View metadata, citation and similar papers at core.ac.uk
brought to you by CORE
provided by NASA Technical Reports Server

/8/

N90-22105

DEVELOPMENT OF CABLE DRIVE SYSTEMS FOR AN AUTOMATED ASSEMBLY PROJECT

Charles A. Monroe, Jr.*

ABSTRACT

In a robotic assembly project, a method was needed to accurately position a robot and a structure which the robot was to assemble. The requirements for high precision and relatively long travel distances dictated the use of cable drive systems. This paper will discuss the design of the mechanisms used in translating the robot and in rotating the assembly under construction. The design criteria will be discussed, and the effect of particular requirements on the design will be noted. Finally, the measured performance of the completed mechanism will be compared with design requirements.

INTRODUCTION

The further exploration and utilization of space will include larger and more complex structures, requiring in-orbit assembly. This repetitive, time-consuming task is better suited for robots than astronauts. To develop the technology and experience necessary to carry out this endeavor, the Automated Structural Assembly Laboratory[1] was developed at NASA Langley Research Center (Fig. 1).

Completed in 1988, this facility involves a robotic arm that translates over a six- by six-meter area and a structural assembly support platform that rotates about its axis. The structure that the robot assembles is a tetrahedral truss. It consists of two-meter composite struts joined by aluminum nodes. The facility will accommodate trusses composed of three "rings" of tetrahedrons for a total diameter of 12 meters.

A design requirement for the equipment was that the robot must always "know" the position of its end effector in relation to the individual nodes of the structure it was assembling. For the mechanical components that convert the output from the motors to the desired translation or rotation, this requirement necessitated a very stiff system with essentially no backlash or slippage.

DESIGN CRITERIA

The assembly approach the research engineer chose required the robot to translate over a planar area and the assembly support turntable to rotate about its axis (Fig. 2). The specific requirements of the drive systems are as follows:

---

*NASA Langley Research Center, Hampton, Virginia

X and Y Translation Systems
Travel: 6 meters in X and Y directions
Speed: 150 mm/s
Acceleration: 610 mm/s^2
Accuracy: ± 0.25 mm

Turntable
Rotation: 6 revolutions
Speed: 1.45 degrees/s (150 mm/s at a node at the six-meter radius)
Acceleration: 5.8 $degrees/s^2$ (610 mm/s^2 at a node at the six-meter radius)
Accuracy: ± .0024° (±0.25 mm at a node at the six-meter radius)

X- AND Y-DRIVE SYSTEMS

Several drive systems were considered for the translation systems. A geared drive, such as a rack and pinion, would have an inherent backlash that would result in inaccuracies greater than the 0.25 mm allowed. The slippage in a traction system would also be greater than the allowable error. A ball screw arrangement would have sufficient positioning capability, but the need for a six-meter shaft would make this method impractical. A cable drive system was selected, which offers high accuracy over the required distance of travel.

This cable drive system must move 1400 kg in the X-direction, requiring an 854-N force to achieve the desired acceleration of 610 mm/s^2. The system consists of two parallel shafts, identified as the main drive shaft and the secondary shaft (Fig. 3). The output of a servomotor is increased via an 89:1 torque multiplier. This torque multiplier has a backlash no greater than one arc minute. This drives a 152-mm-diameter drum mounted on the secondary shaft. This drum drives the main drive shaft via an 8-mm cable that is wrapped around this drum and a 305-mm-diameter drum on the main shaft (Fig. 4). This shaft runs the length of the X-carriage and has 305-mm-diameter drums mounted on either end. The carriage is pulled along 9.5-mm cables that wrap around each end-mounted drum and terminate at either end of travel.

The Y-drive system (Fig. 5) must translate a 602-kg mass. Just as on the X-drive, a servomotor drives an 89:1 torque multiplier. However, rather than transmit this torque to another shaft, this shaft drives the lighter Y-carriage directly. Two cables are wrapped around a 203-mm-diameter drum once, and each is anchored at either end of travel.

The positioning requirements created a stringent deflection criteria which superseded stress considerations. On the X-drive system, the maximum angular deflection of the drive shaft between the center and end drums could not result in more than a 0.25-mm linear deflection at the 152-mm radius.

The primary reason for having a drum on each end of the drive shaft on the X-drive system instead of a single drum, as on the Y-drive, was to prevent "racking" of the X-carriage. The rails under the X-carriage are almost five meters apart, whereas the rails supporting the Y-carriage are slightly less than a meter apart. Also, while the center of mass of the Y-carriage remains fairly constant, the center of mass of the X-carriage varies with the position of the robot in the Y-direction. These two factors made "racking" a design consideration in the X-direction.

TURNTABLE

To give the truss and turntable (Fig. 6) the desired angular acceleration, a torque of approximately 4880 N-m was required. A system was needed to transmit and multiply the motor torque while maintaining the desired accuracy. As with the translation systems, other systems were considered and rejected because of the positioning criteria. A cable drive concept was judged to offer the best opportunity for meeting the accuracy requirement. Commercially designed systems[2] were unacceptable because of time and cost constraints.

A basic description of the system is as follows (Fig. 7). A 1.07-m-diameter drum is rigidly attached to the rotating portion of the turntable. Aligned parallel to the drum is a 51-mm-diameter shaft. Five cables were wrapped around the large drum seven times and the shaft once, with the cable ends attached at the top and bottom of the drum. A servomotor is attached to the shaft via an 89:1 torque multiplier that, along with the 21:1 gear reduction between the shaft and the drum, creates a 1869:1 reduction. This makes possible a large torque from a small motor and reduces the error in the already accurate servomotor.

A 760-N load is carried by the turntable's cables. A conservative design convention is to choose cables with a combined breaking strength of approximately 10 times this value. Also, to ensure that the cables were not damaged by too small of a bend radius, a safe practice is to have a bend-radius-to-cable-radius ratio of approximately 25:1. Considering the shaft's radius of 25 mm, the cable radius could not be larger than 1.0 mm. Five 1.6-mm-diameter cables were chosen with a breaking strength of 2200 N each for a total breaking strength of 11 kN.

