FINAL PROJECT REPORT

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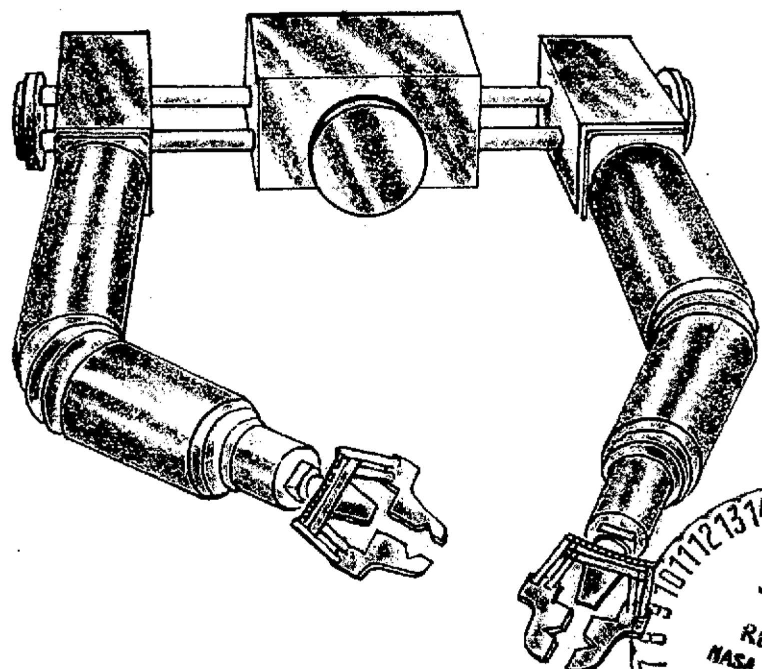
RAM

Rancho Anthropomorphic Manipulator



Submitted by

THE ATTENDING STAFF ASSOCIATION
OF THE
RANCHO LOS AMIGOS HOSPITAL, INC.

Contract No.
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FINAL PROJECT REPORT

* DESIGN AND FABRICATE A PAIR OF RANCHO ANTHROPOMORPHIC MANIPULATOR ARMS

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TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

F I N A L   R E P O R T

RAM

This report presents the basic design features of the Rancho Anthropomorphic Manipulator (RAM), a bilateral manipulator system constructed for the George C. Marshall Space Flight Center, Huntsville, Alabama. In contrast with other previous electrically powered manipulators, the RAM features increased payload capability, structural integrity, position control and the ability to interchange its own terminal devices.

A set of detailed design drawings and a motion picture are considered an integral part of this report.

1. Overall Description

The RAM system consists of bilateral manipulator arms, each provided with movement in seven degrees of freedom. (An overall picture of the system is shown in Figure 1.) In addition, the system incorporates a movable shoulder mounting structure (shown in Figure 2) with each arm having lateral movement of approximately 15 centimeters and the entire support structure being capable of moving in the anterior/posterior plane a distance of 25 centimeters. The arms have fully extended length of approximately 1.2 meters. The movable shoulder mount is an important feature which gives the manipulator additional flexibility in performing tasks. The shoulder movement can be likened to a person's trunk movement from side to side and forward and backward to facilitate performing a manual task.

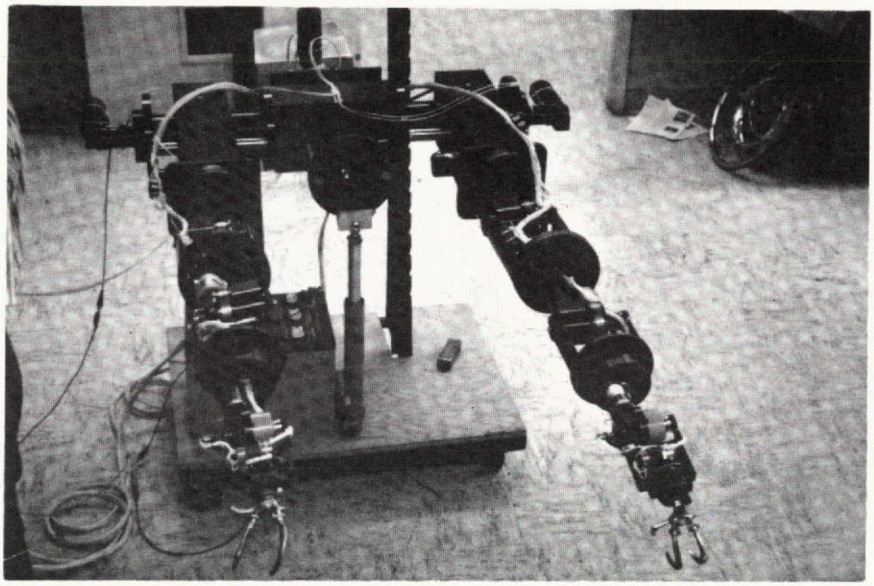


FIGURE 1

RANCHO ANTHROPOMORPHIC MANIPULATOR

(RAM)

