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ADVANCED SERVOMANIPULATOR DEVELOPMENT

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INTRODUCTION

The Advanced Servomanipulator (ASM) System consists of three major components: the ASM slave, the dual arm master controller (DAMC) or master, and the control system. The ASM is a remotely maintainable force-reflecting servomanipulator developed at the Oak Ridge National Laboratory (ORNL) as part of the Consolidated Fuel Reprocessing Program. This new manipulator addresses requirements of advanced nuclear fuel reprocessing with emphasis on force reflection, remote maintainability, reliability, radiation tolerance, and corrosion resistance. The advanced servomanipulator is uniquely subdivided into remotely replaceable modules which will permit in situ manipulator repair by spare module replacement. Manipulator modularization and increased reliability are accomplished through a force transmission system that uses gears and torque tubes. Digital control algorithms and mechanical precision are used to offset the increased backlash, friction, and inertia resulting from the gear drives. This results in the first remotely maintainable force-reflecting servomanipulator in the world.

Slave Arms

The single most obvious difference in this two-arm, all-gear-driven system from traditional servomanipulators is the anthropomorphic or elbows-down stance. The ASM kinematic configuration consists of seven degrees of freedom. The upper three degrees of freedom (shoulder pitch, shoulder roll, and elbow pitch) provide wrist positioning in space. Three of the four wrist motions (wrist pitch, wrist yaw, and wrist roll) establish tong orientation. The fourth wrist motion, tong closure, supplies a grasping ability. This unique wrist design, with four degrees of freedom, provides very dexterous orientation of the tong by virtue of intersecting orthogonal axes and the pitch-yaw-roll kinematic sequence. Conventional master-slave manipulator wrist kinematics (e.g.,

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lower arm roll followed by wrist pitch and roll) could not be used in the elbows-down stance because the lower arm and end-effector axes of motion coincide at the normal operating position. When two joint axes align to form what is often called a singularity, they become redundant and difficult to control independently. The ASM lower arm does not rotate but has all the orientations occurring in the wrist body. In the ASM wrist, all the singularities occur at the extremities of the ranges of motion where they are of minimal concern.

The ASM slave arms have a 23-kg capacity, an end-effector maximum slew velocity of approximately 1.0 m/s, and sufficient dynamic response to follow an operator's normal range of input speed in real time. It is estimated that the ASM will have a force-reflection threshold on the order of 0.45 kg (2% capacity). For comparison, currently available servomanipulators have force-reflection thresholds ranging from 1 to 10% of capacity. Real-time servocontrol techniques will be used to eliminate mechanical counterbalancing weights and mechanisms. The ASM utilizes electronic counterbalancing by calculating weight vectors of the various arm links in real time based on joint position. The weight vector data are then transformed back to the motor-drive coordinate frame where they are treated as incremental additive torques necessary to offset the weight.

The ASM is designed to minimize remote handling system mean time to repair (MTTR) by using eight remotely replaceable module types. Modularity is possible because the gear-torque tube force-transmission concept allows separation of modules at gear or spline interfaces. The ASM concept is based on the philosophy that a manipulator failure can be isolated to a particular module malfunction. The failed module would then be replaced with a working spare in situ by another ASM. Through spare module replacement, the failed ASM system can be returned to operation quickly (relative to removing the entire arm to a decontamination/repair station). The failed module would then be transferred to a repair station for further evaluation. All the ASM modules are designed for remote replacement using fixtures and tooling necessary for synchronization of gear meshes and intermediate arm supports.

The fabrication and assembly of the ASM have been completed. Dimensional inspection was performed on all critical dimensions for study and determination of the actual precision achieved during machining. In general, the performance was within design expectations.

Initial testing has also been completed. All joints are operational and functioning properly. This testing has shown the actual backlash to be about three times greater than predicted by calculations. The initial force reflection was 1.8 to 2.3 kg, with 0.46 kg being predicted. This high level was from two major sources: brake drag and motor/input shaft misalignment. The brake drag could not be eliminated, so a new brake and coupling were designed and fabricated. After installing the new brakes, the brake friction was eliminated. With these changes, the force threshold was reduced to the original design goal of approximately 0.46 kg. Tests are still being conducted. Detailed backlash and friction measurements are being made to improve the prediction models. It is also hoped that some definite conclusions can be drawn on how to upgrade the performance. Thus far, the ASM has not been heavily loaded. The loads will be increased as the tests progress.

Master Arms

The DAMC is the out-of-cell half of the ASM teleoperator system. It is controlled primarily by inputs from the human operator with computer augmentation. The motions of the master are reproduced in the cell by the slave using bilateral position-position servoloops.

The development of the dual arm master controller was intended to optimize both the mechanical design and the human factors aspects. It was designed to minimize inertia, friction, and backlash to offset the large magnitude of these parameters in the slave. The kinematics, handle type, and joint cross coupling were designed to conform to human factors studies and enhance the man-machine interface.

A position-position control loop is currently employed in the ASM control system. This loop is very simple if the master is a kinematic replica of the slave, but becomes very complicated if a nonreplica master is chosen. With identical kinematics, the positions of the individual joints in both the master and in the slave are sensed and compared directly. If a position difference (error) exists, a command is derived from the control algorithm and is given to the master-slave pair to eliminate it. With nonreplica kinematics, the position difference must be derived since the individual joint positions cannot be compared directly. Such a derivation requires motor/joint transformations with significant calculations. Once the position differences are determined, a similar transformation procedure is necessary to obtain the command for each corresponding joint. Since the nonreplica kinematic arrangement offered little advantage over the replica arrangement and since the nonreplica option carried with it the need for increased software complexity, a kinematic replica master was chosen.

A pistol-type handle was chosen to control the tong, as was a new concept that employs a position sensor on the trigger. Traditionally the slave tong is controlled similarly to the other joints, with a bilateral force-reflecting drive train. With this method, the force-reflection threshold for the tong would be on the order of 1.0 kg. The new tong actuator incorporates a position sensor with a spring to give the operator an artificial sense of force reflection. The slave tong is driven by sensing the position of the tong actuator (trigger) and using this information to calculate a current command to the tong motor for force control. This "unilateral loop" can be easily implemented with the pistol-type handle which also provides a good location for the operator to reach the remaining control switches. A prototype of the chosen handle was built and the human factors thoroughly studied to design the final version for the master.

The motors used on the master are the same as those used for the slave. These motors have the highest continuous torque-to-friction-torque ratio of any available motor. This is their most important feature, since they will obtain the lowest static friction possible for the master.

A variety of techniques and hardware is available for transmitting forces from the centralized motors to their respective joints on the master arms. The most likely possibilities that were considered were metal tapes, cables, and polyurethane cable chains. Of these choices, commercial aircraft cables were chosen.

The master has a capacity of 6 kg, approximately one-fourth the capacity of the ASM slave. It has seven degrees of freedom and features the anthropomorphic (elbows down) stance to mimic the slave. The force-reflection threshold has been analytically determined to be about 1/4 kg. This has been verified on a one-degree-of-freedom test stand that simulates the wrist roll joint. Thorough testing of existing servomanipulators at ORNL has shown that the operator normally uses the arms with the hands approximately 38 cm apart. Since the master arms have to be separated 71 to 76 cm, this difference must be considered. It has been decided to mount the arms with the neutral position of the forearms canted in toward the operator about 15°. This provides superior motion range compared to rolling in the shoulder.

The DAMC master is being fabricated. To minimize the overall schedule, the master was divided into independent assemblies. The design and fabrication of these assemblies were then worked in parallel. This approach has some risks at the interfaces of the assemblies but is a good approach for a development item. At this time, the fabrication is complete and assembly is in progress.

Control System

The control system for the ASM is the most advanced of any existing teleoperator system. It is a major component to the success of providing good force reflection in a gear-driven servomanipulator.

The ASM has been operational in the laboratory for one year. During this time, many revelations concerning the control and operation of a gear-driven manipulator have occurred. Many techniques have been used to enhance system performance with varying success. Subtle mechanical details have been improved to allow total performance to meet expectations. Software and control techniques are being developed on what will ultimately be two slave arms. Because the slaves are mechanically optimized for remote maintenance with less emphasis on operator interaction, the total system performance will still be improved significantly when the master arms are installed.

Through special software compensation methods, the adverse effects (friction, inertia, cross-coupled torque) of the working slave arm have been eliminated. Only the master arm adverse effects remain. Of the many control methods implemented, electronic counterbalancing, sensor filtering, inertia decoupling, and direct friction compensation have proven to be successful. Adaptive control based on load variations, acceleration feedback, and large gains on velocity damping feedback have not shown any merit at this time. The system characteristics which directly affect the success of these methods include the amount of backlash, loop closure rate, sensor-signal-to-noise ratio, and large differences between motor inertia and drive-train inertia.

A significant portion of recent efforts has been to expand the control hardware and software into a system that can control all the Advanced Integrated Maintenance System (AIMS). The use of similar hardware and software with communications networks that can link all subsystems together will result in a truly large-scale integrated control network. In addition to the manipulator system, controls and displays for the transporter, interface package, facility cameras, and cranes must be provided. These systems are linked through the operator control system which allows two operators to control any of these subsystems and monitor the status of any activities.

By using flexible digital control and the FORTH language, an expandable system has been developed to meet present and future needs for the Fuel Recycle Division. By replication of similar parts, the cost of radiation hardening of the control equipment has been significantly reduced.

In the year ahead, the fabrication, installation, and debugging of these control subsystems will take place in the Maintenance Systems Test Area of Building 7603 at ORNL.

