel reprocessing plants. These efforts are based on the application of teleoperated, force-reflecting servomanipulators for dexterous remote handling with television viewing for large-volume hazardous applications. These developments fully address the nonrepetitive nature of remote maintenance in the unstructured environments encountered in fuel reprocessing. This paper covers the primary emphasis in the present program; the design, fabrication, and installation of a prototype remote handling system for reprocessing applications, the Advanced Integrated Maintenance System.

INTRODUCTION

The Remote Control Engineering Task of the Consolidated Fuel Reprocessing Program at Oak Ridge National Laboratory (ORNL) is developing advanced techniques for remote maintenance of future U.S. nuclear fuel reprocessing plants. These developments are based on the application of teleoperated force-reflecting servomanipulators for dexterous remote handling with the operator removed from the hazardous environment. Television is used for viewing in this large-volume applications. These developments fully address the nonrepetitive nature of remote maintenance in the unstructured environments encountered in fuel reprocessing. Employing highly dexterous manipulation will allow the attainment of a major goal of decreasing reprocessing plant mean-time-to-repair through increased maintenance system capabilities. In addition, another major goal is to decrease plant personnel radiation exposure through the use of remote maintenance techniques for the maintenance equipment as well as the plant process equipment.

*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.

The application of maintenance systems with the level of dexterity provided by a force-reflecting servomanipulator-based system is a major step forward in reprocessing plant design. Past reprocessing plants in the United States have relied on two major approaches to maintenance within the enclosures, or cells, housing the hazardous materials. In one approach, human entry into the hazardous environment is employed after extensive decontamination to reduce the radiation levels. Use of this approach to maintenance appears to be on the decline due to extensive downtime for decontamination and resulting maintenance personnel exposure.[1] A second approach, pioneered mainly in the defense reprocessing plants in the United States, has been to design cells where the installed process equipment can be totally remotely maintained. Cells with chemical equipment have been furnished with overhead cranes as the only teleoperator to execute maintenance. These designs have had rather successful histories, but require costly special equipment designs and have limited capabilities to respond to unplanned events. Commercial plants have utilized a combination of rate-controlled manipulators and wall-mounted master-slave manipulators where more complex mechanical process steps are necessary.

The Remote Control Engineering Task has been working in this development effort for over seven years. The effort involves all the major subsystems necessary to apply dexterous manipulators to large-volume reprocessing plant maintenance. Included are manipulators, transporters, sensors, tooling, signal and power transmission, and man-machine interfaces as shown on Fig. 1. The development has been step-wise with the design, fabrication, and operation of two major maintenance systems previous to initiating the present efforts. The first large-volume servomanipulator-based maintenance system, shown in Fig. 2, was installed in the Remote Systems Development Facility. The facility was equipped with a pair of TeleOperator Systems SM-229 servomanipulators mounted on an overhead telescoping tube transporter with television cameras mounted on positioning arms. Efforts in this facility included studies of man-machine interface issues for as well as manipulator joint duty cycles.[2,3] The second large-volume system was installed in the Remote Operations and Maintenance Demonstration Facility. The maintenance system in this facility is based on a pair of Central Research Laboratories Model M-2 servomanipulators mounted on an overhead telescoping tube transporter with television cameras on positioning arms and an integral 230-kg hoist.[4] The M-2 system, shown in Fig. 3, was the result of a cooperative development of Central Research Laboratories and ORNL. The M-2 control system was the first successful implementation of digital control techniques for a force-reflecting servomanipulator.[5] Efforts in the Remote Operations and Maintenance Demonstrations Facility presently involve remote maintenance checkout for prototype reprocessing equipment. In addition, detailed testing of various technical issues in the application of remote manipulator systems is carried out in this facility.

ADVANCED INTEGRATED MAINTENANCE SYSTEM

The primary emphasis in the present Remote Control Engineering program is the design, fabrication, and installation of a prototype remote handling system for reprocessing applications, the Advanced Integrated Maintenance

System (AIMS). This system will be the culmination of the development program representing prototype for maintenance systems in future nuclear fuel reprocessing plants. The AIMS system, shown in Fig. 4, will incorporate all the subsystems required for large-volume reprocessing applications. The key feature of the AIMS system is the use of the Advanced Servomanipulator slave arms, force-reflecting servomanipulators designed for modular remote maintainability. These manipulators, combined with the other AIMS subsystems, will be utilized to perform remote maintenance demonstrations on simulated process equipment such as the equipment rack shown in Fig. 4. The purpose of these demonstrations is to verify the performance of the maintenance system and to verify the remote handling design of the prototype process rack. The subsystems of the AIMS are described in the following paragraphs.

Advanced Servomanipulator Slave Arms

The Advanced Servomanipulator (ASM) slave arms were developed specifically for the extremes of a reprocessing environment. Radiation and surface contamination levels are very high in a reprocessing cell and the atmosphere contains nitric acid vapors. The final version of the slave arms must function reliably in this environment.

A major goal is to provide modular remote maintenance of these slave arms in this reprocessing environment. Previus design for bilateral, force-reflecting servomanipualtors have utilized tendon drives for reduced inertia and friction. These drives are very difficult to repair after failure. In reprocessing applications, extensive decontamination followed by lengthy contact maintenance is required for tendon drive repair. The ASM slave arms have been designed with all gear and shaft drives inorder to allow segmentation of the arms into modules for remote handling. The slave arms were designed for 23-kg capacity in any orientation, end effector maximum no-load velocities in excess of 1.0 m/s for each individual joint, and low no-load backdriving torque (approximately 5% of capacity) for force-reflecting operation with bilateral, position-position servocontrol. A special brush-type dc servomotor with very low inertia was developed by Inertial Motors Corporation for this application. The first two prototype arms were designed and fabricated at ORNL, and a single arm is shown in Fig. 5. The arms have six degrees-of-freedom for generalized positioning in space with a grip as the seventh degree-of-freedom. An anthropomorphic (man-like) kinematic arrangement was employed to provide for horizontal reach capabilities into constrained areas. The range of motion of the arms is shown in Fig. 6. The unique four degree-of-freedom wrist utilized on the ASM has pitch, yaw, and output roll motions with axes intersecting at a single point and followed by the grip. The arm is composed of fifteen individual modules for each of which are less than 23 kg in weight for handling by another manipulator. These modules are illustrated in Fig. 7. The modularized design is accomplished by the use of precision gear and shaft drives throughout. In addition, electronic counterbalancing is employed to eliminate balance weights and thus reduce the arm cross section. A detailed description of the ASM slave arms can be found in Ref. 6.

Master Controllers

The master controller arms for the ASM were designed for operation in the human-occupied control room and did not require the modularity provided in the slave arms. Stainless steel cable drives were employed for all joints below the shoulder in order to minimize friction and inertia. The master controllers were designed for 6-kg capacity in any orientation, end effector maximum no-load velocities in excess of 1.0 m/s for each individual joint, and low no-load backdriving torque (approximately 4% of capacity is expected) for force- reflecting operation with bilateral, position-position servocontrol. The arms are one-to-one kinematic replicas of the slave arms so that realtime transformations for 30 joints at 100 Hz are not required. The slave arm torque cross coupling is mimicked for simplification of control. The first two prototype arms were detail designed and fabricated at ORNL and a single arm is shown in Fig. 8. The arm axes of motion are shown in Fig. 9. Mechanical counterbalancing is used on the master for reduced drive friction compared to the electronic counterbalancing of the slave arms. A detailed description of the master controller arms can be found in Ref. 7.