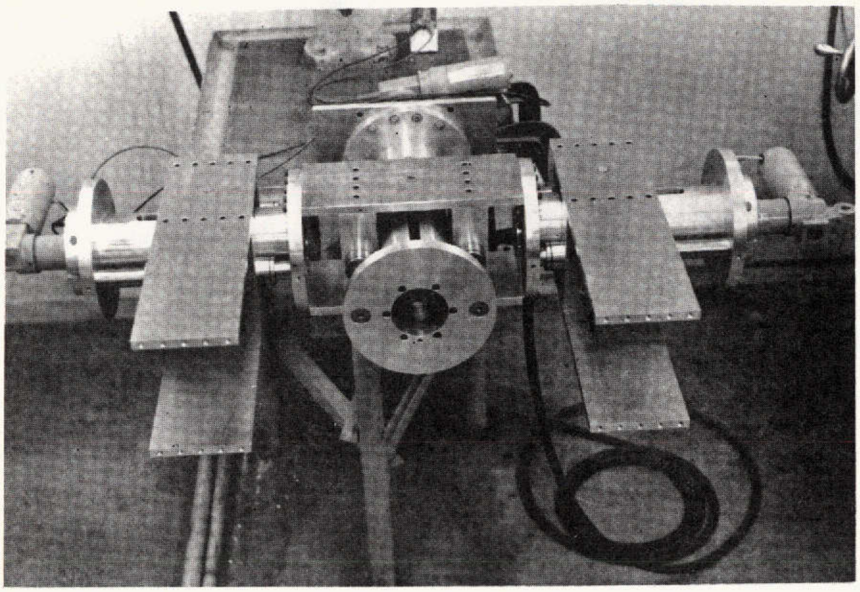


FIGURE 2 A

RAM POWERED SHOULDER MOUNT

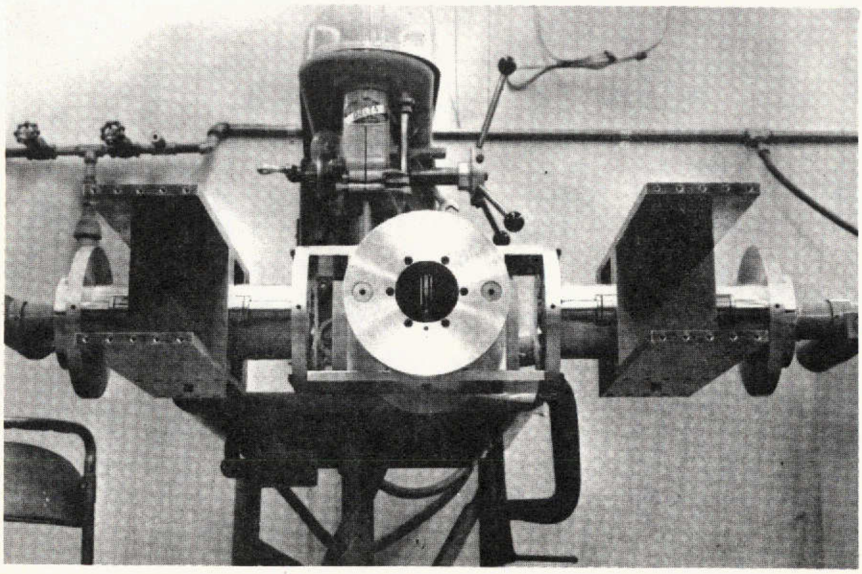


FIGURE 2 B

RAM POWERED MOUNT

The RAM system is designed to provide movement in seven degrees of freedom: two in the shoulder (abduction/adduction and flexion/extension), humeral rotation, elbow flexion/extension, supination/pronation, wrist flexion/extension and prehension or grasp. The joint structures of the RAM feature a range of movement of 300 degrees on all joints except the wrist, with 180 degrees of movement in the wrist. As described in detail in Section 2, the joint design includes worm gear and harmonic drive reduction at the shoulder, elbow flexion and wrist joints; with spiroid gears and planetary gears used in the other joints.

An important feature of the RAM is its ability to change its own terminal devices, which included a modified Dorrance hook and a parallel jaw actuator (Figure 3). The maximum payload capability is 25 pounds with a pinch force of 15 pounds. The segmental structures that provide for joint suspension are constructed of semi-circular beams (cut from a tubular section of aluminum) that are easily bolted to circular face plates of the powered joints. These joint suspension members may be easily removed and replaced with additional members of different lengths thereby providing for the convenient changing or selection of either the humeral or forearm length. The joints themselves are sealed through O-ring connectors. The circular face plates of each of the joints gradually diminish in diameter from the shoulder joints to the supination joint. These circular face plate attachments are designed so that dust covers or waterproofing may be provided.

The main control system provided with the RAM is a closed loop servo that provides position control and variable velocity of the various joints. An auxiliary control system using switches for independent control of each joint was also provided. The servo controls may be actuated by a multichannel, toggle action, pressure (strain gage) transducers or multiple potentiometers.

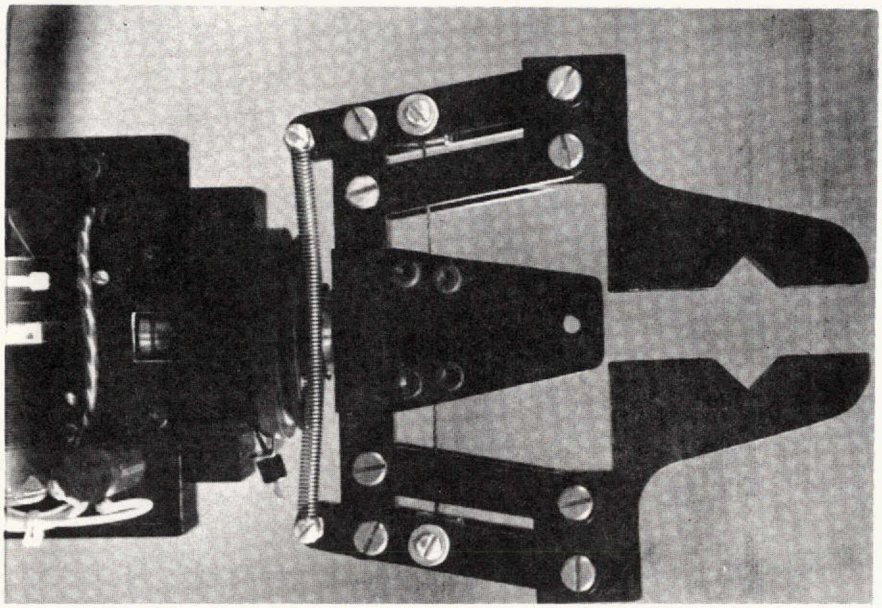


FIGURE 3 A

PARALLEL JAW TERMINAL DEVICE

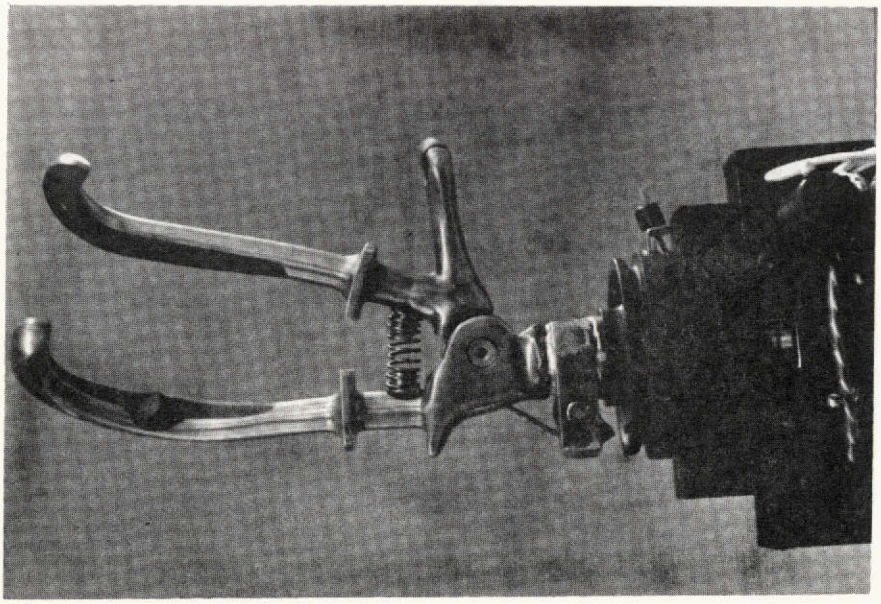


FIGURE 3 B

DORRANCE HOOK TERMINAL DEVICE

2. Joint Design

Figure 4 shows the segments and joints of the arm at full extension.

