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PREFACE

Cable in bending was used for the first time in 1957. One of the first uses was to mount the first electronics systems to be flown through reentry. The project manager was Dr. Von Braun and the work was done for the Army Jupiter missile. There were thirteen systems, and they all performed their function well from blastoff to landing.

This original work was all curved cable. It was used primarily for isolation from shock, vibration, and noise. These curved cable shock and vibration systems are now being made in at least five countries throughout the world with a gross sales reaching many millions of dollars. Even after 30 years, the number of engineers using cable isolation continues to expand.

Cable compliance started at Goddard Space Flight Center in 1972. The primary purpose for the first system was to control motion in three degrees of freedom while allowing compliance in the other three degrees of freedom. These new systems use straight cable instead of curved cable.

Four years ago, Wayne Eklund, Ray Burkhardt, and Jim Kerley started the typical configuration developed in the first section of this report. Since that initial patented system, compliance has moved into various areas for many uses for both the space centers and the commercial world as well. It has found a most useful solution as an aid to the elderly and the handicapped. This report will summarize much of this latest work and demonstrate its possible use in many other areas.

Chapter 11 is a complete compliant system developed by Peter Rosonni. It shows the development of design, the assembly, and the installation in the robotics laboratory.

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CHAPTER 1

COMPLIANCE IN ROBOTICS

The best way to visualize robotic compliance is to study the action of human finger, wrist, and elbow motions as a whole. The simple act of pulling open a desk drawer illustrates this. At first the hand goes down in a limber manner until it finds the handle. Next, the hand, the wrist, and shoulder increase their forces slightly as they translate and rotate in all three planes until they are aligned for the pull. The fingers tighten up as the arm pulls the drawer open. In robotics the same problem is encountered every day. The robot has a gripper or grasping mechanism that mates with the target to be lifted. Since the robot arm is heavy and stiff, it can damage the target if it is not lined up properly. It could be a little high, it could be a little wide, it could be too far away, and it could approach the target at the wrong angle. This misalignment is a combination of translation, along with rotation, about the X, Y, and Z axes. It would be very desirable, then, to have a compliant wrist on the robot that could conform to all six degrees of freedom and perform the desired task with the target. This report describes a new compliant patent (4,946,421) that does just that.

This paper describes robotic compliant systems with capabilities of handling a few ounces, several pounds, 200 pounds, 800 pounds, and 4,000 pounds. The detailed descriptions of these compliance mechanisms for different weights are described later in various sections of this report.

Applications and other inventions are described in this report. These include various hand controllers ("joysticks") for stimulating robotic motion with the operator's hand, a walker for the handicapped that improves physical therapy, a variable compliance mechanism that approaches the target with considerable compliance and then tightens up to perform a function, various methods of manufacturing for the handling of cable in large and small compliant systems, and a compliant robotic station for the handicapped. All of these compliance mechanisms add another dimension to the robotics field by making the robotic action more like the normal arm. They further take the work of compliant robotic principles from the NASA labs and apply it to the elderly and handicapped.

Six-Degree-of-Freedom Action With Cables

The basic patent in compliance is 4,946,421, shown in Figure 1. The parts are described as follows: (1) the attachment arm to target, (2) attachment to robot, (3 through 18) cable that gives the compliance, (19) a "U" spreader bar attached to the robotic arm, (20) a U spreader bar that attaches to the target, (21) cable holders, (22) the screws used to clamp the cable, (23) corner angles, and (24) cable ends.

Figure 2 is a Pal2 computer model of the basic device drawn in Figure 1. Each cable is made up of eight short beam elements attached end to end. The remaining structure is composed of relatively stiff beams and plates. The next seven figures give a graphic description of how the cable six-degree-of-freedom compliant mechanism bends and moves. One of the Pal2 computer models and solutions is included in an addendum to this section on page 13.

Figure 3 illustrates the cable motion with a torsion about the Y axis. The lower U frame is held rigid, while the upper U frame is rotated about Y. Notice the rotation of the corner angles. Notice the symmetric motion of all four cables illustrated and that any motion of the upper U frame causes all of the cables to move.

Figure 4 illustrates the same torsion load as Figure 3. This view demonstrates the similarity of the motions of the cables on the right and on the left. In Figure 3, the corner angles rotate about the Y axis. Figure 4 rotation shows that rotation is the same for all four corners.

Figure 5 is a view of rotation about the Z axis. Notice that cable pairs have rotation shapes that are mirror-images of adjacent pairs. The torque is positive about the Z axis and puts the cables in the upper right and lower left in tension, as well as in bending. It compresses the cables in the lower right and the upper left. This presents one general rule about cable motion in this form. When the cables are in tension and taking a load, the cables tend to straighten out. The cable about the corner angle tends to open up. A different situation occurs when the cables are unloading; they form an angle less than 90 degrees.

Figure 6 is a top view of the same positive torque about the Z axis. Notice in the upper right and lower left that the cables are tending to straighten out. They are taking most of the load. In the upper left and lower right, the cables are taking little or no load. Notice that the cables that are unloading must have a place to go. If they don't, the cables will tend to go into compression, causing the cable strands to open up or "bird-cage." This could cause a permanent set in the cables and change their characteristics. Notice that the bending load in all eight of the cables in tension is the same. The other eight have a loss of load, and they take the same bending configuration.

Figure 7 illustrates a force in the X direction. Notice that the loads are primarily taken by the cables on the left side of the drawing. They have a combination of bending and tension depending upon the load. The cables on the right are bending but not nearly as high as the cables on the left. As the deflection goes up, the right-hand cables take on more and more bending and eventually approach the tension similar to the left. The cables on the left are tending to go in tension. The only structure preventing this is the corner angle. This corner angle is most important, since it completely controls the actions of both the left and right cables.

Notice that the corner angles are rotating as they take on load. It is only by rotating the right-hand angles that the cable can take on some of the load. These rotations and these proportions of the loads are very important when the cables are prestressed. This type of variable compliance will be covered in another section, but it is essential to see these simple motions first.

Figure 8 is a computer model of a force in the Z direction. Note in this type of load that all of the cables take the same shape in bending. This is the simplest type of action to predict. It is very easy to test one cable and proportion it up to any number of cables; in one case, 386 cables were used. Note that a large load will draw all of the cables in toward the center, as the upper U goes up. It will thus bend in two directions at the same time, up and in. This is another feature of this type of patent. If the cable were a stiff bar, the stresses would be very high, but with compliant cable, the deflections do not go up proportionally to force. The cable gets stiffer as it moves, while a bar will maintain a constant stiffness ratio. This feature makes this compliant patent adaptable to a wide variation of loads.

Figure 9 is a combination of loads in the X direction, the Y direction, and the Z direction simultaneously. The degrees of bending in any of these loads can be calculated. However, since the stiffness of the cable system depends on deflection, the loads in the cables are not a simple matter of adding one load on top of the other. Another item to consider is that a force in the Y direction also causes motions in the X and Z directions. Thus the system, with the floating corner angle, can adapt itself to many of these load conditions. Over a period of years, many types of load conditions have been tried, and the cables have always been adapted to suit the particular application. Remember that for some of these features, variable compliance is necessary, which will be described later in this report.

The Pal2 finite element analysis was chosen as a computer program to analyze these systems because it gave a good picture of what the cable was doing. When we use 1/4-inch cable, we load it in shear of approximately 10 pounds. This same cable in tension has a breaking strength of over 6,000 pounds. Thus the stress in the cable is low. The stress readings on the computer runs are fictitious and the deflections are fictitious, but the proportional deflections are correct in the lower load conditions. In order to get a good similitude, each individual cable was broken down into eight segments. Then the properties were inserted in the matrices that would give the desirable motion. Once this program was set up for 1/4-inch cable, it could be applied to any size cable by dimensional analysis. It could also be applied to any length cable suitable for compliance.

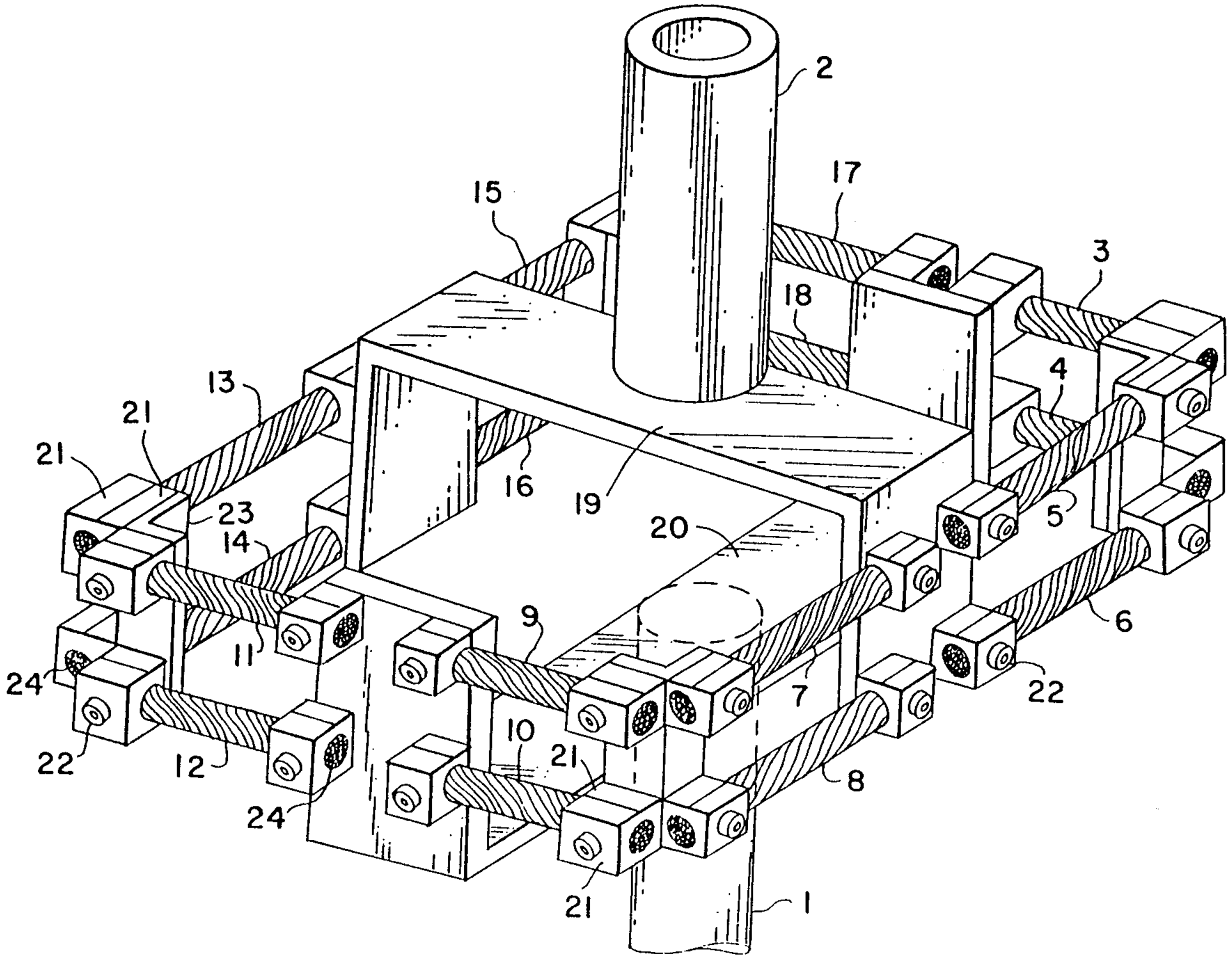

Figure 1. Typical compliance model.

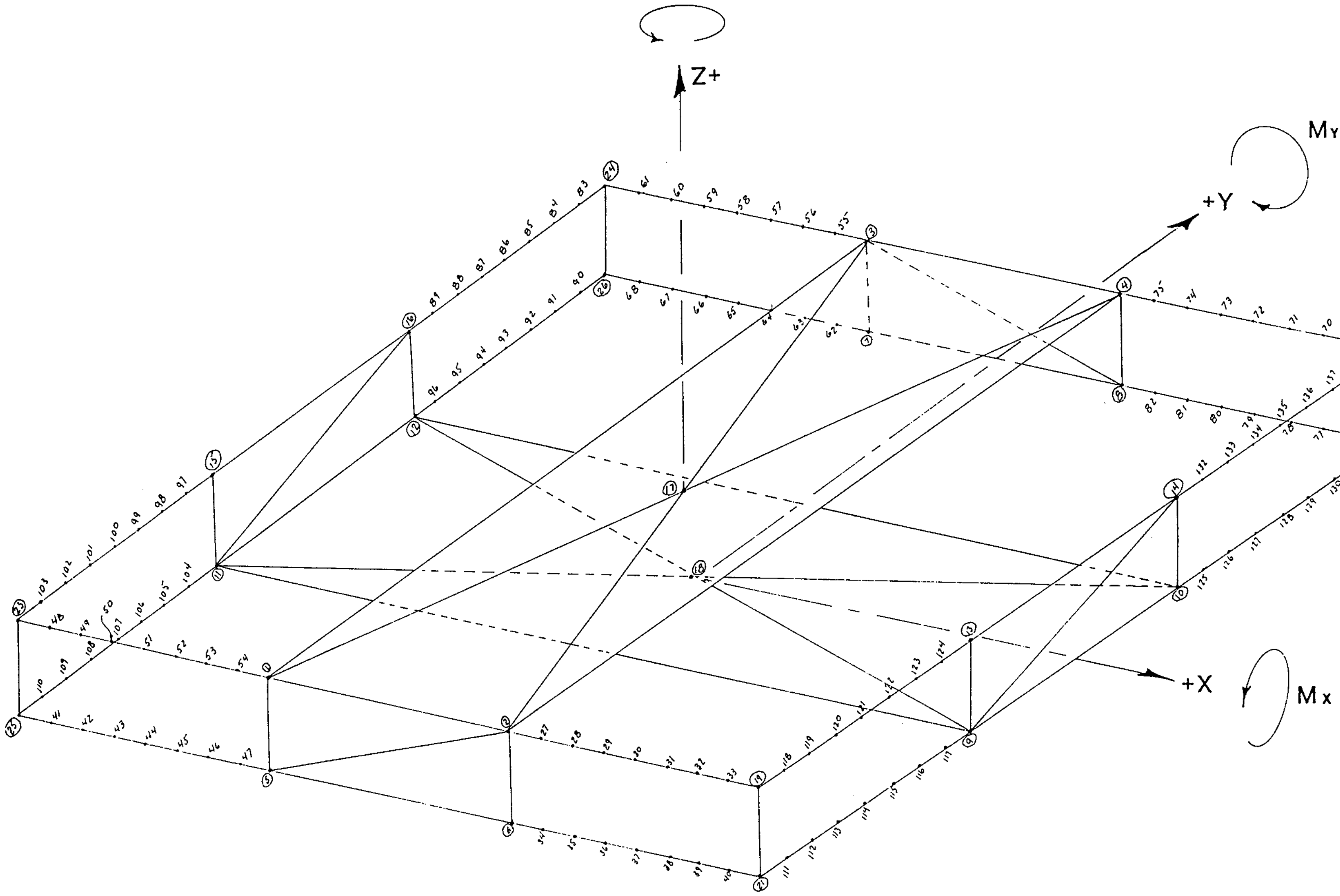

Figure 2. Computer model.

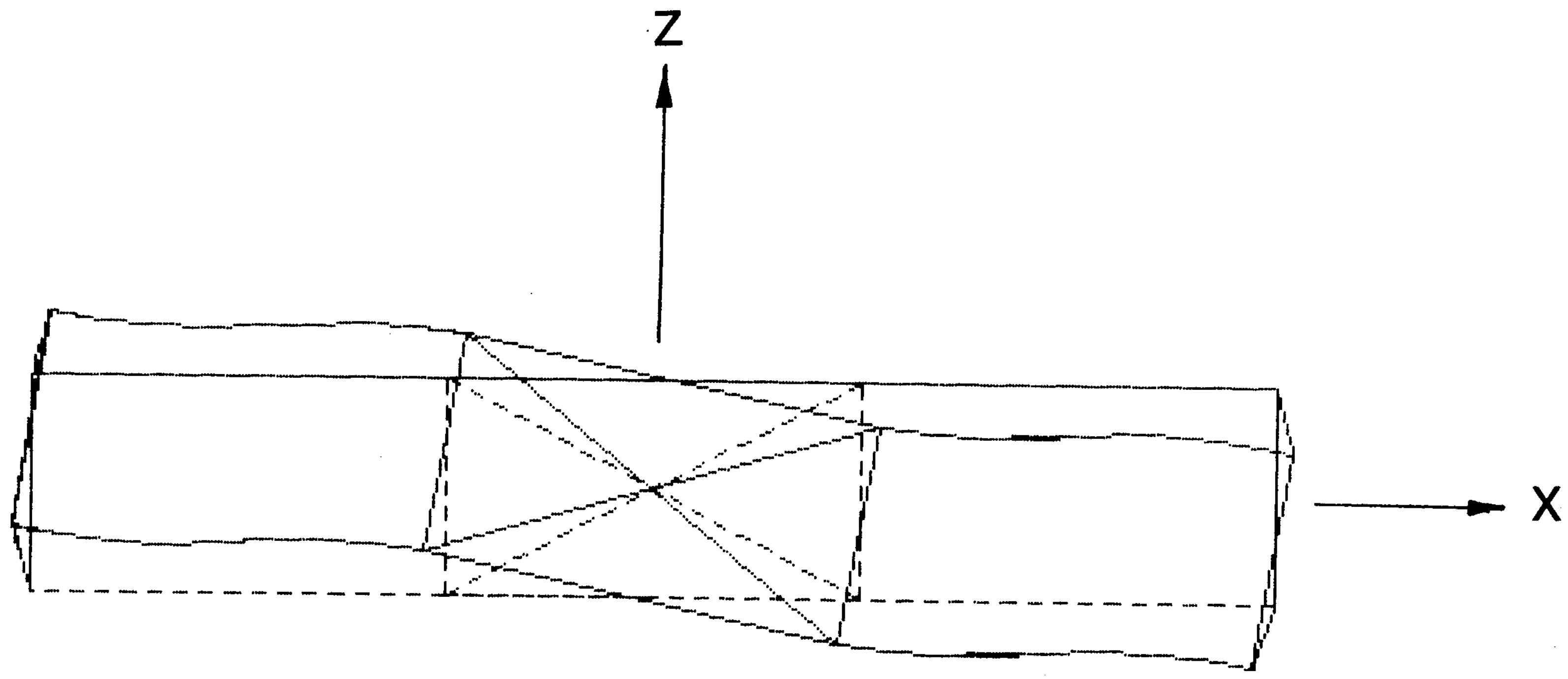

Figure 3. Torque about Y, end view.

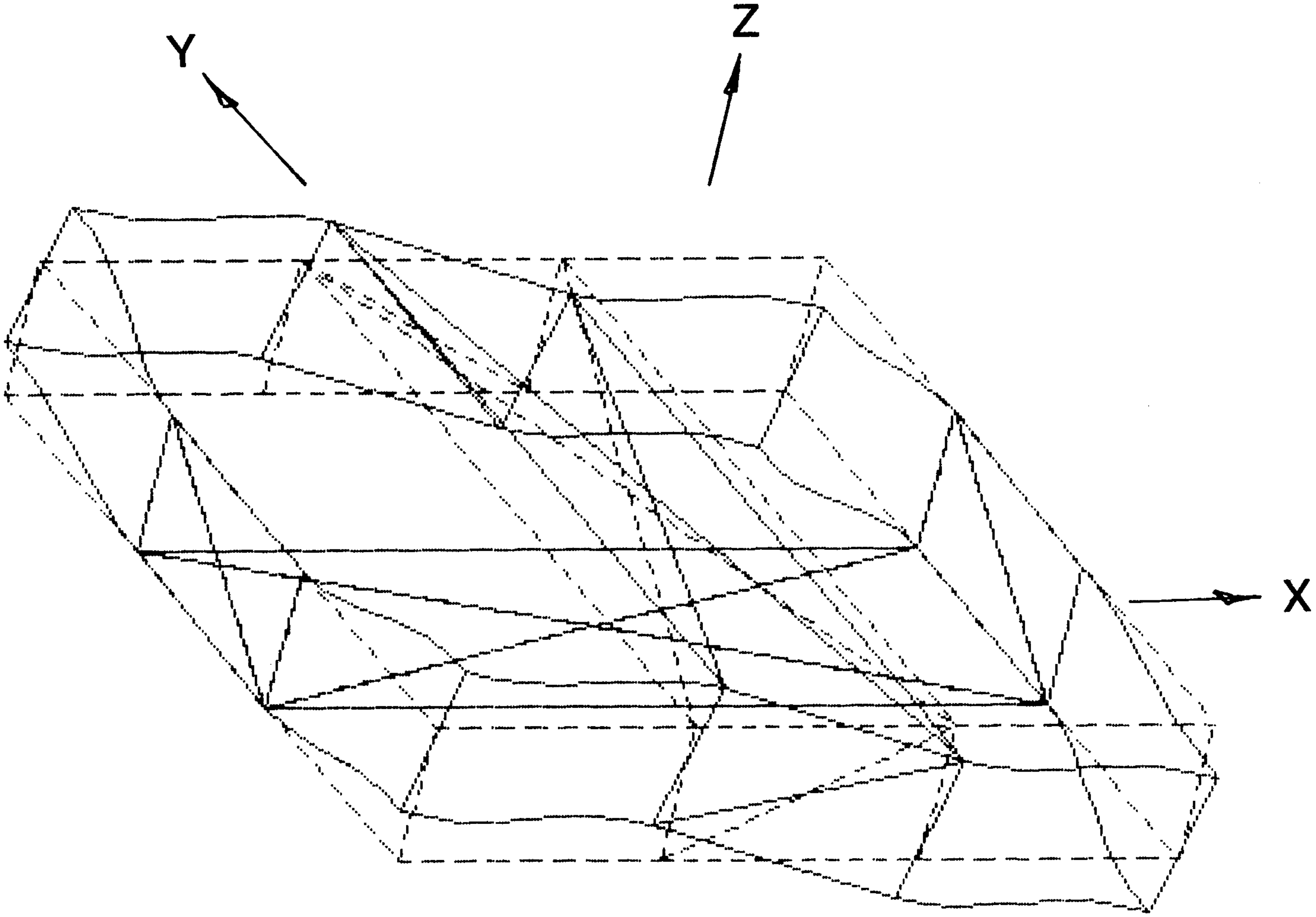

Figure 4. Torque about Y.

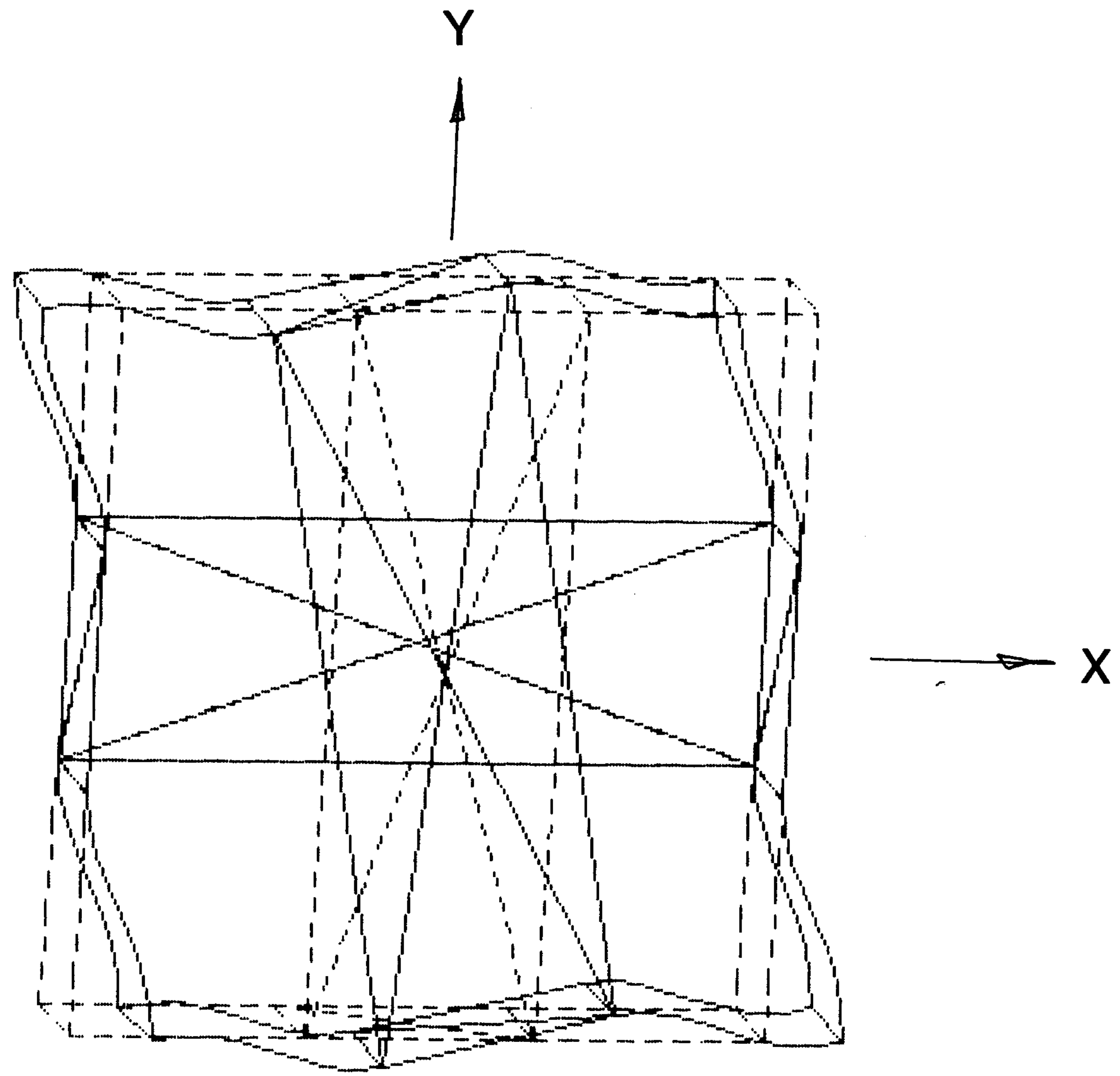

Figure 5. Torque about Z, perspective.

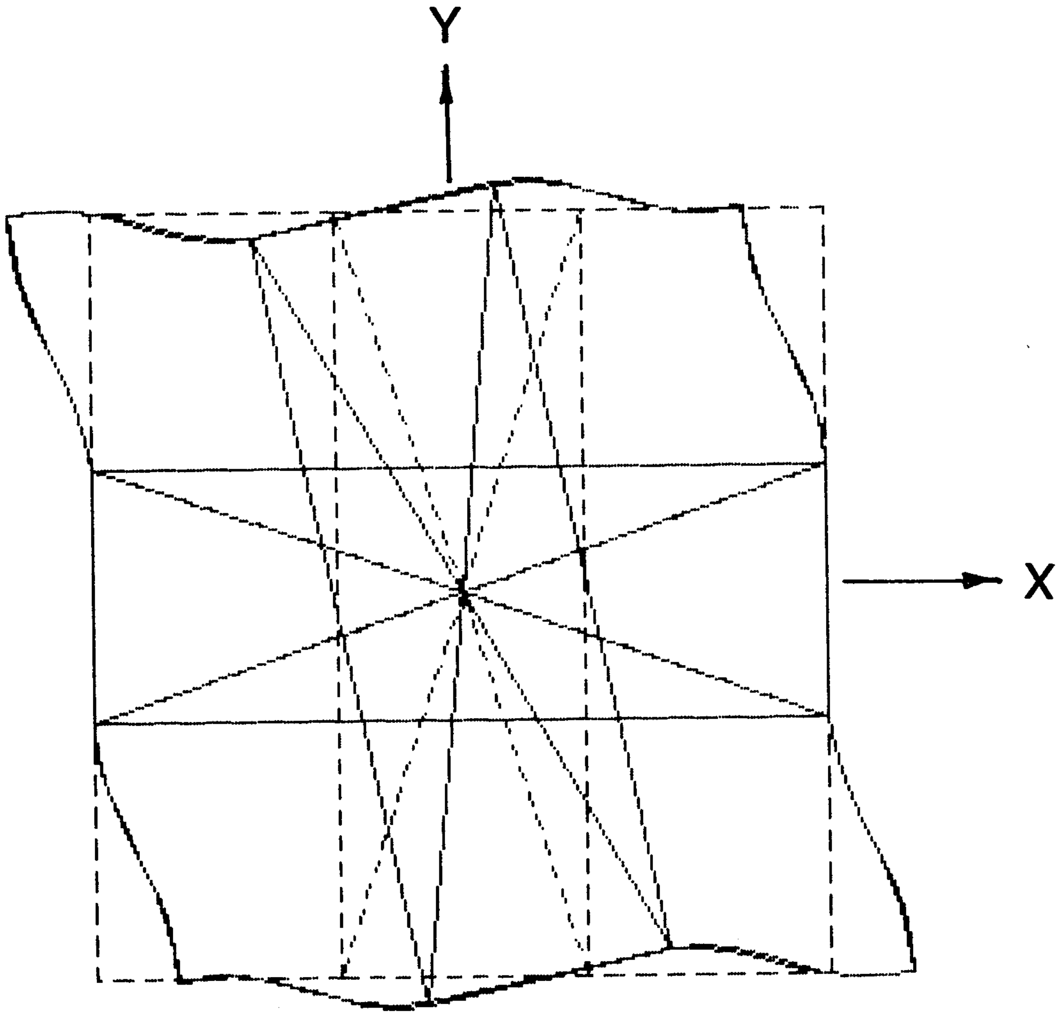

Figure 6. Torque about Z.

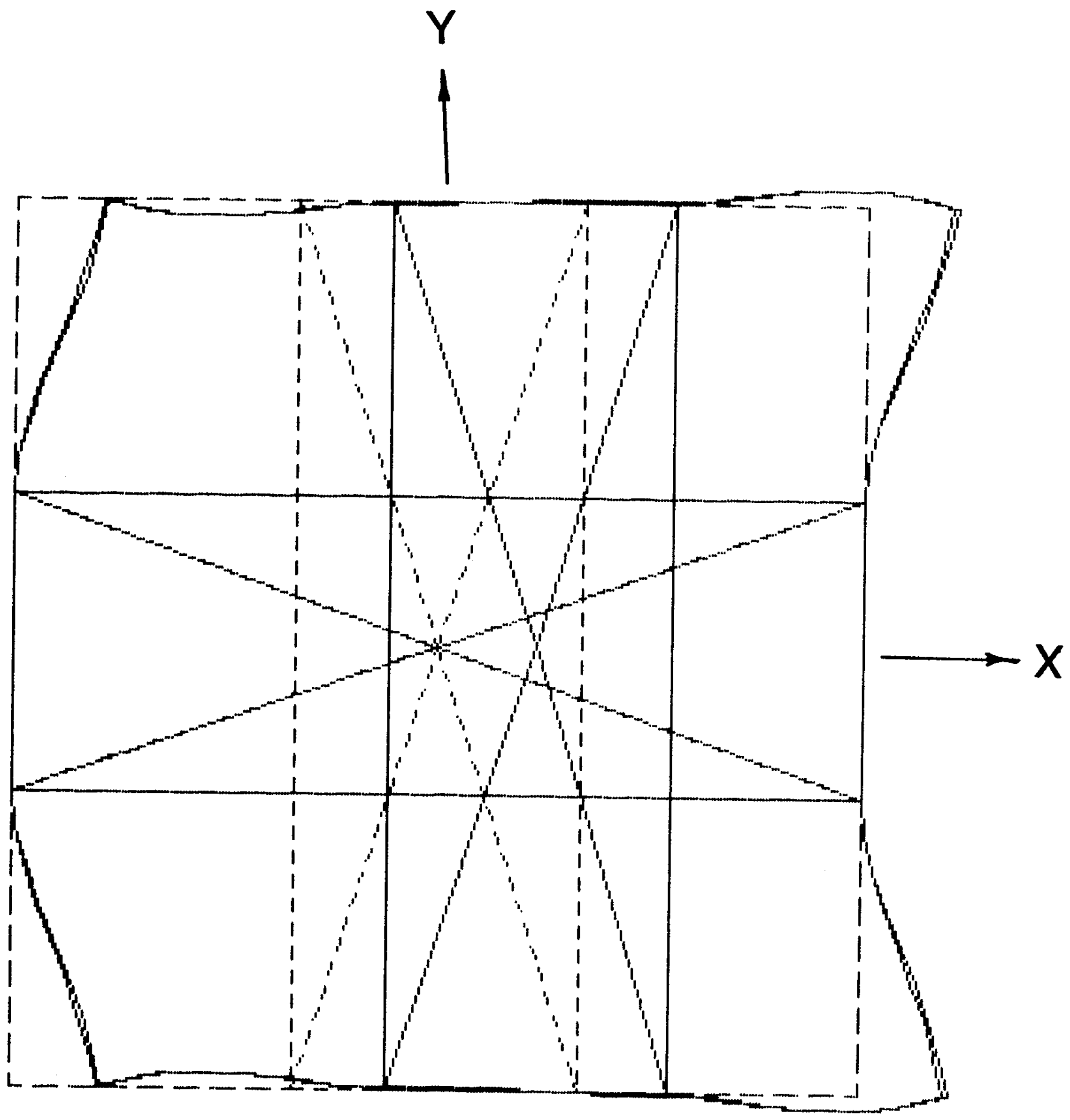

Figure 7. Force in X.

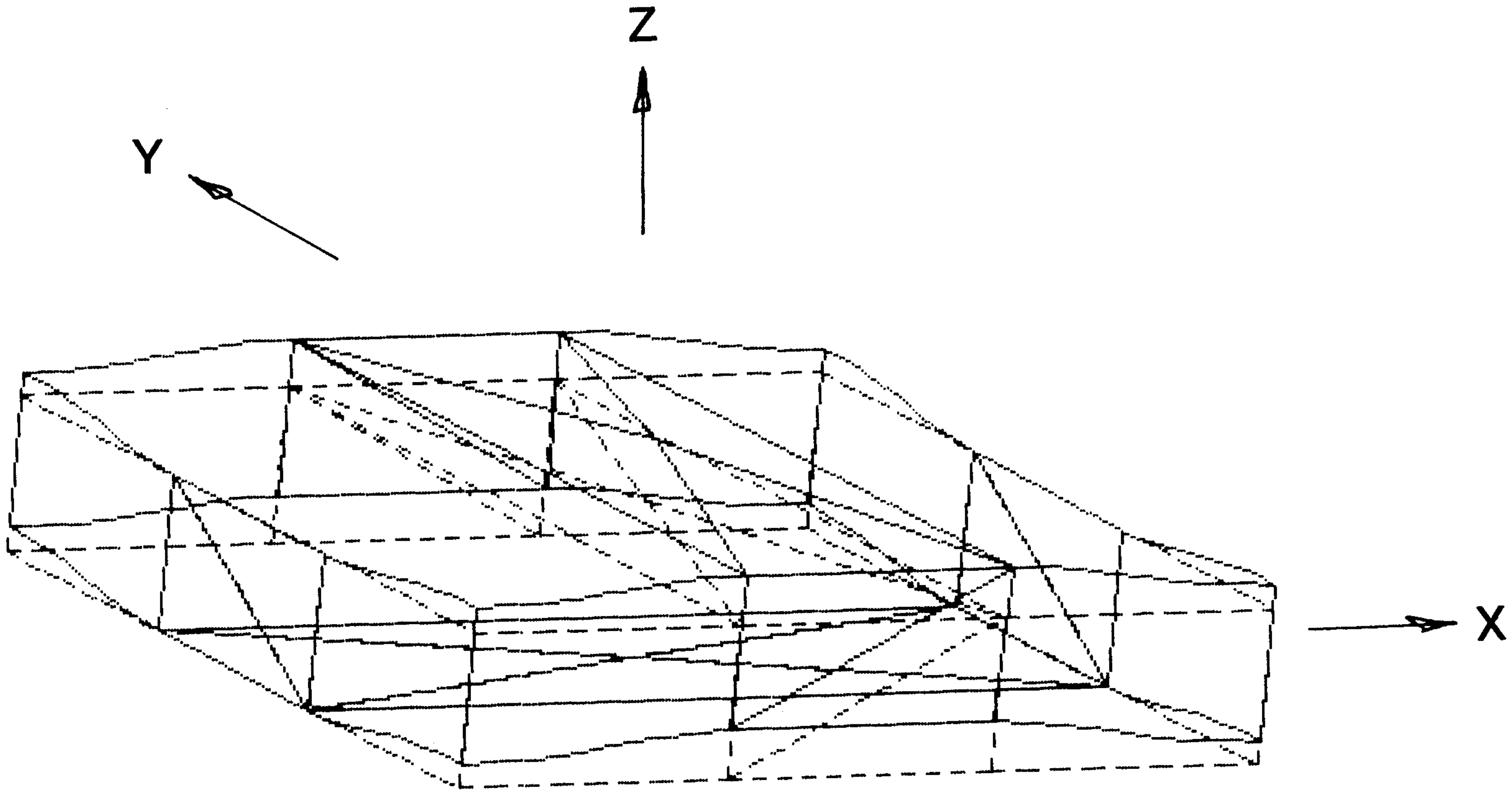

Figure 8. Force in Z.

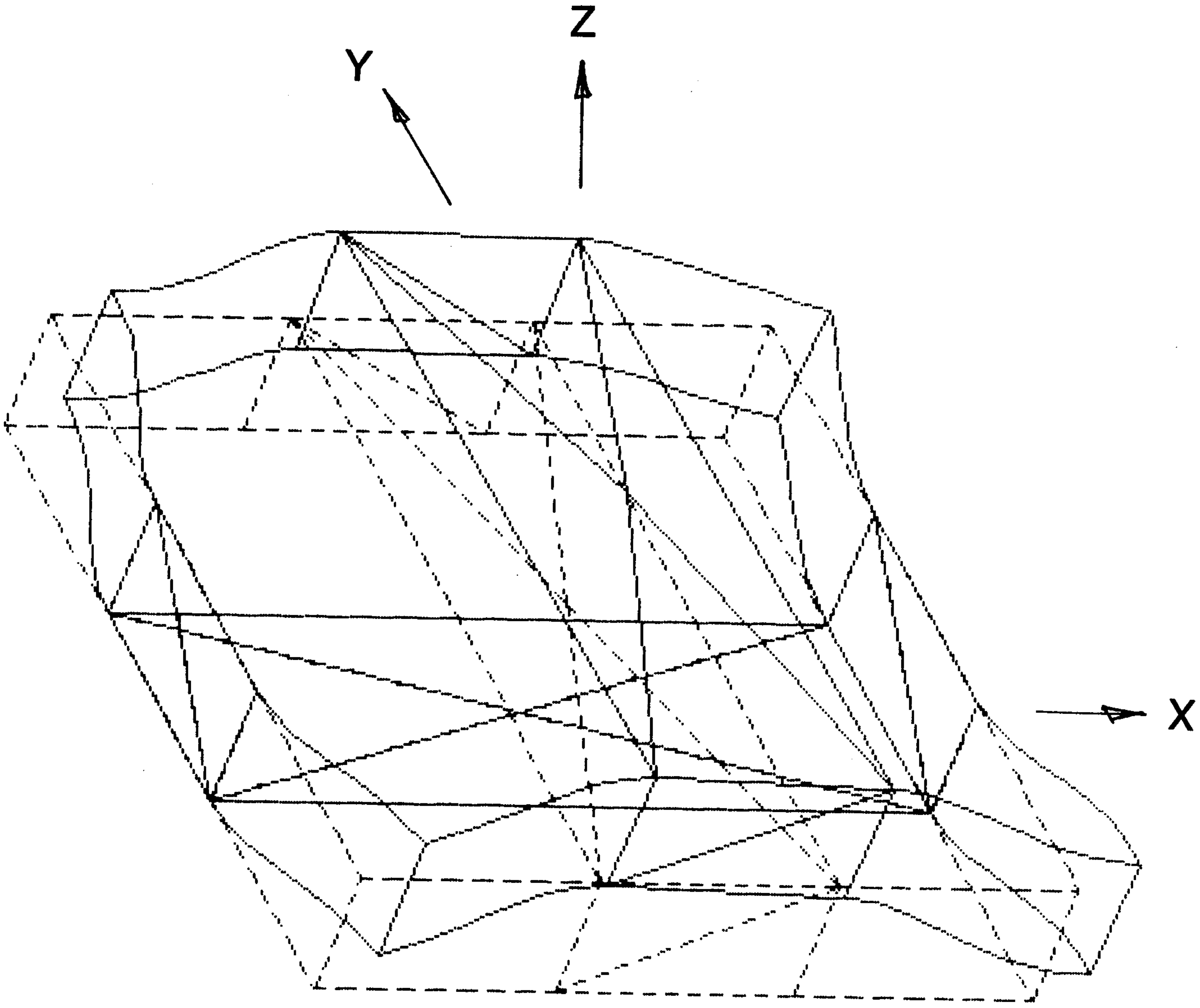

Figure 9. Force in X, Y, Z.

THE FOLLOWING COMPUTER PROGRAM IS FOR FIGURE 5 AND FIGURE 6 (TORQUE ABOUT Z)

THE COMPUTER SOFTWARE IS FROM
MACNEAL SCHWENDLER CORP.

THE PROGRAM IS PAL2

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connect 104 to 105
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connect 108 to 109
connect 109 to 110
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mz 17 50.0

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tx 0.0 9,10,11,12,13,14,15,16
ty 0.0 9,10,11,12,13,14,15,16

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quit
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CHAPTER 2

CABLE IN BENDING

Chapter 1 demonstrated the use of cable in compliant systems. In this chapter the nature of cable in bending is addressed. What kinds of cables are used? What different wire combinations can be used? What are the limitations? What are the other factors? Figure 10 is an illustration of most of the cables that are available today for compliance. (Permission has been granted to reproduce Figure 10 from pages 240 and 241 of the Engineers Illustrated Thesaurus, published by Chemical Publishing Co., New York, N.Y.)

The desirable features are as follows:

(1) The wire should be preformed. In this way, fabricating the cable is primarily laying the wires together and not just twisting straight wires together. If the cable is not preformed, it will spring open when it is cut and will be unmanageable for compliance construction.

(2) For most uses, the wire should be stainless, since stainless wire can be cleaned readily. Carbon steel wire will rust and, in time, will fail outdoors.

(3) For some uses, the cable should be quite flexible, and with other uses, it should be rather stiff. The use determines the type of cable to use.

(4) It is important to recognize that both the spacing between the holders and the construction of the cable go together to make up the stiffness. The use calls out the stiffness desired.

(5) If the overall envelope is critical (there is little space) the compliance should be primarily in the cable and not in the spacing between the cable holders. Refer to Figures 1 - 9 in Chapter 1 to see how much space is required for all six degrees of freedom.

(6) The bending of the cable is nonlinear. One of the reasons that it is nonlinear is because of the friction that gives it excellent damping characteristics. The rubbing of the cable strands causes this friction. The second reason that it is nonlinear is because the cable center sections go into tension with bending on the ends as the loads get higher and higher. Note Figure 11.

Since the wire in cable is pretwisted in the form of a helix and laid against other cables, the designer will never know what part of what wire is touching the next wire. No two feet of a given cable are the same. It can never touch along the entire length because of its geometric forms. So much of the load in bending is taken by friction that there has never been a model of a cable section analyzed by the finite element method. The friction is too strong a factor. However, despite this randomness, the response of the cable in bending is predictable and is reproducible.

(7) In right regular lay cable, such as OO and PP in Figure 10, the interior wire rope core (IWRC) rotates counterclockwise, while the exterior strands rotate clockwise. Thus in 7 x 19 cable stranding, the center wire rope core rotates counterclockwise, and the six exterior lays of 19 cables each rotate clockwise. The same is true for left regular lay, but rotation is in the opposite direction for each. (See G on Figure 10.) The damping can be increased (particularly for vibration) by twisting the cable in the direction of the six exterior lays. This will force the outer cable to form a smaller circle, but it will cause the IWRC to expand. This means that more cables will rub against other cables if they are pretwisted, the inner layer cables against the outer layer cables. Care must be taken not to rotate the cable too much or the IWRC will pop out of the outer layer and damage the cable. There are other uses when less damping is needed, and the opposite twisting, within limits, will give the desired results.

(8) There are cases where the inner layer and the outer layer of cable rotate in the same direction. This is called lang-lay, illustrated as QQ and RR on Figure 10. Lang-lay can be made to be much more limber, but too much motion will cause the entire structure to become unstable. There are uses that will be given in detail later where lang-lay is a better choice.

(9) A close look at Figure 10 shows where 38 different kinds of stranding can be used. If a large amount of cable is necessary, the wire rope company can strand it at a reasonable cost. However, in designing the compliant mechanisms, the designer is able to get only a few types of cables off the shelf. These cables are for marine and aircraft use. Elevator, dredging, and lifting cables are usually very large, while most compliance mechanisms are for lighter loads, a maximum of 3/8 inch in diameter. The general range is to have the cable between the sizes of 1/16 and 1/4 inch in diameter. The strandings most often used are (a) 7 X 19, (b) 7 X 7, (c) 6 X 37 IWRC, (d) 1 X 19, (e) 7 X 7 X 3, (f) 6 X 41 IWRC, (g) 6 X 19 IWRC, (h) 6 X 22 IWRC, and (i) see JJ on Figure 10.

Air cord is the most commonly used type of cable. This type of cable is specified in aircraft design. It is carefully inspected and tested from time to time to guarantee quality control. It is not uncommon to use the same stranding, such as 7 X 19, in two different countries and find out that one country has a much stiffer cable than the other. The strength of the wire in the cable depends on how it is drawn and then preformed.

(10) Different types of holders will have different effects on the cable, which will be discussed in a later chapter.

(11) It is very important that the cable be held securely in the holder. Figures 11 and 12 show that the cable does not take on a severe bending motion until it is out of the holder. Later in this report, details of holding devices, including machined, sheet metal, and plastic, will be given.

(12) The ratio of the diameter of the cable to the length of the span between holders usually varies between 1/6.1 to 1/8.8. Thus a cable of 1/4 inch in diameter can usually have the spacing vary between 1.5 inches to 2.2 inches, depending on the load to be handled and the amount of compliance desired. In special cases with light loads, the spacing ratio has gone up to 1/14.5. These uses were applied on cable between 1/16 inch and 1/4 inch in diameter. With these spacings and the range of cables, the loads have varied from ounces to 4,000 pounds.

Figure 10 shows the types of commercial wire rope that is available today. Figure 11 shows the normal bending of 7 X 19 wire rope. Figure 12 shows excessive bending in commercial wire rope. Figure 13 shows a triple stranding of cable called 7 X 7 X 3. It is extremely flexible. Figure 14 shows cable held by plastic holders.