Transporter and Interface Package

An adaption of an industrial rigid mast crane has been used for the AIMS transporter system. Rigid mast cranes have been used extensively in industry for many years for material handling and automated warehouse storage/retrieval systems. Harnischfeger Corporation performed the detail design and fabrication of a remotely maintainable rigid mast crane system for ORNL under subcontract. The full remote cell version of this transporter will be constructed as shown in Fig. 10. The initial prototype for AIMS is a gantry bridge version and can be seen in Fig. 4. The transporter has a three section, externally telescoping mast with an inner rigid section, a moving secondary mast, and an outer moving carriage which is used to support and move the servomanipulators. Hoists are used to provide independent vertical motions to the secondary mast and the carriage. The rigid mast section is mounted on a rotating turntable supported by a large diameter bearing and an external gear to provide 370° rotation of the mast.

The interface package, shown in Fig. 11, is remotely detachable from the transporter and provides the balance of the in-cell remote maintenance system. The interface package, designed and fabricated at ORNL, supports two overhead television cameras with lights on four degree-of-freedom positioners, a center camera with lights on a two degree-of-freedom positioner, mounts for the ASM slave arms, and a 460-kg capacity auxiliary hoist with extend/retract motion. A rotation drive about the interface package centerline is also provided for ease of in-cell positioning in arbitrary orientations.

Operator Control Station

The operator control station design for AIMS benefited extensively from the Remote System Development Facility and Remote Operations and Maintenance Demonstration control station operation. In addition, the design is based on the extensive program of human factors research in teleoperation which has been active within the Remote Control Engineering Task for over seven years. The AIMS operator station,[8] shown in Fig. 12, is based on a two operator team approach to control of maintenance operations and the use of flexible graphic display-based controls. Good interoperator communication, both visual and verbal, is essential. The manipulator operator, shown on the right of Fig. 12, is responsible for performing dexterous maintenance operations using the master controllers with television viewing. He is also provided with three color graphic displays for status and menu selection using a master controller grip-mounted cursor control. The secondary operator, shown on the left side of Fig. 12, is responsible for control of the transporter, a large overhead 20-ton crane, television camera positioning, control station displays, and overall maintenance supervision. Prior to fabrication, the control room arrangement shown in Fig. 12 was designed based on ergonomics principles, mocked up, and thoroughly tested for ease of use by the required operator population.

Control System

Control of the AIMS is a sizable challenge due to the breadth of the requirements. The control system must provide for 30 bilateral, force-reflecting joints which require updating at 100 Hz. In addition, 56 nonforce-reflecting drives, over 100 discrete outputs, 6 graphics displays, 21 television displays, and two separate operator control stations must be controlled. This problem has been solved by a hierarchical, building block approach (see Fig. 13) utilizing an industry-standard Multibus backplane (IEEE-796) for expandability and flexibility. Single-board Motorola 68000-based computers for control calculations and Megalink boards for communications are used throughout the system. Input/output and special devices are chosen to meet individual subsystem requirements. All software modules in the system are being programmed in FORTH for speed of execution in a high-level language environment.

The ORNL has led the world in the development of digital-based control systems for bilateral force-reflecting servomanipulators. The controls for the ASM,[9] based on the hardware described above, are the most advanced of any existing force-reflecting servomanipulator. Through special software compensation methods, the adverse effects of much higher levels of friction, inertia, and cross coupling of torques on the slave arm have been minimized. In addition, electronic counterbalancing of the slave arms has been achieved without significant adverse effects on force-reflection sensitivity.

Other Subsystems

The task is developing two other major items for the AIMS system; wireless signal transmission and radiation-hard television cameras. Wireless signal transmission methods are very important for the implementation of a remotely-maintained transporter in a very large cell. The AIMS system, with five television cameras mounted on the transporter/interface package and three 1.0-megabaud rate data channels is a very demanding application. A prototype microwave-based signal transmission system is being developed for this application. This system will utilize a single bidirectional link operating in the 10-GHz frequency range.

In order to provide radiation hard television cameras, a radiation-hard version of the commercially available MTI/Dage camera shown in Fig. 14 has been developed. The illustrated camera head and Fujinon lens have been successfully radiation tested to 10^8 Rad absorbed dose in their commercially delivered form. The circuits in the camera control unit have been modified for improved radiation hardness. These modifications have been verified in irradiation testing to give control box radiation hardness in excess of 10^6 Rad absorbed dose.

PRESENT AIMS STATUS

The AIMS equipment is presently being installed at ORNL. The ASM slave arms have been operational for two years in the laboratory and the master controller arms and operator control station have recently been completed. The transporter has been installed and installation of the balance of the "in-cell" equipment has started. It is expected that AIMS will begin limited operation by mid-year 1986. Early demonstrations will concentrate on verification of the concept and on demonstrations of servo manipulator maintenance for prototype large reprocessing equipment.

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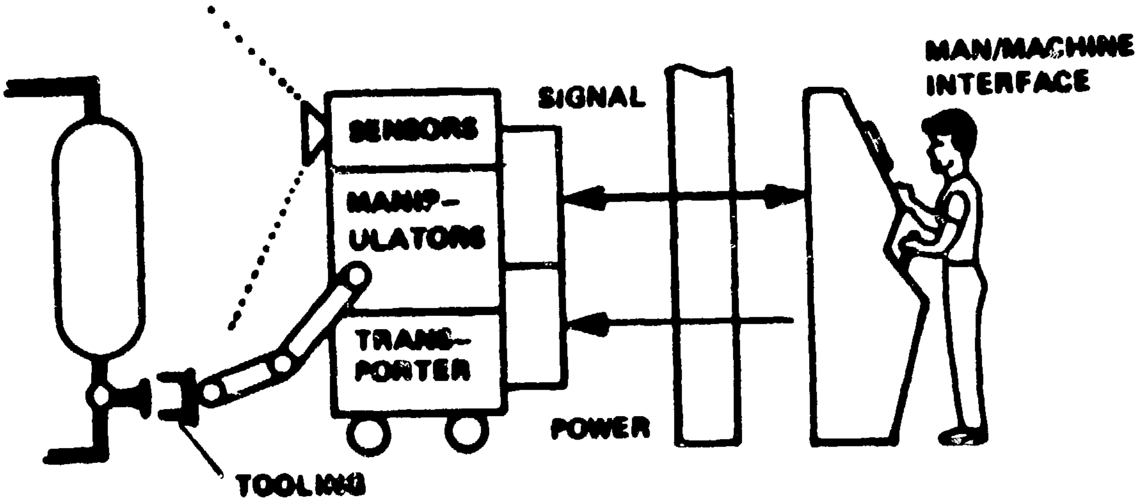