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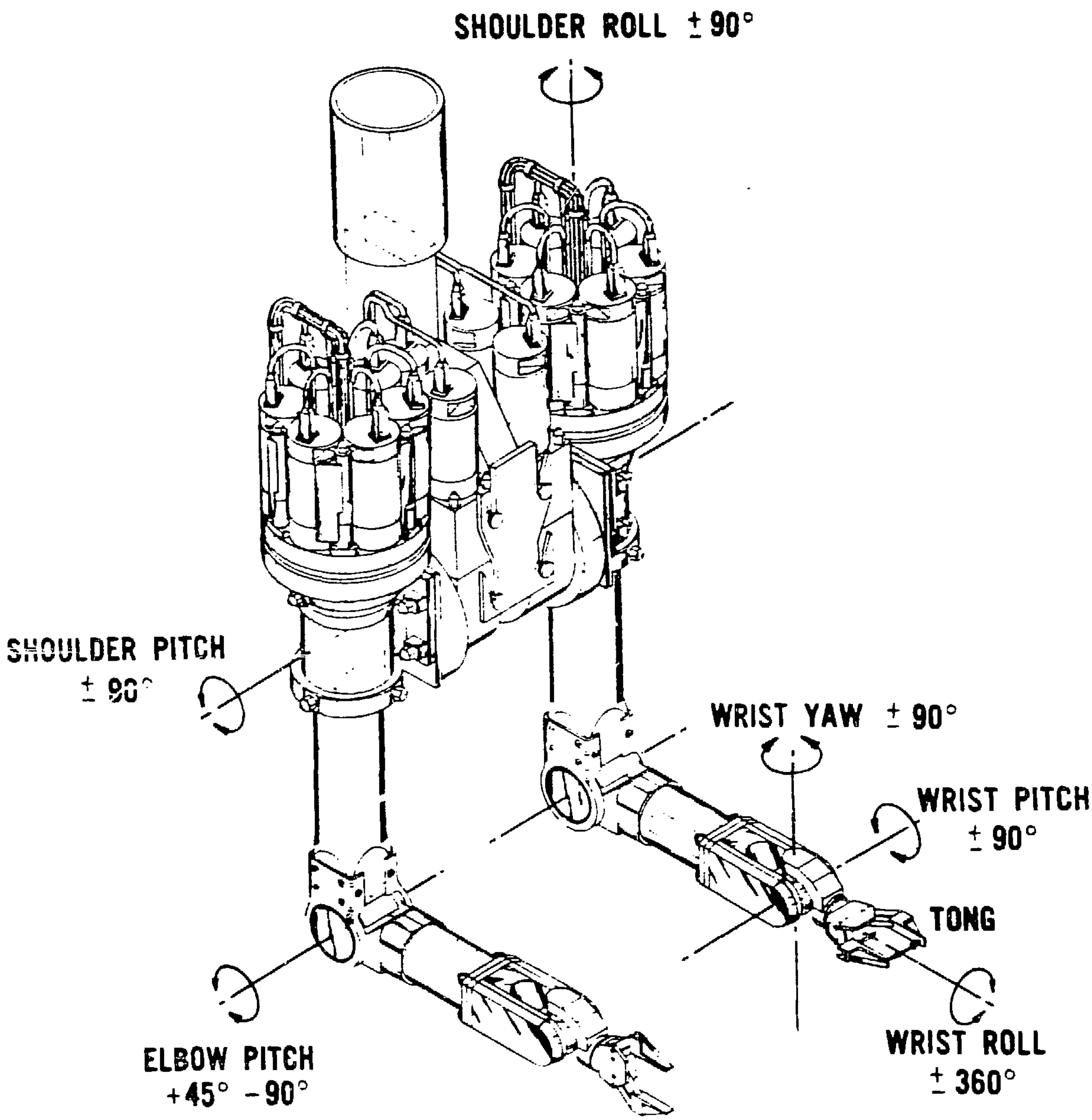
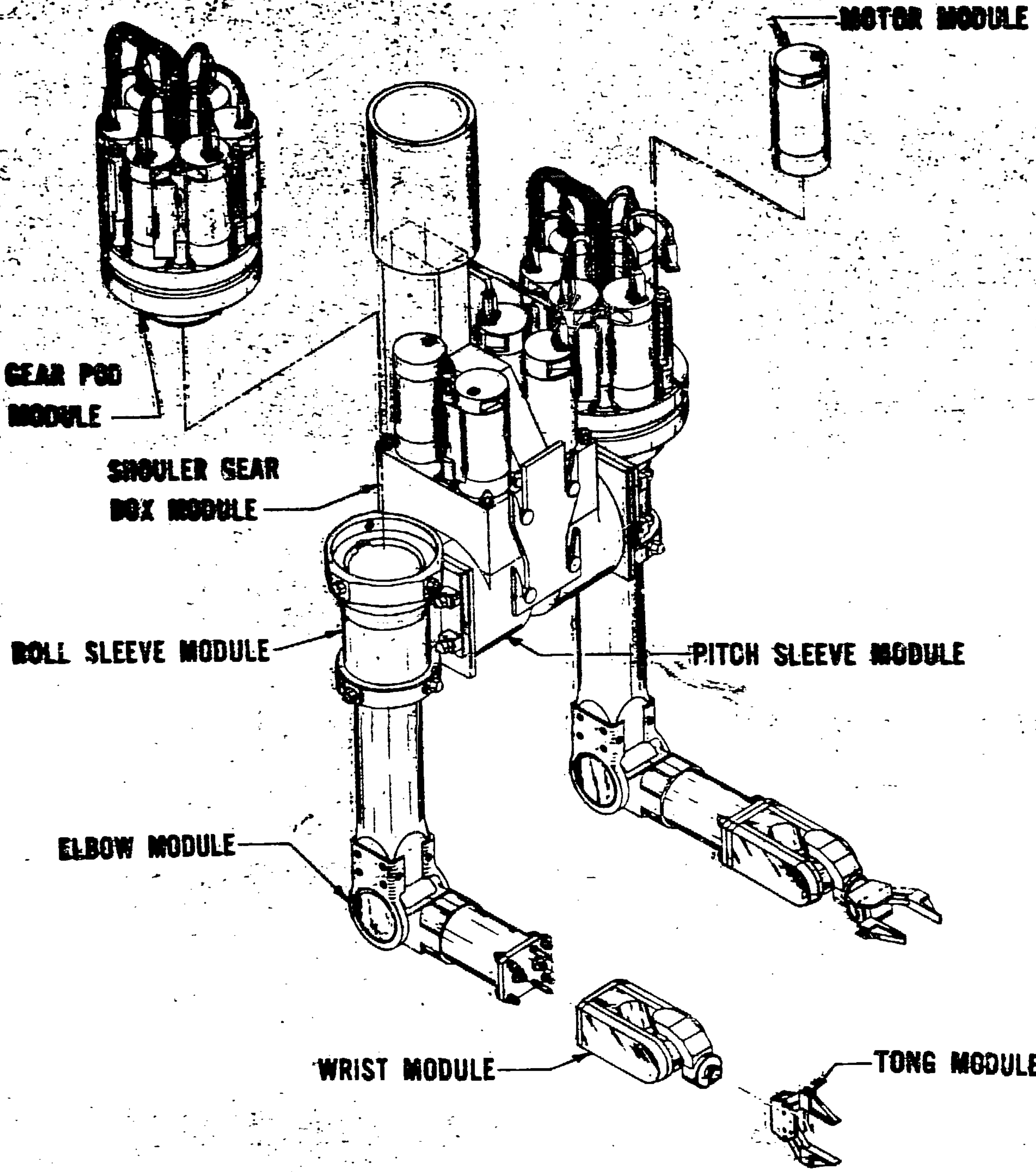