CLASS IV. BASIC MECHANICAL MOVEMENTS

Section 35a. Commercial Wire Ropes

In designating wire-rope construction, it is customary to state first, the number of strands; second, the number of wires in a strand; third, the kind of center or core whether fiber, hemp, wire strand or wire rope. When wire rope remains in a fixed position (such as in cables for suspension bridges) or where little bending is required, a wire core is desirable. For transmission of motion, flexibility over grooved pulleys is desirable and is secured by thinner wires and hemp or fiber cores.

A–3 × 7; fiber center.
B–6 × 7; fiber center.
C–7 × 7; wire center.
D–6 × 8; hemp center.
E–6 × 13; hemp center; filler wire.
F–6 × 16; fiber center; filler wire.
G–7 × 19; wire-strand center.
H–6 × 19; fiber center; two stranding operations.
J–6 × 19; hemp center; Seale patent.
K–6 × 37; fiber center; filler wire.
L–6 × 41; wire-rope center.
M–18 × 7; nonpinning type hoisting rope.
N–6 × 19; flexible; Seale patent; wire-rope center.
O–6 × 19; hemp center; Warrington patent.
P–6 × 19; hemp center; filler wire.
Q–8 × 19; hemp center; Seale patent.
R–8 × 19; fiber center; filler wire.
S–8 × 19; hemp center; Warrington patent.
T–6 × 19; wire-rope center; filler wire.
U–6 × 22; wire-rope center; filler wire.
V–6 × 31; fiber center.
W–8 × 19; fiber center; two stranding operations.
X–6 × 12; one hemp center.
Y–6 × 12; seven hemp centers.
Z–6 × 37; wire-rope center; Seale patent.
AA–6 × 37; fiber center; two stranding operations.
BB–6 × 37; hemp center; three stranding operations.
CC–6 × 24; seven hemp centers.
DD–6 × 42; seven hemp centers; most flexible; called "tiller" or "hand rope."
EE–3 × 37; wire center.
FF–Typical wire-rope center.
GG–Typical hemp or fiber center.
HH–Typical strand center.
JJ–Steel wires twisted into a single strand of nineteen wires.
KK–Steel wires twisted into a single strand of fifty-one wires.
I L–Armored wire rope; 6 × 19; fiber center; sometimes wire center; used under severe hoisting conditions, such as dredging and heavy steam-shovel work.
MM–Marline-covered rope; 5 × 19; hemp center; used for ship's rigging and hoisting service where moisture is encountered (American Chain and Cable Co.).
NN–Stone sawing strand; three wires twisted together.
OO, PP–Regular-lay (right and left) wire rope; wires in strands twisted together in one direction and strands twisted in opposite directions.
QQ, RR–Lang-lay (right and left) wire rope; wires in strands and strands twisted in the same direction

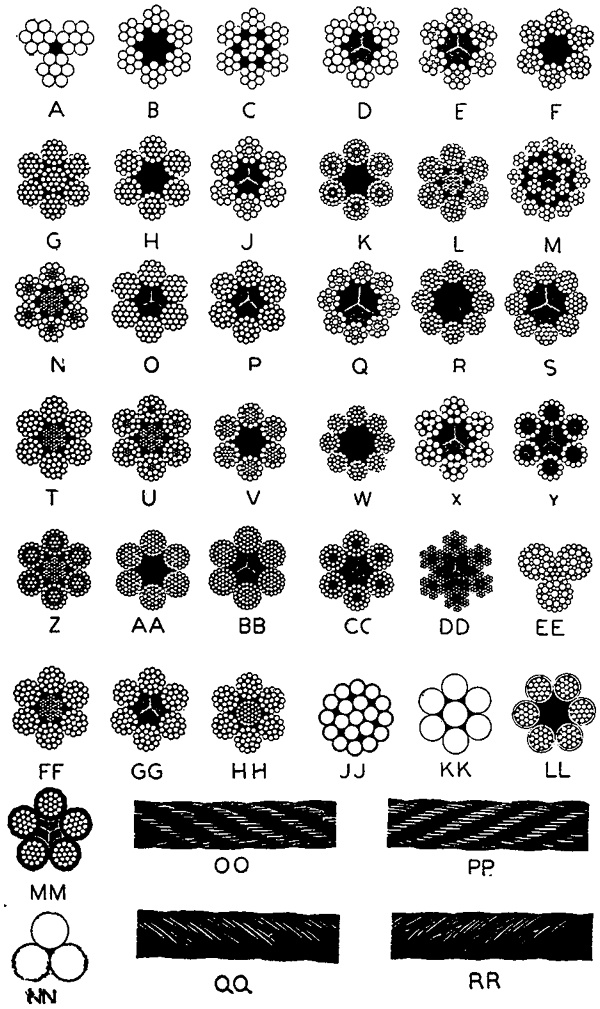

Figure 10. Types of cable used in bending.

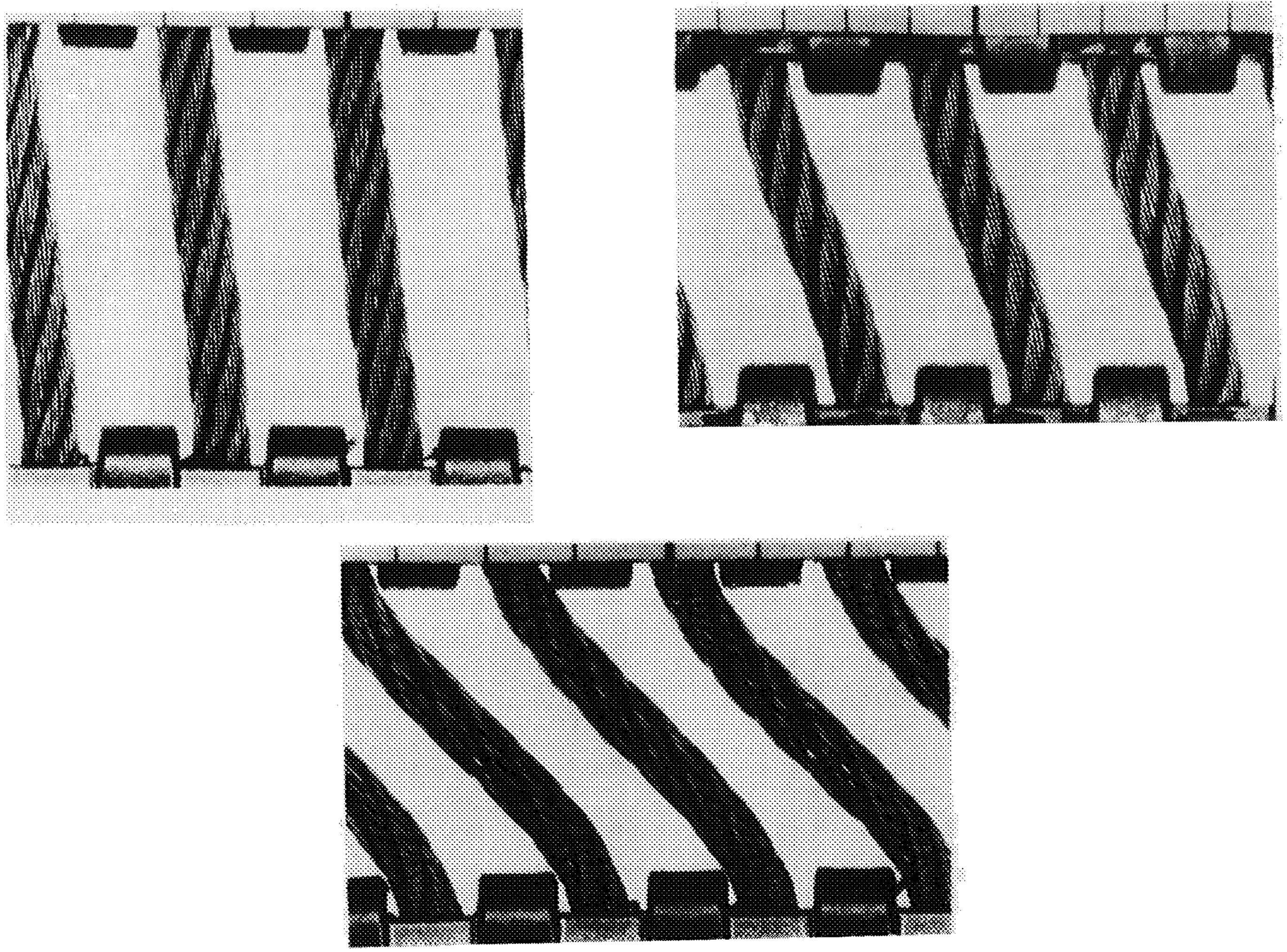

Figure 11. Normal loading on 7 x 19.

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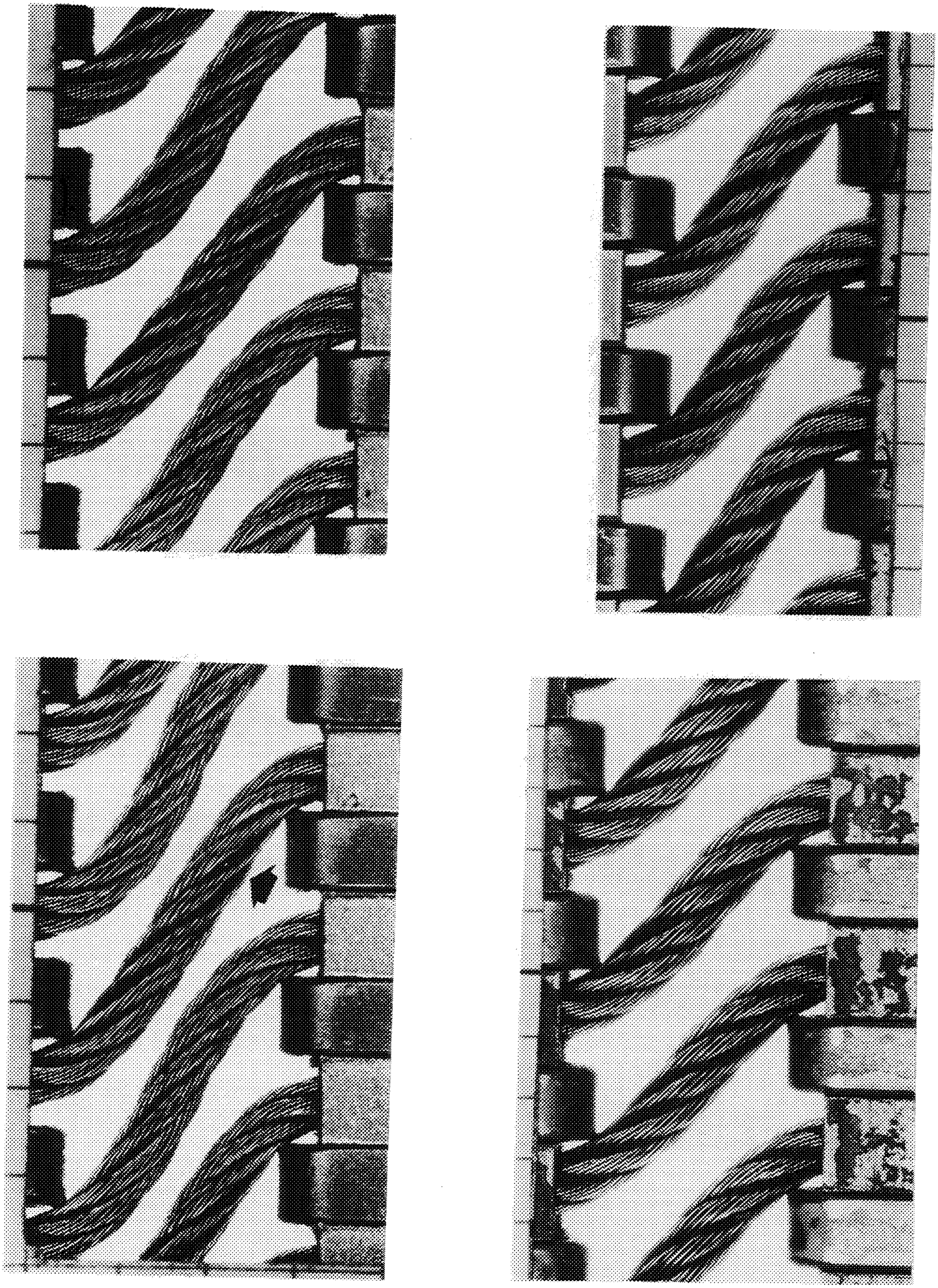


Figure 12. Overload of 7 x 19.

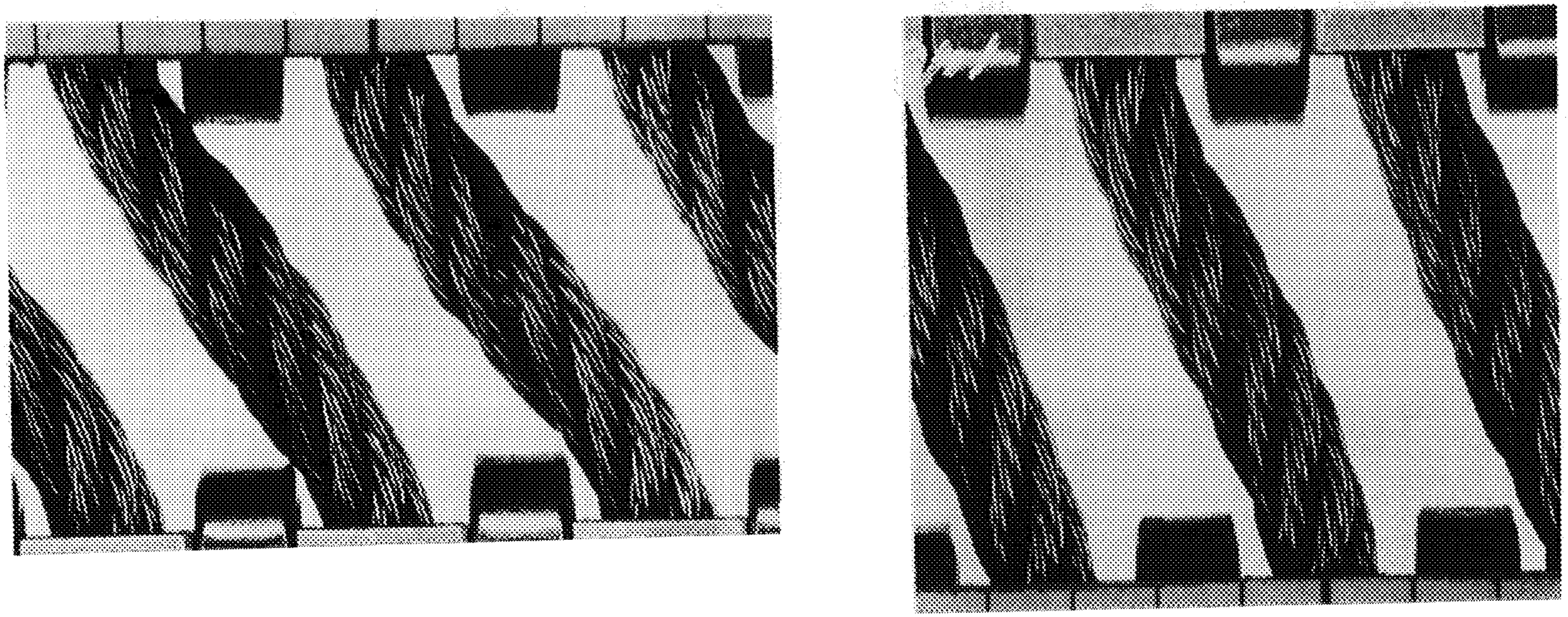


Figure 13. Normal load of 7 x 7 x 3 cable.

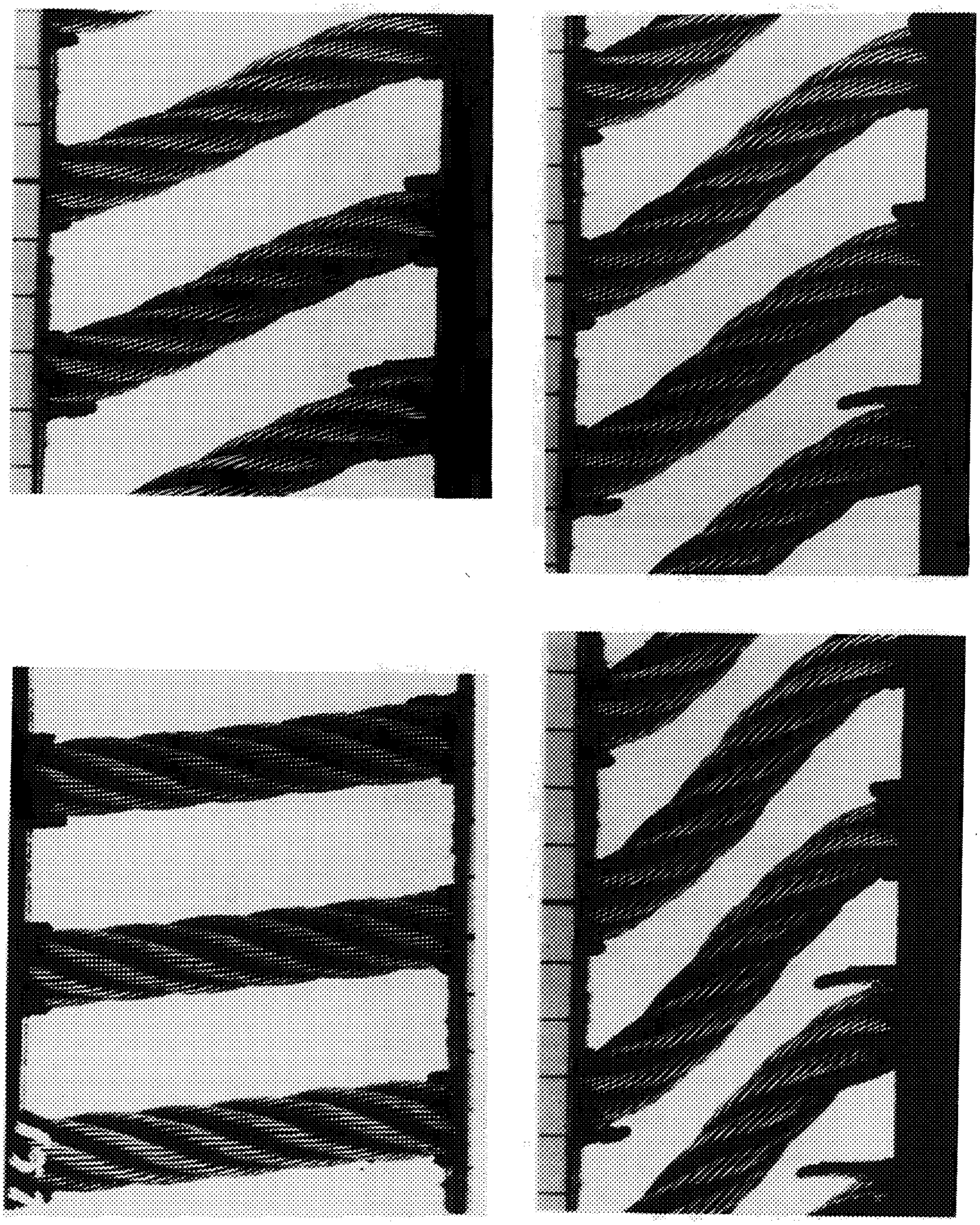


Figure 14. Plastic holders.

CHAPTER 3

ONE-, TWO-, AND THREE-DEGREE-OF-FREEDOM SYSTEMS

The Three-Degree-of-Freedom System

The three-degree-of-freedom system, as built, is shown in Figure 15. There is translation in the Z axis and rotation about the X or Y axis. The use at Goddard Space Flight Center is for a vibration system that would fit the end of a 450,000-pound centrifuge. The center moving weight is a 10,000-pound magnesium casting, shown in Figure 15. Test models of the system are shown in Figures 16 and 17. Figure 18 shows a patent drawing of the system. The center moving weight is a 10,000-pound magnesium casting, shown in the figure as 12. The actuators that drive the shaker are 16. The cables allow only motion in the Z axis and rotation about the X and Y axes are 20. There are sixteen cables 1 1/4 inches in diameter, and each cable is prestressed to 30,000 pounds. The total preload on all of the cables is 480,000 pounds. One end of the cables is mounted to the vibrating 10,000-pound mass (26, Figure 18). The other ends of the cables are mounted to the outside frame (10, Figure 18). There is a table (14) that vibrates back and forth mounted on top of this assembly (21). Thus it is possible with four actuators to translate in the Z and the X direction and to rotate about the X and the Y axes. The cables allow these motions, but they keep out all the other vibration and translation loads that would be detrimental to the operation of the system.

Figure 15 is a picture of the system without the top table.

Figure 16 shows a model of the final mechanism that was necessary to demonstrate the capability of the system to take the vibration of the upper round table and keep the system stable at the same time. During these tests, it was clearly demonstrated that the ends of the cable had to be held securely and not allowed to rotate. All of the motion had to be in the bending of the cable and not in the rotation of the ends. This same principle is used in all cable compliance systems today.

Figure 17 shows the same model of the three-degree-of-freedom system mounted on the end of a vibration table. This test was performed to demonstrate that any vibration that would cause the frame to vibrate would not affect the alignment and compliance of the system. These tests also demonstrated that it was necessary to hold the ends of the cable so that they could not rotate. Thus all of the motion was taken in the bending of the cable. This motion would also dampen the external forces, since cable in bending causes many strands to rub against each other, and friction damping results. The higher the amplitude, the more the rubbing and the damping increases.

Figure 19 is a top view of the assembly. The cables (34) are firmly attached to the magnesium moving part (12). Notice the 4340 steel machined parts, which hold the cables in place and keep them from rotating. The 480,000 pounds applied by the cable are taken out by the external frame, causing the unusually high bending moment. The external frames (94) were needed to take the extra moment.

In the bottom part of Figure 19 is an exaggerated view of what the cables look like during vibration input. Note that this configuration also allows for a certain amount of rotation about the X and Y axes. The dynamic principle of the system was straightforward, but the stresses were high, and this caused many difficulties. The tooling of the welding and the welding were so difficult that the Lincoln Welding Society gave this design an award for being one of the top weldments of the year. The assembly and testing of the parts was very difficult. Large forces applied to a magnesium casting caused creep, and that had to be handled by special design techniques. If the frame were used to hold a pile driver or a pneumatic hammer, then the problem would be very simple and the system easy to apply.

Figure 20 shows the complex assembly to a magnesium block. Eight steel bars go completely through the magnesium casting to keep the compression forces from causing stress concentrations on the magnesium.

Figure 21 shows the outboard end of the cable attachments. Note the adjustment screws (80) that were installed to pull up on the cables if they started to creep. Over a period of several years, the cables moved less than .020 inch, and it was never necessary to use the adjustment screws. In a less complex system, this means that the cables are installed once without further attention.

Figure 22 is a sketch of the Launch Phase Simulator centrifuge. This centrifuge weighs 450,000 pounds, and it has been rotated up to 50 G's, or the tip rotates at 200 miles an hour. These high forces must be taken by the three-degree-of-freedom cable system. Special features were added for this difficult problem. The system was designed so that the cables would have to take 30 G's on the centrifuge and, at the same time, act as a compliant system. This it did very well. This feature shows, in a simple pneumatic hammer problem, that the cables could take the weight of a person who leans on the frame, which remains rigid while the bit of the chipper bangs its way into the concrete. One of these has been made, and it demonstrates this ability quite well.

One-Degree-of-Freedom System

A one-degree-of-freedom system is the same as a three-degree-of-freedom system with one addition. On Figure 23 is shown a sketch of the cables mounted to the top and bottom of the moving structure. This prevents rotation about the X and the Z axes. The lower layer of cables prevents the rotation of the mass. The rotational motion about the Z axis is prevented by placing the cables in the positions as indicated in Figure 19.

Two-Degree-of-Freedom System

This system is sketched on Figure 24. The structure can now rotate about the X axis, but not about the Y axis. The lower cables were eliminated in the Y plane. Thus the two degrees of freedom are translated in the Z axis and rotated about the X axis.

Forces Necessary to Operate the System

Cable Length = 36 inches.
Cable Diameter = 1/4 inch.
Z Cable Motion = 1 inch.
Change in cable length to go 1 inch in the Z direction = .013 inch.
Deflection = PL/AE.
E = 20,000,000.
L = 36.
A = (for 1/4-inch diameter cable) .0329.
P = Deflection X A X E/L = 247 pounds.
Breaking strength of 1/4-inch cable = 7,000 pounds.
Angle for deflection of 1 inch = 1.59 degrees.
Force necessary to move cable up 1 inch = 6.8 pounds.

These calculations are based on the assumption that the modulus of elasticity of cable in tension is 20,000,000 pounds per square inch (psi). It is further assumed that the cable is in pure tension. There is bending on the ends of the cable, but most of the cable is in pure tension, particularly with a motion of only 1 inch. Another assumption is that the system is linear. Cable is not linear, but in these low stress ranges, calculations can be used assuming the cable analysis to be linear.

Limitations on the System

The pictures show a three-degree-of-freedom system that only had to move 1 inch. Large motions in the Z direction could cause major problems. However, the maximum input for most vibration cases is no more than plus or minus 1 inch. Further, it is noted that a rigid frame is necessary to hold the cables in place. This requires quite a bit of weight. Also notice that for the system to operate in the ranges indicated, a large space is required. In the design of the Goddard Space Flight Center 1972 patent, the weight and size were not excessive. If weight is a problem, then the motion of the outside ring must be taken into account.

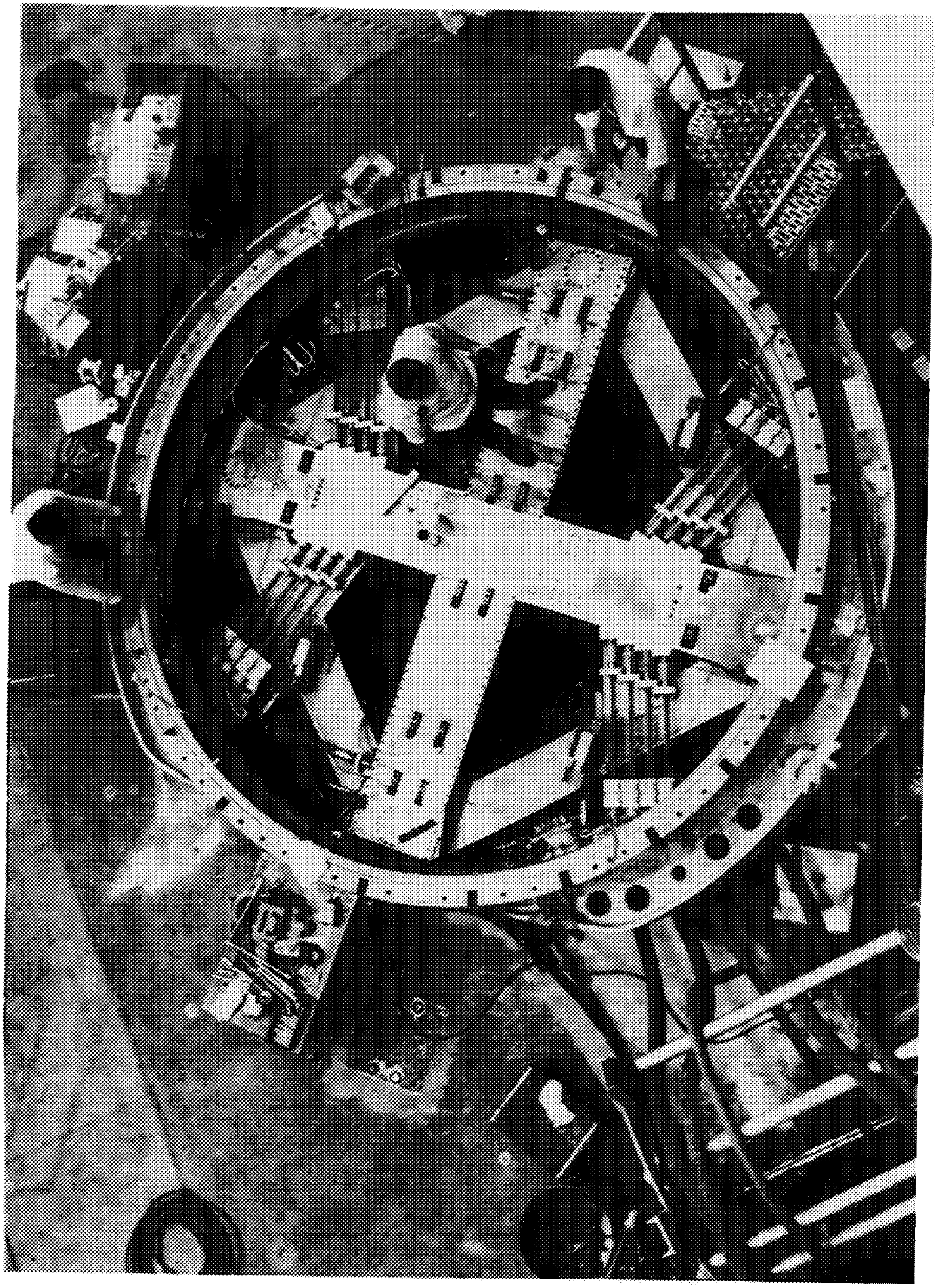


Figure 15. Three degrees of freedom assembled.

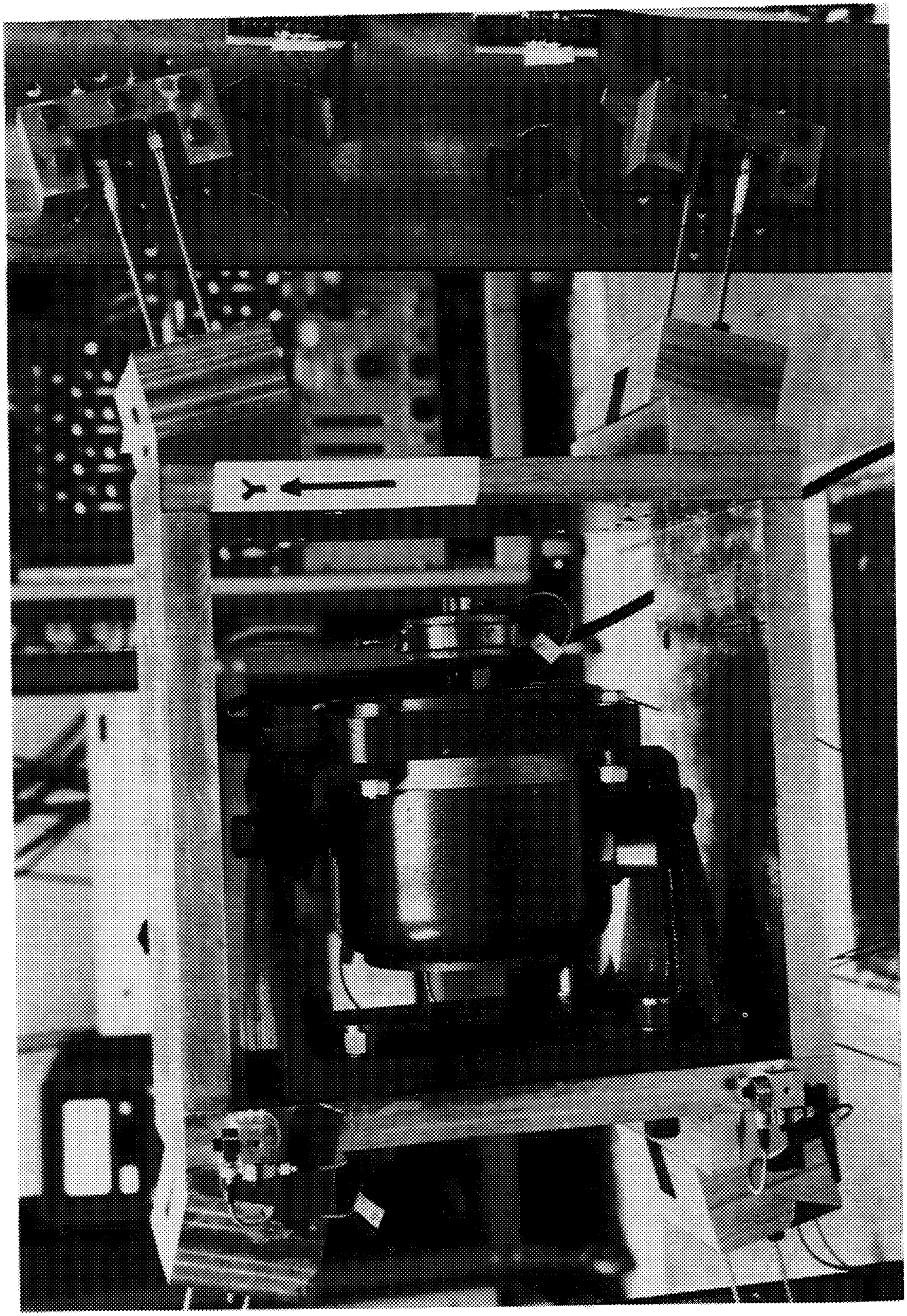


Figure 16. Testing three-degree system.

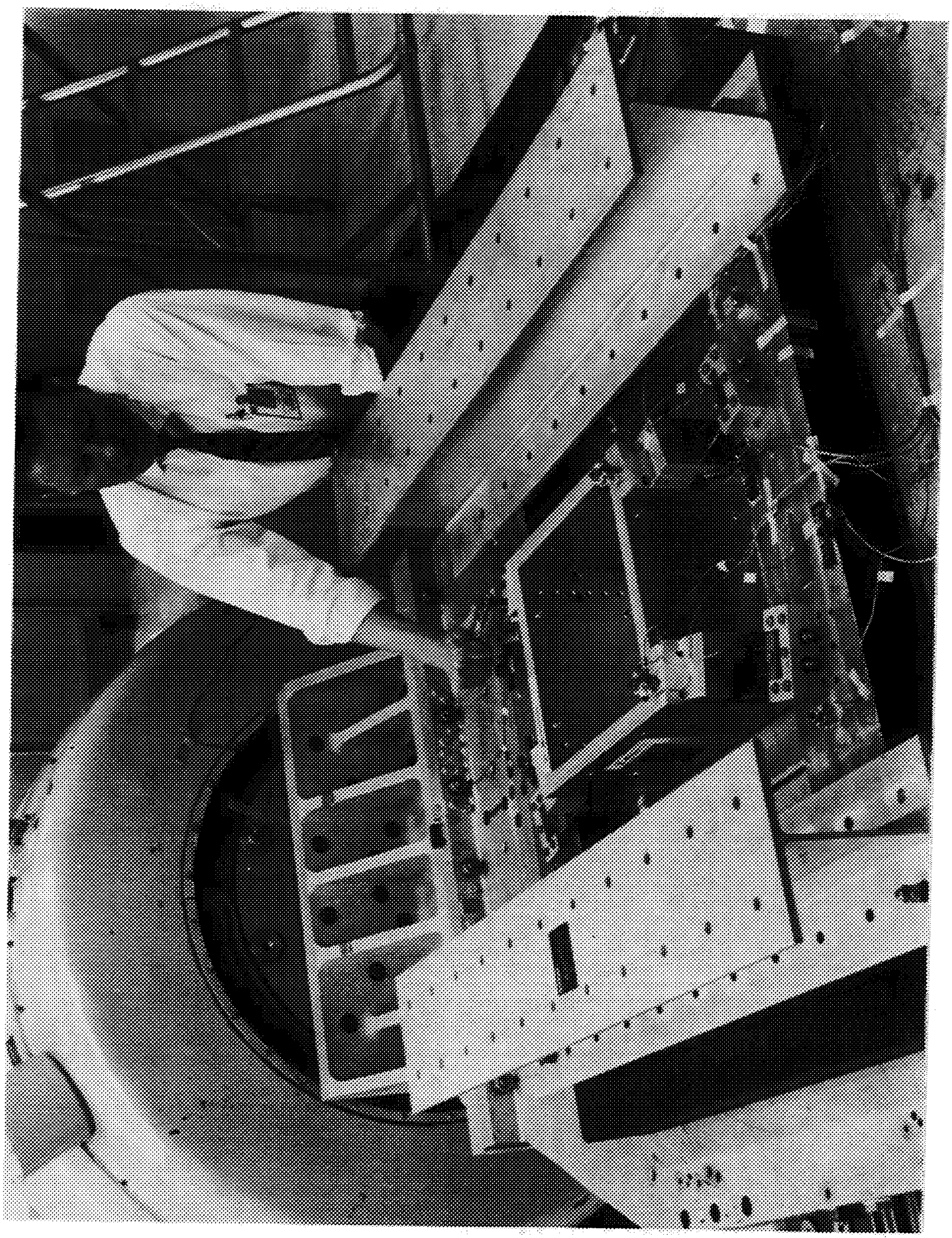


Figure 17. Vibration testing of system.

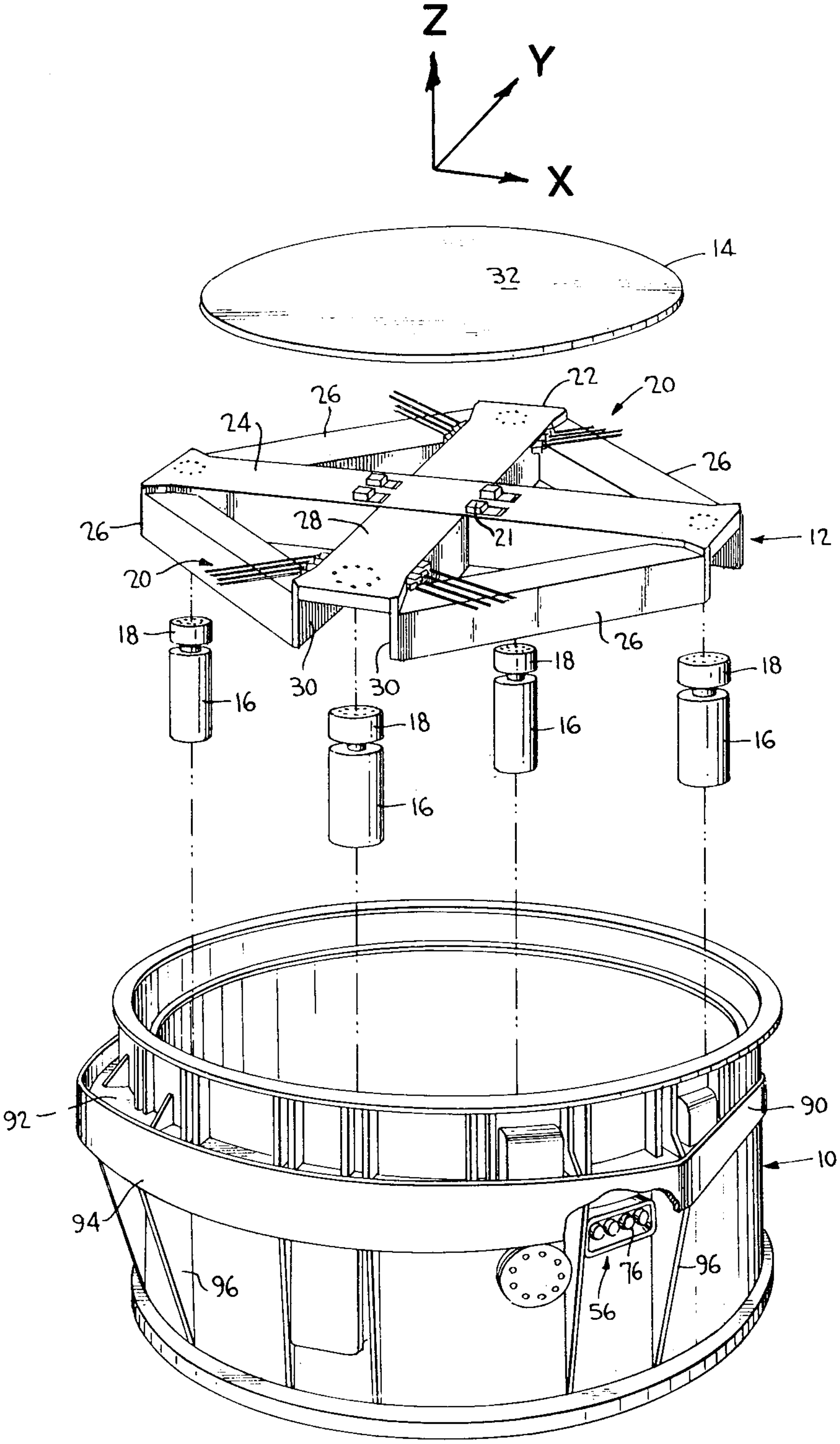


Figure 18. Patent drawing of assembly.

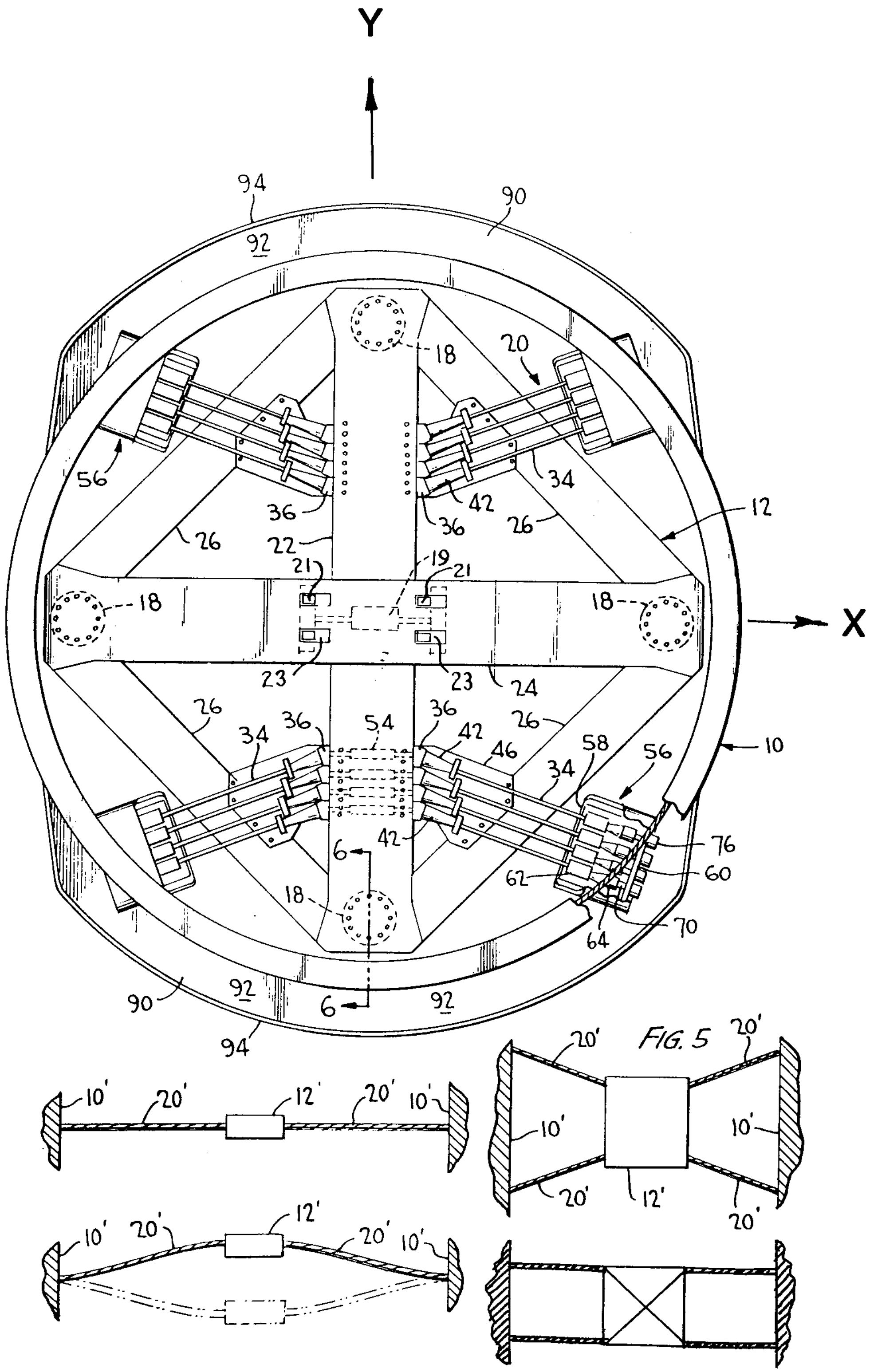


Figure 19. Top view of assembly.

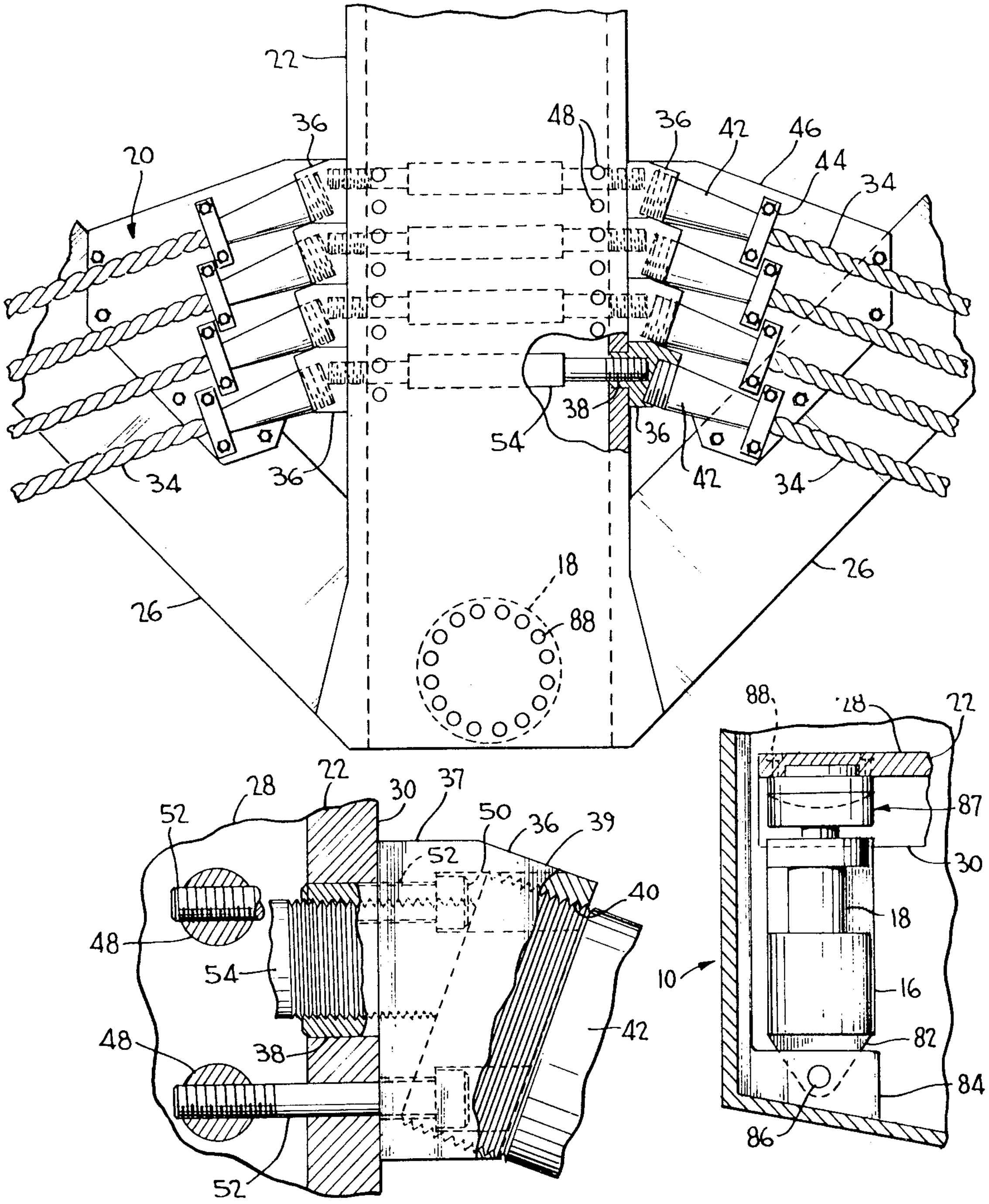


Figure 20. Cable end fixity.

