Design Methodology to Reduce the Number of Actuators in Complex Mechanisms

by

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Abstract

This thesis explores the possibility of using mechanical control in the design of a complex end effector. A design methodology is developed and demonstrated. The main goal of this methodology is to maximize reversible steps to direct the design. By attempting to obtain as much mechanical control as possible, several mechanisms are developed which could be used in applications where control of multiple operations by one motor is desired. Along with the demonstration of the design methodology with an end effector design, application of this methodology to cigarette packaging machines is discussed.

Acknowledgements

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I am grateful to my parents, Frank and Barbara Denkins, for over the years they have given me the tools and encouragement to succeed.

Finally, I would like to express thanks to my beautiful wife, Louise, for all that she has done for me. Without her support, I would not be where I am today.

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Chapter 1
Introduction

The main objective of this thesis is to develop a design methodology to reduce the number of motors in the design of complex mechanisms. By reducing the number of motors, the weight and complexity of the mechanism should be reduced and the reliability should be increased. This developed methodology is demonstrated in the design of a complex end effector and is also applied to a cigarette packaging machine.

Today, mechanical control of mechanisms has been almost eliminated and the trend is toward controlling sequences of operations electronically. Current studies of mechanical control seem to be almost non-existent. For example, in internal combustion engines, the firing order for the spark plugs has been controlled by a distributor driven by the cam shaft for many years. Many modern engines use electronics to control the firing order. This shows the trend toward using more electronic control. The control of the valve opening and closing in most internal combustion engines has always been controlled mechanically by cams. No efficient electronic method of controlling the valve operation has been developed. This shows that electronic control is not always the best method, but today electronic control is usually the first choice. It is easy to overlook the idea of mechanical control with all the electronic methods available for controlling mechanisms.

Table 1-1 shows the advantages of using mechanical control and the advantages of using electronic control. The items in Table 1-1 are listed in order of decreasing

Table 1-1. Advantages of Mechanical and Electronic Control

Strong Mech Adv				Strong Elec Adv	
X					Ease of control
X					Positioning speed
X					Number of sensors required
X					Programming time
	X				Maintenance
	X				Reliability
		X			Positioning Accuracy
		X			Cost
		X			Power output to power input ratio
		X			Weight
				X	Versatility
				X	Mean time between failures for motors
				X	Design and Redesign time
				X	Required designer expertise

mechanical control advantage. For some items such as cost and positioning accuracy it is difficult to tell whether mechanical or electronic control is better. It cannot be said that one control method is always better than the other. Mechanical or electronic control is chosen depending on the requirements of the system. For this thesis, mechanical control was chosen because for this end effector ease of control was very important. Allowing the mechanism to control the motions, reduces the chances of operator error. In order to reduce the number of signal lines, previous designs used a microprocessor on the end effector to control the sequence of motions. By allowing the mechanism to control the motions, these microprocessors would not be needed and the weight could be reduced. The number of signal lines can also be reduced by using mechanical control, since fewer sensors would be required. The design and redesign time could be reduced, and a less experienced designer could design mechanically controlled mechanism if a methodology to systematically design mechanisms with mechanical control is developed. Therefore, by developing this design methodology, mechanical control becomes a more attractive approach.

The design method developed in this thesis for designing complex end effectors was developed from looking at various end effector design methods. The design evolved from reviewing industrial end effectors, end effectors performing similar tasks and various mechanisms. End effectors were reviewed which were able to manipulate objects or do more than just grip an object. For this thesis an end effector was to be developed which can perform many tasks with one motor. Mechanisms that can vary or stop motion while the input remains constant were therefore reviewed.

Chapter 2
Literature Review

2.1 Aerospace End Effectors

Some of the end effectors reviewed (Katzberg et al., 1986) are shown in Figures 2-1 through 2-7. These are various end effectors which have been developed and studied for in space use. Most of these end effectors simply grasp objects. This seems to be the most studied type of end effector.

The most proven and accepted end effector used for in space use is the Standard Snare Type End Effector shown in Figure 2-1. This is used in conjunction with the Standard Grapple Fixture shown in Figure 2-2. It grasps the grapple fixture using three wires. When locked, it also can supply power through an electrical connection. This end effector has been proven time and time again for in-space use. Although it must be refurbished regularly, this does not cause problems for flight on the shuttle, since flights are relatively short.

Another end effector which has been studied is shown in Figure 2-3. This is the Robo-Tech Multiple Prehension Manipulator System. The gripping method on this end effector can be adjusted, as shown in the upper part of Figure 2-3, by turning the finger turning motor.

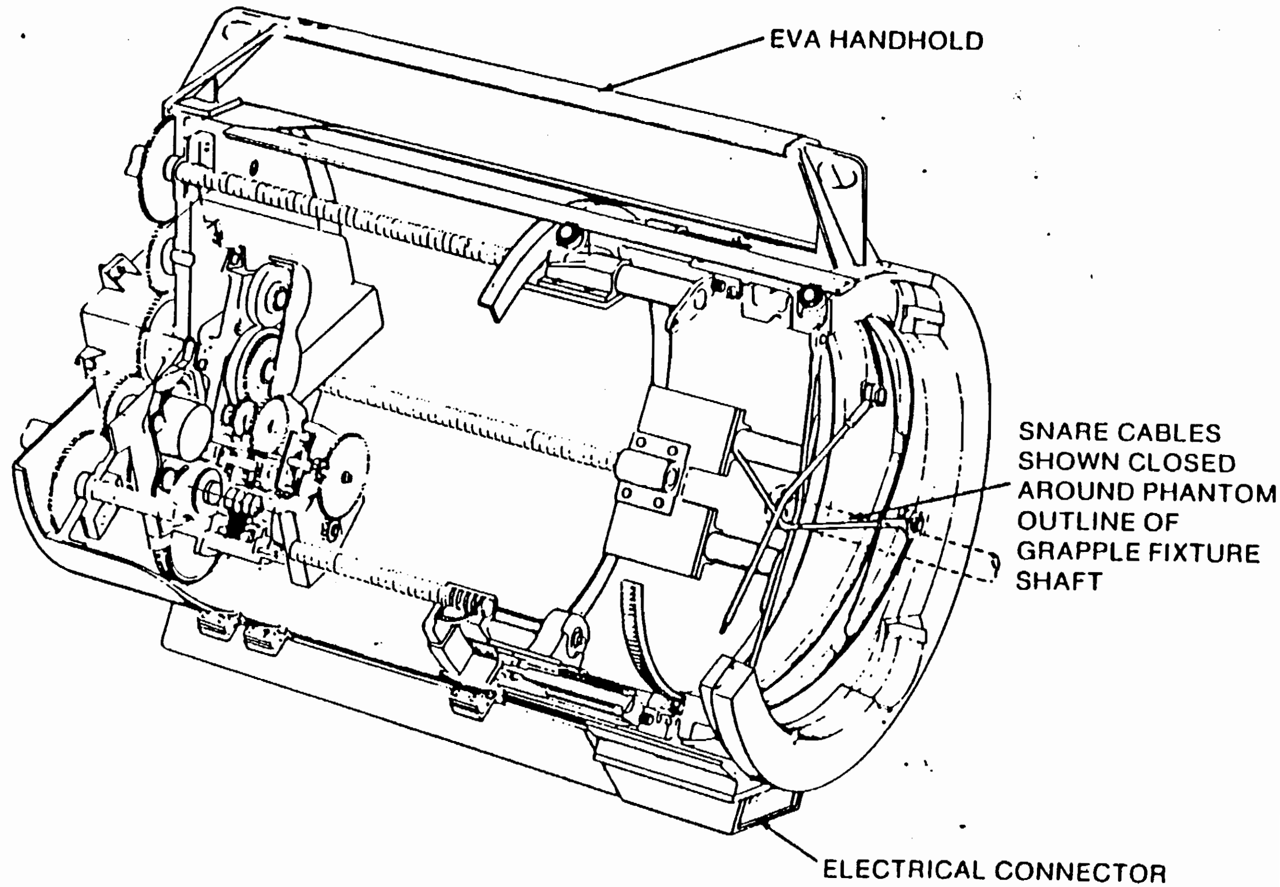


Figure 2-1. Standard Snare Type End Effector (From reference 17)

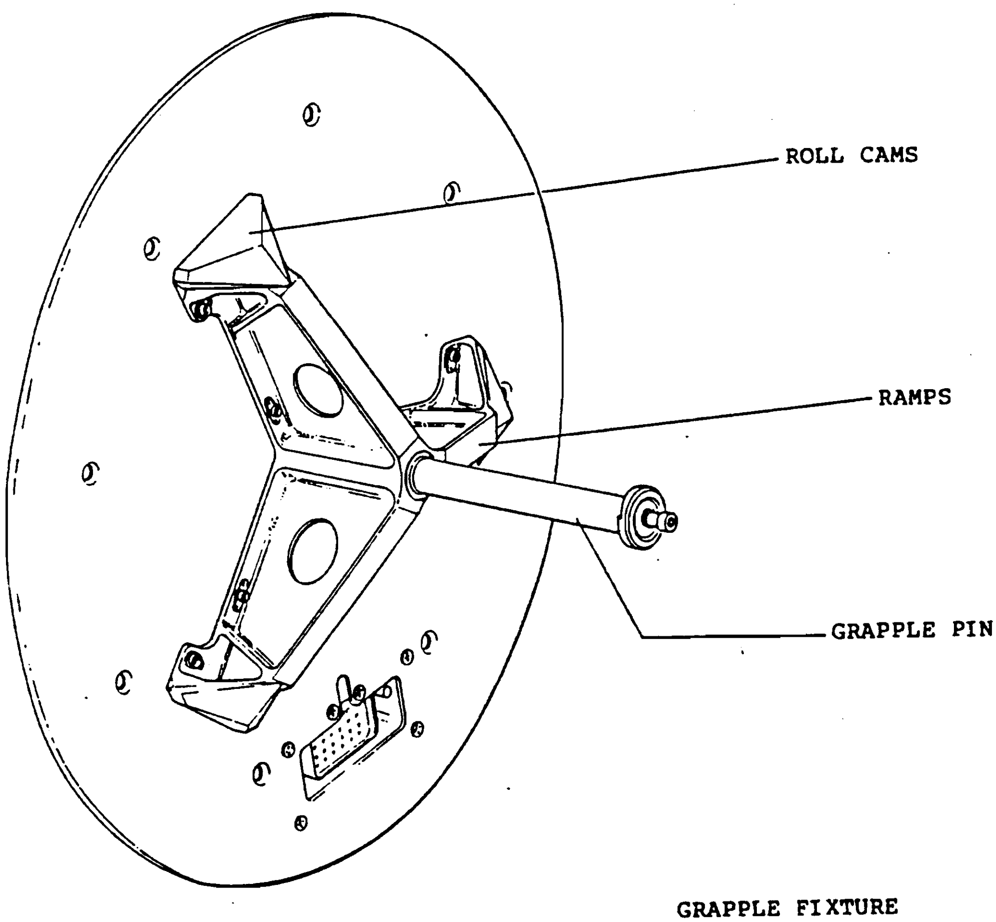
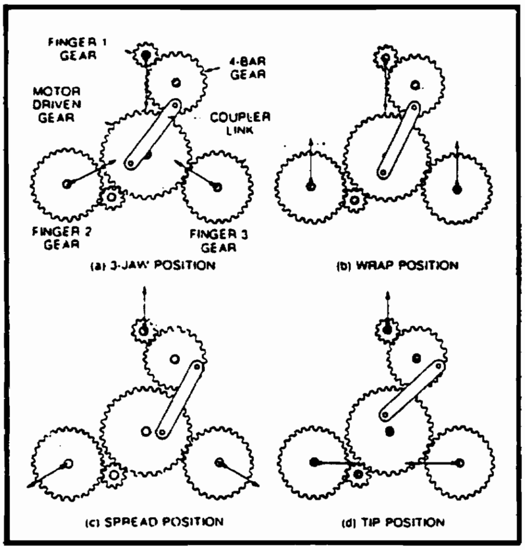


Figure 2-2. Grapple Fixture (From reference 17)



The double-dwell finger turning mechanism.

MPMS hand with a double-dwell mechanism located in its base

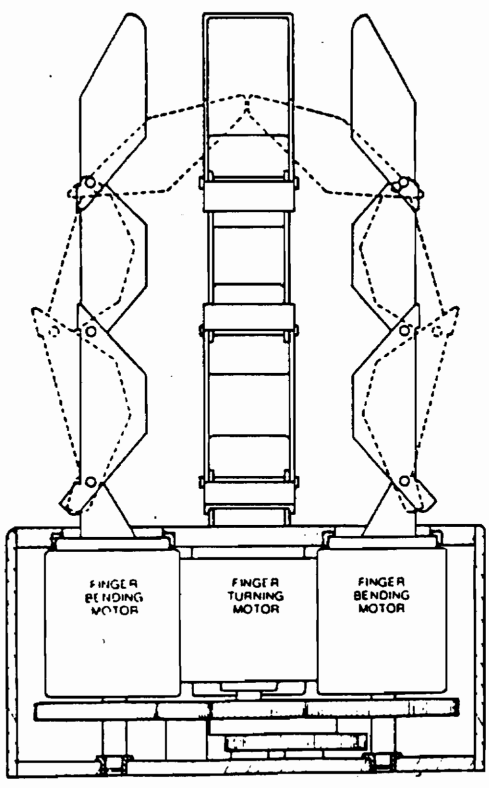


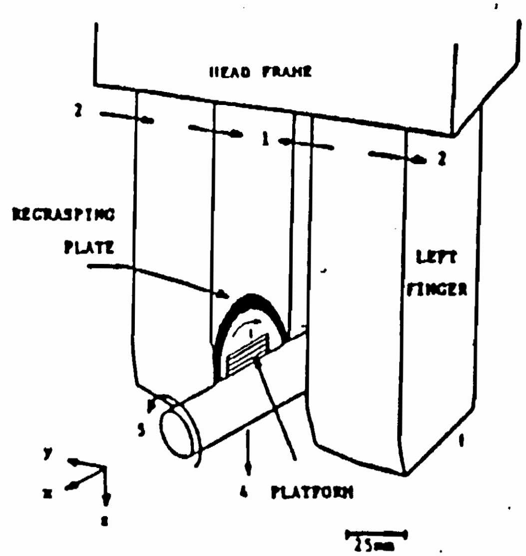
Figure 2-3. Multiple Prehension Manipulator System (From reference 17)

The URI Gripper end effector is one of the few end effectors which is able to both grasp and manipulate an object. This gripper, as shown in Figure 2-4, can rotate an object about two axes and translate the piece.

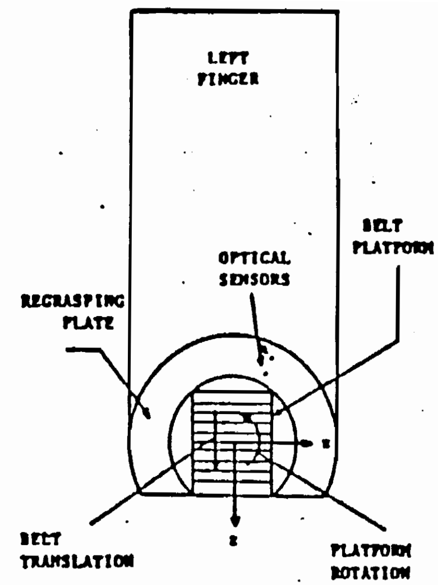
The Langley Parallel Two-Jaw Gripper demonstrates the use of a force torque sensor and compliance and is shown in Figure 2-5. This end effector has force sensors in its gripping jaws to determine how much force is being applied to the grasped item. This could be useful for grasping delicate items. This end effector has a torque force sensor at its base, which measures the forces and torque applied to the base of the end effector. Feedback from this sensor can be used to adjust the robot arm to eliminate any forces being applied to the work piece. This end effector uses a worm gear and sector gears to move the jaws. This end effector also has compliant springs at the mounting surface to eliminate overloading the work piece.

A type of end effector which can grasp an object without being accurately positioned is an inflatable device as shown in Figure 2-6. This device, while deflated, can be placed into a hollowed section of a work piece and then as it inflates it grasps the work piece. This end effector can grasp irregular shaped objects and does not need to be positioned accurately.

An end effector which can grasp rotating objects and arrest their rotating motion is shown in Figure 2-7. This could be used to interface with a spinning satellite, stop its rotation and secure the satellite. The internal ring with an inflatable section can rotate relative to the outside ring. This end effector is slid over a rotating object and



Representation of the hand's motions with a cylindrical workpiece.



Finger configuration.

URI GRIPPER (EE)

Figure 2-4. URI Gripper (From reference 17)

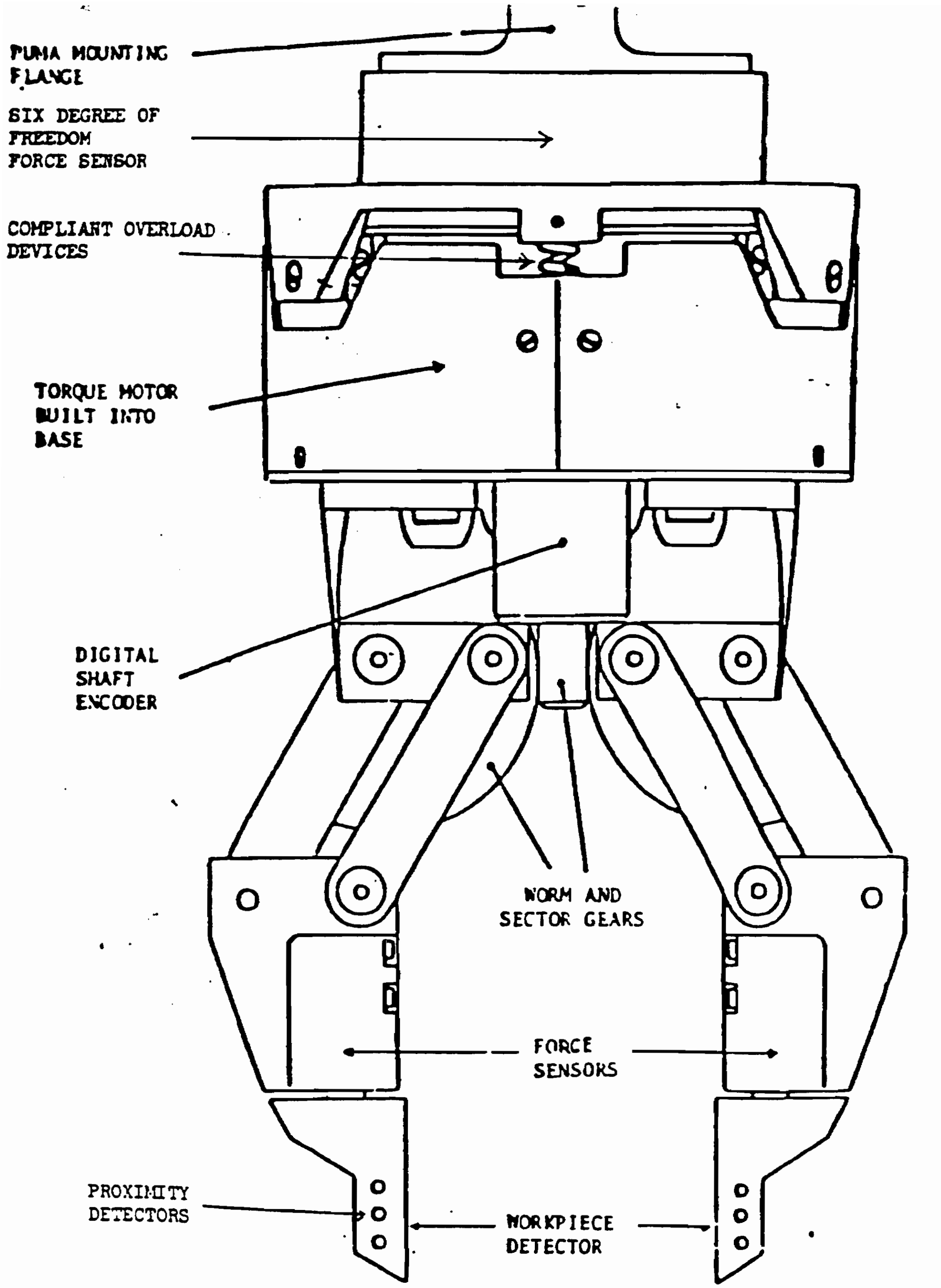
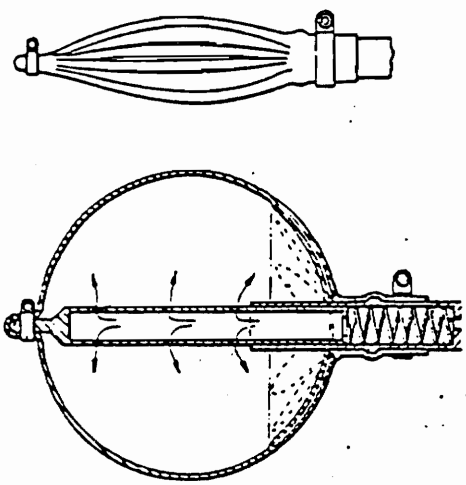


Figure 2-5. Langley Parallel Two Jaw Gripper (From reference 17)

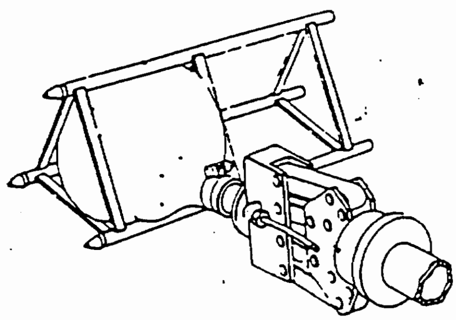
INTERNAL GRASP VARIABLE GEOMETRY



REF. U.S. PATENT #4,273,505 - Clark, et al

SPECIFICATIONS:

- BLADDER OF MED 6600 ELASTOMER
- STIFFENING WIRES MOLDED INTO BLADDER FOR TORSIONAL RIGIDITY
- CENTRAL TELESCOPING STIFFENING MEMBER PROVIDES HANDLING RIGIDITY



ADVANTAGES:

1. WILL HANDLE MANY DIFFERENT CONFIGURATIONS OF HANDLING POINTS
2. REQUIRES ONLY ONE GRIPPING BLADDER
3. LARGE EXPANSION RATION PERMITS A LARGER POSITIONING ERROR