DESIGN CONSIDERATIONS

Slippage on the drums is a function of the angle of contact of the cable on the cylinder (Fig. 8). The ratio of the taut side tension, T_1, to the slack side, T_2, must be less than shown in the equation[3]

$$T_1/T_2 < e^{(mu)(theta)} \qquad (1)$$

For this design, the critical angle of wrap, (theta), is 2(pi) and the coefficient of friction, (mu), is conservatively assumed to be 0.15. In this case, the ratio T1/T2 must be less than 2.57. This was accomplished by designating a sufficiently large preload.

On the X-drive system, there was difficulty achieving sufficient preload on the cable connecting the drums between the two shafts. To solve this problem, the bearings supporting the secondary shaft and the housing of the torque multiplier were mounted on slotted plates (Fig. 9). Threaded rods that are attached to each bearing support plate are inserted through holes in blocks attached rigidly to the carriage. When bolts are tightened on the rods, the secondary shaft is pulled away from the main drive shaft, thus tightening the cable.

There are a few design differences worth noting between the turntable and the X- and Y-cable drive systems. On the turntable, the ends of each cable are attached to the large drum by a spring (Fig. 10). Since the spring constant is known, the preload can be determined by measuring the deflection of each spring. This ensures that the required preload is used and that the tension of each spring is equal. As long as a sufficient angle of wrap is maintained between the spring and the point that the cables separate from the drum, friction will prevent the springs from affecting the mechanism's performance.

On the X- and Y-systems, springs could not be used at the cable termination points because of transient expansions and compressions that would occur during acceleration and deceleration. Instead, the cables were tied to eye bolts at the termination points. The eye bolts were threaded so that the tension in the cables could be estimated by the number of turns used in tightening each eye bolt. Since the cables were oversized, they could be tightened to a point that is above the required tension to avoid slip on the drums, yet well below the cable breaking strength. A disadvantage of this procedure is that cables operating on the same drive system may have slightly different tensions. This has not proven to be a problem in the operation of the system. In applications where assurance of proper operation is critical, such as in-space construction, strain gauges or load cells on the cables would be advisable.

Another difference between the turntable and the X- and Y-drive systems involves using a grooved surface as opposed to a flat surface on the face of the drums. On the X- and Y-drive systems, each cable is wrapped around a flat-surfaced drum and terminated at either end of travel. The cable termination points are offset so that the cable will "walk" from one end of the drum to the other as it rotates along its length of travel (Fig. 11). This offset ensures that the cable will "walk" evenly without binding and that, on the Y-drive, the two cables will not tangle. The preload of the cables is great enough to ensure that no slippage on the drum occurs.

On the turntable, there are two factors that require a grooved shaft as opposed to the flat-surfaced drums in the translation system. First, the grooves are needed to guide the cables. The possibility of tangling or binding is increased by having five cables wrapped around a large drum rather than one or two cables extended linearly as on the translation systems.

Secondly, the grooves increase the friction between the shaft and the cables. As mentioned previously, 1.6-mm cables were selected to prevent damage due to the shaft's 25-mm bend radius. These small cables could not carry the excessive preload that is used in both the X- and Y-drives. With the shaft being grooved, a smaller preload could be used without bringing about slippage.

RESULTS

On the X-drive system, the position accuracy and repeatability is ±.05 mm, bettering the goal of ±.25 mm maximum. The speed is 124 mm/s, slightly less than the 152 mm/s design criterion, and the acceleration of 564 mm/s^2 is less than the desired 610 mm/s^2. The speed and acceleration are less than anticipated because a larger-than-expected force is required for motion. As the project evolved, unexpected items were added to the carriage's payload. Also, additional electrical wiring and air hoses in the cable carriers increased the carriers' resistance to motion. In retrospect, the sizing of the motor required to move the carriage could have allowed for these inevitable changes in an experimental project. These deficiencies do not have a significant effect on the facility's operation and could be easily corrected by providing a larger motor.

All of the design criteria have been surpassed with the Y-drive system. The positional accuracy and repeatability of the cable system is again ±.05 mm, bettering the ±.25-mm goal. The speed and acceleration achieved with the lighter Y-carriage are 223 mm/s and 743 mm/s^2 both surpassing the goals.

The rotational accuracy of the turntable is ± 0.0041°, which is the minimum command step from the motor with the given gear ratio. This falls short of the design criteria of ± 0.0024°, which was based on the goal of ±0.25-mm accuracy of a node at a six-meter radius. The achieved results have proven adequate. The maximum speed is 5.60 °/s and the acceleration is 19.32°/s^2, both surpassing the requirements.

It is worth noting that all of the position accuracies were achieved running the motors open-loop. While the equipment does contain positioning sensors, no feedback from the sensors is necessary to obtain the above results.

CONCLUDING REMARKS

The purpose of the Automated Structural Assembly Laboratory is to prove that in-space robotic assembly is plausible and to develop the technology needed to carry this assembly out. The cable drive systems further this project in two ways. First, it is a fairly simple and inexpensive method for achieving the motion needed to conduct the robotic experimentation. Secondly, it offers a proven concept for accurate motion transmission that could ultimately be used for in-space assembly.

Similar drive systems could be used for other experimental and commercial applications. The design procedures could be essentially duplicated for even much larger systems to achieve similar accuracy.

REFERENCES

1. Rhodes, M.D.; Will, R.W.; Wise, M.A.: A Telerobotic System for Automated Assembly of Large Space Structures. NASA TM 101518, March 1989.