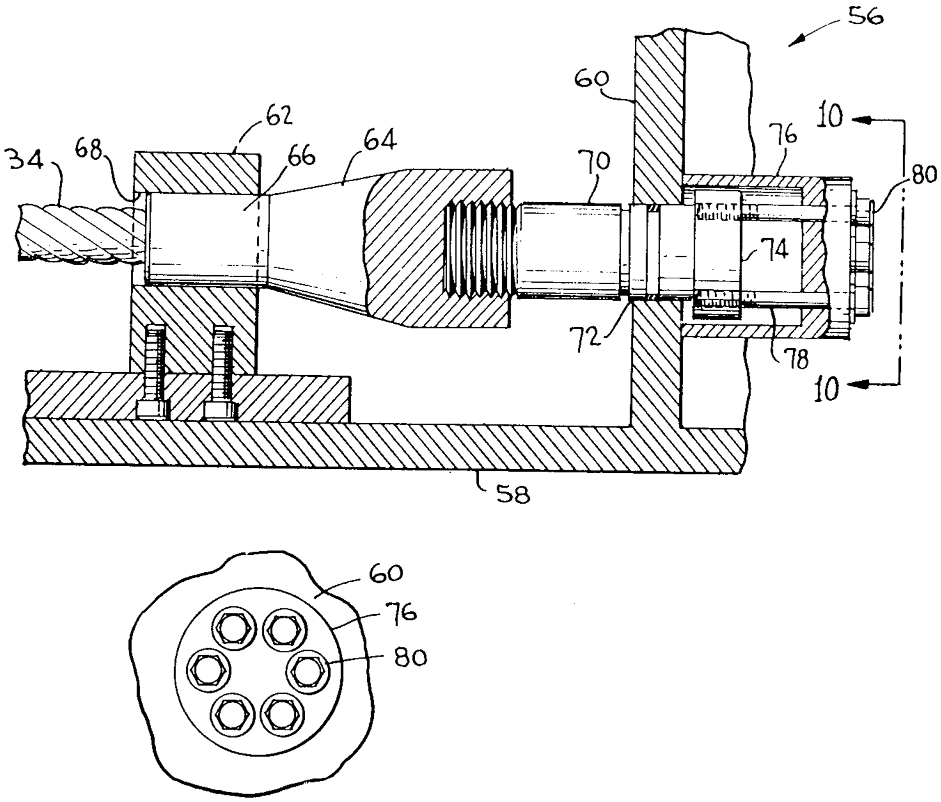


Figure 21. Cable end.

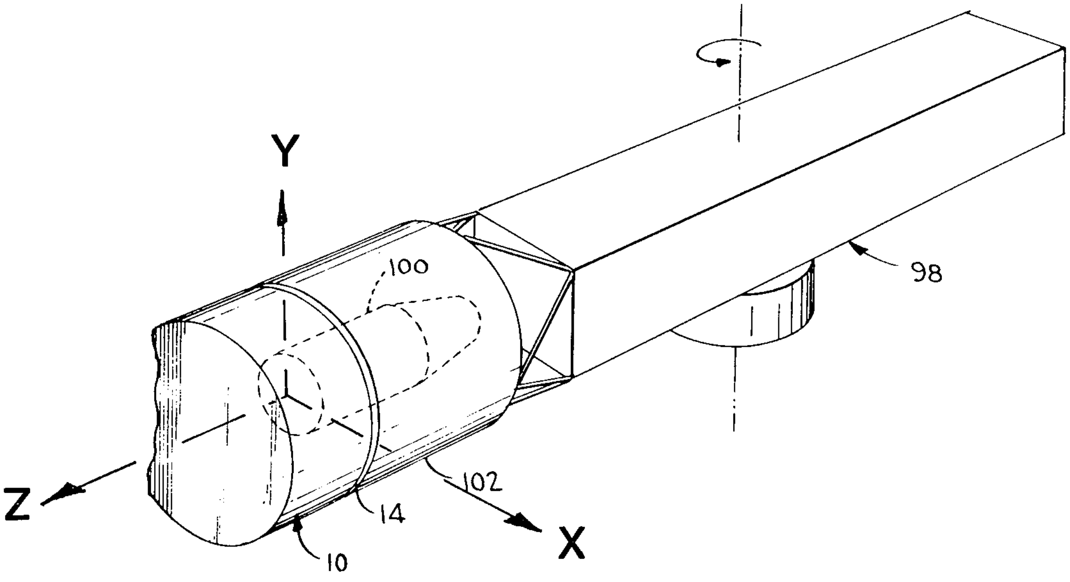


Figure 22. Mounted to centrifuge.

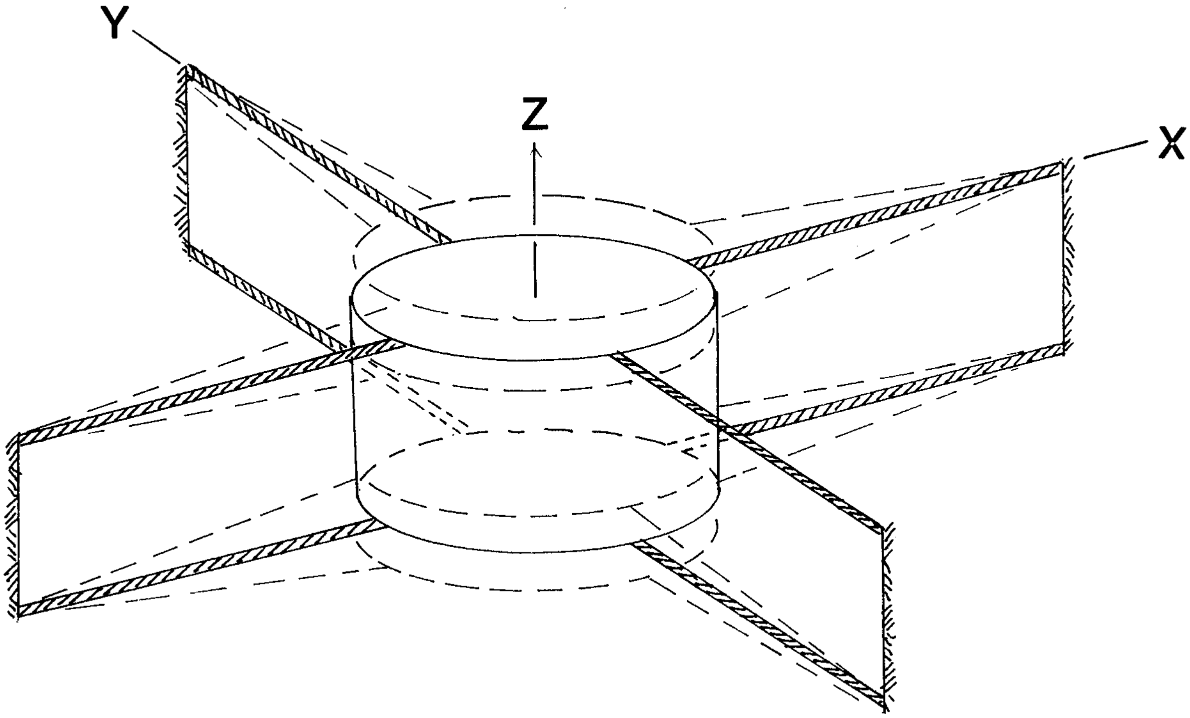


Figure 23. Single degree of freedom.

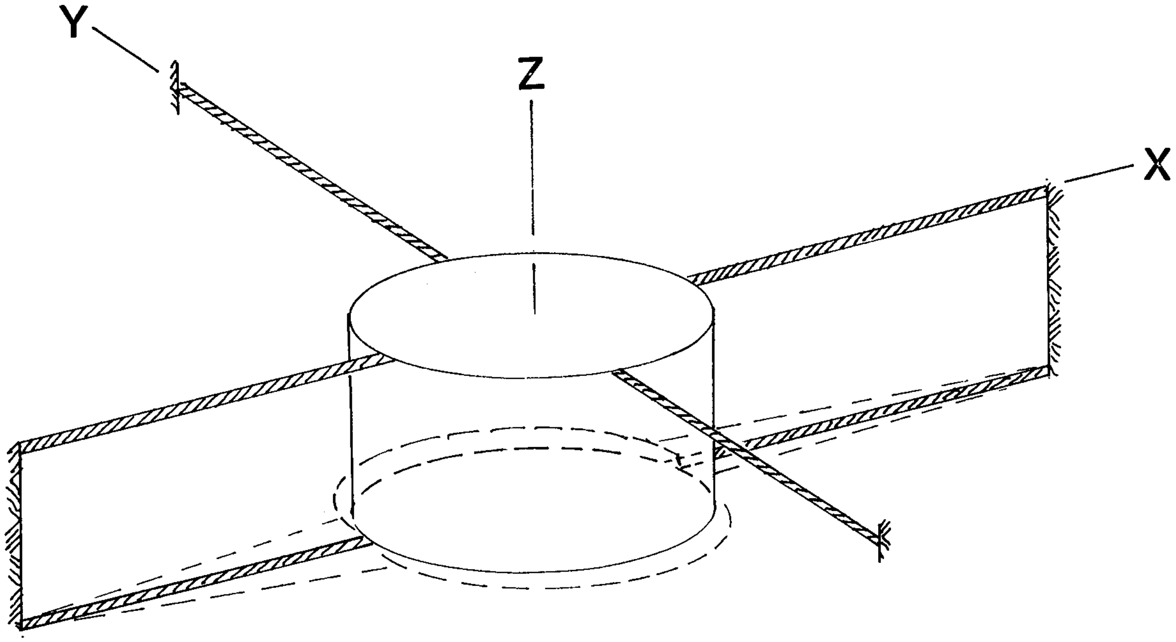


Figure 24. Two degrees of freedom.

CHAPTER 4

CABLE CONTROL SYSTEMS

Technical Field

This chapter describes a joystick invention that implements cable for increasing control and reducing fatigue of the operator. A feedback loop to the operator's hand is an option that makes the joystick more "user-friendly."

Introduction - Background Art

There are many hand-operated controls known as joysticks available commercially. Joysticks have numerous applications in the electric control of moving bodies such as cranes, small vehicles, remote handling apparatus, robots, and aircraft. The joystick shaft has a neutral position that is perpendicular to the plane of the switches or contacts and is moveable about the X and Y axes to control the device to which it is attached. The joystick shaft pivots, and its lower end makes contact with switches that send appropriate signals to the machine to be controlled. By hand manipulation of the joystick, the operator selectively causes a specific contact to complete a circuit, which, in turn, activates a specific operational control (i.e., left turns, right turns, reverse movement, forward movement, etc.) Some joysticks have variable response; the harder or farther one pushes, the more response is achieved. Most joysticks also have a means for returning to a neutral position, such as a spring or other resilient means. Their limitations are that they are either too "hard" or too "linear." That is, the commercially available joysticks tend to move either too little or too much in response to operator input. The operator also has no sensory feedback from the joystick that would indicate how hard or fast the machine is moving. Because of this, joysticks do not work well with the natural action of the hand, the brain, and the body's feedback characteristics.

Statement of the Invention

This invention is a joystick with nonlinear response. The handle deflection is not proportional to the amount of force input. The mechanism gets stiffer with increasing force. This provides superior control and feedback to the operator, since it reflects the natural action of the operator's hand, his brain, and the feedback nature of man. In this way, it feels better to the user and thus increases his control and cuts down on his fatigue.

The foregoing benefits are achieved by the User-Friendly Joystick (Figure 25). It is composed of a lower U bracket and an upper U bracket connected with cables in the standard compliant configuration. The cable segments and their configuration are critical for establishing the compliant characteristics of the joystick. The compliance may be modified in a number of ways: by varying cable segment lengths and stranding; by pretwisting the cable; and by varying parameters such as the spacing of the cable sets, the number of cable sets, the cable diameter, the cable material, and the angle between cable segments.

As the operator moves the joystick handle, the cable compliant joint initially provides a low reaction force, but as the joystick handle is moved farther in any direction, the reaction force becomes nonlinearly greater. The cables are virtually indestructible and may be bent to angles over 90°. The joystick may be calibrated for use in the operator's range of comfort.

Internal vibrators within the knob on the joystick handle provide feedback to the operator. When a machine controlled by the joystick moves, the inertial and reaction forces are measured by a force sensor. The operator will then know by tactile feedback through the hand when the target has been contacted, in what position the target has been contacted, and the magnitude of the force exerted on the target.

A detailed discussion of the cables, swaging, four cable set-up configurations, configuration angles, and the degrees of freedom available can be found in Chapters 1 and 2, plus additional references later in this report.

The compliant joystick may be used to modify hard or stiff response joysticks to make them more user-friendly. A drawing of this control system is shown in Figure 26. The upper left sketch shows a top view of the cable angles and the cables in one quadrant. The lower left sketch shows the inverted upper U frame, which holds the handle and the cables. The lower right sketch shows the lower U frame, which is also inverted to hold the hard joystick. The base of the stiff joystick is mounted to a stable platform.

In many cases, it is desirable to add compliance to a stiff joystick to make it user-friendly and less tiring. Further it enhances brain-to-hand coordination with kinesthetic movement, which allows smoother and more accurate control of the stiff joystick.

In the previous application, a stiff joystick was made more compliant. Figure 27 shows the control system of a joystick mounted directly to the hard surface. The handle motions are converted to signals by linear variable-displacement transformers (LVDTs). In this application, the joystick may be used to control motion in all six degrees of freedom, not, for example, just the X and Y axes.

Figure 27 is a vertical view of six LVDTs. This particular arrangement will provide positional information in six degrees of freedom. When mounted between the upper and lower U bracket, the LVDTs will act as input devices when the user moves the handle of the joystick. The upper U bracket and the lower U bracket are wider in order to accommodate the six LVDTs. The LVDTs are inclined at an angle of 30 degrees as shown. Figure 27 shows a top view of the lower U bracket with six LVDT mounts positioned so as to place the LVDTs in their proper orientation. Matrix transformation algorithms convert LVDT signals into six-degree-of-freedom commands for either position, velocity, or acceleration.

Figure 28 shows a joystick in operation. the upper left-hand picture shows the joystick in the neutral position. The upper right-hand picture shows the joystick moved to the left. The lower left-hand picture shows the joystick rotated forward. The lower right-hand picture shows the joystick rotated sideways.

Figure 29 shows four possible configurations. The upper left-hand sketch shows a typical hand control system with compliance added. The upper right-hand sketch shows the lowering of the knob for better horizontal control. The lower left-hand sketch shows the compliance with LVDT controls. The lower right-hand sketch shows the compliance with LVDT control and feedback to the hand to indicate that the item controlled is touching the target.

Summary

Described above is a joystick that is superior in all aspects to current commercially available joysticks. Thus, as the operator grabs the knob (2) and moves the handle (25), the cable compliant joint shown in Figure 25 initially provides a low reaction force, but as the handle is moved farther in any direction, the reaction force provided by the compliant joint becomes nonlinearly greater until a limit is reached, either by providing a "stop" or by reaching the limit of the bending of the cables in the compliant joint itself. It is also possible to provide internal vibrators within the knob in Figure 25, to measure the direction and intensity with which a robot controlled by the knob moves into the target. The operator will then know when the target has been contacted, in what position the target has been contacted, and the magnitude of force exerted on the target.

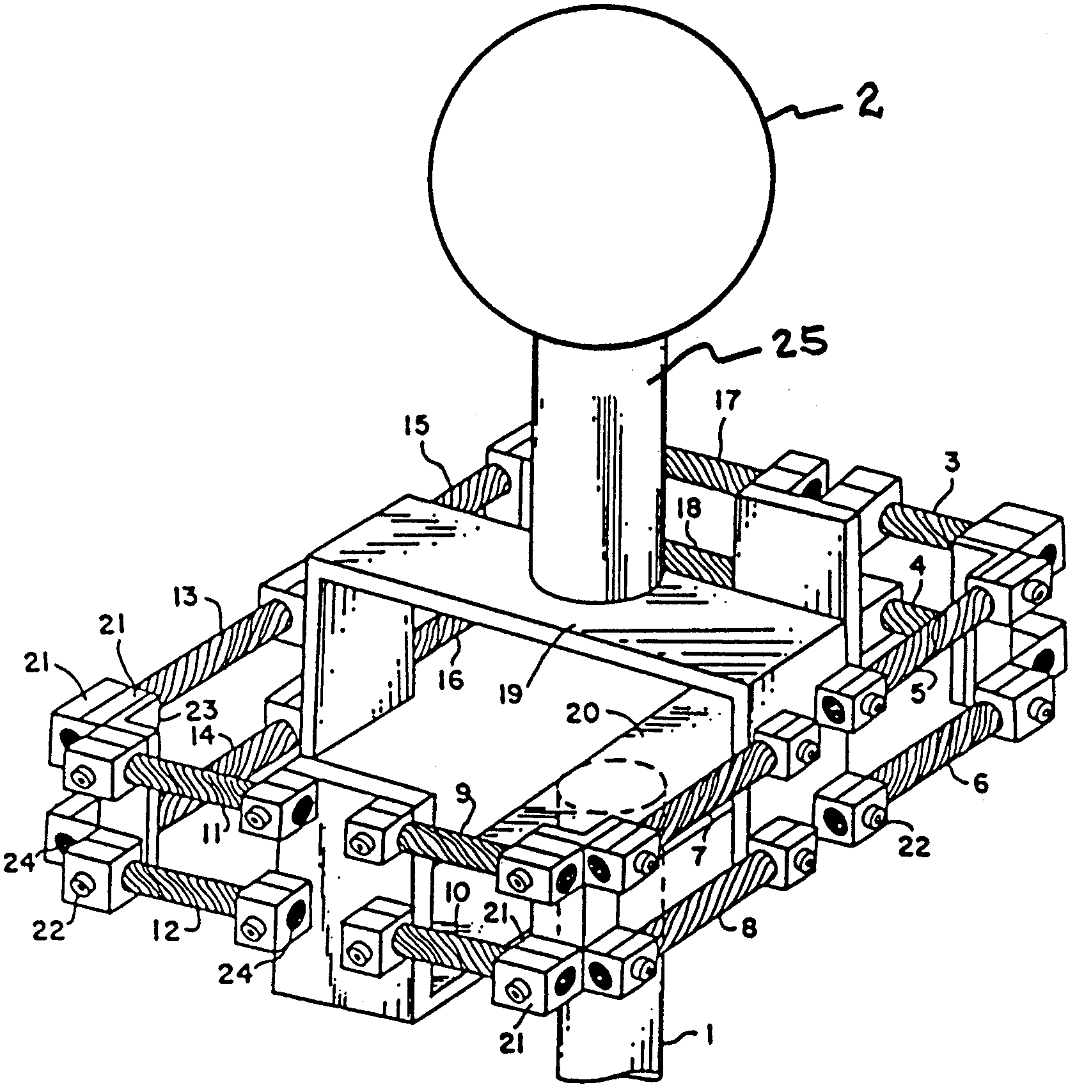


Figure 25. Typical joystick.

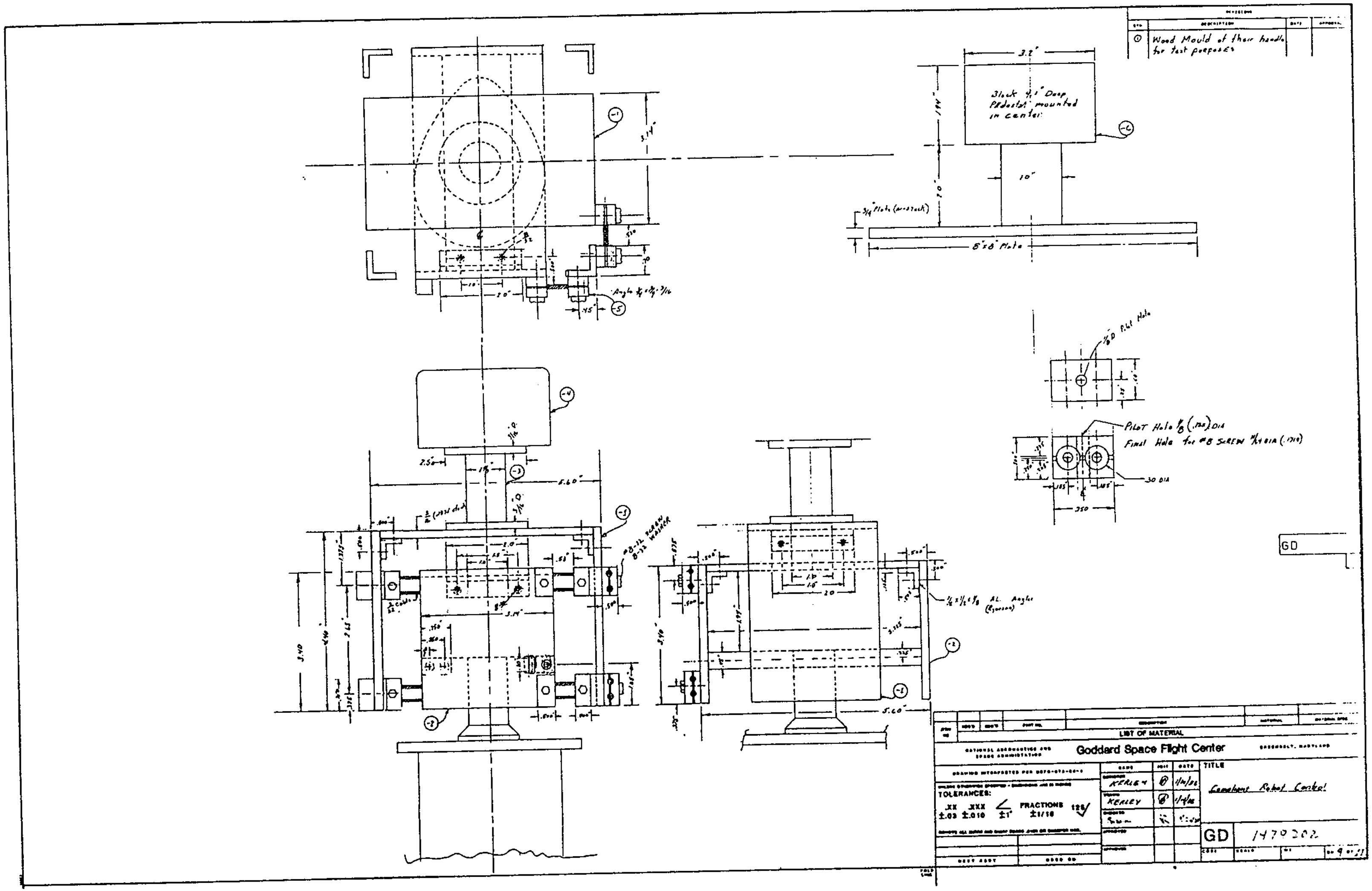


Figure 26. Drawing of typical system.

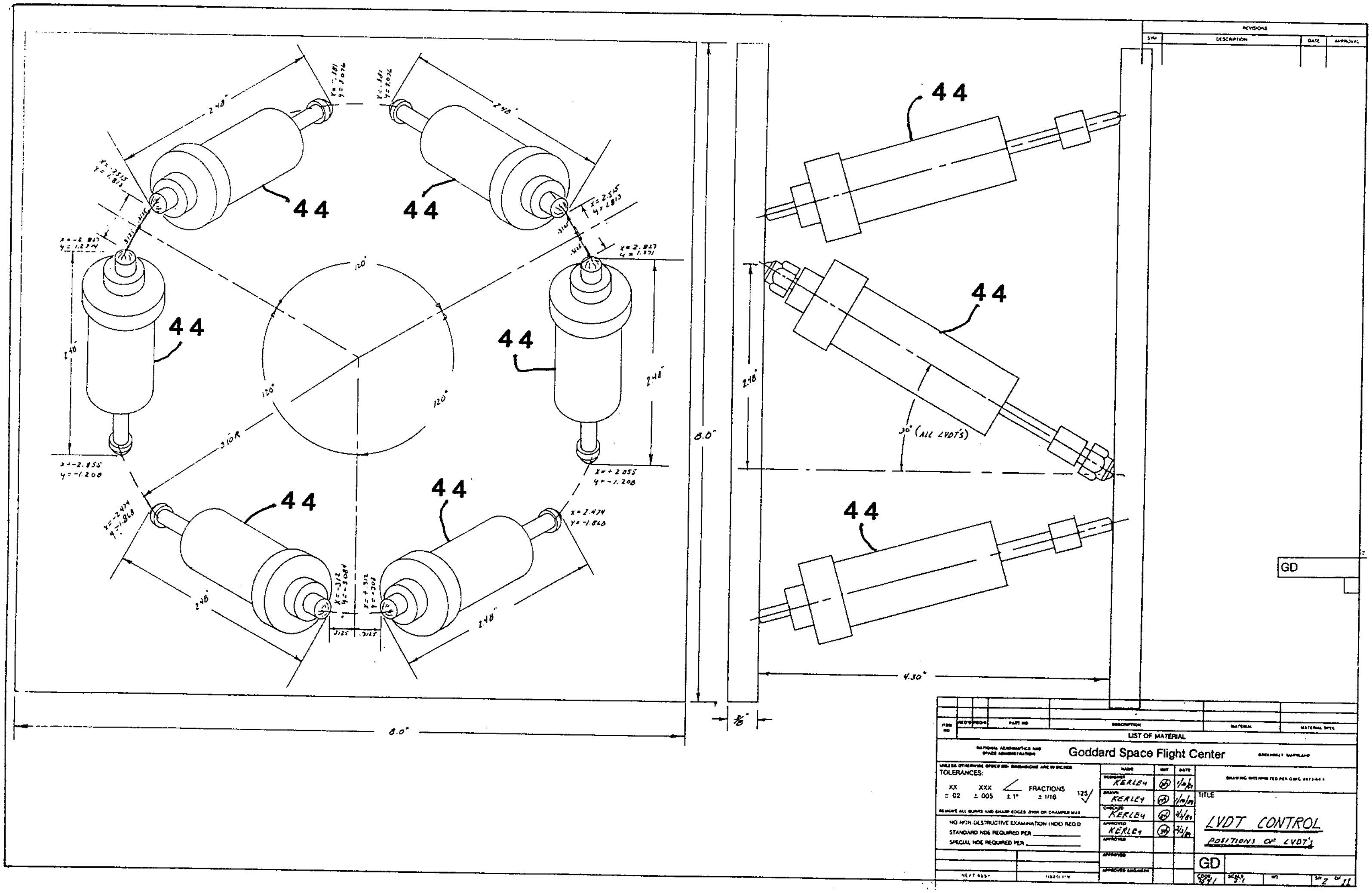


Figure 27. LVDT controls for joystick.

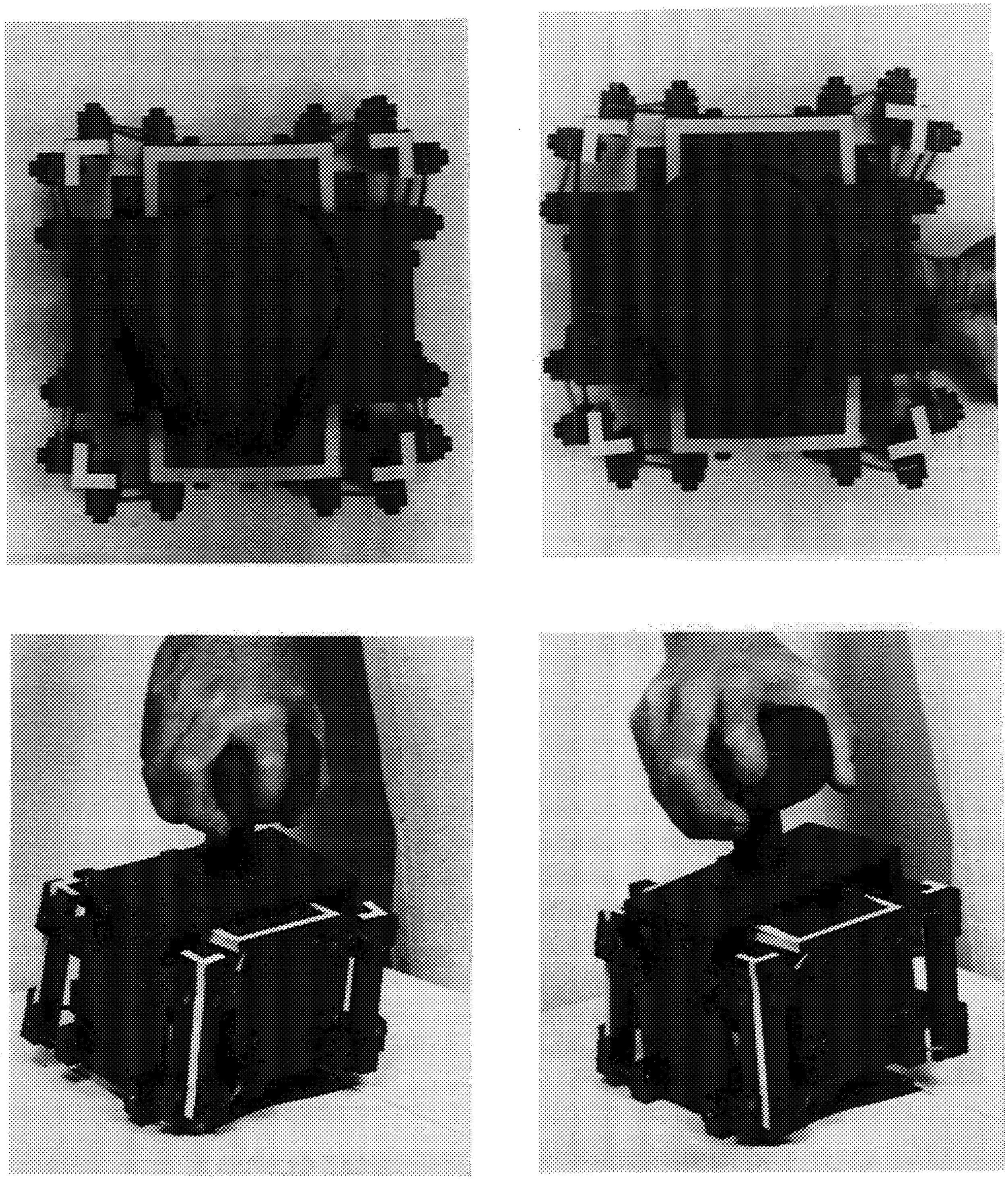
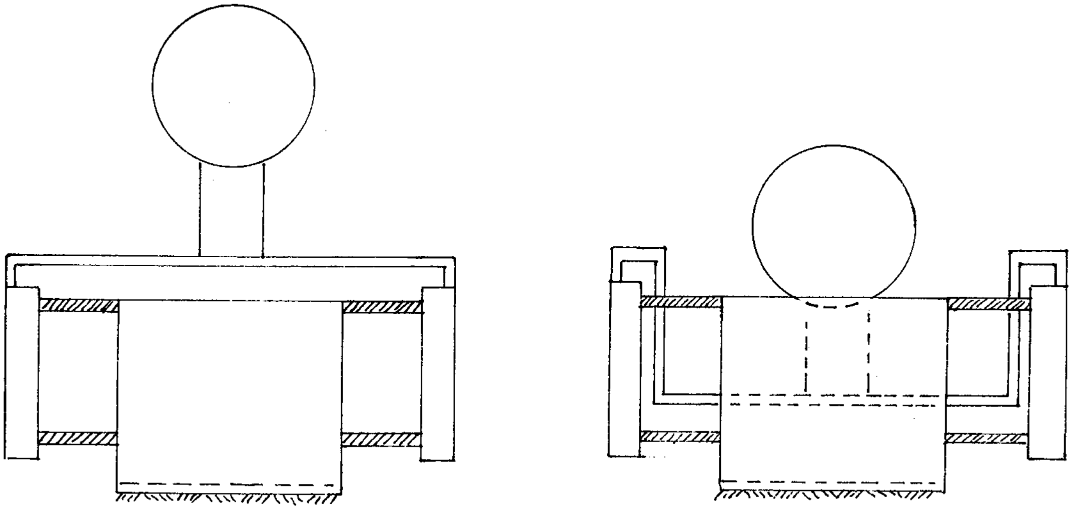
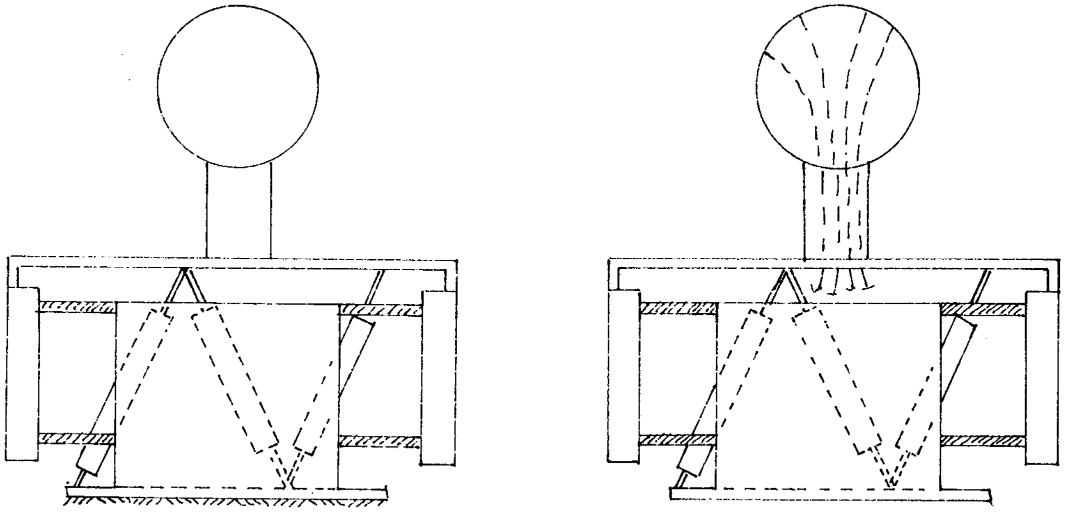


Figure 28. Joystick motions.



TYPICAL HARD CONTROL
CABLE COMPLIANCE ADDED

GOOD HORIZONTAL CONTROL



LVDT CONTROL

LVDT CONTROL
HAND FEEDBACK

Figure 29. Four types of control.

CHAPTER 5

COMPLIANCE FOR A 200-POUND TO 800-POUND TARGET

The control systems listed in Chapter 4, "Cable Control Systems," used cable 1/16 inch in diameter. When these systems were completed, an immediate need came for using compliance on a 200-pound target. Figure 30 is a sketch of the aluminum frame used to hold the cables and mount to the robot. The angles are 7 inches by 7 inches by 1/2 inch, with the width of one leg cut back to 4 inches. On the top are the two angles mounted to an intermediary plate, which is bolted to the mounting plate. The lower angles are mounted to a frame, which is bolted to the other mounting plate. The 200-pound system uses 16 cables. Figure 30 shows 64 cables to hold 800 pounds.

Figure 31 is a sketch with more details. The sixteen cables are shown. The 7 X 4 X 1/2-inch angles are shown. The top and bottom mounting plates are shown. An intermediate plate is shown mounted to the bottom mounting plate. This plate holds six monoballs formed into a "Maltese" cross. The LVDT transducer, which measures deflections down to .001 inch, is shown mounted in the monoball. An adapter fitting is mounted to the other end of the transducer, which, in turn, screws into a tie rod end. The tie rod end is screwed into an intermediate plate on top. This intermediate plate is bolted to the upper mounting plate.

The 7 X 4 X 1/2-inch angles have slots on the sides and on the bottom so that the angles can be moved back and forth. This motion changes the characteristics of the cable. When the angles are moved inward, the mechanism has a maximum compliance. When the angles are moved outward, the mechanism has a maximum stiffness. The sketch shows the cables moved inward for moderate compliance.

Figure 32 shows the lower intermediate plate that holds the six monoballs used to form a Maltese cross. The upper right section of the sketch shows the upper intermediate plate. There are six tapped holes that hold the tie rod ends.

Figure 33 shows the Maltese cross of six LVDT transducers. The output from these transducers can record six-degree-of-freedom motion, which includes translation in the X, Y, and Z axes. Further, they can measure rotation about the X, Y, and Z axes. In this way, the exact rotation and translation between robot and the end effector are always known.

Also shown are the angles with the cable clamps holding the cable to the angles. Further, the corner angles and the clamps used to hold the cable to the angles are shown. In this particular configuration the angles are moved out to give a stiff compliance to the system.

Figure 34 shows the cable stiffness adjustment in the vertical plane. The slots in the angles allow the cable to move up and down. When the upper cables (as shown) are moved up while the lower cables (as shown) are moved down, the compliance is stiff in the vertical direction. By reversing this motion, the cables are more compliant in that vertical axis. The upper left part of Figure 34 shows the slots on the bottom of the angle, which allow the angles to move in and out. The cables are moved out for maximum stiffness. The upper right sketch on Figure 34 is a drawing of the cable holder.

Figure 35 shows the actual installation of the compliant system from parts already shown in the previous sketches. The upper mounting plate is mounted to the robot on top. There are 16 cables used to hold 200 pounds. This amounts to 12 1/2 pounds per cable. The spacing is approximately 1 3/4 inches. The cable used is 1/4-inch 7 X 19 stainless steel air cord. The two upper angles are bolted to the upper mounting plate. The two lower 7 X 4 X 4 X 1/2-inch angles are bolted to the lower mounting plate. This plate holds a force transducer, which, in turn, holds the grippers (end effectors) of the robot. Notice the slots in the 7 X 4 X 4 X 1/2-inch angles that allow for stiffness adjustment. Another feature of this type of system is that the stiffness can be adjusted without taking the system apart. The upper and lower angles can also be adjusted without taking the system apart. The cable holders are mounted to the inside of the angles. They could have been mounted to the outside of the angle, but this would have required a larger corner angle and would have made the system approximately 4 inches wider.

Figure 36 shows this same system mounted to a robotic gantry with 64 cables capable of lifting 800 pounds. This gives the same 12 1/2 pounds per cable. The spacing is approximately 1 3/4 inches. The robot is in the upper left. The cable compliance is mounted directly under it. The end effector is a rotary clamping mechanism that meets with its mating mechanism shown in the lower right. The overall purpose is to operate the gantry by computer. With compliance, the matching attachment need not be exact, since the cable allows for misalignment in the six degrees of freedom.

Figure 37 shows the robot coming down to meet the target.

Figure 38 shows the end effector meeting the target at an angle of approximately 5 degrees. This angle does not ordinarily occur, but it is made large to illustrate the compliance of cable. In this case, the LVDTs are not needed. An additional element is a 3/4-inch threaded rod that goes from one angle to the other. This rod is used to help control the moment on the angles when the 800 pounds is applied. Further, this angle makes adjustment after installation easier and stronger, particularly in the stiff mode. In this particular installation, it was necessary to change the adjustment to meet the requirements of the robotic laboratory.

Figure 39 shows the robot coming down to meet the target while the cables bend to conform to the misalignment. There is a noticeable different angle between the upper mounting plate and the lower mounting plate. As stated previously, it was approximately 5 degrees. The cables are bent to conform to this large angular misalignment. The lower clamping mechanism is rotated, and the robot is firmly attached to the target, which can be lifted in this manner. However, in practical usage, the operator notices the large angle and rotates the robot arm to take care of some of this misalignment.

These previous pictures and sketches demonstrate the ability of compliance to adjust itself to all six degrees of freedom. In this particular case, the difficulty was not so much misalignment in the X, Y, and Z plane but rotation about the X and Y axes. There is a smaller need for the adjustment of rotation about the Z axis.

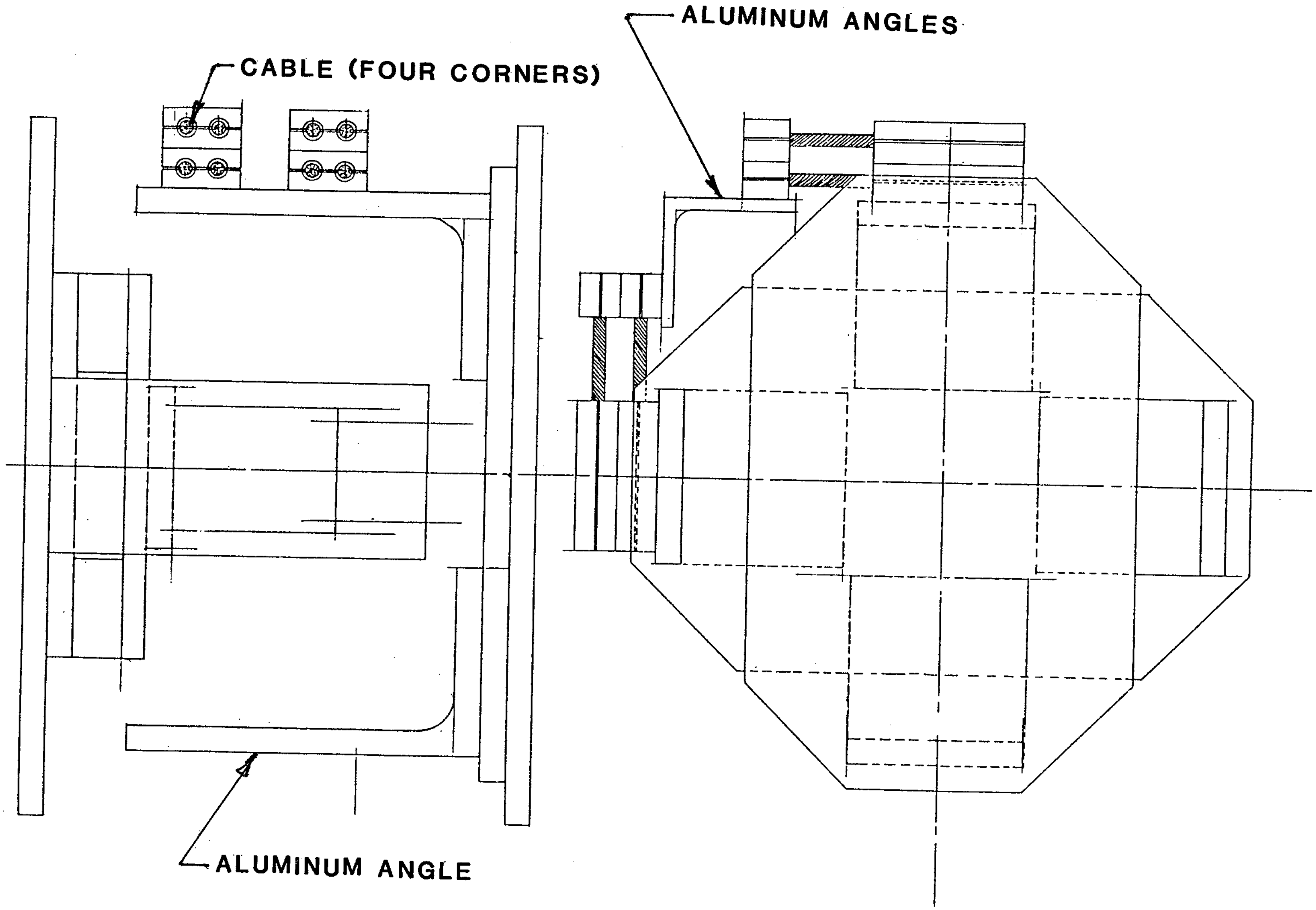


Figure 30. Mechanical structure.

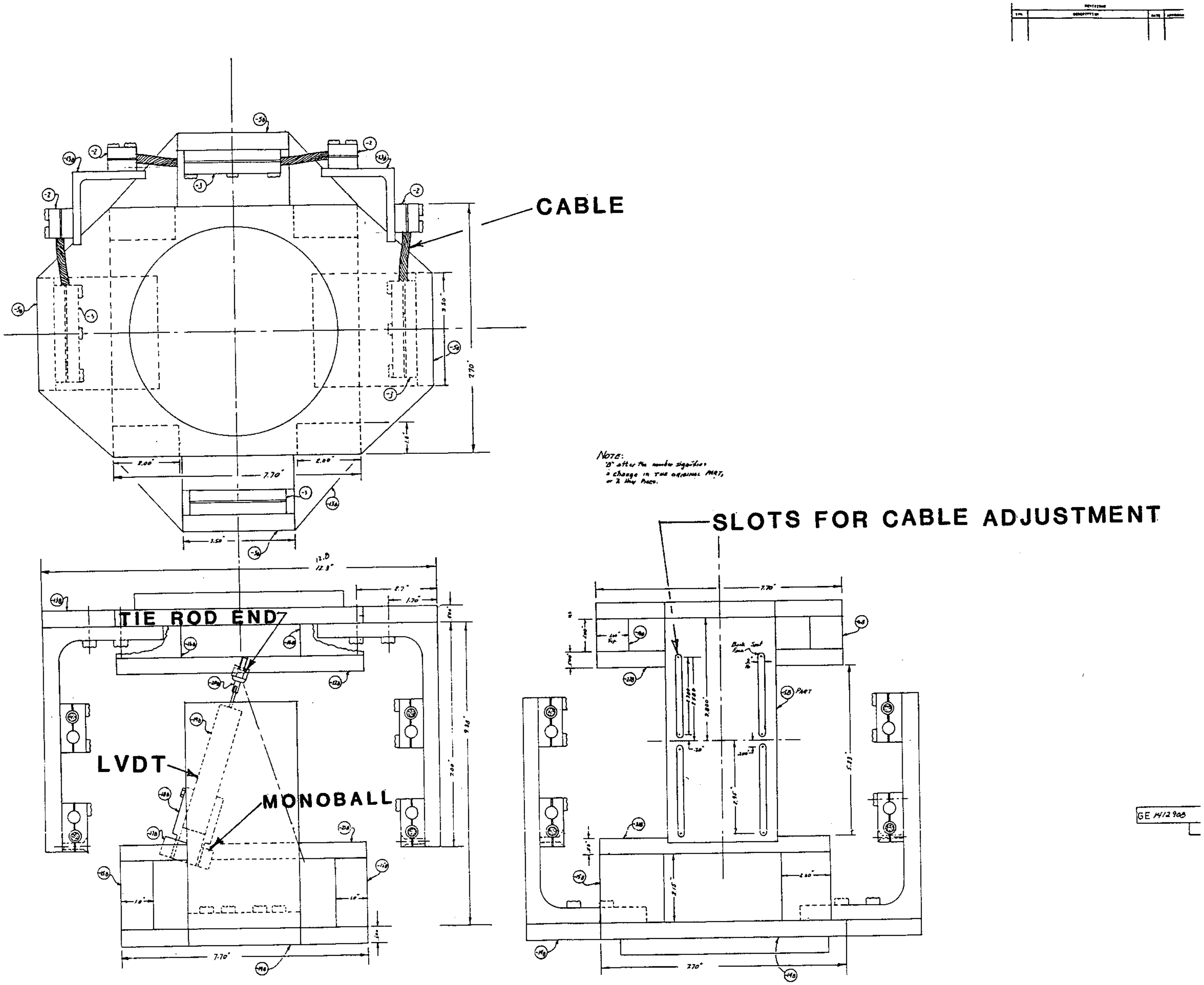


Figure 31. LVDT installation.

