N76-19174

2. A MANIPULATOR ARM FOR ZERO-G SIMULATIONS

By Shepard B. Brodie, Christopher Grant,
and Janos J. Lazar

Martin Marietta Corporation
Denver Division
Denver, Colorado

INTRODUCTION

Martin Marietta has designed and fabricated a 12-ft counterbalanced Slave Manipulator Arm (SMA), to be used for resolving the questions of operational applications, capabilities, and limitations for such remote manned systems as the Payload Deployment and Retrieval Mechanism (PDRM) for the Shuttle, the Free-Flying Teleoperator System, the Advanced Space Tug, and Planetary Rovers. As a developmental tool for the Shuttle manipulator system (or PDRM), the SMA represents an approximate one-quarter scale working model for simulating and demonstrating payload handling, docking assistance, and satellite servicing. For the Free-Flying Teleoperator System and the Advanced Tug, the SMA will provide a near full-scale developmental tool for satellite servicing, docking, and deployment/retrieval procedures, techniques, and support equipment requirements. For the Planetary Rovers, it would provide an oversize developmental tool for sample handling and soil mechanics investigations.

The design of the SMA was based on concepts developed for a 40-ft NASA technology arm to be used for zero-g Shuttle manipulator simulations.

COUNTERBALANCE CONCEPT

The SMA uses an articulated counterbalance scheme for shoulder and elbow and a self-counterbalanced design for the wrist. The articulated counterbalance scheme is essentially a second arm at the end of the shoulder extension with one or two counterbalance weights which are driven (via mechanical linkage) in phase with the lower arm (elbow to wrist). This system provides an arm whose shoulder and elbow torques need not, <u>in any orientation</u>, overcome the force of gravity on either the upper or lower arm, and whose motion is completely unrestricted.

The concept of articulated counterbalance is difficult to grasp intuitively, especially when the arm is in an orientation where the tip of the slave is on the counterbalance side of the fulcrum (Figure 1). An analytical proof of this scheme follows.

The slave arm with articulated counterbalance can be modeled as shown in Figure 2.

The counterbalance weights are w_1 and w_2. The tubes of the slave are represented by w_3 and w_5. The elbow joint is w_4; and the wrist joints, wrist extension, and terminal device are lumped in w_6.

For the system to be balanced, the total moments about A and B should be equal. This is given by Equation [1], Table 1. The system can also be considered a rigid body whose governing moment equation for balance about the shoulder is given in Equation [2], Table 1. The distances D_1, D_2, . . . can be written in terms of the arm segments L_1, L_2, . . . and the cosine of angles α and β. Substituting these expressions into Equations [1] and [2], and solving the two equations simultaneously, we get Equations [3] and [4], Table 1.