2. Roto-Lok^R Rotary Drive System, Trax Instrument Corporation, Albuquerque, New Mexico.

3. Fuller, D.D.: Marks' Standard Handbook for Mechanical Engineers, Eighth Edition. Chapter 3: "Friction" p. 3-32, 1978.

ORIGINAL PAGE
BLACK AND WHITE PHOTOGRAPH

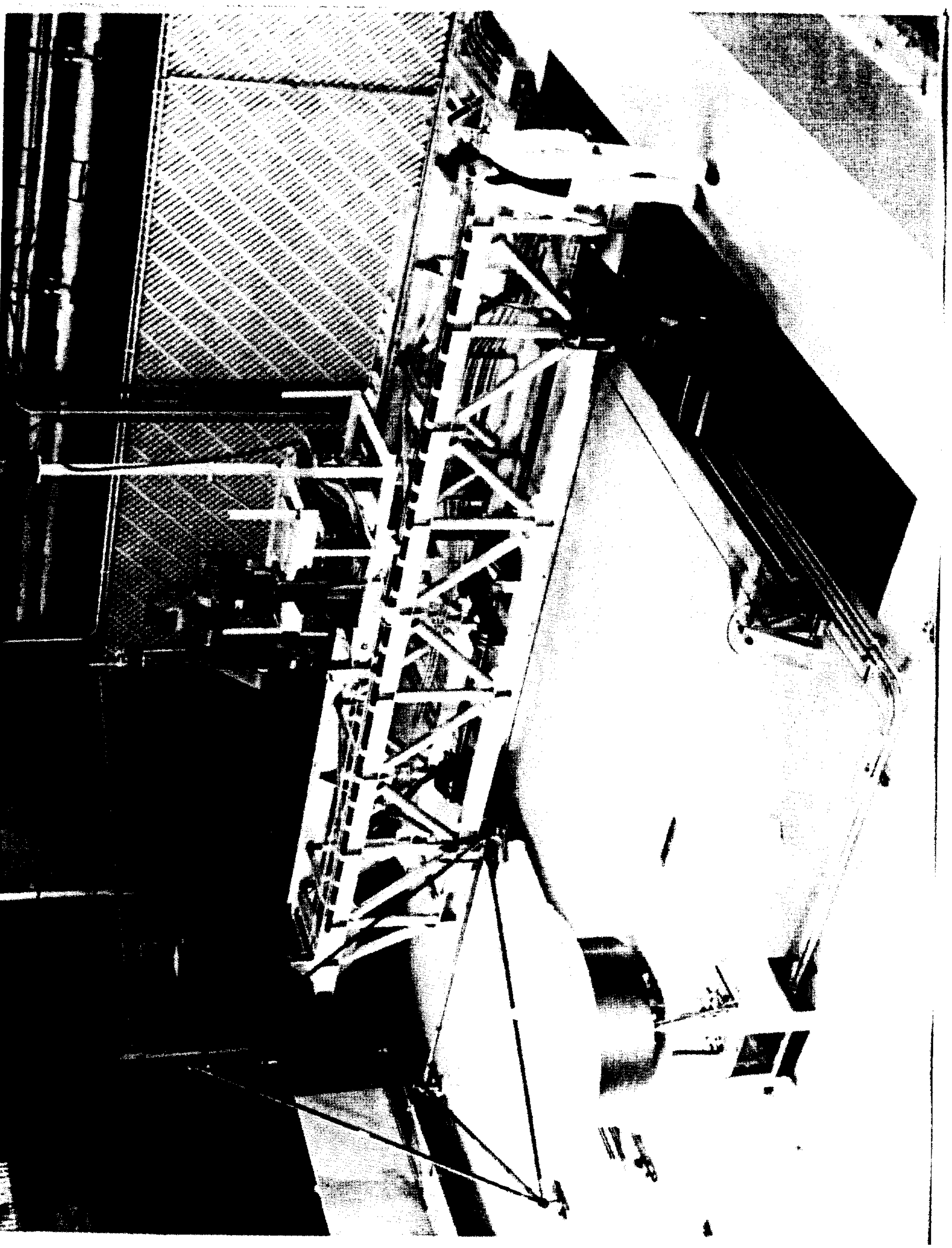
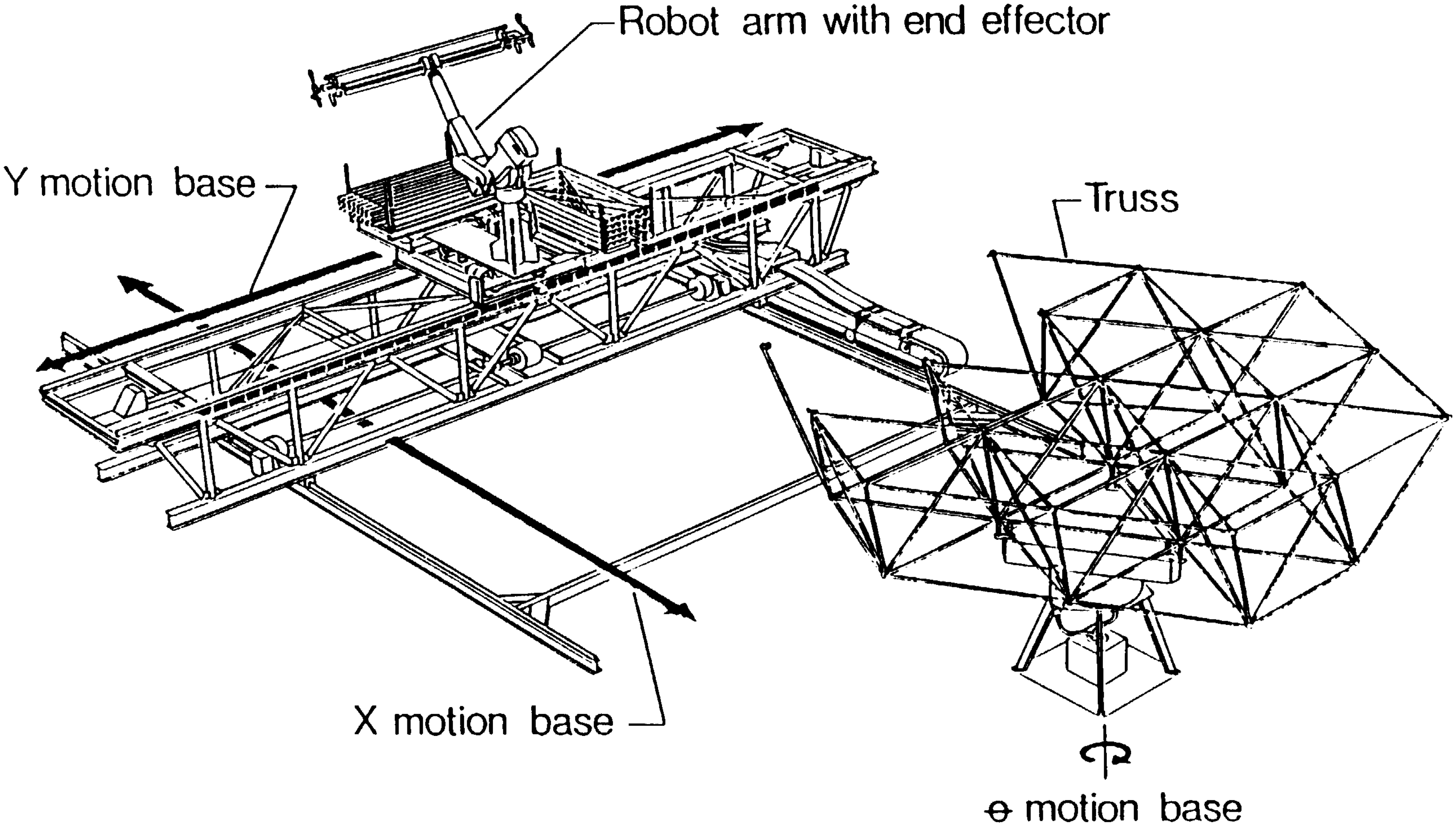