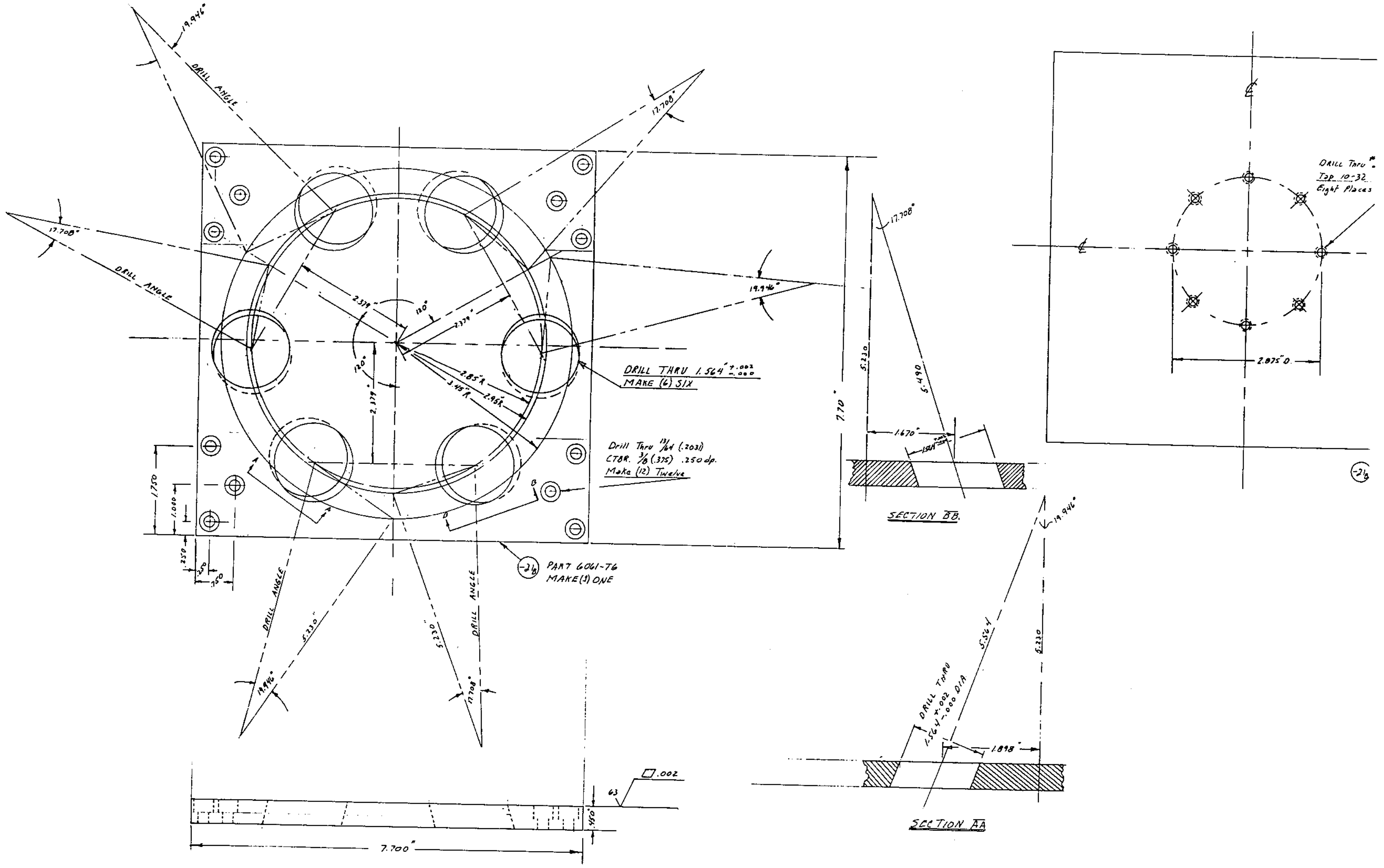


Figure 32. Plate to hold monoballs.

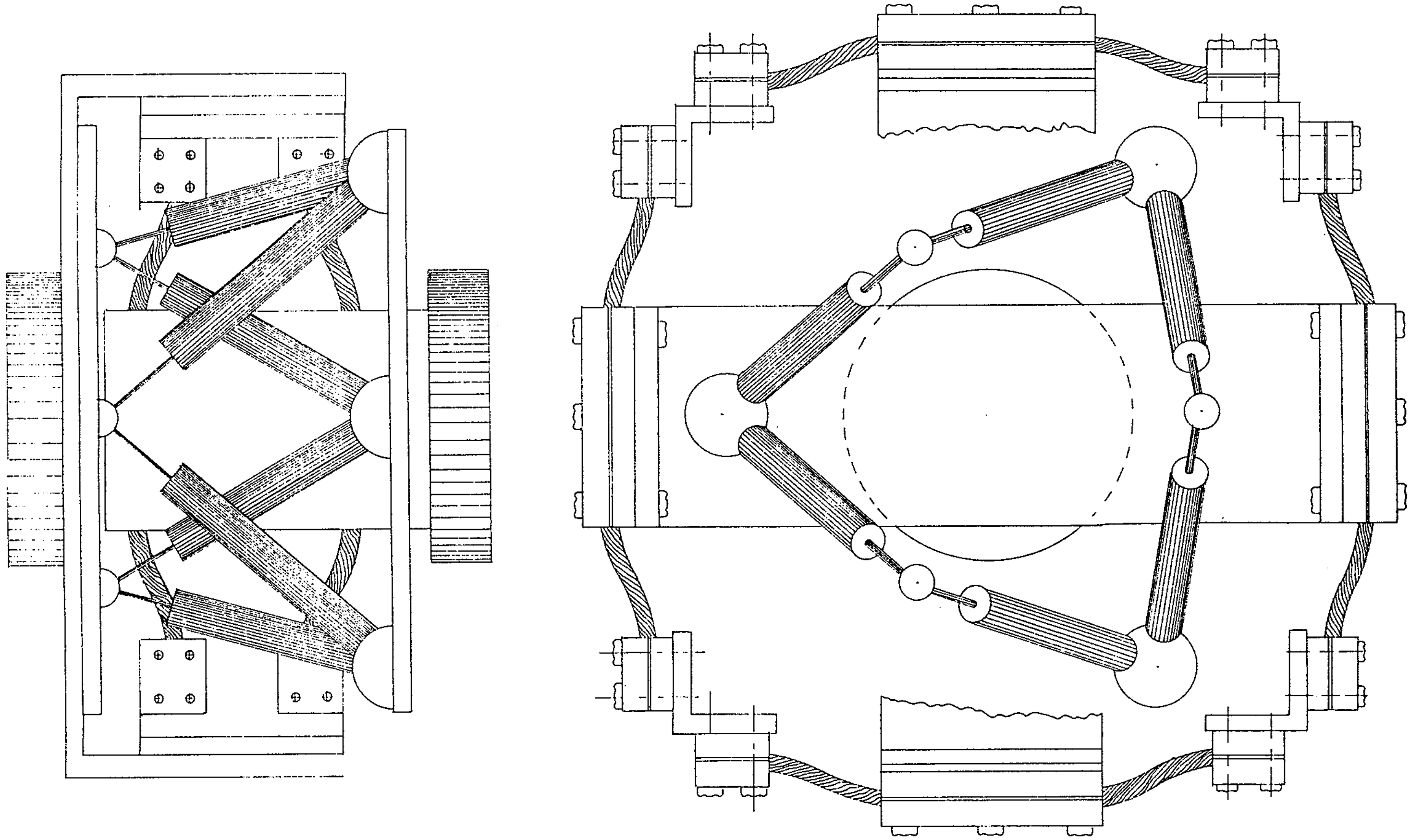


Figure 33. LVDT maltese cross.

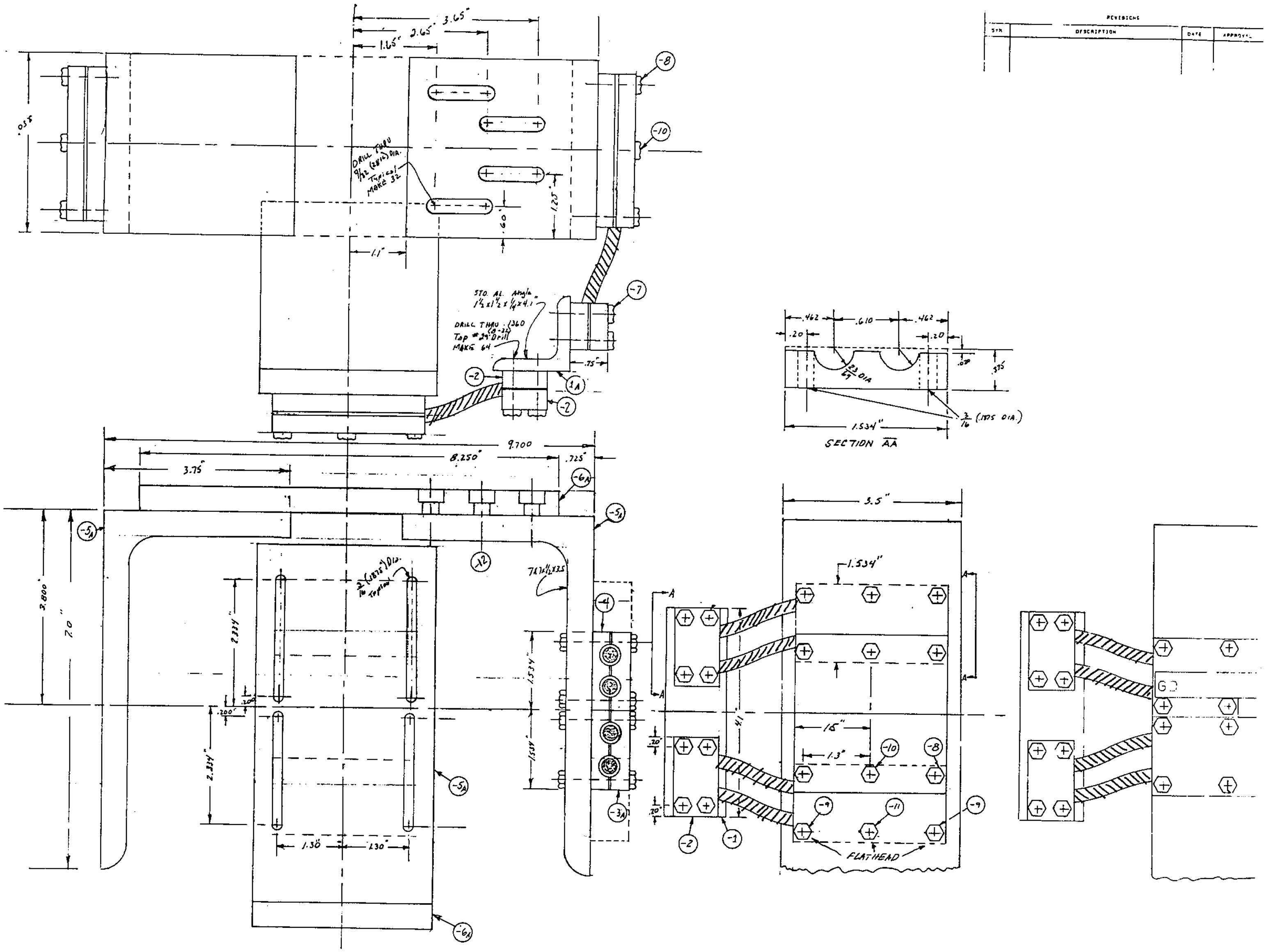


Figure 34. Cable adjustment.

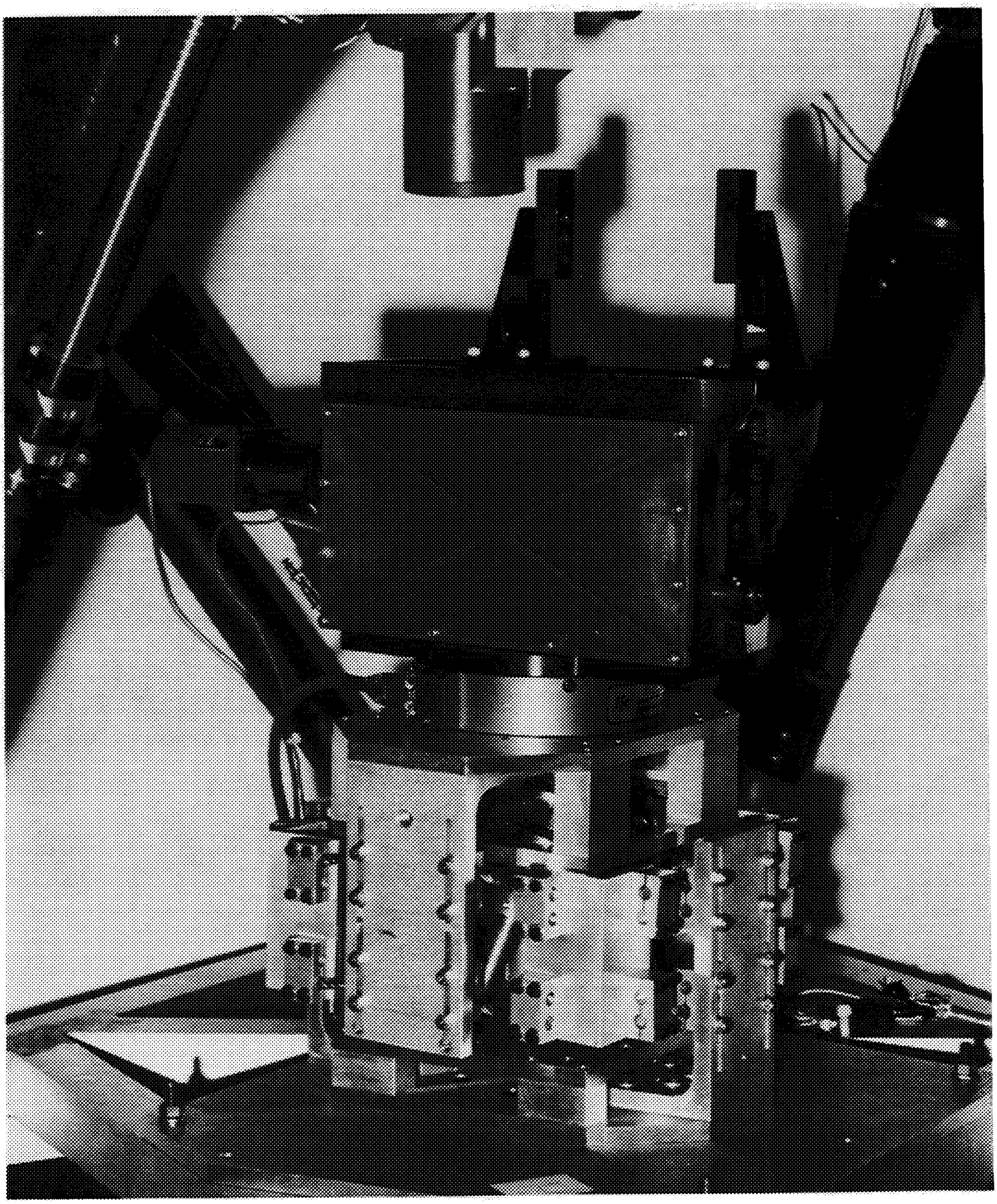


Figure 35. Compliance installed on robot.

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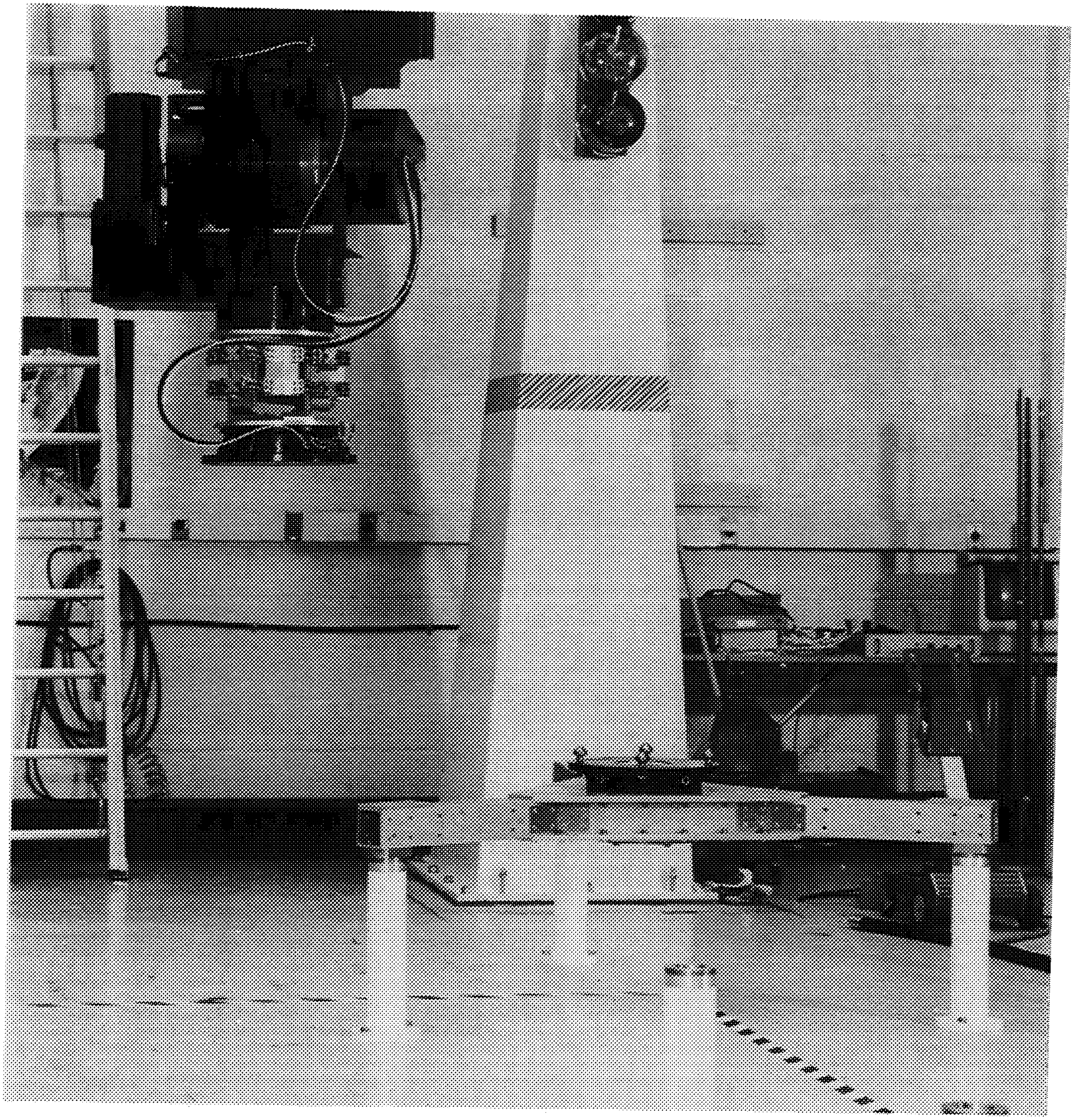

Figure 36. Gantry robot with compliance.

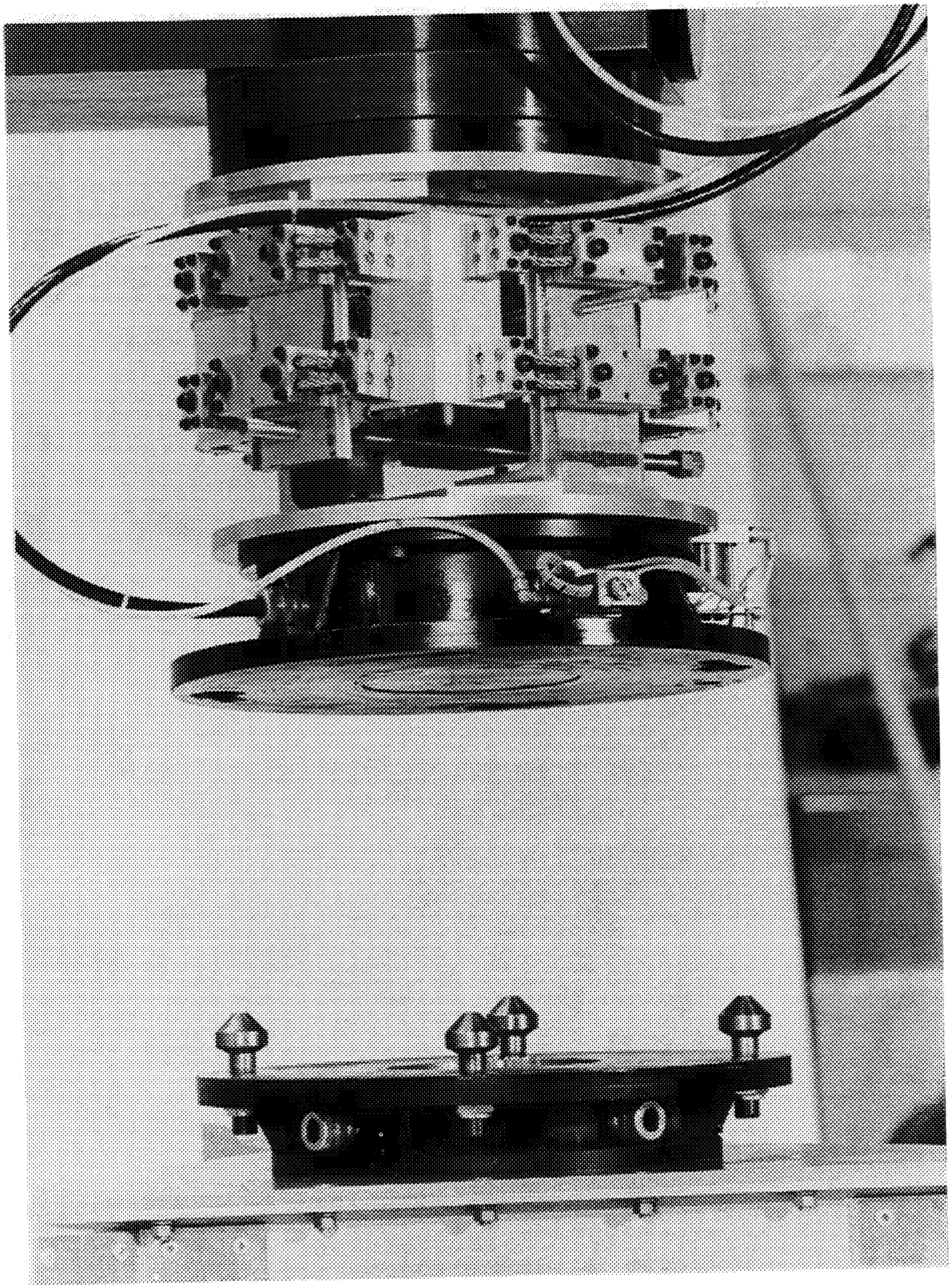

Figure 37. Gantry approaches target.

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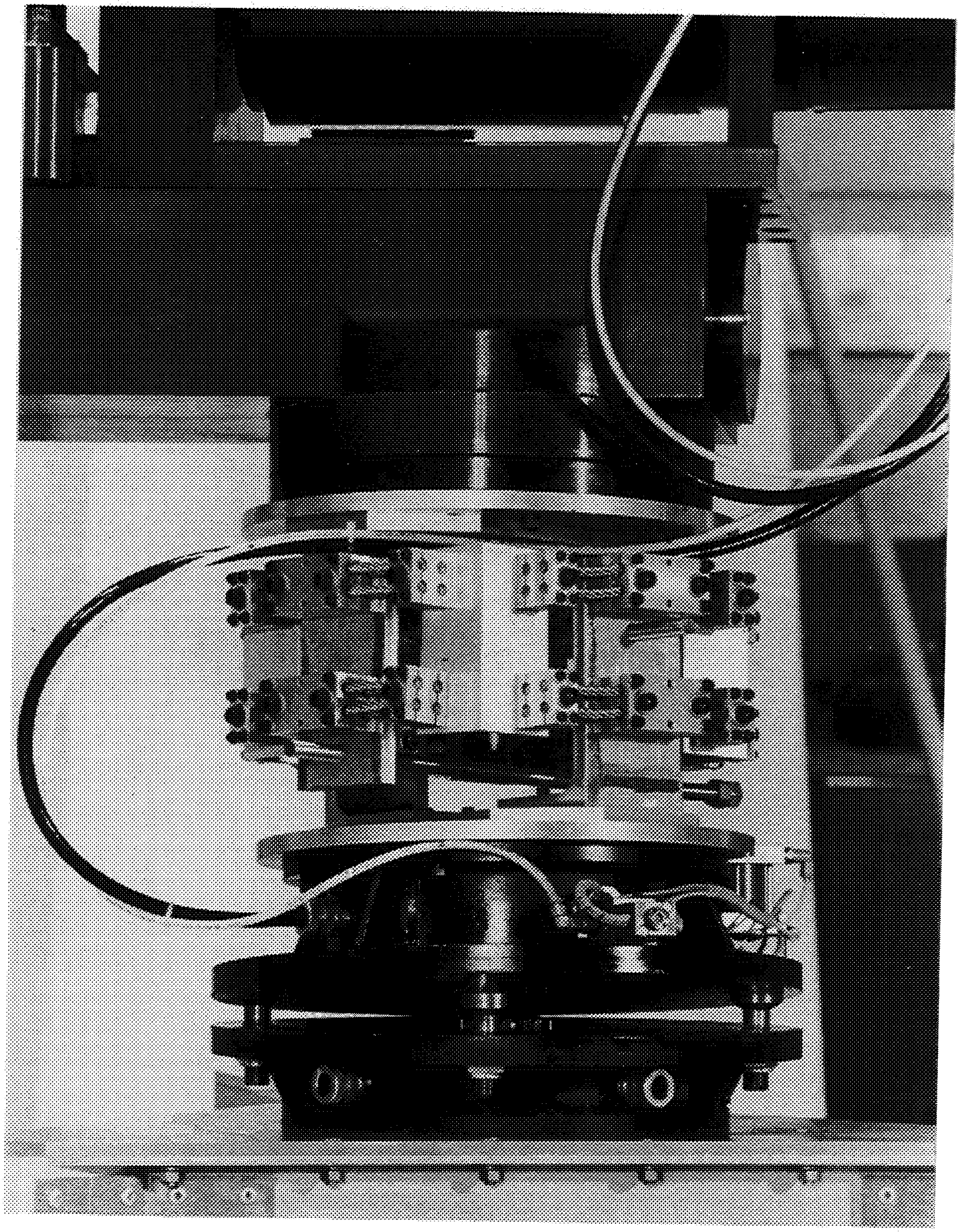

Figure 38. Gantry touches target.

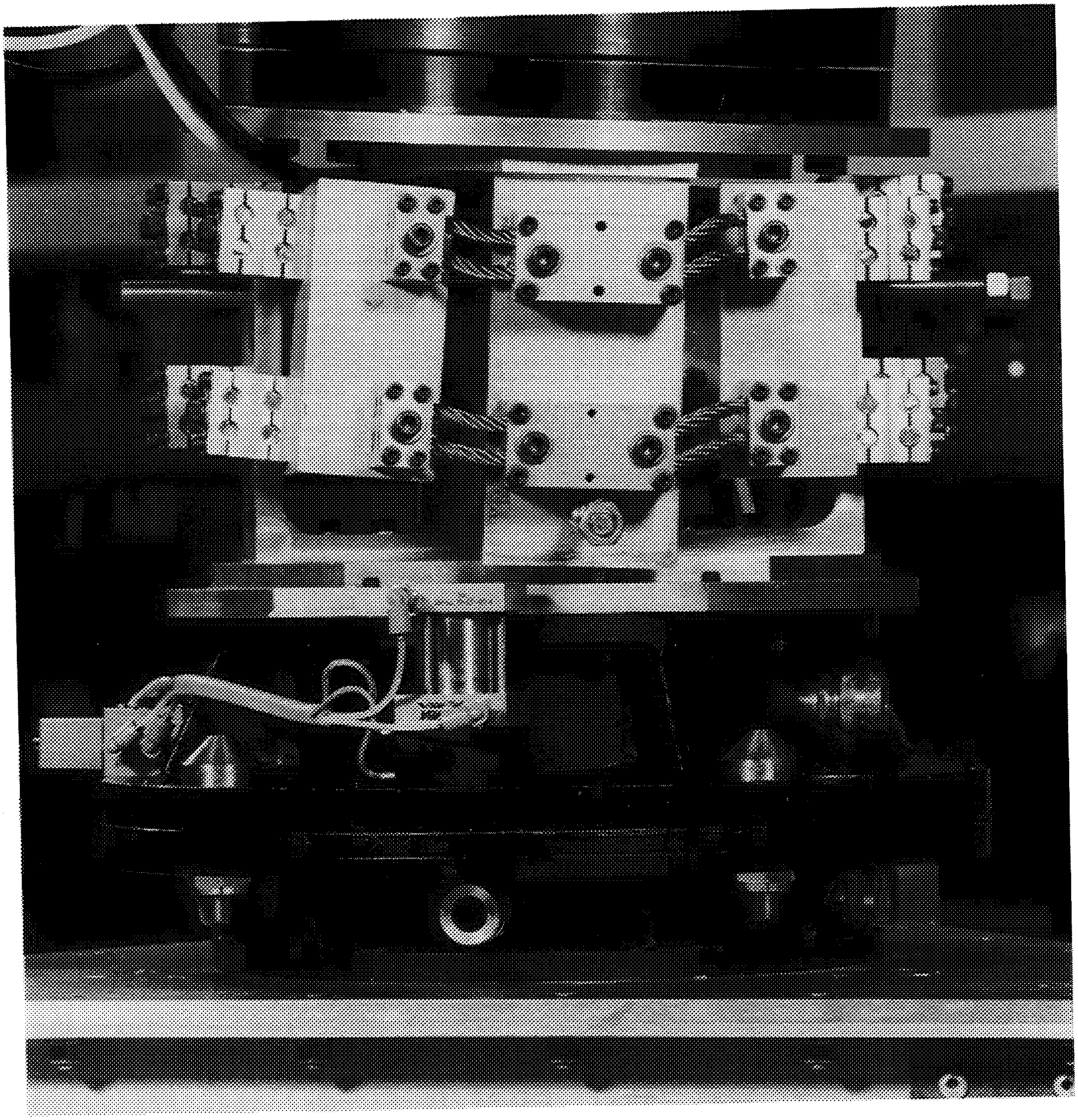

Figure 39. Cable adjusts to misalignment.

CHAPTER 6

VARIABLE COMPLIANCE

Many times the robot has to make a contact with the target and grasp it to perform a function when the robot may not know the exact position of the target. However, a mechanism with large compliance on the end of the robot will enable it to grasp the target. Then when the robot has to take the target and put it into a precise position, it is desirable to have the cables on the compliance mechanism tighten up and become linear and accurate. At the same time, the compliant mechanism with limber maximum compliance may not be able to operate with the full force necessary to do the job. In this case the cables can be made to be very compliant to grasp the tool but not in a position to handle heavy weights and forces. With variable compliance, it is possible to approach the target with much compliance, but to stiffen up (with little compliance) when a precise task is to be performed.

Figure 40 shows such a variable compliance mechanism. Note the 12-inch ruler in the center of the picture. There are 320 cables of 1/4-inch 7 X 19 stainless steel air cord. The cables in the bottom and top of the picture are pushed in and quite limber. The cables on the side are in the neutral position. The circular rings are not made for the compliance mechanism, but they are added to hold the LVDTs in the form of a Maltese cross, explained previously. This offers another desirable function. The LVDT signals go to a computer where they always know the angular and rotational positions of both the robot arm and the target. The LVDTs can then show the computer how to line up the compliance mechanism so that it will be in the same line as the target even if that line is not perfect when the arm first meets the target.

Figure 41 shows the top view of the same variable compliance mechanism. This picture shows the complete symmetry of the cable positions in order to get a six-degree-of-freedom system for contact and control.

Figure 42 shows the cable holder in the center with the cables attached to both ends. The cable holder moves up and down to become soft or hard. It is moved by the ball screw shown in the center of the picture. The threaded rods sticking up are used to keep the cable from moving too far in case of overload.

Figure 43 shows the complete drive mechanism with the cable attached. This compliance mechanism consists of a top plate and a bottom plate. In this view only the bottom plate is shown. The upper plate is exactly the same but rotated 90 degrees.

Figure 44 shows the drive mechanism without the cable.

Figure 45 shows a close-up view of the drive mechanism with the ball screw.

Figure 46 shows a close-up view of the cable assembled on the corner angle.

Figure 47 shows the assembly drawing of one half of the compliance mechanism. Marked in particular are the cable support brackets, the ball nuts, the ball screws, the worm drive, the flanged bearing, and the shaft support bearing.

Figure 48 shows a computer-simulated model of the position of the cables as they are pushed out and made stiff. This means that the angle support bracket is moved outward on all four sides to a point where the cable is stretched and bent before the load is applied.

Figure 49 shows an applied load upward. The upper cables that have been previously stretched out are now straight. To allow this motion, the cables on the other side must be stretched farther. This limits the motion of the upper cables, and the cable compliance mechanism is stiff. It is possible to have the lower cables stretched out so far that the upper cables move only slightly.

Figure 50 shows the cables moved inward before loading. They are quite limber in this form, and there is quite a bit of compliance. This is a characteristic of cable in this form. The ball screws turn and move the end cable holders inward.

Figure 51 shows the deflected cables of Figure 50 with a vertical force. This force has the same value as the force in Figure 49. There is a completely different pattern of deflection. The cables move much farther than those in the previous example of Figure 49. This brings the compliant mechanism to its maximum compliance. It moves in any direction very easily. It is good to note here that the motion of any cable on the compliant mechanism affects every other cable and either abets or hinders the motion attempted.

Figure 52 shows a static hysteresis test on the compliance mechanism when the cables are in the neutral position. A positive load of 5,000 pounds and a negative load of 4,000 pounds were applied. The loads were applied in 1,000-pound increments. The friction of the rubbing wires while bending causes this damping. It should be noted that the response has heavy damping and is non-linear, but at the same time, it is reproducible. Thus, there is no yielding of the cable.

Figure 53 shows the loading of the compliance mechanism as the cable is initially positioned inward and in the most limber configuration. These hysteresis curves are much weaker than those in the previous tests. With 2,000 pounds, the compliance mechanism moved approximately 1.6 inches. In the previous example of Figure 52, when the cables were in the neutral position, the mechanism moved no more that .55 inches with 2,000 pounds. This soft compliance is very good for mating of the target for the first time, since it takes very little force to line up two items.

Figure 54 shows the hysteresis curves of the cable when they are previously moved outward. The hysteresis is almost gone, and it acts as a linear system with a slight amount of damping. Note that the deflection is approximately .85 with a load of 4,000 pounds, while the neutral position deflects 1.4 inches with a 4,000-pound load. Within the accuracy of the test, this compliance for the stiff mechanism is linear and reproducible. It is understood that it is possible, with a much larger preload, that the cables would be nonlinear, both because of damping and also because the cables change their characteristics when they are bent beyond a certain point. This is a desirable feature because a severe overload would not break the system, but it would change the hysteresis of the cables. There would be some yielding of the cables near the holders, but they would not break.

Summary

It is desirable to have a compliance mechanism between the robot and the target to make a coupling of the two, even if they are severely misaligned in the six degrees of freedom. It is not desirable to have a largely compliant mechanism act as the robot is moving and performing its task with the target. Thus, with one compliant mechanism, it is possible to have a variable compliant system that would accomplish both ends. While the system is built for a 4,000-pound target, it is important to note that this same principle can be applied to a much smaller compliance mechanism. Usually in the small devices, the mechanism has two positions—stiff and limber. With the motor used in the 4,000-pound compliance mechanism, it is possible to get over many positions.

It must be further noticed that the system illustrated is nothing but eight 4-bar links with two solid links and two cable links. They are balanced and can be reproducible and predicted. There are many other cable devices that do not have the same characteristics, largely because the cable is curved, which causes a certain amount of unstranding that can lead to many forms of nonlinearity. This report is centered around this type of system that is adapted to many sizes and loads and many forms of compliance.

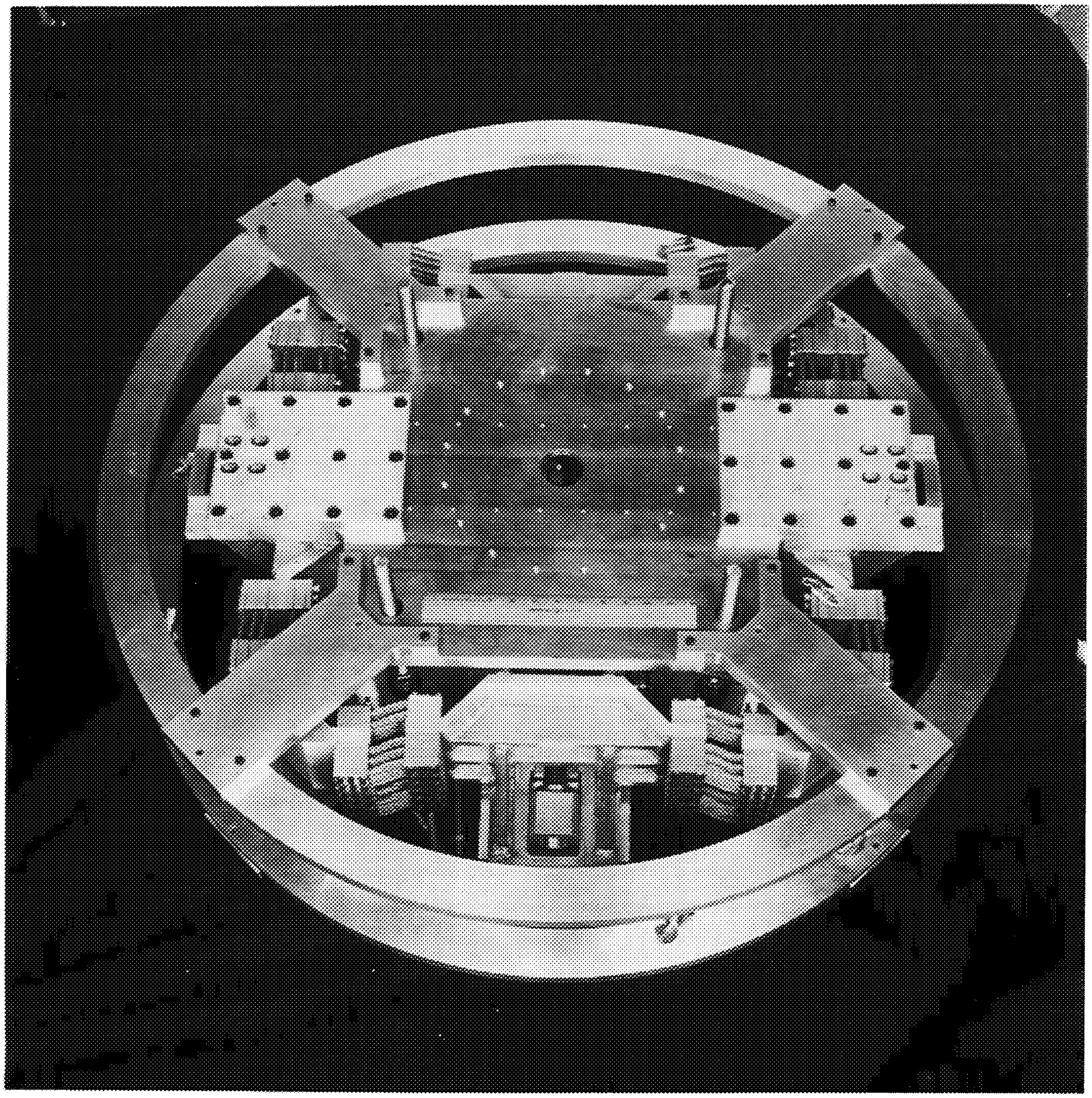

Figure 40. Perspective view of compliance mechanism.

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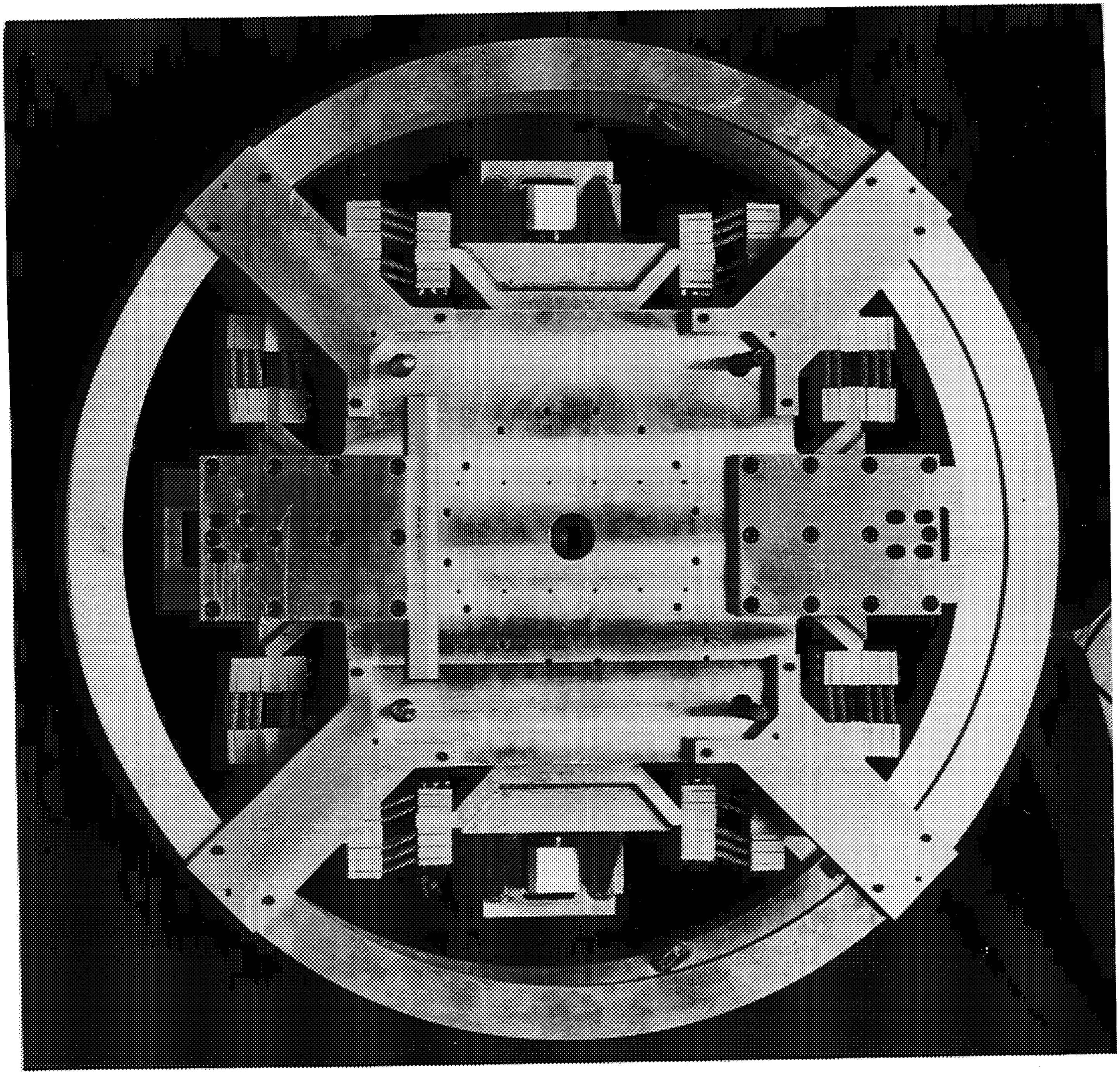

Figure 41. Top view of compliance mechanism.