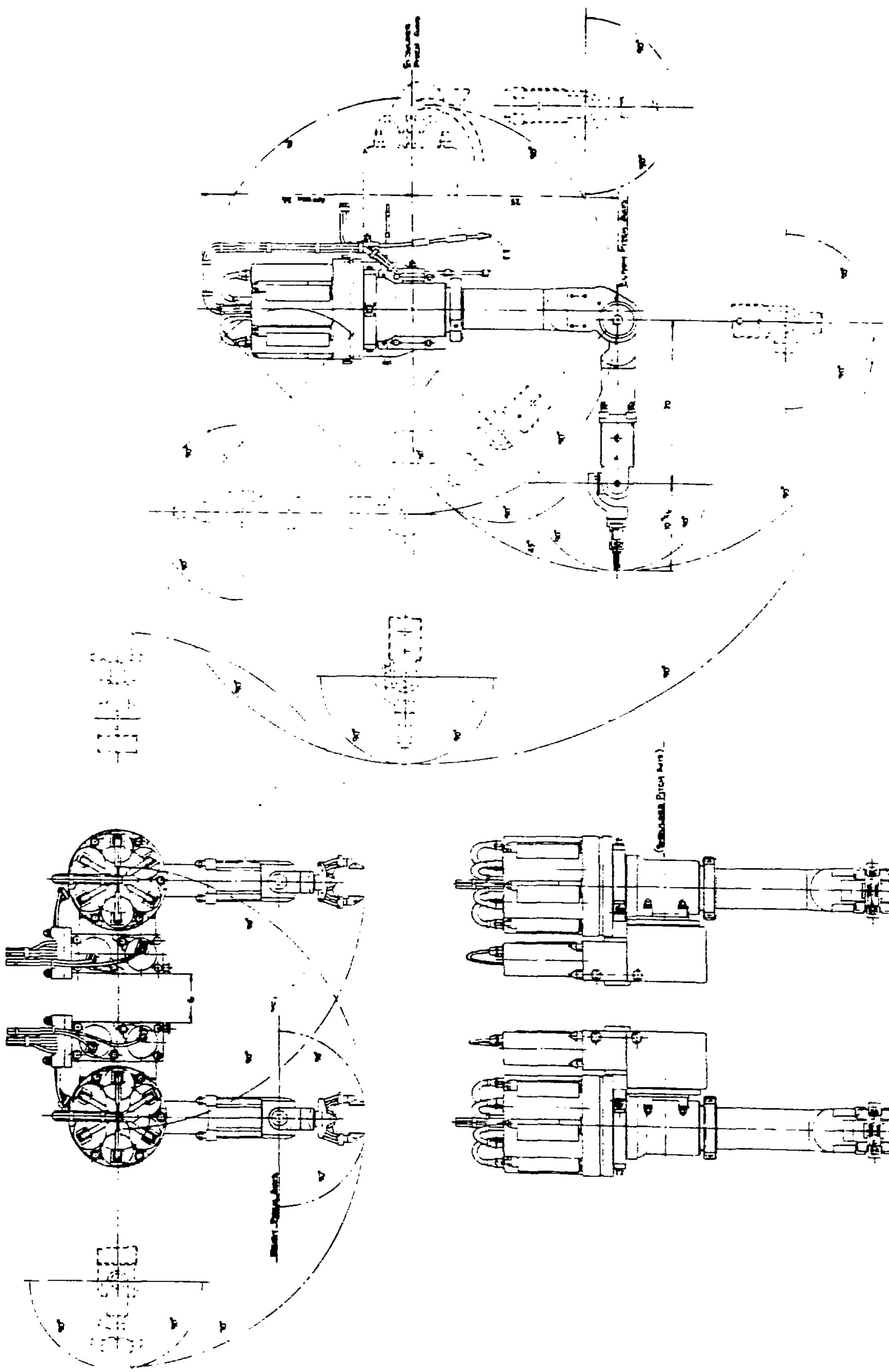
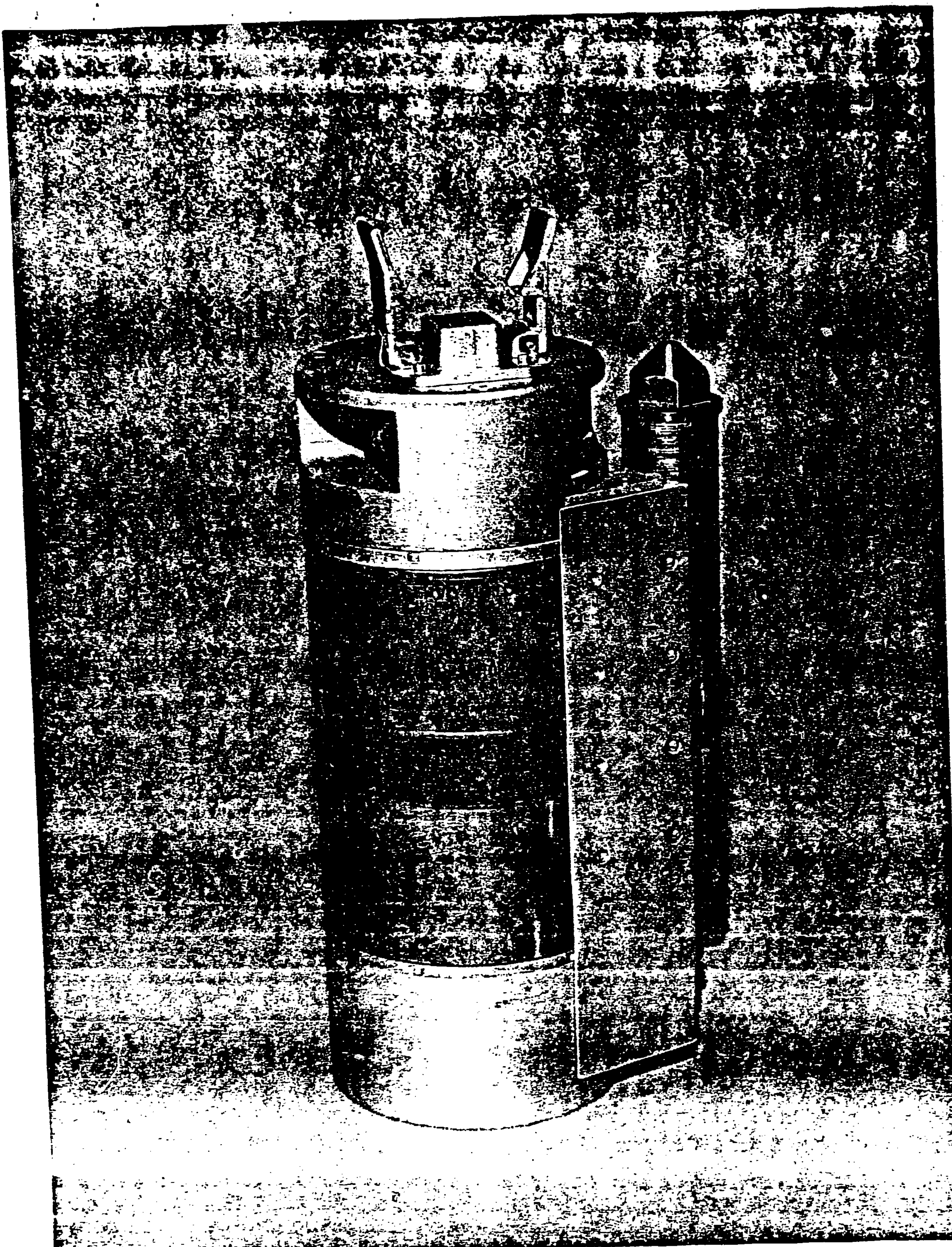
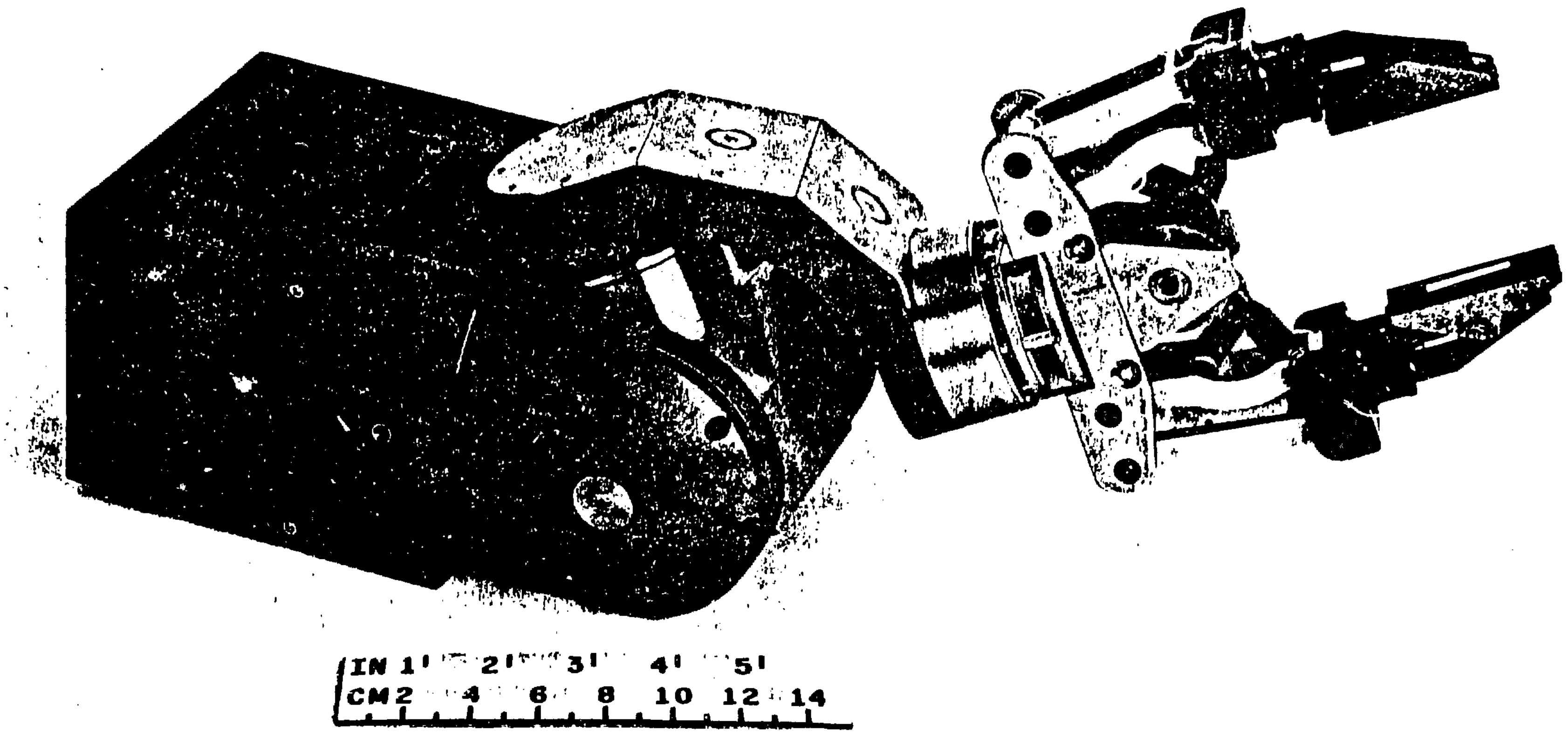



