N85-33526

Consolidated Fuel Reprocessing Program

DUAL ARM MASTER CONTROLLER DEVELOPMENT*

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ABSTRACT

The advanced servomanipulator (ASM) salve was designed with an anthropomorphic stance gear/torque tube power drives, and modular construction. These features resulted in increased inertia, friction, and backlash relative to tape-driven manipulators. Studies were performed which addressed the human factor design and performance trade-offs associated with the corresponding master controller best suited for the ASM. The results of these studies, as well as the conceptual design of the dual arm master controller, are presented.

INTRODUCTION

The dual arm master controller (master) is the out-of-cell half of the advanced servomanipulator (ASM) teleoperator system. It will be used to operate the ASM slave from the control room, safely behind the biological shielding as shown in Figure 1. It is primarily controlled by inputs from the human operator, with computer augmentation for selected features. The motions of the master are reproduced in the cell by the slave, using bilateral position-position servoloops.[1] The slave was designed to be remotely maintainable in-cell with another ASM slave.[2] This was achieved by designing the ASM slave with remotely replaceable modules and with a gear/torque tube force transmission. These functional requirements increase manipulator inertia, friction, and backlash in comparison to conventional tape-driven servomanipulators. It was also felt that conventional systems needed an improved man/machine interface.

Therefore, 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 increase of these parameters in the slave. This combination will allow the entire master/slave system to perform comparably to the conventional systems. The human factors of the master were also studied to enhance the man/machine interface. The kinematics, handle type, and joint cross coupling were designed to conform to these results of the studies.

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*Research sponsored by the Office of Spent Fuel Management and Reprocessing Systems, U.S. Department of Energy, under contract No. DE-AC05-84OR21400 with Martin Marietta Energy Systems, Inc.

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CONTROL SYSTEM FEATURES

In a master/slave (M/S) teleoperator control system, a primary objective is to provide high-quality force-reflection. First of all, the operator must be able to feel the forces he is generating in-cell to operate efficiently. A "high quality" system would accurately reflect the forces being generated in the cell, be highly responsive and stable, and have a low force reflection threshold. The last characteristic is particularly important as it determines the sensitivity of the teleoperator system. Present systems' sensitivities are about 0.5 to 1 kg, but with their different capacities this ranges from 1 to 10% of maximum lift. The goal for this system is 0.5 kg (2%), which has been verified on a single-degree-of-freedom test stand.

Other features of the control system are indexing, force scaling, and position scaling. When indexing, the control system servos the slave about its present position and frees the master. The operator then moves the master to any position desired and restores M/S operations. The system then continues as before, but with the offset between the joints. The force scaling feature allows the operator to select the percentage of the force generated in-cell that is reflected back to him. Presently the ratios available are 1:1, 2:1, 3:1, 4:1, and 8:1. For small delicate tasks 1:1 would be used to maximize sensitivity. For heavy tasks 8:1 would be selected to minimize fatigue. Another useful feature is position scaling. This allows the operator to move the slave only half the distance of the master. This is very useful for delicate tasks and complex motions, such as aligning and inserting a multipin electrical connector. These options are selected from a CRT menu display. The cursor for the menu is controlled from the handle, and once the choice has been selected it is executed by a push-button on the handle.

KINEMATICS

The most basic criterion for designing a manipulator is the kinematic arrangement. The joint relationships and the length of the links can greatly influence the performance and dexterity. These factors were studied in detail,[3] and master kinematics were recommended that were similar to the ASM slave. The kinematics were investigated from a variety of viewpoints, but the overall objective was to maximize the dexterity and transparency to the operator. If this objective is met, it will maximize the operator's performance and efficiency by providing human-like flexibility and by minimizing fatigue and frustration. The master must be capable of motions comparable to a human and should not interfere with the operator's body. Since several kinematic arrangements can achieve this objective, other criteria were established to evaluate these arrangements more closely. One such additional criterion was implementation complexity. Some of the arrangements, though geometrically similar, were not kinematically identical and therefore were difficult to implement. Geometric similarity consists of identical link lengths and joint orientations. Kinematic similarity includes this, but goes further than the structural linkages to include identical force and torque transmission. This also means that the entire manner in which forces are transmitted through the master, including joint interrelations, must be the same as in the slave.