Figure 2-6. Inflatable Gripper (From reference 17)

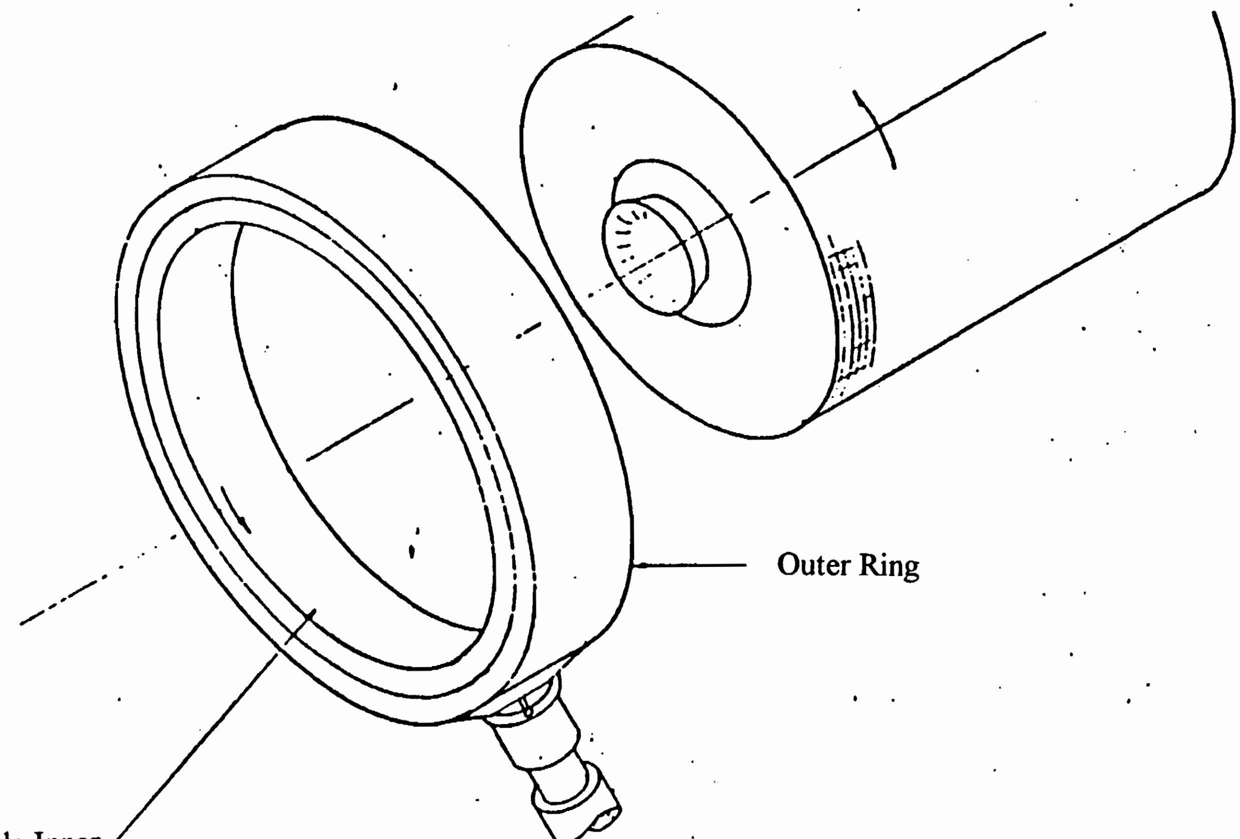


Figure 2-7. Satellite Capture Device (From reference 17)

the bladder in the internal section is inflated. As the bladder comes in contact with the rotating object the internal section begins to rotate with the object. Then various methods could be used to stop the objects rotation including brakes, viscous fluid or reversing nitrogen jets.

2.2 Industrial End Effectors

An end effector, developed by Kenneth Hall (1986), which is similar to the one studied in this thesis is shown in Figure 2-8. This is an end effector designed to assemble a circuit breaker which is shown in Figure 2-9. This end effector assembles three components of the circuit breaker while they are in its grasp. This method is chosen over the pick and place method in order to save travel time of the robot. This makes it possible to pick up the three parts from their respective locations serially then move to the assembly location. Otherwise, using the pick and place method, the gripper would move to the part location then to the assembly location after each part is picked up.

This end effector consists of two components which are joined to make an upside down U shape. The component on the left is used to assemble the coil, lever and handle and is shown in Figure 2-10. The component on the right is used to assemble the cover to the circuit breaker and is shown in detail in Figure 2-11. The assembly sequence for the coil, lever and handle is shown in Figure 2-12. The end effector moves into position over the coil, and the gripper grips the coil. Then the end effector moves into position near the lever and inserts the coil into the lever and the

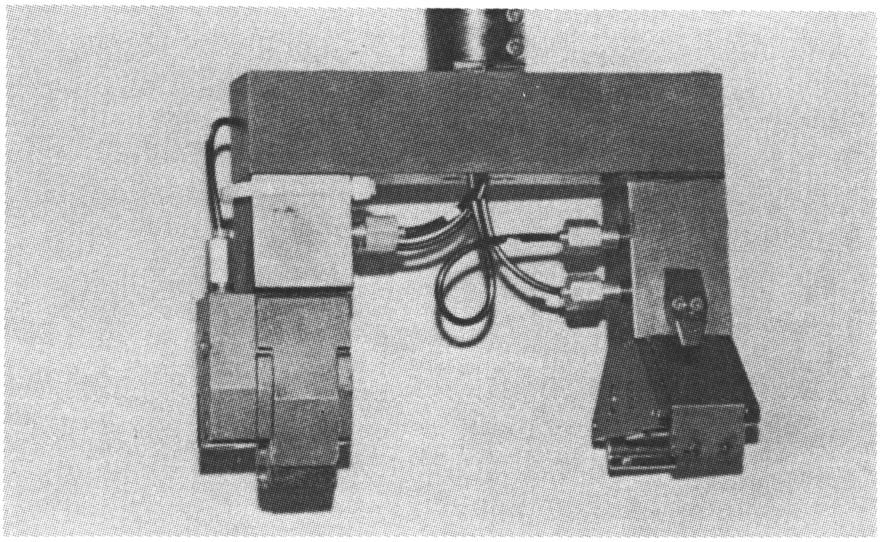
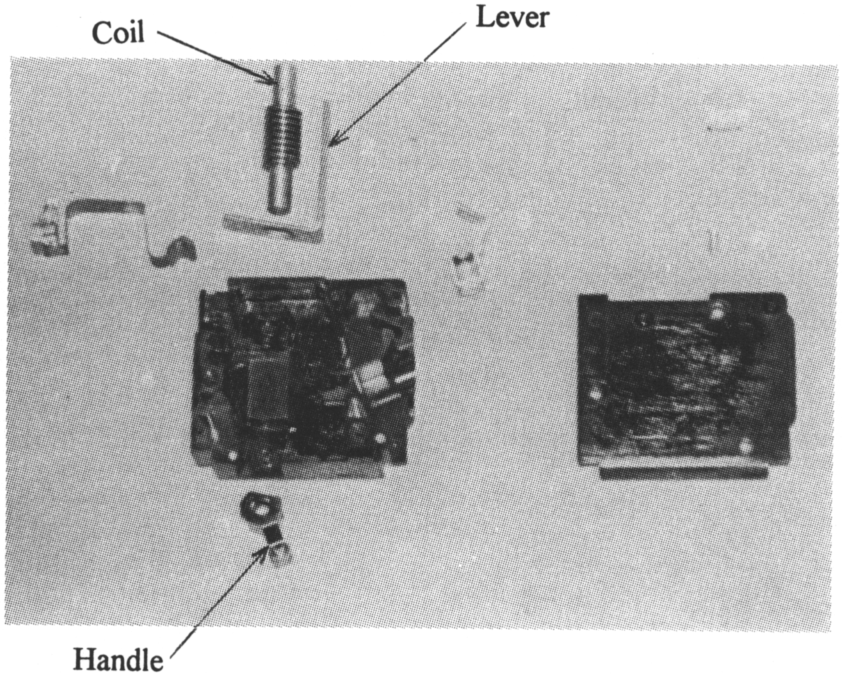
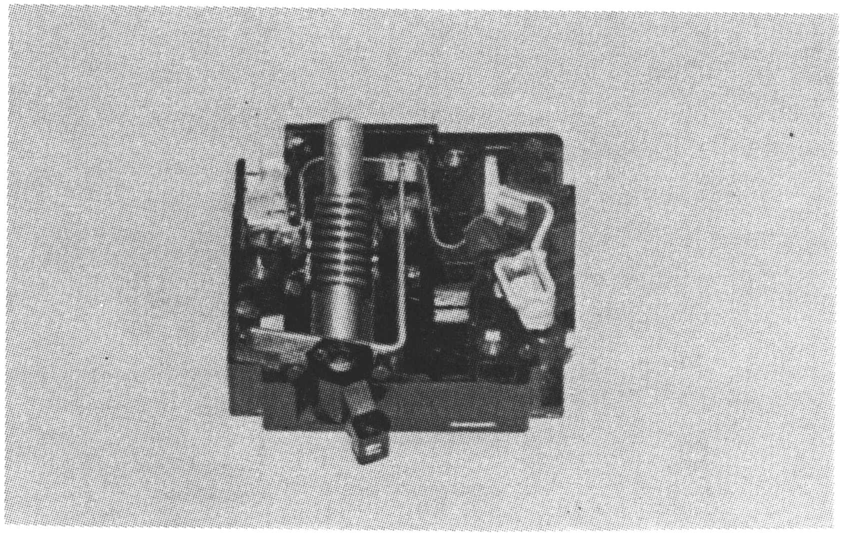


Figure 2-8. Circuit Breaker Assembly End Effector (From reference 11)



(a)



(b)

Figure 2-9. Circuit Breaker Assembly (From reference 11)

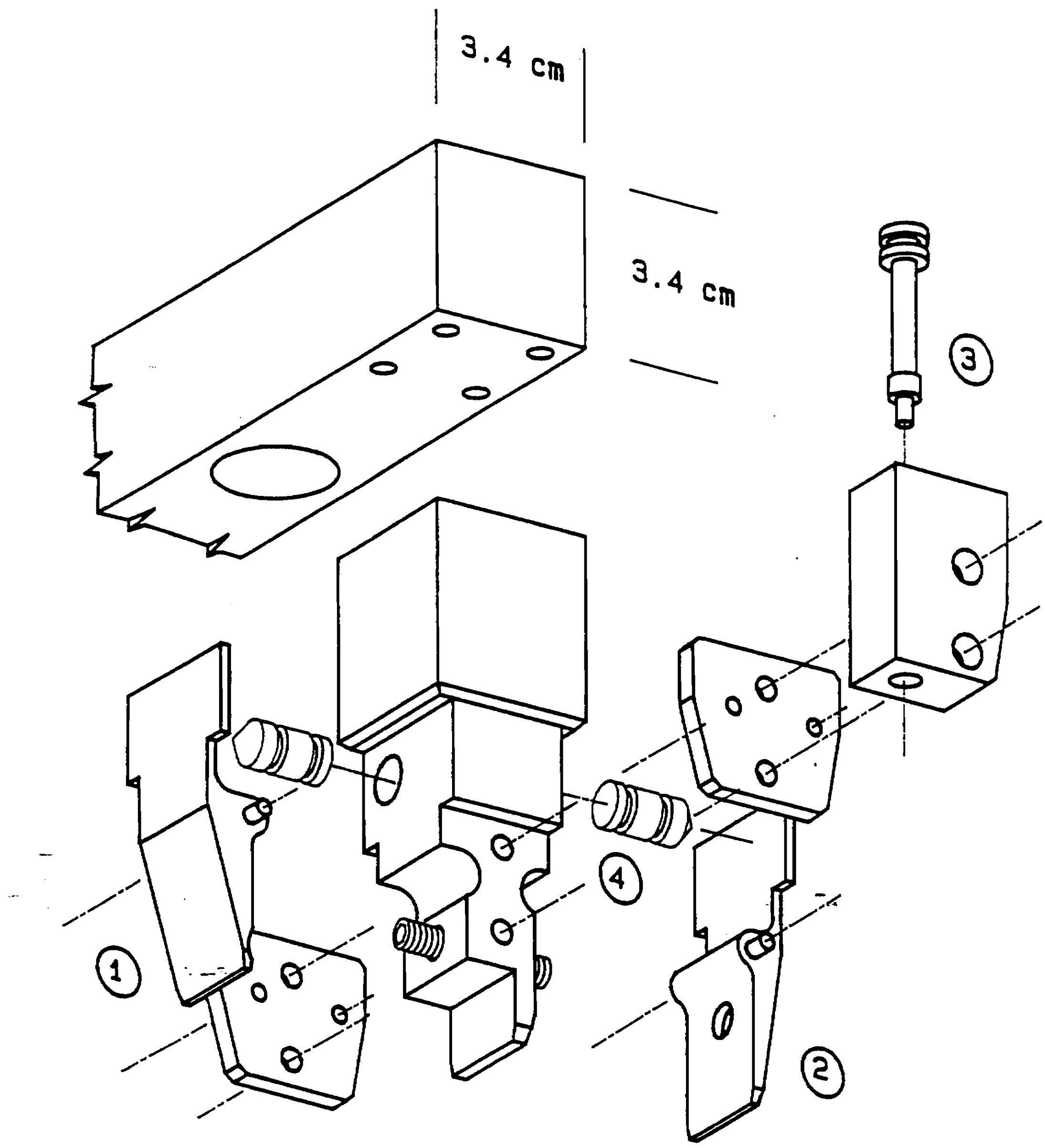


Figure 2-10. Coil, Lever and Handle Assembling Gripper (From reference 11)

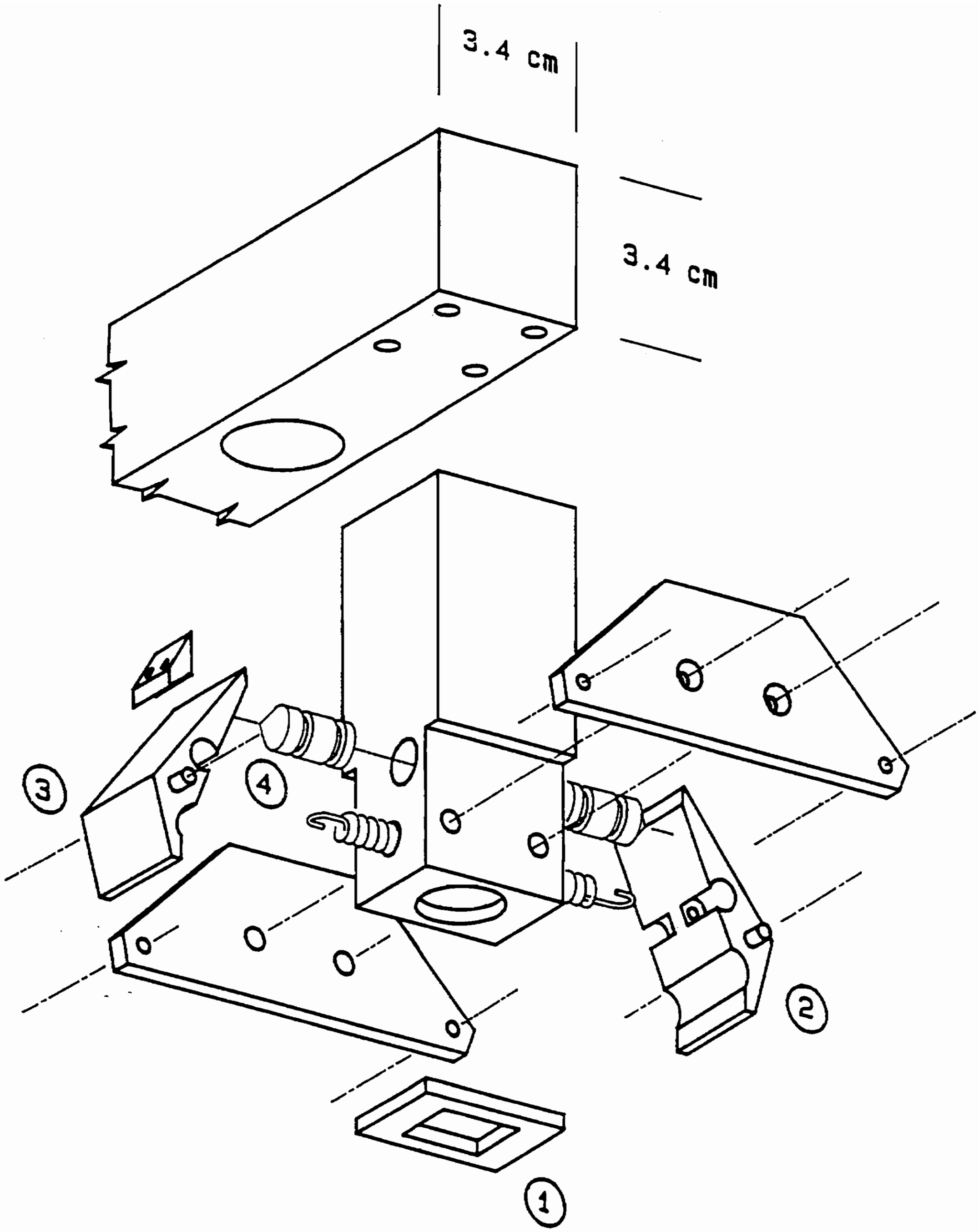


Figure 2-11. Cover Installation Gripper (From reference 11)

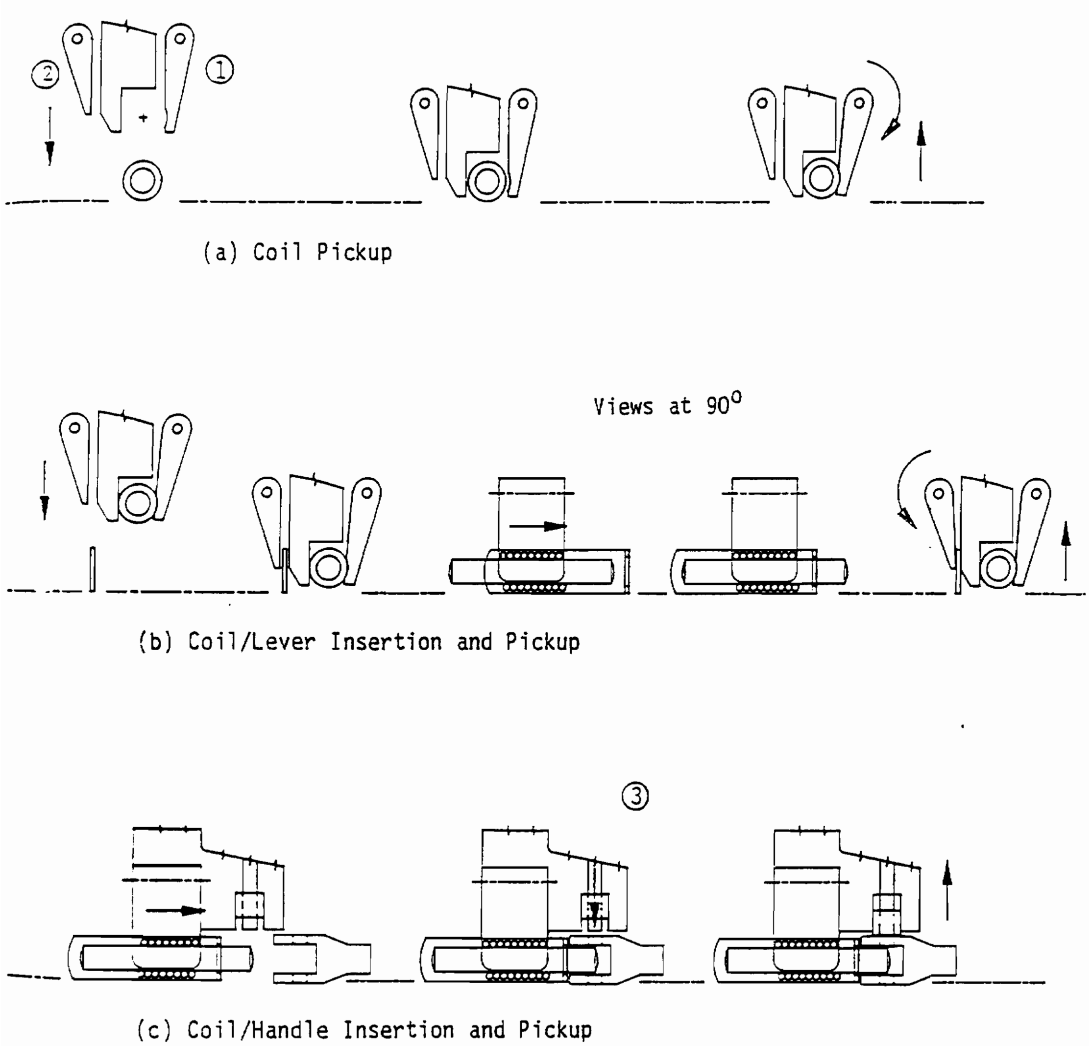


Figure 2-12. Assembly Sequence (From reference 11)

other gripper grips the lever. After the lever is installed, the end effector moves over to the handle and inserts the coil into the handle. At this point a pin in the end effector is inserted into the handle to secure it in place until it is installed into the body where a pin holds it in place on the other side of the handle.

After all the components have been installed in the circuit breaker, the cover is ready to be installed. The components other than the coil, lever and handle can simply be installed using pick and place operations. The cover is installed using the cover installation gripper, which consists of a vacuum pad and grippers and is shown in Figure 2-11. The cover is picked up using the vacuum pad and the grippers are used once the cover is placed over the body to align the cover to the body.

Figure 2-13 shows a flexible gripper (Wright and Cutkosky, 1985) for turbine blades. The upper two fingers on this end effector are connected to the closing mechanism and to each other by ball joints. This allows the top two fingers to conform to the shape of the object being grasped.

One gripper which is similar to the inflatable gripper for space use is shown in Figure 2-14 (Wright and Cutkosky, 1985). This gripper can be used to grasp internal features of objects. It is inserted into the feature and, as the gripper is lifted, fluid is forced from the central hydraulic cylinder into the cylindrical rubber membrane. The membrane expands and contacts the item to be lifted. When the object is set down, a spring in the hydraulic cylinder forces the cylinder down and the fluid leaves the membrane and goes into the cylinder.