Fig. 1 Subsystems for large-volume remote maintenance

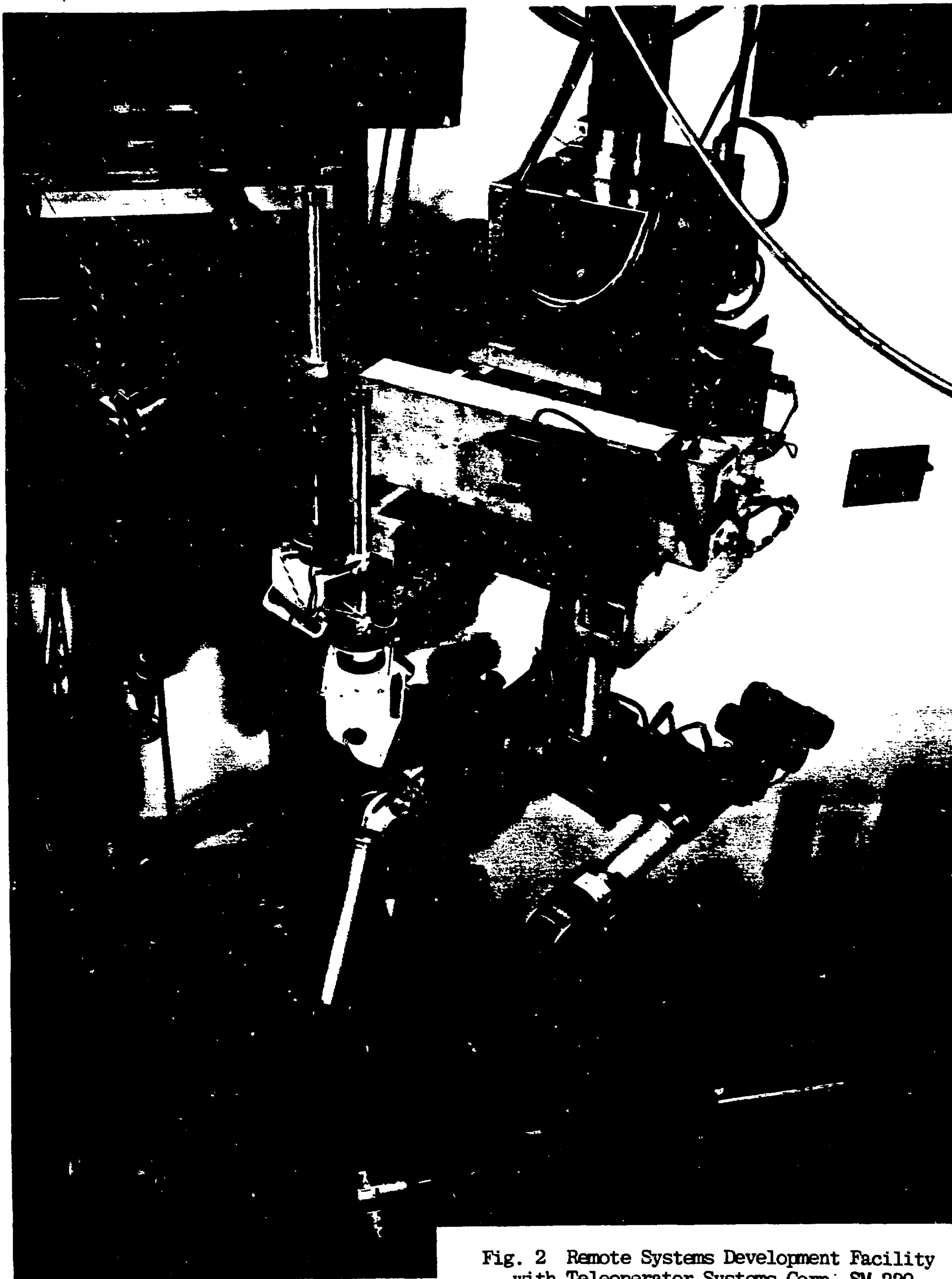

Fig. 2 Remote Systems Development Facility with Teleoperator Systems Corp. SM-229 servomanipulator slave arms