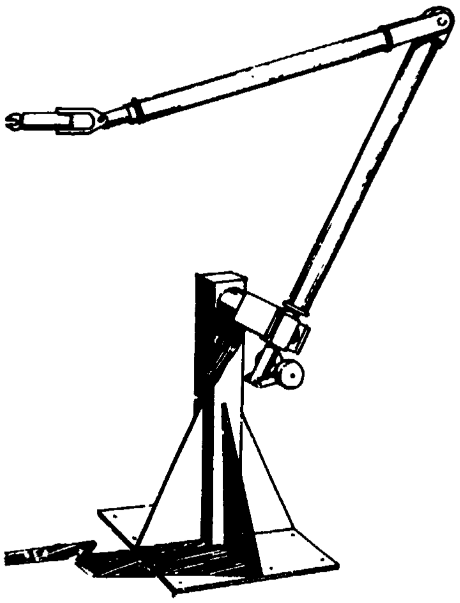

Figure 1. Manipulation in Cross-Over Position

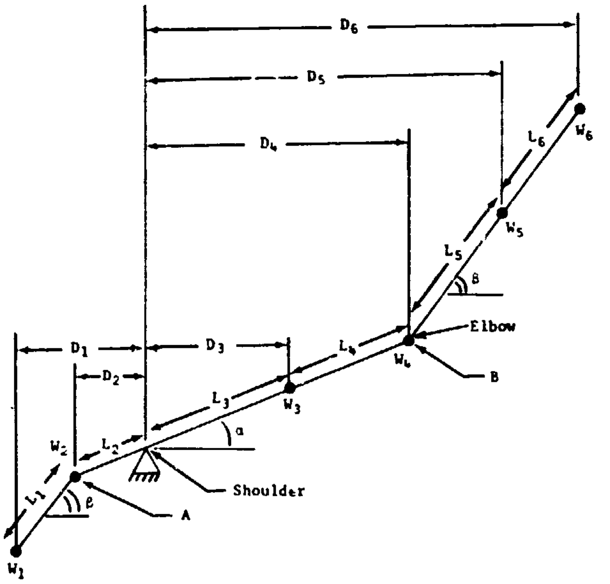

Figure 2. Articulater Counterbalance Model

Table 1. Counterbalance Equations

$w_1(D_1-D_2) = w_5(D_5-D_4) + w_6(D_6-D_4)$ Equation [1]	$w_1D_1 + w_2D_2 = w_3D_3 + w_4D_4 + w_5D_5 + w_6D_6$ Equation [2]
$L_1 = L_5(w_5+2w_6)/w_1$ Equation [3]	$L_2 = L_3[w_3+2(w_4+w_5+w_6)](w_1+w_2)$ Equation [4]

It can be seen that both α and β have cancelled in the solution of the balance equations. Thus, if Equations [3] and [4] are satisfied with proper values of the lengths and weights, the system is entirely counterbalanced at all angles of α and β. It can be shown that the system is also independent of roll angle so long as the slave arm and counterbalance arm roll as one about the centerline of the upper arm tube.

The SMA counterbalance linkage configuration is a three-bar direct-drive system that was selected to meet the design requirements for low friction and high stiffness. Each of the three bars is mounted on a separate crank plate. These assemblies were put together to form a crankshaft-rod type system. The pin locations in the plates are 120° apart. Figure 3 is a schematic of the linkage system. An optimization program was used to determine the yoke and mass sizes for minimum increase in inertia as seen by the joint drives. Figures 4 and 5 are photographs of the SMA.

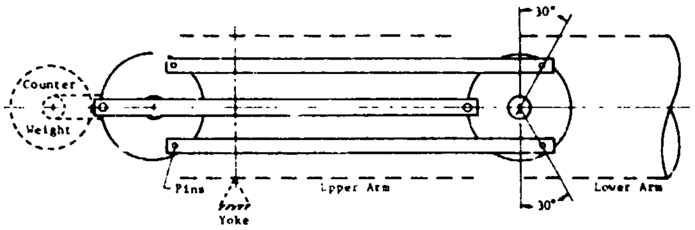

Figure 3. Counterbalance Linkage Concept

DRIVES

Table 2 illustrates the general joint capabilities. The drives are the most significant portion of the design because of their close approximation to flight hardware. All joints contain 60V dc motors, potentiometers, tachometer-generators, and fail-safe 28V dc friction brakes. The gear ratios are in the range of 115:1. Each joint is servo controlled, and may accept commands from manual or computer sources. Of particular interest in the drives during simulations are joint flexibility/stiffness, gear backlash/backdrive, finite motor torque, friction/stiction, and response.