The difficulty of implementation that arises when one tries to use a geometrically similarly (not kinematically identical) arrangement is in the type of control loop that must be used. A position-position control loop is currently employed in the ASM control system.[1] 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 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 the difference. 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 this method is theoretically feasible, an analysis was performed to determine if such a control loop could be closed fast enough to be stable. The analysis indicated that the loop could be implemented, but would require development of complex software. 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.

HANDLES

To properly design the handle for the master, the kinematic arrangement must be considered. Many handle designs were conceptualized.[3] Once the kinematics were chosen, several possibilities were eliminated. Four handle types were evaluated for the replica master kinematics. The criteria for this evaluation were primarily concerned with the human factors that affect the performance of the operator. The handle must be comfortable and nonfatiguing, and must provide the operator with a transparent man/machine interface to the master. From previous studies[4] it was shown that an operator often uses either hand on either handle, so the design must be also be ambidextrous. After a new tong-actuator control concept was selected, the pistol-type handle (Figures 2, 3, and 4) looked most favorable. The initial tong control concept was a backdriveable electromechanical gear train the same as the rest of the joints. However, for this application, it was decided to control the tong with a new concept that employs a trigger with a position sensor (see section on design concept). This control can be easily implemented with the pistol-type handle. This handle 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 were thoroughly studied to design the final version for the master.

CROSS COUPLING

In the slave, all the wrist motors are located above the shoulder on the gear pod, and the forces required for the wrist are transmitted through the elbow, which results in elbow/wrist cross-coupling. A cross-coupled joint is one in which the torque in that joint is a function of the load in that joint and the load in another joint. For example, the summation of torques about the elbow joint is equal to the torque supplied by the elbow motor, plus an amount proportional to the torques supplied by the wrist motors. Another way to look at it is that the torque required from the elbow motor to support the elbow depends on how the wrist is being loaded. So the force reflected to the operator in the elbow of the master would be changed as the load in the slave wrist changed. The implications of this coupled relationship (as well as the coupling itself) are subtle, but it results in reduced controllability and inaccurate force reflection unless it is properly handled. In the first master design study,[3] a concept was recommended for the master controller. This design was light, with low inertia and almost no backlash, but the wrist motors were located behind the elbow attached to the forearm. This completely eliminated the elbow/wrist cross-coupling in the master. In most manipulator systems, this would be an advantageous feature, but in actuality it was detrimental to the performance of this master/slave system. Since the slave would be coupled but the master would be uncoupled, this unsymmetrical coupling would give the operator of the master a very confusing force and positional response.

The only was to account for this coupled-uncoupled relationship would be to employ motor/joint transformations. This would also require development of the transformation software. Therefore, a new concept was developed based on the knowledge that was gained through the conceptual design efforts on the master and the slave. This new concept is coupled in an identical manner as the slave. The coupling effects will then be reproduced in the opposite direction and cancelled out by the position-position loop. This will give the operator an accurate force and positional response because all the coupling effects have been effectively "eliminated." As electronic advances continue, such motor-joint transformations that are now avoided may be come routine enough to reconsider an uncoupled master. If this transformation option is chosen, then the other kinematic arrangements should also be reconsidered.

MOTORS

The motors used on the master are the same as those used for the slave.[2] These motors have the highest continuous-torque/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. This is very desirable in order to offset the increased friction in the slave. The gear ratio required with these motors ranges from 2:1 to 12:1.

The only disadvantage is that the weight of the motors is approximately 50% of the estimated total master weight. This high weight contribution is because the master is of much lighter construction than the slave. This is an unusually high contribution, but it is warranted by the low overall friction of the motor. A smaller motor (less weight) with a higher gear ratio was considered in order to reduce the high weight contribution. This was not done because friction would actually be increased, since the absolute value of the motor friction torque (42 N.mm) is the same in both the smaller and the larger motor. Also, since the smaller motor has lower continuous torque, it yields a lower continuous-torque/friction-torque ratio, which increases the static friction and therefore degrades the force reflection. The present slave motor then provides the minimum static friction and, therefore, the minimum force-reflection threshold. In essence, the motor development effort for the slave system identified a nearly optimal servomotor in terms of capacity and friction characteristics. Using this motor on both the slave and the master will assist in producing the best force reflection possible.