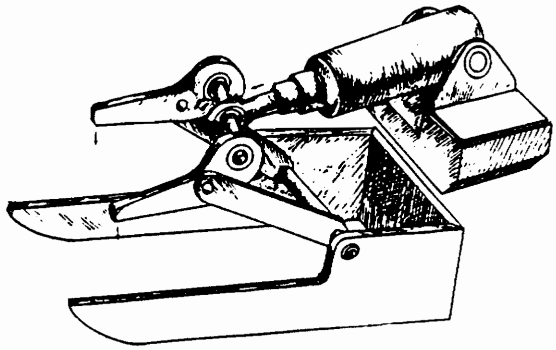


Figure 2-13. Flexible Gripper For Turbine Blades (From reference 32)

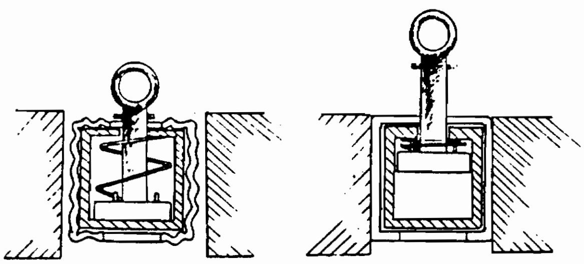


Figure 2-14. Self Expanding Internal Gripper (From reference 32)

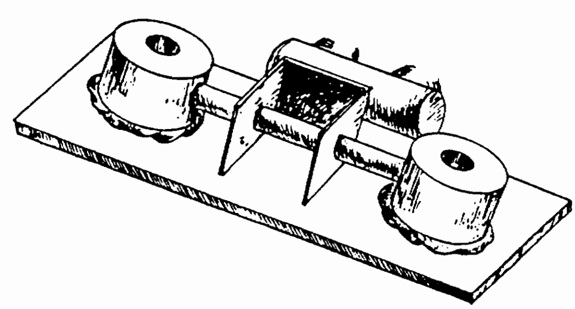


Figure 2-15. Magnetic Gripper (From reference 32)

Figure 2-15 (Wright and Cutkosky, 1985) shows an end effector which uses magnets to grasp objects. This particular end effector is very useful for picking up even irregularly shaped ferrous objects. This end effector has bags filled with iron particles, which take the shape of the object to be grasped. Once in place, the particles are electromagnetically excited.

Figure 2-16 (Wright and Cutkosky, 1985) is a good example of a versatile yet relatively simple gripper. The conformal gripper can grip a wide variety of shapes. The opening and closing of this end effector is achieved by pulling wires routed through the links of its chain-like fingers.

The end effector shown in Figure 2-17 (Tanie, 1985) has been used for robotic fingers for hand simulating end effectors. The schematic for this end effector is shown in Figure 2-17a. This is a four bar linkage which can wrap around an object. A finger using this mechanism is shown in Figure 2-17b to show how this mechanism can be used.

One end effector which is fairly versatile with only one drive motor is shown in Figure 2-18 (Tanie, 1985). This is a prosthetic hand for a handicapped person. This hand can grasp varying shapes because the gripping members are driven through flexible elements by one motor. The motor moves the cable attached at C to the right to grasp an object. The top two fingers are actuated by moving the top of lever 1 to the right, while the bottom two fingers are closed by moving the bottom of lever 1 to the right. As C is pulled, this rotates lever 2 about D, which in turn pulls on lever 3.

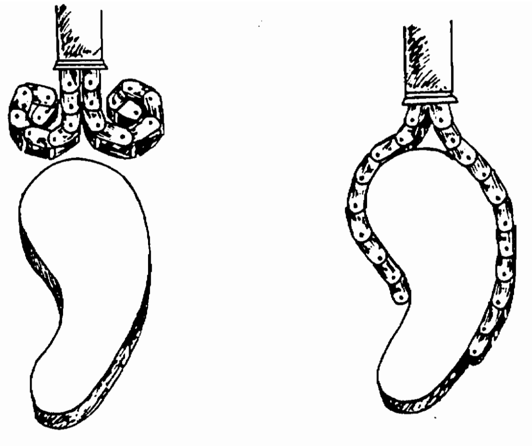


Figure 2-16. Conformal Gripper (From reference 32)

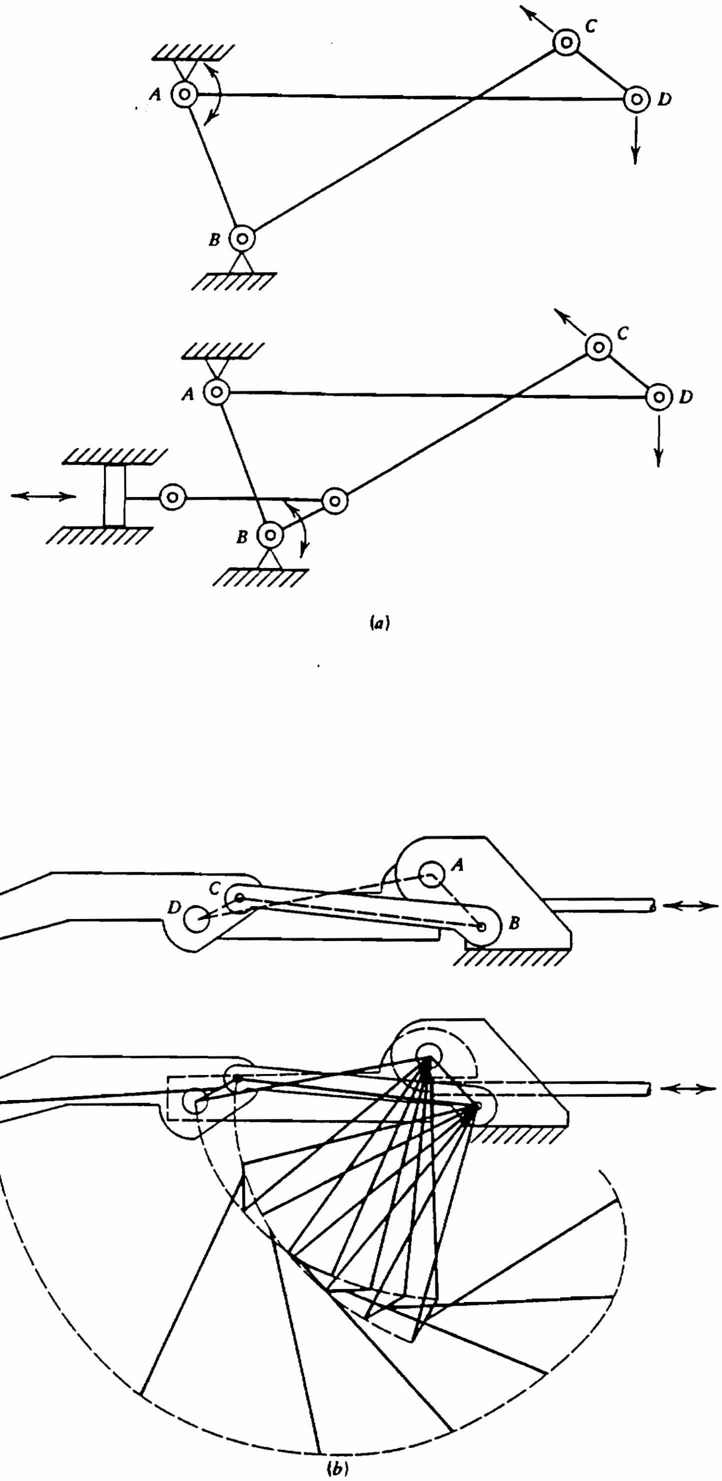


Figure 2-17. Finger Using Four Bar Linkage (From reference 28)

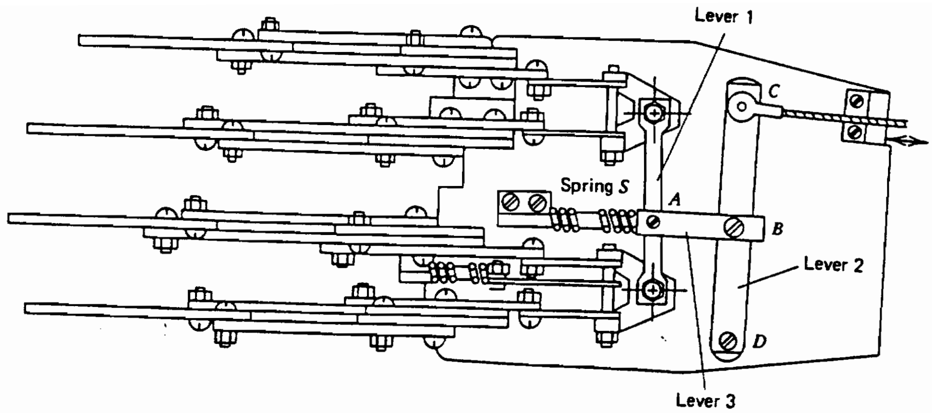


Figure 2-18. Prosthetic Hand (From reference 28)

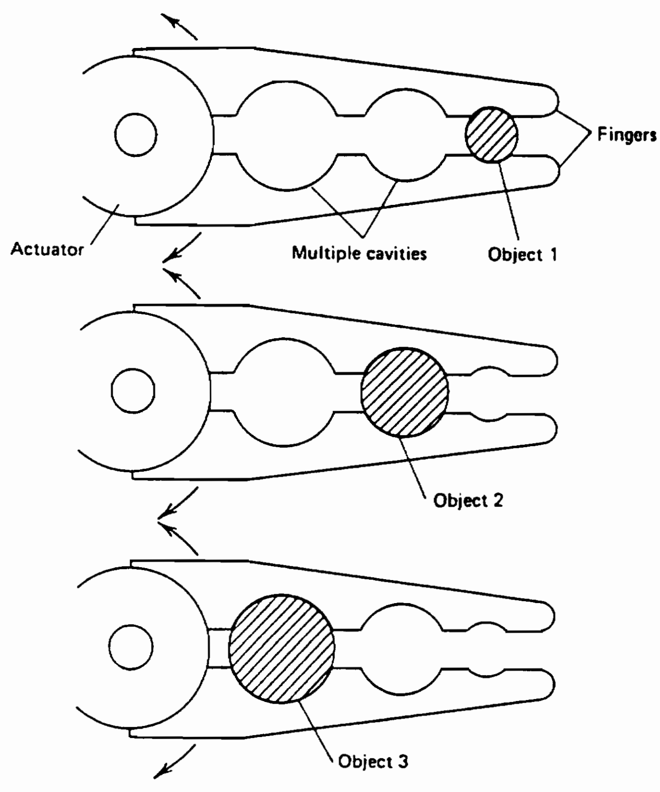


Figure 2-19. Finger with Multiple Shaped Cavities (From reference 28)

Lever 3 pulls on point A of lever 1, this pulls all fingers closed until one or two of the two sets of fingers comes in contact with an object. At this point for example if the bottom two fingers come in contact first, then these two fingers would stop motion and lever 1 would rotate about the attach point of lever 1 to the bottom two fingers. The top two fingers would continue to close until they come in contact with some object.

Another example of a versatile end effector is shown in Figure 2-19 (Tanie, 1985). This is a versatile end effector with a much simpler design. The jaws on this gripper have different shapes at different locations on the gripper. In this way, different objects can be gripped at different areas of the jaws.

2.3 Mechanisms

To help in generating design concepts and to learn what type mechanisms have been developed, many different types of mechanisms were reviewed. The focus of the review was, as stated earlier, on mechanisms which give intermittent output motion with a constant input.

Figure 2-20 shows a Programmed Rotary Intermittent Motion device (Chironis, 1991). Output motion is rotational along the same axis as the input. This mechanism consists of a cam, program gear, output gear, locking lever and idler gear. The cam and the program gear are pinned together and fixed to the input shaft. The gears on the program gear are lined up with the indents of the cam. The locking lever rides on the cam and locks the idler gear in place when a high spot on the cam is reached.

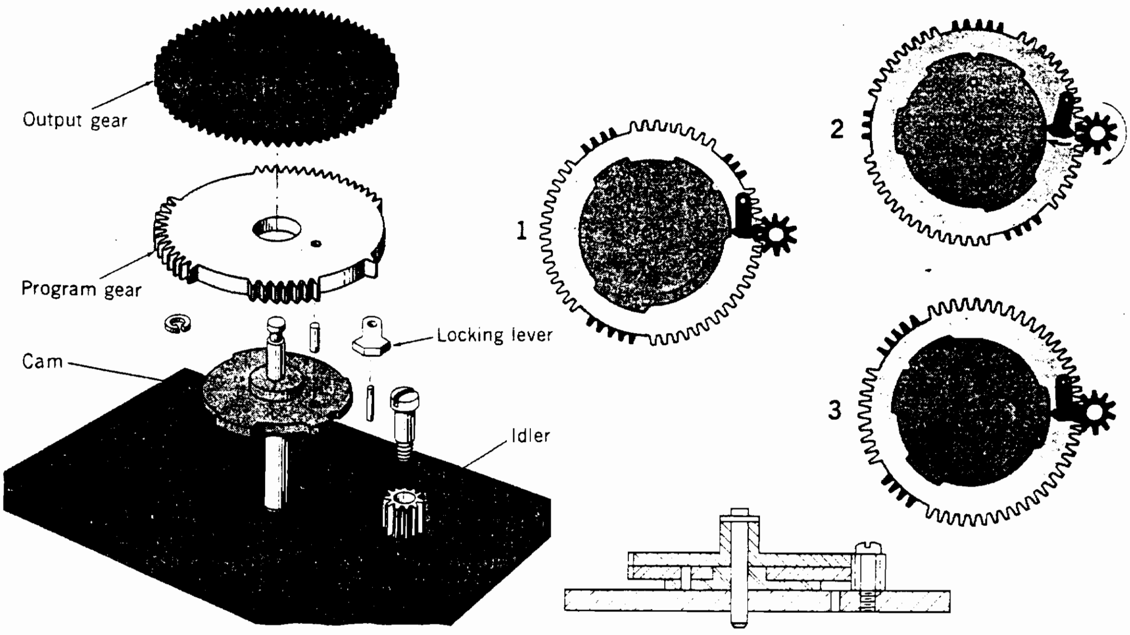


Figure 2-20. Intermittent Motion Mechanism (From reference 4)

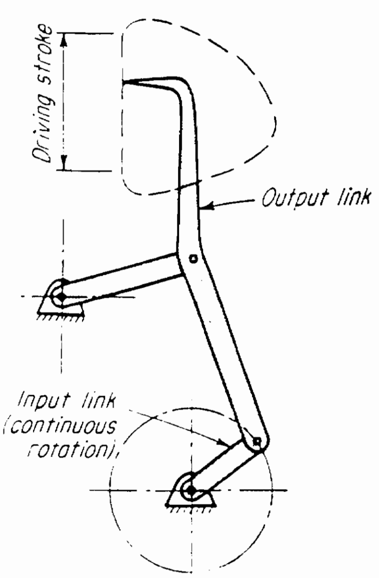


Figure 2-21. D-drive Mechanism

(From reference 4)

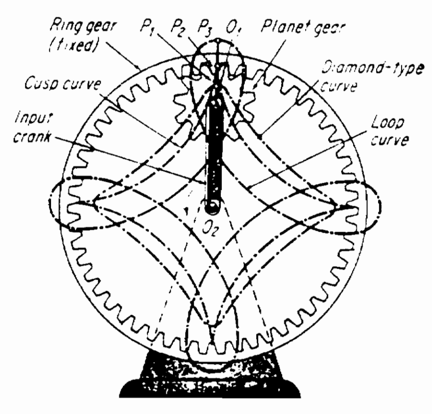


Figure 2-22. Hypocycloid Curves

(From reference 4)

The idler gear drives the output gear. The output motion is repeated with every rotation of the input shaft. The idler gear can be replaced with a gear train to allow the output to be a different ratio than the input gear, making the device much more versatile.

Mechanisms which produce curves with straight-line or approximate straight-line sections can be used to produce intermittent motion. One mechanism which can produce this motion is shown in Figure 2-21 (Chironis, 1991). This mechanism, a motion picture film advance mechanism, produces a D-shaped output path from a rotating input. The point on the mechanism which produces the D-shape could have a pin on it which rides in a grooved follower. The groove would be parallel to the back of the D-shape and the follower would be restricted to travel perpendicular to the back of the D. This would result in intermittent motion.

A pin moving in a square-shaped motion driving a grooved follower can produce intermittent output motion. The hypocycloid mechanism is one device which can produce such square-shaped output curves. This mechanism uses an internal ring gear and planet gear, which is mounted on a crank. The crank rotates and a driving pin is attached to a location on the planet gear. The output motion of the driving pin depends on where it is attached. Some possible motions are shown in Figure 2-22 (Chironis, 1991). The sizes of the gears and the drive pin location can be adjusted to produce variations in the output curve.

The Geneva mechanism can produce intermittent motion. This mechanism has an output which rotates through a predetermined angle (depending on the number of nodes) as the input turns at constant speed. With a simple Geneva wheel, as shown in Figure 2-23 (Chironis, 1991), the output rotates this predetermined amount and stops for each revolution of the input. This Geneva has a locking arm to hold the output in position while the input continues to rotate.

The Mast I Shuttle borne flight experiment invention (Chew, 1988) is shown in Figure 2-24. This mechanism is used to unlatch and latch three latches in a predetermined order. The original design used three separate motors and latches. This new design, developed by Dr. M. Chew (Chew, 1988), reduced the number of motors, cost, space used and increased the reliability. A shaft is driven upward to sequentially activate the beam tip canister assembly catch, tube latch and beam latch. As can be seen, one motor is now able to activate three latches.

Another mechanism is the trochoidal indexing drive (Weber, 1993). This mechanism operates by forming a trochoid with a planetary gear train. The Planet gear is attached to a crank which drives a slotted disk as shown in Figure 2-25. This crank goes in and out of the slot and rotates the slotted disk 180 degrees for every 360 degree rotation of the input crank.

2.4 Design Methods

In their paper "Design of Grippers", Wright and Cutkosky (1985) discuss prehension and grip, which is the process used to grasp objects. This involves choice of grip, gripping and controlling of the object. This process for humans involves

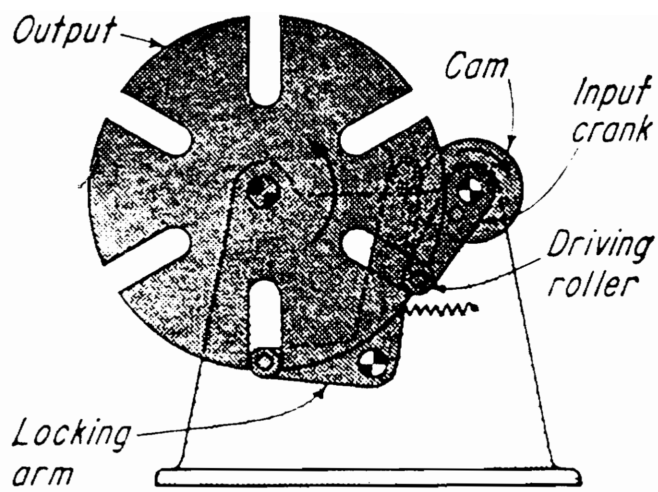


Figure 2-23. Locking Arm Geneva Mechanism (From reference 4)

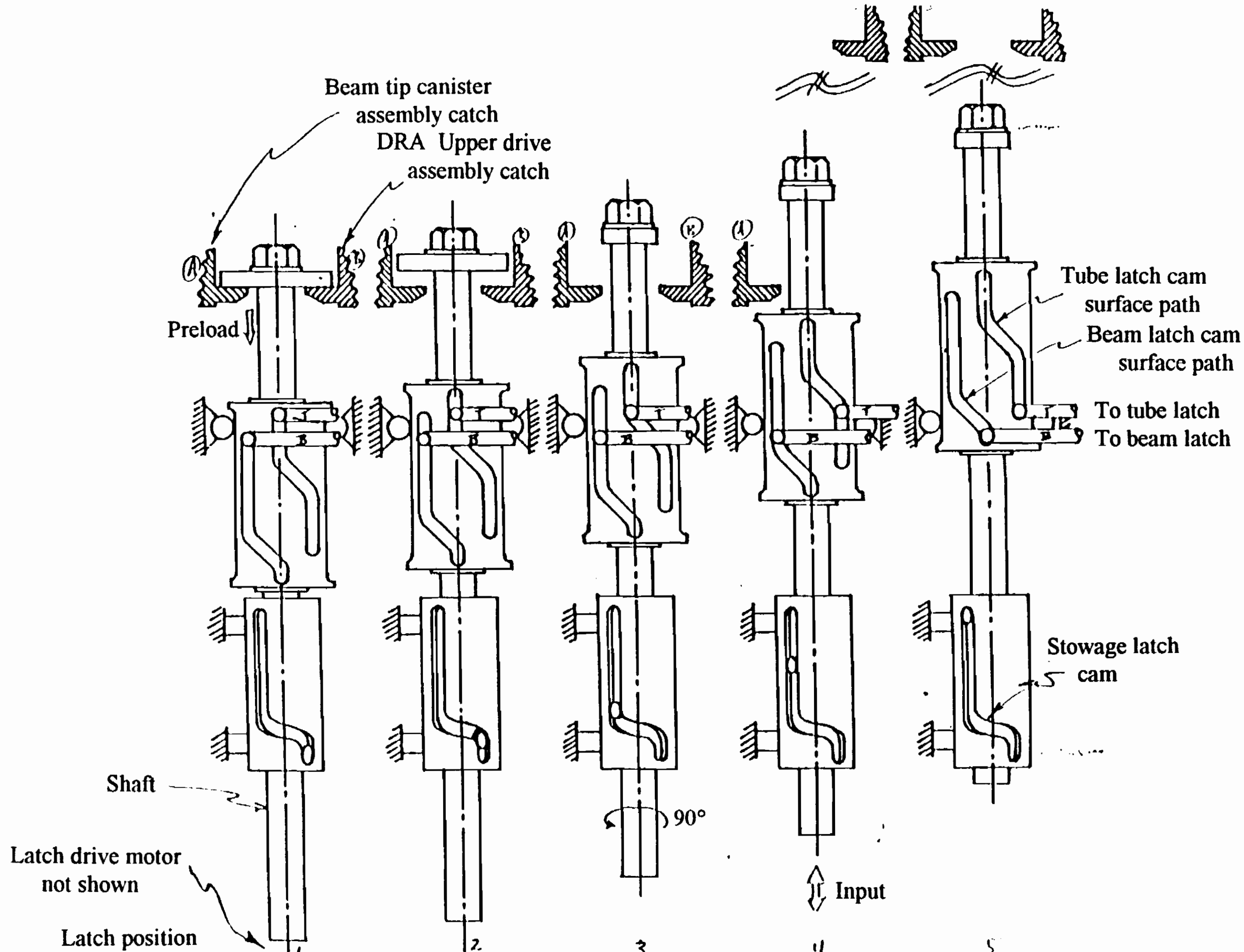


Figure 2-24. Mast I Shuttle Borne Flight Experiment Mechanism (From reference 3)