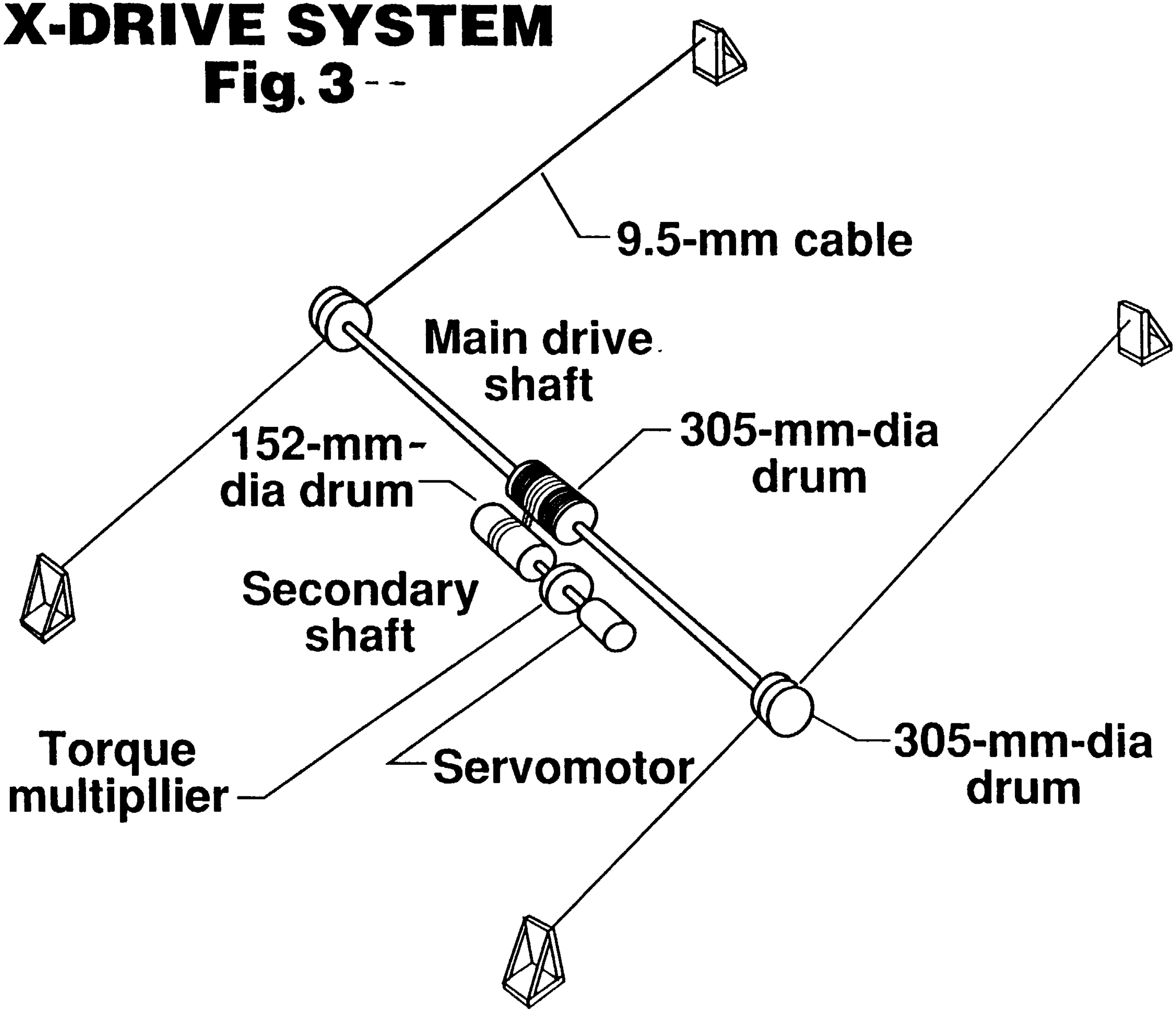
FIG. 1 -- AUTOMATED ASSEMBLY LAB

FIG. 2 – –

TELEROBOTIC ASSEMBLY FACILITY



X-DRIVE SYSTEM
Fig. 3



ORIGINAL PAGE