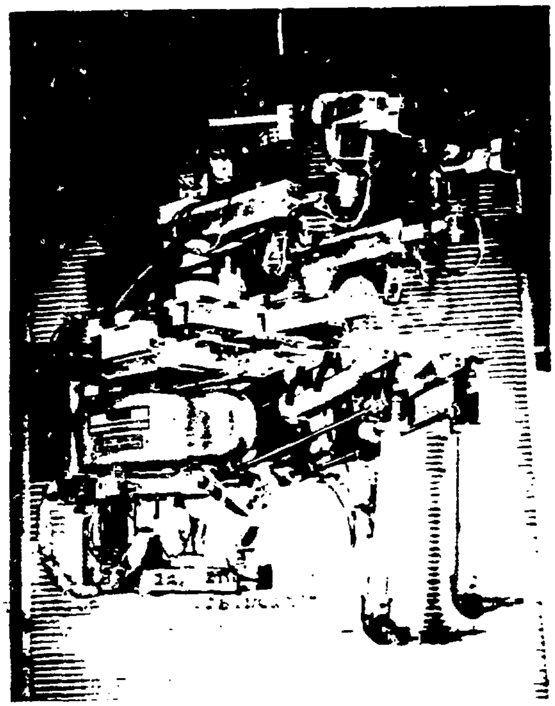

Fig. 3 Central Research Laboratories
Model M-2 servomanipulator slave arms

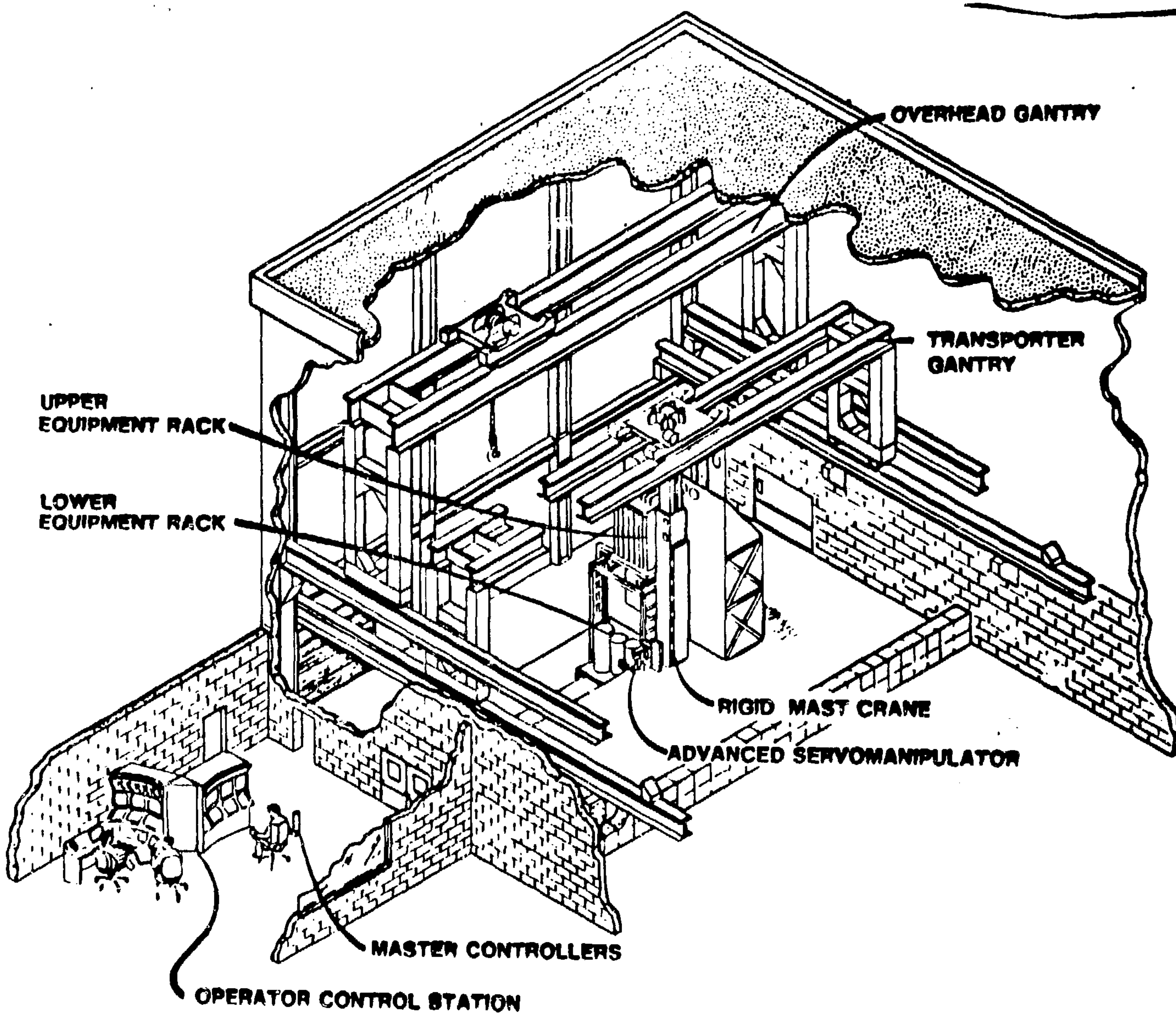

Fig. 4 Advanced Integrated Maintenance System installation

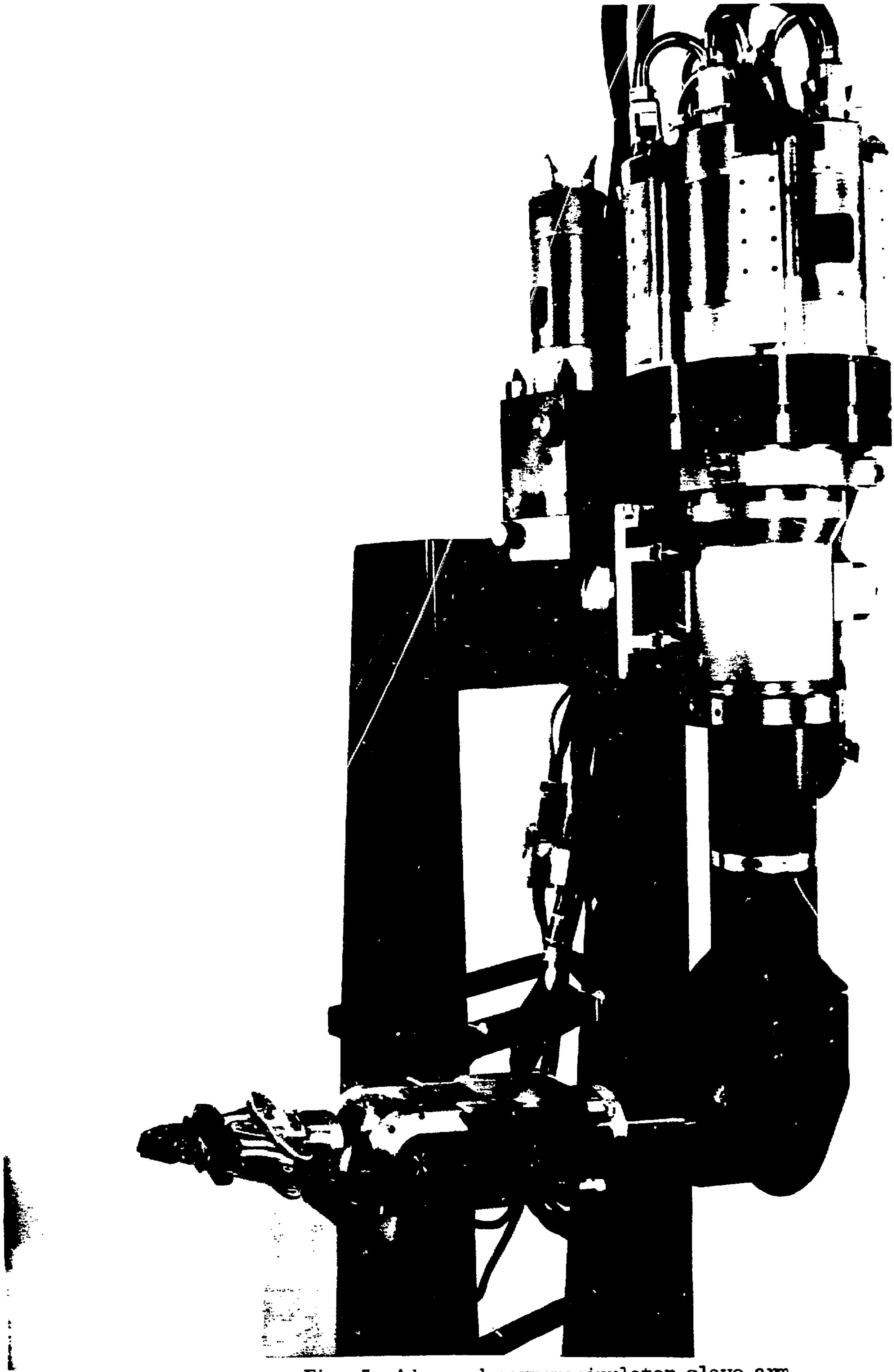

Fig. 5 Advanced servomanipulator slave arm

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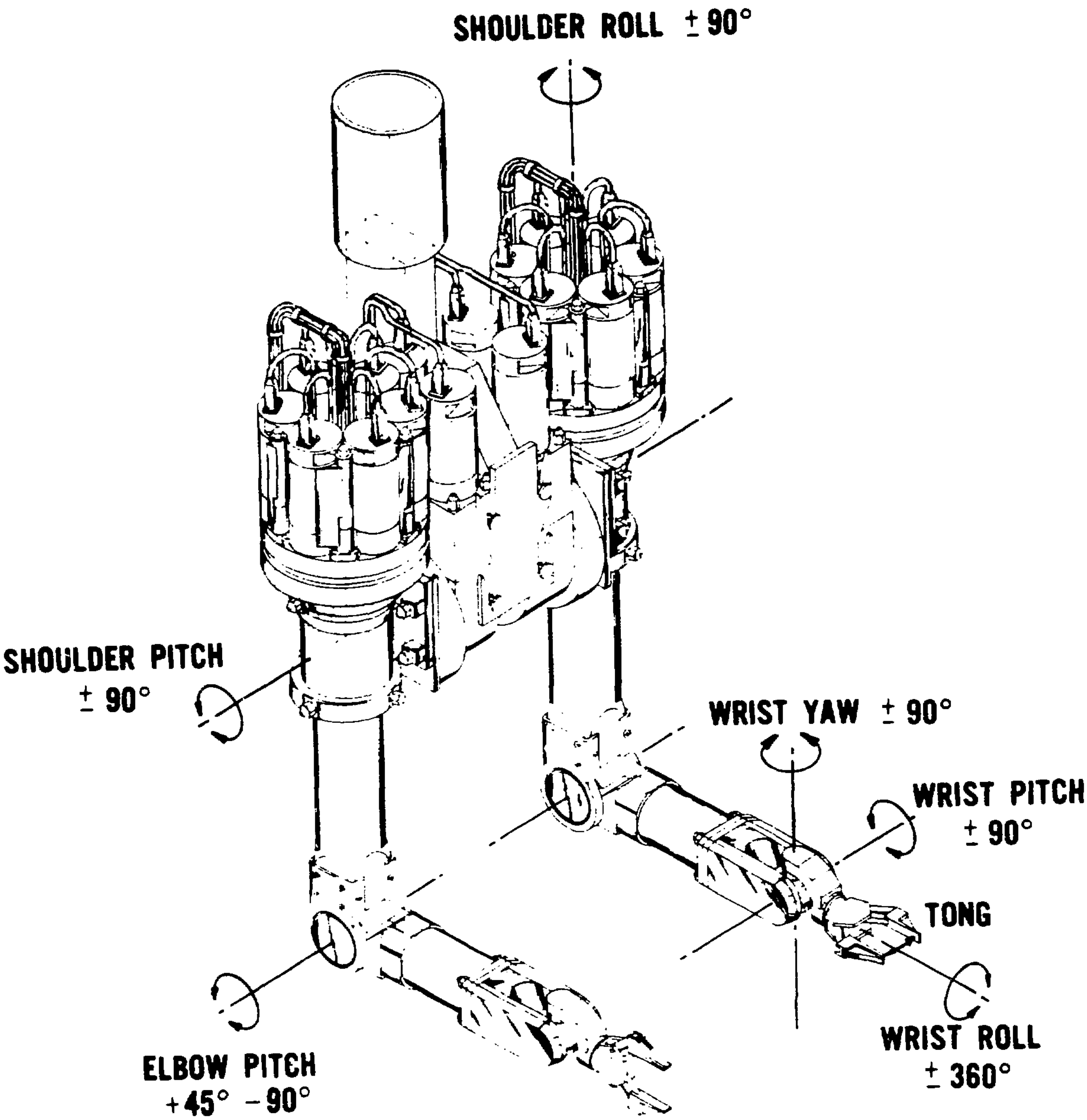