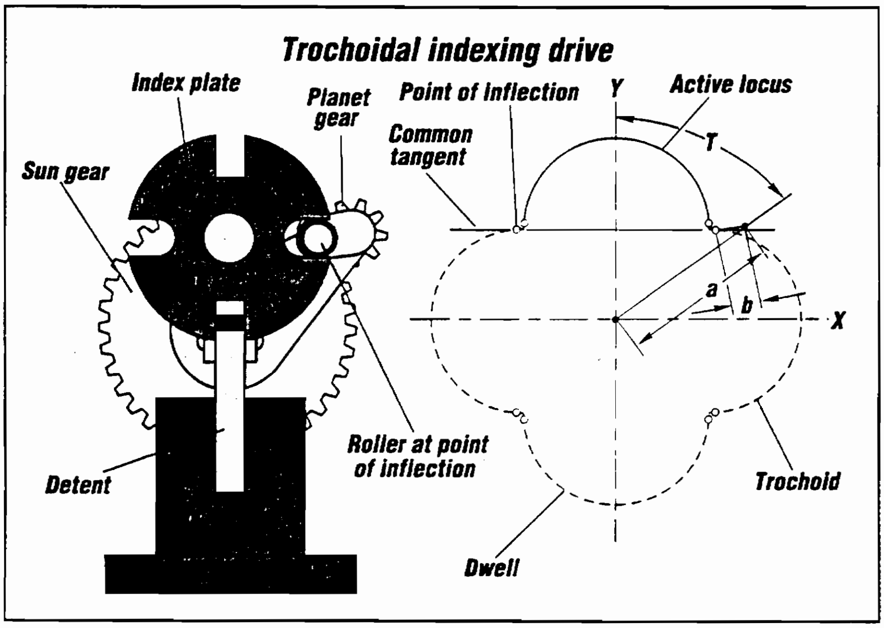


Figure 2-25. Trochoidal Indexing Drive (From reference 30)

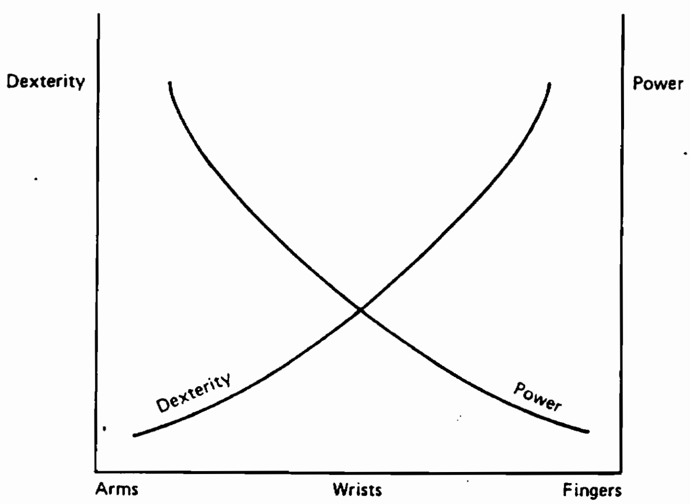


Figure 2-26. Trade-off Between Arm, Wrist and Finger Manipulation (From reference 32)

feedback from the eyes and feeling in the hands. The eyes are used to roughly position the hand and then the feeling in the fingers is used to feedback accurate locating and gripping force. Most grippers in industry are not closed loop because of the complexity involved with this type of control. Wright and Cutkosky's paper discusses two grips primarily used in industry. These are the three finger grip and the "wrap around" grip used to grab a screw driver or hammer.

Wright and Cutkosky discuss the fact that it is not always better to have a very versatile end effector. The graph, reproduced in Figure 2-26 (Wright and Cutkosky, 1985), shows how adding dexterity to the wrist and fingers decreases the power. Added dexterity allows the end effector to possibly be used for more than just one job. This versatility adds cost and usually reduces the strength of the gripper. Wright and Cutkosky suggest designing the end effector to perform the task at hand.

Wright and Cutkosky (1985) give an example which shows how versatile an end effector should be and this example is shown in Figure 2-27. If the part to be captured is not accurately shaped, as in the lower figure, it may be necessary to add a pivot on the lower or upper finger of the gripper to allow contact at all four points. This may not be necessary if the part is very light or the weight distribution does not change.

Wright and Cutkosky (1985) also touch on compliance of grippers. Compliant grippers protect against overloading or flex when interfering with surrounding objects. Compliant grippers can ease the severity of damage when programming errors or

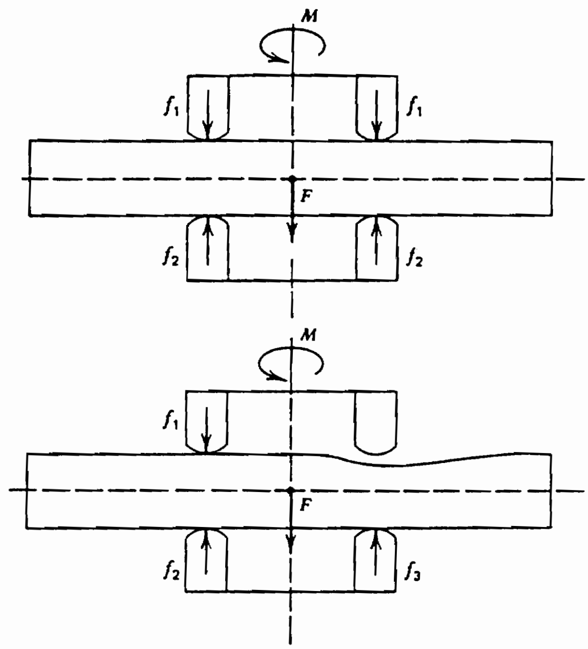


Figure 2-27. Holding a Bar with Three and Four Points of Contact (From reference 32)

robot malfunctions occur. They talk about commercially available compliant wrist units. These can be mounted between the gripper and the robot arm.

Wright and Cutkosky (1985) discuss the following six guides for developing grippers with passive fingers.

"Guide 1: Study the parts to be grasped and the task to be performed."
The parts which the gripper is to grasp must be reviewed carefully and all the tasks which must be performed must be very well understood.

"Guide 2: Determine additional requirements, not directly related to the act of acquiring and gripping the part."
These additional requirements might be environmental conditions or the need for the gripper to disengage from the arm in the event of a crash.

"Guide 3: Determine specific solutions to the requirements in Guides 1 and 2."
At this point, no single combination of sensors, actuators or mechanisms should be considered. Develop many ideas for each task or design requirement.

"Guide 4: Begin to develop designs combining the foregoing modular solutions."
Combine the solutions from Guide 3 to develop the optimum design.

"Guide 5: Consider designs with two or three grippers mounted together at the end of the arm."
This could make it possible to develop a few simple end effectors rather than one complicated one.

"Guide 6: Redesign the part and/or task."
It is very important to consider a change in part and/or task which could simplify the end effector. Design the gripper and part and/or task integrally as one unit.

In his paper, End-of-Arm Tooling, Ronald D. Potter (1985) defines end of arm tooling as the subsystem of an industrial robot system that links the mechanical portion of the robot to the part being handled. The author states that end of arm tooling is made up of an adapter plate, power, mechanisms and sensors.

Ronald D. Potter discusses some general design criteria for end-of-arm tooling. The end-of-arm tooling must be as light weight as possible. Light end-of-arm tooling can allow quicker starts and stops, thereby reducing the assembly time. The author also states that end-of-arm tooling should be as small as possible to ease maneuverability around confined areas. Reducing the size also keeps the work piece closer to the mounting plate, which reduces the moment of inertia about the mounting plate. It is important to handle the widest range of parts. The tooling can be made to grasp several objects, thereby reducing tooling changes and saving assembly time. The tooling must also be rigid, so that position accuracy can be maintained and vibrations are not put into the tooling. Maximum applied holding forces must be designed into the tooling to grip the work piece tight enough to counteract acceleration motions of the end-of-arm tooling and weight of the work piece. The end-of-arm tooling should be designed with maintenance in mind. Wear areas should be easily accessible and same size and type fasteners should be used to reduce maintenance tools.

Some design tips for end of arm tooling (EOAT) discussed by Potter (1985) are listed below:.

1. Design for quick removal or interchange of tooling by requiring a small number of tools to be used. Use the same fasteners wherever possible.
2. Provide locating dowels, key slots, or scribe lines for quick interchange, accuracy registration, and alignment.

3. Break all sharp corners to protect hoses and lines from rubbing and cutting and maintenance personnel from possible injury.
4. Allow for full flexure of lines and hoses to extremes of axes of motion.
5. Use lightweight materials wherever possible or put lightening holes where appropriate to reduce weight.
6. Hardcoat lightweight material for wear considerations and put hardened, threaded inserts in soft materials.
7. Conceptualize and evaluate several alternatives in EOAT.
8. Do not be "penny wise and pound foolish" in EOAT: make sure enough effort and cost is spent to produce production-worthy, reliable EOAT and not a prototype.
9. Design in extra motions in the EOAT to assist the robot in its task.
10. Design in sensors to detect part presence during transfer(limit switch, proximity, air jet, etc.)
11. For safety in part-handling applications, consider what effect a loss of power to EOAT will have. Use toggle lock gripper or detented valve to promote safety.
12. Put shear pins or areas in EOAT to protect more expensive components and reduce downtime.
13. When handling tools with robot, build in tool inspection capabilities, either in EOAT or peripheral equipment.
14. Design multiple functions into EOAT.
15. Provide accessibility for maintenance in EOAT design, and quick change of wear parts.
16. Use sealed bearings for EOAT.
17. Provide interchangeable inserts or finger for part changeover.
18. When handling hot parts, provide heat sink or shield to protect EOAT and robot.
19. Mount actuator and valves for EOAT on robot forearm.
20. Build in compliance in EOAT or fixture where required.
21. Design action sensors in EOAT to detect open/close or other motion conditions.
22. Analyze inertia requirements, center of gravity of payload, centrifugal force, and other dynamic considerations in designing EOAT.
23. Look at motion requirements for gripper in picking up parts (single-action hand must be able to move part during pickup: double-action hand centers part in one direction: three or four fingers center part in more than one direction).
24. When using electromagnetic pickup hand, consider residual

magnetism on part and possible chip pickup.
25. When using vacuum cup pickup on oily parts, a positive blow-off must also be used.
26. Look at insertion forces of robot in using EOAT in assembly tasks.
27. Maintain orientation of part in EOAT by force and coefficient of friction or locating features.

2.5 Manual Assembly of Space Structures

Research has been performed at the National Aeronautics and Space Administration's Langley Research Center (NASA LaRC) on manual assembly of space structures using specially designed joints for use by man. A photo of this type of joint is shown in Figure 2-28. This joint is unlocked by pulling the operating collar away from the node and rotating it 90 degrees counter clockwise. It is locked by rotating the operating collar 90 degrees clockwise. There is also an intermediate position, which is achieved by rotating the operating collar clockwise 45 degrees. In this position the joint can be pressed firmly into the joint receptacle and the joint holds itself in position. Then the operating collar can be rotated another 45 degrees to lock the joint in position. This intermediate position was found to be useful for manual assembly, because the struts could be placed in position with one hand and then the operating collar could be rotated to lock the joint (Heard et al., 1992). This extends the reach envelope of the astronaut, which is essential for in-space assembly. In-space assembly needs to be made as easy as possible because the space suit limits the mobility of the astronaut and a lot of the astronaut's strength is used just to manipulate the suit. The space suits are bulky and moving in them requires much

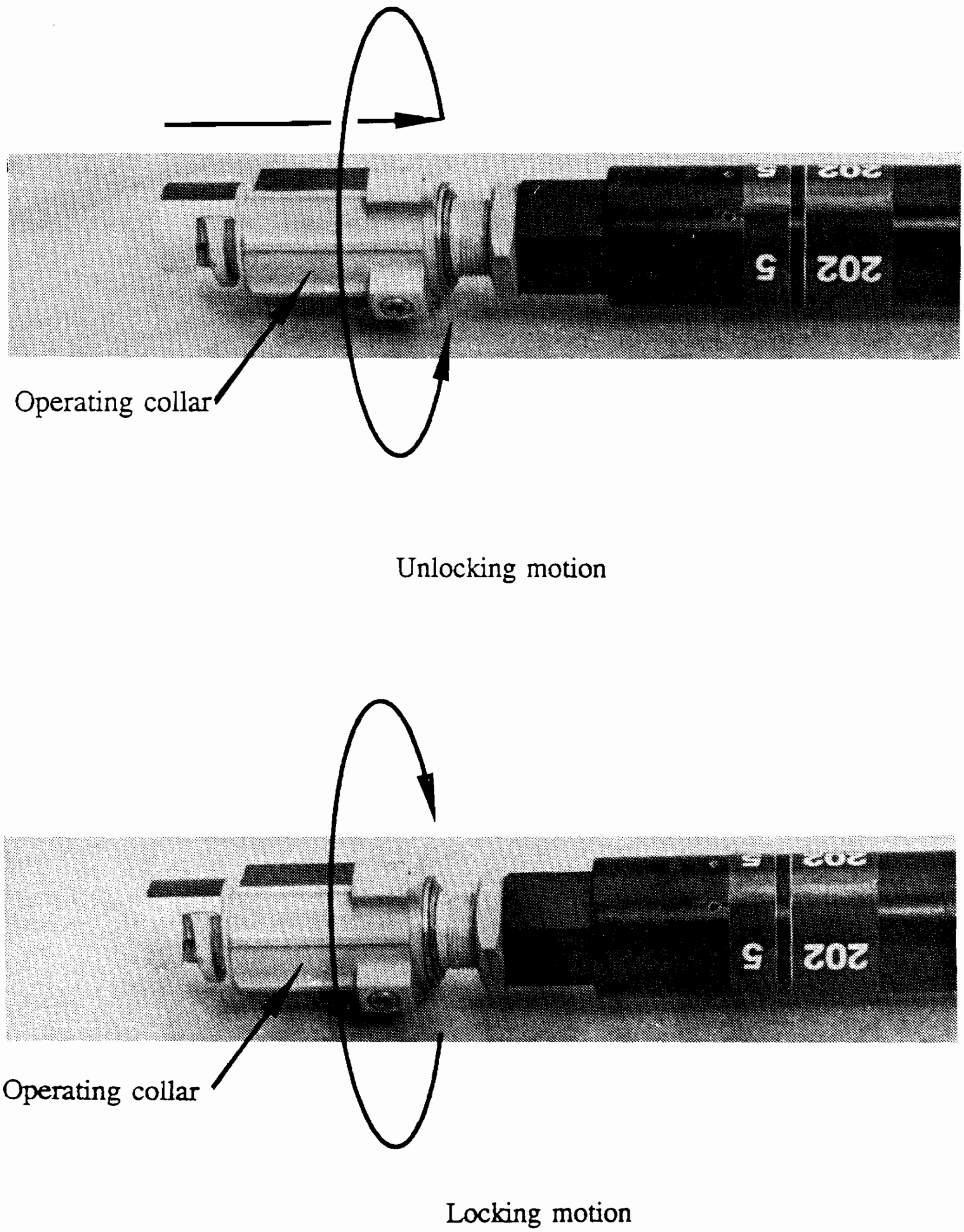


Figure 2-28. End Joint Designed for Manual Assembly

greater effort than moving in ground conditions.

Two neutral buoyancy tests have been performed in the investigation of manual assembly of space structures. A neutral buoyancy test is conducted underwater, with the astronauts dressed in space suits, to simulate operations in space. The first test (Heard et al., 1992) involved assembly of a small section of an antenna structure. For this first test, a flat structure with equal length struts was used. This assembled structure is shown in Figure 2-29. This structure includes three panels which represent the reflector panels in an antenna. Since this was a flat structure, it could not really be used as an antenna, but this test does give insight into the feasibility of building these type structures in space.

Another neutral buoyancy test (Heard and Lake, 1993) was performed which included the assembly of an entire curved antenna structure such as the one shown in Figure 2-30. This required the assembly of various sized struts which had to be assembled in specific locations. Also the nodes and reflector panels have specific locations. This structure was fourteen meters across. For the real antenna, thirty-seven reflectors would be installed, but for this test only seven were installed.

Both of these neutral buoyancy tests required extensive planning and supplemental hardware to allow the astronauts to assemble these structures. The struts and nodes were stored separately for these tests and they were assembled as needed. During this testing, the strut to node capture feature was found to be very helpful in assembling these structures. One problem found during this testing is that certain joints at nodes

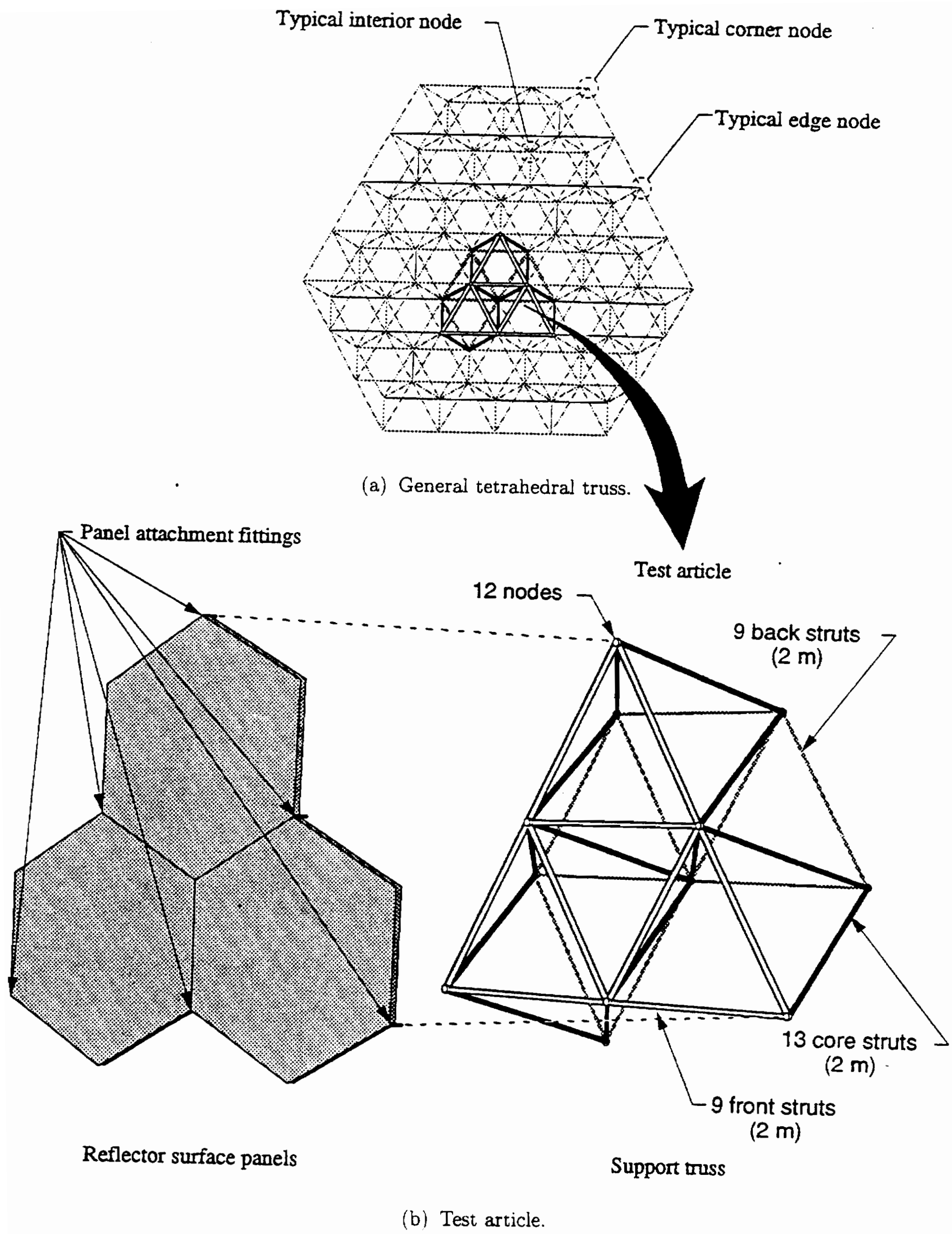


Figure 2-29. Truss and Panel Configurations Used for Manual Assembly Tests (From reference 12)

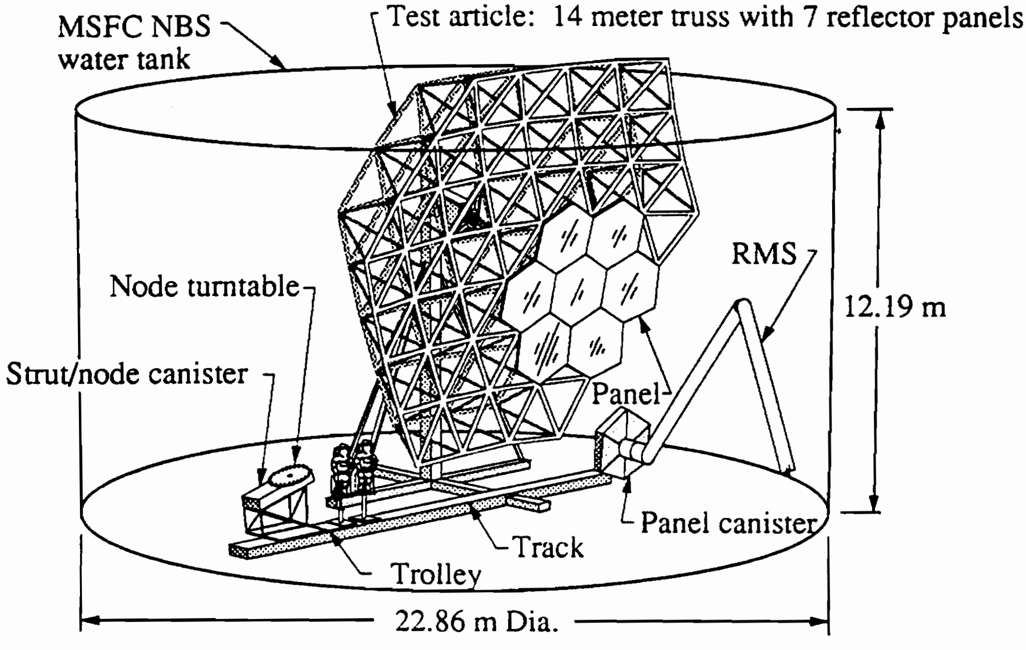


Figure 2-30. Sketch of the test article attached to the Assembly Fixture Installed in the Neutral Buoyancy Simulator Water Tank (From reference 13)

with many other joints attached were difficult to lock. In some cases the astronaut was only able to grasp the operating collar with one or two fingers (Heard and Lake, 1993). One solution to allow the astronaut to grasp the operating collar might be to extend the length of the operating collar to get the operating collar out away from the node. Another problem found in the hardware was that the joints were sometimes inadvertently knocked out of the capture position (Heard and Lake, 1993). One solution to prevent the operating collar from being knocked out of the capture position might be to make a more positive detent in this position. The above discussion has only dealt with problems associated with the structure and has not gotten into details and the fixtures used during this assembly. For further information on manual assembly testing, refer to references 12 and 13.