FORCE TRANSMISSION

A variety of techniques and hardware are available for transmitting forces from the centralized motors to their respective joints. The most likely possibilities that were considered were metal tapes, cables, and polyurethane cable chains. Cable chains are relatively new compared to the metal tapes or cables. They are available commercially and have been successfully used in many critical applications.[5]

Cable chains were initially selected because they appeared to meet performance requirements and were very inexpensive. Testing is under way to determine how the backdrive friction torque varies with preload. Standard aircraft cable is also being tested for comparison.

DESIGN OBJECTIVES

As stated earlier, the objective of the master design was to provide a system that was best suited for the gear-driven slave. Therefore, the master was designed to minimize friction and inertia with zero backlash while enhancing the man/machine interface. All of these features can be grouped under the single category of improving the operator's performance. Consequently, it also important to achieve a very clean and aesthetically appealing master that is comfortable to operate. In addition, the design options for the master considered simplicity and low cost as high priorities to balance the cost of the slave.

DESIGN CONCEPT

The conceptual design for the dual arm master controller is shown in Figure 5. The master has a capacity of 6 kg, approximately one-fourth the capacity of the ASM slave. It has 7 degrees of freedom and features the anthropomorphic (elbows down) stance to mimic the slave. The master will use an advanced handle developed from rigorous human factors analysis and experimental tests of a prototype handle. The force-reflection threshold has been analytically determined to be about 0.25 kg. A single-degree of freedom test stand that simulates the wrist roll joint has been fabricated to verify these analytical results.

The kinematic arrangement of the joints is identical to that of the slave. All the force transmission, the length of the links, and the location and orientation of the joints are identical, except for the wrist L-housing. Here the distance from the wrist pitch axis to the tong actuator is only 200 mm 50 mm less than the slave) to allow the slave tongs to touch without the master handles colliding. The master is mechanically counterbalanced to reduce friction. This is accomplished with a 4-bar linkage located inside the support arm tube.

The two upper degrees of freedom are all gear-driven as in the slave. Since the capacity of the master is much less than that of the slave, the gear trains are smaller and simpler. Precision gears, with weight and inertia minimized, and precision bearings are used throughout. This results in a gear train with very low backlash and low inertia.

The elbow is partially gear-driven and ues the 4-bar counterbalance linkage to also transmit the drive forces to the lower arm structure in the elbow joint. This yields a very clean, compact design which is much easier to implement than a bevel gear/drive shaft arrangement.

The three wrist motions (pitch, yaw, and roll) are driven by 1:1 ratio gears to translate and rotate the torque from the motor at the edge of the gear box to the sheave assembly in the center of the gear box. From the sheave assembly to the wrist, the forces are transmitted using commercial aircraft cable. One cable transmits forces from the sheave assembly to the elbow, and a second cable continues the transmission from the elbow to wrist gearing. In the wrist itself, the traditional differential is used to drive pitch and yaw motions, and a partial second differential is nested inside this to drive the roll motion. The roll forces are transmitted from its differential through the L-housing, with a special three-dimensional cable arrangement, to turn the corner and transmit the wrist roll forces to the handle interface.

Another unique feature is the "unilateral loop" that is used to control the slave tong. 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. Since this threshold level is so high, a new idea was pursued that was much simpler and more reliable. The new tong actuator is electromechanical, but it is not a backdriveable gear train. Instead, it incorporates a position sensor with a spring to give the operator an artificial 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. The control system then servos the tong about this resulting force. Since the position of the tong actuator is related (through the spring constant of the actuator spring) to the force applied by the operator to the trigger, this is actually a force-force loop. This control method is very flexible since the gains can be changed in the software to make the tong very sensitive to the tong actuator force for fragile jobs, or insensitive for heavy tasks. The spring in the handle itself can also be changed for various tasks or for individual operators. Overall, this method is deemed very acceptable for the function it is to perform, but it will be thoroughly evaluated during the testing of the master.

PRELIMINARY TEST RESULTS

Much testing of this new teleoperator system has been done with one-degree of freedom test stands: two gear-driven stands (Figure 6), one representing the slave and one representing the master, and one cable-driven stand (Figure 7) representing the master. All of the stands simulate the wrist roll joint, which has the most gear meshes, largest length, and most friction. This joint was chosen because it is obviously the most difficult. Since the most important criterion for the system is force-reflection threshold, the performance of these test stands was quantified by this parameter in Table 1.