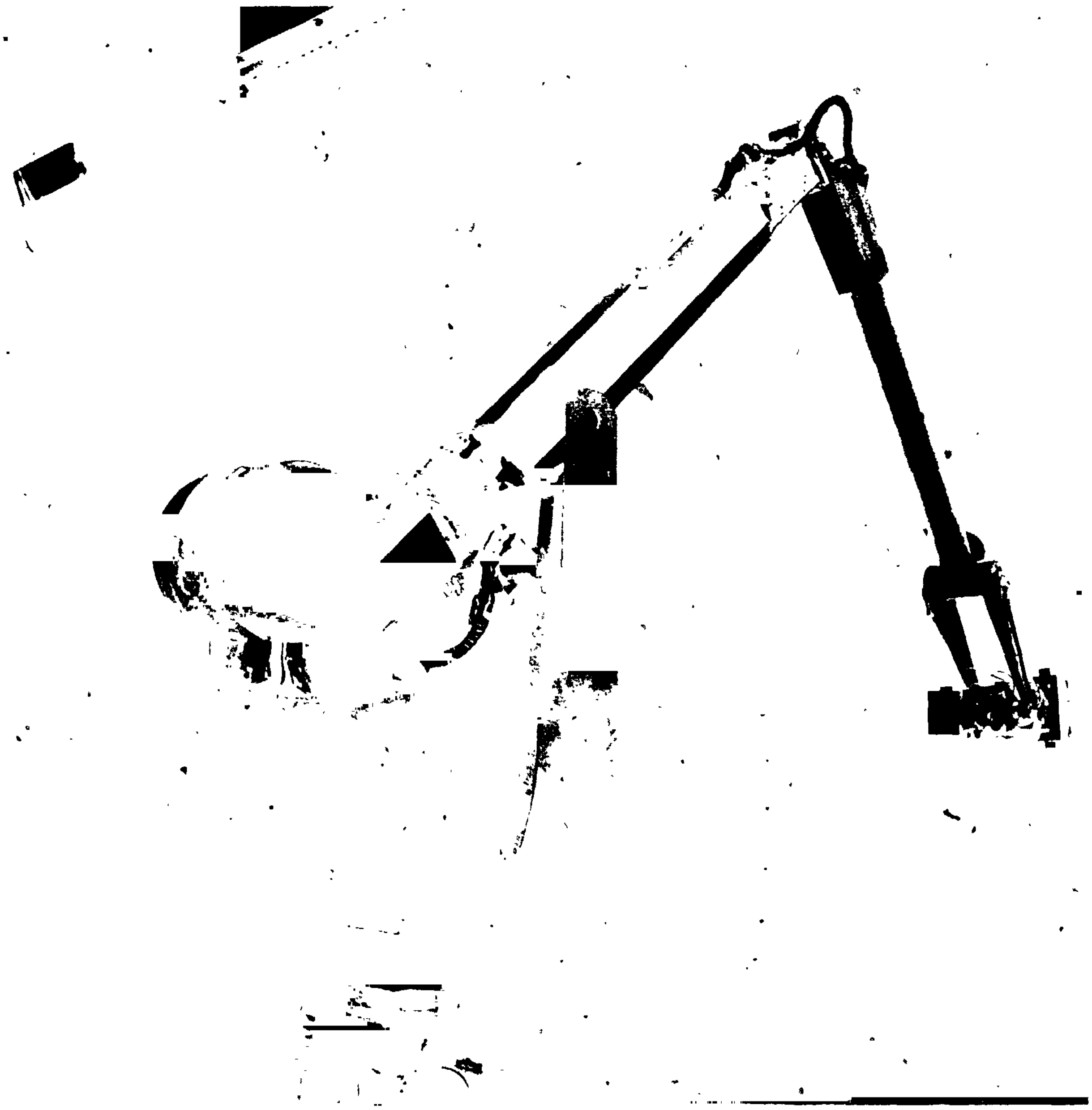

Figure 4. Slave Manipulator Arm

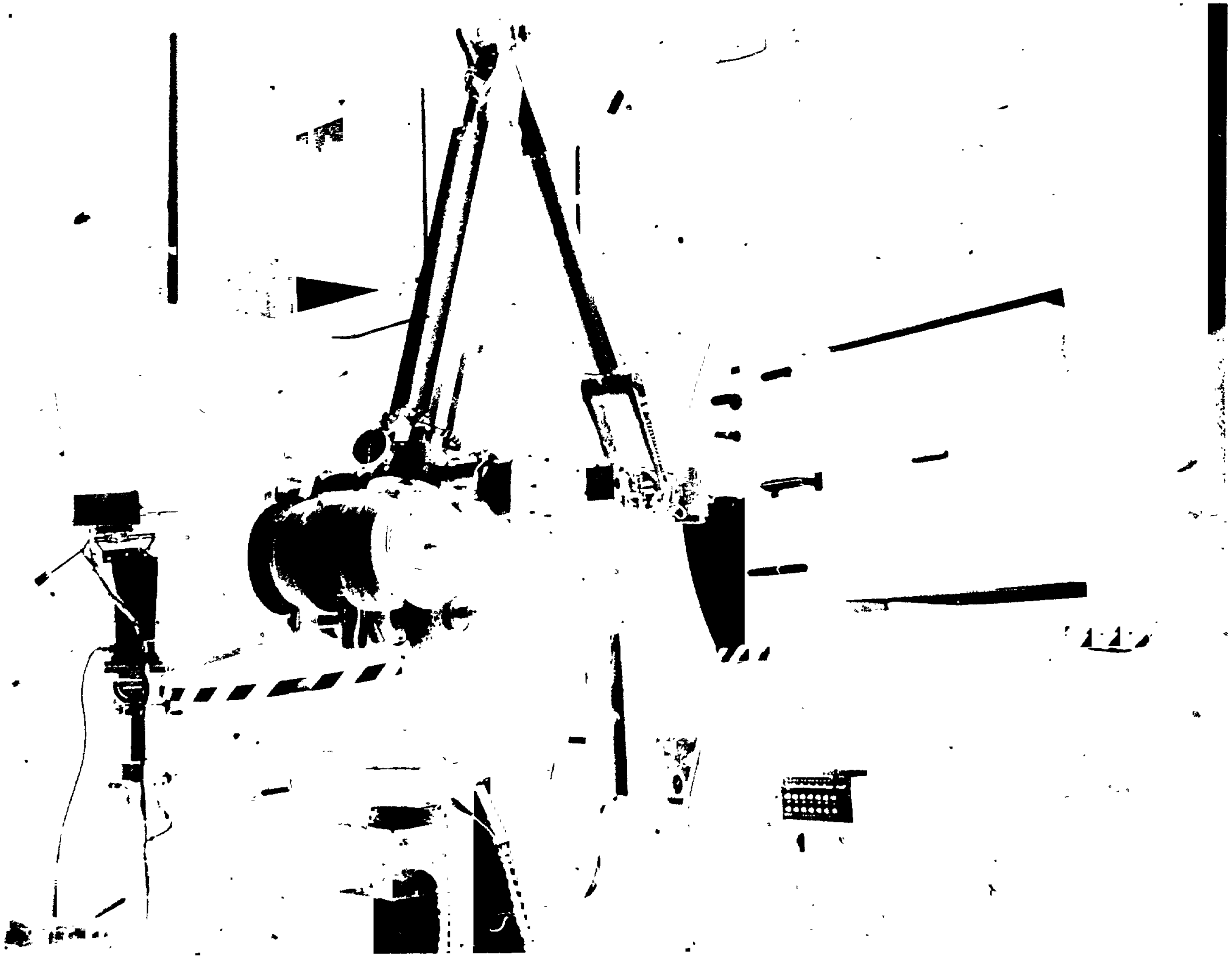

Figure 5. Slave Manipulator Arm Working at Task Panel

Table 2 Electro-Mechanical Joint Capabilities

	Shoulder			Elbow		Wrist	
	Pitch	Yaw	Roll	Yaw	Pitch	Yaw	Roll
Design Stall Torque Ft-lbs	100	100	66	66	30.5	30.5	15
Joint Travel in Degrees	±200	+150 - 75	±200	+ 10 -160	±80	±130	±200
Design Slew Angular Velocity Rad/sec	0.1	0.1	0.03	0.15	0.2	0.2	0.1
Actual Backdrive Torque Brake On Ft-Lbs	69	60	--	75	40	42	40

The wrist consists of three degrees-of-freedom. Counterbalancing is accomplished by the proper placement of equipment around each axis, as shown in Figure 6. By placing the pitch axis at the center of gravity of the roll drive and the end effector/TV camera assembly, the pitch axis is balanced. By locating the yaw axis at the center of gravity of the pitch motion equipment and the pitch/yaw drive assembly, the