MOTOR MODULE
GEAR POD MODULE
SHOULER GEAR BOX MODULE
ROLL SLEEVE MODULE
PITCH SLEEVE MODULE
ELBOW MODULE
WRIST MODULE
TONG MODULE



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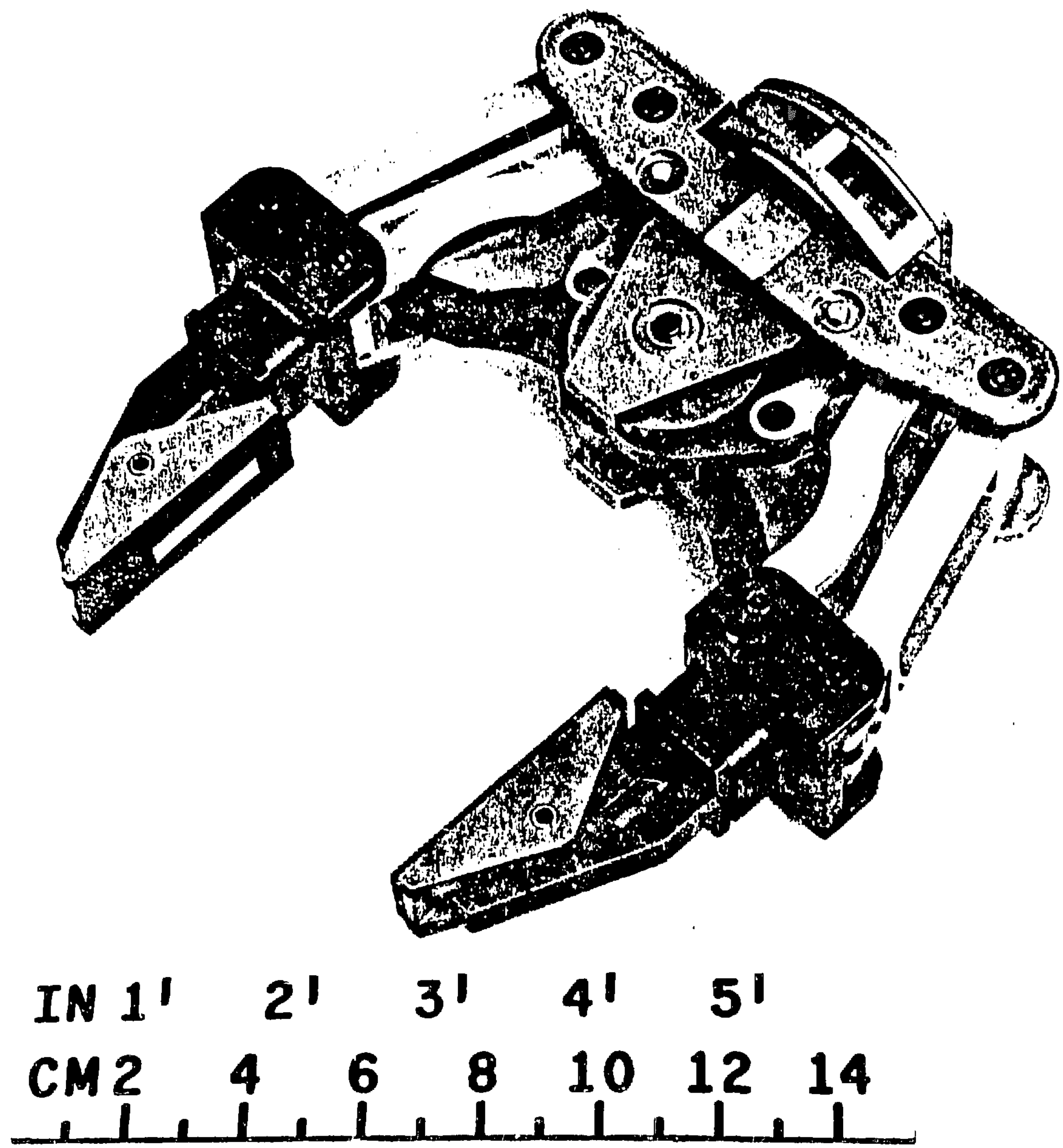
CM 2 4 6 8 10 12 