Fig. 6 Advanced servomanipulator slave arm range of motions

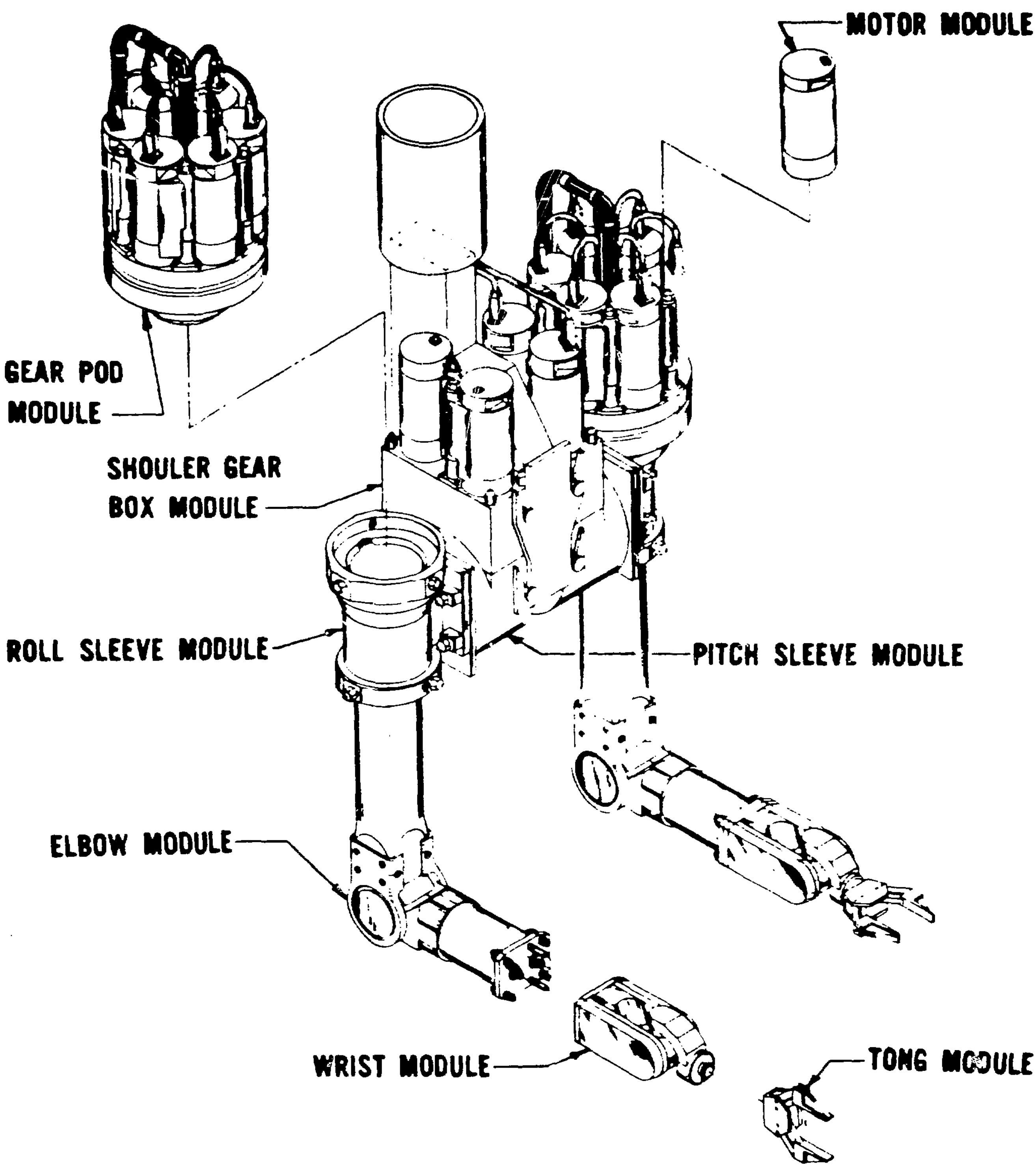

Fig. 7 Advanced servomanipulator modularity
for remote maintenance

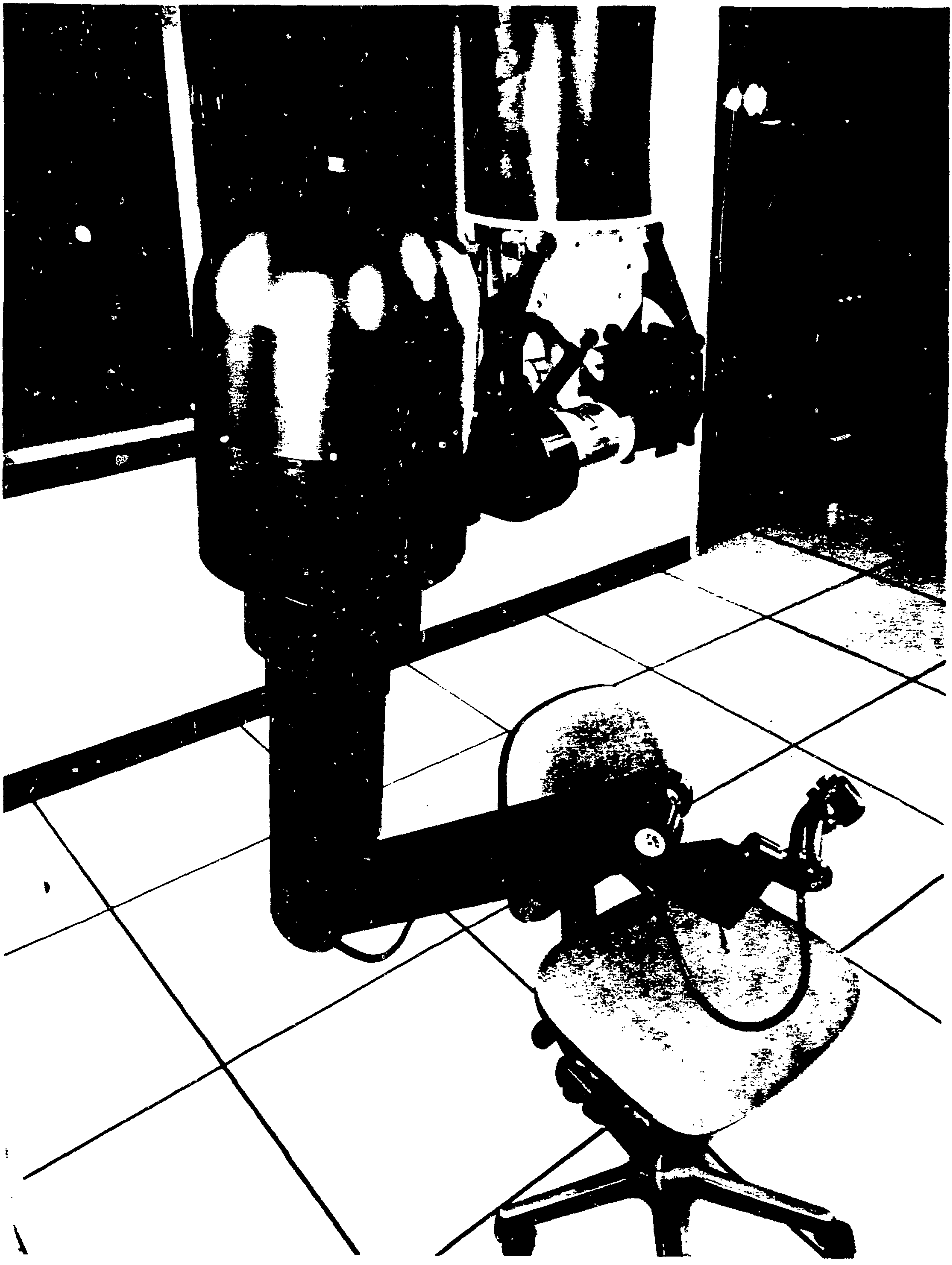

Fig. 8 Single master controller arm