SUMMARY

As can be seen from Table 1, the results are very encouraging. The results are well within the predictions and confirm that the present design is quite satisfactory. The dual arm master controller therefore should achieve all of the objectives of a low friction, inertia, and backlash system. Fabrication of the arms is scheduled to be completed in June 1985, and assembly completed in July. Overall, the master represents a significant engineering achievement. It provides a major performance improvement by employing high-achievement. It provides a major performance improvement by employing high-performance commercial components and human factors engineering. This will result in an ASM master/slave system that provides increased performance and capabilities that are competitive with existing servomanipulator systems.

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Results of Force-Reflection Threshold Tests On One-Degree Of Freedom Test Stands.

Table 1

TEST CONDITION	EXPERIMENTAL FORCE-REFLECTION THRESHOLD (kg)	ANALYTICAL FORCE-REFLECTION THRESHOLD (kg)
1. Slave[1] only (open circuit)	1.3	0.9
2. Master[2] only (open circuit)	0.3	0.4
3. Master/slave, no compensation	1.0	1.3
4. Master/slave, with compensation algorithm	0.6	0.9
5. Cable chain master only, no preload (open circuit)	0.2	0.2
6. Cable chain master only, 45-kg preload (open circuit)	1.0	0.3
7. Cable master only, minimum preload	NA	0.2

[1] Slave built with standard gears and bearings, lubricated with grease.

[2] Master built with precision gears and bearings, lubricated with light machine oil.