BLACK AND WHITE PHOTOGRAPH

ORIGINAL PAGE IS
OF POOR QUALITY

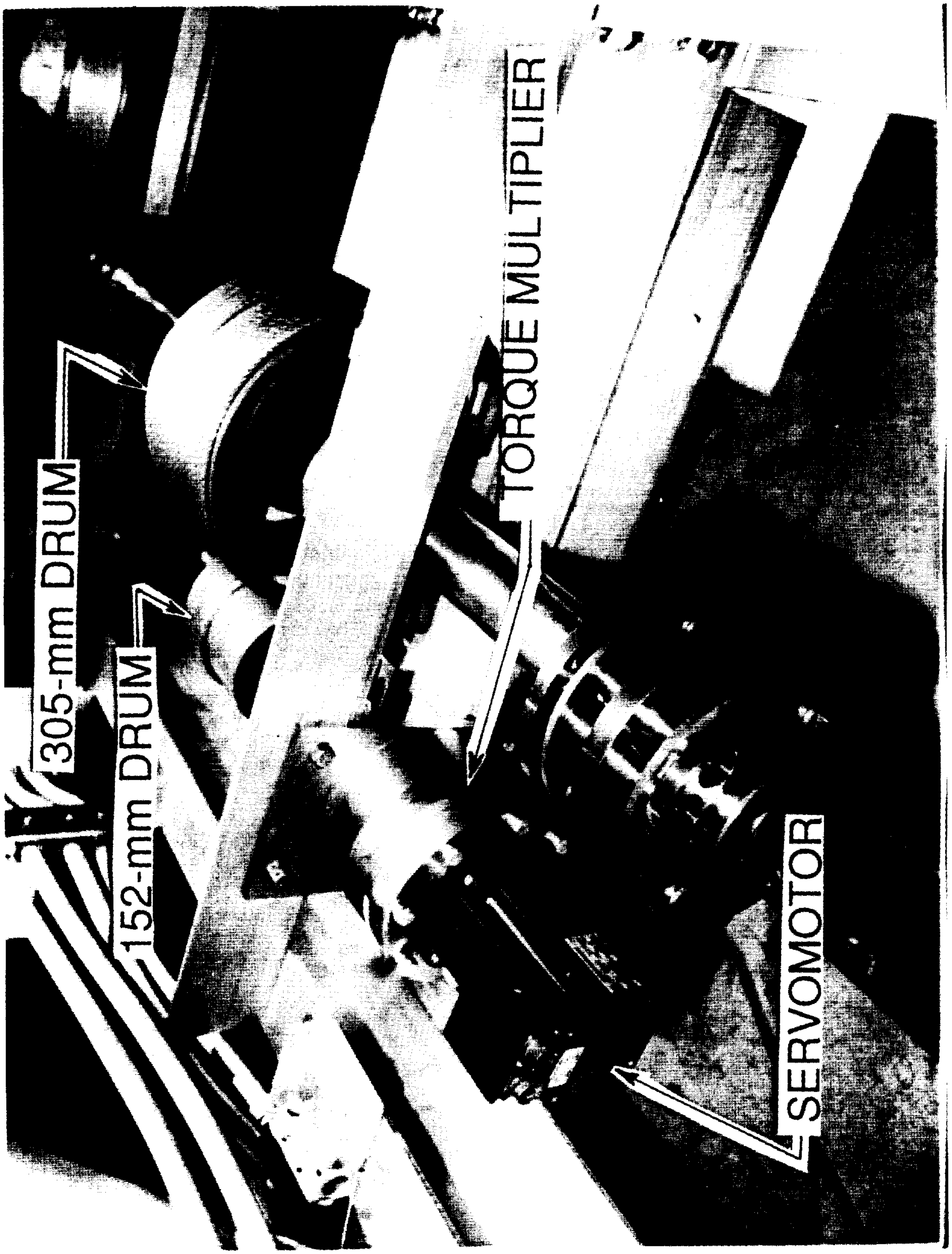
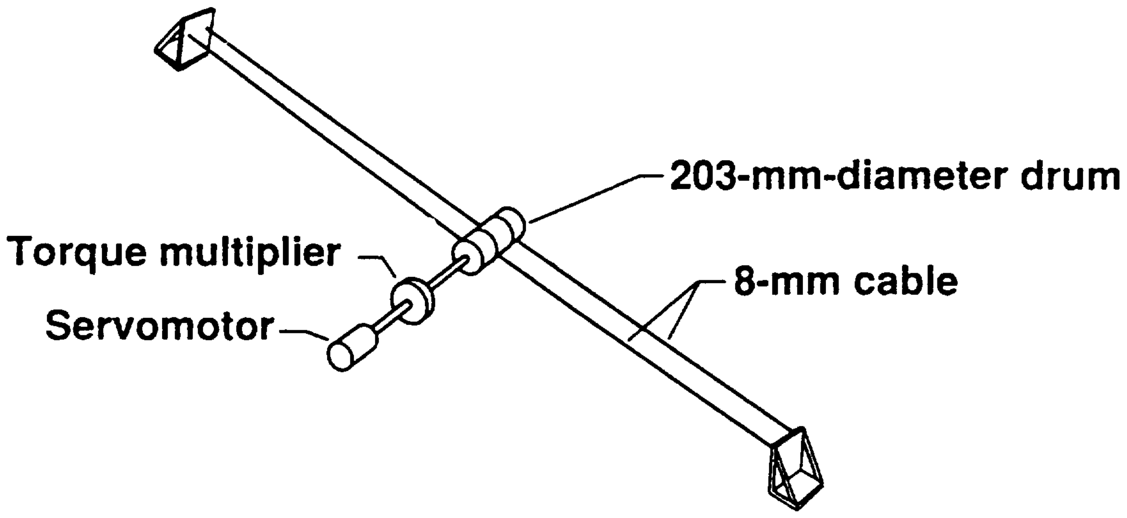
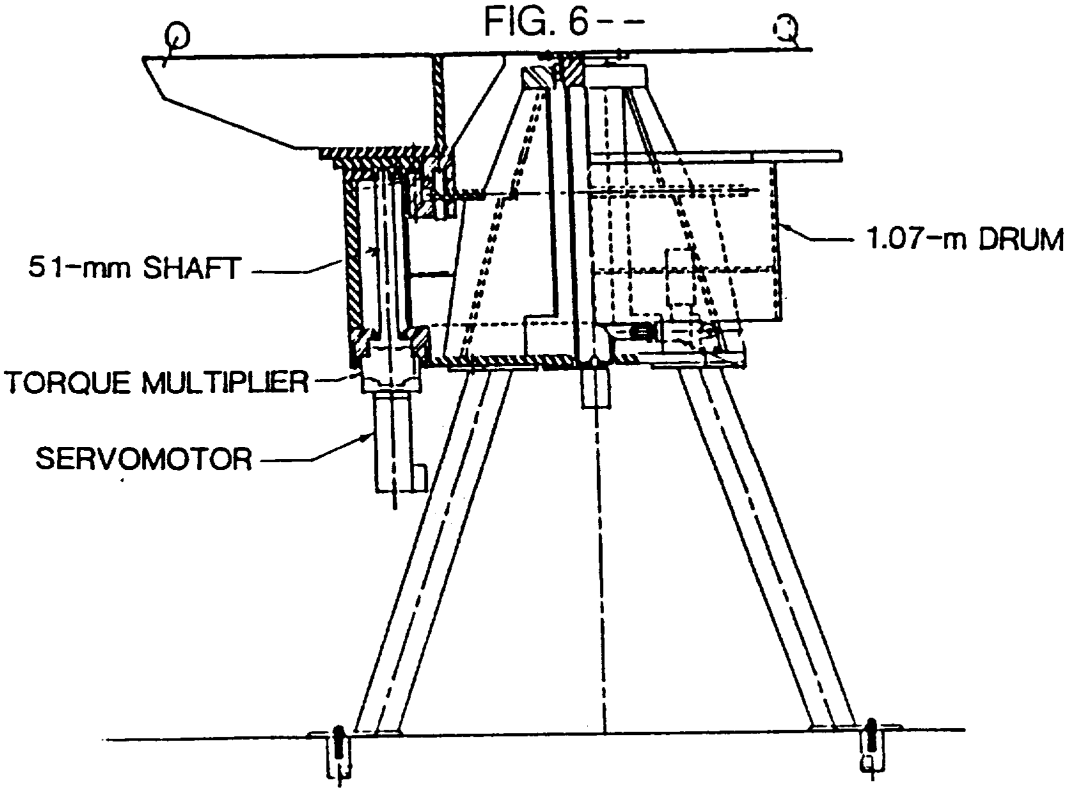