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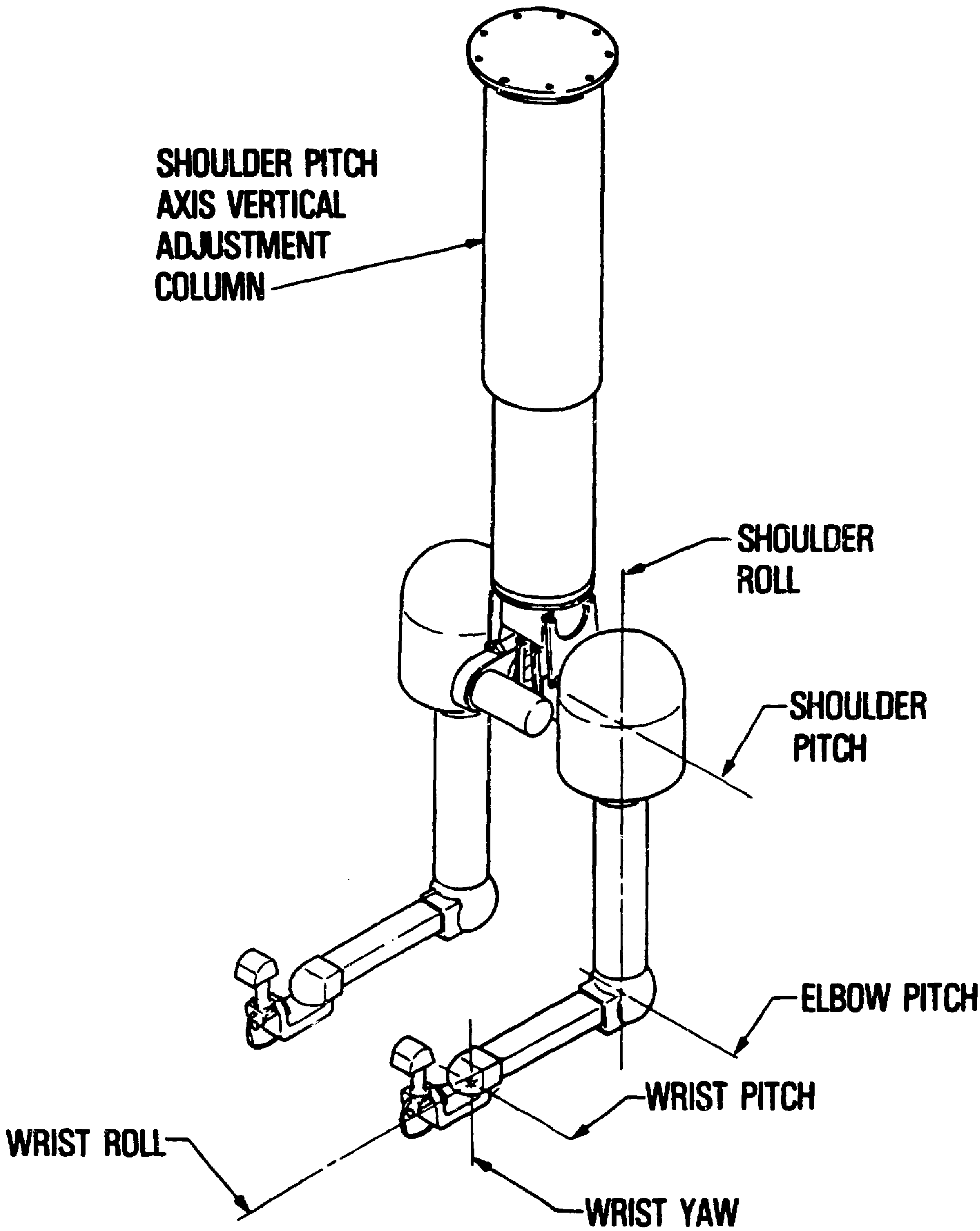

Fig. 9 Master controller axes

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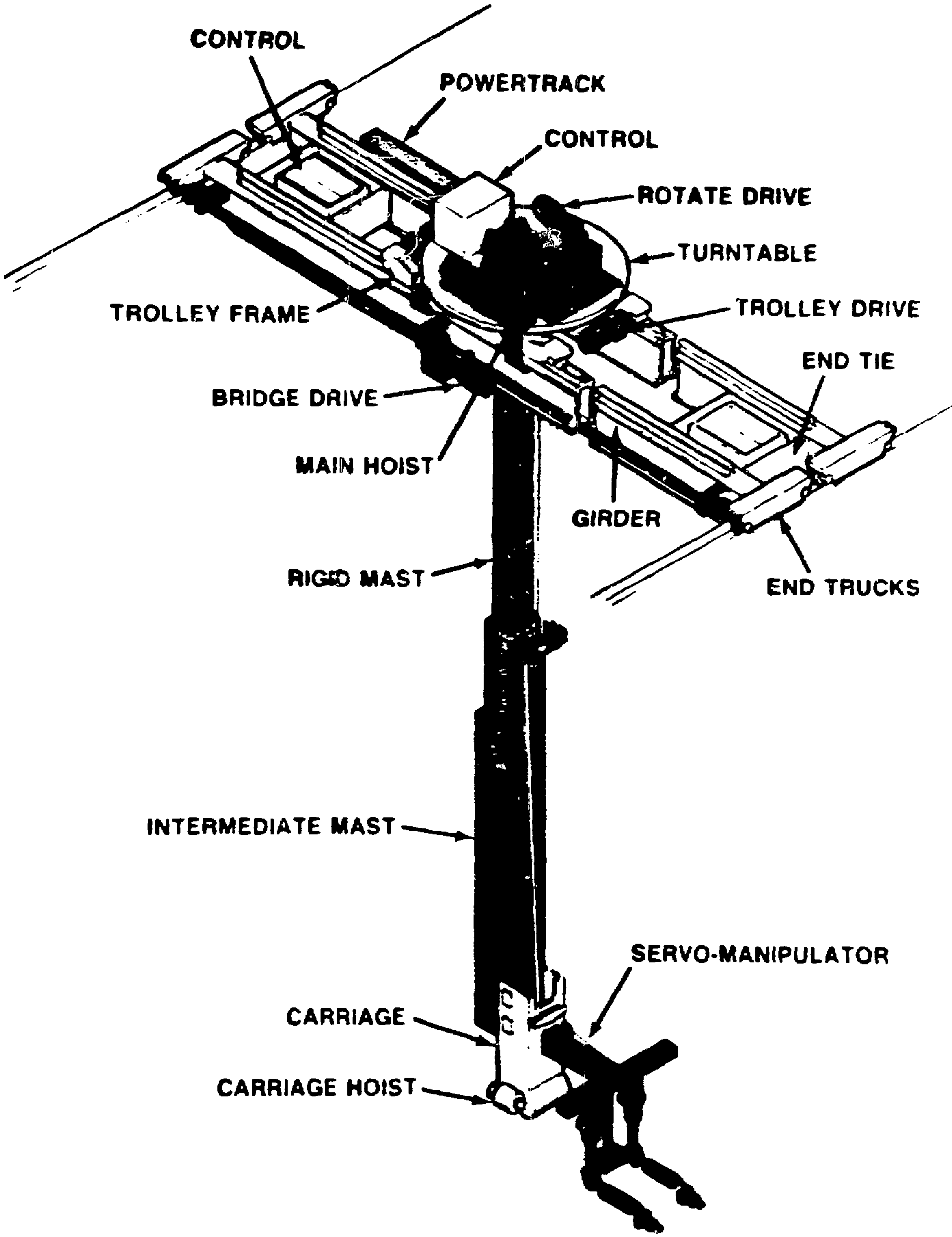