14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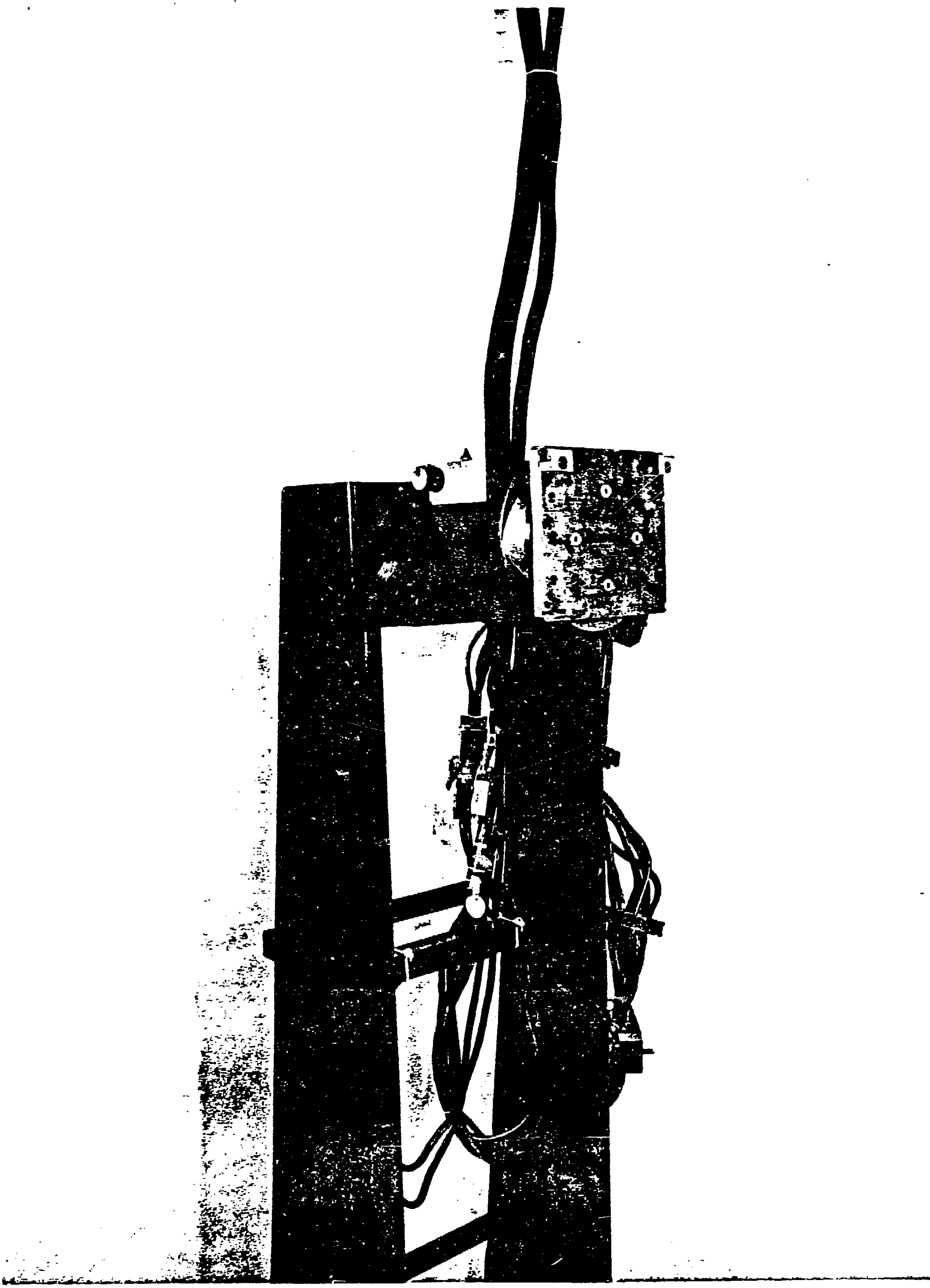
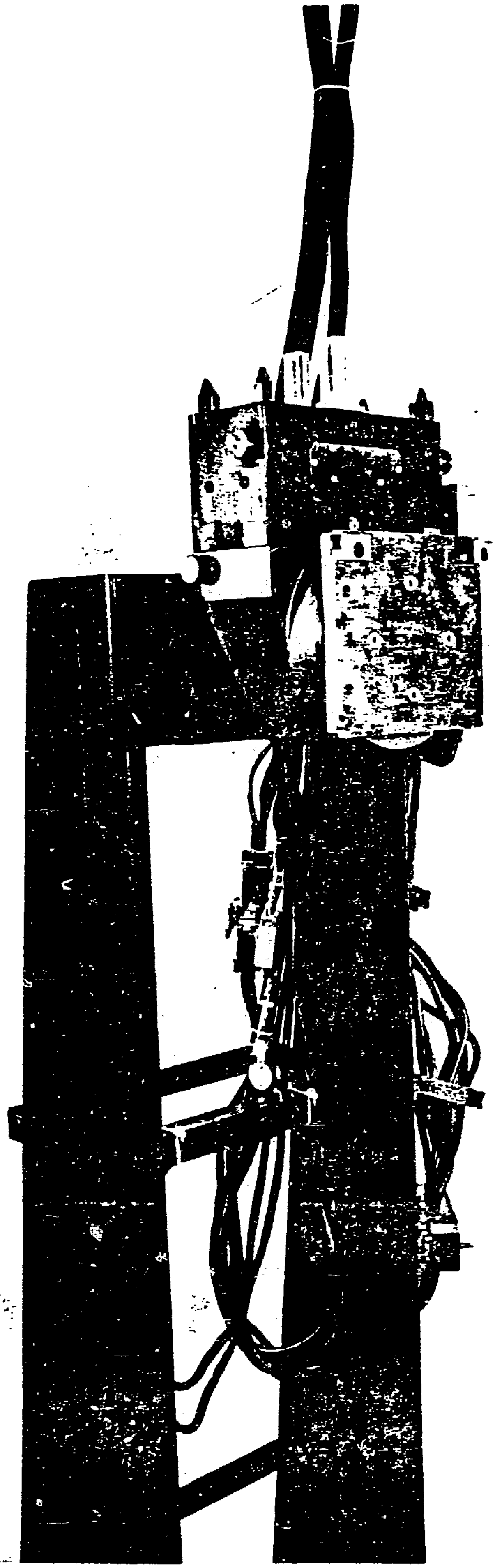
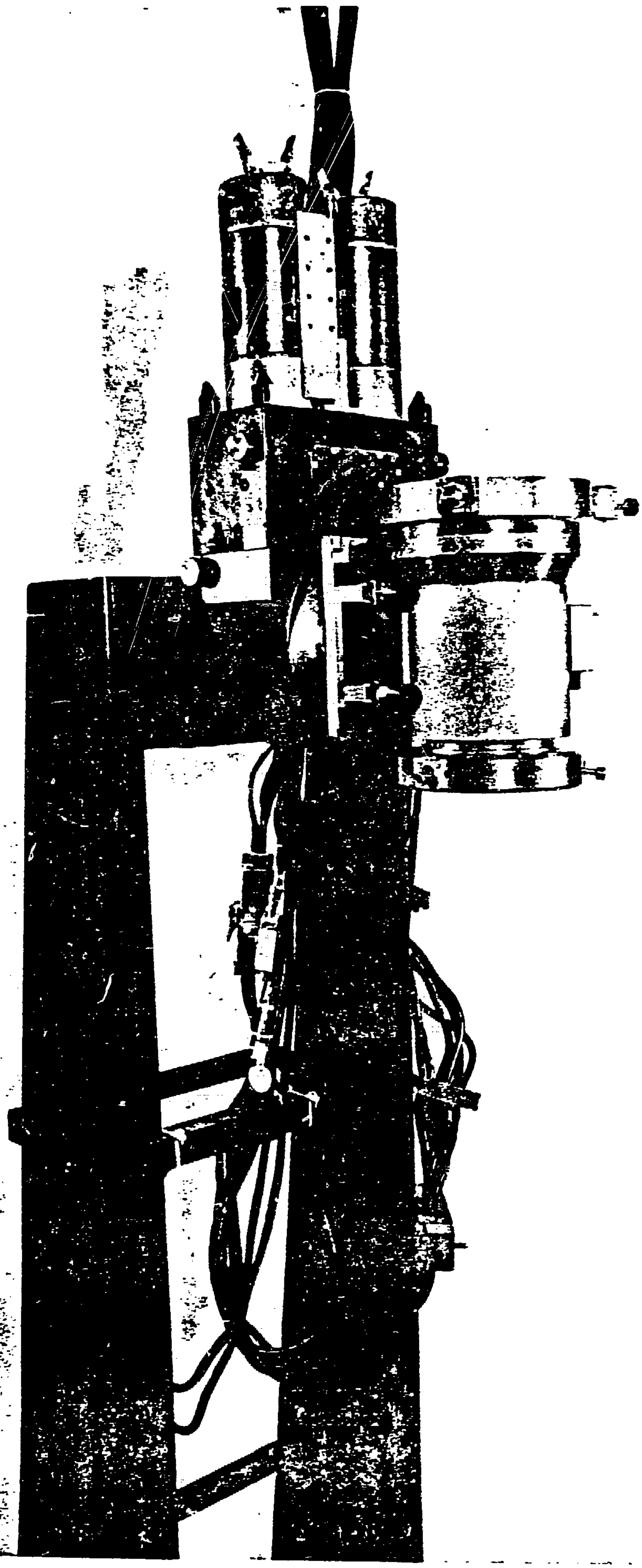
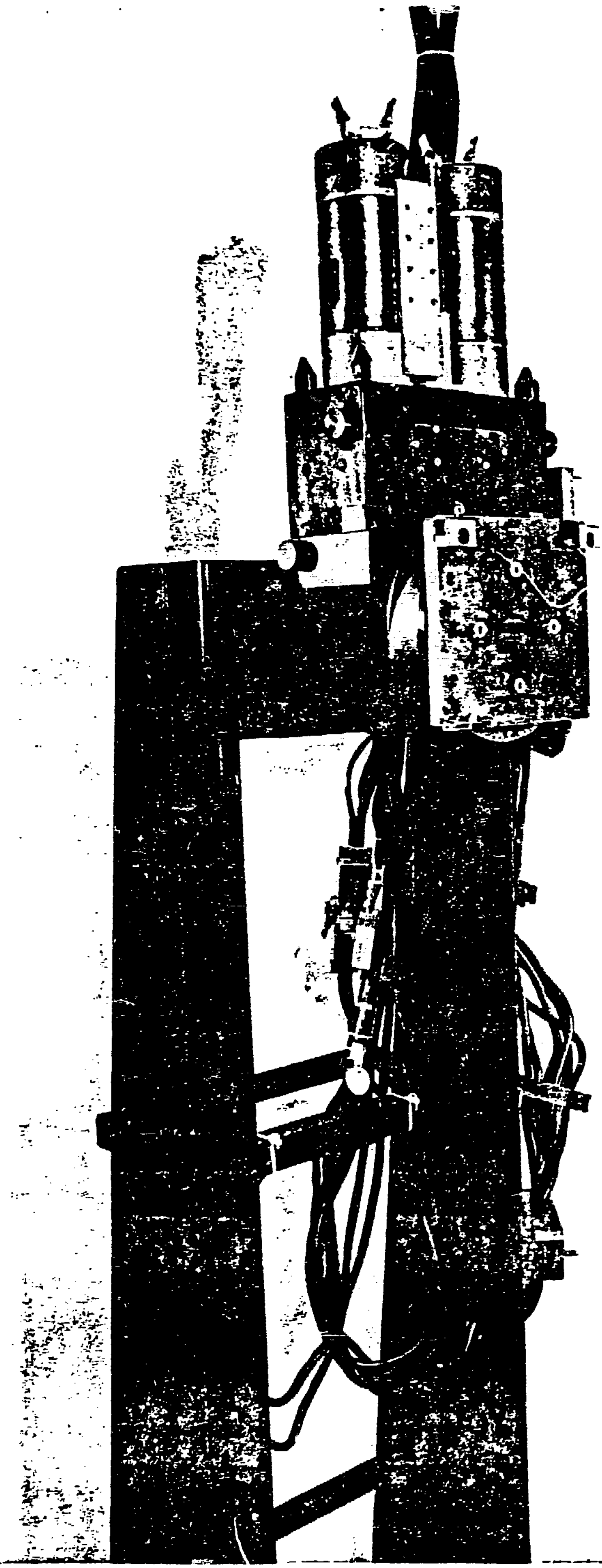
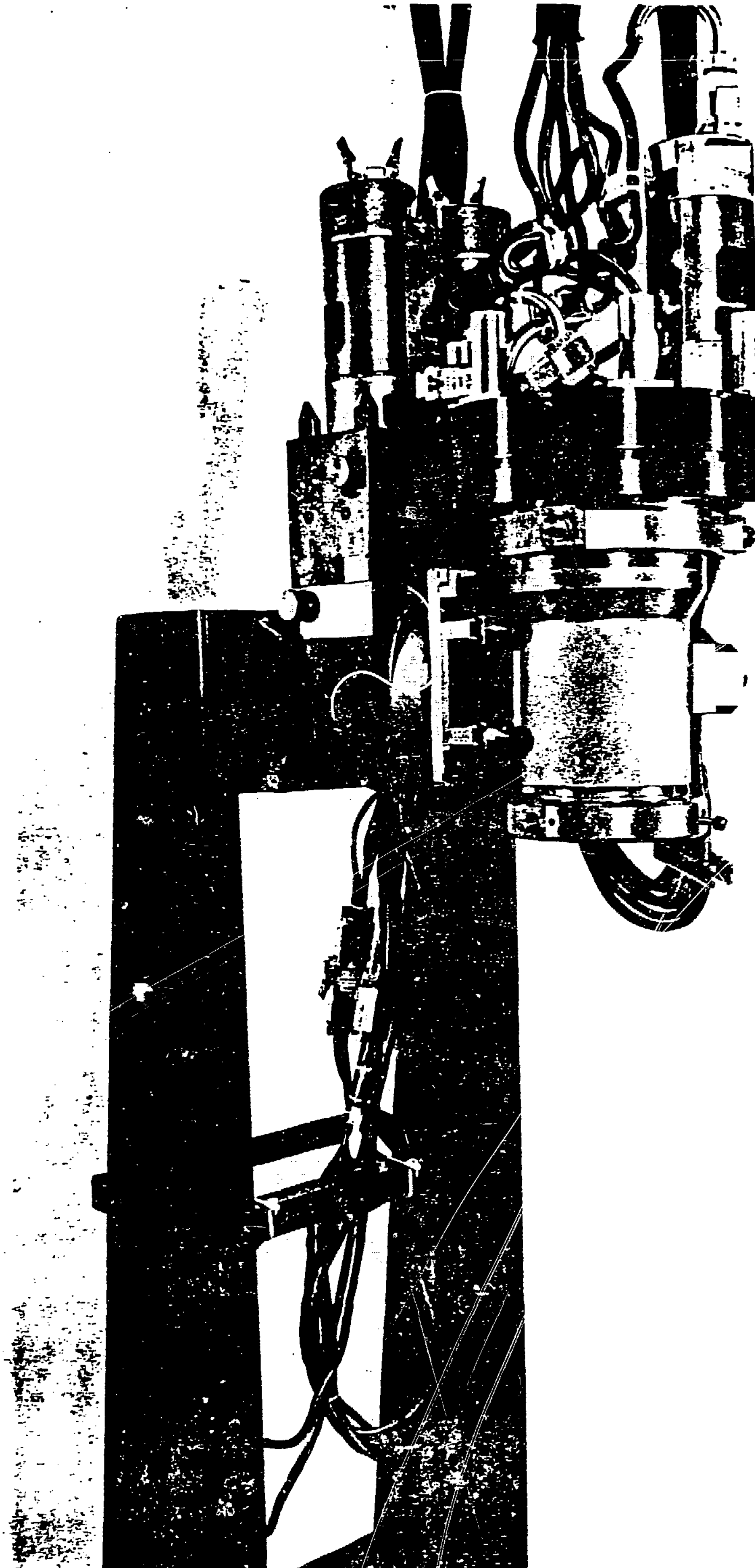
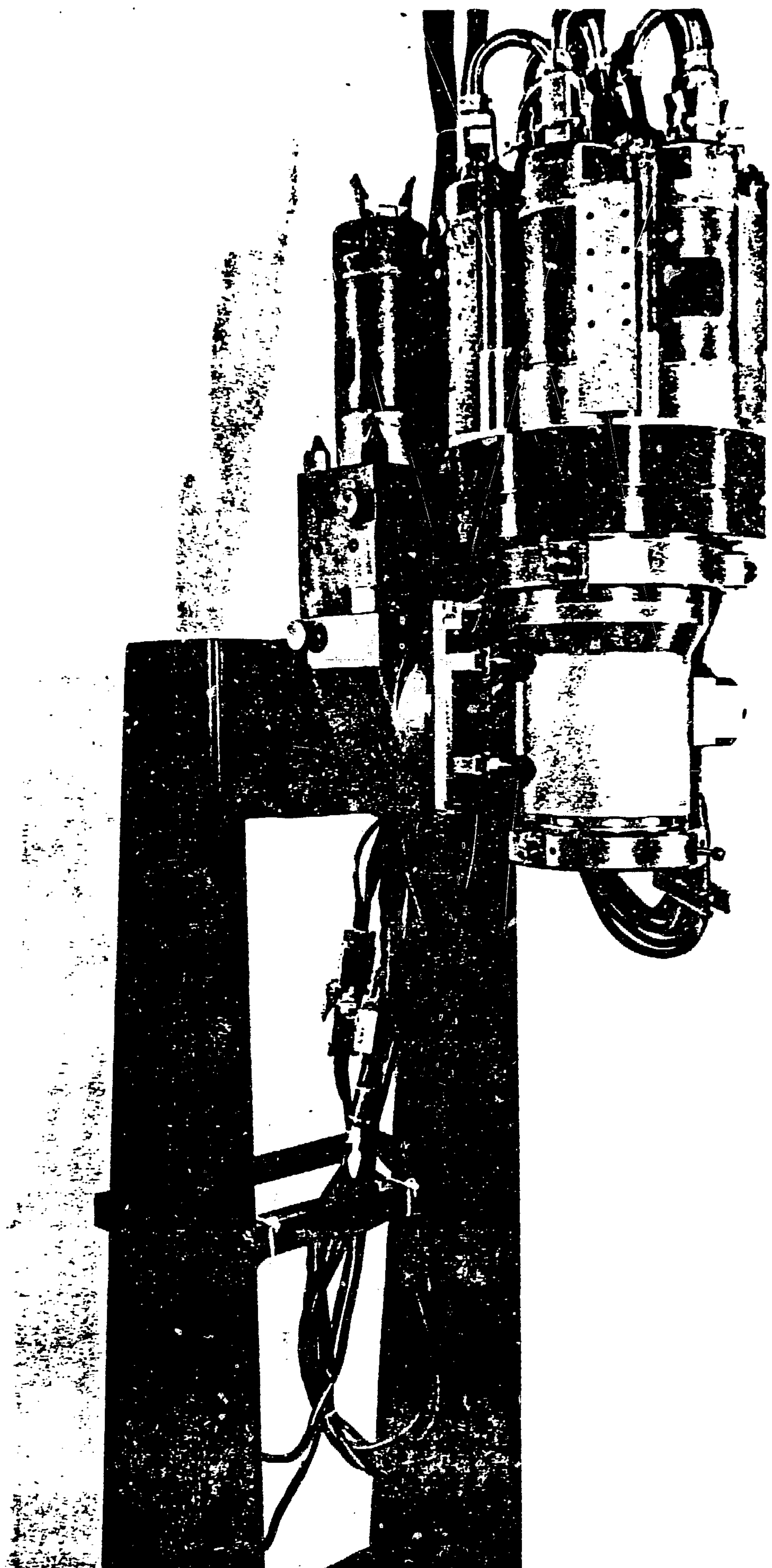