FIG. 4 -- X-DRIVE COMPONENTS

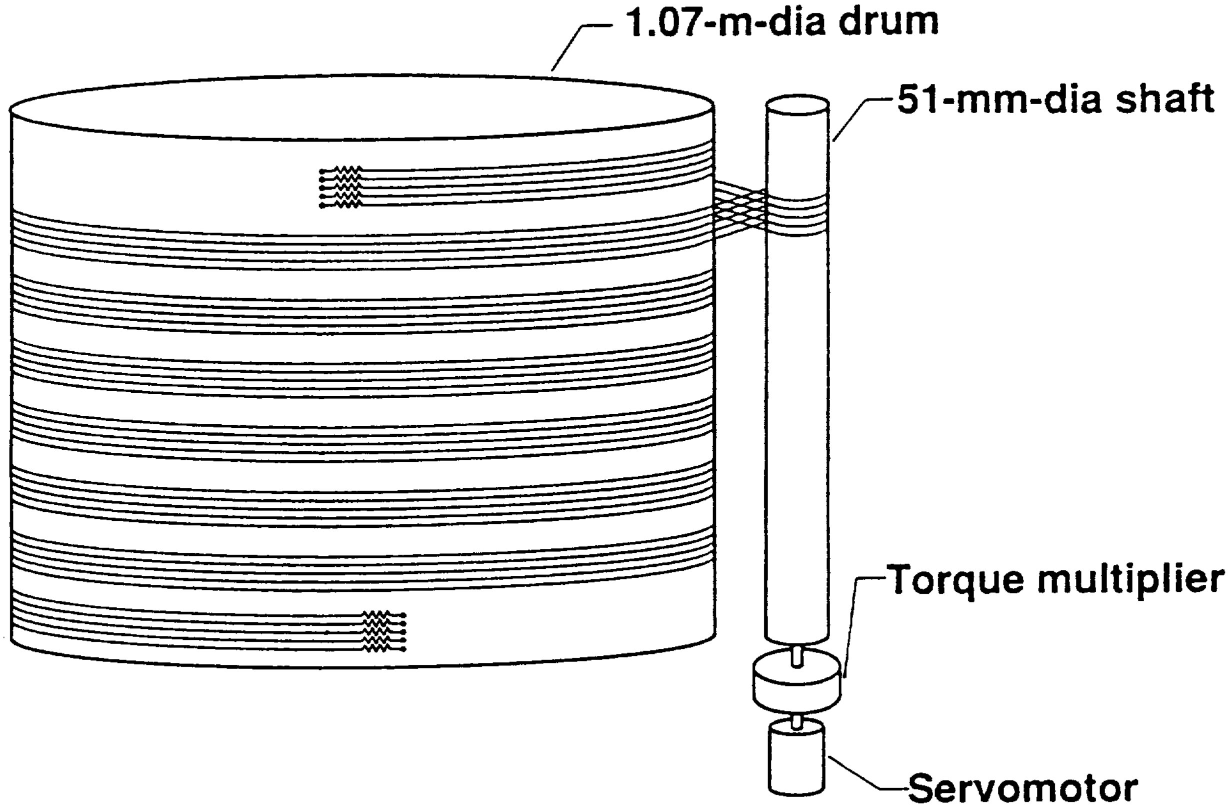
Y-DRIVE SYSTEM
Fig. 5 – –



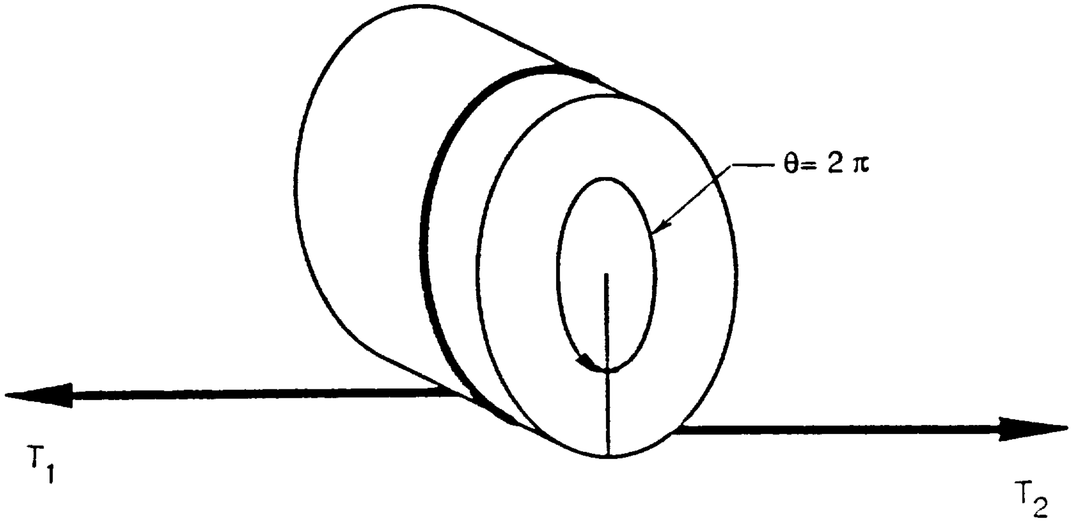
TURNTABLE
FIG. 6 – –



TURNTABLE DRIVE SYSTEM
Fig. 7--



ANGLE OF CONTACT
FIG. 8--



ORIGINAL PAGE
BLACK AND WHITE PHOTOGRAPH

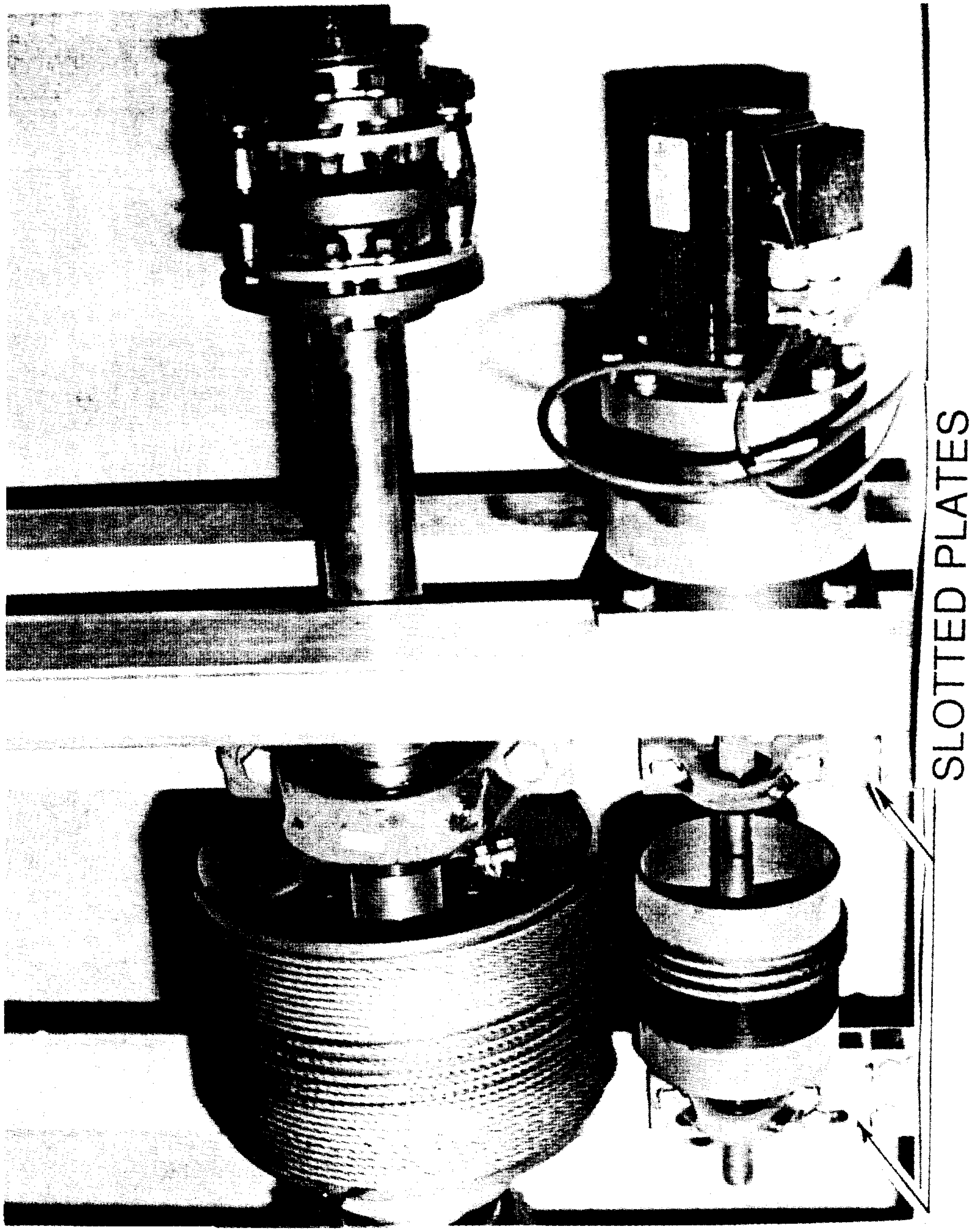


FIG. 9 -- X-DRIVE CABLE TENSION

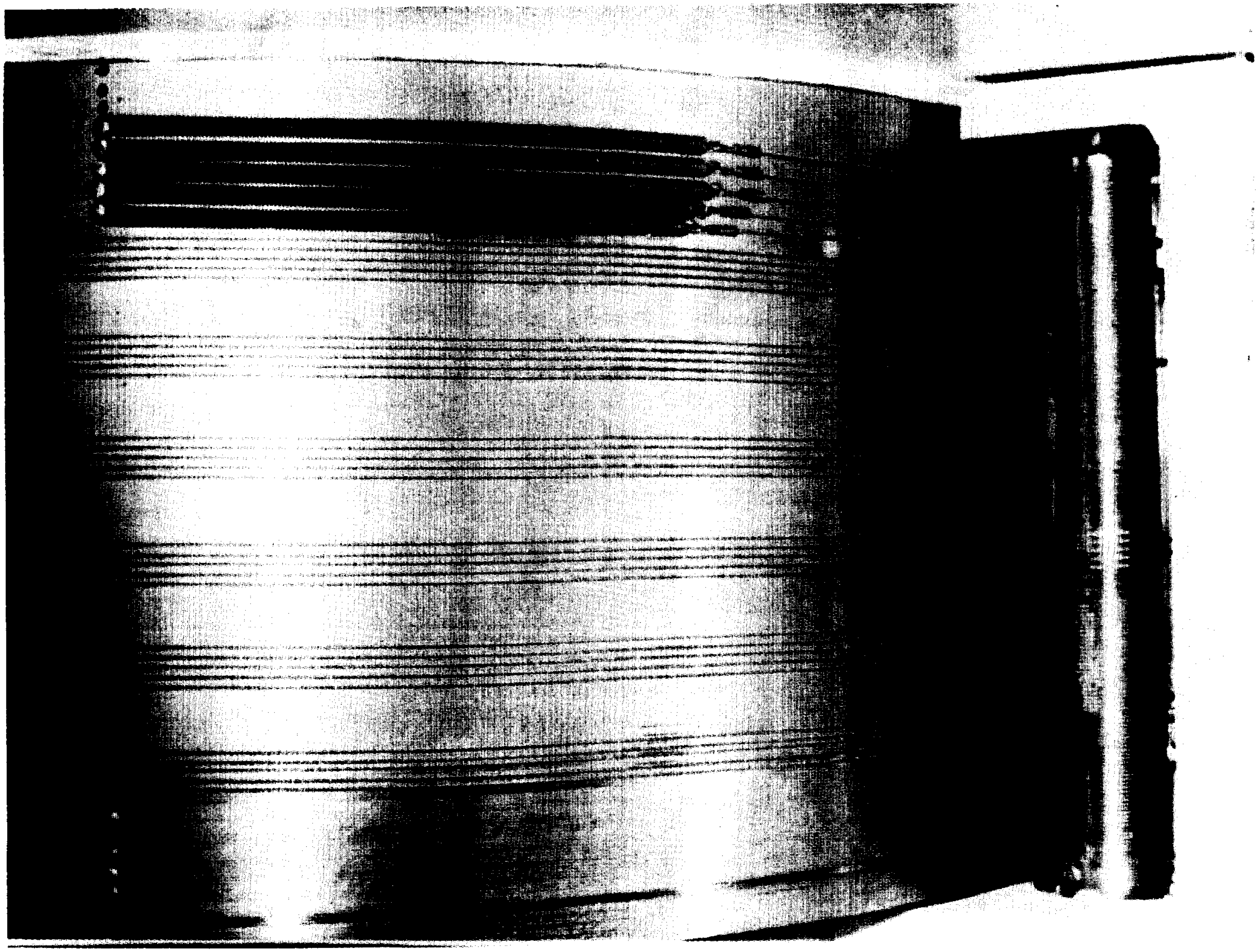
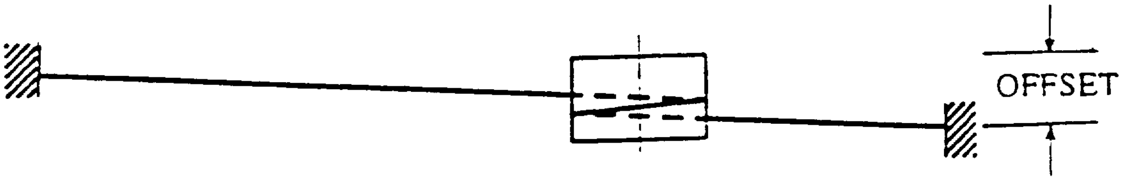


FIG. 10 -- TURNTABLE DRUM & SHAFT

CABLE TERMINATION OFFSET

FIG. 11 – –



NASA

Report Documentation Page

1. Report No. NASA CP-3062	2. Government Accession No.	3. Recipient's Catalog No.

4. Title and Subtitle

24th Aerospace Mechanisms Symposium