Fig. 10 Rigid mast crane-based overhead manipulator transporter

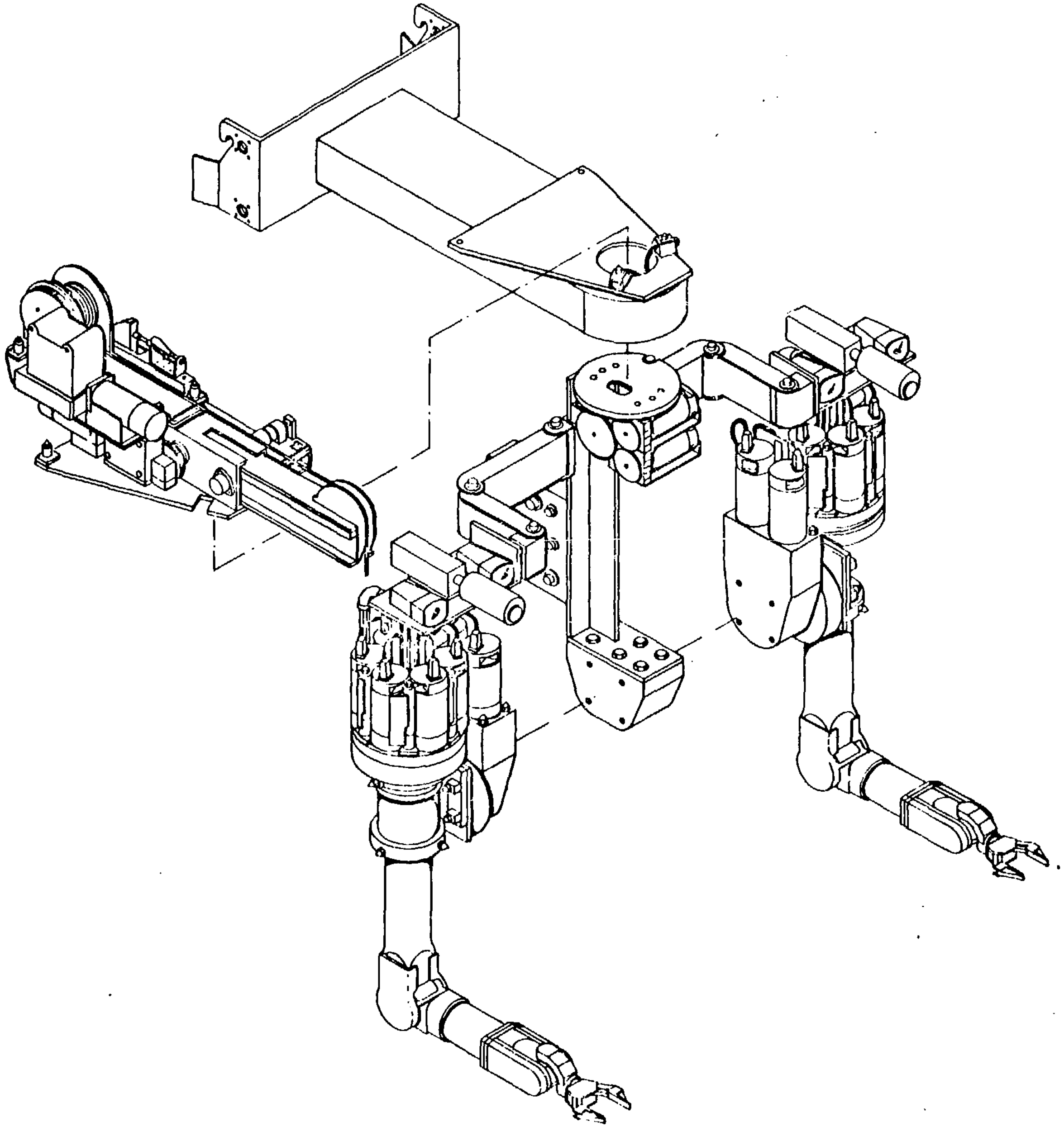

Fig. 11 Interface package with dual ASM slave arms and camera positioners

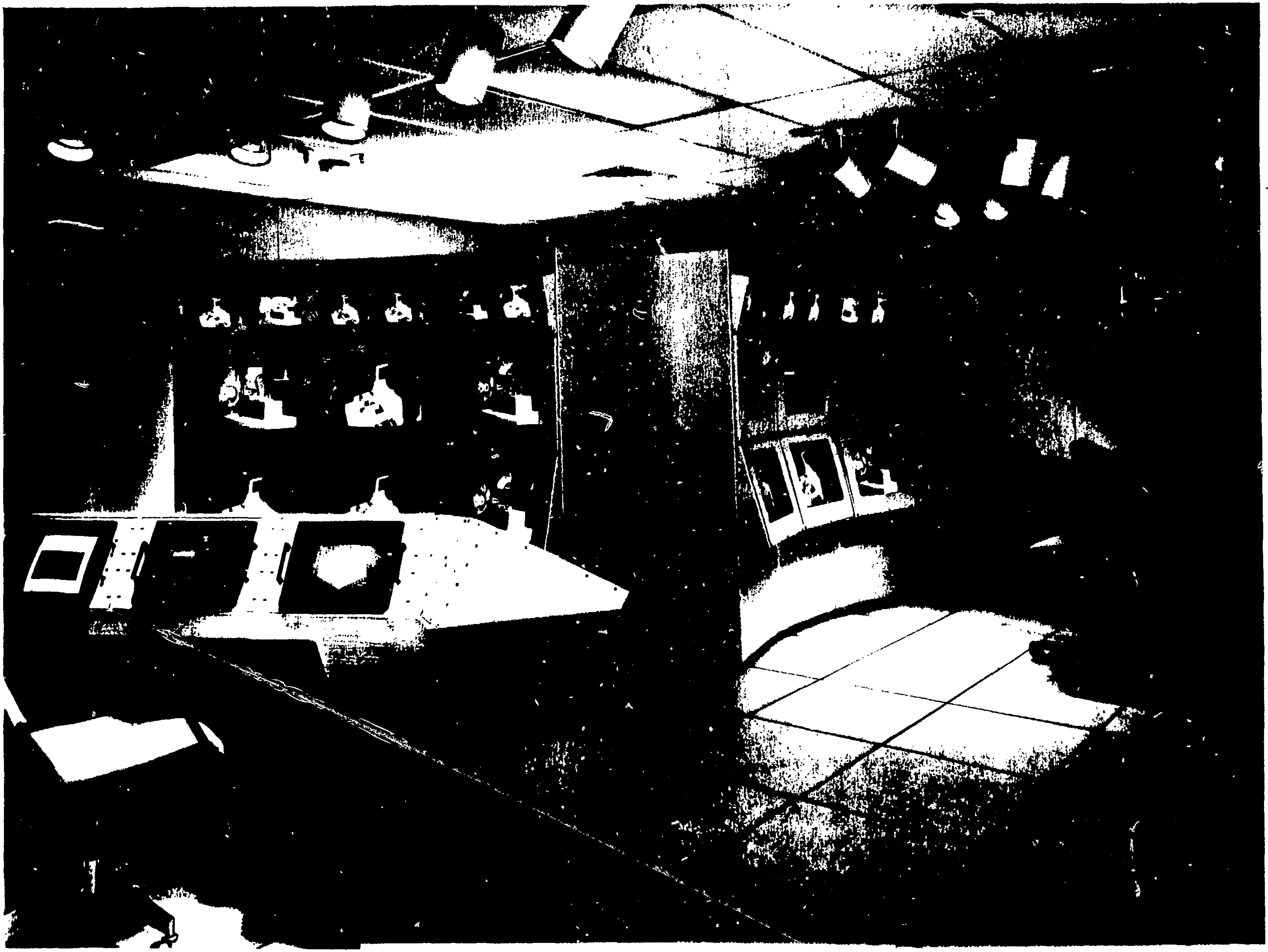