A. Shoulder Joints. Both joints at the shoulder use a combined worm gear and harmonic drive reduction system powered by a Globe Model No. 166A100-7 motor. The joint arm is illustrated in Figure 5. The worm gear is driven directly from the motor armature and provides a 10-1 reduction. The worm gear is coupled to the harmonic drive wave generator by an intermediate shaft. The harmonic drive provides an additional 80-1 reduction in the gear box thereby giving an overall reduction of 800-1.

It was originally planned to utilize a spiroid gear reduction system for the rotation joint at the shoulder (shoulder abduction/adduction); however, it was found upon testing that under the severe load requirements of this joint, the primary reduction could not withstand the loads and would not operate efficiently. It was therefore decided to utilize the hermonic drive reduction system in that joint.

B. Humeral Rotation. The humeral rotation joint is driven by the same type Globe motor as the shoulder joints with two stages of spiroid gears. The first spiroid stage is driven directly off the armature shaft and provides a reduction of 20-1 and the second spiroid gear provides a reduction of 38-1 giving an overall reduction of 760-1.

C. Elbow Joint. The elbow flexion/extension joint (see Figure 6) is identical to the two shoulder joints except that a smaller motor (Trojan Industries, Motor No. 20B175) is used and a 5-1 reduction is used providing an overall reduction of 400-1. The change in worm reduction was necessitated by the fact that the smaller motor runs at half the speed of the larger motor used in the shoulder joints.