5. Report Date

April 1990

6. Performing Organization Code

7. Author(s)

8. Performing Organization Report No.

10. Work Unit No.

9. Performing Organization Name and Address

John F. Kennedy Space Center
Kennedy Space Center, Florida 32899

11. Contract or Grant No.

13. Type of Report and Period Covered

Conference Publication

12. Sponsoring Agency Name and Address

National Aeronautics and Space Administration
Washington, D.C. 20546

14. Sponsoring Agency Code

15. Supplementary Notes

California Institute of Technology, Pasadena, CA 91109
Lockheed Missiles and Space Company, Inc., Sunnyvale, CA . 94088

16. Abstract

The proceedings of the 24th Aerospace Mechanisms Symposium, which was held at the John F. Kennedy Space Center, Kennedy Space Center, Florida, on April 18-20, 1990, are reported. Technological areas covered include actuators, aerospace mechanism applications for ground support equipment, lubricants, latches, connectors and other mechanisms for large space structures.

17. Key Words (Suggested by Author(s))

Circularity
Piezoelectrics
Robotics
Hand Controller
Telescoping
End-Effector
Satellite Attitude Cont.
Bearings
Tribology
Friction Brakes

18. Distribution Statement

Unclassified - Unlimited

Subject Category 39

19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of pages 448	22. Price A19

NASA FORM 1626 OCT 86

NASA-Langley, 1990