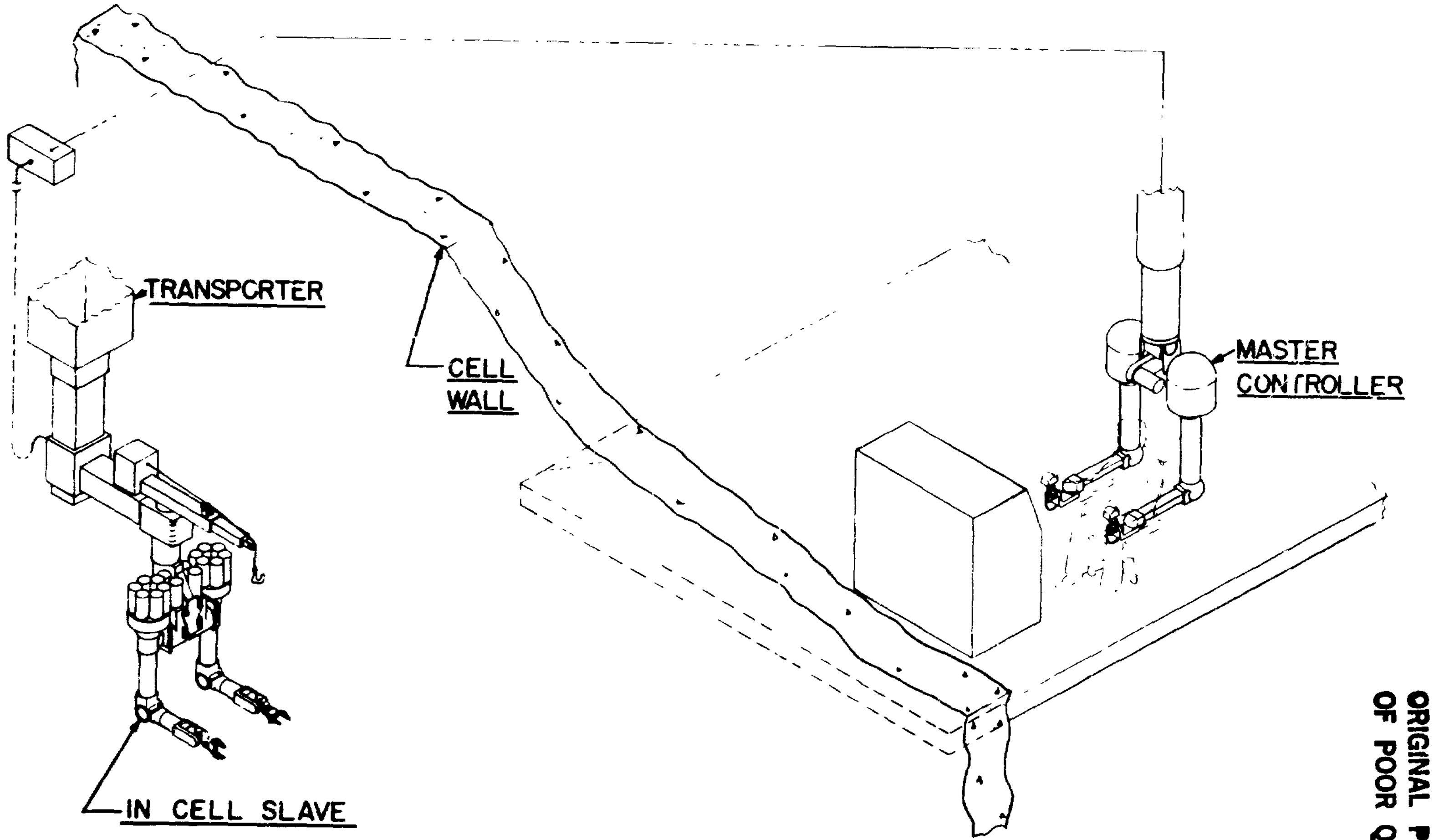

Figure 1. Master/Slave Teleoperator System

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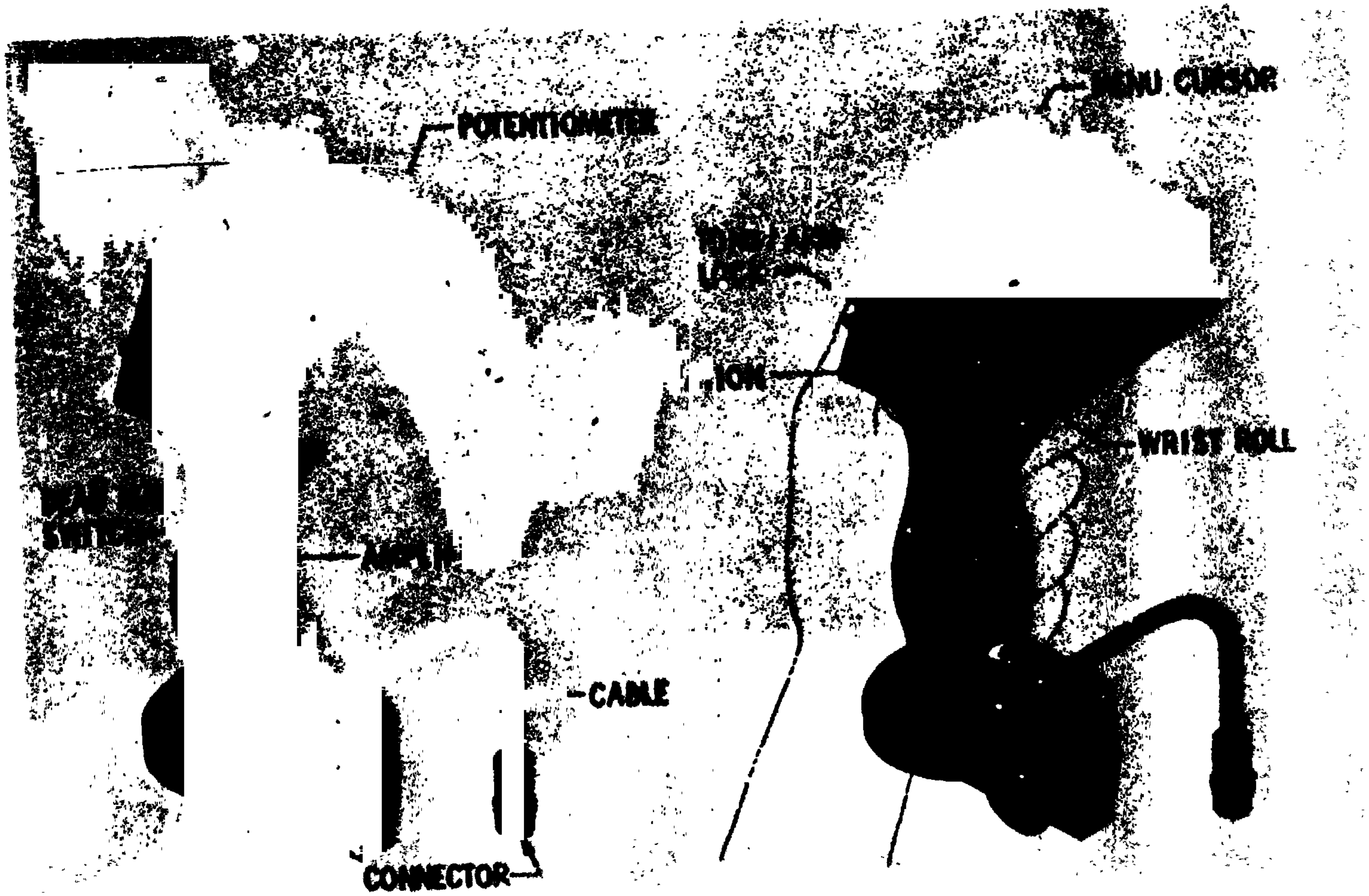