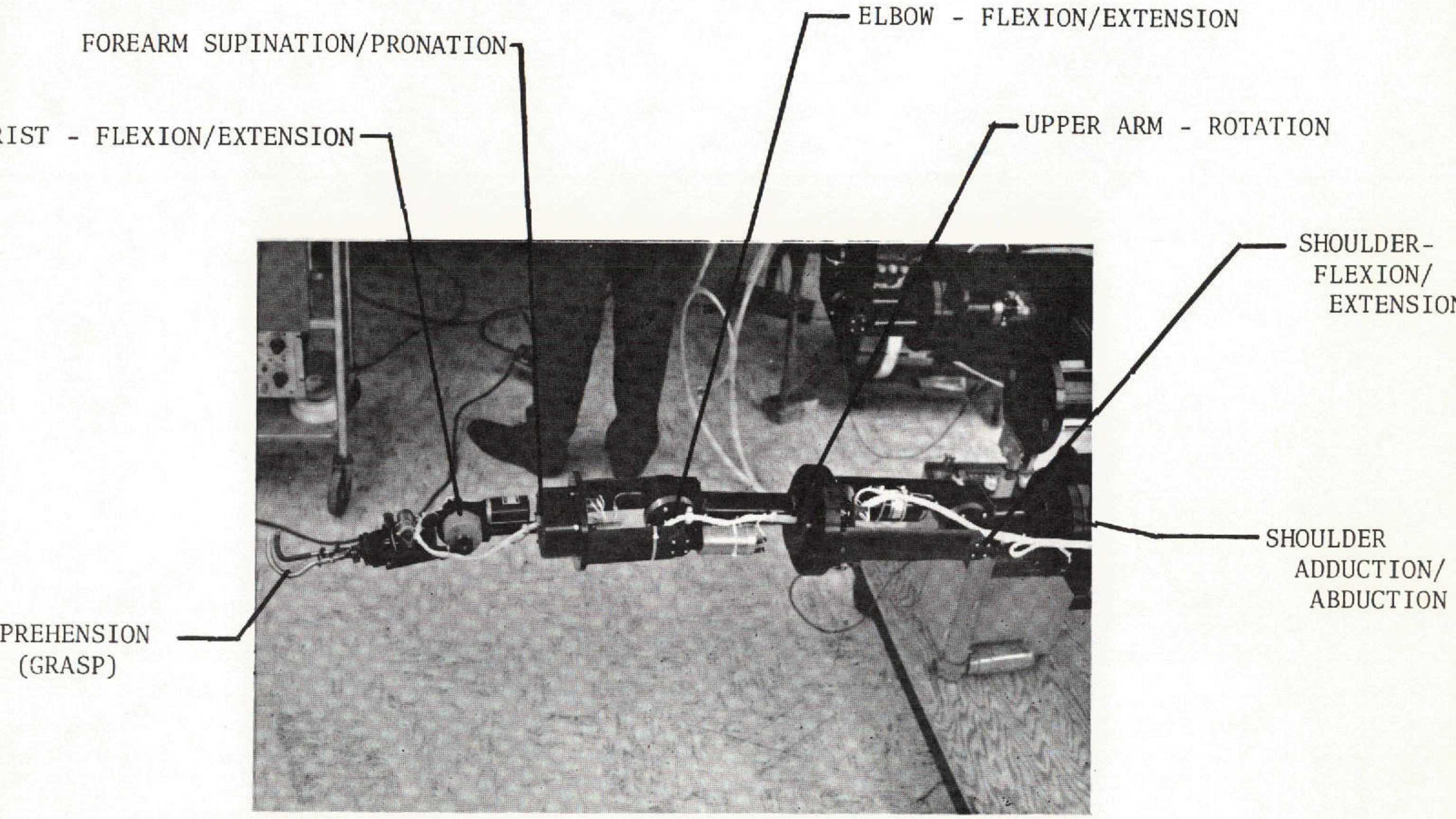


FIGURE 4

RAM ARM AT FULL EXTENSION

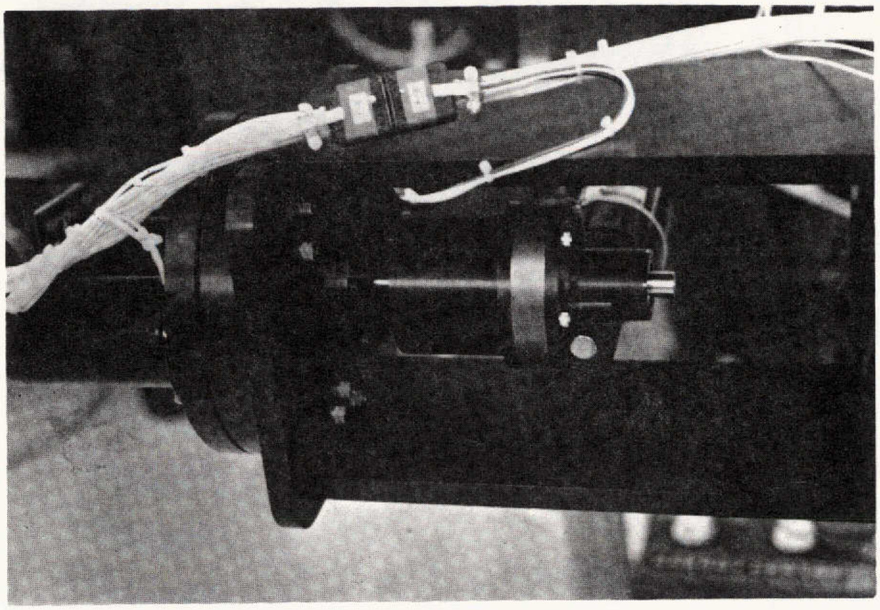


FIGURE 5 A

SHOULDER ABDUCTION/ADDUCTION JOINTS

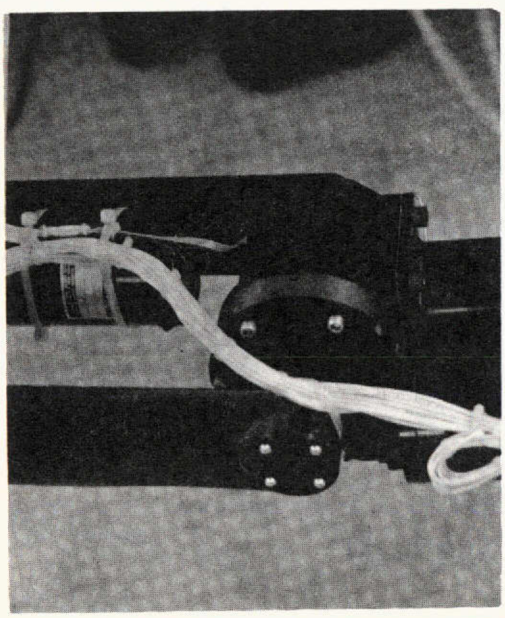


FIGURE 5 B

SHOULDER FLEXION/EXTENSION JOINTS

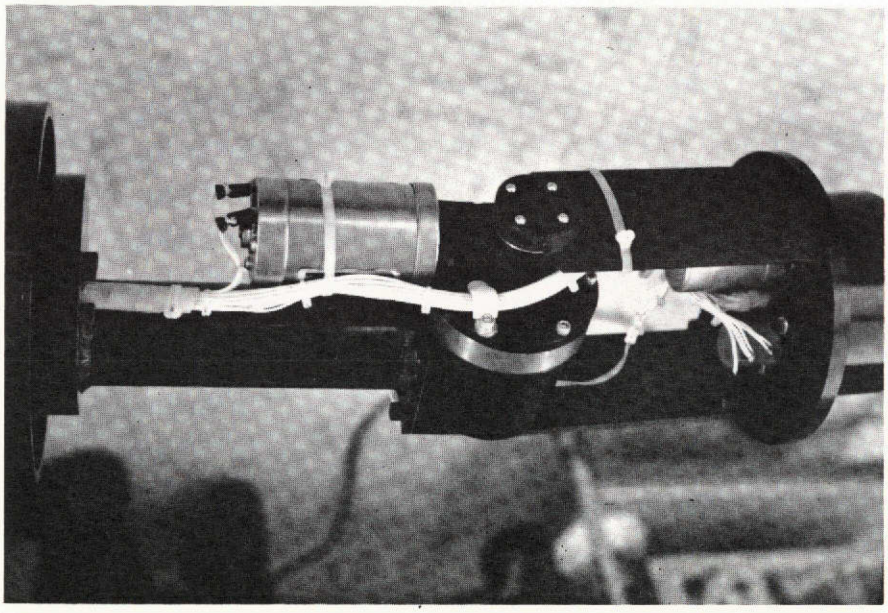


FIGURE 6

ELBOW FLEXION/EXTENSION JOINT

D. Supinator Joints. The supinator joint utilizes a Globe DG-3 gear motor with a planetary gear train providing a reduction of 120-1. The output of this planetary gear train drives a spur gear reduction in the form of a pinion and internal ring gear.

E. Wrist Joint. The wrist flexion and extension joint (see Figure 7) is similar to the shoulder and elbow flexion joints in that it utilizes a worm gear and harmonic drive reduction. However, the units are smaller since the loads are less at this joint. The motor is a Globe Motor No. 100A104-10 which drives a worm gear at 10-1 reduction. The harmonic drive is a USM Part No. HDUP-20-80 plastic unit which provides an 80-1 reduction and has been modified to increase its torque capabilities.

Detailed drawings of all the joint designs are included with this report.

3. Terminal Device Structure

The RAM is designed for an easy removal and attachment of terminal devices. The prehension function (in both the Dorrance hook and the parallel jaw device) is powered by an Otto Bock motor with a planetary gear reduction and 5-1 step down load sensing automatic transmission. Spur gearing drives a rack gear which, in turn, provides the thrust for opening and closing the terminal device. The terminal device disconnect mechanism is powered by the same motor. The disconnect mode operates only when the terminal device has been fully opened and an override control is operated thereby driving the terminal motor in the direction which would open the terminal device further.

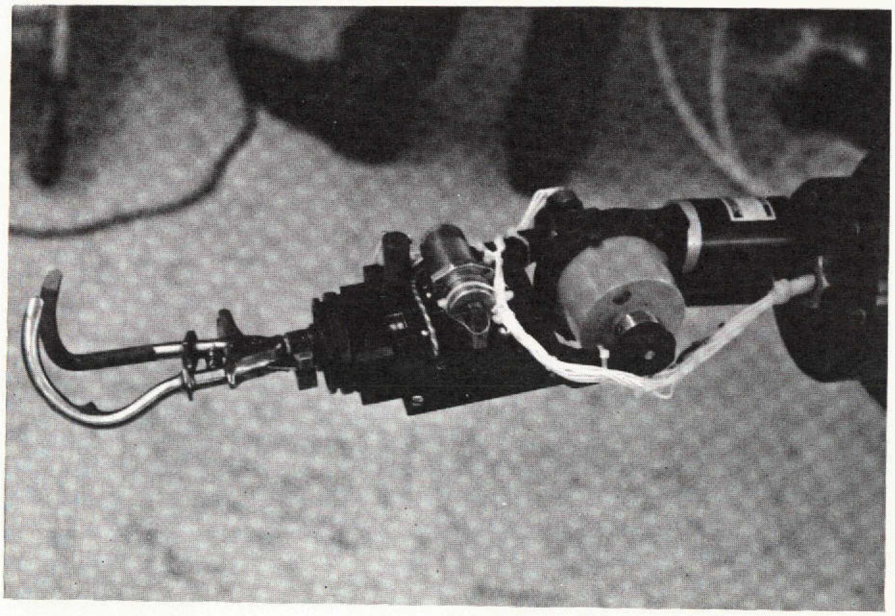


FIGURE 7

WRIST FLEXION/EXTENSION JOINTS

Operating the terminal device control in the opposite direction to provide a pinch function first locks the terminal device to the arm and then drives the terminal device in a closing direction.