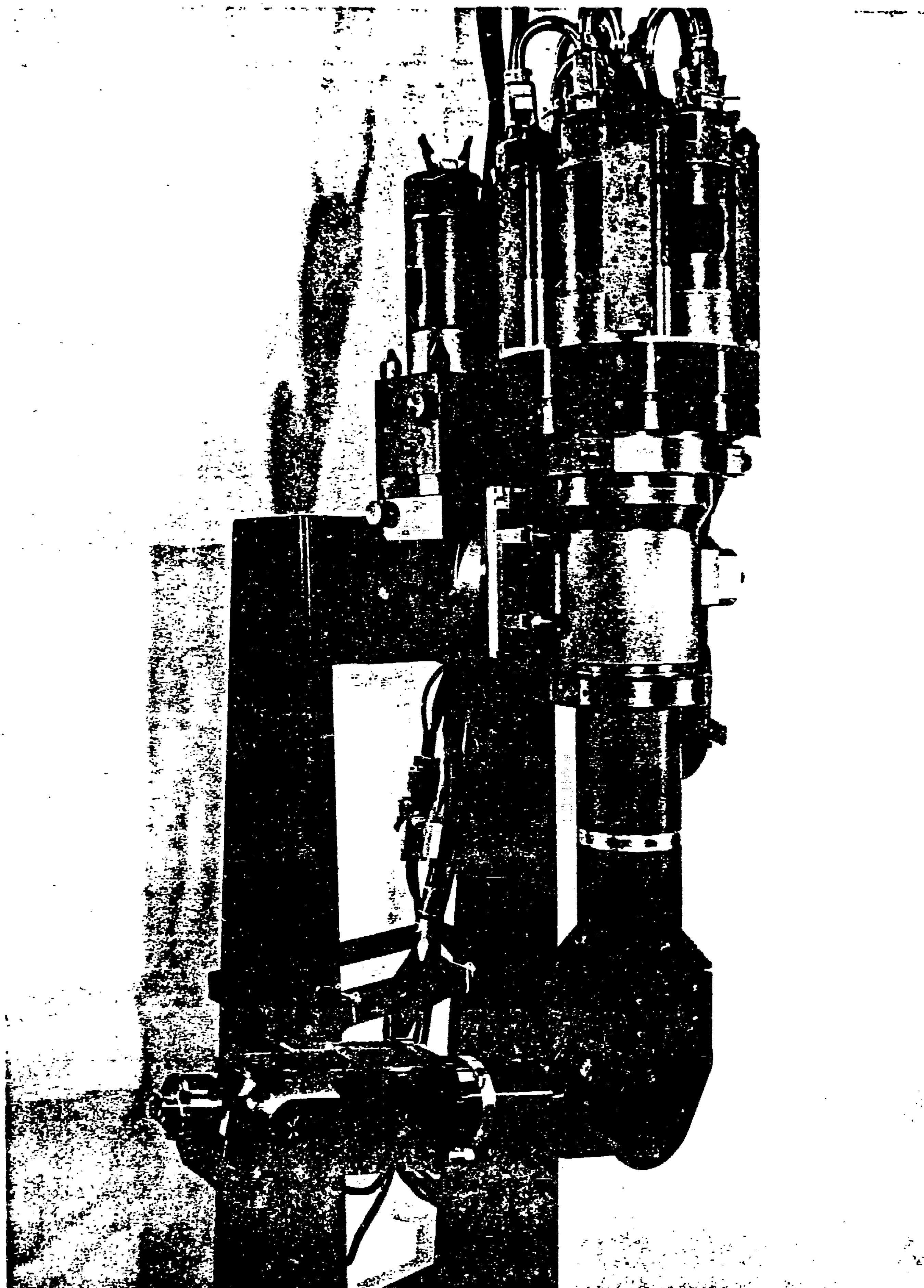


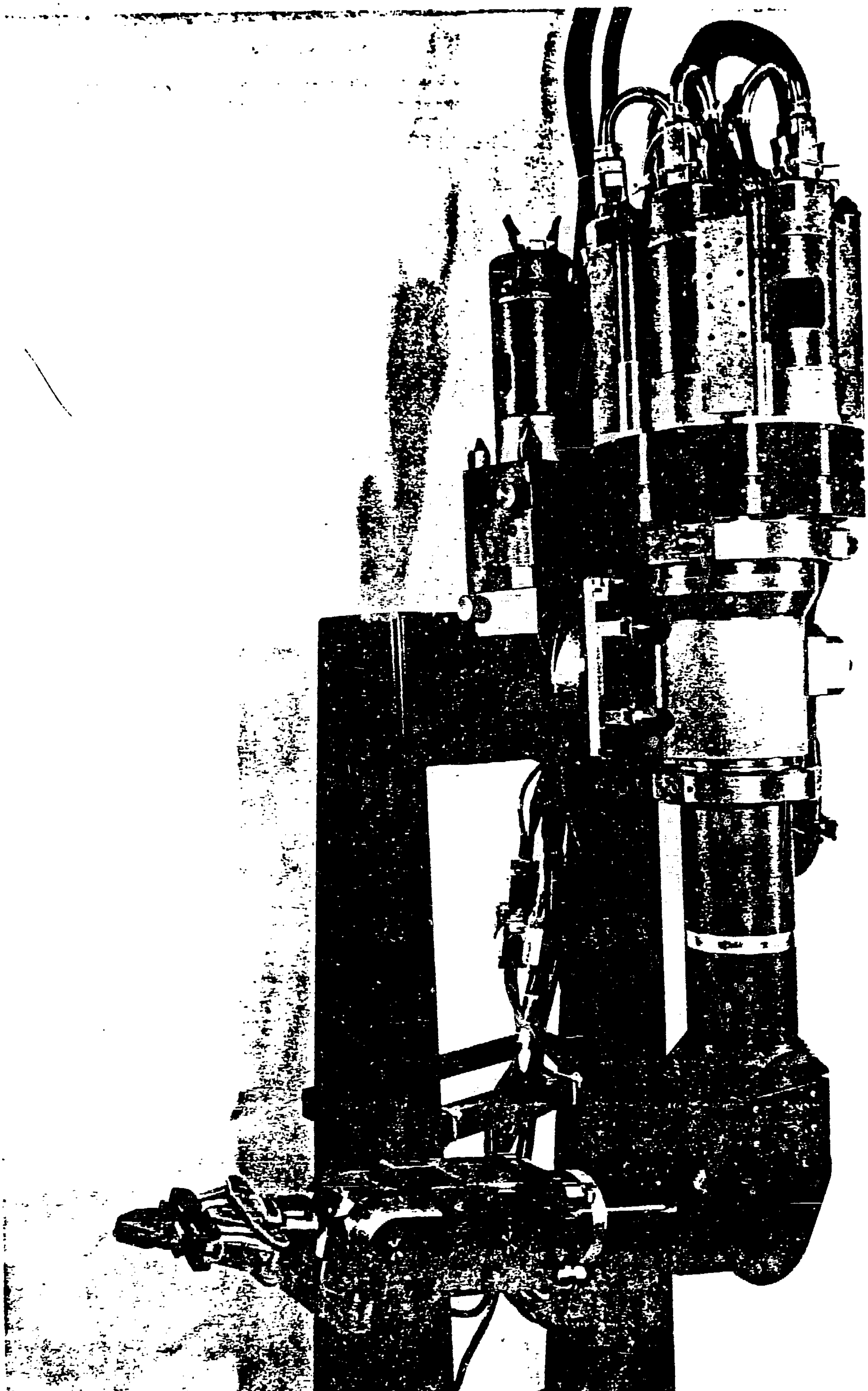


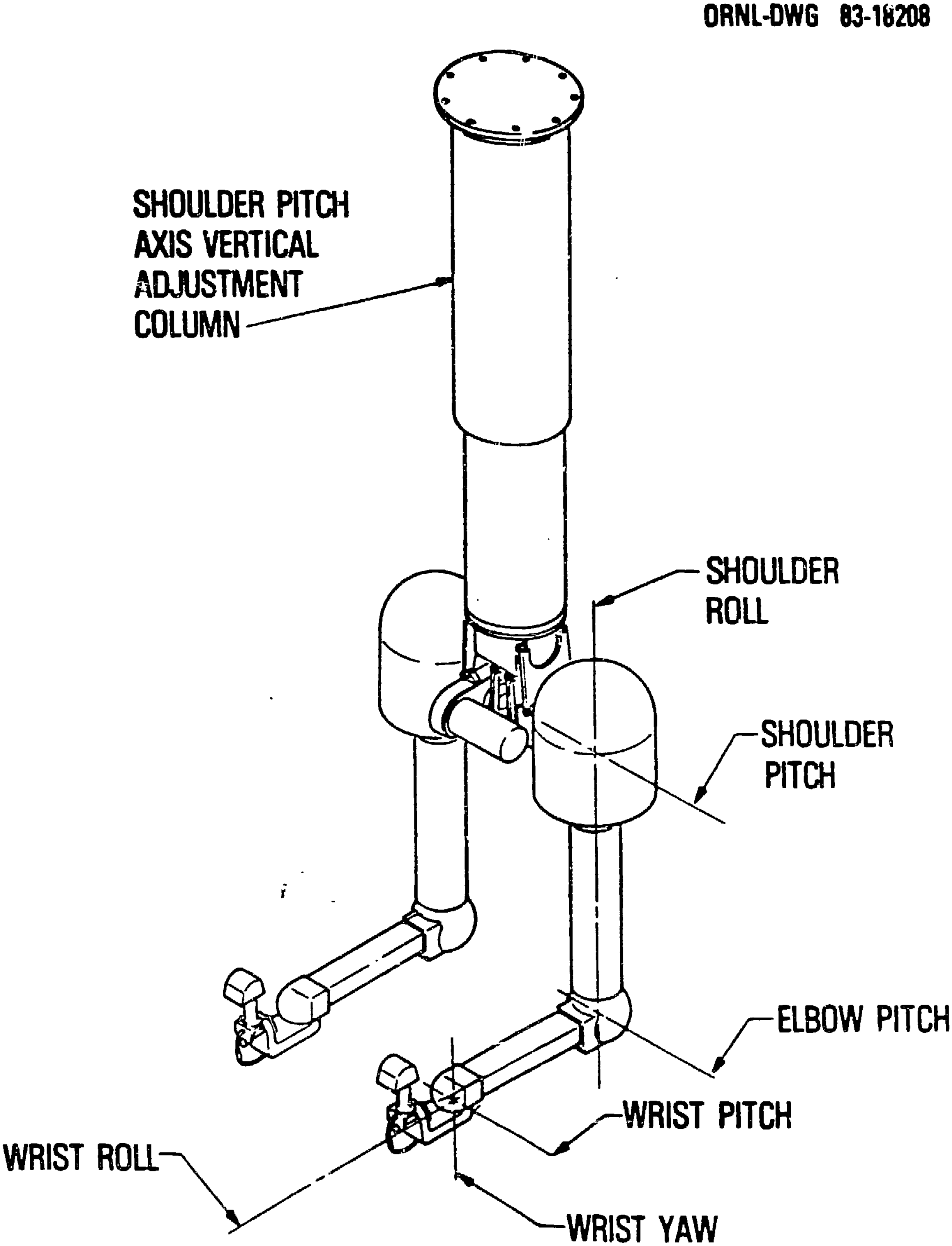











ORNL-DWG 83-18208
SHOULDER PITCH
AXIS VERTICAL
ADJUSTMENT
COLUMN
SHOULDER
ROLL
SHOULDER
PITCH
ELBOW PITCH
WRIST PITCH
WRIST ROLL
WRIST YAW

- THE ASM WAS DEVELOPED TO ANSWER THE NEED FOR A NEW MANIPULATOR WHICH PROMISED A LARGER MEAN TIME BETWEEN FAILURE AND A MUCH LOWER MEAN TIME TO REPAIR.

- THIS WAS ACHIEVED WITH GEAR/TORQUE TUBE FORCE TRANSMISSION AND MODULAR CONSTRUCTION

- ALTHOUGH THIS WAS A GIANT STEP FORWARD FOR SERVOMANIPULATORS, THE SOLUTION BROUGHT WITH IT SOME DISADVANTAGES

  - INCREASED FRICTION

  - INCREASED BACKLASH

  - INCREASED INERTIA

- o THE RESULTS OF SEVERAL STUDIES INDICATED THAT AN IMPROVED MAN/MACHINE INTERFACE WAS ALSO REQURIED TO ENHANCE THE OPERATOR'S PERFORMANCE

- o THEREFORE, THE DUAL ARM MASTER CONTROLLER HAS TWO MAJOR OBJECTIVES TO YIELD A M/S SYSTEM THAT IS BEST SUITED FOR USE WITH THE ASM

    - LOW FRICTION, BACKLASH, AND INERTIA

    - IMPROVED OPERATOR INTERFACE

MASTER ARM PERFORMANCE REQUIREMENTS

- ANTHROPOMORPHIC
- SEVEN D.O.F.
- 12 1/2 LB CAPACITY (1/4 ASM)
- FORCE REFLECTION THRESHOLD 1/2 LB
- WEIGHT 100 LB
- MECHANICAL COUNTERBALANCE
- MOTION RANGE

  SHOULDER: ±45° PITCH, ±45° ROLL

  ELBOW: +45°, -55°, PITCH

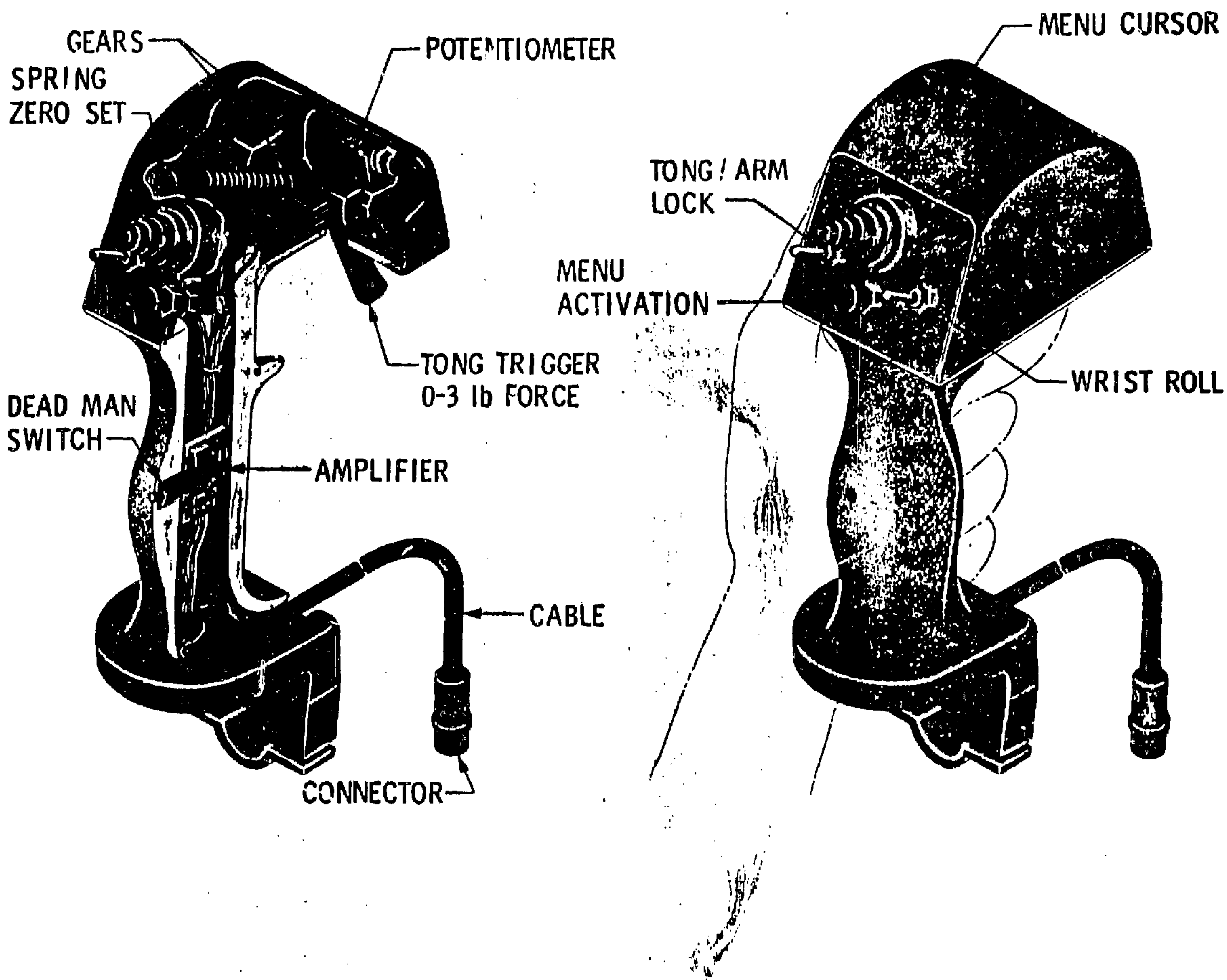
  WRIST: ±50° PITCH, ±90° YAW, ±180° ROLL