Figure 2. Ambidextrous Master Handle

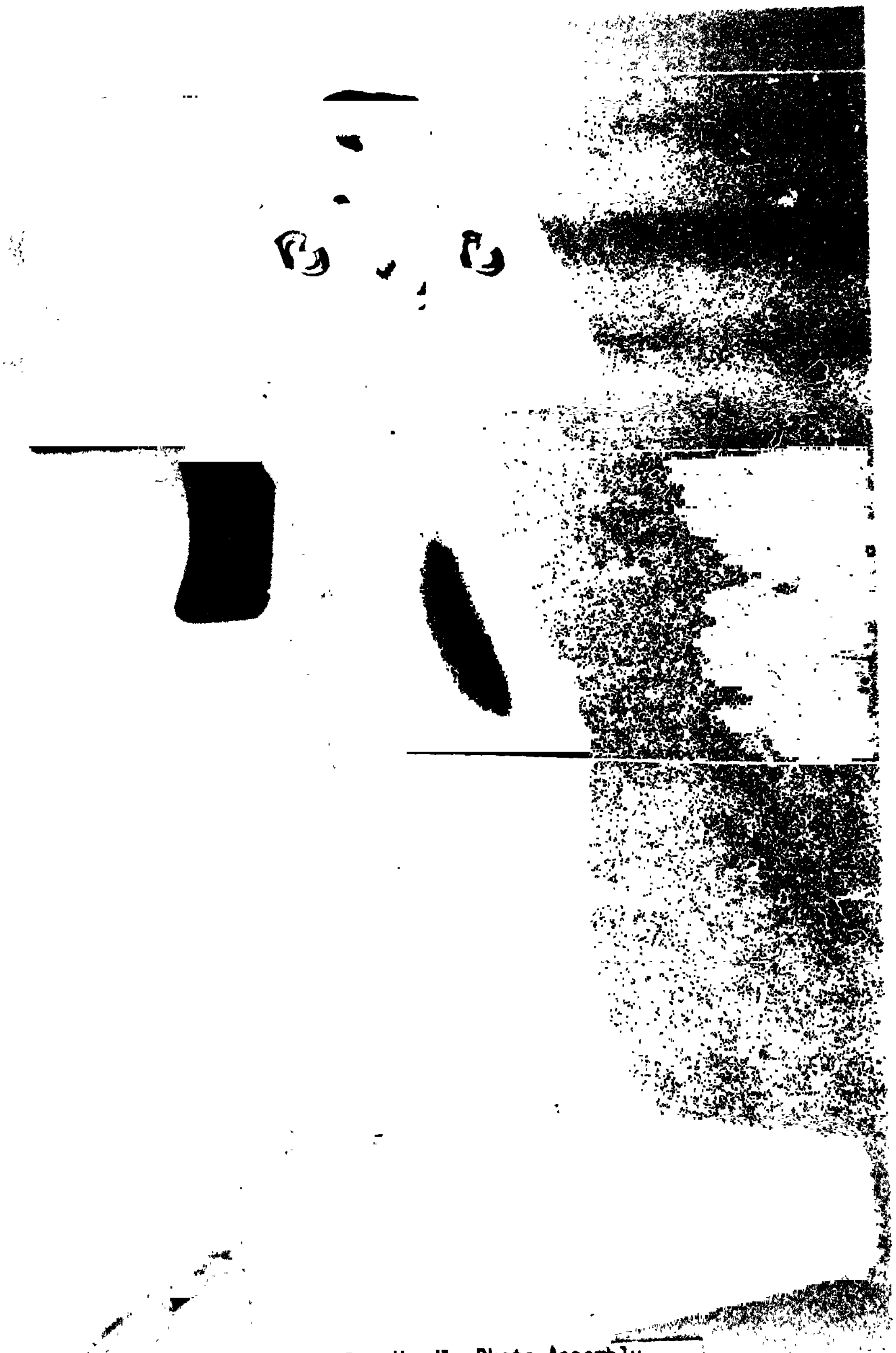

Figure 3. Handle Photo-Assembly

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Figure 4. Exploded View of Handle