yaw axis is balanced. The pitch and yaw drives are separated from their respective drive centers by the use of steel drive tapes. All equipment is mounted on the main wrist support member which pivots around the yaw axis. Figure 7 is a photograph of the SMA wrist.

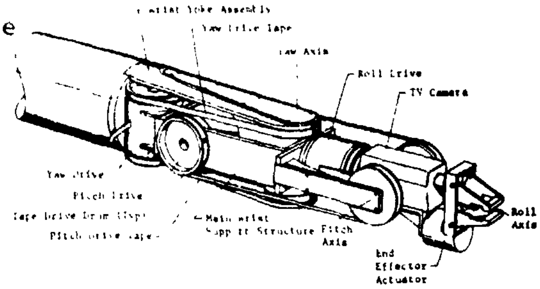

Figure 6. Self-Counterbalanced Wrist Assembly

END EFFECTOR

The end effector is an electro-mechanical device utilizing a 60V dc motor to drive a screw thread which actuates the linkage opening and closing the jaws. The closing force of the jaws is 6.8 kilograms (15 pounds) [11 kilogram-meters (or 80 ft-lbs) of torque] and is capable of being actuated in less than one second. The jaws are designed to grasp a 0.025-meter (one-inch) square bar placed at a 45° angle to the horizontal. This configuration may be changed by exchanging the jaws with the desired shape. Figure 5 illustrates the end effector/grasp bar relation.