  TRIGGER MOTION: 1 INCH

THE CABLE FORCE TRANSMISSION METHOD WAS CHOSEN TO GIVE THE BEST PERFORMANCE FOR THE MONEY INVESTED

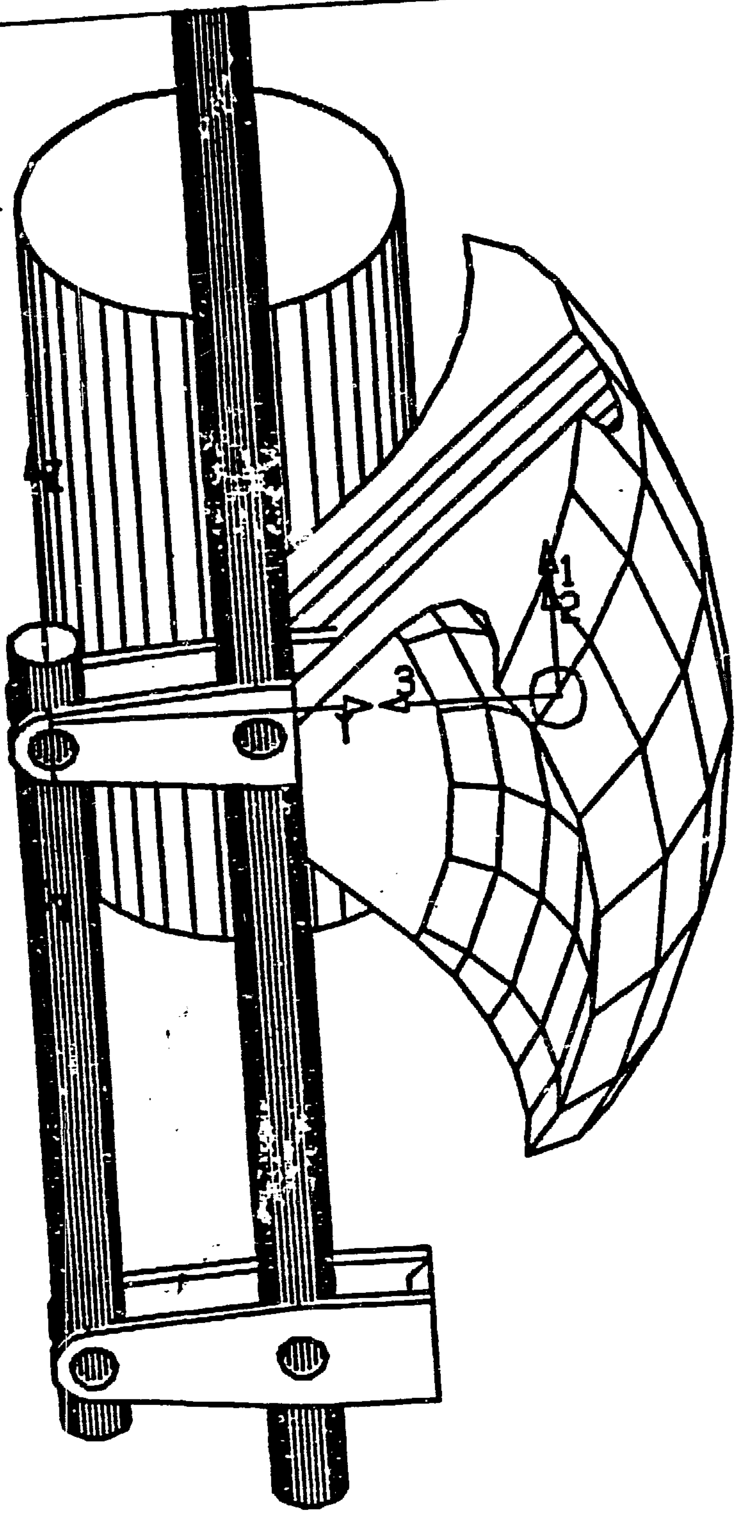
- LOW FRICTION
- LOW INERTIA
- LOW BACKLASH
- HIGH STIFFNESS
- LOW COST
- HIGH RELIABILITY

AMBIDEXTROUS MASTER HANDLE



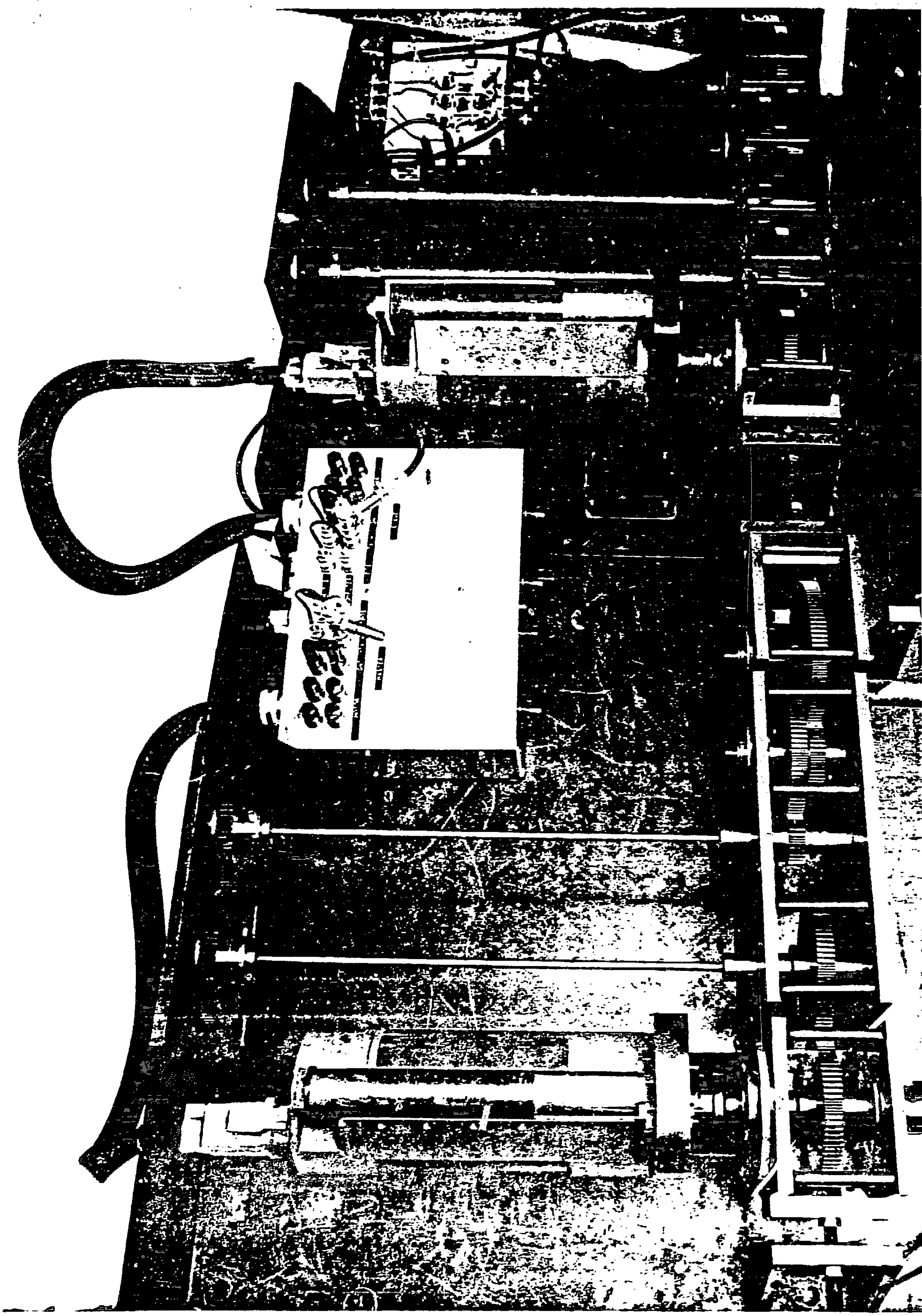
COMPUTER AIDED DESIGN
HAS BEEN VERY BENEFICIAL

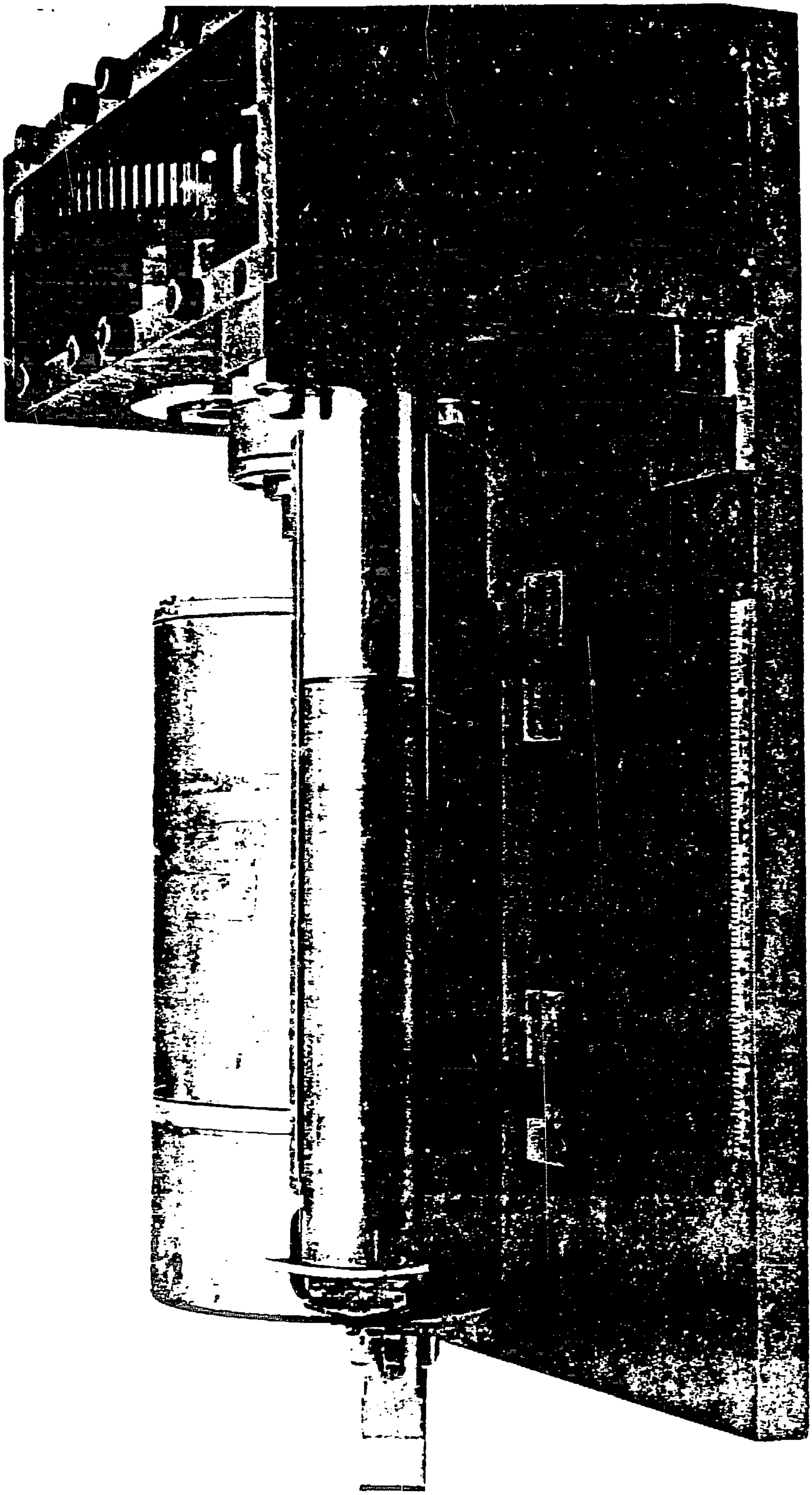
- o COUNTERWEIGHT
- o MOTION RANGE DIAGRAM
- o FABRICATION DRAWINGS
- o ANALYSIS