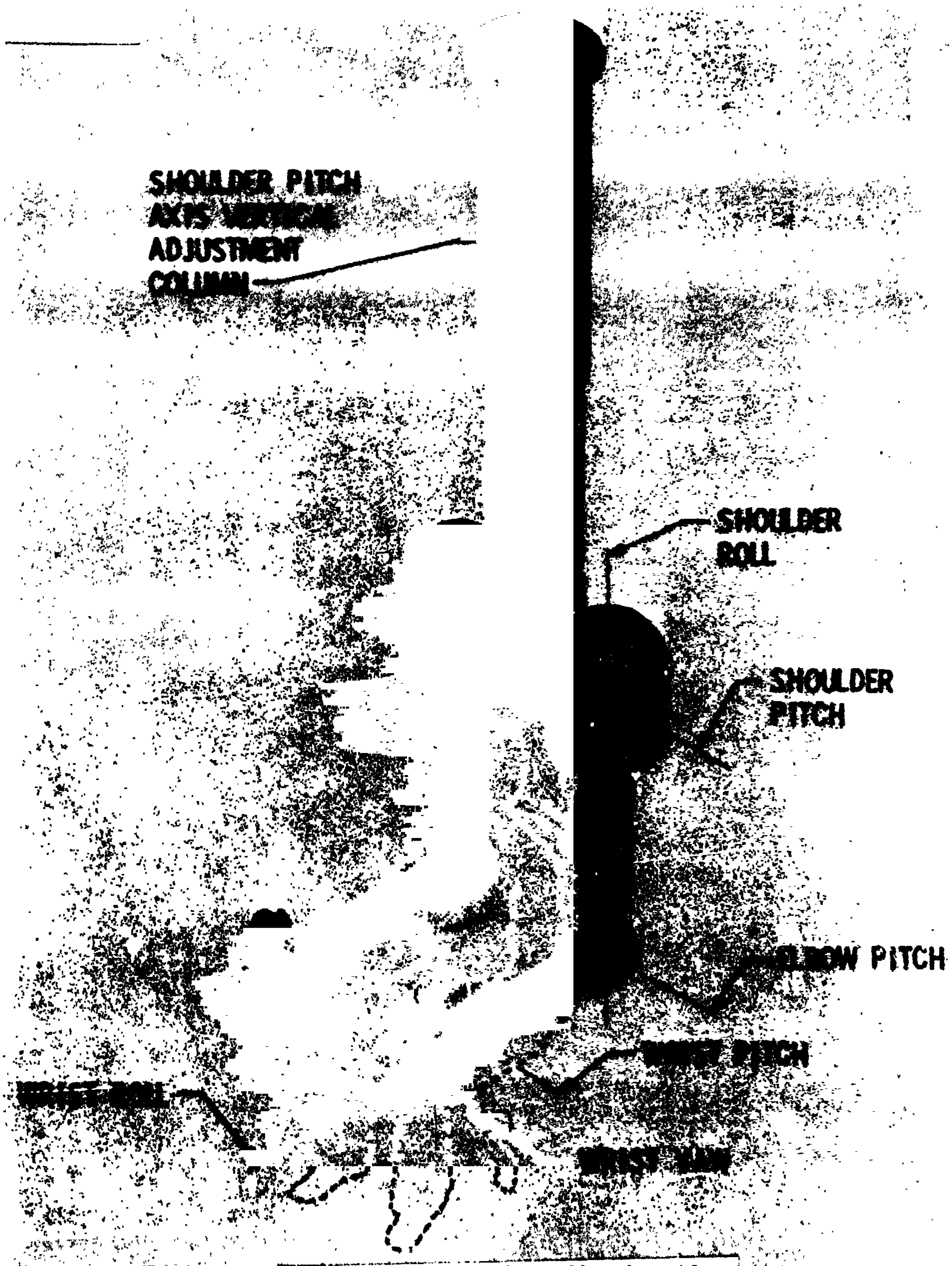

Figure 5. Master Controller Assembly

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