The terminal devices are illustrated in Figures 3A and 3B. Note the grooved attachment surface which is identical in the hook and parallel jaw devices.

4. Structural Design

The major structural elements of the RAM are fabricated of aluminum and have a black anidized finished. Wires, cables, gears and drive mechanisms are so designed that they could be enclosed by an outside skin if so desired.

5. Control System

Potentiometers are provided at each joint for measuring angular position or for providing an error signal for servo control. Two types of controls are provided with the system. One of these is a direct switch control with the operator input commands to each joint motor provided by means of a handheld switch control box. This method allows for control of one arm at any given time, but a switch can be activated to alternate the controls from one arm to the other. The switch control is shown in Figure 8. The second control system is a servo control system which can be operated either as a velocity or position control system. The control system is a pulse width modulated system with the pulses to the motor occurring at a rate of 200 Hz (Figure 9). The input signal varies the width of the pulses from zero width to full dc. In the position servo mode the control or error signal is provided by means of a potentiometer for each joint. This type of input makes the system ideal for control by means of an exoskeletal brace structure worn by a human operator. The control system electronics were housed in a separate cabinet shown in Figure 10.

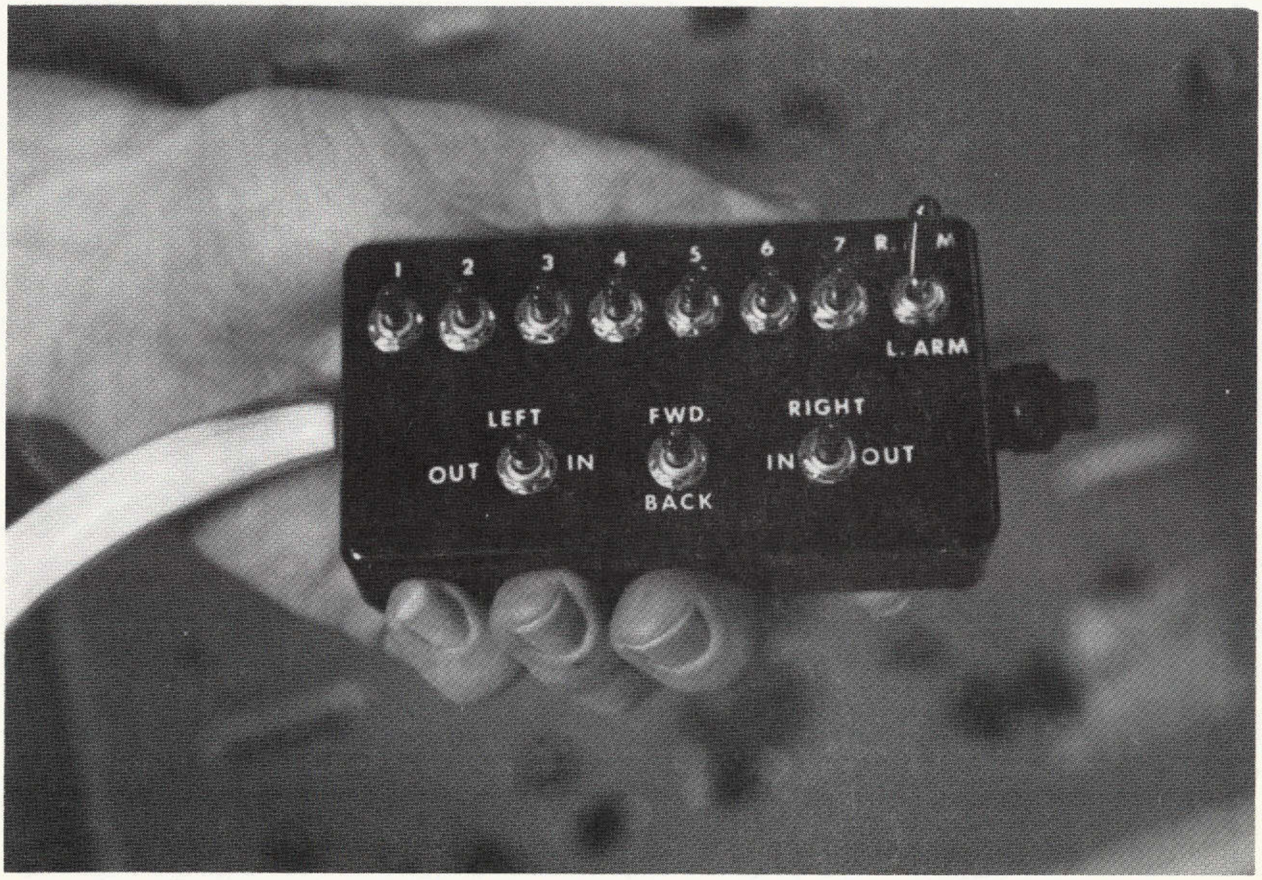


FIGURE 8

SWITCH CONTROL

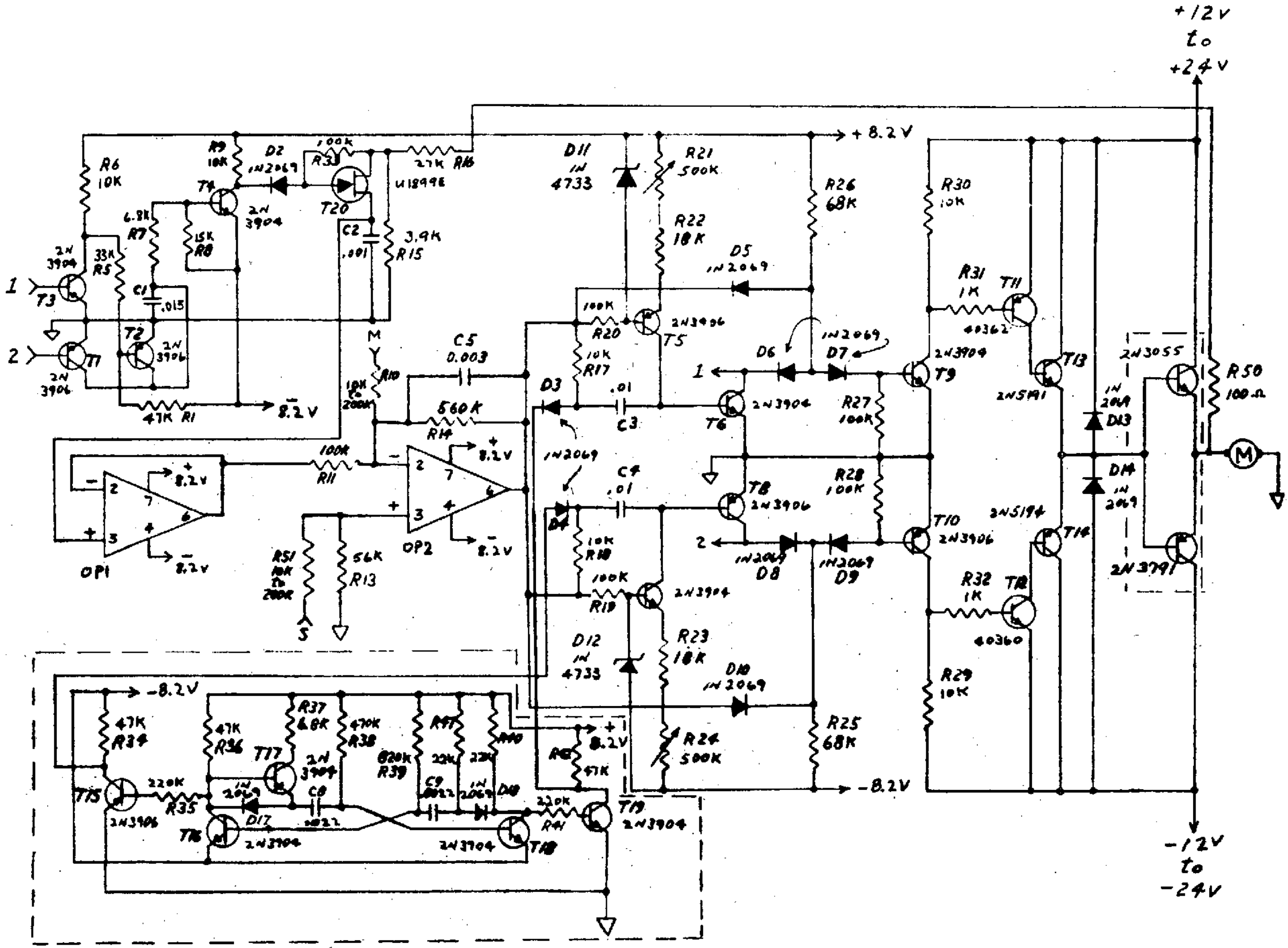
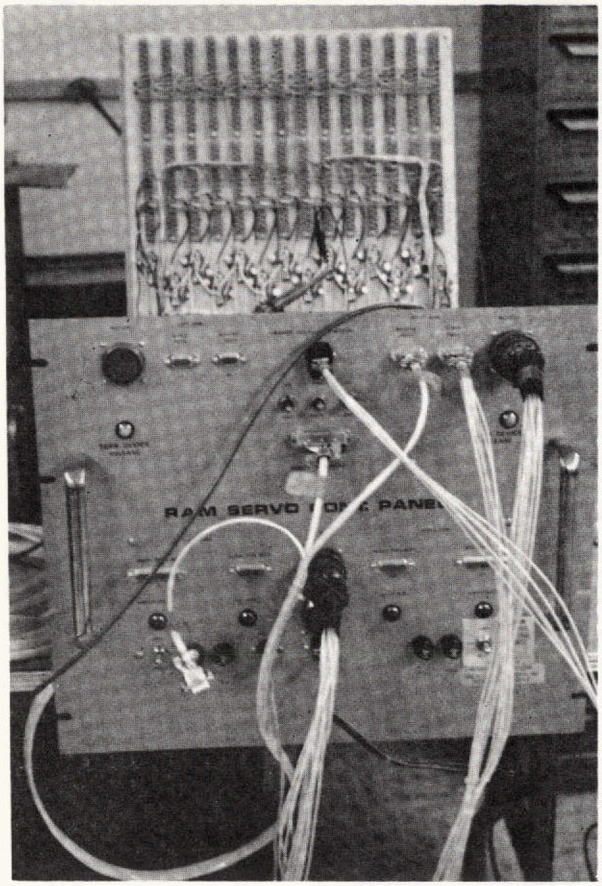


FIGURE 9

PULSE WIDTH MODULATOR, MOTOR CONTROL



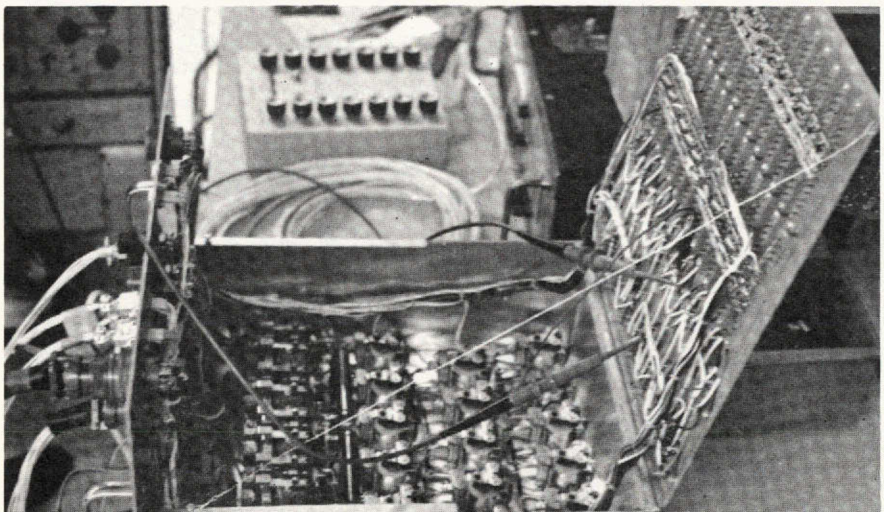


FIGURE 10

CONTROL SYSTEM ELECTRONICS CABINET

6. Bench Tests

Bench tests (Figure 11) were conducted with the joints to determine their capabilities and typical torque speed curves of the shoulder flexion and shoulder adduction/abduction joints and are provided in the following graphs, (Figure 12).