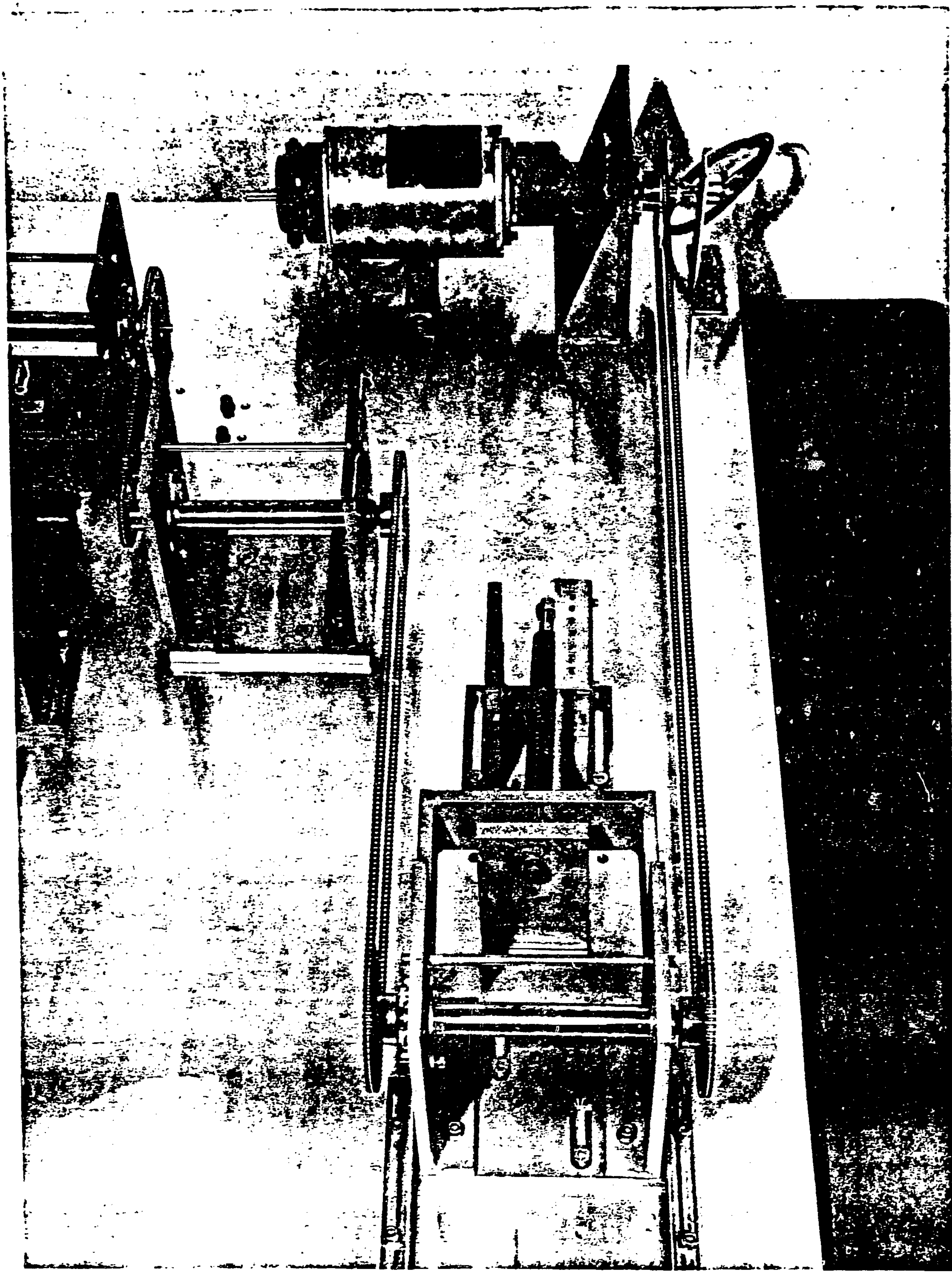


TESTING HAS BEEN COMPLETED ON ONE-DEGREE-OF-FREEDOM TEST STANDS

- TWO GEAR-DRIVEN STANDS, ONE STD, ONE PRECISION
- ONE CABLE-DRIVEN STAND
- ONE CABLE CHAIN-DRIVEN STAND
- ALL STANDS SIMULATE WRIST ROLL AXIS
- COMPENSATION ALGORITHMS IMPLEMENTED
- ANALYTICAL RESULTS VERIFIED







ADVANCED HARDWARE AND UNIQUE SOFTWARE UNITE TO PROVIDE AIMS CONTROL

frd

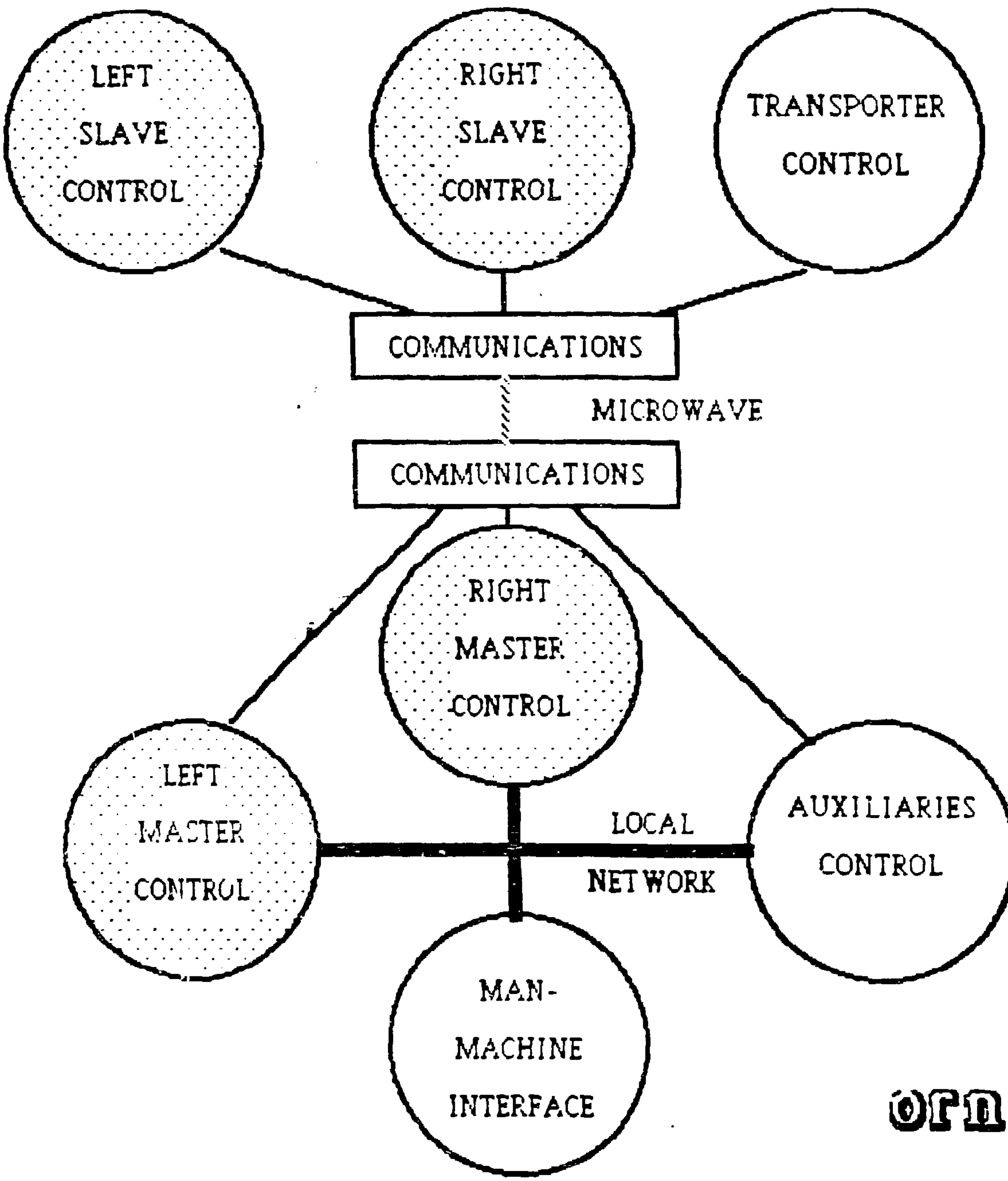
- CONTROL DISTRIBUTION SUBDIVIDES A COMPLEX SYSTEM INTO MANAGEABLE MODULES

- THE ADVANCED SERVOMANIPULATOR (ASM) PROVIDES SIGNIFICANT CONTROL CHALLENGES
  - REMOTELY MAINTAINABLE CONSTRUCTION EFFECTS CONTROL REQUIREMENTS

- UNIQUE COMPENSATIONS ENHANCE ASM PERFORMANCE
  - POSSIBLE WITH DIGITAL CONTROLS

COORDINATED INDEPENDANT CONTROL MODULES PARTITION AIMS INTO MANAGEABLE SUBSYSTEMS

frd



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"BUILDING BLOCK" APPROACH STREAMLINES SYSTEM INTEGRATION

frd

- COMMERCIALLY AVAILABLE BACKPLANE USED
  - EXPANDABLE/FLEXIBLE

- SINGLE-BOARD COMPUTER PERFORMS CONTROL CALCULATIONS
  - MOTOROLA 68000

- BOTH DIRECT HIGH-SPEED LINK AND LOCAL AREA NETWORK PROVIDED BY A SINGLE DEVICE

- I/O AND SPECIAL DEVICES CHOSEN TO MEET INDIVIDUAL SUBSYSTEM REQUIREMENTS

DETAILED CONTROL EFFORTS HAVE FOCUSED ON ADVANCED SERVOMANIPULATOR

frd

- REMOTE MAINTENANCE OF REMOTE MAINTENANCE SYSTEM HAS INFLUENCED MANY DESIGN DECISIONS
  - RELIABILITY EMPHASIZED
  - MAINTAINABILITY STRESSED

- CONTROLS HAVE BEEN CHALLENGED TO PRODUCE A HIGH-PERFORMANCE SYSTEM
  - SPECIAL COMPENSATIONS ADDRESS MECHANICAL CONSTRAINTS
  - NEW TECHNIQUES ENHANCE PERFORMANCE

REMOTE MAINTENANCE DESIGN AFFECTS CONTROL IMPLEMENTATION

frd

- REMOTE MODULARITY
  - ADDS WEIGHT
  - ADDS INERTIA
- RELIABLE GEAR DRIVES
  - ADD BACKLASH
  - ADD FRICTION
- PRECISION BACKDRIVABLE GEARING FOR FORCE REFLECTION
  - PASSES CROSS-COUPLING TORQUES BETWEEN DRIVES

ornl

SINGLE-AXIS TEST STAND ALLOWED FUNDAMENTAL DEVELOPMENT BEFORE ASM WAS AVAILABLE

frd

- CONTROL SOFTWARE DEVELOPMENT
  - SOFTWARE/HARDWARE FILTERS
  - ELECTRONIC COUNTERBALANCING
  - FRICTION MASKING
  - INERTIA DECOUPLING
- MOTOR TESTING
- ENCODER TESTING
- GEAR/BRAKE ANALYSIS

ELECTRONIC COUNTERBALANCING LOCKS BACKLASH AND REDUCES SLAVE WEIGHT, INERTIA, AND ENVELOPE

frd

- REQUIRED OFFSET TORQUES CALCULATED EVERY 0.01 SECOND
- IMPLEMENTED IN INTEGER ARITHMETIC
- ALSO ACCOUNTS FOR JOINT CROSS-COUPLING TORQUES DUE TO GEARING INTERACTION

BUILT-IN DATA LOGGING CAPABILITIES AID UNDERSTANDING OF ASM SYSTEM OPERATION

frd

- SOFTWARE EXTENSION OF EXISTING SYSTEM
- EXTREMELY USEFUL IN DEBUGGING
- OBSERVE DATA AT RATE COMPUTER USES IT
- SEE "NOISE" EFFECTS DIRECTLY

ADVANCED HARDWARE AND SOFTWARE COMBINE TO ENHANCE ASM AND AIMS PERFORMANCE

frd

- "BUILDING BLOCK" CONTROL MODULES:
  - REDUCE SYSTEM INTEGRATION PROBLEMS
  - ALLOW FUTURE EXPANSION

- SIGNIFICANT COMPUTATIONAL POWER AND UNIQUE COMPENSATION TECHNIQUES:
  - REDUCE ASM WEIGHT AND INERTIA
  - REDUCE PERCEIVED FRICTION AND INERTIA
  - REDUCE OPERATORS' BURDEN PHYSICALLY AND MENTALLY

- MUCH HAS BEEN LEARNED THAT CAN BE APPLIED TO FUTURE SYSTEMS

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