2.6 Automated Assembly of Space Structures

The most useful information for this thesis was that obtained from research on automated assembly of similar space structures. Without this previous research, the feasibility of this new design and design methodology would not have been able to be evaluated. NASA Langley Research Center has developed and tested two types of end effectors for automated assembly of space structures. These end effectors were developed along with the special joints used to attach the struts of the space structure. The first end effector was a double-ended end effector and performed operations on both ends of the strut at the same time in order to assemble the strut to the structure. The second end effector is a single-ended end effector, which grasps one end of the strut, performs operations to assemble that end, then releases that end and moves to the opposite end, if necessary, to attach the opposite end.

Research at NASA Langley Research Center with automated assembly of space structures (Will et al., no date) involves the assembly of a tetrahedral truss, which is shown in Figure 2-31. This is a flat structure, similar to the structure used for the first neutral buoyancy test. The truss structure is mounted on a rotating base. The robot arm, which is a six degree of freedom industrial robot, is used to position the end effector for pick up and storage of the struts in the pallets and installation and removal of the struts to/from the truss assembly. The robot is mounted on a moving base which moves in the X and Y direction shown in Figure 2-31a. As the truss is assembled it is rotated and new struts are installed.

The joint used for automated assembly is shown in Figure 2-32. Figure 2-32 also shows the receptacles with a node attached. This joint was designed to be easily assembled by robots. Once this joint is pushed into the receptacle, a nut on the joint is turned to tighten the joint. This joint also has indicator pins to verify that it is locked. These pins are retracted into the joint when the joint is locked. These pins were used so that the joint could be verified to be locked by using a remote camera.

For this assembly operation, the struts were initially assembled to the nodes. The struts with nodes attached were then installed into the storage trays for the robot to assemble the struts. Before this assembly could be done, a sequence of assembly was developed. In this sequence of assembly, struts with either one node attached or

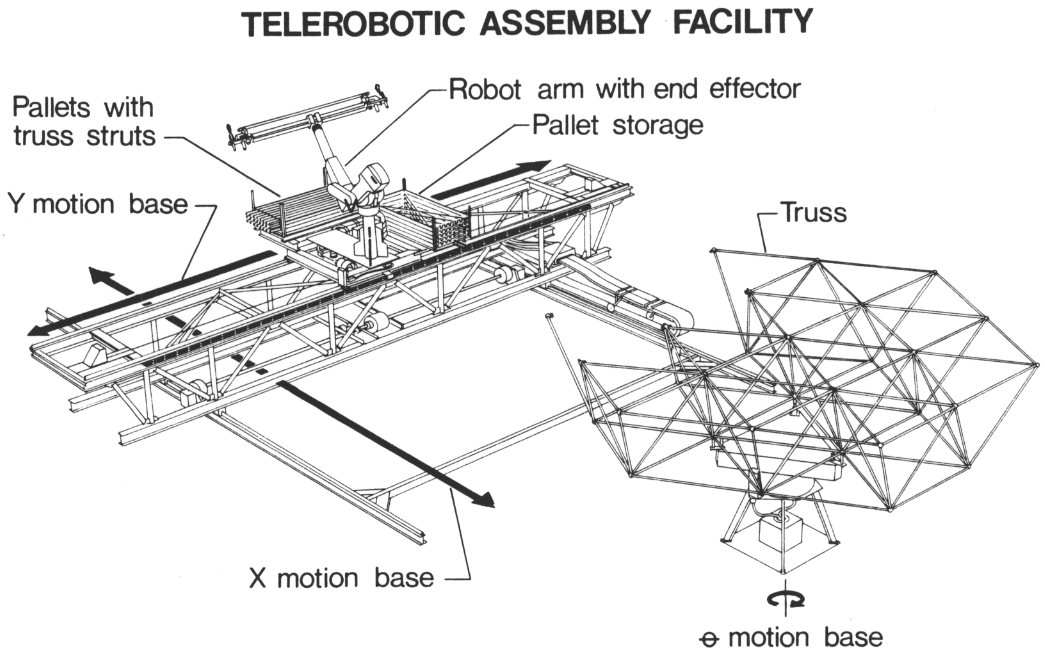


Figure 2-31a. Schematic of Automated Structures Assembly Laboratory

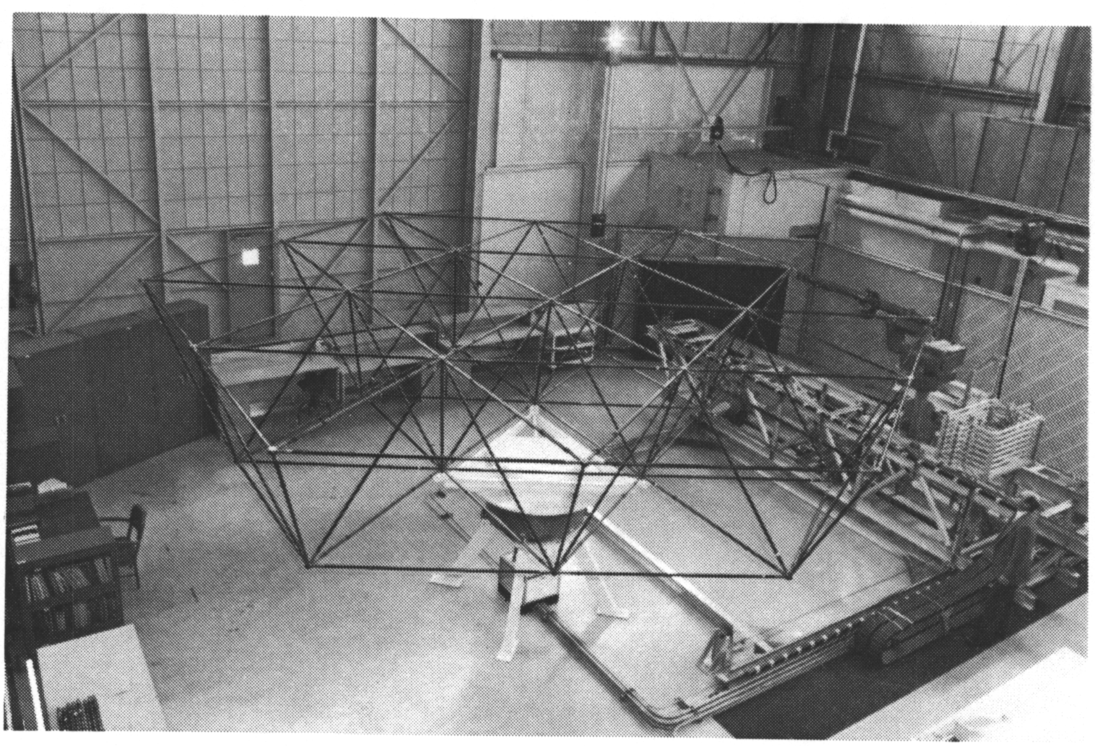


Figure 2-31b. Photograph of Automated Structures Assembly Laboratory

Figure 2-31. Automated Assembly Facility (From reference 31)

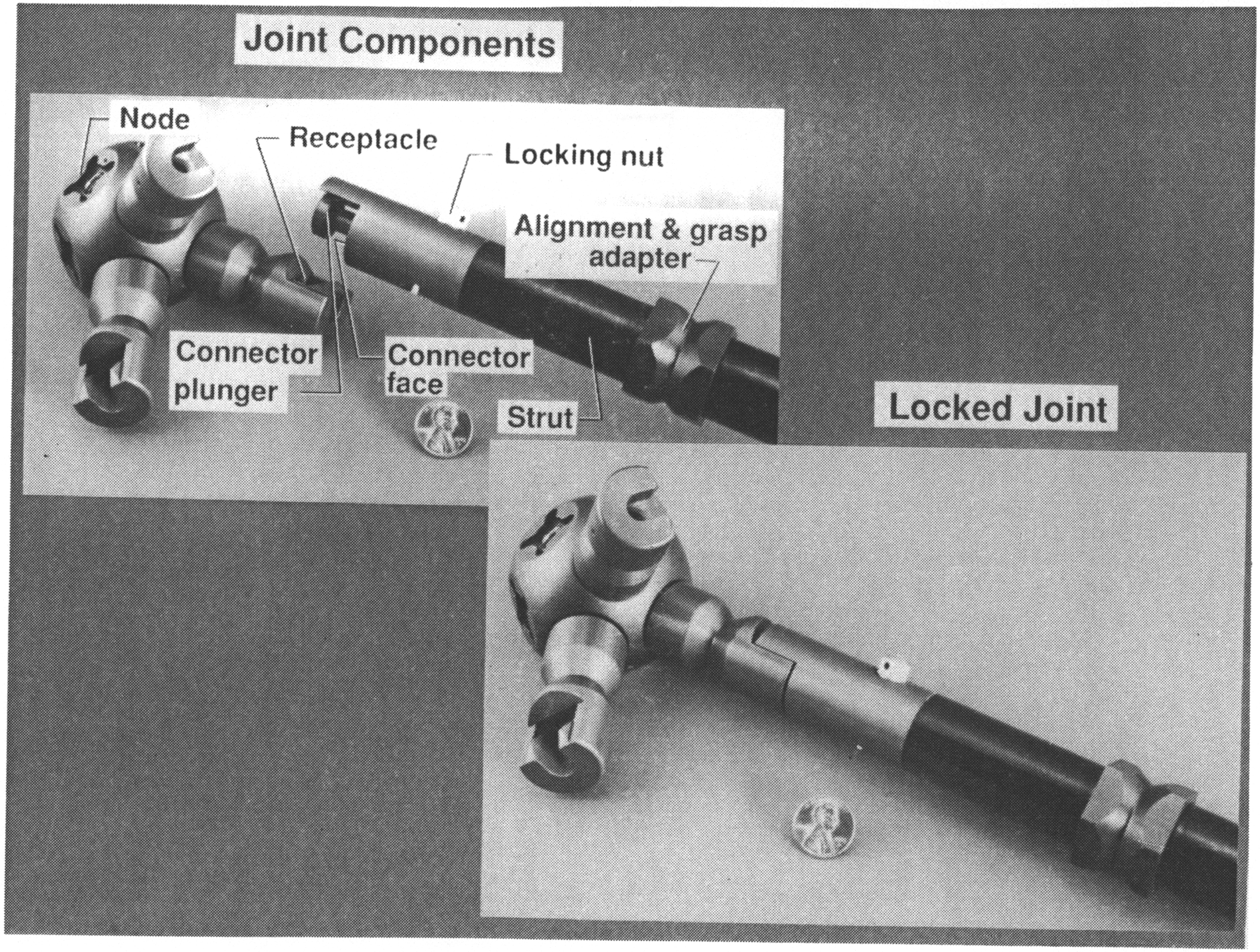


Figure 2-32. Strut/Node Joint Connection Hardware (From reference 31)

struts with no nodes attached must be stacked in a certain order for access when needed. A strut, with a node attached, is assembled to the structure with the noded end suspended, while struts with no nodes attached are assembled with both ends attached to the structure. In subsequent operations another strut would be attached to the node which was suspended.

The first end effector developed by NASA Langley Research Center (Will et al., no date) for automated assembly of space structures is shown in Figure 2-33. The platform slides up and down for strut installation and removal. The platform is powered by a pneumatic cylinder. The nut driver and strut holder are mounted to the platform. The nut driver is attached to an electric motor which locks and unlocks the joint. The strut holder is used to grip the strut, and it is actuated by an electric motor. The receptacle fingers are used to grab the joint receptacle and position the end effector for strut installation. At the base of the end effector is a torque force sensor. This sensor allows the robot arm to adjust the position of the end effector as the receptacle fingers or strut holder close or any other time adjustment is needed. After discussions with Marvin Rhodes (no date), the sequence of assembly for this end effector was determined to be as follows:

For installation of the strut the following steps are performed:

1. Prior to moving into the storage tray location, the receptacle fingers are either open or closed. One side may be open and the other side may need to be closed. The receptacle fingers are closed if they will interfere with an adjacent strut with a node attached. The receptacle fingers will be open on an end if the end has a node on it, so that after the strut is grabbed and

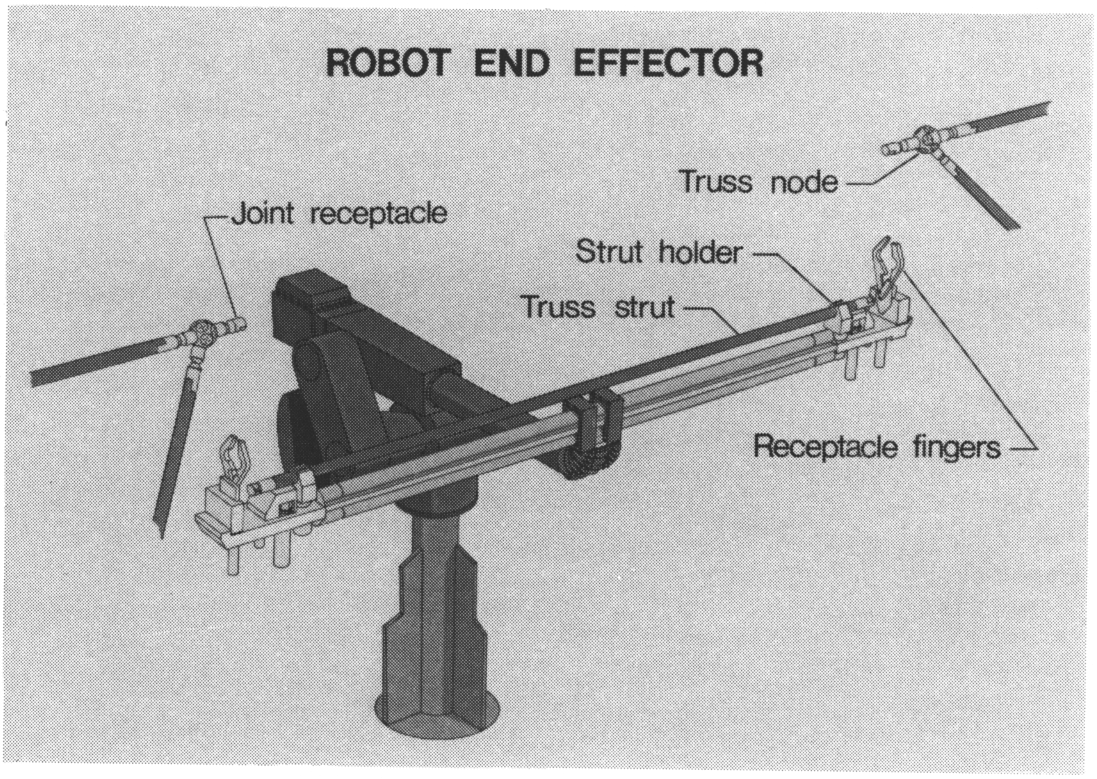


Figure 2-33a. Schematic of End Effector and Strut Insertion Concept.

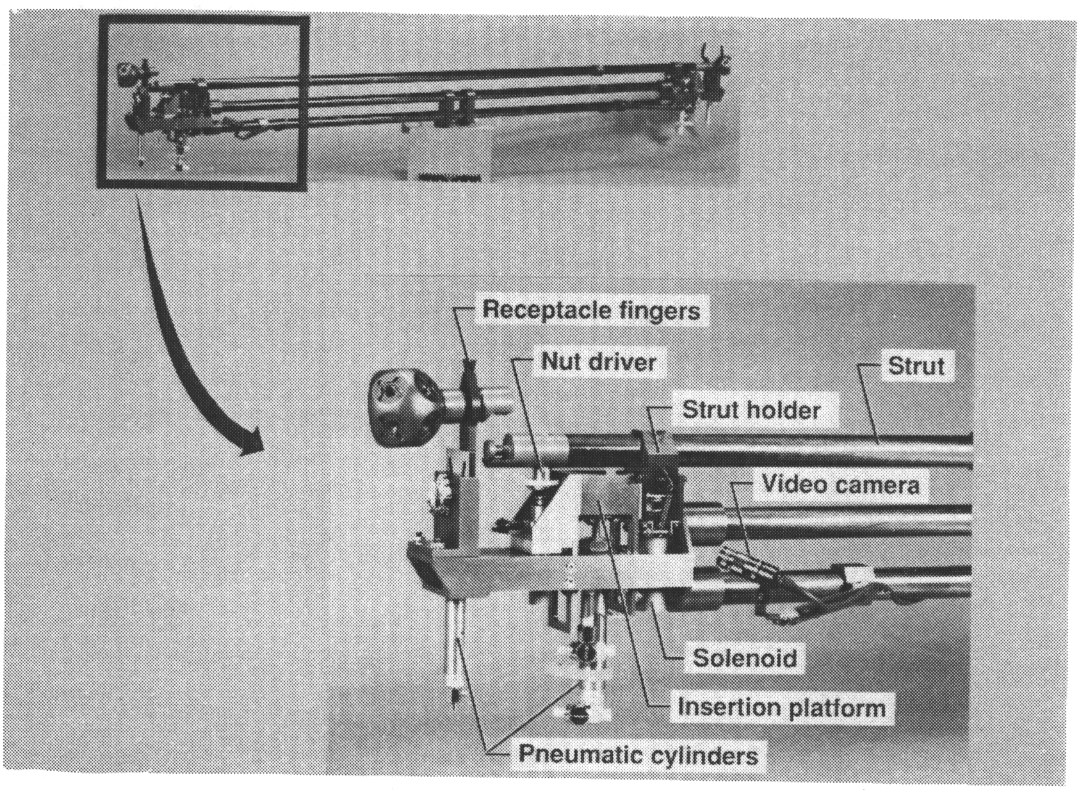


Figure 2-33b. Photograph of End Effector and Actuator Mechanisms.

Figure 2-33. First Generation End Effector (From reference 31) pulled away from the tray the receptacle will not interfere with the receptacle fingers.

2. The end effector is placed in position over the strut in the storage tray by the robot.

3. The platform is then moved out toward the strut.

4. The strut holder is closed onto the strut.

5. The platform is moved back, pulling the strut out of the storage tray.

6. Both receptacle fingers will then open.

7. The end effector is placed in position near the structure.

8. The receptacle fingers are closed on the end or ends with no joint attached and the torque force sensor is used to make adjustments to properly position the end effector.

9. The platform is pushed out toward the structure inserting one or two joints into the joint receptacles

10. The nut driver turns the nut on the one or two joints just installed if the joint is not already locked.

11. The strut holder releases the strut.

12. The platform slides back in.

13. The receptacle fingers release the receptacles.

14. The end effector is moved away.

For removal of the strut the following steps are performed:

1. The end effector is placed in position for strut removal.

2. The receptacle fingers close on the receptacle(s) attached to the strut to be removed. As the receptacle(s) close the torque force sensor is used to adjust the position of the end effector.

3. The platform moves forward toward the strut.

4. The Strut holders close onto the strut.

5. The nut driver turns the nut(s) on the joints to be removed from the receptacle

6. If a node is to remain attached to the strut, then the receptacle fingers at this joint will now open.

7. The Platform moves in, pulling the strut away from the structure.

8. If one of receptacle fingers interferes with an adjacent strut with an attached node, then this receptacle finger will be closed.

9. The end effector with the strut attached is now moved over the storage tray.

10. The platform moves out pushing the strut into the storage tray.

11. The strut holder releases the strut.

12. The platform moves in away from the strut.

13. The end effector moves away from the strut.

Each of these steps need to be verified remotely, so the end effector is fitted with various sensors and cameras to verify these operations. Initially the assembly of these struts was performed by moving the end effector to a calculated location.

Some work has also been done using a vision system (Will et al., no date) to locate the end effector. This vision system could allow this method of assembly to be more flexible for actual in-space assembly. This system consists of a camera and targets with a distinguishing pattern. The camera used in this preliminary research was mounted on the side of the end effector and could not view the target while the end effector is in position to grasp the receptacles. Therefore the camera had to line up with the target to acquire the end effector's position and then move from that position to grasp the strut. Future end effector designs should allow for the camera to be mounted in a position to allow view of the target while in position to grab the receptacles.

This automated assembly testing found problems which could not have been found using graphic simulations or bench tests of separate components (Will et al., no date). Some important findings during testing are as follows:

1. The idea of grasping the structure and inserting the strut into the node receptacles using the end effector proved to work well.

2. The force/torque feedback in the wrist of the end effector was found to be necessary to eliminate the large forces generated from even small displacements.

3. Positive actuation of all capture and release devices was necessary. Spring actuated release mechanisms and solenoid-actuated latching mechanisms were not effective.

4. Every operation must be interuptible and must be able to be reversed for the operator's convenience. Having the capability to reverse operations is useful when errors occur to allow the operator to evaluate the situation.

This automated assembly testing has proven that using the techniques used in this study, that automated assembly is possible for in-space construction.

The second-generation end effector developed at NASA is shown in Figure 2-34. This is a single-ended end effector designed to assemble the same type end joints as the first-generation end effector. It is designed to grasp one end of the strut at a time, so it can grasp many different sized struts for assembly of curved space structures.