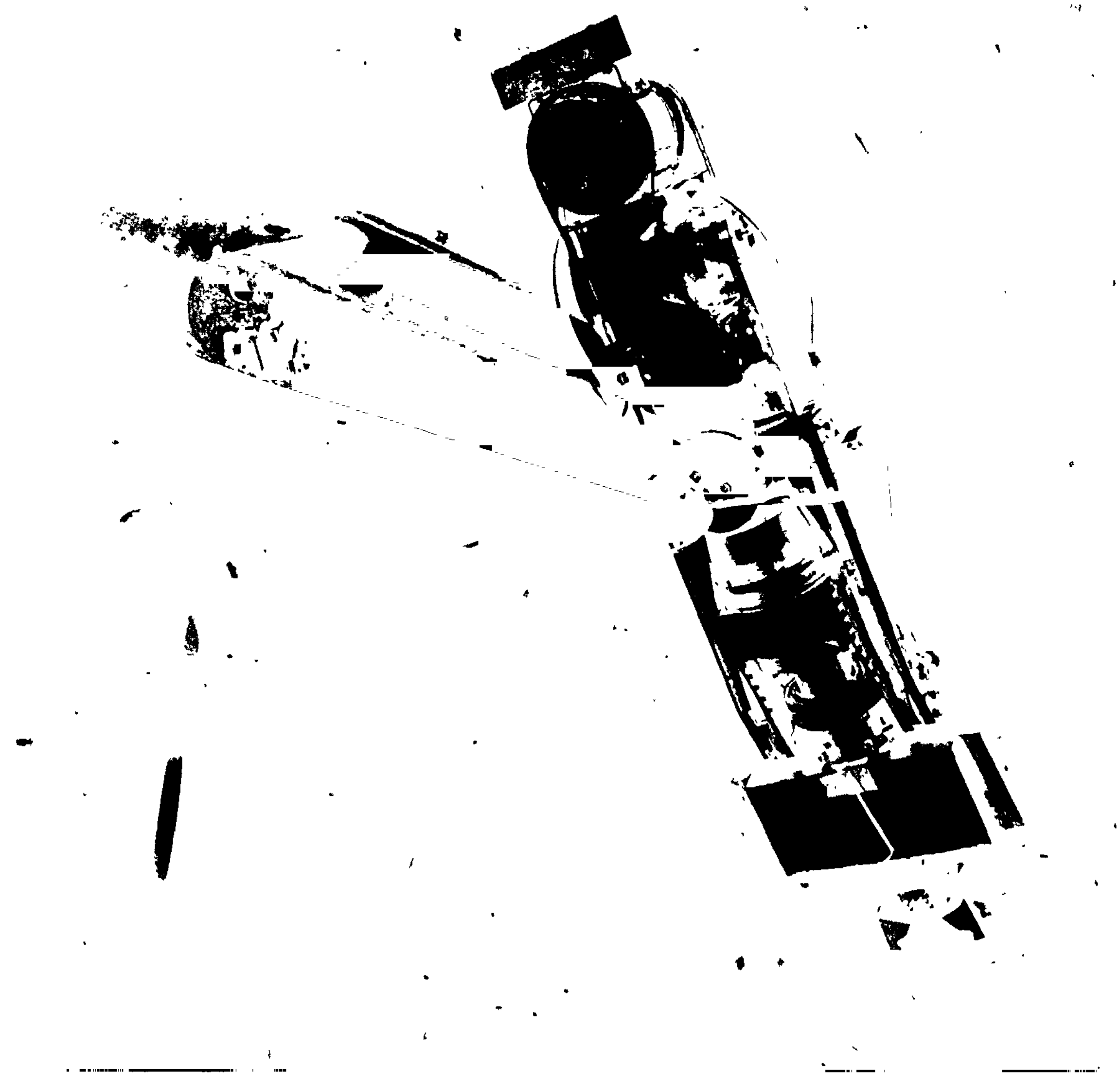

Figure 7. Slave Manipulator Arm Self-Counterbalanced Wrist Assembly

TELEVISION SYSTEM

The television system used on the arm itself is located immediately behind the end effector. The mounting bracket will accept either one or two videocon tubes for monaural or stereo TV viewing. The resolution point begins approximately 0.02 meter (one inch) behind the jaws of the end effector and continues forward. The electronics for the videocon tubes are located at the wrist-forearm attach point.