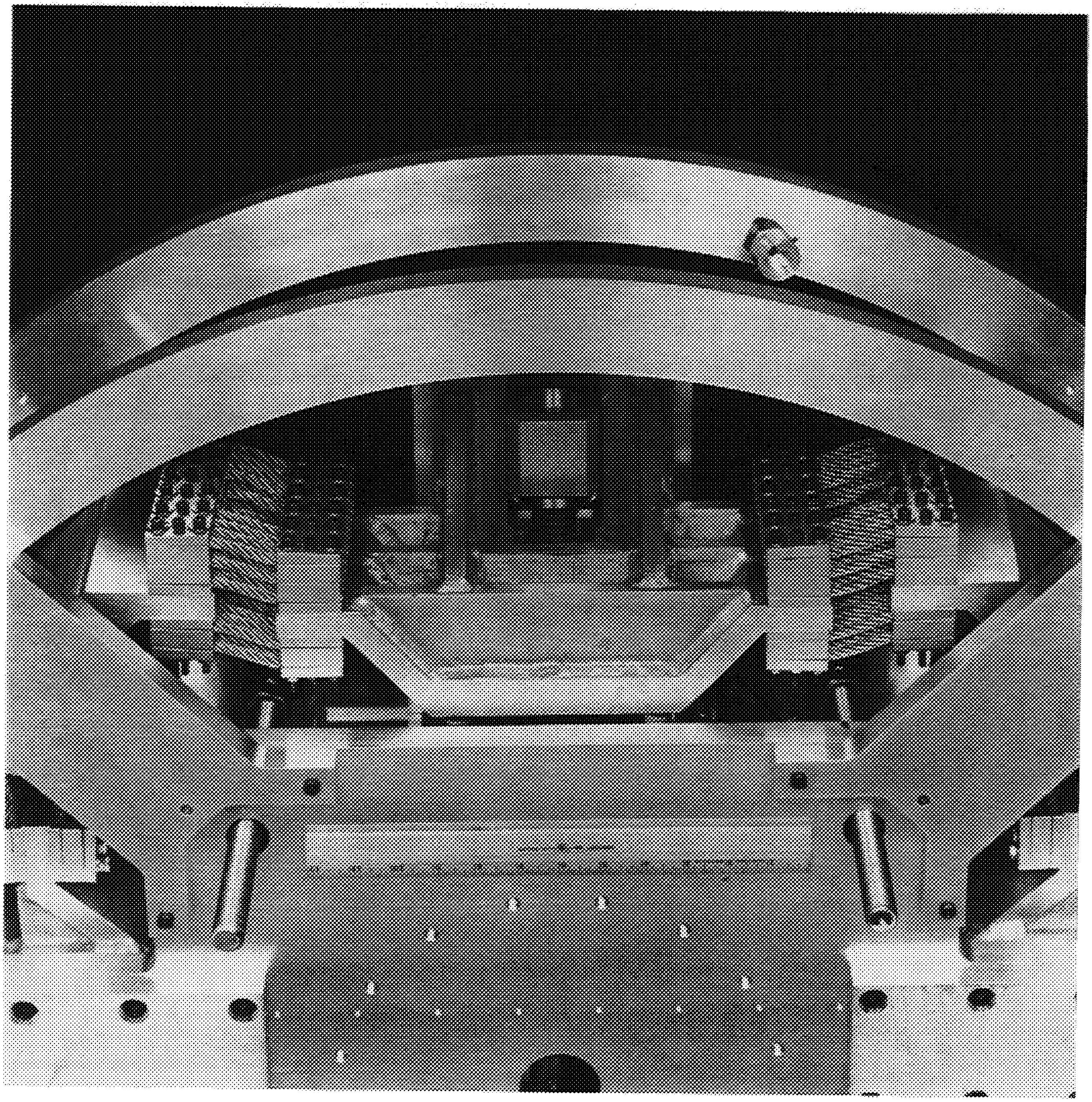

Figure 42. Cable holder, cable, and ball screw.

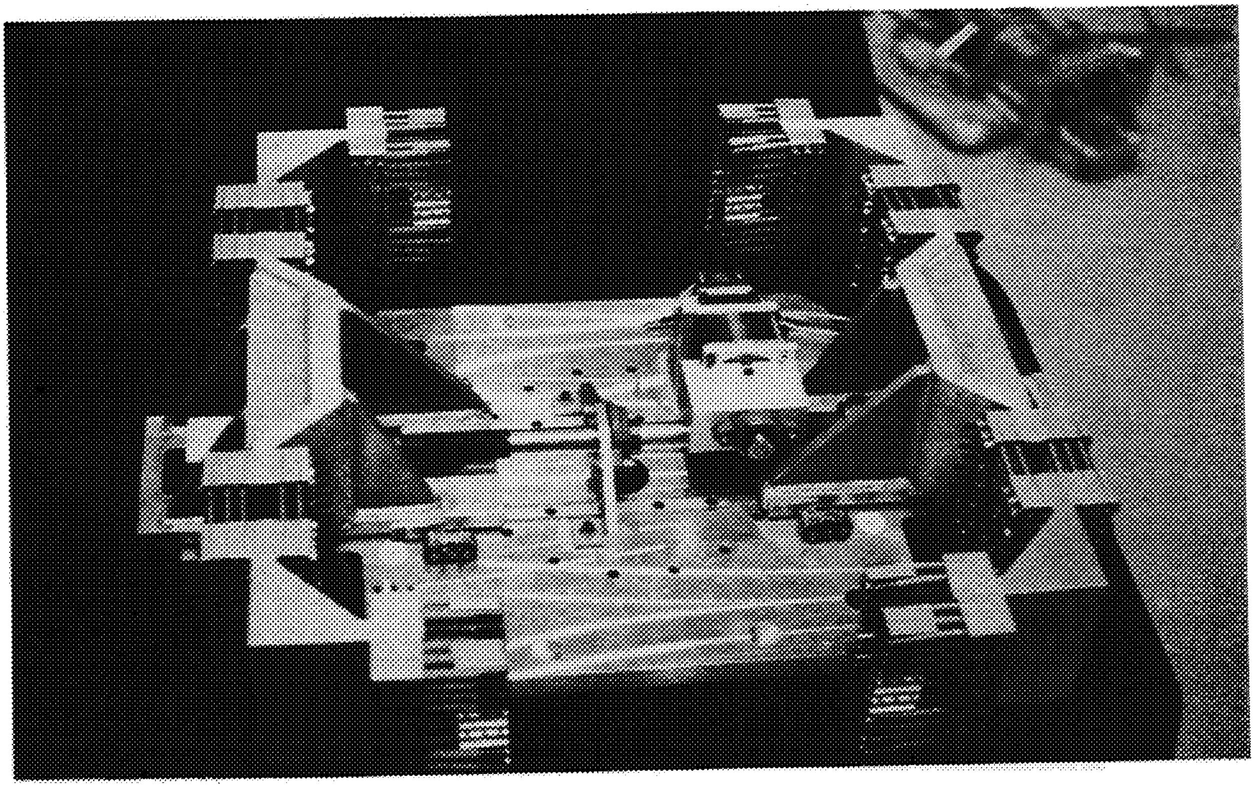

Figure 43. Drive mechanism and cable.

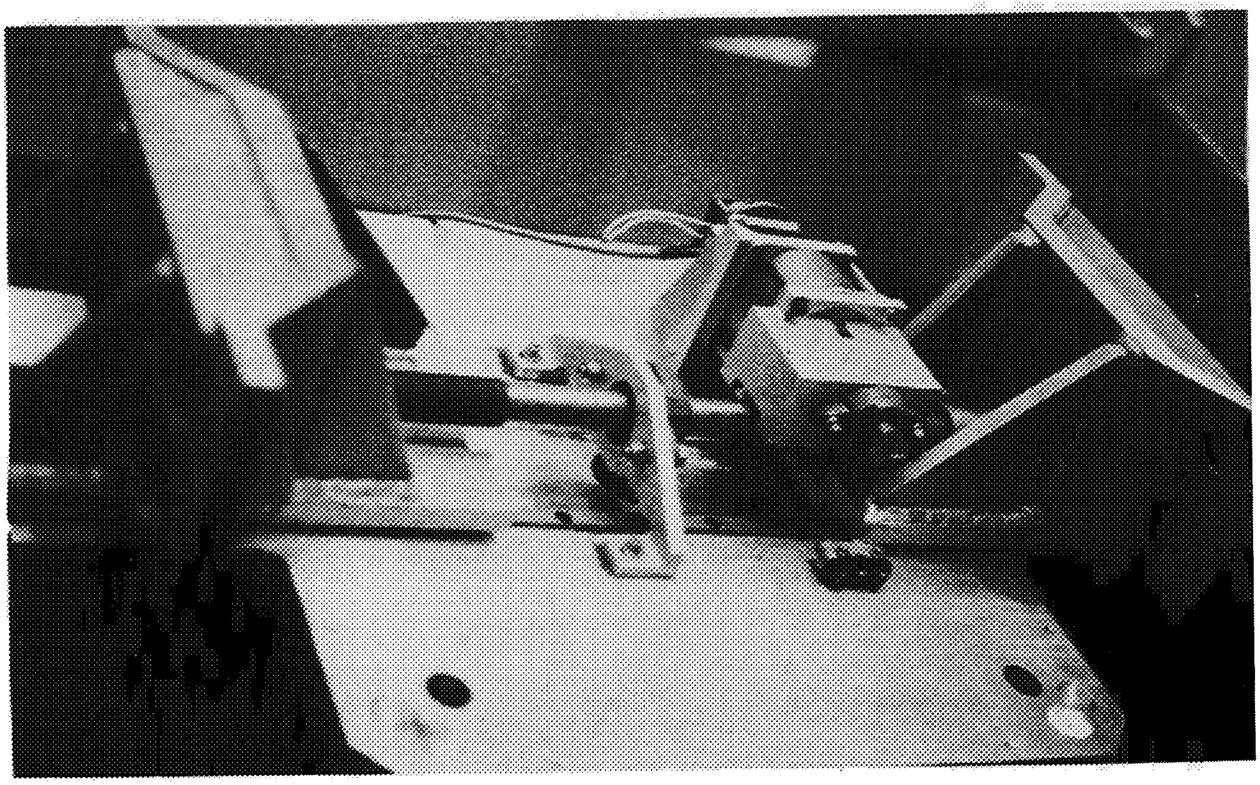

Figure 44. Drive mechanism.

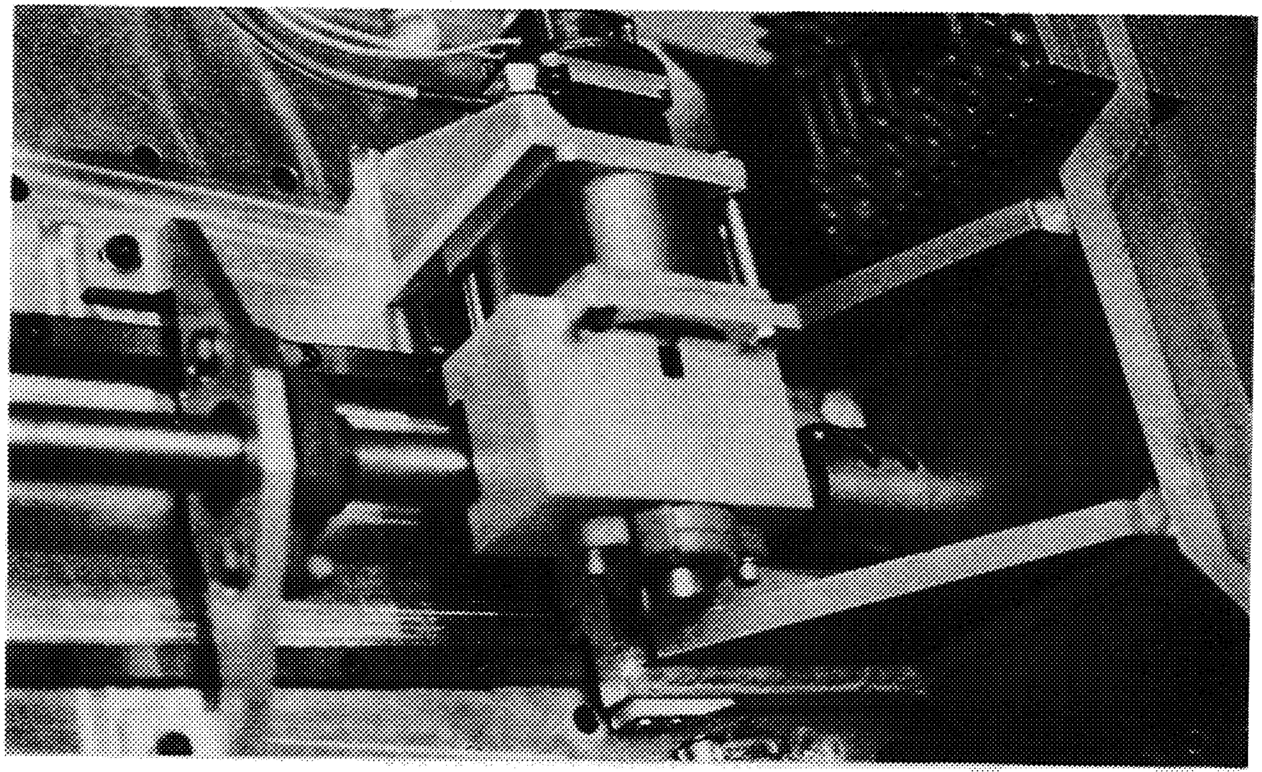

Figure 45. Drive mechanism with cables.

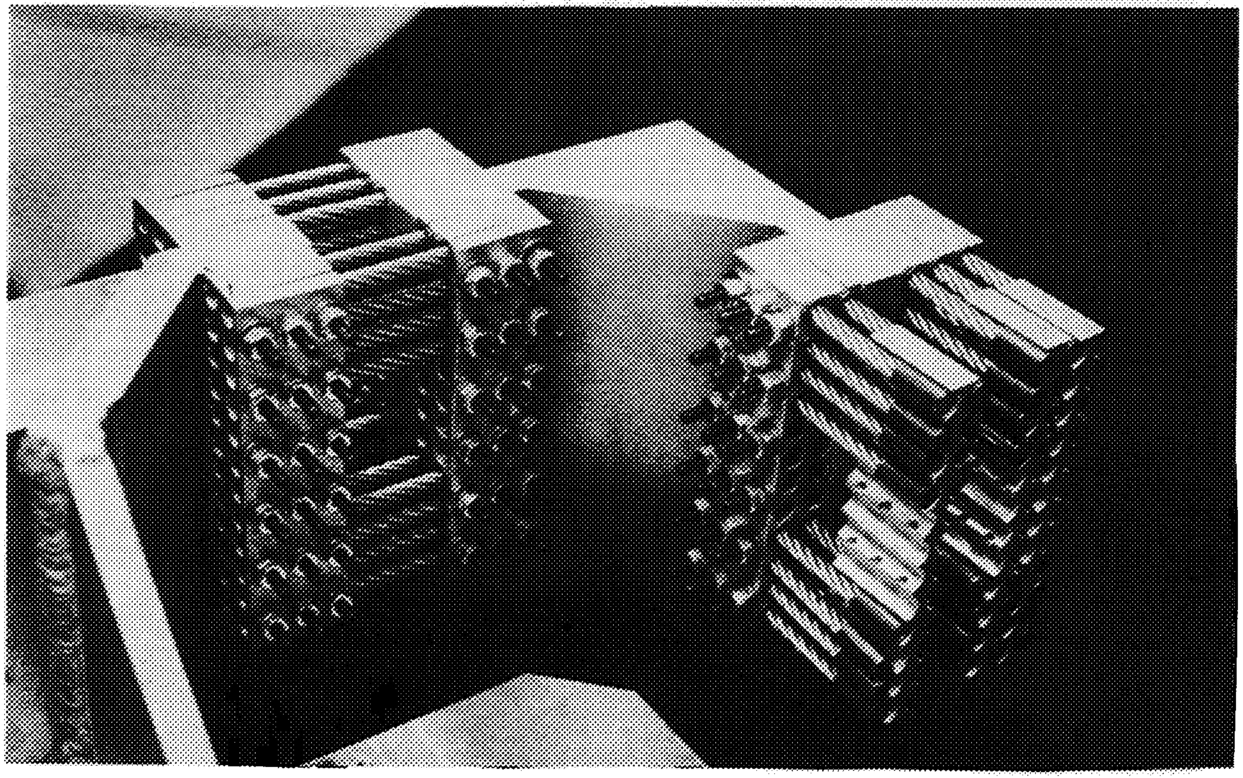

Figure 46. Cable assembly.

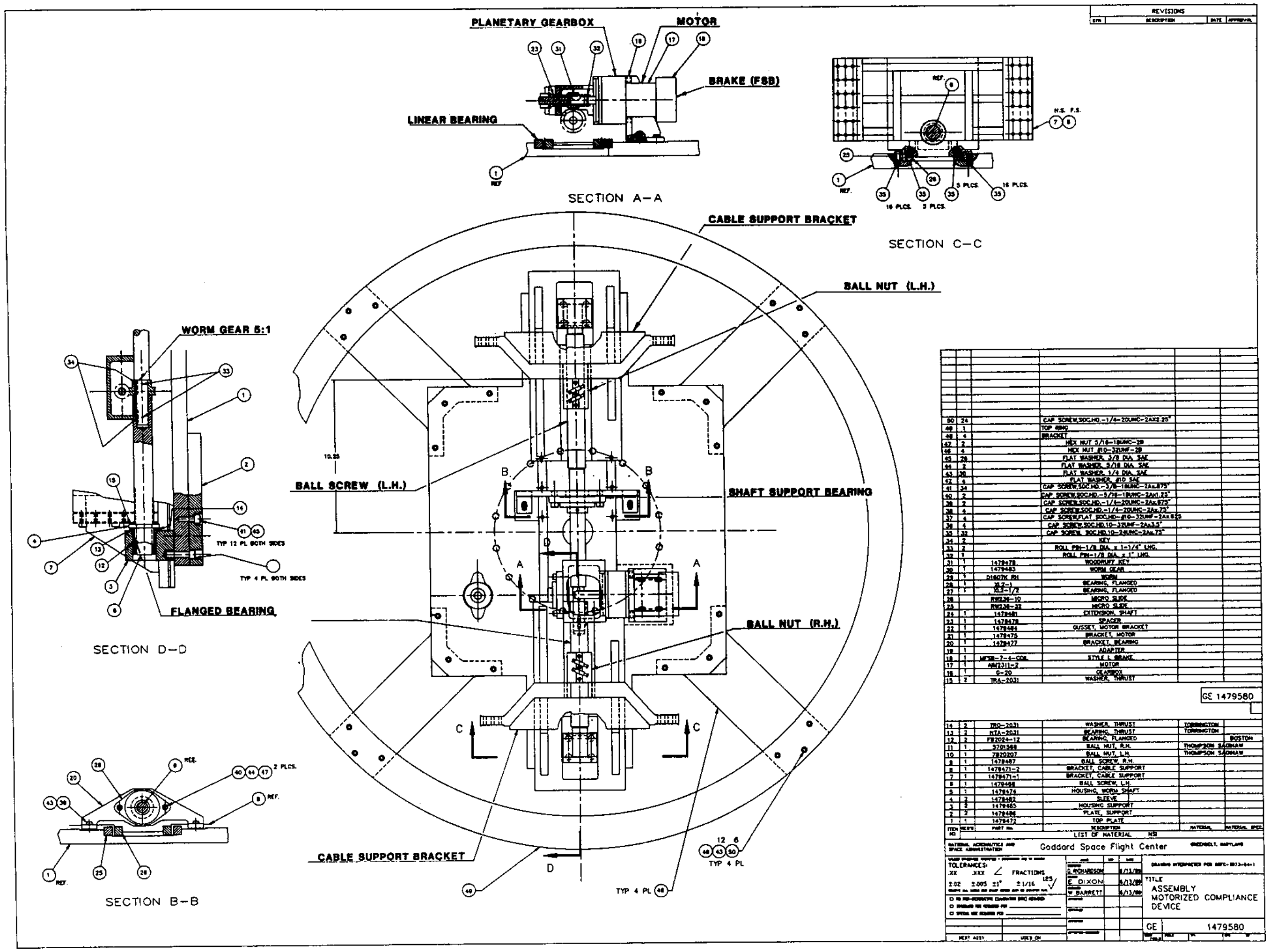

Figure 47. Drawing of assembly.

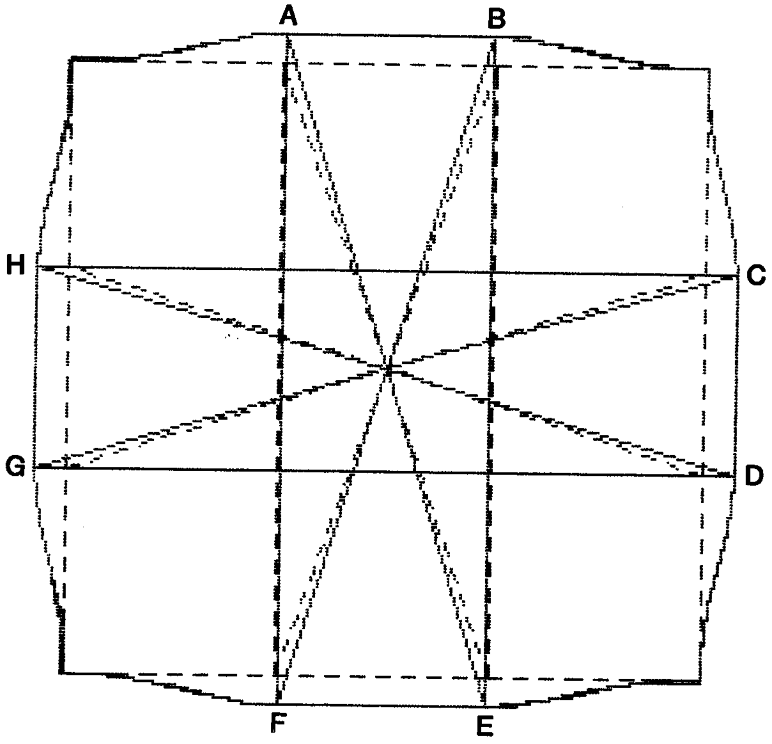

Figure 48. A,B,C,D,E,F,G,H extended before external load applied.

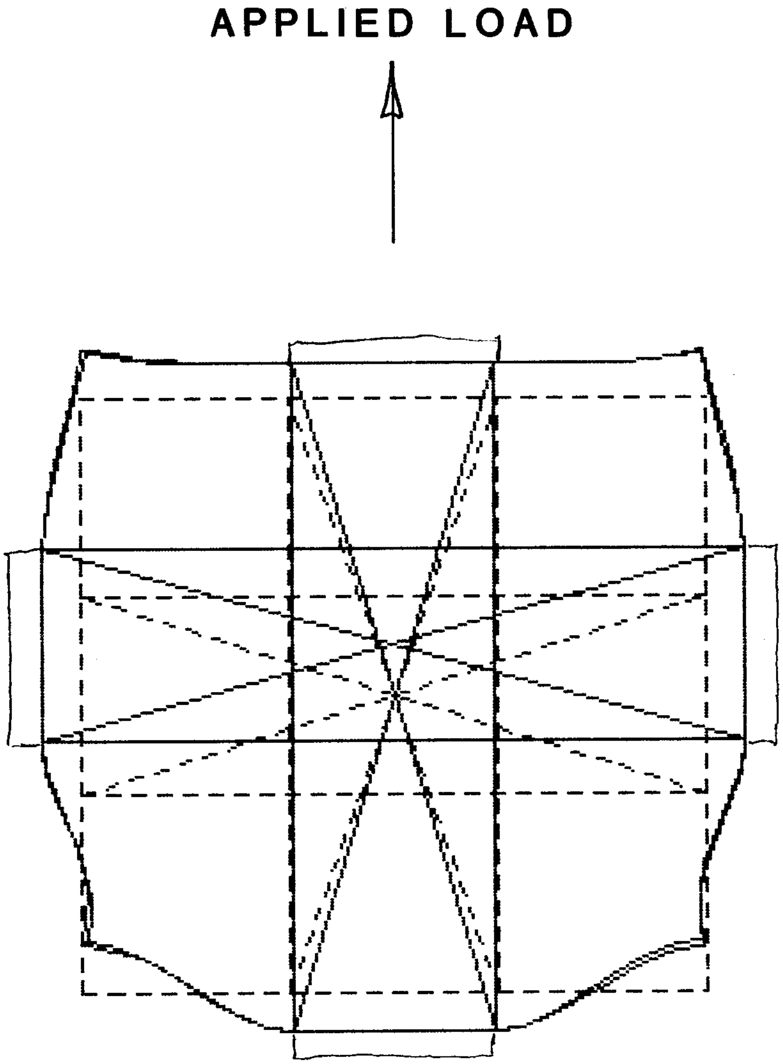

Figure 49. Deflected cables with external load applied after preload of Figure 48.

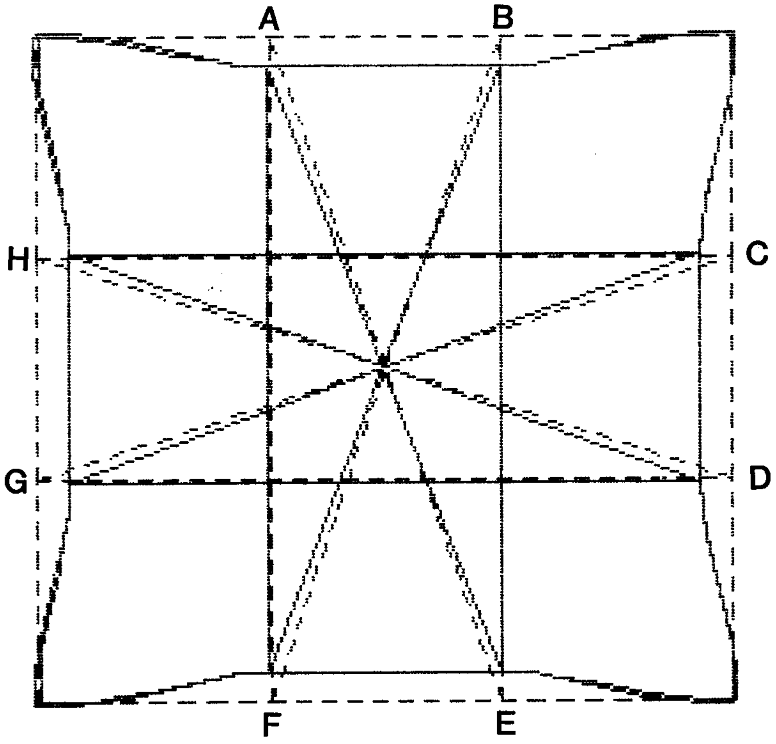

Figure 50. A,B,C,D,E,F,G,H contracted before external load applied.

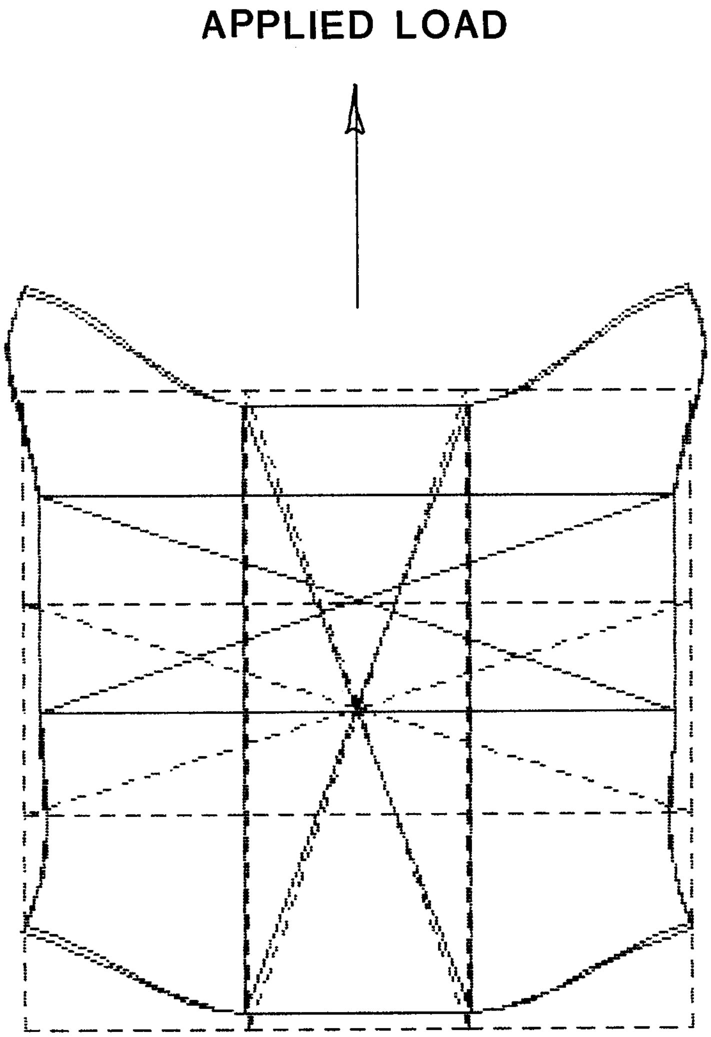

Figure 51. Deflected cables with external load applied after preload of Figure 50.

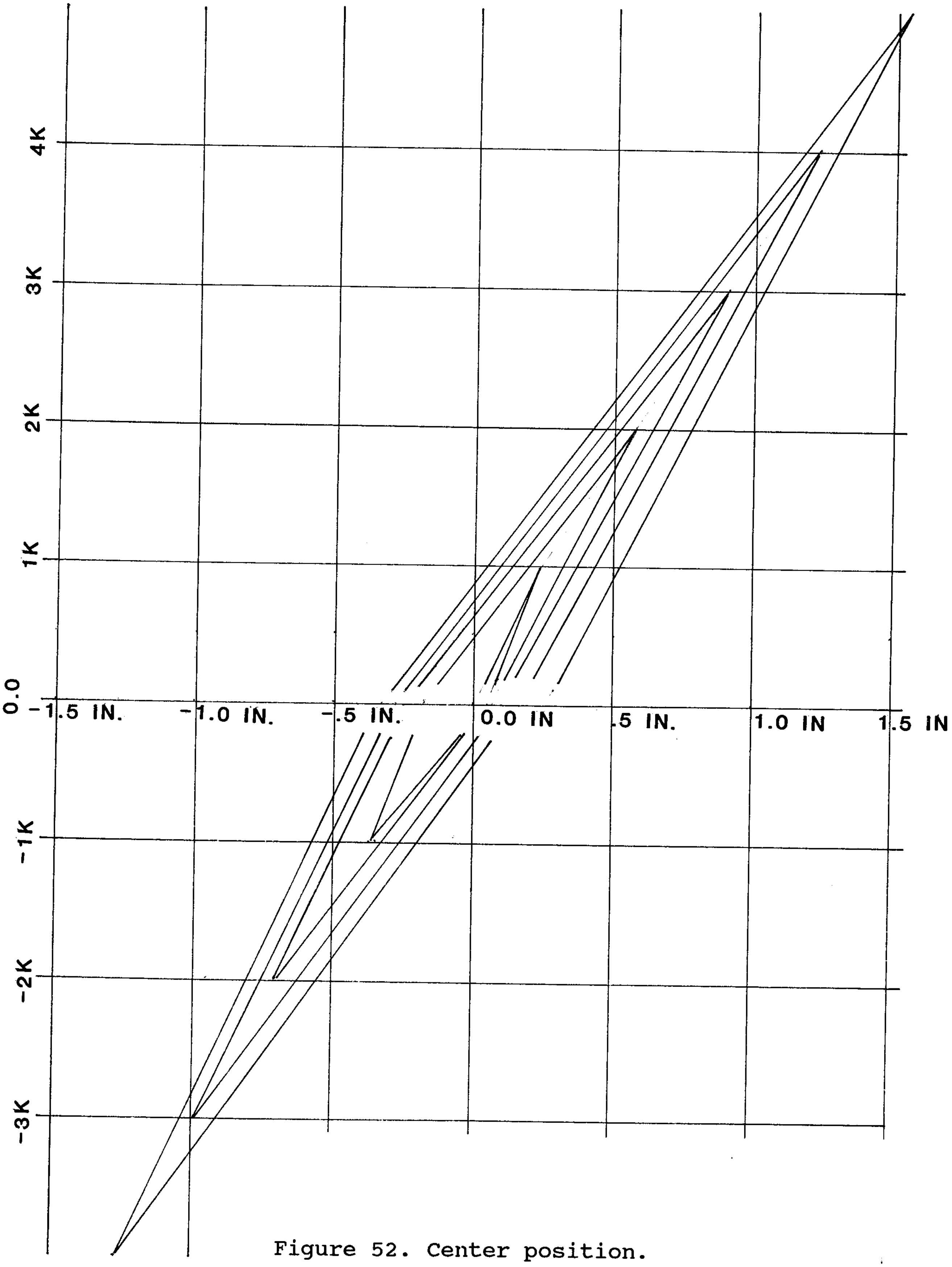

Figure 52. Center position.

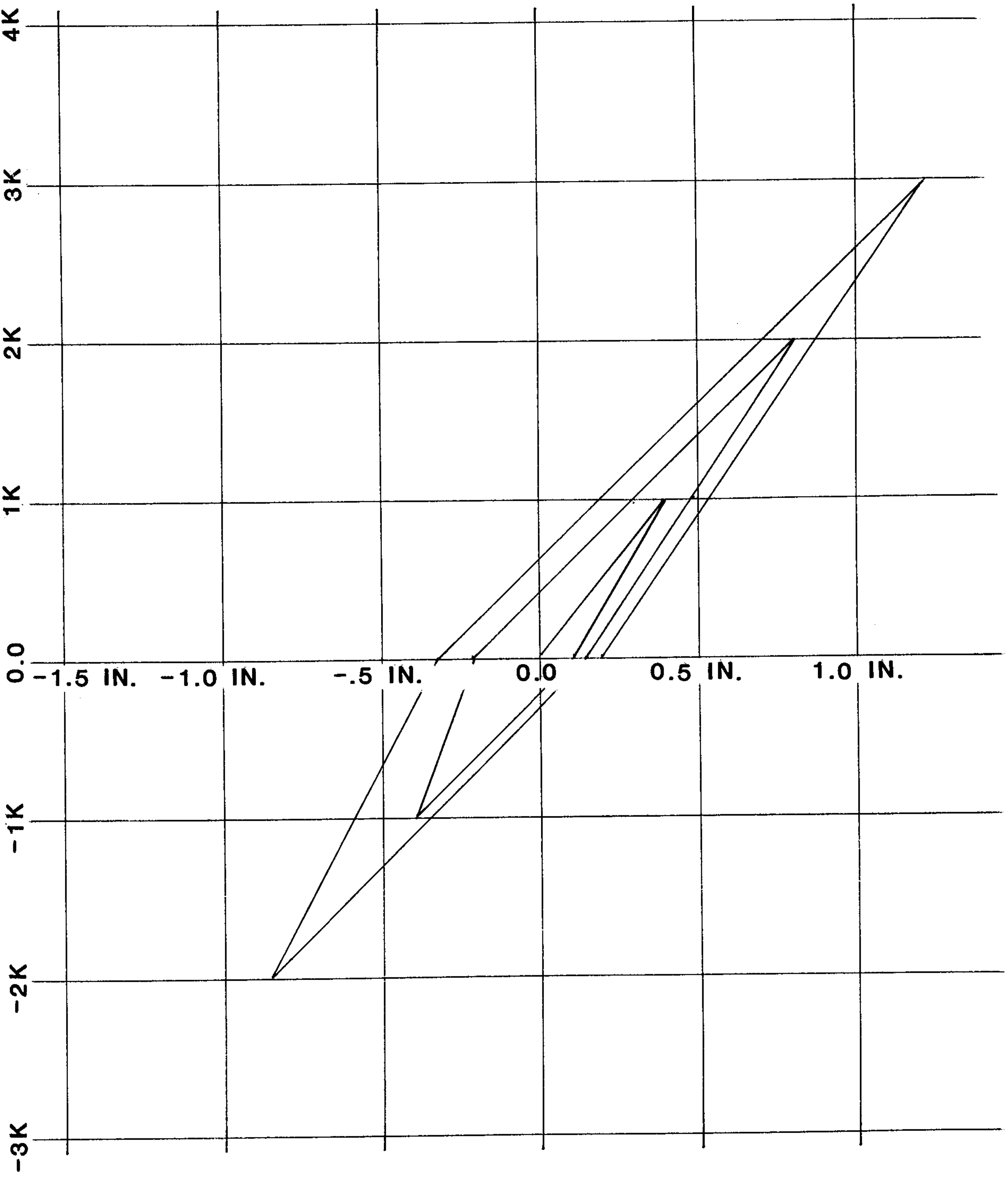

Figure 53. Cables in.

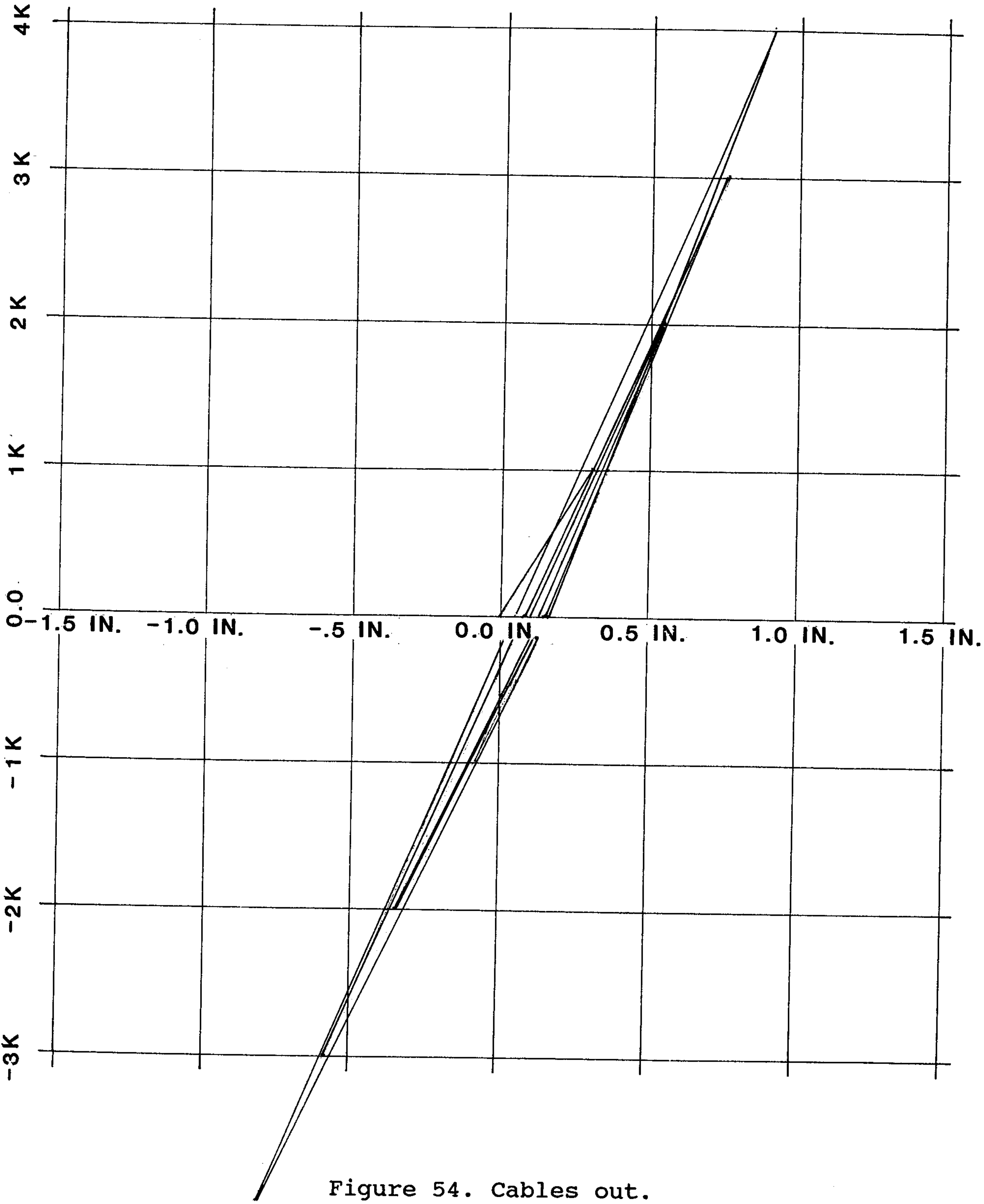

Figure 54. Cables out.

CHAPTER 7

CABLE HOLDING METHODS FOR MASS-PRODUCED CABLE COMPLIANT MECHANISMS

This chapter details the recent advances in methods for holding stainless steel cable in mass-produced cable compliant mechanisms (CCMs). The goal in these investigations has been to devise fast, inexpensive, and secure methods to provide cable end fixity. Two types of fastening methods have been investigated: polymer and formed metal holders. These processes can be used with prototypes as well.

Formed Metal Holders

Metal holders lend themselves most readily to mass production because they are simple to form, and the forming technology is very mature. Two examples of completed CCMs are shown in Figures 55 and 56. These hand-made prototypes took about 1 day to build. Mass production time is estimated to be between 5 and 15 seconds.

The forming process is illustrated in Figure 57. In Step 1, the metal is formed around a mandrel. In Step 2, a dowel mandrel is inserted and the metal is further bent into the final configuration. In Step 3, the cable is passed through the hole. In Step 4, a piece of metal is forced between the cables. The parts are identified as follows:(72) is the metal holder; (74) and (76) are the cables; (80) represents the first bend; (81) represents the metal forced between the cables; and (82) is a spot weld, solder, or braze used to hold the metal in place. Figure 58 is a sketch of the final product. The center may be left open, depending upon the use. Figure 59 shows the same techniques applied to the corners. A punch and dye tool set can assemble this unit in a matter of seconds. Figure 60 shows a view (front and back) of the assembly after the manufacturing process.

The hand-made metal prototypes were made from sheet copper. Various thicknesses were tested. The optimum thickness was found that gave the best compromise between stiffness and forming ability for the size cable used. For the 3/32-inch and 1/8-inch cables, the copper could vary from 1/32 inch to 1/16 inch. The metal plate could be 1/8 inch thick.

Other metals found suitable for mass-produced CCMs generally had elongation of 30% to 50% and yield strengths of 10 thousand pounds per square inch (ksi) or better. These materials include aluminum alloys (annealed state) and 303 series stainless steel. To stack more than two cables together, another fabrication step had to be added to join cable pair holders. Shims and sheet metal acted as buffers between two or more rows of cable.

Not shown are the forming tools necessary for this type of operation. Preforming pliers can be used for prototypes, while in production, a dye set can be used. The forming process is separate from the assembly process.

Polymer Cable Holders

Figure 61 is a picture of Polyamide Splint (white) at both ends with a fiberglass mould (clear) in the center. The splints are heated and formed around the cable. The fiberglass uses the heat of its own mixing to form around the cable.

Figure 62 is a combination of four elements. They are listed from left to right as Devcon (2-ton epoxy), 3M (2216 epoxy), Propylux and Co-propylux.

Figure 63 is a picture of Polymend Splint wrapped around 1/4-inch cable.

Figure 64 is a picture of Propylux and Co-propylux wrapped around a piece of 1/4-inch cable.

Figure 65 is epoxy formed in a mould.

Figure 66 is an embedded metal gripper that is molded in the center of the cable to prevent rotation after assembly.

Figure 67 is a fiber polymer that could be put together in layers.

Corners offer a difficulty with plastic holders. They can be made flat and bolted together, or a high strength plastic that has a moderate viscosity could hold the cable. We have not extended our work into this area as yet.

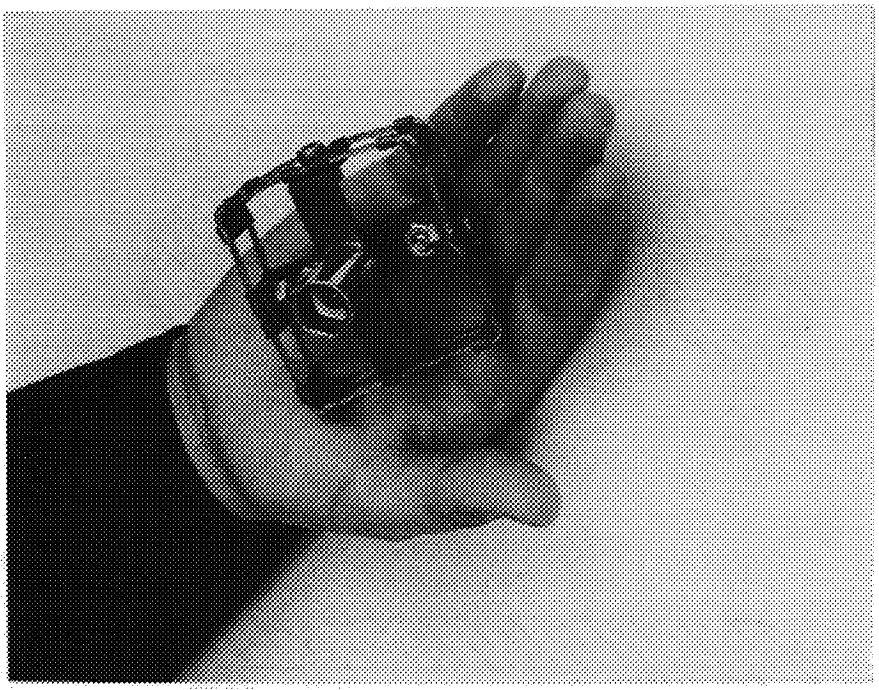

Figure 55. Cable metal holder - 3/32.

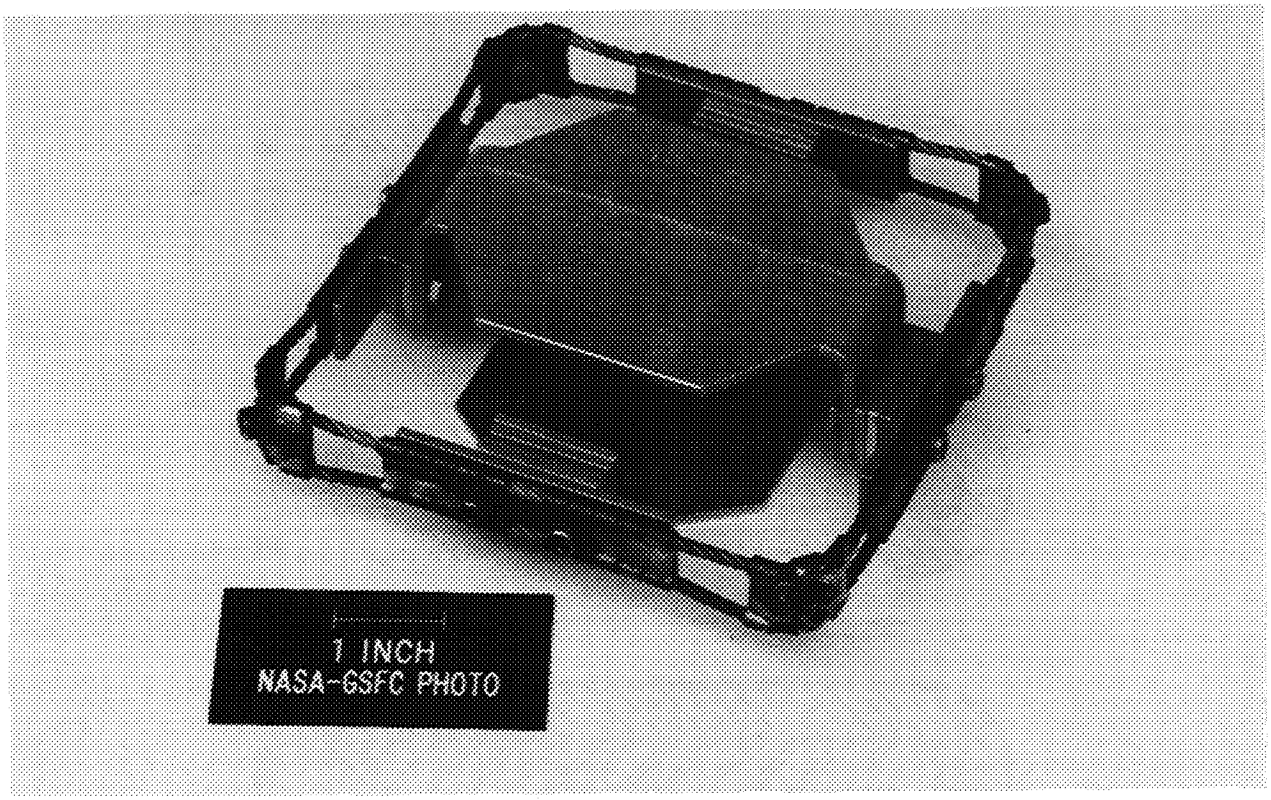

Figure 56. Cable metal holder - 1/8.