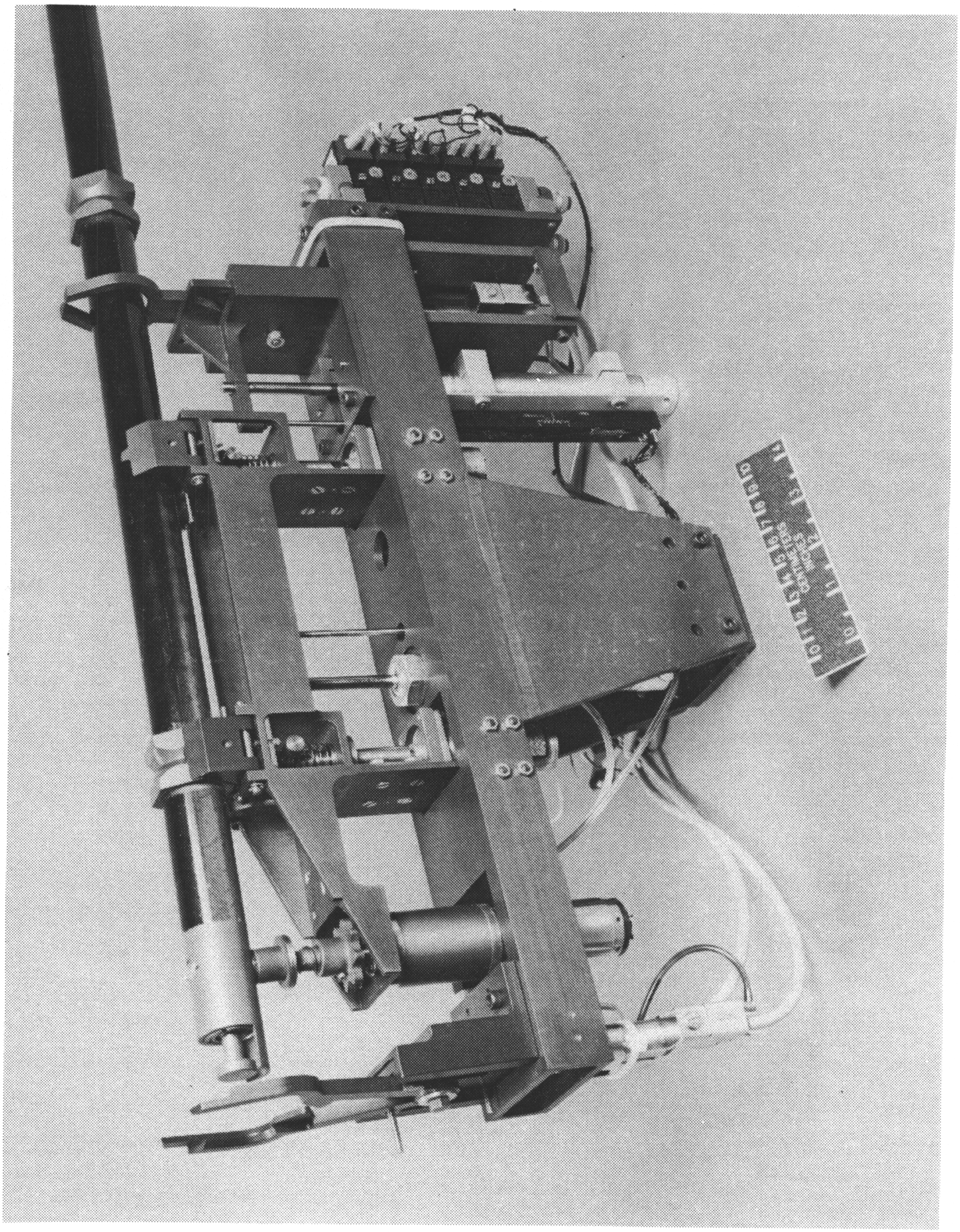


Figure 2-34. Second Generation End Effector

This end effector has been designed, manufactured and tested, but it has not been tested to the same extent as the first-generation end effector.

The operation of this end effector is shown in Figure 2-35. The alignment fingers are used to position the strut for capture by the strut holders when the strut is cantilever. Once the strut holders have captured the strut, the alignment fingers are released and the insertion platform is pulled in. The receptacle fingers close on the node receptacle to align the end effector for insertion and removal of the strut into and from the node receptacle. The insertion platform is moved in and out to insert and remove the strut into and from the node receptacle. The nut driver is turned to lock the strut to the node. The specific steps for removal and installation of the strut, as determined from discussions with Marvin Rhodes (no date) and Dan Sydow (no date) are as follows:

Strut installation:

1. Move the end effector near the strut in the storage tray.
2. Since the relative location in the storage tray of the strut is known accurately, the alignment fingers need not be used and the insertion platform is moved forward.
3. The strut holders are closed on the strut.
4. The insertion platform is then pulled back in to remove the strut from the storage tray.
5. The end effector is then moved over near the node.
6. The receptacle fingers then close on the node receptacle to position the end effector.

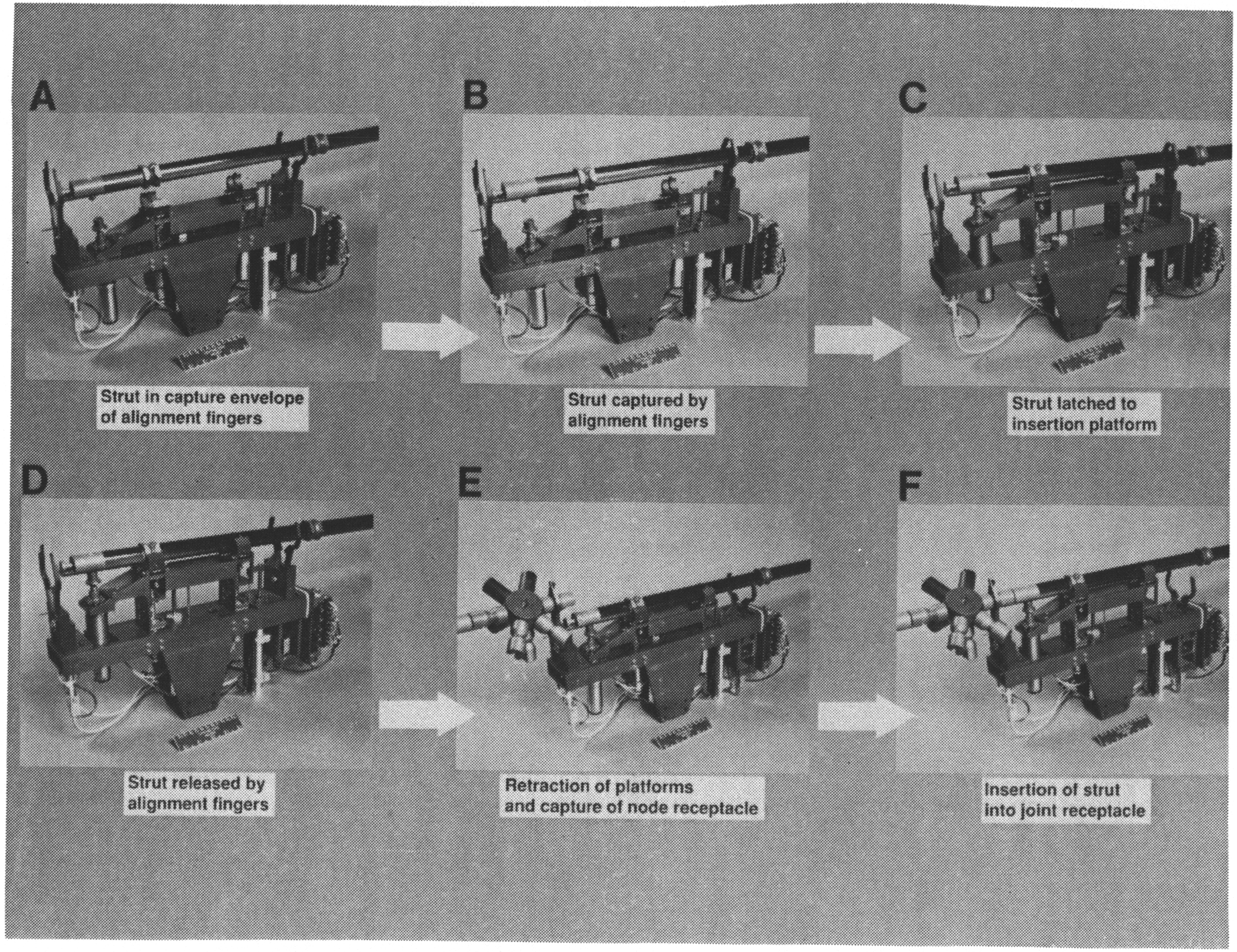


Figure 2-35. Second Generation End Effector Assembly Sequence

7. The insertion platform is then moved out to connect the strut to the node receptacle.

8. The nut driver is then turned to lock the strut to the node receptacle.

9. The strut holders are released.

10. The insertion platform moves back in away from the strut.

11. the receptacle fingers are opened and the end effector moves away from the strut.

12. If the other end of the strut has a node attach, no other assembly is required for this strut and the noded end is left hanging cantilever. If the other end of the strut does not have a node attached, then the other end must be attached as follows:

    a. The end effector moves near the other end of the strut.

    b. The alignment fingers move out toward strut.

    c. The alignment fingers close to position the strut for capture by the strut holders.

    d. The insertion platform moves out toward the strut.

    e. The strut holders are closed on the strut.

    f. The alignment fingers are opened.

    g. The alignment fingers move in away from strut

    h. The insertion platform is moved back in.

    i. The end effector is moved so that the receptacle fingers are around the node receptacle.

    j. The receptacle fingers close.

    k. The insertion platform moves out, inserting the strut into the node receptacle.

l. The nut driver is turned to lock the strut to the node receptacle.

m. The strut holders are released.

n. The insertion platform is moved back in.

o. Receptacle fingers are released, and the end effector is moved away from the strut.

Strut Removal:

1. The end effector is positioned at one end of the strut.

2. The receptacle fingers are closed on the node receptacle.

3. The insertion platform is moved out toward the strut.

4. The strut holders are closed on the strut.

5. The nut driver turns to unlock the strut from the node receptacle.

6. The insertion platform is pulled in removing the strut from the node receptacle.

7. The receptacle fingers are opened.

8. At this point if the other end of the strut is attach to a node which is free from the rest of the structure then follow steps 17-20, but if the other end of the strut is attached to a node, which is in turn attached to the rest of the structure, continue with step 9.

9. Strut holders are opened.

10. the end effector is moved over near the other end of the strut.

11. The receptacle fingers close on the node receptacle.

12. The insertion platform is moved out toward the strut.

13. The Strut holders are closed on the strut.

14. The nut driver is turned to unlock the strut from the node.

15. Insertion platform is pulled in, pulling the strut away from the node receptacle.

16. The receptacle fingers are opened.

17. The end effector with the strut attached is moved away from the node and is moved over near the strut storage tray.

18. The insertion platform is moved out forcing the strut into the storage tray.

19. The strut holders release the strut.

20. The insertion platform is moved in away from the strut and the end effector moves away from the storage tray.

The above steps were proposed during the design of this end effector, but, after testing, changes to this sequence were necessary and will be discussed later.

Chapter 3
End Effector Review and Problem Definition

3.1 Review of Current and Past End Effector Designs

In order to have a more versatile system, it has been proposed to develop an end effector that can assemble curved space structures using joints designed for manual assembly. In order to assemble curved structures, different size struts must be assembled. Also, this end effector must be able to assemble joints designed for manual assembly as discussed in Section 2.5. Design concepts for these type of end effectors and previous designs will now be reviewed.

Reviewing the end effectors developed for automated assembly of space structures it can be seen that these end effectors were designed by combining several different mechanisms with a motor for each mechanism. This type of design requires control and feedback for each motor.

The first-generation end effector designed for assembly of flat structures with joints designed for automated assembly has a total of eight motors, sixteen binary sensors and five analog sensors. The weight of this end effector is approximately twelve and one half pounds before the vision system was added. The first-generation end effector uses air actuated cylinders for ground testing, but for an actual in-space use these would have to be replaced by electric motors. Therefore this weight is slightly under what would be expected for an actual in-space end effector.

The second-generation end effector designed for assembly of curved structures with joints designed for automated assembly has a total of seven motors. This end effector has fourteen binary sensors, four analog sensors and weighs approximately six and one half pounds. Initial testing of this end effector verified that a better design would be possible using a double-ended end effector with adjustable length.

According to Marvin Rhodes (no date), along with the design developed in this thesis two other designs have been proposed for assembling curved structures using joints designed for manual assembly. They are shown in Figures 3-1 and 3-2. The first is a NASA LaRC design and uses the same components for strut holders and receptacle fingers as the previous single-ended and double-ended end effectors used. A new idea has been developed for unlocking and locking the joint. This uses a helical groove to manipulate the end joint. The operation of this will be discussed in Section 5.1. This design uses four motors to actuate the strut holders, end joint, insertion platform and the receptacle fingers. There would be one of the assemblies shown on each end of the double-ended type end effector with some type of adjustment for variable length struts. This end effector has a total motor count of

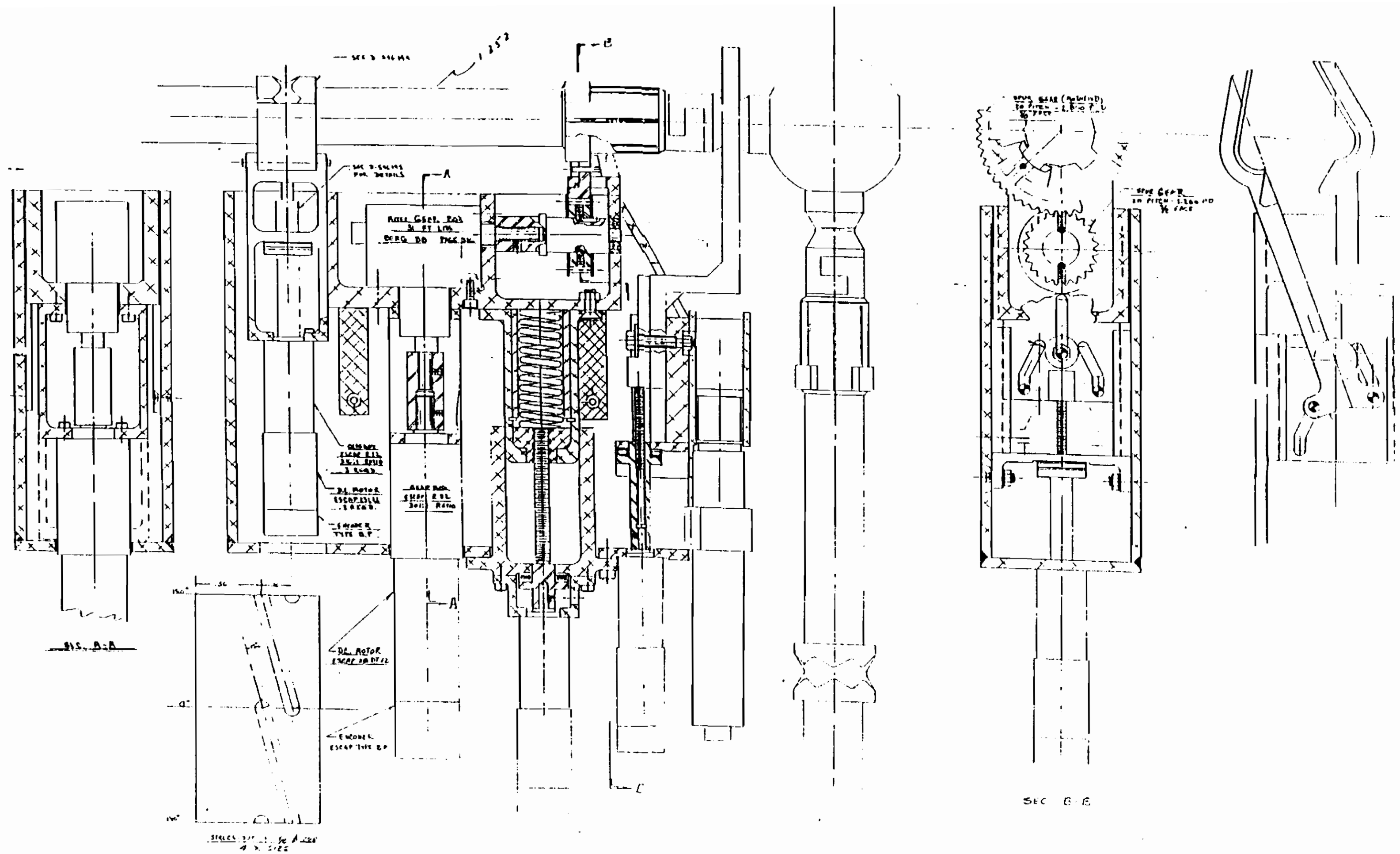


Figure 3-1. Langley End Effector Design Concept

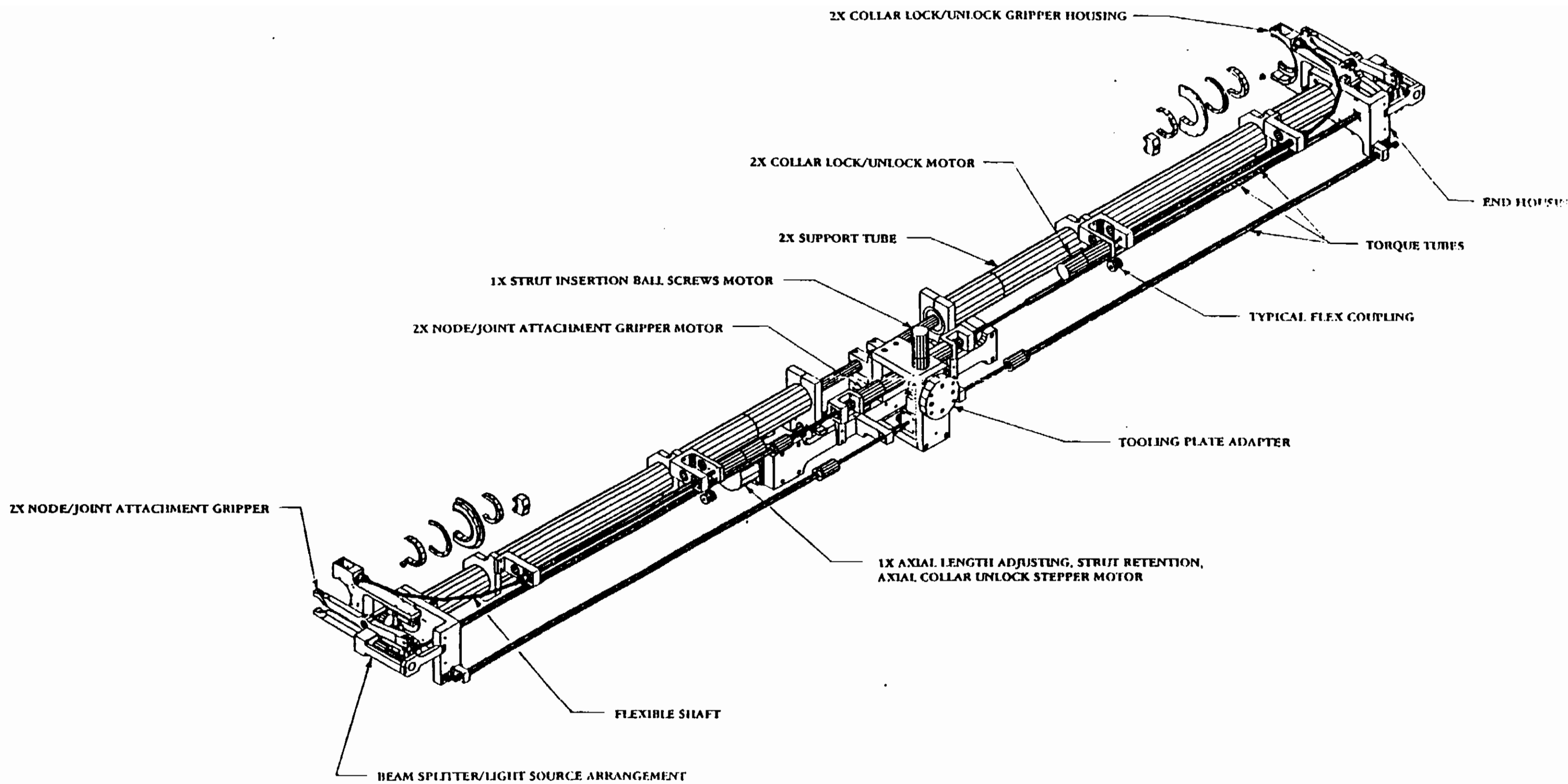


Figure 3-2. Honeybee Robotics End Effector Design Concept

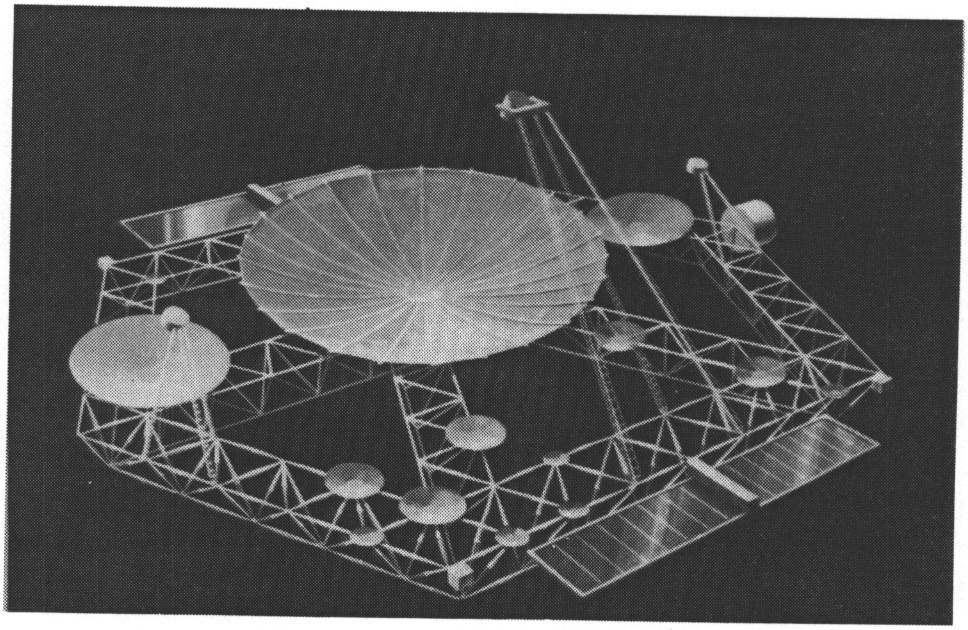


Figure 3-3a. Space-based Antenna.