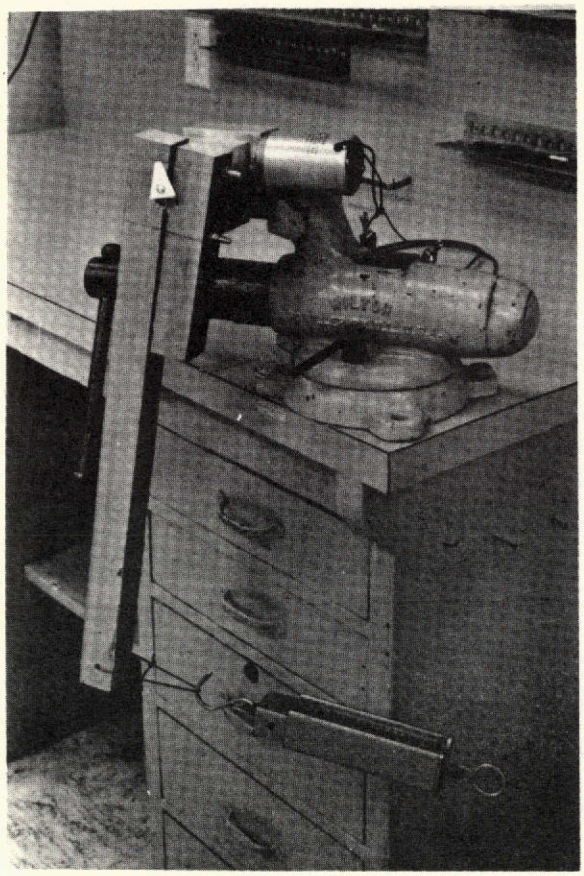


FIGURE 11

BENCH TEST SETUP

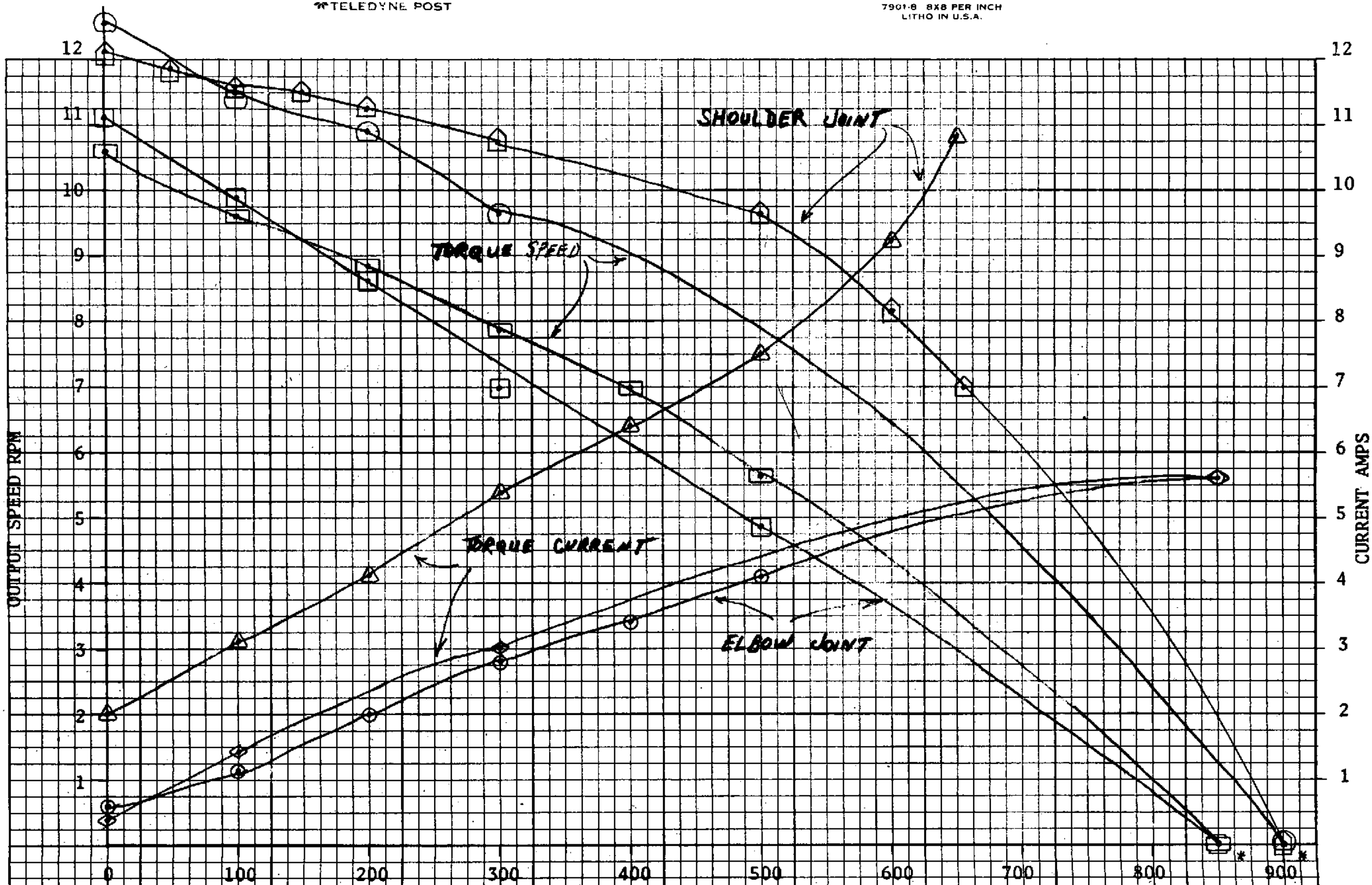


FIGURE 12

TORQUE IN - LBS.

TORQUE SPEED CURVE - RAM HARMONIC DRIVE REDUCERS

7. General Specifications

1. Weight:

(a)	Bilateral Mounting Structure	68 Kilograms
(b)	Full Arm (7 degree of freedom)	17.4 Kilograms
(c)	Shoulder Flexion Joint	3.3 Kilograms
(d)	Shoulder Adduction	2.4 Kilograms
(e)	Humeral Rotation	5 Kilograms
(f)	Elbow Flexion	2.8 Kilograms
(g)	Forearm Rotation	2.2 Kilograms
(h)	Wrist Flexion	.73 Kilograms
(i)	Terminal Device Actuator	.68 Kilograms

2. Dimensions:

(a) Mounting Structure

(1)	Length	.77 Centimeters
(2)	Width	122 Centimeters
(3)	Height	20.4 Centimeters

(b) Single Arm

(1)	Length	1.27 Meters
(2)	Largest Diameter	19 Centimeters

3. Velocity (Unloaded)

(a)	Shoulder Adduction Joint	12 RPM
(b)	Shoulder Flexion Joint	12 RPM
(c)	Humeral Rotation Joint	13 RPM
(d)	Elbow	11 RPM
(e)	Forearm Rotation	9 RPM
(f)	Wrist Flexion	12 RPM
(g)	Grasp - Full Open to Full Close	1.5 Seconds

4. Torque

(a)	Shoulder Adduction Joint	1070 kg.cm	900 in lbs.
(b)	Shoulder Flexion Joint	1070 kg.cm	900 in lbs.
(c)	Humeral Rotation Joint	690 kg.cm	600 in lbs.
(d)	Elbow	980 kg.cm	850 in lbs.
(e)	Forearm Rotation	173 kg.cm	150 in lbs.
(f)	Wrist Flexion	92 kg.cm	80 in lbs.
(g)	Grasp - Full Open to Full Close	9.1 kg	20 Lbs at Tip