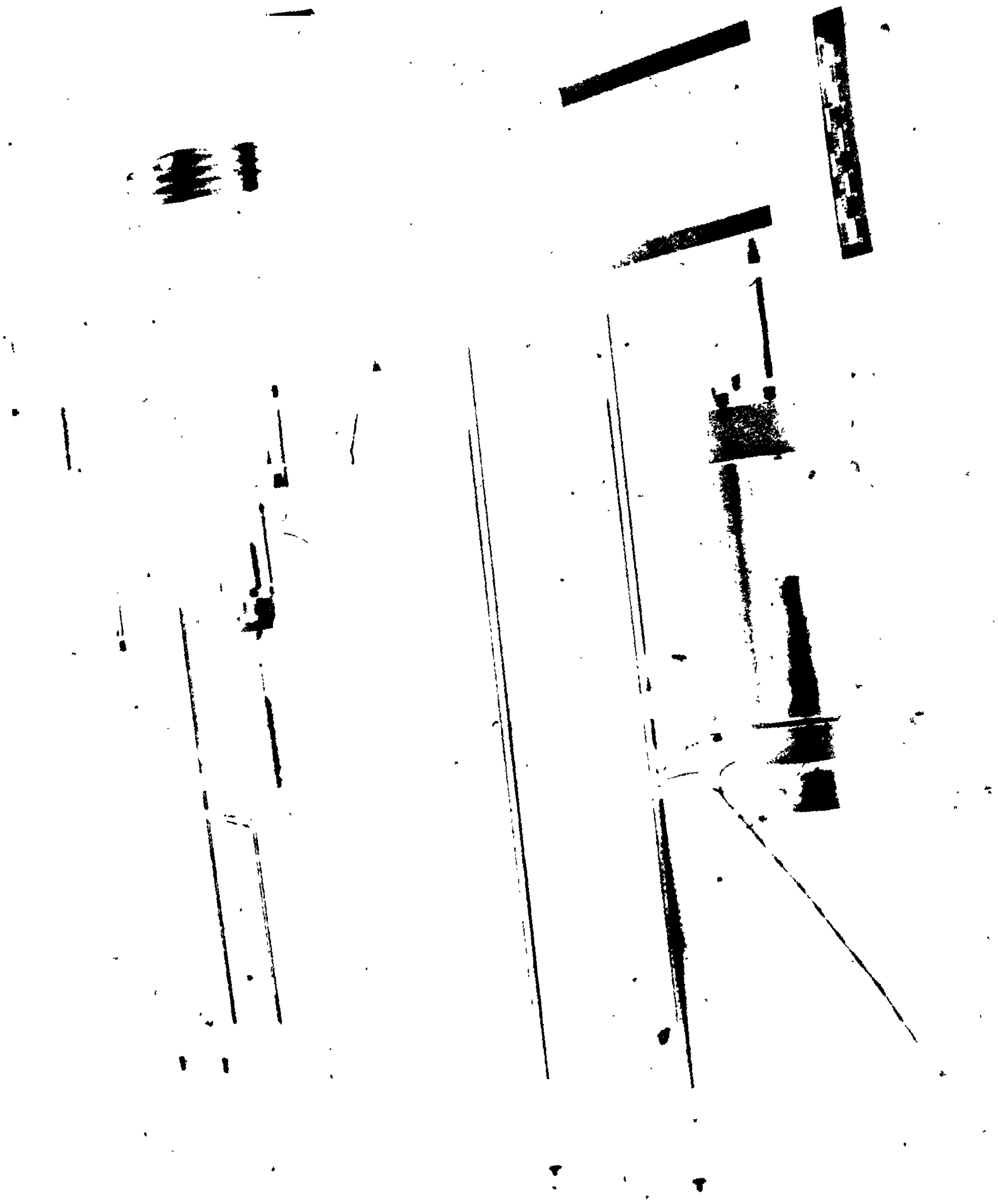

Figure 6. One Degree of Freedom Test Stand: Slave

Figure 7. One Degree of Freedom Test Stand: Master