Fig. 12 Operator control station

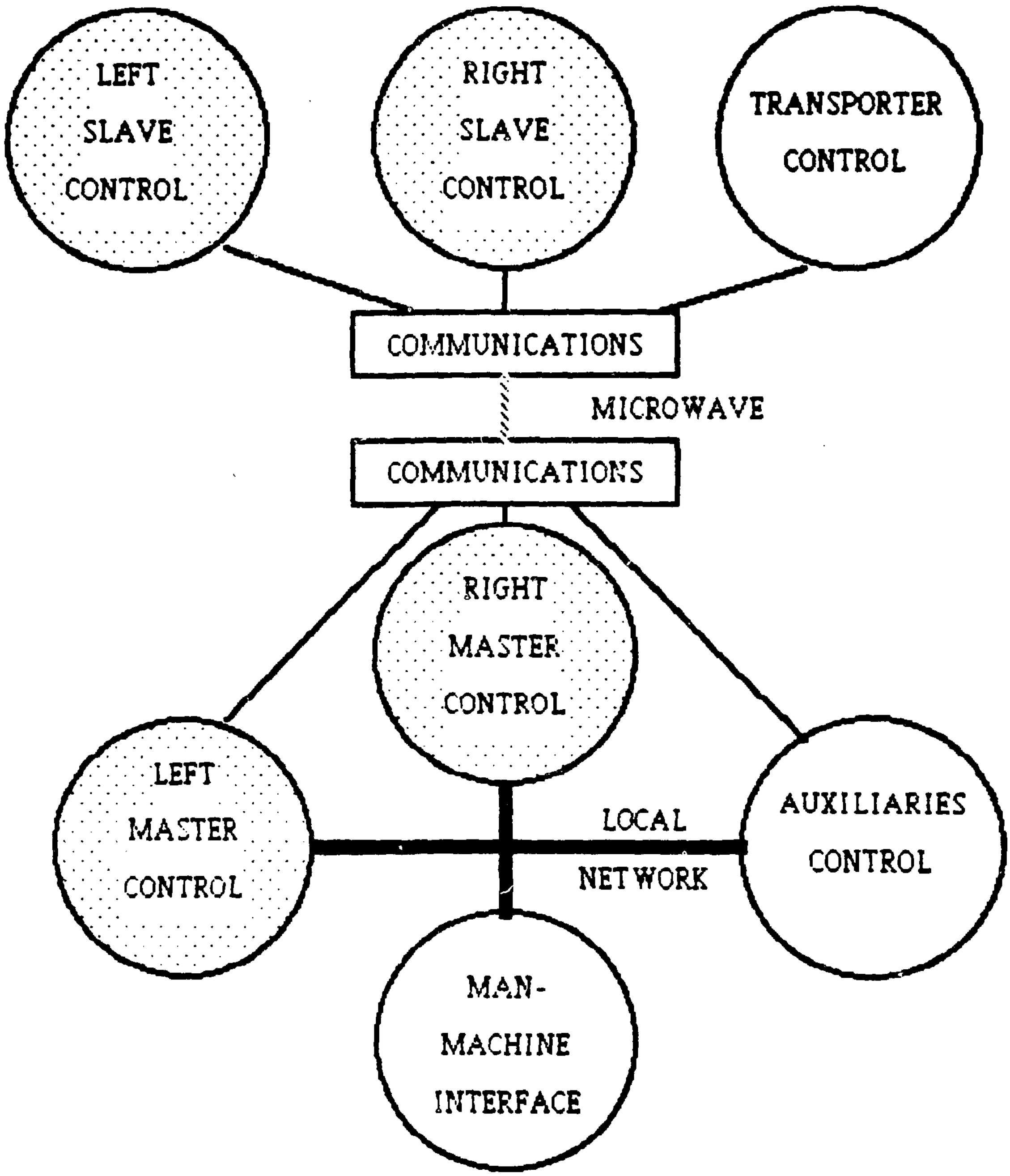

Fig. 13 AIMS control block diagram

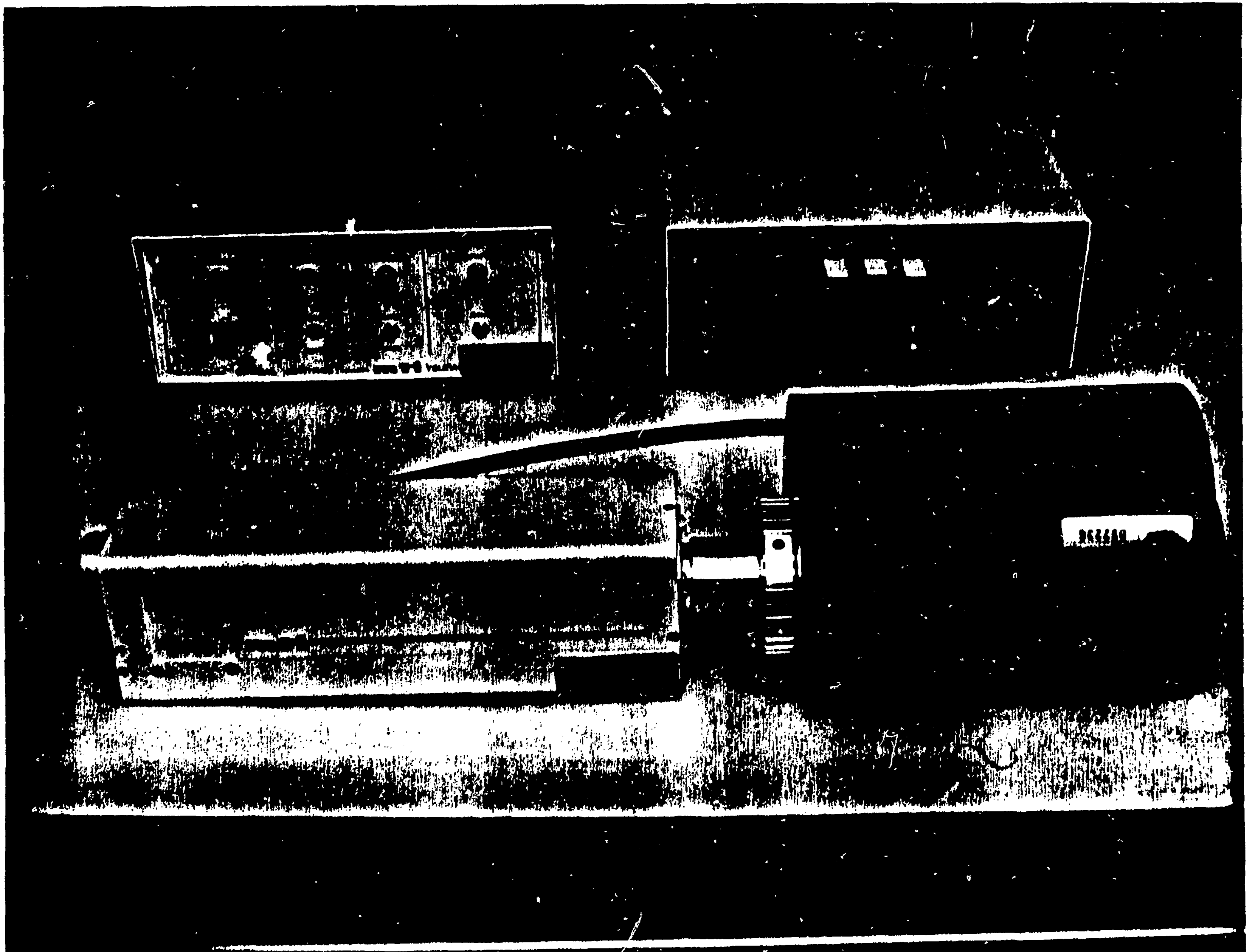

Fig. 14 MTI/Dage television camera with
Fujinon lens