6. Power Requirements - 24 Volts DC

		At Stall
(a)	Shoulder Adduction Joint	14 amp
(b)	Shoulder Flexion Joint	14 amp
(c)	Humeral Rotation Joint	14
(d)	Elbow	5.6 amps
(e)	Forearm Rotation	8 amps
(f)	Wrist Flexion	5 amps
(g)	Grasp - Full Open to Full Close	1/2 amp

7. Range

(a)	Shoulder Adduction Joint	270^{o}
(b)	Shoulder Flexion Joint	270^{o}
(c)	Humeral Rotation Joint	360^{o}
(d)	Elbow	270^{o}
(e)	Forearm Rotation	360^{o}
(f)	Wrist Flexion	180^{o}
(g)	Grasp - Full Open to Full Close	31 Inch Opening

8. Material and finish - 6061-T6 Aluminum with Black Anadize

9. Power requirements - 24 Volts - 36 amp capacity

8. Conclusions

The experience gained by the development of the RAM indicates that all of the original goals, both those that were formally stated in the contract and the somewhat idealistic performance concepts visualized by the developers, are achievable. However, all of these goals were not totally realized for reasons of limited resource and time. Ideally, the RAM would be a high performance oversized anatomical arm structure capable of approaching human arm and hand ability to perform a wide variety of types of tasks efficiently and without undue operator strain and fatigue. Such a device would have the following minimum capability and advantages:

A. Light weight plus high power and speed. The slave arm structure should be as efficient as possible in terms of weight to power (torque and joint velocity). This requirement was adequately achieved in terms of current state of the art electrical joint components (motors and gear trains). It is possible that a significant increase in this requirement may be realized, provided advance gear trains and power transmission devices are developed. These items will be discussed in greater detail under "Recommendations".

B. High joint rotational range: Each joint should have the greatest range possible in order to provide the manipulator with the ability to operate in any area of space within its total range envelope. This criteria was adequately achieved by the RAM. It is possible that a few degrees of extra rotation could have been designed into some of the joints, however, the increased operational performance would have been negligible.

C. Rigidity: The arm structure should exhibit minimal deflection under load. Also, there should be negligible back lash of the gear system, i.e., gear backlash should be undetectable without the use of sensitive measuring instruments: Superb results were achieved in the elimination of backlash in all of the RAM joints except forearm rotation. Backlash in the forearm rotation joint motion can be visually detected, however, it is not sufficiently great to adversely affect the operation of the manipulator. Under heavy rotational loads, the segmental joint conducting structures will excessively deflect.

D. The arm should have joints that are automatically locked in position when control current is not applied to the motors. These criteria were not adequately achieved by the RAM design. All joints do automatically lock or remain stationery provided they are not loaded, however, under any appreciable load, the joints will back drive. The system utilized to achieve static joint locking is gear friction. The efficiency of the gear train was so nigh that back drive of the joint became possible.

E. Reliability. The arm structure should be sufficiently durable to withstand a relatively high operation duty cycle (40%) without undue maintenance problems. Sufficient operation time of the arm has not as yet occurred to ascertain the reliability of the RAM. It is likely that the most unreliable components of the structure are the wiring harness and the control system. A hazard situation for the mechanical structure would be to subject it to excessive impact loading such as could occur if the arm struck a stationery object at high speed.

This could possibly strip gears or sever power transmission shafts. Prolonged stall of the arm would not be likely to injure the arm itself but could result in the overheating and failure of the control power transistors.

F. The arm should be waterproof. Waterproofing of the arm would prevent damage by foreign matter such as dust, moisture, and solid objects. It would also extend the operating capability of the arm to environments other than air. The arm was designed and fabricated with sealed joints and a structure to facilitate the attachment of waterproof covers. The Electrical cabling is completely enclosed except the cable entrance at the shoulder adduction joint.

G. The arm should have the capability of unilaterally changing its own terminal devices by remote operator control only. This requirement was achieved.

H. The arm should be equipped with a variety of terminal devices. In order to achieve the equivalent of a semblance of human hand dexterity and ability, the hand should have as many different terminal devices as possible. It is not feasible to even remotely approach the capability of the human hand by a single mechanical device, however, it is possible to perform a wide variety of tasks, comparable to those commonly performed by the anatomical hand by use of many end effectors each of which is designed to perform a specific type of task. The RAM was supplied with two terminal devices - a prosthetic Dorrance hook and a conventional parallel jaw end effector.

I. The control system should be capable of providing smooth slave arm motion at any velocity. The control system supplied with the RAM is a proportional system that supplies pulses to the slave arm that are pulse width modulated by analog input signals. The system may be operated as a closed loop or open loop system.

J. The control system should be easily interfaced with most input devices such as: (a) switch control, (b) analog to transducers (potentiometers or strain gages), (c) anthropomorphic operator brace controls, (e) computer control and, (g) telemetered controls. The RAM control system meets these specifications.

9. Recommendations

The RAM system represents a first model of a high performance electrically powered manipulator system that attempts to take advantage of current state of the art technology to produce a complete system having maximum versatility and capability. Observation of this first model demonstrates that certain improvements in the design are desirable in order to realize the full potential of the system.

These improvements with the exception of gear train and power transmission design individually require relatively moderate design effort. They are:

A. Rigidity: The structural integrity of the RAM could be significantly improved by replacing the segment attachment bars with structures capable of withstanding greater rotational and bending forces.

B. All joints should automatically lock in place, regardless of loading when not being actuated by the operator. This could be achieved by electromagnetically operated brakes attached to the armature shaft of the joint motor. This modification is considered to have very high priority.

C. Wrist Flexion Joint. The wrist flexion/extension joint should be replaced with a higher torque unit. Greater torque capability is required at the wrist than originally anticipated.

D. A wide variety of terminal devices should be available for this RAM. A terminal kit assembly is currently being designed and fabricated by the RAM developers that will provide the use of most common hand tools. by a manipulator. These end effectors should be made available for use by the RAM as well as any special purpose terminal device required for anticipated specific tasks.

E. The control system should have increased power delivery capability. This would increase the reliability of the control system by making it unaffected by prolonged stall current. Higher quality performance at low speed could also be achieved.

F. A load sensing automatic transmission should be designed for use on all manipulator joints. This unit would automatically down shift the joint gears when predetermined loads were encountered by the manipulators. The benefits of such a device are:

(1) Extremely large loads may be moved by a compact and lightweight joint.

(2) High velocity of the unloaded joint is not sacrificed.

(3) Power requirements of the joints may be reduced by a factor of ten thus enabling the long-term use of the manipulator by a miniature battery supply.

The development of an automatic gear changer that would respond to uni-directional loads and could conceivably be fabricated for any size motor should have the highest priority. Such a design would require considerable effort; however, the benefit to teleoperator technology would be enormous.

It is recommended that Items A through E be implemented on the RAM system as soon as convenient. A separate development effort to produce an automatic loading transmission (Item F) should commence immediately.