BASE SUPPORTS

The base assembly is made up of six components. These components may be assembled in combination to provide six locations for shoulder yoke orientation. The shoulder yoke may be located at 1.22, 2.13, or 3.66 meters (4, 7, or 12 feet) from the floor to the shoulder pitch (yaw) axis in either a vertical or horizontal position. The base plates are constructed of structural steel and weigh a total of 431 kilograms (950 pounds).

TEST CONDUCTOR'S CONTROL CONSOLE

The Test Conductor's Control Console (TCCC) provides the equipment necessary to (1) power up the SMA, (2) select operating modes, (3) monitor system operation and provide limit warnings, (4) allow manual SMA control, (5) bring the SMA to a safe stop in an emergency, (6) control the associated analog computer, and (7) house the system electronics. Figure 8 is a photograph of the TCCC.

The TCCC was designed to be as flexible as possible to accommodate experimental configuration changes and operational improvements. Plug-in circuit boards are used extensively and all cabling is terminated in connectors so that large sections (such as an entire panel) can be completely removed for modification or maintenance. System reliability is enhanced by the use of solid-state switching in all signal circuits.

Power for the SMA and TCCC is obtained from 117V ac and 28V dc mains. The internal power supplies provide dc voltages of +60, +15, -15, +10, -10, and +5.

The TCCC makes provision for several modes of operation including both rate and position servo control. In the normal operating situation with an analog computer in the loop, the command signals (either rate or position) from controllers located in the Operator's Station (OS) are routed to the computer. The computer represents a servo rate command which is amplified in the TCCC and applied to the proper joint servomotor. As an alternative, the computer may utilize the joint position potentiometer outputs to produce a