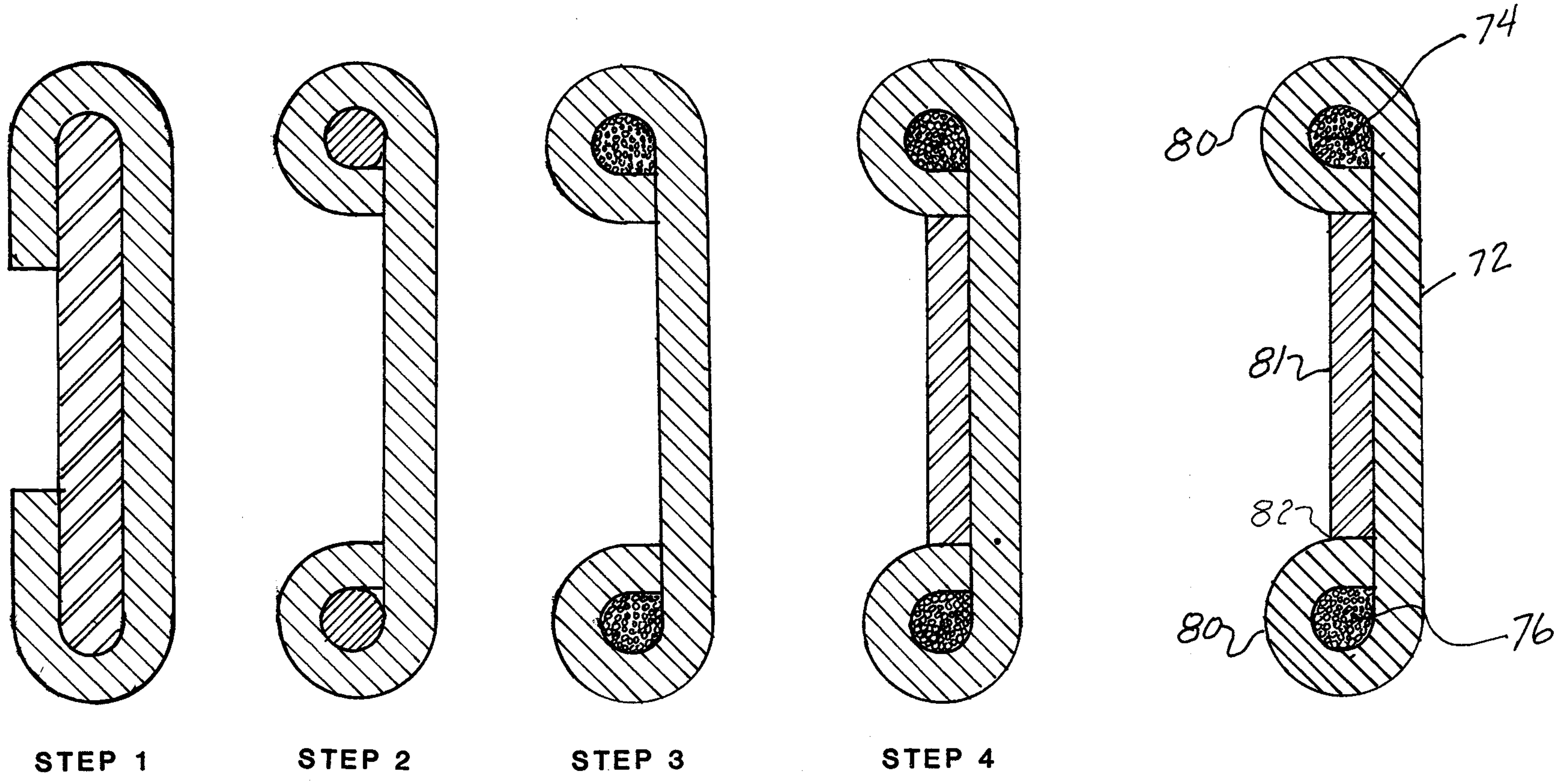

Figure 57. Four steps to clamp cable.

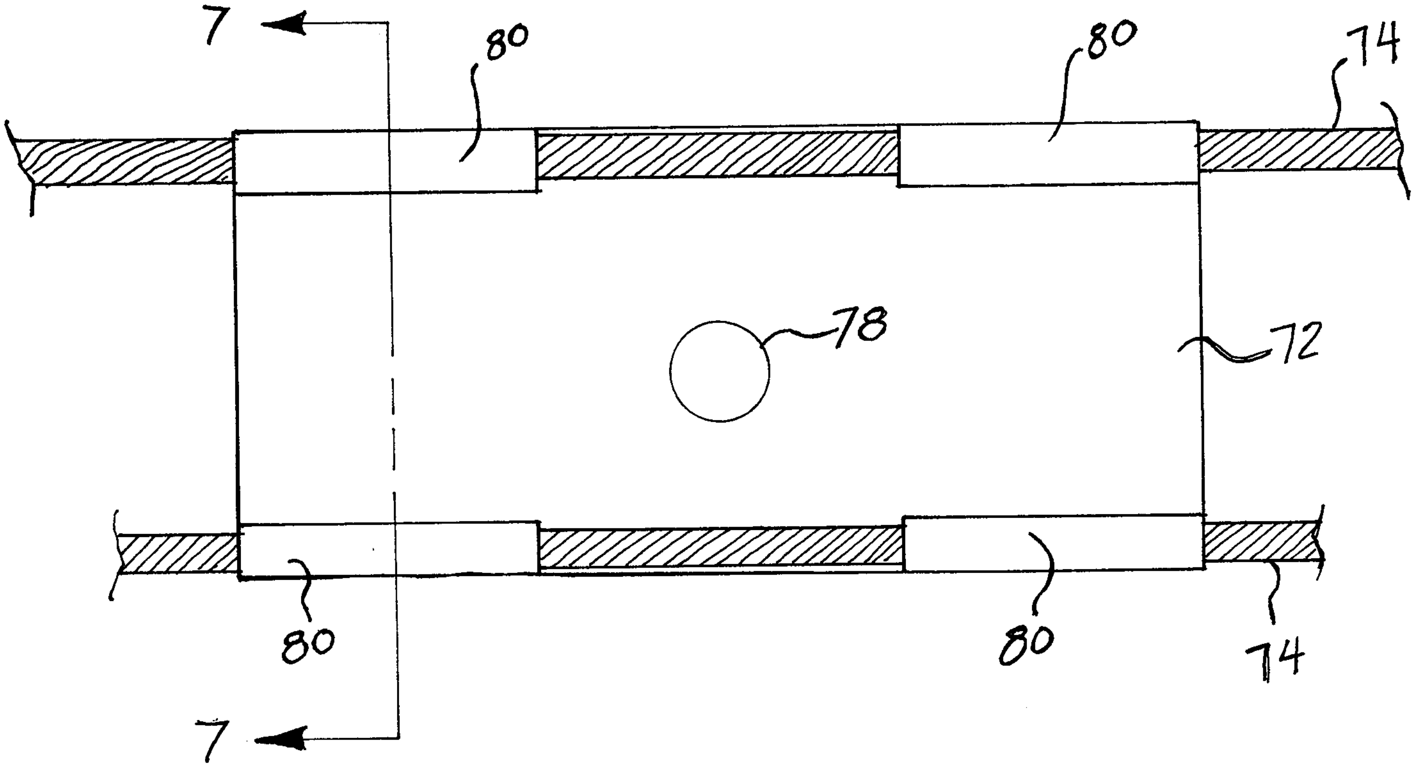

Figure 58. Sheet metal cable holder.

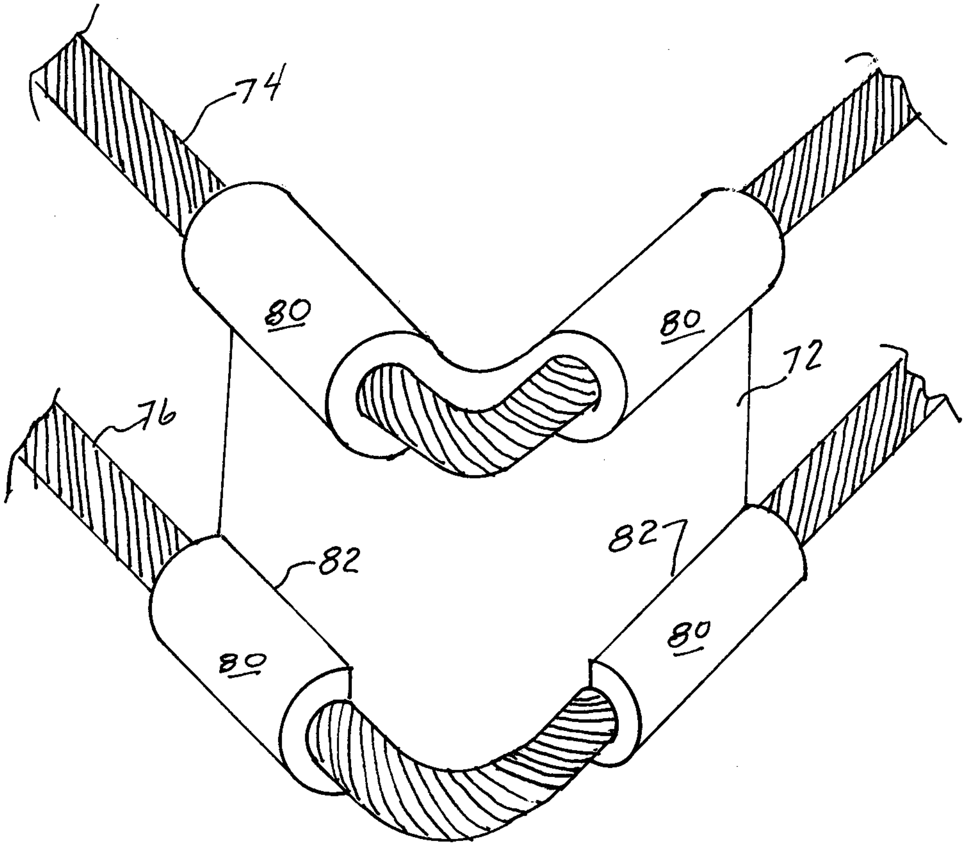

Figure 59. Corner cable clamping.

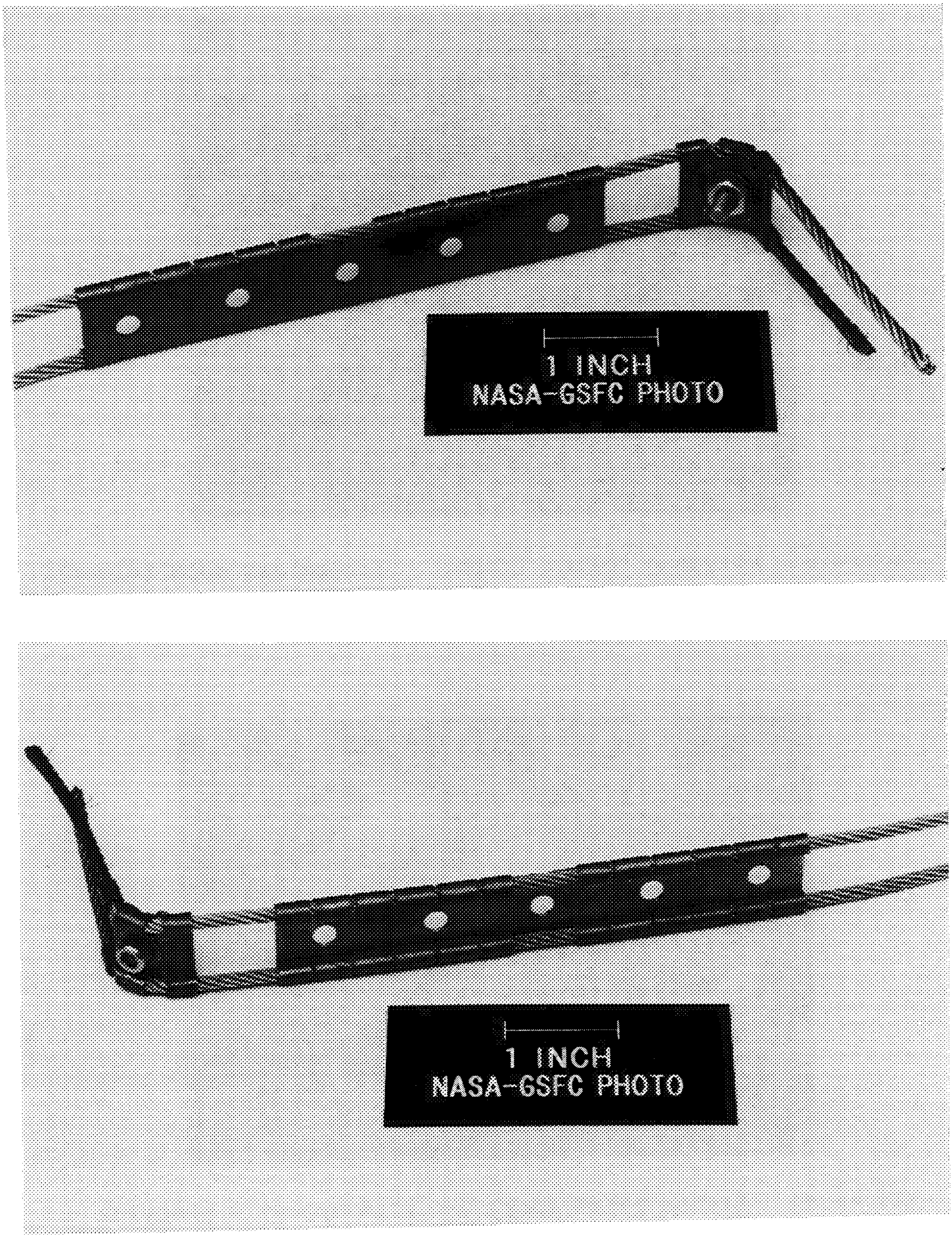

Figure 60. Cable assembly techniques.

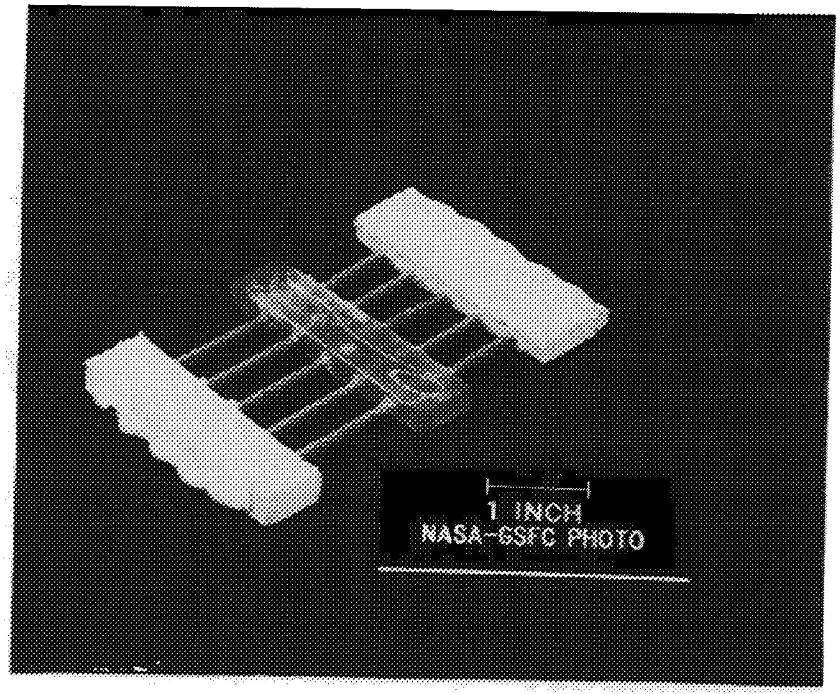

Figure 61. Polymead splint (white). Fiberglass mold (clear).

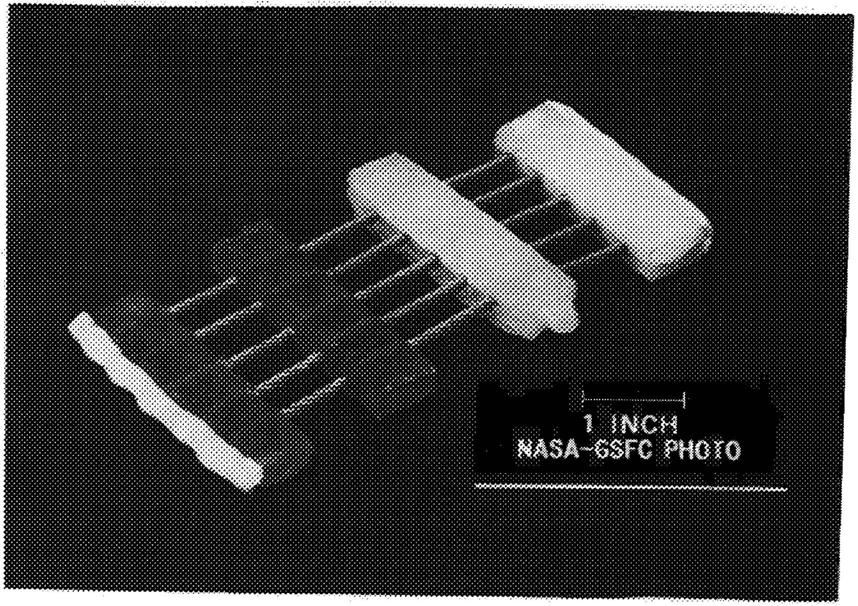

Figure 62. Devcon 2-ton epoxy 3M (2216 epoxy) - propylux - co-propylux.

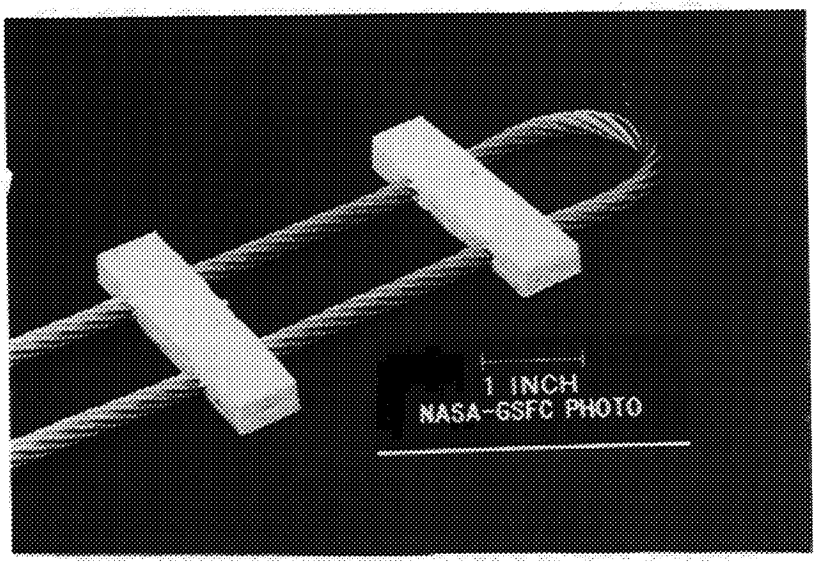

Figure 63. Polymend splint.

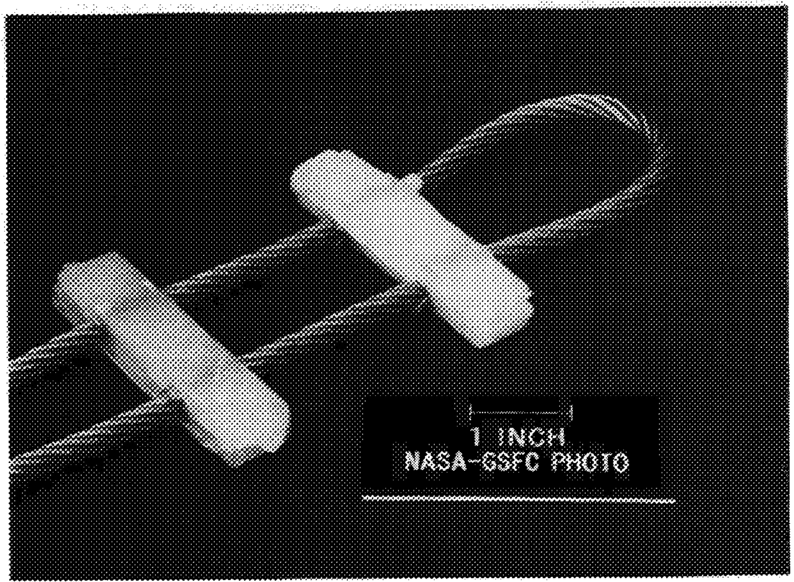

Figure 64. Propylux and co-propylux.

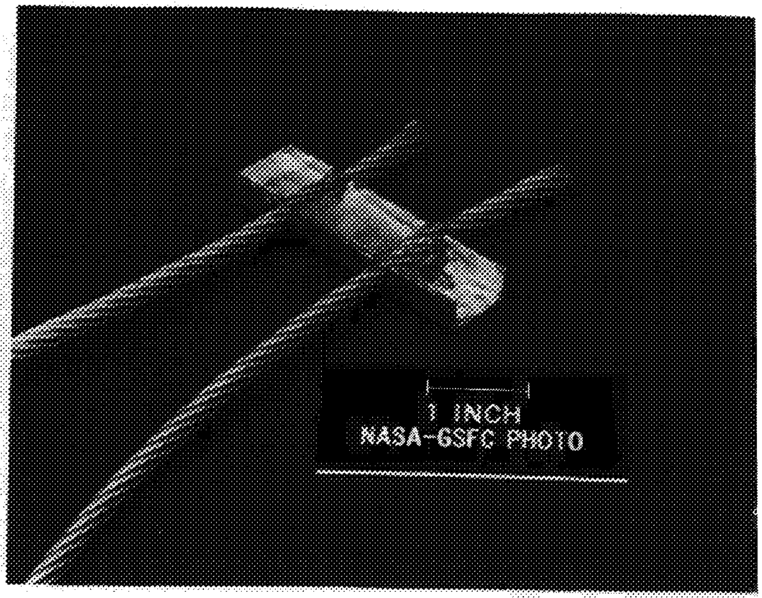

Figure 65. Epoxy in mold.

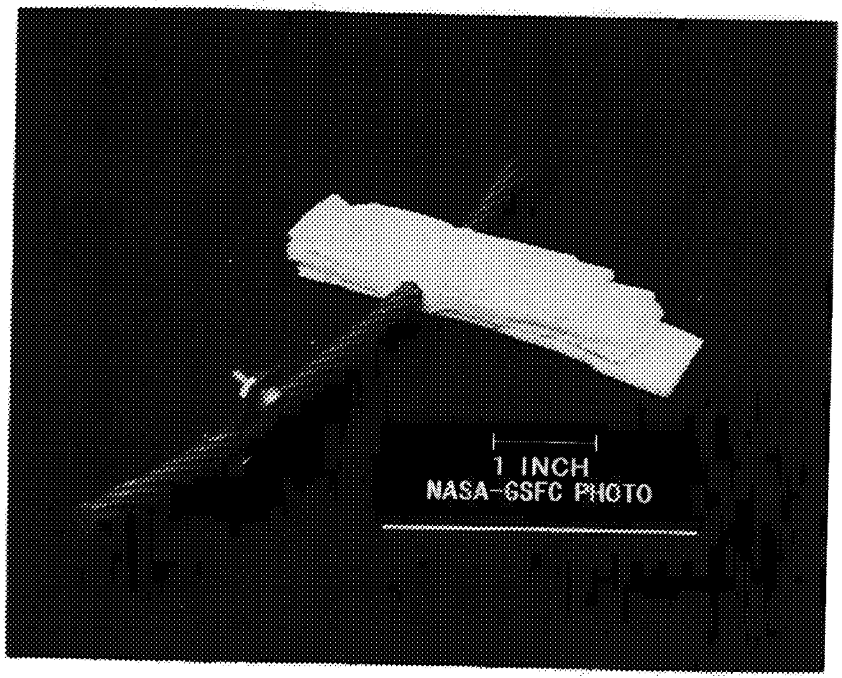

Figure 66. Embedded metal prevents rotation.

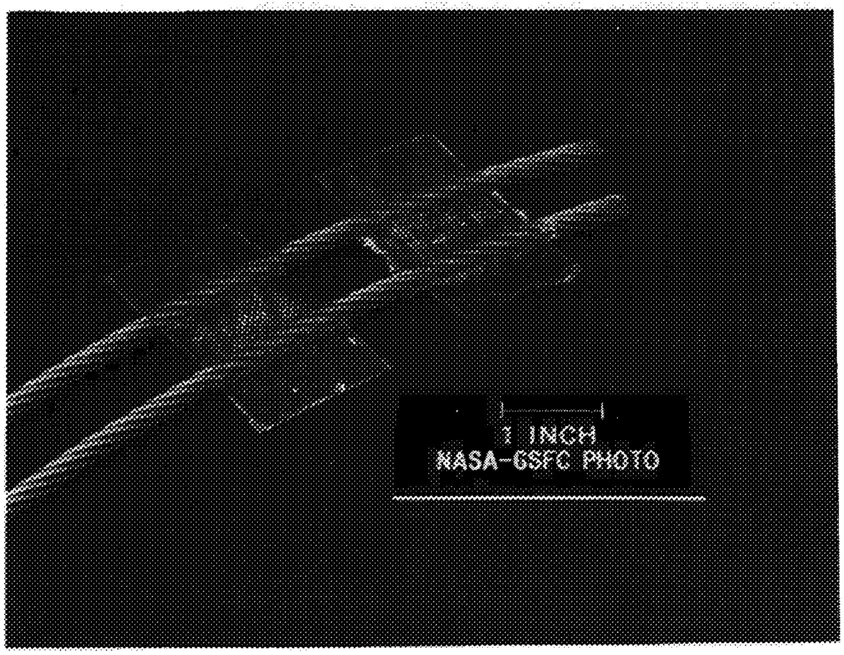

Figure 67. Fiber polymer.

CHAPTER 8

COMPLIANT KNEE JOINT

This invention relates to a compliant joint for prosthetic and robotic devices that permits rotational movement in three different planes and, more specifically, to a joint that provides for the controlled use of cable segments coupled into a common mounting joint.

In the field of robotic devices, there is a need for joint structures that connect robotic limbs or components that will permit precision-controlled rotation in three planes. This is also a desirable feature for joint prosthesis for replacing a diseased or damaged joint between human body skeletal members where the joint prothesis should simulate the durable and resilient characteristics of the joint it replaces, as well as duplicate the rotational movement and flexibility of the replaced joint.

There are numerous prior art devices that disclose protheses for the replacement of knee, elbow, hip, and knuckle joints, but problems have been encountered with each type of design. Usually the joint protheses have hinging elements formed with metal-to-metal or metal-to-plastic bearing elements that provide insufficient resiliency or flexibility at the hinging element to cushion and absorb impact loads or lateral and compressive loads that are applied to the joint in everyday use. Thus, the joints eventually fail and must be replaced.

To combat the problem of insufficient resiliency or flexibility, some devices have been proposed in which the prothesis is formed almost entirely of a flexible member such as an elastomer. Problems have occurred here, since shear forces, over a period of time, cause the elastomer to tear, resulting in the eventual failure of the prothesis. Also, if the elastomer is too flexible or becomes more flexible because of prolonged use, the skeletal components have sometimes become dislocated, resulting in failure.

For robotic devices, there are other problems. Conventional robot arms are built up from a number of elements and joints, which, besides the tool and the load, also must support the equipment for the motion and power generation for the separate elements. This equipment usually comprises pneumatic or hydraulic cylinders, electric motors, etc., which means that the elements and joints must be relatively coarse or heavy in order to support the equipment. Thus the robot will have a bulky shape and comparatively large external dimensions, which will reduce the flexibility of the robot arm.

There are robotic couplings available that use cable. However, there do not appear to be any in the prior art that disclose the controlled use of the cable to allow precise and predetermined control of the compliance flexibility and rotational movements. This applies to the robotic joint in three planes, as well as to its ability to absorb heavy loads.

The following are features of the rotational compliant joint:

(1) The joint must be flexible and compliant.

(2) The joint should have a high level of damping.

(3) The robotic application shall have a high load capacity.

(4) The rotation can be in all three planes, but should favor one.

(5) This joint should be very durable and inexpensive.

(6) It is a goal of this invention to provide a compliant joint prosthesis that can be used to replace a diseased or damaged joint for human body skeletal members and that has the capability of simulating the movement and flexibility of the replaced body joint.

Figure 68 shows the cable knee joint rotating on the bearing. Figure 69 shows the cable knee joint coming to a stop on the bearing. It is at this point that the cable begins to torque up until it is very stiff and stops. This requires only a few degrees of motion.

A Brief Review of the Descriptive Drawings

Figure 70 is a pictorial perspective view of the compliant joint. Figure 71 is an exploded view of the knee joint as shown in Figure 70. Figure 72 shows a cross-sectional view along III-III as shown in Figures 70 and 71. Figure 72 shows a cross-sectional view along IV-IV as shown in Figures 70 and 71.

The compliant joint is shown in Figure 70 and in the exploded view in Figure 71. A centerpiece (12) is preferably shown in the center of the compliant joint (10). The centerpiece is shown as a cubit-shaped element in the embodiment shown in Figures 70 and 71; however, it could be spherical or take other geometric shapes, depending upon its usage.

Extending through the centerpiece are cables (14 and 16). The cables pass through the centerpiece at substantially right angles to one another. The cables shown are preferably metal such as stainless steel or any metal that can be spun into cable. The cable can be regular-lay cable or lang-lay cable; however, it is important that the cables be independent wire rope core (IWRC). The ends of the cable (14) are joined to a U-shaped bracket (18) by swaging the ends of the cable to an end swage (22). The ends of the other cable (16) are joined first to bearings (24) using a bearing clamp (26), or they can be joined to the bearing by swaging. The bearing is, in turn, mounted into a second U-shaped bracket (20). The bearing has a stop arm (28) or rod-like member positioned so that the stop arm can rotate back and forth between stops (30 and 31). An end grip (32) extends from the outer surface of the U-shaped bracket, and a second end grip (34) extends from the outer surface of another U-shaped bracket (18). The end grips are shown broadened out so as to connect to a flat surface such as a robotic machine element, but they could be smaller and round-shaped so that the end grips could connect to the center of a bone or a knee or elbow joint, as will be discussed later.

Figure 71 illustrates an exploded view of the compliant joint (10) that can be used for a knuckle, knee, hip, or elbow joint. This joint is used where free rotation is needed through certain degrees of motion in one plane but, at the same time, there is compliance in all degrees of rotation. This allows the joint to absorb large loads in any of the three-dimensional planes and, at the same time, have the ability to demonstrate or possess the characteristic of easy motion and compliance in the other planes. The free motion is shown as the region of rotation or angle Theta (θ), which shows the range of movement or rotation for the arm, which is allowed to rotate back and forth between stops. The rotation here is described as free rotation because the arm is attached to a bearing (24), which reduces a substantial amount of the resistance caused by friction. Angles Alpha (α) and Beta (β), however, are representative of the region of compliant motion or rotation that is allowed because of this unique arrangement of cables. After the arm rotates through its maximum range of free movement and comes into contact with a stop (30 or 31, depending upon the direction of rotation), the end grip (32) can yet rotate farther through angle β because of the compliant characteristic of cable (16). This movement is much more damped than is the movement that occurs during angle θ, and the degree of compliance or damping can be controlled or varied by varying cable segment lengths, cable diameter, and cable stranding; by pretwisting the cable; and/or by changing the cable material.

The end grip (34), which is mounted to the U-shaped bracket (18), rotates through angle α. Since one cable (14) is not mounted to a bearing system such as bearing (24), there is no free motion or angle of free rotation for the end grip (34). Thus, only compliant movement is demonstrated or allowed for that end grip, as shown in this configuration, because it simulates the movement in a knee, hip, elbow, or finger joint, where free movement is desired only in one plane. Yet some degree of compliance is required to simulate the flexibility of a human joint in the other two planes.

Figure 72, top, shows a cross-sectional view III-III of Figures 70 and 71, illustrating in more detail how cables (14 and 16) are connected to the centerpiece and how one cable (14) is connected to a mounting bracket (18) by means of an end swage (22). The swage material could be soft silver, gold, platinum, or copper, depending upon the use of the compliant joint and the budget of the manufacturer. It should be noted that copper was preferred for this design. The same swage joint could be used for connecting the cable (14) and connecting mounting bracket (18), either swaged individually or together. It should be noted that the swaging techniques used for these joints are not those commonly used in cable fittings, such as those used for slings and ship rigging. The cables used for the compliant joint are subjected to less force because they are not used in applications in tension but rather are used in applications in shear and rotation. The cable itself can be regular-lay IWRC or lang-lay IWRC. The cable in the single strand can be regular-lay going to the right side of the centerpiece and lang-lay going to the left side of the centerpiece; however, in this case, two additional swages would be required at the junction (40). The centerpiece would have to be adapted for this center swage connection. The junction shows a swage of cable (14, topside) and cable (16, bottom side) to prevent rotation or slippage of said cables. This center swage could be performed with a pin or a set screw (not shown) or by making the centerpiece out of steel, driving a piece of copper through the hole (38) to hold the cable in place. The preferred solution would be to thread the hole and use a set screw to swage the cable. Note that the hole of the centerpiece is the junction at which the cable segments would meet. If the center of rotation of the cable segments going to the left and right of the junction cannot be in the same direction, then four pieces of cable segments would be required, and accordingly, four swage connections would be necessary.

On the bottom of Figure 72 is shown a cross-sectional view IV-IV of Figures 70 and 71, illustrating in more detail how the cables are connected to the centerpiece and how one cable (16) is connected to the bearings (24) and the mounting bracket (20). This view shows the bearing and the rotational arm and rotational stops for the rotational arm. There are two bearings, two rotational arms, and four rotational stops shown in Figure 72. It should be noted that it is possible to have only one bearing located at one end of a cable (16) and a swage (with no bearing) at the opposite end of that cable for special kinds of hinge action.

The bearings can be of various types such as ball bearings, roller bearings, or friction bearings; however, the bearing shown in Figure 72 is a ball bearing, which has been tested successfully. The type of bearing required will be dictated by the use of the compliant joint, whether it be a human skeletal body joint or joint for robotic applications. The bearing can be captured by the same material (copper, gold, silver, or platinum) that is used to swage the cable. If copper is used, then the copper is first swaged to the cable and the end is left free to move up. Then the cable (16) and the centerpiece are positioned in place, and the same copper is used to hold the assembly to the bearing. The other end of the bearing can be attached to the mounting bracket with the same swaging material. Another method for attaching the cable to the bracket or bearing would be to use a form of silver solder with a tensile strength of approximately 20,000 psi. This kind of silver solder has been successfully used; however, the temperature of the cable must be carefully controlled. The depth of the temperature along the cable must also be controlled to keep the silver solder and any other strong solders from flowing along the cable.

The shearing strength of the joint is controlled by the diameter, stranding, material composition of the cable, and the width of the centerpiece. The centerpiece can be carefully drilled to receive a precise diameter of cable and to create a specific bearing boundary for the cable; thus, a 1/4-inch diameter steel cable could withstand a shearing load in excess of 1,000 pounds. The length of the cable hole in the centerpiece also must be used to control the degree of compliance. There must be a balance between the cable diameter and the width of the centerpiece to achieve a designated shearing force in conjunction with a designated compliance. A compliant joint for a human body should be subjected to small shear loads; thus, small diameter cable can be used. But in robotic applications where substantial loads have to be supported, larger diameter cables will be required.

This is a detailed description of the parts and the way in which they are assembled. There are many modifications to this joint, and some of them are described in Patent No. 4,932,806, "Compliant Joint." In robotics, if two arms come together and a certain amount of allowance for nonlinearity is desired, the joint can be simplified. The same is true if damping is added in a robotic arm.

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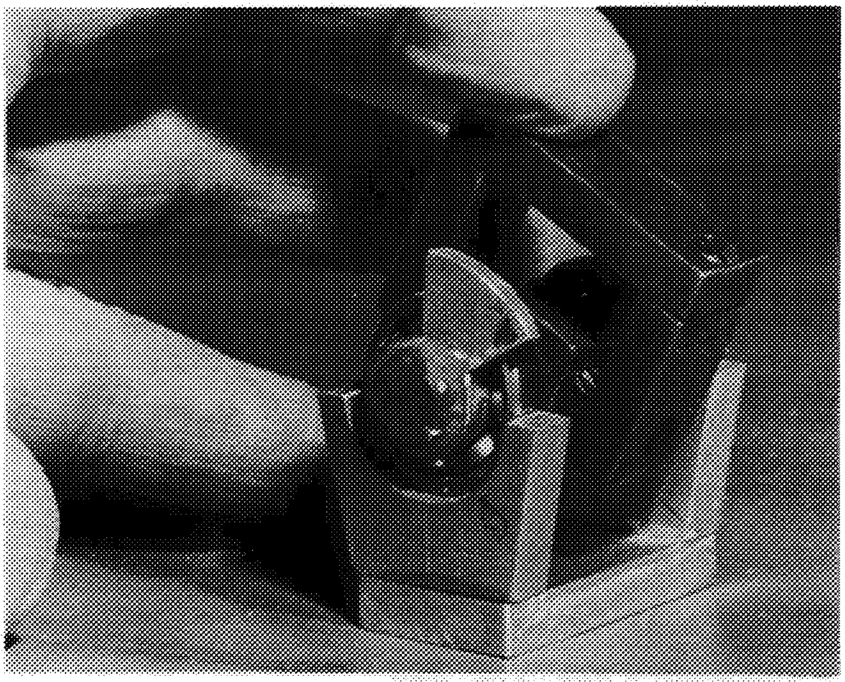


Figure 68. Bearing rotation.

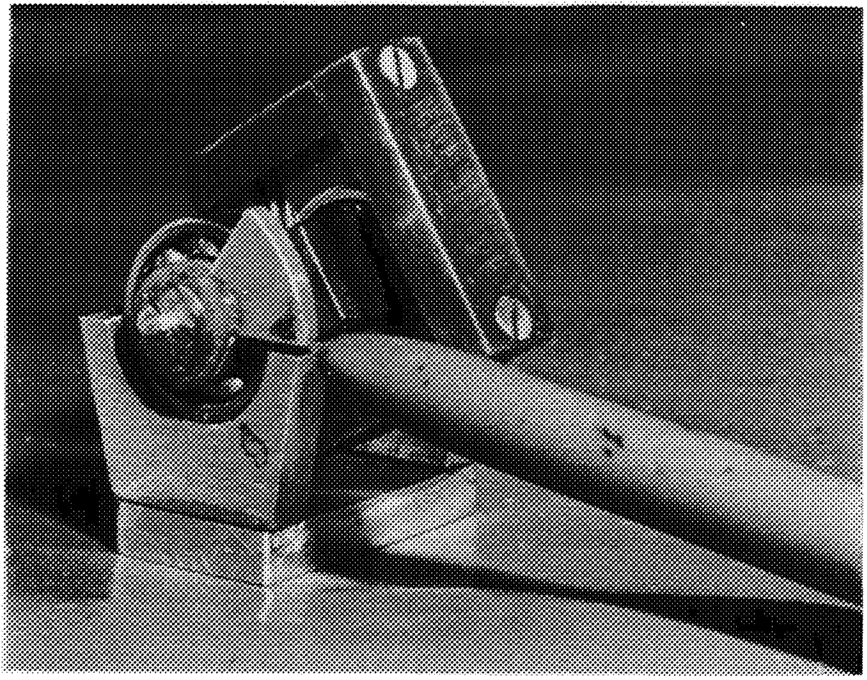


Figure 69. Cable compliance takes over.

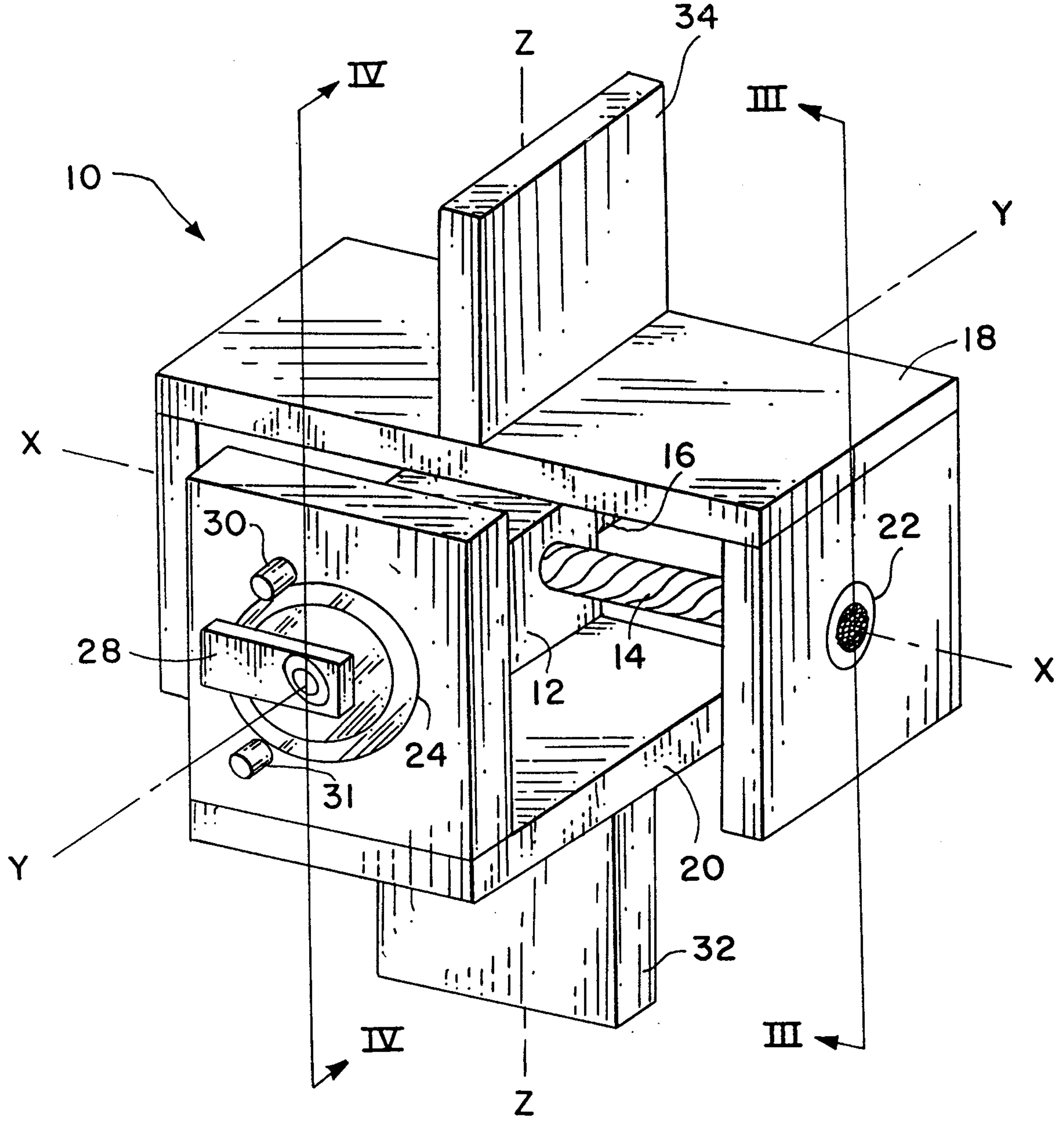


Figure 70. Sketch of knee joint parts.

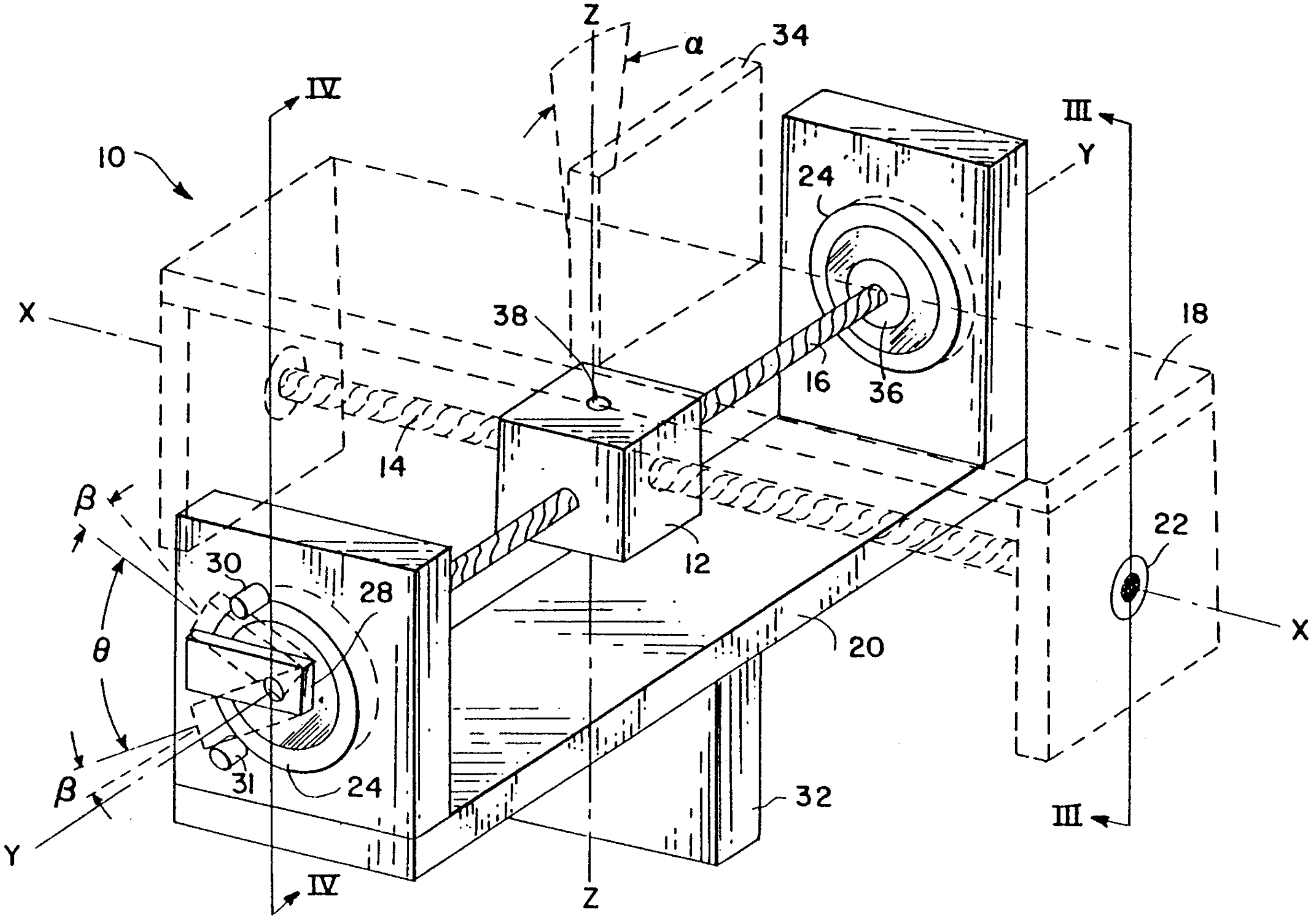


Figure 71. Internal parts illustrated.