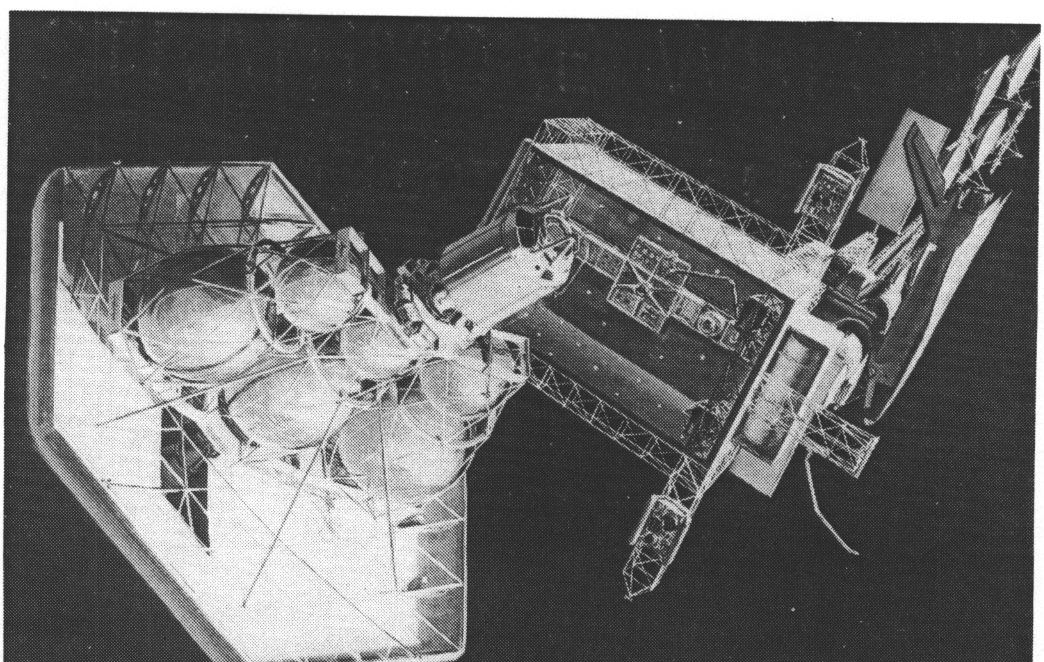


Figure 3-3b. Truss-supported Aerobrake Configuration.

Figure 3-3. Artist's Conception of future Space Missions (From reference 30) nine. Each of the motors would have encoders to monitor position. The weight of the assembly shown in Figure 3-1 is approximately seven pounds. The overall end effector weighs approximately twenty pounds.

The end effector shown in Figure 3-2 was developed by Honeybee Robotics. This is a double-ended type design and the designer attempted to keep the motors located near the center of the end effector. This design has a total of six motors. There is one motor on each side to grab the nodes, one motor on each side to unlock the joint and one motor in the center to insert the strut into the nodes. One motor is used to adjust the length, hold the strut and pull the end joint operating collar toward the center of the strut. This end effector has no method of stopping the strut from rotating during locking and unlocking the end joints, thus this design does not appear feasible.

3.2 Problem Definition

The example problem selected to demonstrate the methods developed in this thesis is the design of an end effector to assemble curved space structures using joints designed for manual assembly. Examples (Will et al., no date) of potential uses of these structures are shown in Figure 3-3. The major difference from this design and previous designs is in the method of locking and unlocking the joint. The end joint is the joint discussed in Section 2.5. This joint requires rotation about the strut axis to lock and unlock. In order to assemble curved structures, the strut lengths must be different and the end effector must allow for this.

This end effector must be able to assemble and disassemble struts using the robot arm of the shuttle or a similar robot arm. This end effector must be adaptable for space use, although this design will not be space qualified. Some items which must be considered for space use are materials selection for outgassing, heat survivability, cold survivability and extended periods in the vacuum of space. The assembly process must be completely automated, therefore various feedback sensors and cameras must be integrated into the end effector in order to know the position of each item during operation. It would also be helpful to allow for installation of a vision system mounted such that it can view the node receptacle in the node receptacle grasping position. This end effector has to be small in order to reach into the crowded area near the nodes to unlock and lock the joints.

Chapter 4
Design Methodology Development

The main objective of the design method proposed in this thesis is to reduce the number of motors needed to control the end effector. By reducing the number of motors, the weight and complexity of the device should be reduced and the reliability will be increased. To reduce the number of motors, it is necessary to have several operations controlled by the same motor. Therefore, groups of steps in the assembly sequence must be found which can be controlled by a mechanism operated by one motor.

As a starting point, the steps necessary for strut assembly using the LaRC second-generation end effector were reviewed and a method to reduce the number of motors was investigated. First, steps were written out as listed previously, but this listing made it difficult to group steps which could be operated by the same motor. Eventually the author decided to use schematics to represent the end effector position during each step of the assembly process.

These schematics are shown in Figure 4-1. The meaning of each item of these

Figure 4-1a. Strut Installation (Refer to Steps for Strut Installation p. 52)

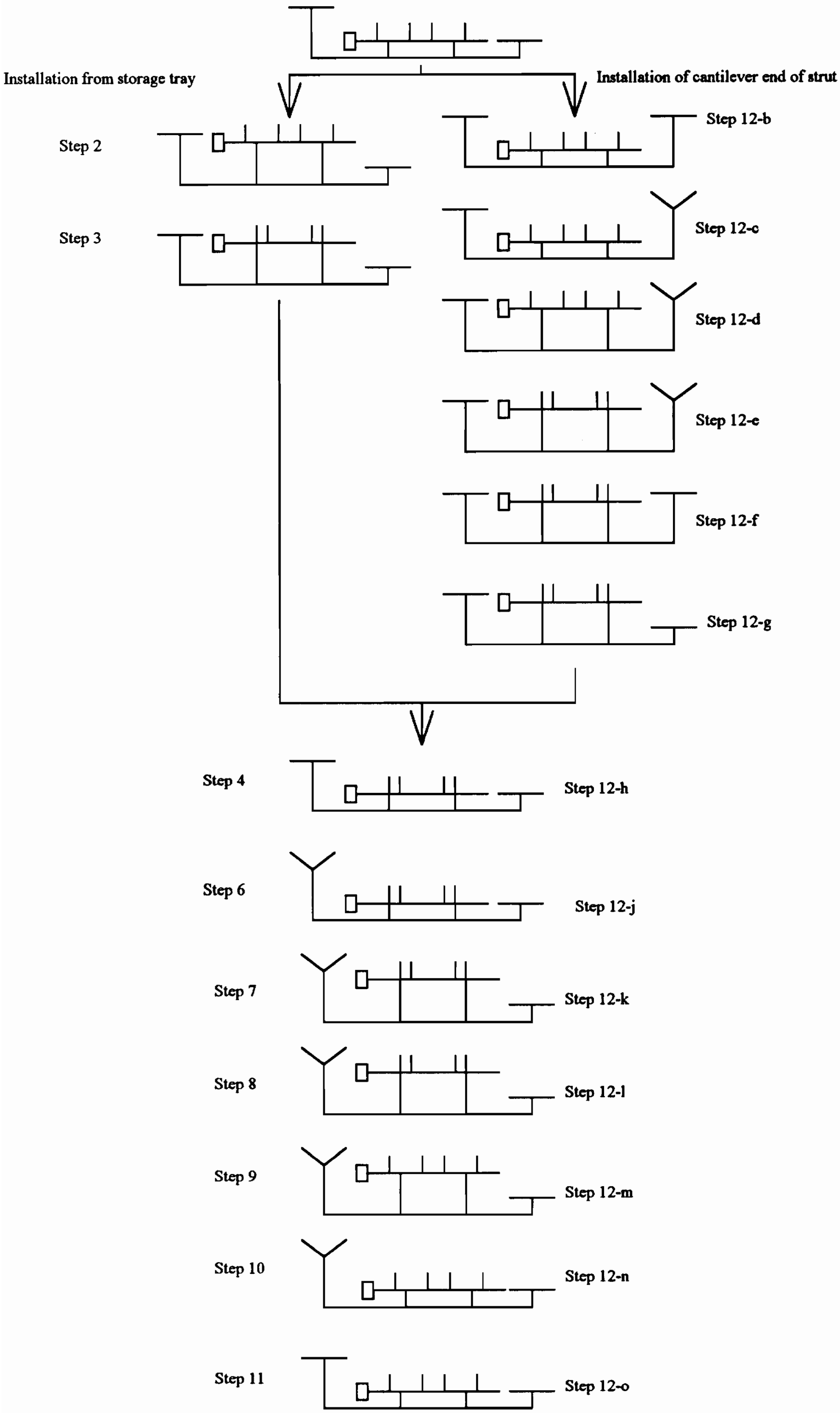
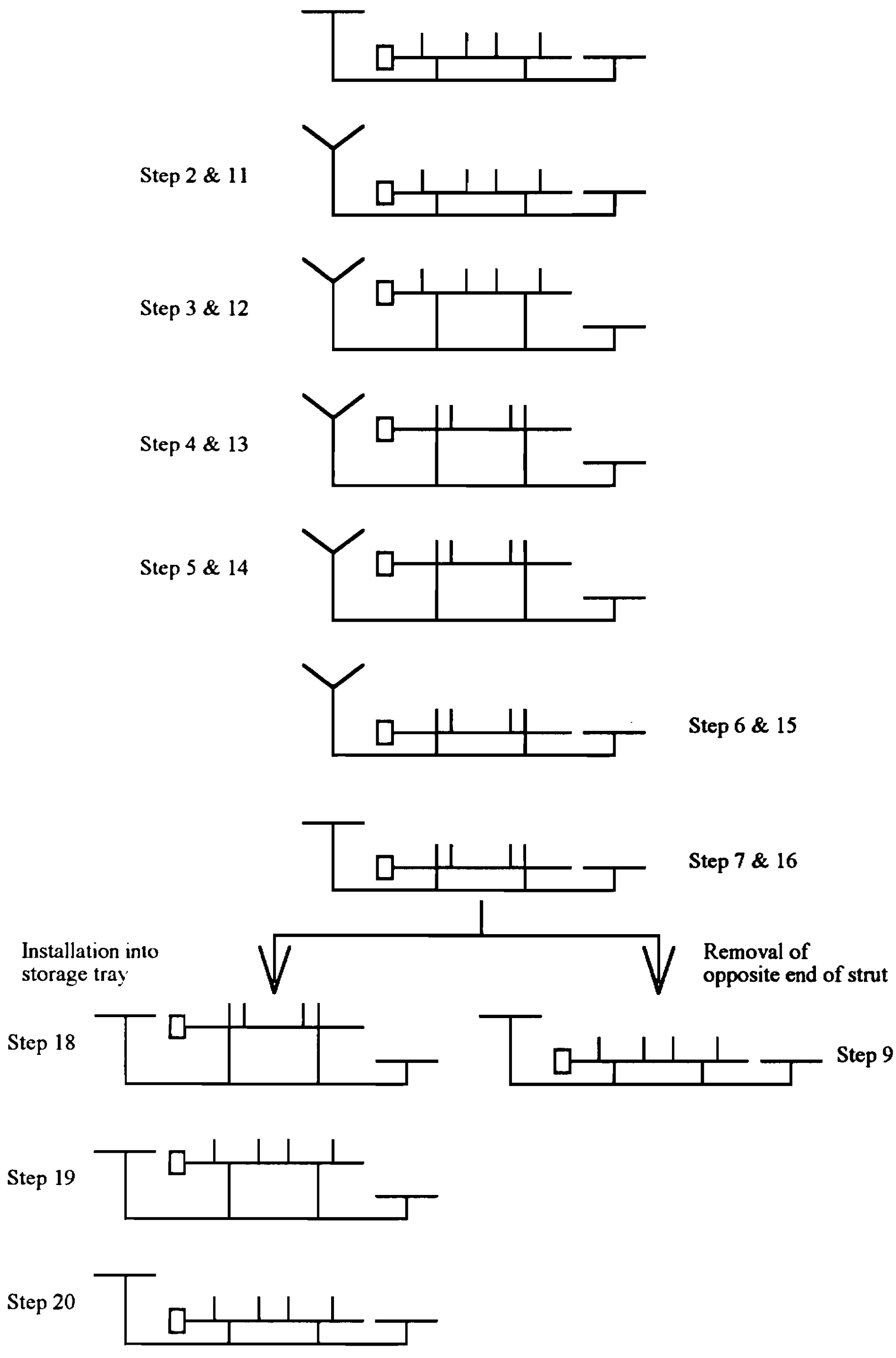


Figure 4-1b. Strut Removal (Refer to Steps for Strut Removal p. 55)



schematics is shown in Figure 4-2. Figure 4-1a shows the various steps as outlined in Section 2.6 for strut installation and Figure 4-1b shows the various steps as outlined above for strut removal. In reviewing these steps, it is not immediately apparent which steps should be grouped together for operation by one motor. There are many combinations of steps which could be grouped together. In order to come up with some criteria for grouping steps, various simple mechanisms were reviewed. By grouping these steps based on the operation of simple mechanisms, the developed mechanism should be simple.

The simple mechanisms shown in Figures 4-3a and 4-3b can be seen to be reversible. If they are driven one way they perform a certain task. If they are reversed, they perform that task in reverse order.

Another mechanism which is simple and reversible is the Mast I Shuttle borne flight experiment, which was discussed in Section 2.3. If the input motion to this mechanism is reversed, all output motions also occur in reverse order. These mechanisms are simple reversible mechanisms. The author decided to group reversible steps for the design method developed in this thesis. The simple mechanism examples do not provide proof that this is a good method, but they may give insight to the soundness of this method. A design will be developed using this method and its validity will be investigated by comparing this design with previous designs.

After sketching the schematics of the end effector, it was necessary to group

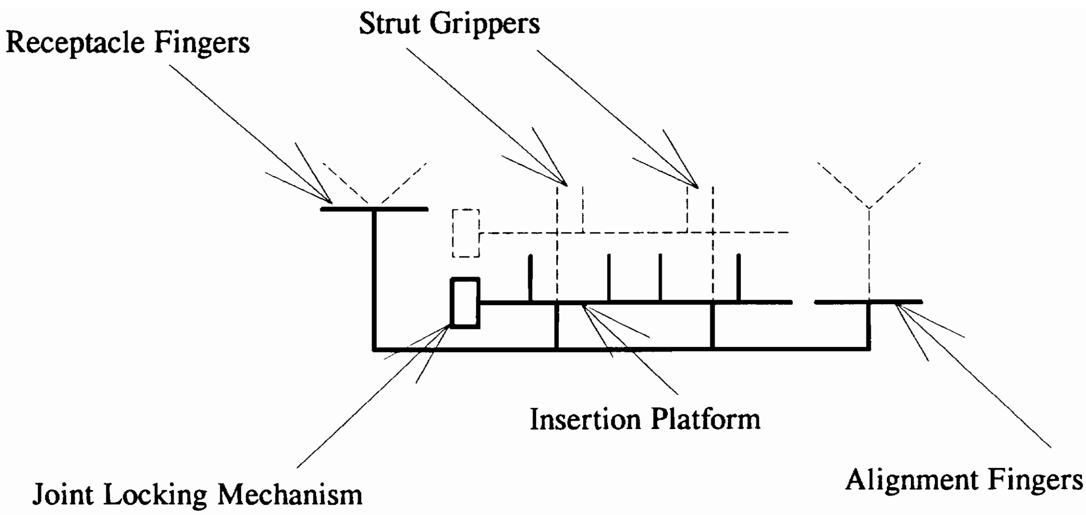
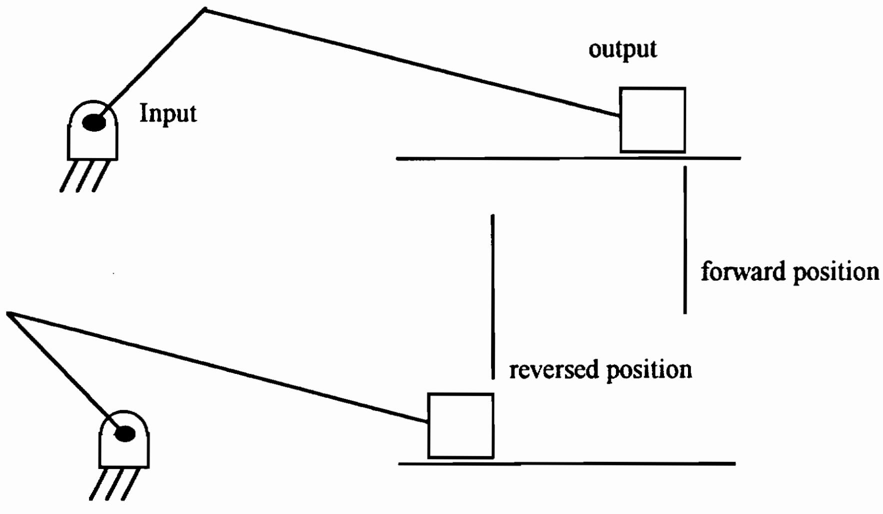
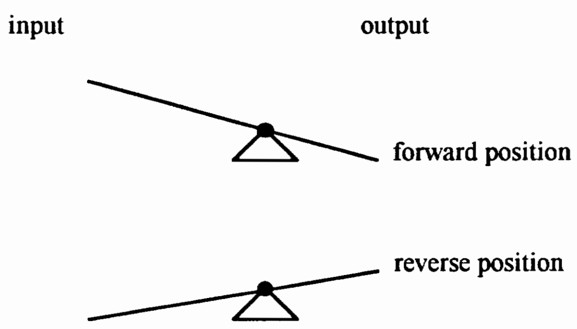


Figure 4-2. End Effector Figure Labels



(a)



(b)

Figure 4-3. Simple Reversible Mechanisms individual operations into reversible sets of steps. Figure 4-4 shows the steps grouped into reversible sets for the single-ended end effector. The three combinations of letters and numbers after each figure represents respectively the mechanism, the step in that mechanism and whether it is functioning in reverse or forward. For example A1F means this is mechanism A, first step and it is operating forward. In the sequences of the installation figure, the installation from the storage tray was left out because these steps were also performed when installing a cantilever end of a strut. Also, the removal of the opposite end of the strut was not used in the removal sequences, because this same step is performed in the installation into the storage tray steps. In the strut installation sequence, a step was added after the strut was clamped to unlock the end joint. Also, in the strut removal sequence, a step was added before the release of the strut in the storage tray to lock the end joint. These steps were added to make these two sets of steps reversible for all operations. Adding these steps requires that the struts be stored in a locked configuration.

Figure 4-4 shows that three simple mechanisms should be able to operate this end effector. These mechanisms are A, B and C. Each mechanism can be operated by a single motor, therefore reducing the number of motors from 7 to 3, assuming one motor is used to operate both strut holders. As can be seen in this figure, each step in any one mechanism does not have to immediately follow the previous step. For example, the last two steps of strut installation are mechanism B Step 3 then mechanism B step 2, but then, going back to the first operation, mechanism C is

Figure 4-4a.Strut Installation (Organized into sets of reversible steps)

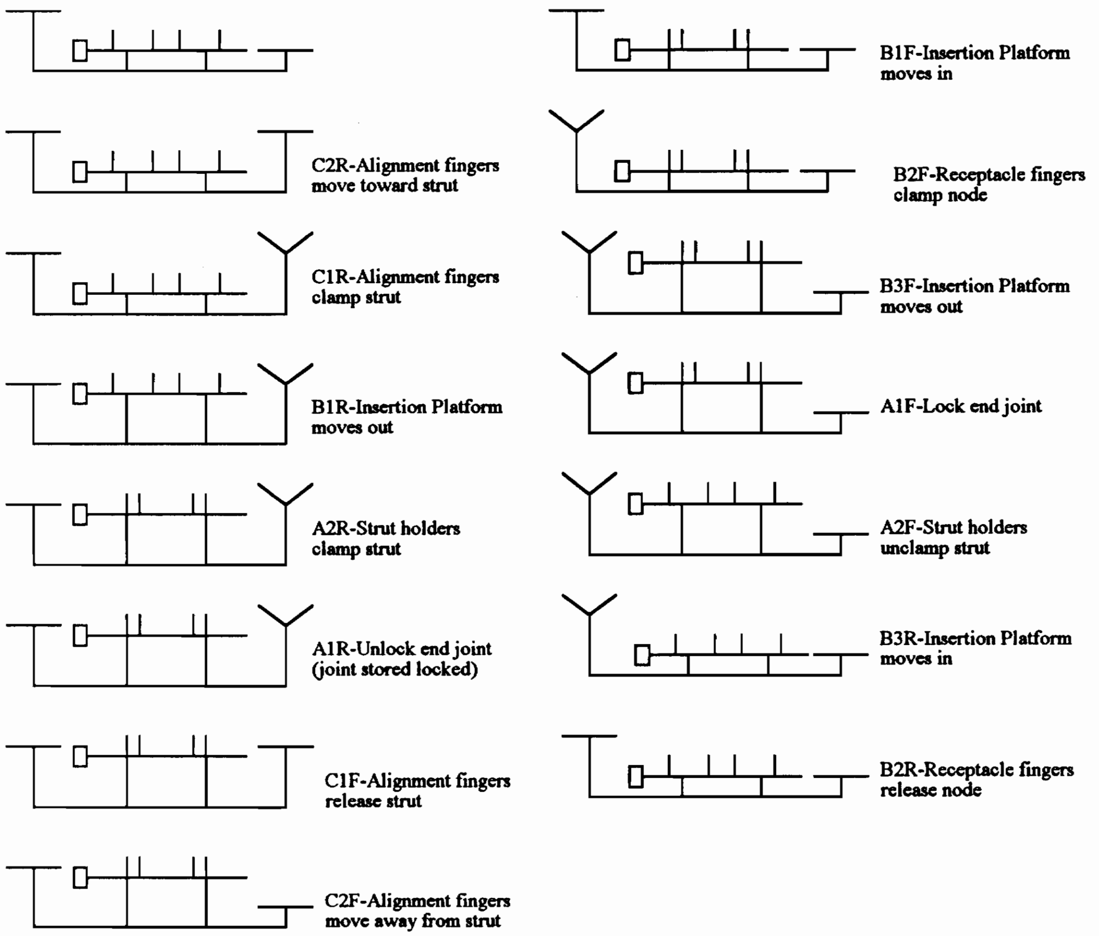
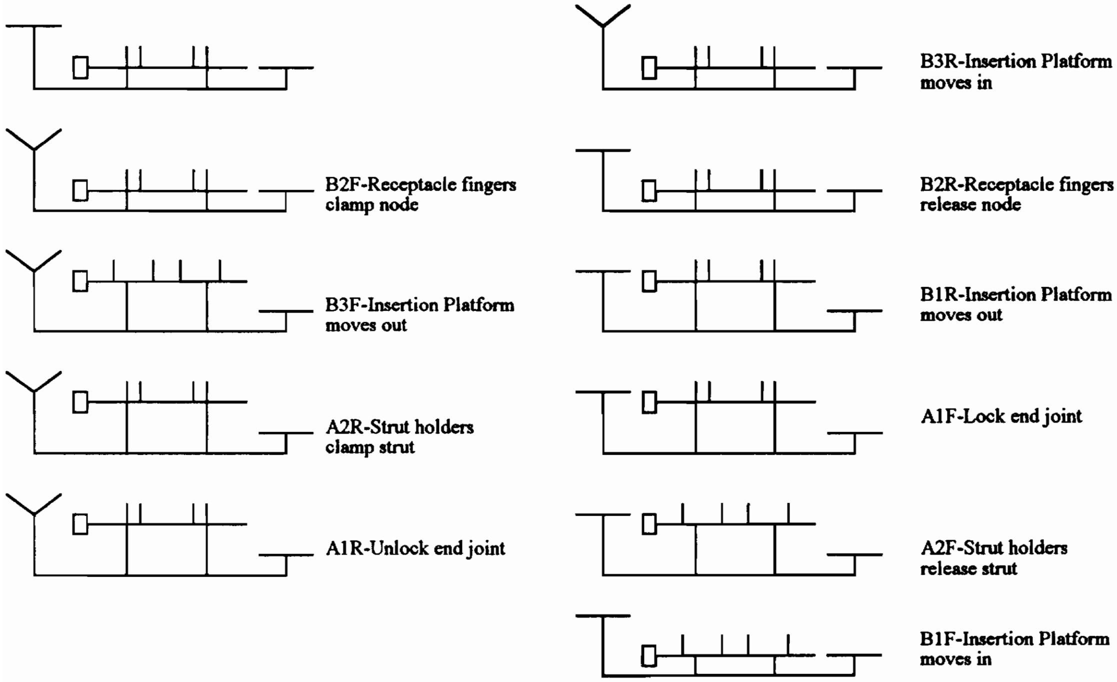


Figure 4-4b. Strut Removal (Organized into sets of reversible steps)



operated in reverse before mechanism B step 1 is operated in reverse. The schematic of the steps for an existing end effector gave a starting point for developing the design method.