ORIGINAL PAGE IS
OF POOR QUALITY

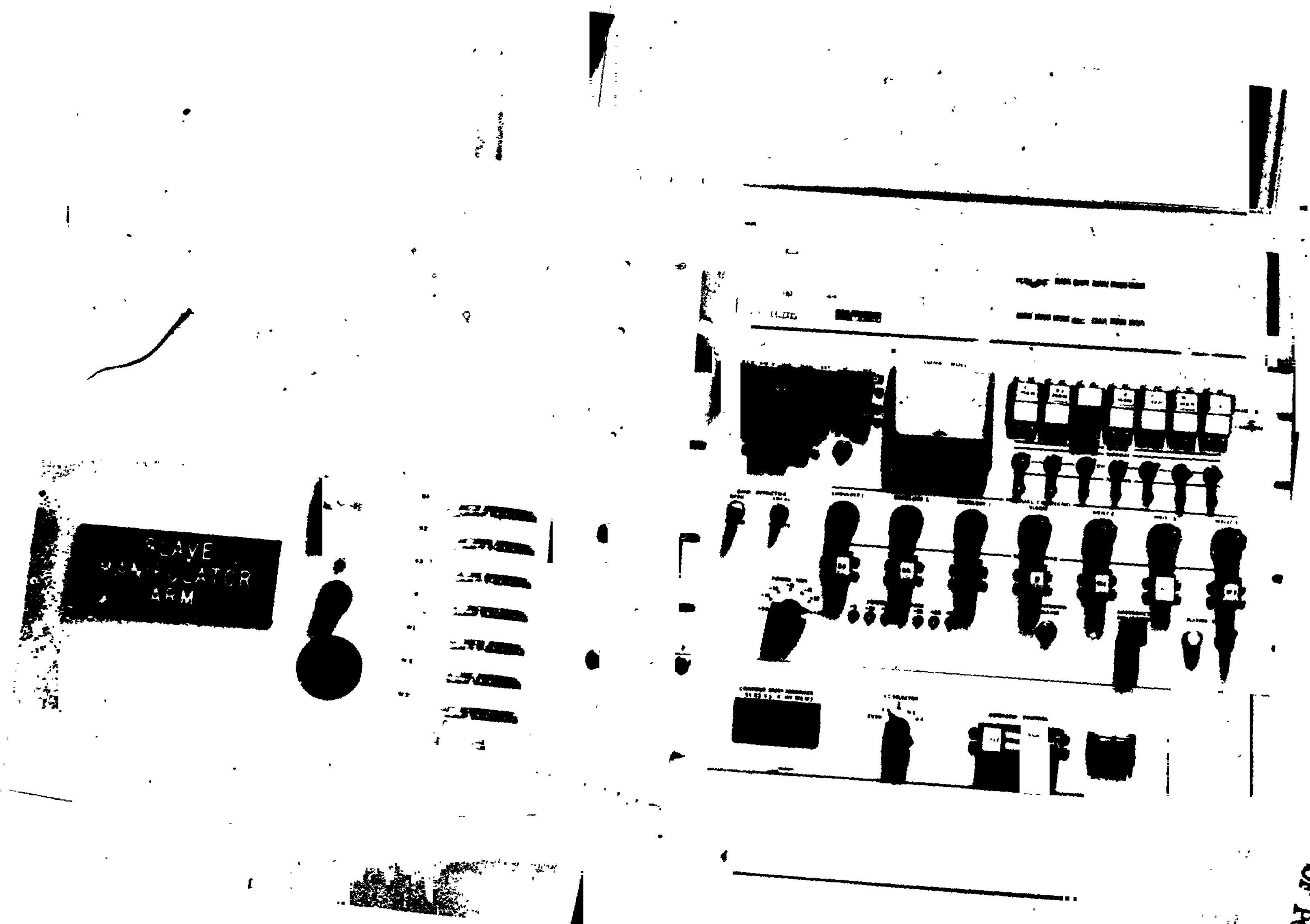

Figure 8. Slave Manipulator Arm Test Conductor's Control Console

servo drive signal based upon arm position. Either of these situations are termed the OPERATE mode.

Once an exercise has been completed, it is necessary to return the SMA to some initial position. First, the SMA is placed in the HOLD mode by a pushbutton on the TCCC. In HOLD, control of the servo loop is removed from the computer and transferred to the TCCC. Local control from the console is a position loop. In the HOLD mode, the joint position pot output is used as the position command so that the servo drive signal is always zero. Next, the SMA servos are placed in the RESET mode by the TCCC. The initial conditions are determined by the settings of a group of potentiometers, one for each SMA axis. The output voltage of the pot represents a specific joint position. Four sets of initial conditions are obtainable from the TCCC. In the RESET mode, each servo position command is integrated between the position at the beginning of RESET and the desired end position. The rate of return is controllable from the TCCC. In addition, there is a reset sequencer which allows each joint to be reset individually or in any desired sequence. The reset sequencer logic operates in 10 asynchronous steps. For example, if the reset thumbwheel switches on the TCCC are set up so that joints E and W2 are reset during step 2, both joints will remain in the HOLD mode during steps 0 and 1, then go into the RESET mode during step 2, and return to HOLD in steps 3 through 9. The reset sequencer will not progress to step 3 until both E and W2 reach their desired initial condition points.

Two other modes of operation are possible. The first of these is the ALIGN mode. This sequence causes the position track and hold circuits to sample the present joint positions and then throw the mode control into the HOLD mode. ALIGN occurs automatically when the system is powered up and can be activated at any time during use. The last mode is MANUAL operation. In this mode position commands come from 3-turn potentiometers on the TCCC Main Control Panel. SMA joints may be placed in the MANUAL mode individually while other joints remain under computer control. In the MANUAL mode, the other mode controls have no effect on that particular joint.

The Mode Control logic is accomplished by a read only memory (ROM) which either accepts or rejects an action of a mode control pushbutton depending upon system conditions. For example, it is generally undesirable to go to OPERATE before completing RESET. Thus, the ROM will not permit a mode change directly from OPERATE to RESET.

Other provisions are included for system safety. A power interrupt circuit removes servomotor power and applies the electromagnetic joint brakes when activated. Power interrupt can be initiated manually by observers located in various parts of the facility or automatically when a joint angle limit occurs. When a joint angle is approaching its limit, an early warning is provided by the limit circuitry. An audible boxing sound occurs and a red warning light flashes to indicate an approaching limit. At this time the operator can reverse the action and drive normally back to a safe condition at which time the warnings cease. If the limit is exceeded, however, the power interrupt will be initiated as described above. It is then necessary to bring the SMA out of the limit under manual control.

The TCCC contains a digital voltmeter to monitor the various dc voltages in the system. Selector pushbuttons are provided for all power supply voltages and the following signal voltages for each joint: (1) position pot, (2) computer output, (3) reset pot, and (4) manual control pot.