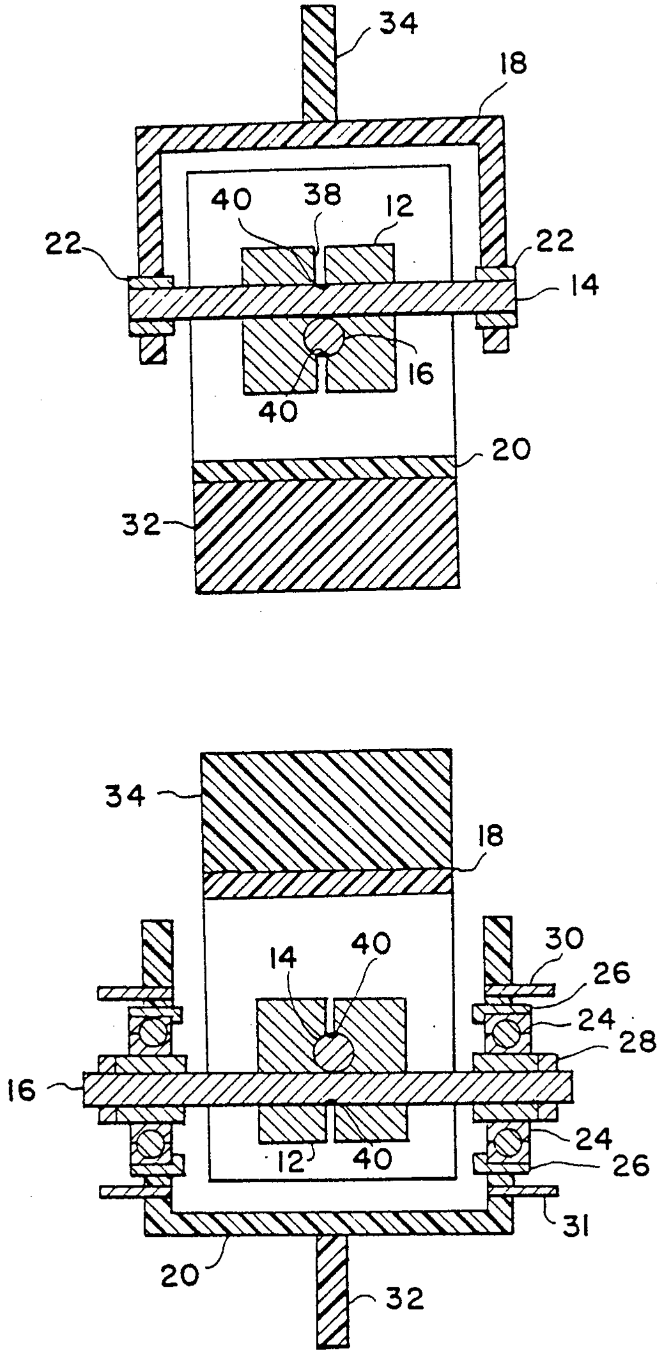


Figure 72. Cross-sectional parts.

CHAPTER 9

WALKER

Technical Field

This invention relates generally to a mobile support system for the human body and, more particularly, to a cable-compliant support system for dynamically supporting persons having limited use of their lower extremities.

Background Art

Numerous devices presently exist for supporting injured or postoperative patients and handicapped persons having limited use of their legs. This refers to those devices that permit such persons to become ambulatory under their own power. Such devices include crutches, wheelchairs, and upright walkers, to name a few. The elderly, who wish to move around and take care of themselves, have a strong need today for this invention. It further can be used by multiple sclerosis (MS) patients and paraplegics in the course of their daily work and keep them going when, without it, they would be forced to remain still.

Included in the prior art are what is known as compliant devices, (more particularly cable-compliant devices), which heretofore have been used to provide some degree of protection against shock and/or vibration, as well as correction for variations and misalignments between the two devices brought together under some external control.

Robot technology has found a need to position an element at a certain location where the possibility of substantial side and angular misalignment exists between parts that are to become mutually engaged. Such apparatus is taught, for example, in U.S. Patent 4,946,421, entitled "Robot Cable-Compliant Devices," issued on August 7, 1990, to James J. Kerley, Jr., one of the present inventors. The compliant device disclosed therein is comprised of at least two sets of cable segments whose longitudinal axes lie in at least two planes and couple to two orthogonal frame members by angle brackets that interconnect the cables to the frames. Depending upon the stiffness imparted to the cable segments, six degrees of freedom are provided to translate along mutually orthogonal X, Y, and Z axes, as well as to rotate around each of these axes. These six degrees of freedom are referenced to a single point, which is the center of the compliance device lying along the central logitudinal axis.

Heretofore, this technology has not been used in connection with mobile assistance devices for enabling permanently or temporarily handicapped persons to regain their mobility.

Summary

Accordingly, it is an object of the present invention to provide an improvement in body support systems.

Another object of the invention is to provide an improvement in walker-type systems for aiding in the treatment and recovery of persons who have temporarily or permanently lost the use of their legs.

The foregoing and other objects are realized by a compliant walker system comprised of an upright wheeled frame, which at least partially surrounds an upright person wearing a body harness. The harness is attached to the frame by means of a cable-compliant connection composed of sets of cable segments and angle bracket members connected between opposite side members of the frame and adjacent side portions of the harness. The type of partial body harness used takes two forms: the first is a torso harness that completely encircles the waist or rib cage of the user, while the second type is a hip harness that fits around the hips and buttocks. The frame lends itself to several embodiments, one of which completely surrounds the user. Other embodiments include an open-ended frame that is adjustable in height to accomodate the particular height of the user, with a pair of upright side members that attach to the cable support system. This further allows the user to increase the upper pressure on the body so that it will not fatigue in the legs. This excessive fatigue usually comes later in the day. With this adjustment, it is possible to bring the walker down to the user, who can enter the walker in the seated position and then, by the use of the ball screws, raise himself to the upright position. Many of the elderly find it very difficult to raise themselves into an upright position.

Brief Description of the Drawings

The following detailed description of the invention will be more readily understood when considered with the accompanying drawings.

Figure 73 is a top plan view, partially in phantom, of a first embodiment of the invention.

Figure 74 is a rear plan view of the embodiment shown in Figure 73.

Figure 75 is a side elevational view of the first embodiment shown in Figures 73 and 74, including a phantom view of a user.

Figure 76 is a fragmentary perspective view generally illustrative of one type of caster arrangement used in connection with the invention.

Figure 77 is a top plan view of a second embodiment of the invention.

Figure 78 is a rear plan view of the embodiment shown in Figure 77.

Figure 79 is a side plan view of the embodiment shown in Figures 77 and 78, including a phantom view of a user.

Figure 80 is a top plan view of a third embodiment of the invention.

Figure 81 is a side plan view of the embodiment shown in Figure 80.

Figure 82 is a rear plan view of the embodiment shown in Figures 80 and 81.

Figure 83 is a partial perspective view illustrative of the knock-down capability of the embodiments shown in Figures 80 and 82.

Figure 84 is a partial perspective view illustrative of one means of closing the torso harness in accordance with the subject invention.

Figure 85 is a partial perspective diagram illustrating another means for closing the torso harness in accordance with the subject invention.

Figure 86 is a partial perspective view of a means for raising and lowering the side members of the embodiments shown in Figures 80 - 82.

Figures 87 and 88 are partial side and top plan views of an outrigger subassembly for the walker frames illustrated herein.

Figure 89 is a perspective view of a rear hinge arrangement for the torso harnesses shown herein.

Figure 90 is a perspective view showing one set of cable segments of the cable support system shown in Figure 89.

Figure 91 is a top perspective view of an alternate embodiment of a compliant cable support system used in connection with the embodiment shown in Figures 80 - 82.

Figure 92 is a partial side elevation of a hip harness for use in connection with the subject invention.

Figure 93 is a partial front planar view of the hip harness shown in Figure 92.

Figure 94 is a partial rear planar view of the hip harness shown in Figures 92 and 93.

Figure 95 is a rear plan view of a modification of a hip harness shown in Figures 92 - 94. Figure 96 is a working model of the walker.

Detailed Description of the Invention

Referring now to the drawings and to Figures 73 through 75, reference numeral 24 designates a generally rectangular body support frame of fixed height. The frame is hinged at the rear and includes a plastic-type body harness (26) comprised of a light rubber inner belt (28) that encircles the waist and/or rib cage portion of a standing user (30) (Figure 75). The inner belt (28) is split into two halves (32 and 34), as shown in Figure 73, and is attached to a generally circular outer band member (36), which is hinged at the rear by means of a piano-type hinge (38) connecting semicircular outer band portions (40 and 42). A closure member such as one of those shown in Figures 84 and 85 may also be used.

In the embodiment shown in Figure 84, this device or closure (44) is depicted. Referring briefly to Figure 84, the closure is comprised of a pin member (46), which is adapted to be inserted into a pair of separated eyelet-type members (48 and 50) on the band portion (42), while an intermediate eyelet member (52) is located on the other band member (40).

As shown in Figure 85, an alternate-type closure member (44) is illustrated. This is comprised of a hook-and-pile-type of arrangement where, for example, the part (54) attached to the band portion (42) includes a set of hook elements, while the part (58) attached to the band portion (40) includes a pile section (60). This arrangement is well known and marketed under the trademark name of "VELCRO."

Referring back to Figures 73 - 75, the frame (24) is comprised of two open side frame half sections (62 and 64), which are held together by means of a pair of hinges (66 and 68) straddling two vertical brace members (70 and 71), as shown in Figure 74. Four vertical legs (72, 74, 76, and 78) fit into respective square lower end tube members (80, 82, 84, and 86), on the bottom of which are attached respective wheelchair-type casters (88, 90, 92, and 94).

When further stability is required, an arrangement such as that shown in Figure 76 can be used where the lower tube member (84), for example, terminates in a pair of right-angled extension members (96 and 98) to which casters (92) are attached.

The torso harness (26) comprises a partial body harness and is adapted to encircle the user. The harness is attached to the frame (24) by means of a cable-compliant support apparatus (25) that includes eight sets of wire cable segments (100, 102,... 112, and 114), with four sets located in parallel pairs on either side of the harness between upper side rails (116 and 118) (Figure 73). Each set of cable segments is identical in construction, with one set of cable segments (100) for purposes of illustration in Figure 90. These four equal-length cable segments (27) are held in parallel relationship between two rectangular blocks or end pieces (29 and 31) equally separated. The cable segments can be inserted and swaged into metallic end pieces; however, when desired, the end pieces can be of molded plastic in which the cable segments are set into place during fabrication. Also, they could be machined parts, when desirable. While four cable segments are shown for purposes of illustration, any number of cable segments can be used, depending on the particular design.

Between mutually adjacent sets of end segments (for example, segments 100 and 102, 104 and 106, 108 and 110, and 112 and 114, as shown in Figure 73), there is a respective right-angle bracket (120, 122, 124, and 126) that is secured to the cable. The inside cable segment sets (102, 104, 110, and 112) are bonded to the encircling band portions (40 and 42) or the outer band (26), while the outer sets (100, 106, 108, and 114) are secured to plates (128 and 130) bonded to the side rails (116 and 118), respectively.

As shown in Figure 79, when a person is strapped in an upright position into the torso harness (25), the frame can be moved in any direction by the feet, assuming that there is adequate use of the legs.

If the person using the compliant walker loses his balance or wishes to take the weight off his legs, he simply needs to bend the knees and the compliant-cable support harness (26, in Figure 73) will hold him up regardless of his orientation relative to a central vertical axis through the walker structure. One is thus able to take as much weight off the legs as desired. For example, with 75% of the weight going to the legs, a person undergoing rehabilitation can gradually rebuild leg strength.

If necessary, a robotic device could be attached to the side of the walker to raise and lower the user on demand. The cables are strong enough to hold the user securely, yet are flexible enough to allow swaying of the hips during walking. This allows the person to bend over at the waist to pick up or put down an object.

The materials from which the compliant walker is fabricated can be of any desired type; however, one, in particular, is light-weight fiber plastic currently being used in space technology. For early use, a simple aluminum frame can be used.

This leads to consideration of the second embodiment of the invention, which is disclosed in Figures 77 - 79. This embodiment uses single upright side-support members (132 and 134) located on either side of the user, as shown in Figure 77, while being connected to the compliant-cable support system (25) via the plates (128 and 130). The side members are located midway between a pair of elongated horizontal base members (136 and 138), which additionally include telescoping outrigger members (140, 142, 144, and 146) that can be selectively moved in and out of the respective carriage members (136 and 138) to supply additional stability.

Again, four casters (Figure 76), three of which are shown in Figures 79 and 80 by reference numerals 148, 150, and 152 permit the whole assembly (24') to be rolled across the floor in any direction.

The vertical support members (132 and 134) slide inside an outer jacket (154 and 156, in Figure 78) to permit the cable support system to be raised and lowered to fit the torso of the user, as shown in Figure 79. Means of adjustment (not shown) are included for maintaining a desired fixed elevation of the assembly. Such means may include, for example, a set of holes and retaining pins through the side surfaces of the upright members (132, 154, and 134, 156, in Figure 78). Another solution could be a ball screw with a folding handle on the top. When the right position is attained, the handle folds down and locks the ball screw in place. Another advantage of this type of raising and lowering is that the walker can be lowered until it meets the seated person and raises him to a vertical position. This is a distinct advantage of a walker for older people who are afraid of falling while raising themselves. In the case of others whose weight limits their getting up, this walker helps them rise so that they can be active part of the time.

The embodiment shown in Figures 77 - 79 permits a person using the walker assembly to walk up flush to a counter or work surface (not shown) merely by pushing back the front outrigger members (140 and 142). This embodiment also has an open front (Figure 77), which makes it easier for the user to carry something while he is walking.

A third embodiment of the compliant walker is shown in Figures 80 - 82 and is intended to show, among other things, a "knockdown" assembly (24"), which can be readily transported for travel, as well as for storage. The frame members (162 and 164, in Figure 82) are height-adjustable within vertical channel members (166 and 168), which, in turn, are secured to elongated horizontal base members (170 and 172). The base members have telescoping forward extensions (174 and 176, in Figure 80) to which is attached a pair of casters (178, in Figure 81). A pair of wheels, one of which is shown by reference numeral 182 in Figure 81, is located at the rear portion of the horizontal frame members and can be motor driven, for example, by respective motors (184 and 186, in Figure 82) mounted above the rear wheels. In this way, the entire assembly can be motor driven under the control of the user. At the rear of the assembly, the horizontal frame members terminate into telescoping end sections (188 and 190) by way of angulated connecting members (192 and 194) (Figure 82). This is further shown in Figure 83, where a metal pin (196) is adapted to pass through the holes (198 and 200) when aligned to lock the two halves of the structure in place for use. The compliant support structure is merely modified to provide two equal portions that can be assembled front to back via the eye and pin structure shown in Figure 84 or, when desirable, by the "VELCRO" arrangement shown in Figure 85.

Additionally, the side support members (162 and 164, in Figure 82) are adapted for height adjustment within the lower members (166 and 168). This is provided by a thread or ball screw assembly (not shown) located in the lower frame elements, which couple to respective height-adjustment knobs (198 and 200). The ball screws can be adjusted to allow the body to move down to a sitting position. Likewise, the same ball screw could raise the person to a vertical position. The height-adjustment lever could also be used as a locking mechanism to hold the height desired. It is significant to note that the angled side support members (158 and 160) permit users to more freely use their arms, because there is less obstruction outwardly to the side.

While the embodiment shown in Figures 80 - 82, for example, only calls for forwardly telescoping front-end extensions (174 and 176), when desirable, pivoted outrigger elements such as those shown in Figures 87 and 88 can be used. This arrangement permits better stability of the walker structure, as desired.

As shown in Figure 91, a modification of the compliant-cable support system (designated by reference numeral 25') can be used with the embodiment shown in Figures 80 - 82. This configuration consists of rearranging the sets of cable segments (100 - 114) into a more rectangular arrangement by the inclusion of elongated back plate members (202 and 204) attached to the upper vertical portion of the upright side members (158 and 160). This arrangement includes an additional set of right-angle brackets (206, 208, 210, and 212) to be used in conjunction with the cable sets (100, 102, 104, 106, 108, 110, 112, and 114). Further, as shown, the right-angle brackets (120, 122, 124, and 126) act in conjunction with the angle brackets to provide a rectangular configuration of the compliant-cable structure.

While a torso type of partial body harness has been considered thus far, when desirable, a hip type of harness can be used, shown in Figures 92 - 94. A girdle-type harness structure (26') is adapted to encircle the hip regions (214 and 216) and buttock region (218) while being partially open at the front, where it can be drawn together and fastened by means of a belt-type closure (220) over the abdomen region (222). The belt-type arrangement may be fabricated of nylon and may include a "VELCRO" closure section (224). The harness includes relatively soft quick-release elasticized leg straps (226 and 228) that extend from the hip regions through the crotch area (230), where they attach to the backside portion (232, as shown in Figure 94).

A pair of cable-segment attachment members (234 and 236) are secured to the harness at the hip regions on either side of the user. Thus, instead of being supported in the upper region of his body, the user is now supported around his hips and seat.

A variation of this type of harness is shown in Figure 95. The cable attachment member at the hip is modified as a structure

(234'). This would then attach to a suitable frame structure (as described above), but is modified for the lower height.

Thus, what has been shown and described is a compliant walker structure for dynamically supporting a person having limited use of his or her legs. It is particularly useful as an aid in rehabilitation for patients with temporary or permanent loss of the use of their legs. Furthermore, it can be used by the public as a mobile-assist device for the physically handicapped.

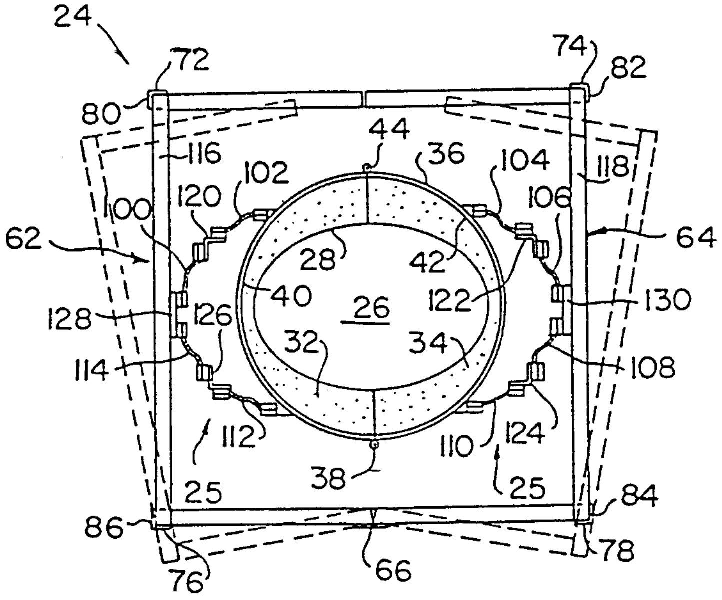


Figure 73. Wraparound walker.

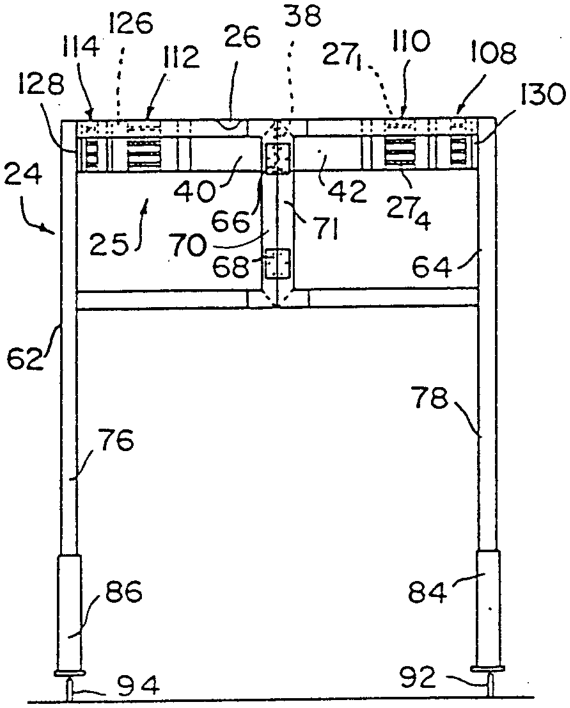


Figure 74. Back view.

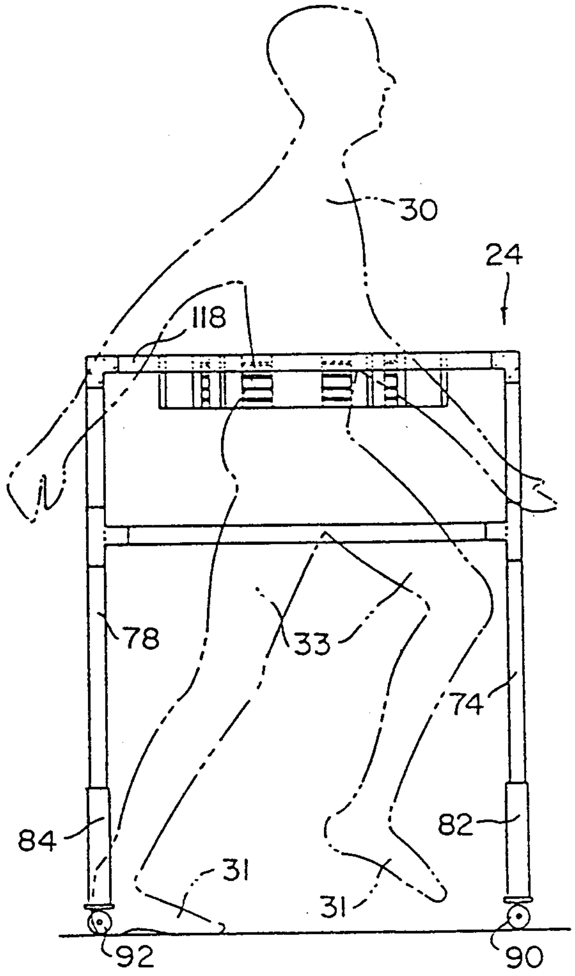


Figure 75. Side view.

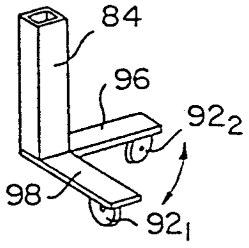


Figure 76. Casters.

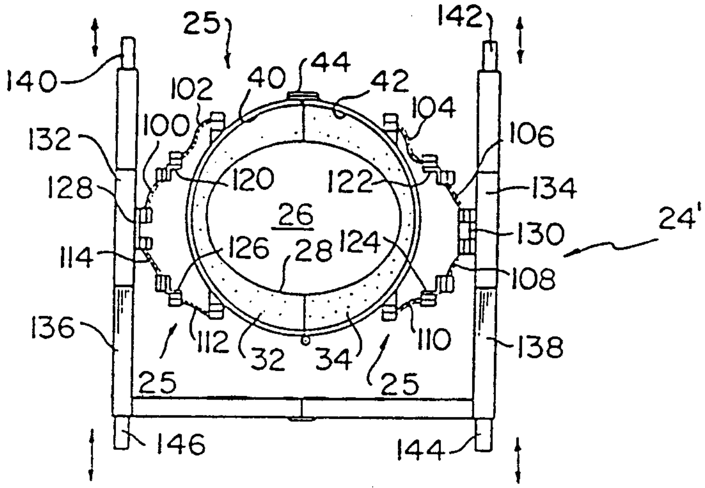
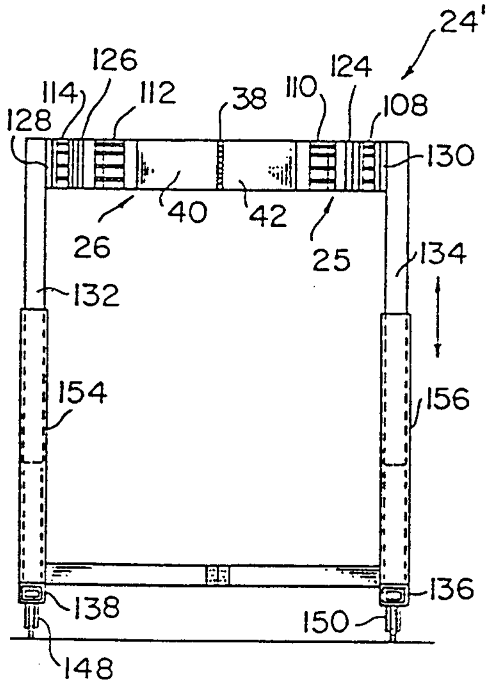


Figure 77. Side support walker.



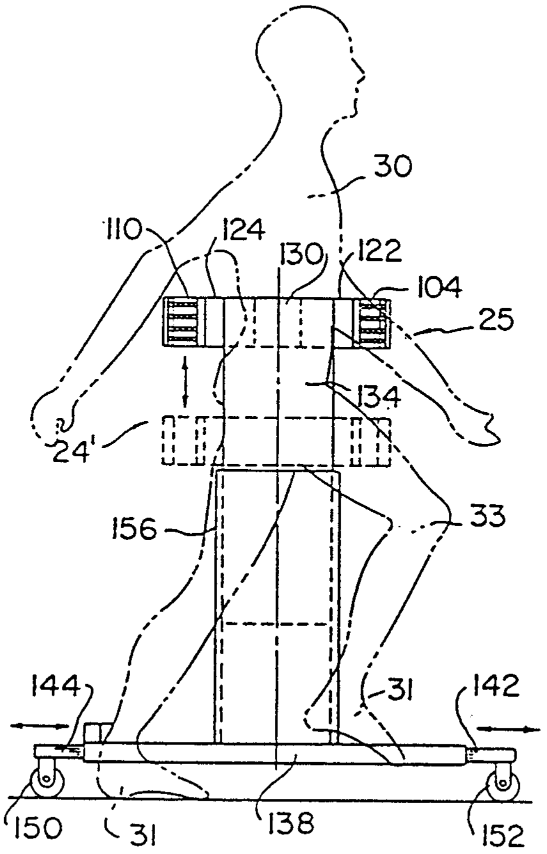


Figure 78. Back view. Figure 79. Side view.

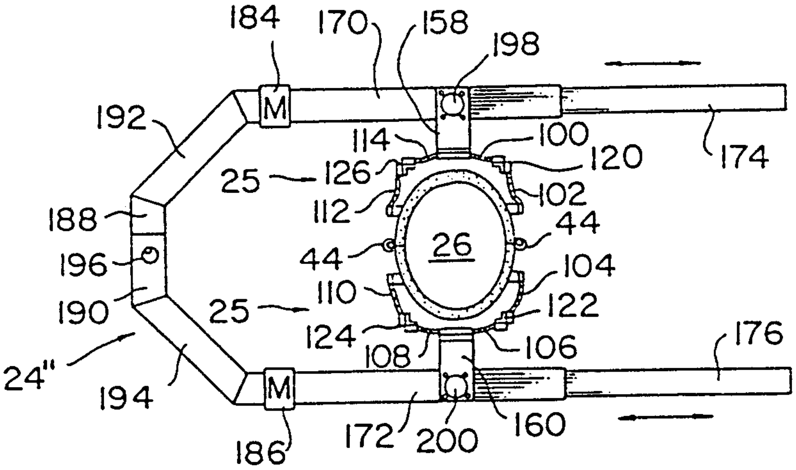


Figure 80. Lightweight walker.

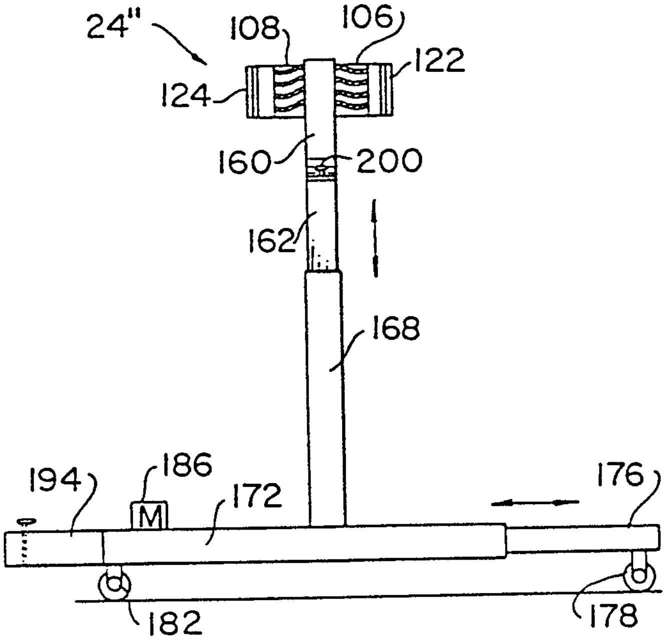


Figure 81. Side view.

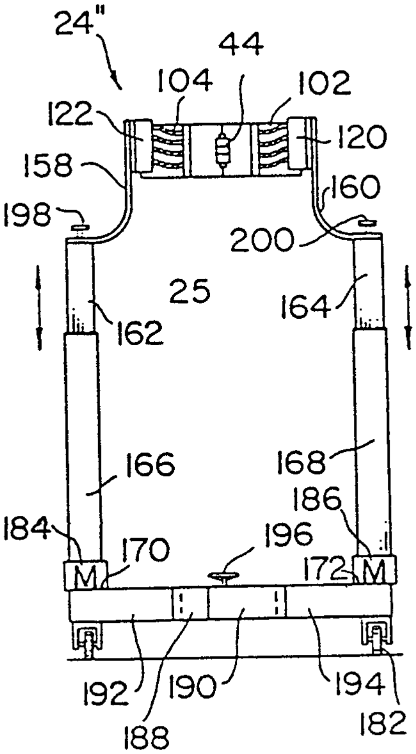


Figure 82. Back view.

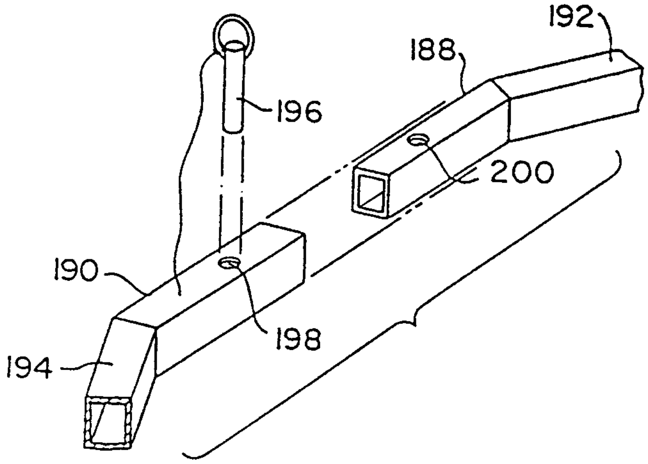


Figure 83. Back separator.

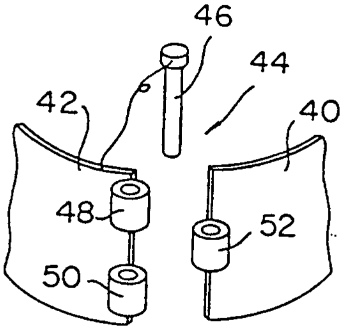


Figure 84. Waist separator.

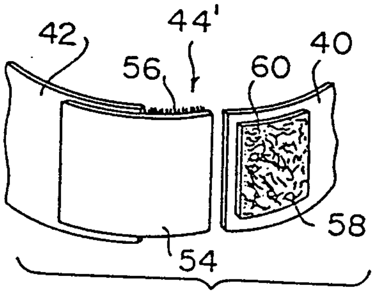
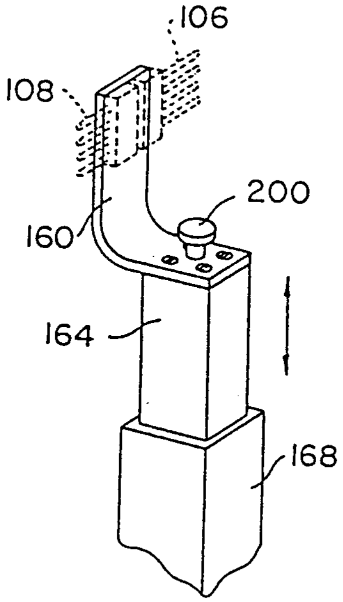


Figure 85. Velcro gripper.



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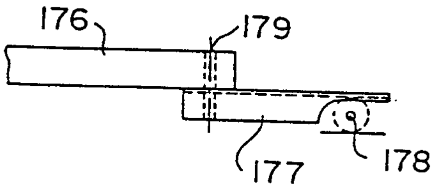


Figure 87. Outboard caster.

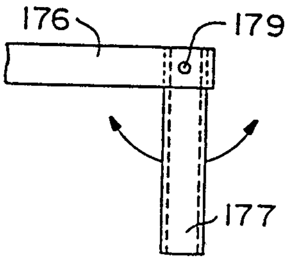


Figure 88. Top view.

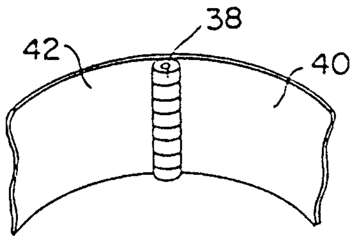


Figure 89. Back hinge.

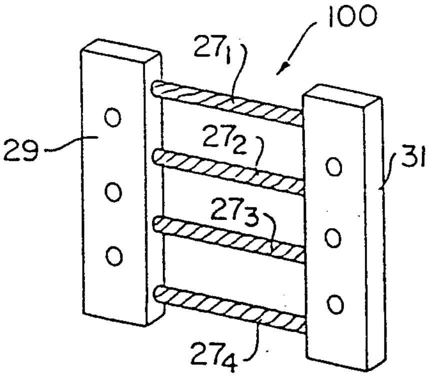


Figure 90. Cables.

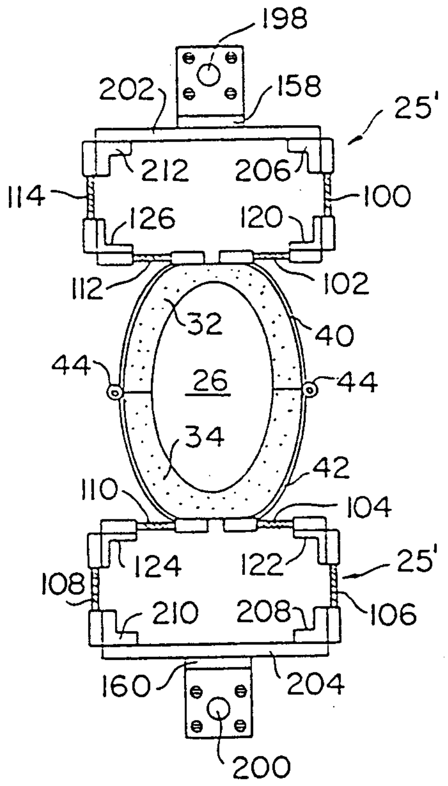


Figure 91. Cable holder.

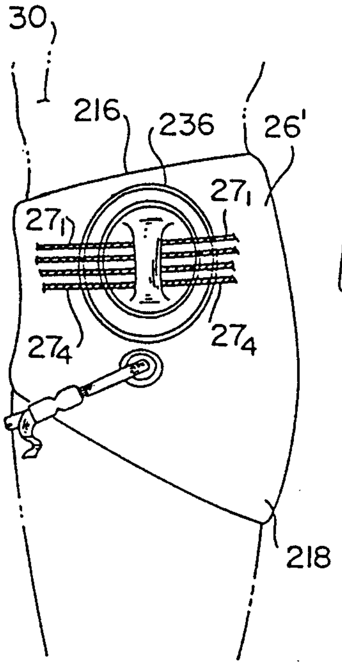


Figure 92. Harness.

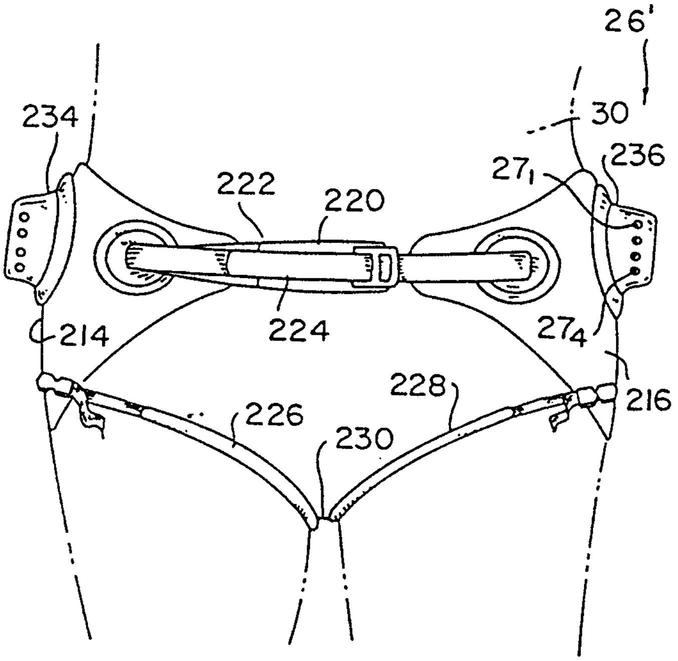


Figure 93. Harness and straps.

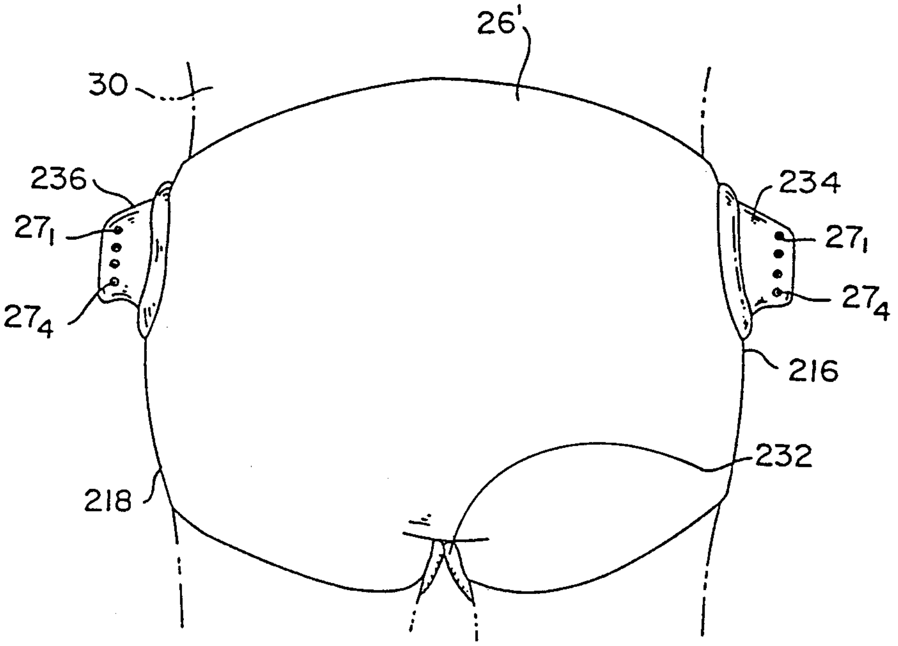


Figure 94. Back view.

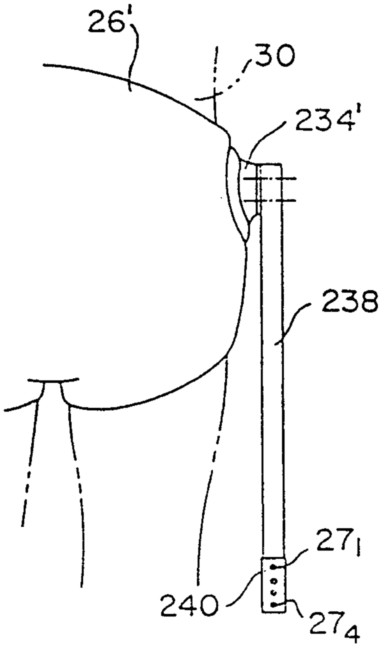


Figure 95. Height adjustment.

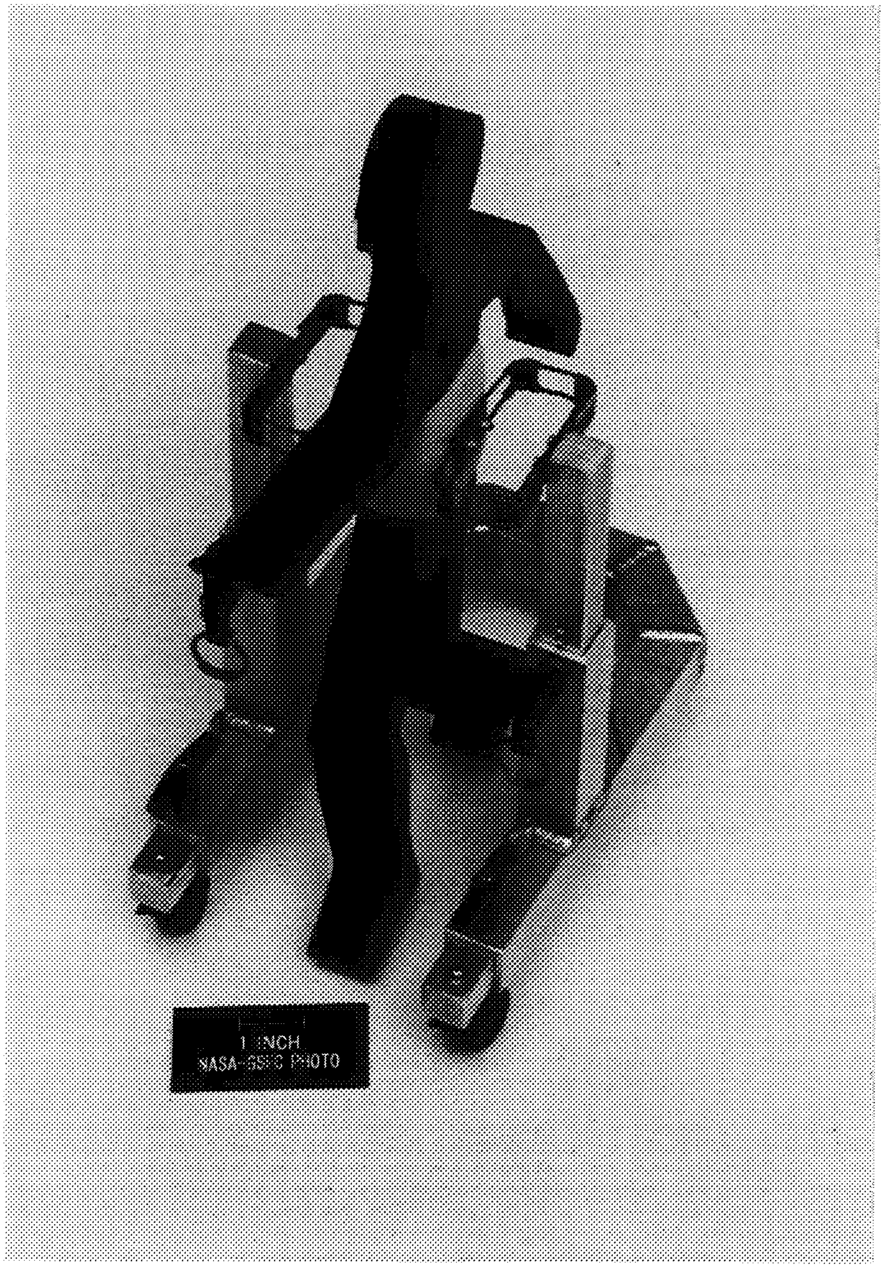


Figure 96. Working model of walker.

CHAPTER 10

COMPLETE COMPLIANT ROBOTIC SYSTEM

There are many needs for a simple compliant analogue-digital system in the machine and machine-tool business. There is a further need for this type of system among the elderly and handicapped who cannot perform all of their bodily functions without help.

Figure 97 shows a picture of a small compliant robotic system that was made to put a socket on a nut and back it off, even if the nut were at an angle to the wrench. Further, the centerline of the wrench could be displaced from the centerline of the nut, and the nut could be vibrating back and forth while the wrench is trying to find the nut. Then after finding the nut, the wrench backs the nut off the bolt at an odd angle while the nut is vibrating back and forth. The man on the left is holding his left hand just on top of the nut. The wrench can be seen lined up with the nut. The man on the far right is moving the robotic system, which can move up and down, back and forth, and in and out. He can also rotate the wrench that turns the nut.

In a robotic station, the entire system can be run with servomotors performing all of these tasks. The robotic system could be analogue, digital, or a combination of both. The man with the oscilloscope at center right is reading the position of the wrench as it meets the nut. This provides a feedback system that could be used to adjust the robot to find the optimum position to be in to perform the task of taking the nut off.

This simple system was designed and fabricated to perform a simple task. However, it could be used to perform far more complex tasks. One will be described later in this section.

Figure 98 shows a six-step function used with compliance to approach a nut that is out of line with the wrench, capture the nut, and then back it off.

Step 1. The nut at the bottom is still, while the socket wrench is on top and twisting.

Step 2. The wrench comes in closer.

Step 3. The wrench comes in even closer.

Step 4. The wrench touches the nut.

Step 5. The wrench is turning as it fits itself over the nut.

Step 6. The wrench is turning the nut and tightening it up.

In Chapter 11, a line-dimension sketch explains this motion.

Figure 99 shows a six-step function to be used by this compliance mechanism to approach a nut that is vibrating. The wrench is moving straight in while it is rotating about its axis. After the wrench captures the nut, it torques it up, even though the wrench is vibrating back and forth.

The same compliance would perform as well if it were the nut instead of the wrench that vibrates. It works equally well if both the wrench and the nut are vibrating, even at different frequencies.

Step 1. The nut at the bottom is moving to the left.

Step 2. The nut is starting to move to the right.

Step 3. The nut is moving to the right.

Step 4. The nut is at the extreme right position.

Step 5. The nut is starting to come back.

Step 6. The socket is fitting itself over the nut. Then it turns the nut while the nut is still vibrating. If a solid wrench were used, it would stop cold or break the nut if it did not have cable compliance. The ability of the cable to handle six-degree-of-freedom compliance means that the nut could be at any angle or any displacement while the nut is vibrating.

Figure 100 shows an electronic feedback measurement while the wrench approaches the nut. In Figure 100, four LVDTs (36), which may be displaced between the compliant joint brackets (as partially shown in Figure 97), sense varying displacement during robotic operations. The transformers operate on ac signals developed from internal oscillators powered by the 6 V dc power supply (37). The larger ac signals, converted internally to dc signals, indicate larger displacements. These dc signals are fed into a signal conditioner that contains four operational amplifiers (38), one for each of the four transformers. These operational amplifiers are adjustable in terms of gains, as well as output, a zero or null signal corresponding to each transformer's static position. During operation, as the distance between the bracket changes, more and less, from the static position, the operational amplifier outputs will vary, plus and minus, about the zero position. The outputs from the signal conditioner operational amplifiers are imputed to another group of four operational amplifiers (40) configured as summing amplifiers and two operational amplifiers configured as differential amplifiers (42) whose outputs may then be employed to drive oscilloscope X, Y coordinate amplifiers (44) to indicate the relative robotic joint position. These outputs may also be employed as feedback control signals to aid in changing the joint position. Alternatively, the oscilloscope "dot" (46) may be used, with human intervention, to aid in changing joint position to acquire a work object.

Figure 101 shows a handicapped patient's station where this robotic system could be used to supply the patient with food, drink, reading material, telephone, desk computer, and the equipment to wash the face and hands and comb the hair. The patient could use this system to operate the robotic system shown on tracks above the table. This is the same principle that is used in the model. Compliance is used because in this way the patient cannot be injured by the robotic arm. Compliance is in the robotic arm wrist, elbow, and shoulder joints. The compliance is useful also, since no expensive robotic system is required to operate it. It is an analogue system, and thus the brain of the computer is simply the thinking of the patient. The patient can use one of the wands shown in the center of the table to follow through on any of the functions shown above. It may take a little time to move the arm to the proper position, but the patient has control of the system at all times. It gives him something to do and, at the same time, gives him the confidence to see that he is an integral part of the system.

This system can also be performed by a digital-analogue technique. Once a function, like opening the oven door, is done by analogue, it can be put to memory by a digital process. The operator, then, can use either an analogue or a digital program to handle his motions.

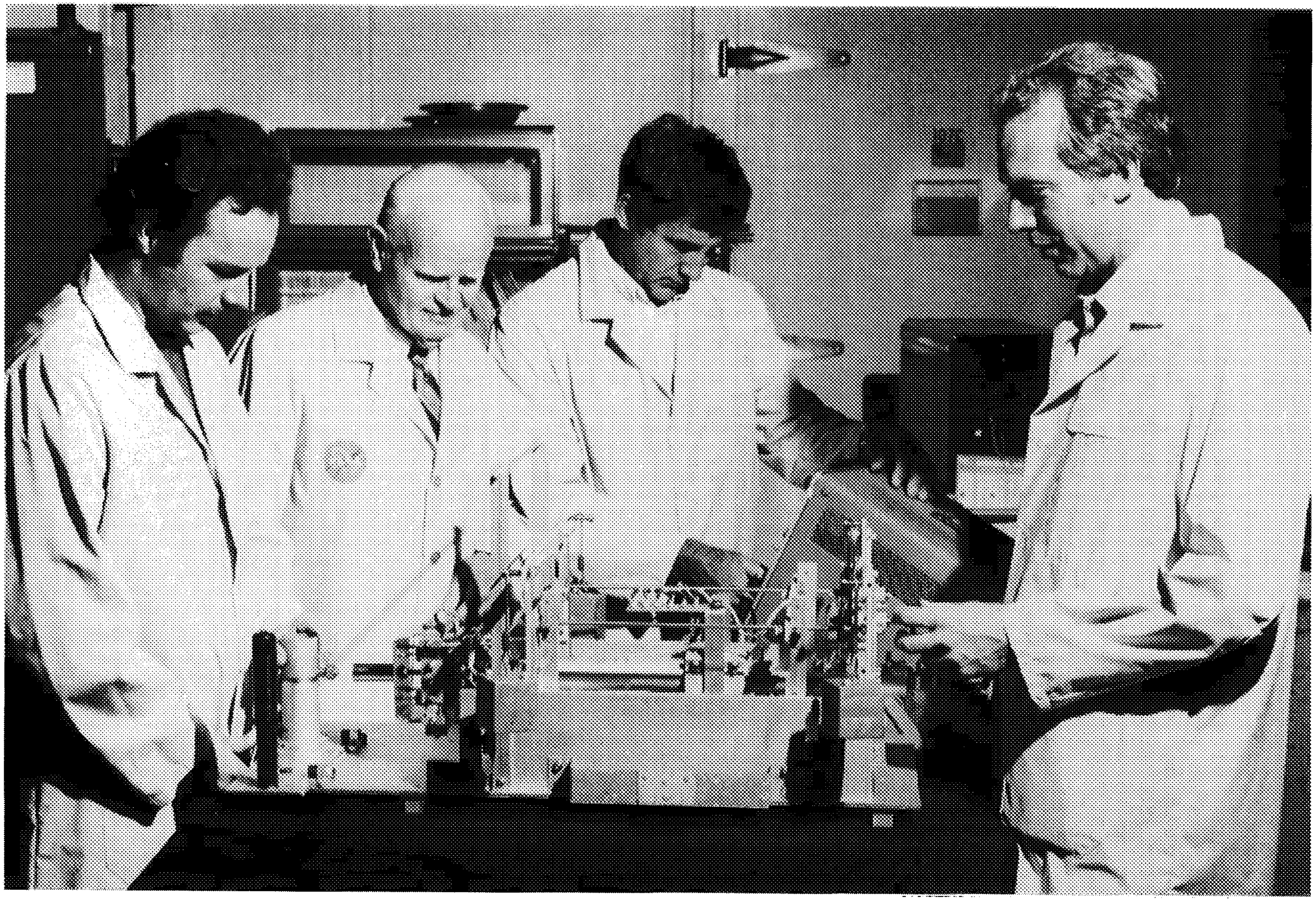
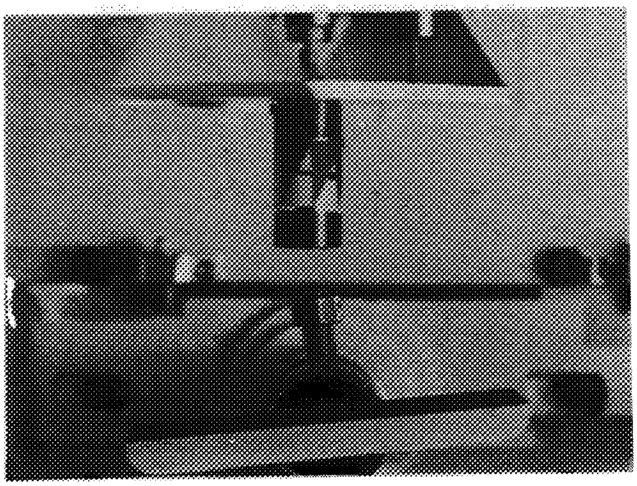
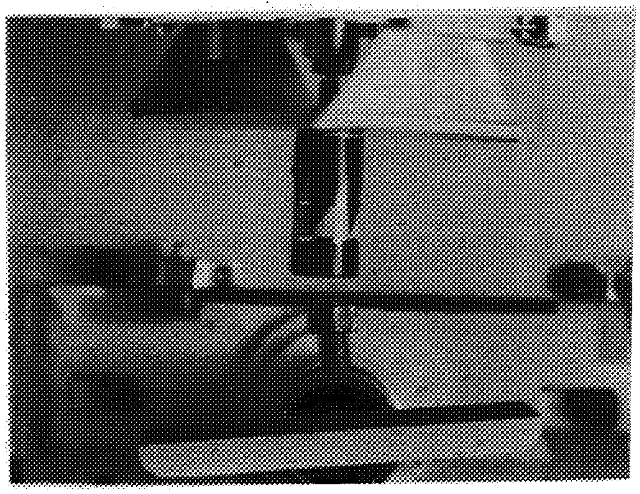


Figure 97. Compliant robotic system.



STEP 1



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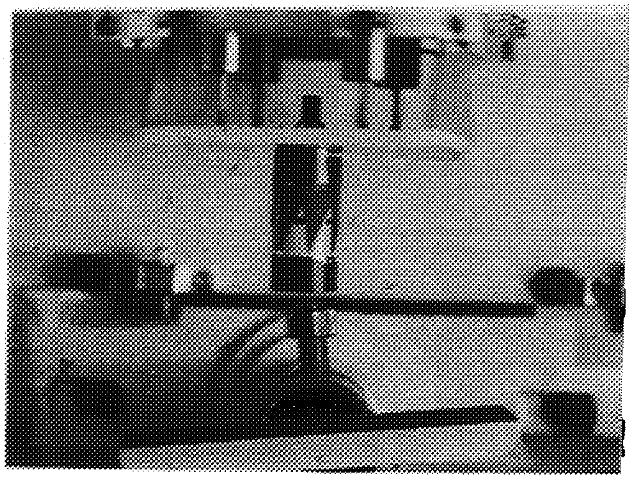

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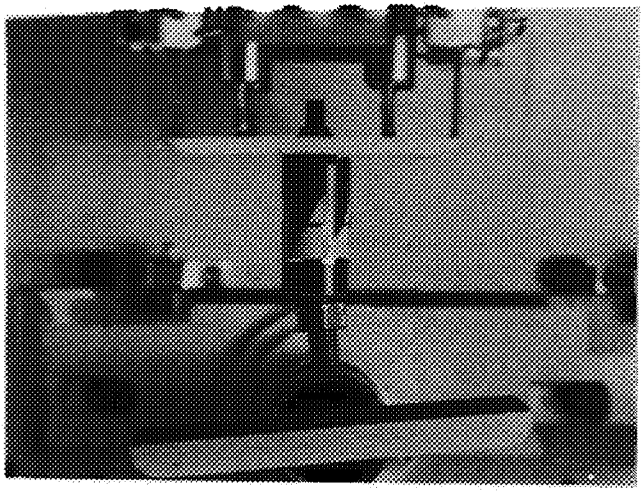

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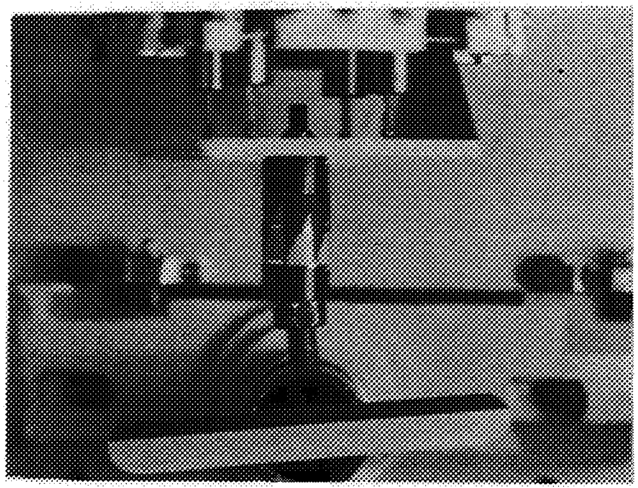

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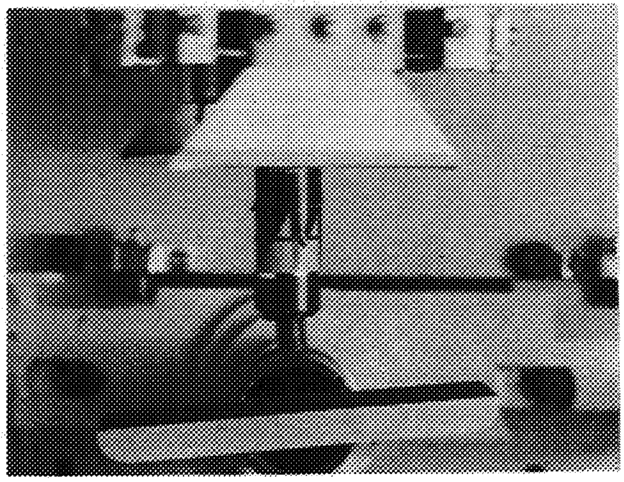
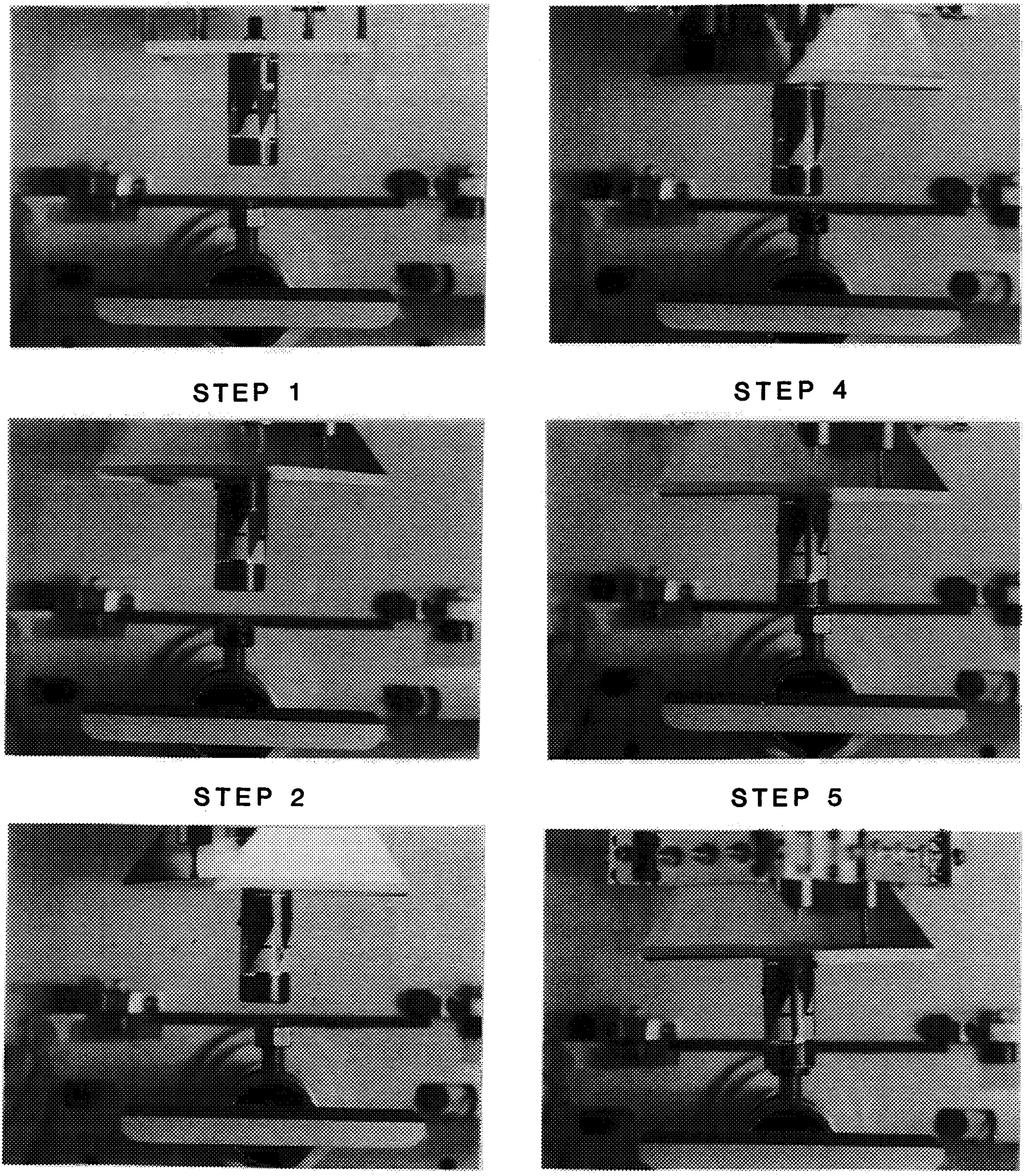


STEP 6

Figure 98. Angular compliance.



STEP 1

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STEP 6

Figure 99. Vibrational compliance.

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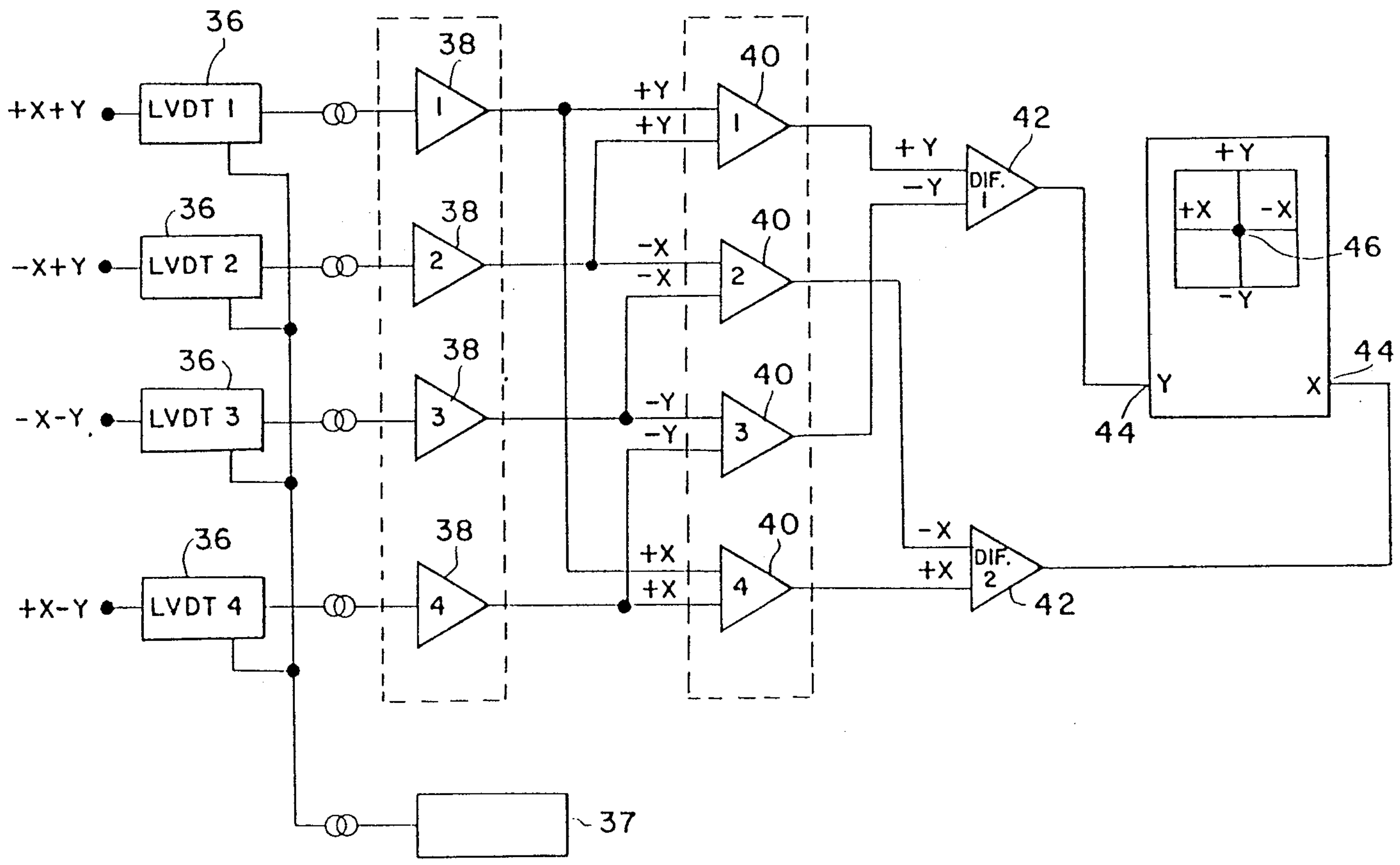

Figure 100. Electronic feedback measurement.

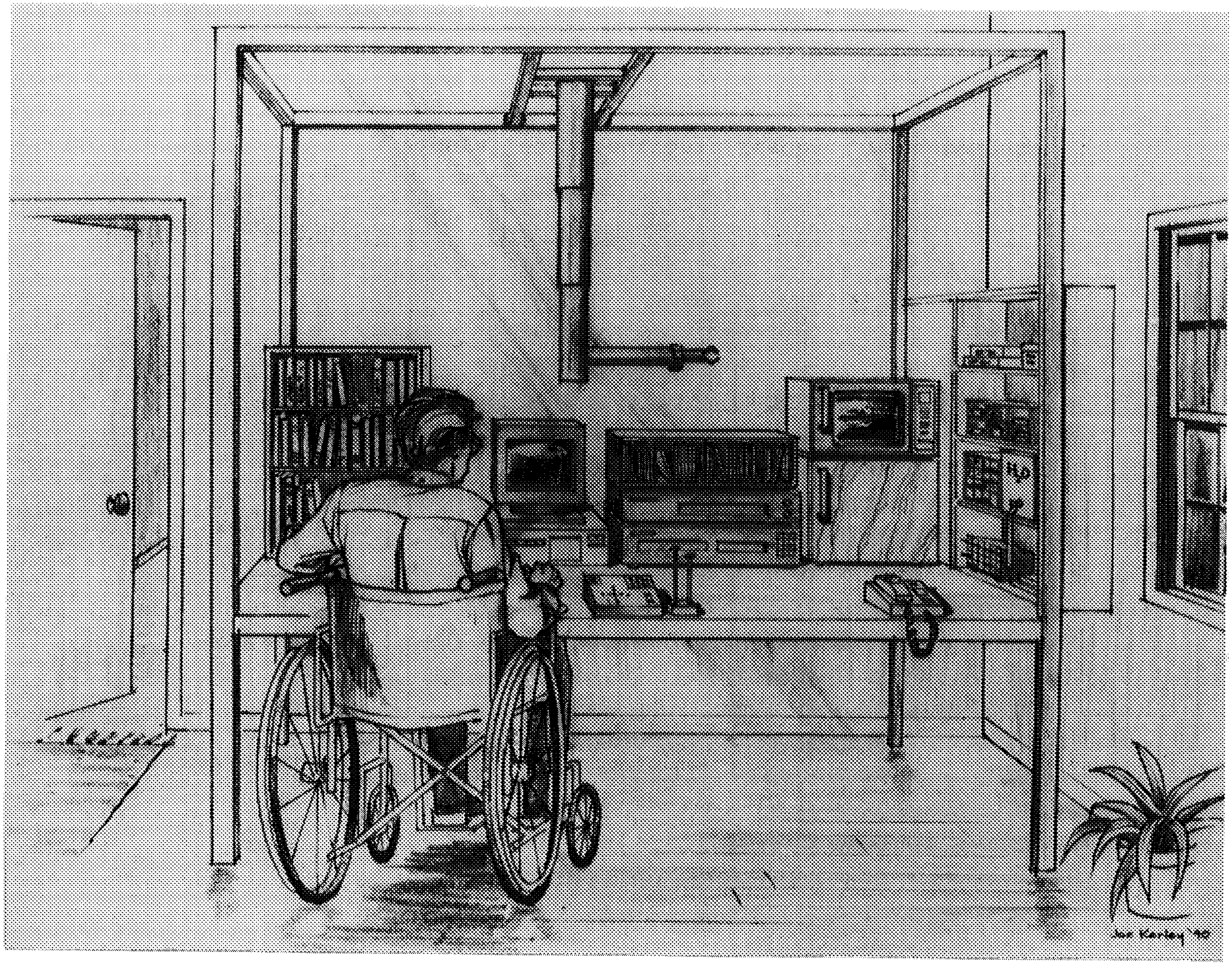

Figure 101. Patient robotic compliance system.

CHAPTER 11

THE MODIFIED CABLE COMPLIANT MECHANISM

Introduction

This chapter describes how the cable compliant mechanism design was specialized for use in robotics and tested. Figure 102 shows the completed CCM, and Figure 103 shows it in operation. There were two main motivations for the new design: maximize its flexibility, and reduce its size. The mechanism height is of primary concern, since it contributes to the distance between the workpiece and the robot pitch, yaw, and roll joints. In operation, a greater distance results in greater load on the joints and less positioning accuracy.

Design Requirements

The original request was for the CCM to carry 200 pounds and fit into a 6 X 6 X 4-inch envelope. The LVDTs were to measure plus or minus 1 inch of compliance in all six degrees of freedom. As mentioned before, the LVDTs are essential for determining the relative plate positions for the robot controller.

Since the LVDTs, as configured to measure six-degree-of-freedom motion, could not fit into a 6 X 6 X 4-inch envelope, the envelope and flexibility requirements were relaxed. The final design fit into a 9 X 9 X 7-inch envelope, but incorporated some of the robot's sensing equipment, thus, giving an effective height of only 5 1/4 inches.

Three-dimensional motions were first visualized on paper with overlays. Semiopaque drafting paper had bottom plate features on one piece and top plate features on the other. The corresponding features were aligned, then moved in various directions to simulate six-degree-of-freedom motion. Orthographic projections facilitated this technique. The most critical motion was found to be a clockwise rotation of the upper U frame about the Z axis. This caused the LVDTs to interfere.

A cardboard and balsa model was developed, which clearly revealed this and also confirmed a solution. In three dimensions, important features showed up that were missed with the other techniques.

An assembly drawing proved very useful for visualizing the design progress. At first, it was more of a layout sketch than a drawing, because none of the component details had been worked out. However, as the project took shape, the assembly drawing provided a useful overall view.

Design of Components

Individual components were designed, keeping in mind the goals of reducing device size and maximizing flexibility. There were three areas of design innovation: 1) the angle pieces, 2) the top and bottom plate positions, and 3) the LVDT positions.

Angle Pieces

The angle pieces keep the cable ends rigid with respect to each other in the four corners of the compliant mechanism. Figure 104, Part a, shows the original design of one angle, consisting of four pairs of clamp halves, with semicircular grooves to hold the cable, and a base to which the clamps were bolted. This concept was strong, simple, and cheap, but bulky.

A proposed modification made three pieces do what nine did before. Figure 104, Part b, shows how the design could be made smaller and the number of screws and their protrusion could be reduced. One of each pair of cable clamp halves was eliminated by putting the semicircular grooves in the base. One large, diagonal screw clamped two pairs of cables where eight were used before. This concept was less bulky and would have been simpler to assemble because there were fewer screws; however, the offset screw could not adequately clamp the cables.

The final version is shown in Figure 104, Part c. It is smaller than either previous design and combines the best features of both. The screws are countersunk into the top cable clamp half to eliminate their protrusion, and they pass between each cable end. The clamping force is more evenly distributed over the cable and is nearly equal to that of the original design. The same concept was used to reduce the clamp size on the U frames where the other ends of the cables are fastened.

Plate Positioning

The distance between the upper and lower U frames was reduced, since it constituted a large part of the device height. This decreased the LVDT angle from the horizontal, providing a secondary benefit by improving the measurement accuracy for horizontal motions. (To yield the same accuracy for both vertical and horizontal plate motions, the LVDTs should be inclined at 45 degrees.) Because of the CCM envelope constraint, the LVDTs were originally inclined at the relatively steep angle of 72 degrees from the horizontal in the neutral position. This favored measurement of vertical motions. Ordinarily, decreasing this angle would mean increasing the CCM length and width; however, it was done with minimum effect on these envelope dimensions.

Originally the LVDTs were attached directly to the surface of both plates with ball ends. Figure 105 shows schematically how the plate and LVDT arrangement changed to compromise between a shallow LVDT angle and small CCM dimensions. (The side members of the lower U frame and five other LVDTs are not shown in this figure.) Figure 105, Part a, shows the LVDT at a 72-degree angle. Figure 105, Part b, shows the first modification: The upper U frame was lowered, and the LVDT passed through the bottom plate on a spherical bearing pivot. The angle was decreased to 65 degrees. A standoff plate was added to attach the CCM to the robot. This reduced the flexibility of the CCM by decreasing the clearance between the two U frames. The clearance was restored by moving the upper U-frame side members upward relative to the frame's horizontal portion, as shown in Figure 105, Part c. The force sensor, shown on the top plate, was nested inside the cable area. The lower side members, though not shown, had to be lengthened.

This compact design reduced the height of the CCM by 1 inch. The LVDT stroke efficiency was improved by 27% for horizontal measurement, but decreased by only 5% for vertical measurement. The next section describes the LVDT positioning in the new plate positions.

LVDT Positions

Positioning the LVDTs in the bottom plate required careful three-dimensional visualization. They had to fit into the smallest possible space and not interfere with either each other or the side members during CCM operation.

Each pair of LVDT rods crossed, as shown in Figure 106, so as to make the angle shallow. Compare this with the original configuration shown in Figure 33. This made interference verification very important. The top view shows how the LVDT rods in each pair point in different directions so as to clear each other when the top plate rotates about the vertical axis. The cardboard model served to illustrate the motions quickly and simply.

Results

Weight calculations, which were confirmed after fabrication, showed an overall CCM weight of 15 pounds. Stress analysis was performed on all critical areas of the CCM. The stress conditions were bending in the side members shear, load on the standoff bolts cable pullout from the clamps and the holding of the cable clamp screws. Each had a factor of safety greater than 6.

Conclusion

The final envelope of the new CCM is 9 X 9 X 5 inches, with ±1-inch flexibility in five degrees of freedom and ±7/8-inch flexibility in 1 horizontal translational degree of freedom. Based on a 200-pound workpiece, stress analysis of the completed design shows a factor of safety of at least 6 for each critical load-carrying area.

After assembly, the CCM was tested to 1 1/4 times its rated load capacity (250 pounds) on the Tinius Olsen static testing machine.

The new CCM was installed on a NASA T3 robot and is simulating tasks to be performed on Space Station Freedom. The CCM was designed to augment the T3 robot capabilities by providing compliance and damping between the end effector and robot arm. This compact design will enhance space- and ground-based robotics work by compensating for misalignment, providing gentler handling, and transmitting adequate force to the end effector to accomplish its task.

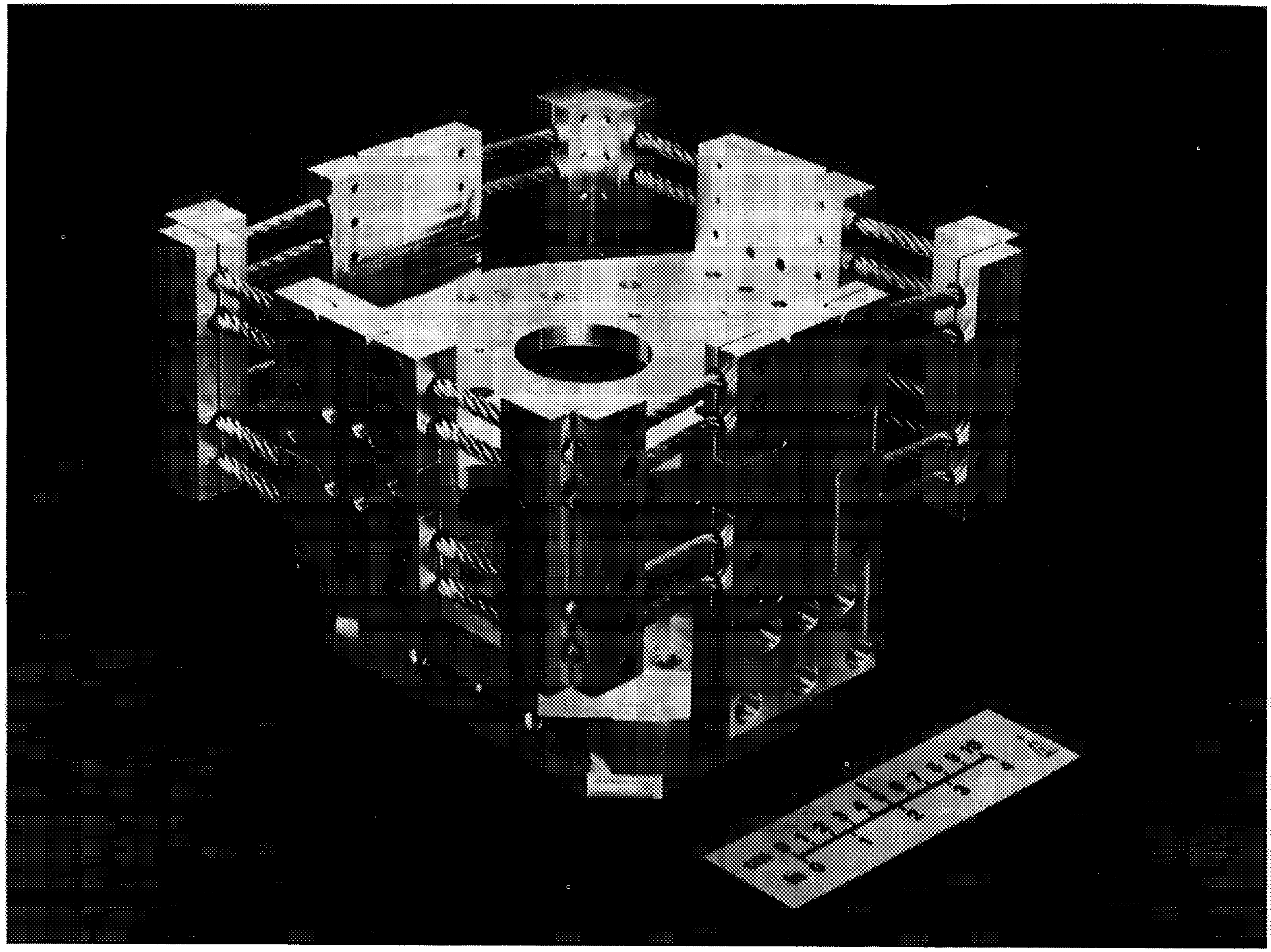

Figure 102. Modified compliant cable mechanism.

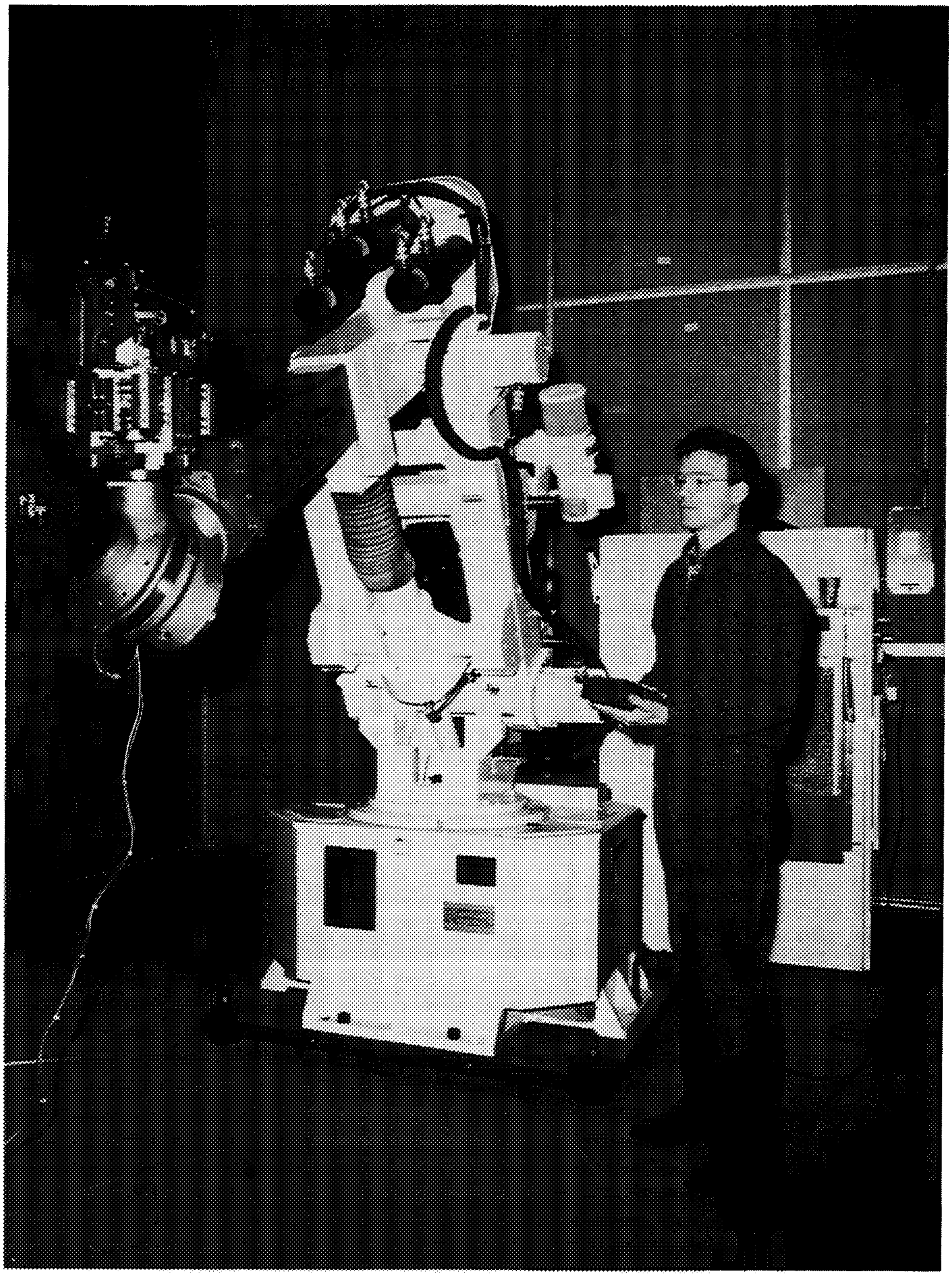

Figure 103. Compliant cable mechanism in use.

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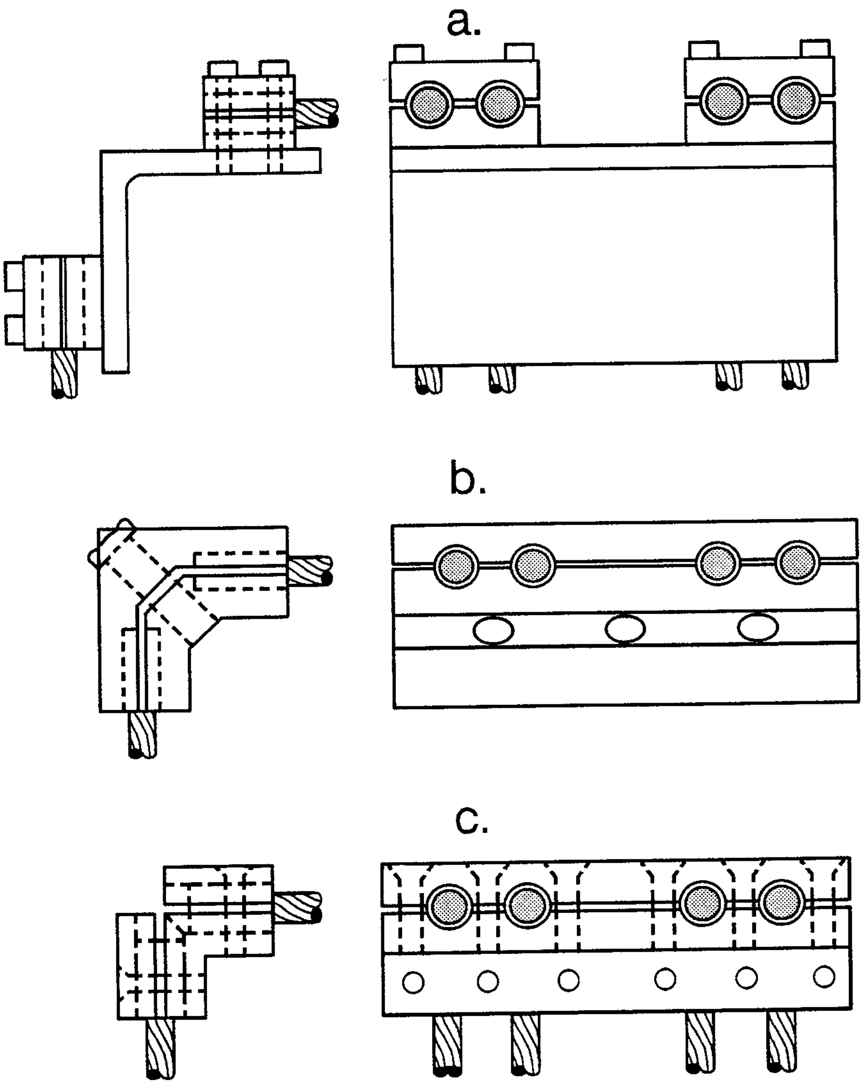

Figure 104. CCM angle piece evolution.

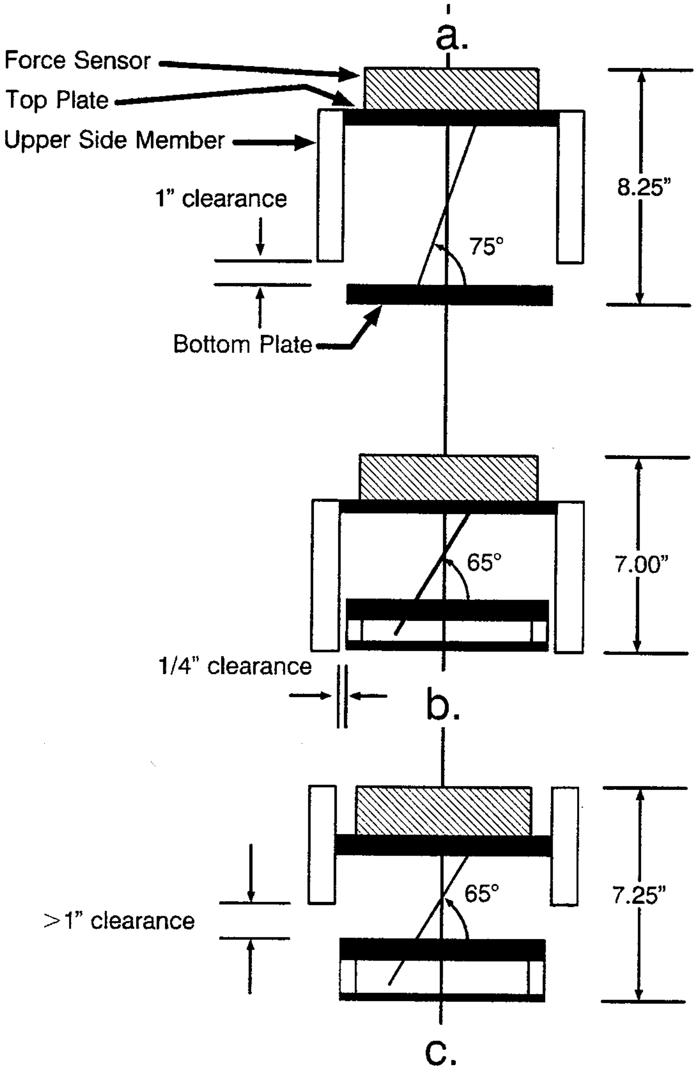

Figure 105. Plate and side member positioning evolution to decrease LVDT angle and CCM height.

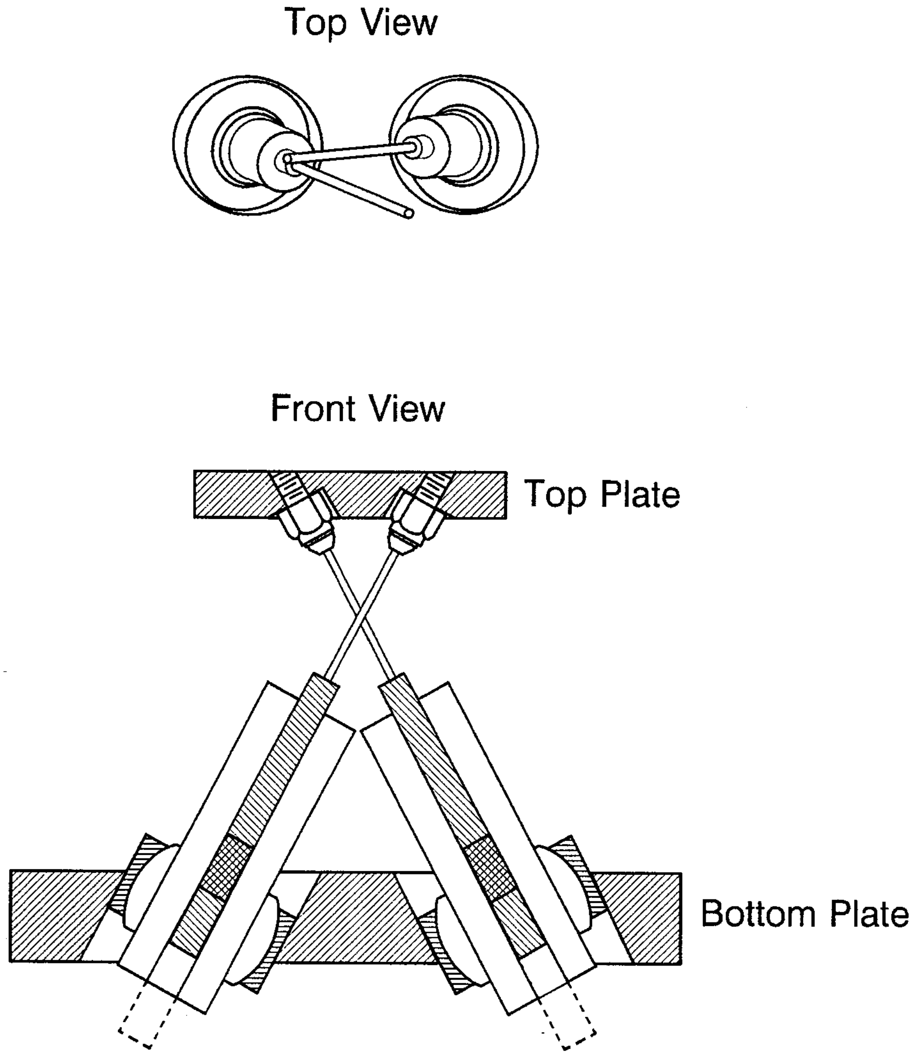

Figure 106. Placement of LVDT pairs.

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13. ABSTRACT *(Maximum 200 words)*

The object of the investigation was to solve mechanical problems using cable in bending and cable in torsion. These problems included robotic contacts, targets, and controls using cable compliance. Studies continued in the use of cable compliance for the handicapped and the elderly. These included work stations, walkers, prosthetic knee joints, elbow joints, and wrist joints. More than half of these objectives were met, and models have been made and studies completed on most of the others. It has been concluded that the many different and versatile solutions obtained only opened the door to many future challenges.

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