The method of grouping different steps to be performed by one mechanism allows the mechanism to control the sequence of operations. Therefore, there will be fewer items to control. Once the mechanism is designed, the operator or computer does not need to control the sequence of operations or the operator may not need to control as many sequences of operations where only one mechanism is not possible. This type of design may take more time initially, but programming time could be reduced since there are fewer items to control. After many of these types of mechanisms are developed it could be possible to select, from a database, certain mechanisms which could be used in sequential operation. After reviewing several design methods for end effectors and robot systems, the following design methodology for development of the most easily controlled end effector was developed. This method consists of the following steps:

1. Define the process of assembly and study the parts to assemble. Investigate how the parts can be modified to make the process of assembly easier. Review other end effectors used for similar operations.

2. Determine any additional requirements, such as space limitations or environmental conditions.

3. Organize the process of assembly into sets of reversible processes, which are used to focus the design. The main objective of this thesis is to develop an optimum design of the end effector through maximizing

reversible processes. At first glance a reversible process may not be apparent and the reversibility may not be in succeeding steps. In some cases it may be helpful to change the process to make it a reversible process.

4. Develop solutions for the individual processes using steps 1-3. For example, develop different gripping mechanisms or different joint locking techniques.

5. Combine parts of different solutions to operate sequentially as outlined in step 3. Identify several different solutions and combine those which work well together.

6. Consider redesign of the part or the process. Once some initial design work has been done, consider modifying the part or the process to make for a simpler end effector. It may be necessary to go back to any step in this design methodology.

These steps have been used for the design of the end effector described in Chapter 5 of this thesis.

Chapter 5
Design Development

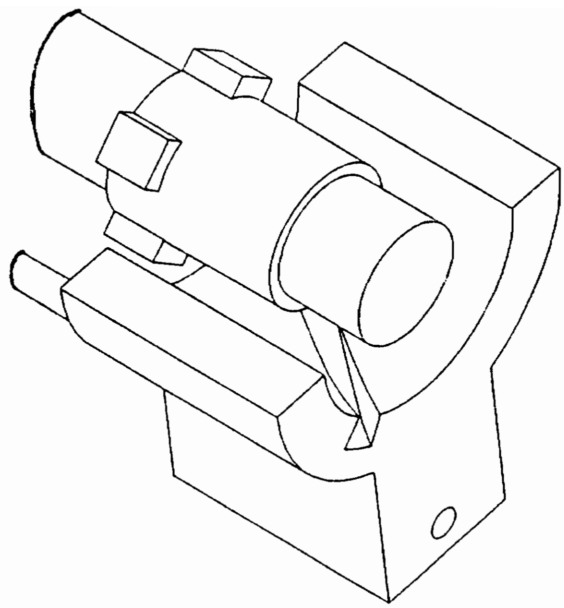
5.1 Initial Design

The first design was a single-ended end effector. This design concept was developed, but at the final stages of this design some testing had been performed with the LaRC developed single-ended end effector. This testing, performed by Dan Sydow (no date), Billy Doget (no date) and others at NASA LaRC, revealed some problems associated with a single-ended end effector design.

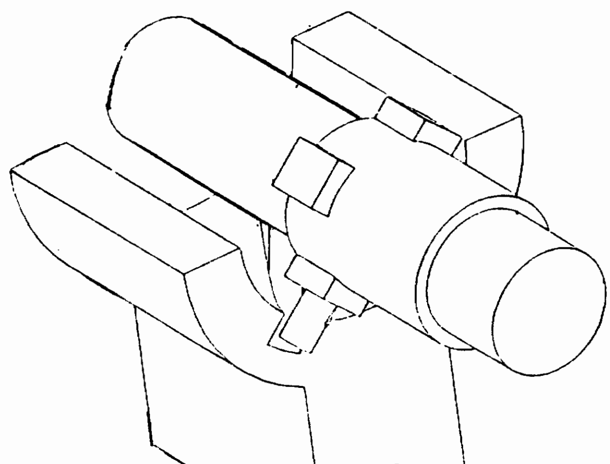
From initial research with the single-ended end effector it was found that during end effector positioning the strut needed to be forced out of the way with the alignment fingers. This requires that the strut sometimes be grasped while the carriage is in and sometimes when the carriage is out. This complicated the process of finding reversible steps in the assembly sequence. For struts with no nodes attached, it is necessary to attach one end then go to the other end and attach that end. This was time consuming when compared to using a double-ended end effector, which can assemble both ends of the strut at the same time. With these additional steps needed to assemble the space structure and the additional time required for assembly, using a single-ended end effector did not seem to be the most efficient method of performing the assembly.

Although this initial design did not prove to be a good method, in the process of developing it, solutions for performing individual tasks of the end effector were investigated. The task investigated first was the method of locking and unlocking the joint designed for manual assembly. The process of unlocking the joint consists of two steps, (1) pulling back the operating collar and (2) rotating the operating collar counter clockwise as shown in Figure 2-28. To lock the strut, the operating collar must be rotated clockwise and then it must be allowed to slide to the left as shown in Figure 2-28. The first concept developed is shown in Figure 5-1. This is an internal helical groove inside a sleeve, which actuates the joint by a roller follower in the joint. This roller follower is screwed into an already existing threaded hole in one of the protrusions on the operating collar of the joint. General equations for the internal helical grooves were developed and shown in Appendix A. Appendix B discusses the helical groove design for this thesis.

Figure 5-1 shows the operation of this joint actuating method. As the sleeve slides out away from the center of the strut, this motion causes the joint to lock by rotating the joint operating collar. As the sleeve is pulled back in toward the center of the strut, the sleeve pulls the operating collar and also rotates the operating collar in the direction to unlock it. But the operating collar cannot be rotated to unlock



(a)



(b)

Figure 5-1. Internal Helical Groove Joint Actuation Method unless it is pulled back. So the helical groove pulls back on the operating collar until the operating collar is able to rotate to unlock.

Another method, developed by NASA LaRC, for unlocking the joint is shown in Figure 5-2. This method also uses a helical groove, but this is an external helical groove. As this helical groove rotates, it drives and positions a gear which in turn drives and positions another gear, which interfaces with a protrusion on the operating collar of the joint. As the helical grooved surface rotates to lock the joint, it forces both gears out away from the center of the strut. As the helical groove rotates to unlock the joint, both gears are forced toward the center of the strut, therefore allowing the strut to unlock.

Another idea investigated is to pull the joint operating collar along with some other operation and keep it held back for locking and unlocking operations. The joint can be locked with the joint operating collar pulled back. After the joint has been locked, the operating collar is released and returns to its original position. An example of another operation which could be performed while pulling the operating collar, is grasping of the strut. Grasping of the strut would be a good candidate to operate in conjunction with the pulling of the operating collar because for all locking and unlocking operations the strut must be held. If the strut is not held, the strut would rotate along with the operating collar.

Various methods of grasping the strut were investigated. Figures 5-3 and 5-4 show two different methods. The first method, called the triangular grip, combined

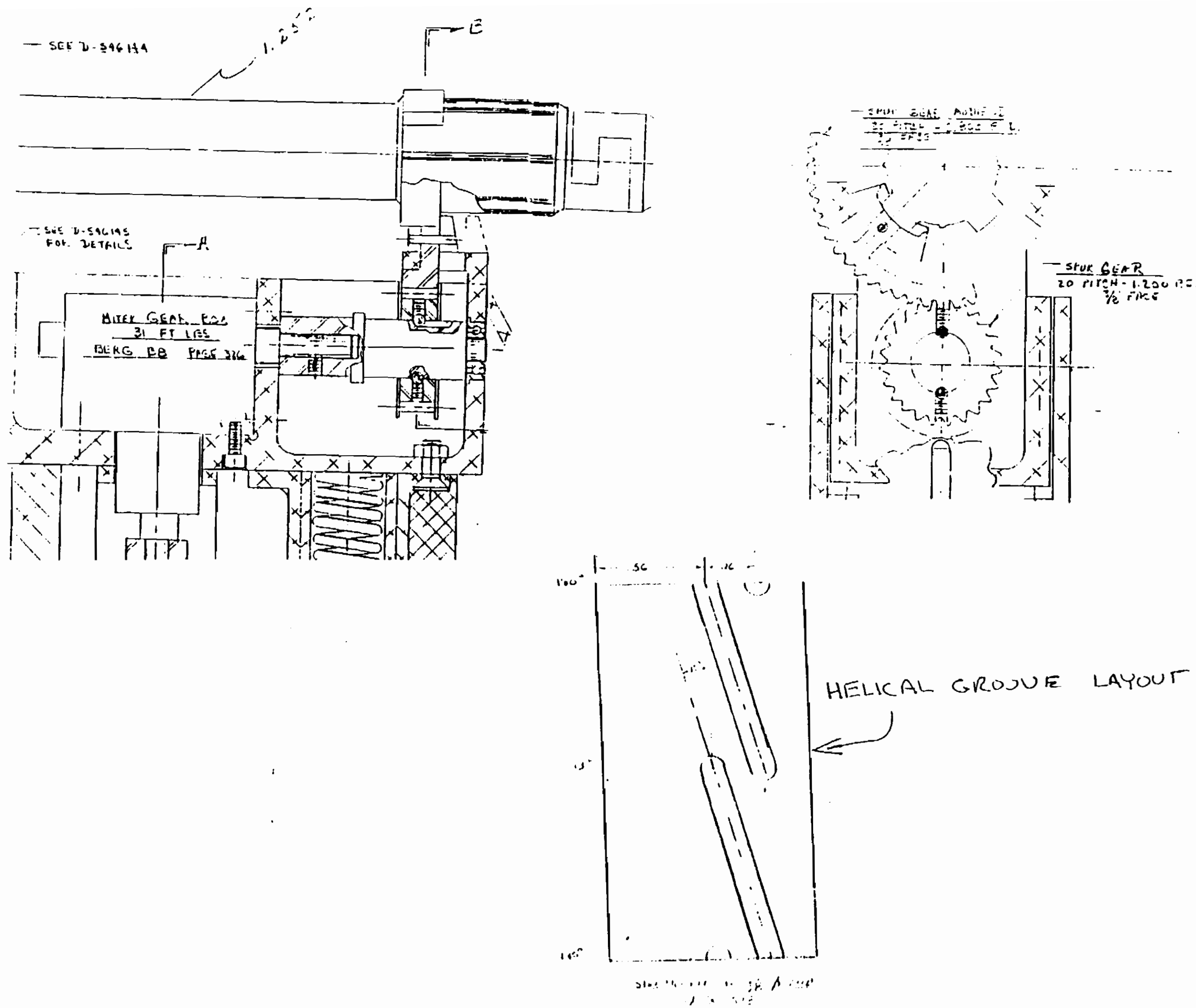


Figure 5-2. LaRC Joint Actuation Method

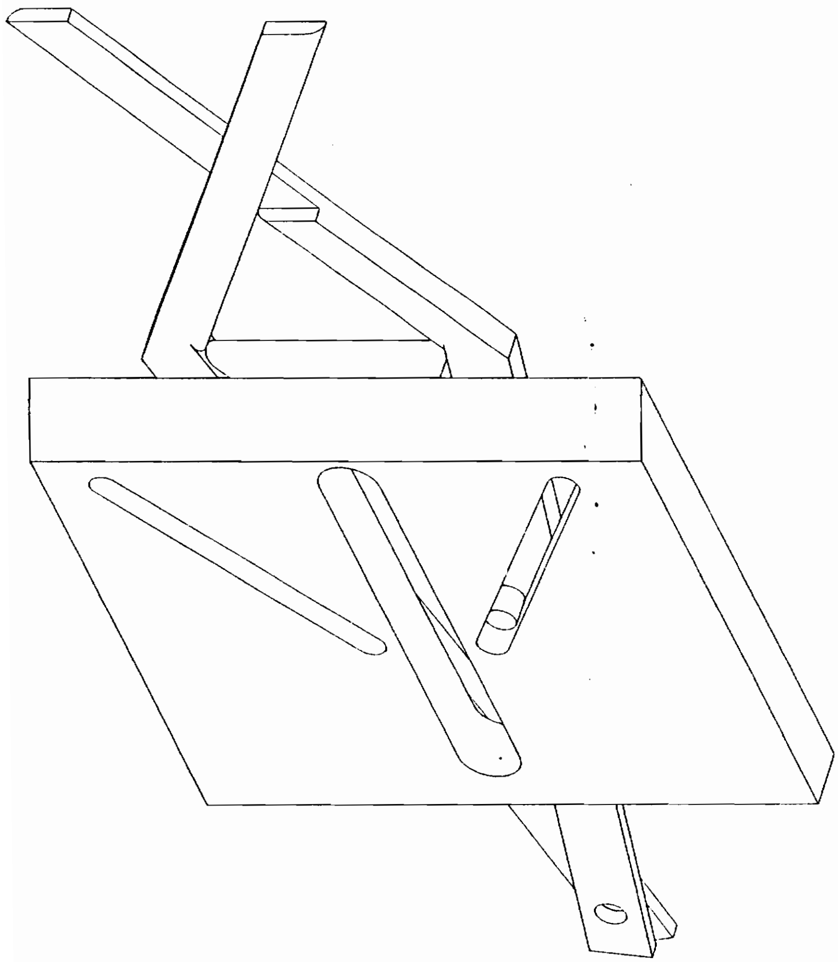


Figure 5-3. Triangle Gripper

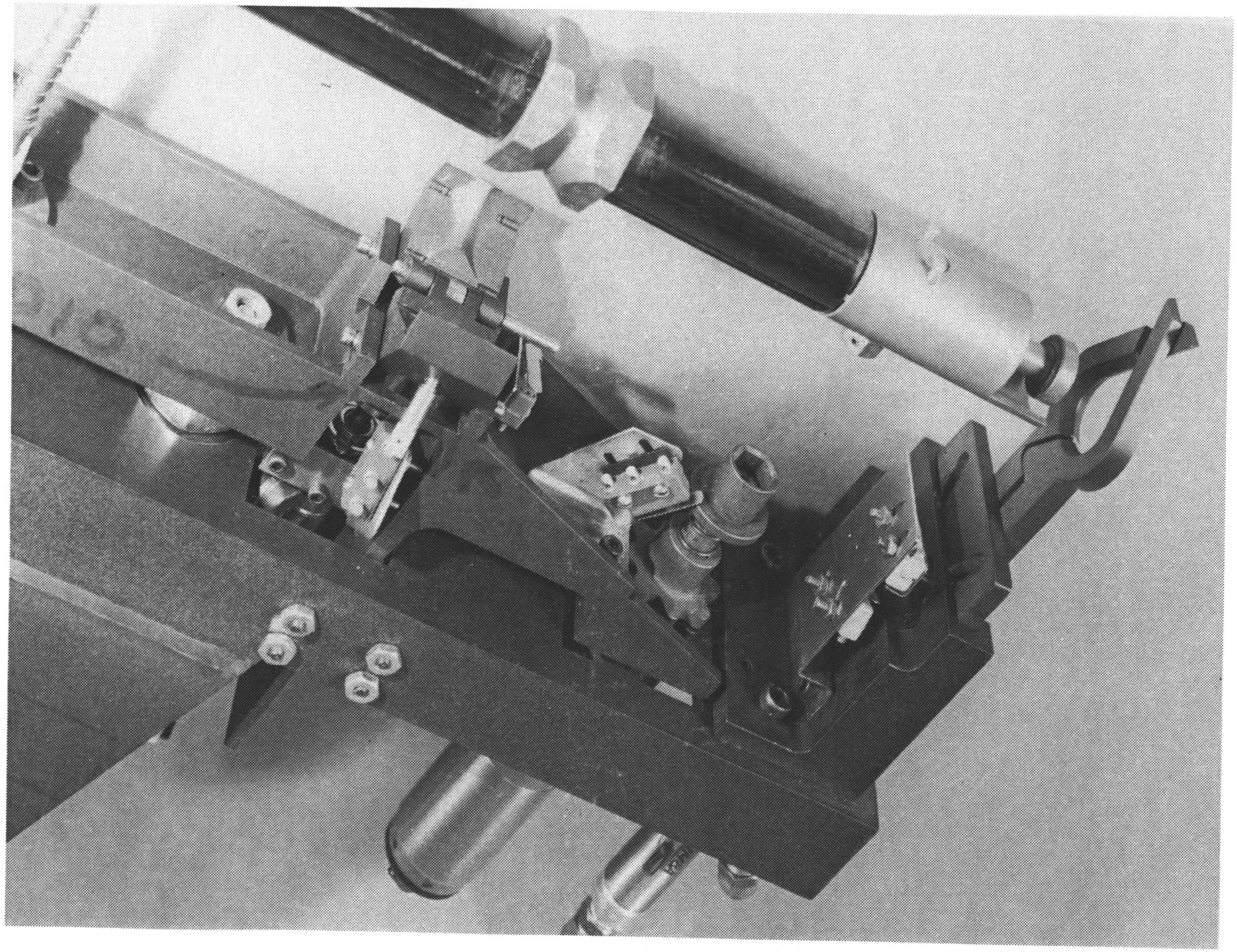


Figure 5-4. Standard Strut Gripper

the alignment fingers and strut holder of the single-ended end effector. Figure 5-4 shows the standard method for gripping the strut which was used on the first and second-generation end effectors. The triangular grip was designed to have a wide grip so that it could grasp the strut and bring it into position at the same time. This way, only one mechanism would be needed for positioning and for grasping the strut using the single-ended end effector design. For steps where it is not necessary to position the strut and where space is limited, such as removal of the strut from the storage tray, the triangular grip could be partially closed before moving near the strut. Once in position, the grip could be closed on the strut.

The standard method of grabbing the strut used for both the first and the second-generation end effectors is to have two jaws shaped to grasp a hexagonal shaped interface bonded to the strut. The jaws have a small amount of motion, therefore the strut must be relatively closely positioned to be grasped. These jaws have been used successfully on the first and second-generation end effectors.

Other items which could be modified from previous designs, are the receptacle fingers. These fingers worked well in previous testing, so no substitute mechanisms were developed for them.

After the above solutions were developed and the single-ended end effector design did not prove to be the best approach, a second design was developed. This second design is a double-ended end effector.

5.2 Second Design

After learning the problems involved with the NASA LaRC developed single-ended end effector, a double-ended end effector was designed. The first step was to lay out the steps of assembly as done previously with the schematics of the end effector. Figure 5-5 shows these steps with one method of grouping them into reversible groups of steps for installation and removal. As can be seen from Figure 5-5, this end effector would require three motors , which would drive mechanisms A, B and C. These schematics show one side with no node attached to the end of the strut and the other with a node attached to the end of the strut. The schematics show only one case, the other case could be with no node on either end, but this one case was shown with the idea of making both ends perform the same operation no matter whether a node is attached or not. The only difference between the two sides is that in mechanism A, step A3 is not performed when a node is attached to the end. By using the internal grooved sleeve and not installing a follower in the joint operating collar with a node attached, the end effector can still slide the sleeve back and forth past the joint, but not lock or unlock this joint. Therefore, by using the internal grooved sleeve, the end effector can perform the same operations whether a node is attached or not.

The only mechanism in this new design which requires multiple actuations is mechanism A. This mechanism needs to perform four steps that actuate the insertion platform, strut holder and sleeve. It is easier to design a strut-holding mechanism

Figure 5-5a. Strut Installation (Organized into sets of reversible steps)

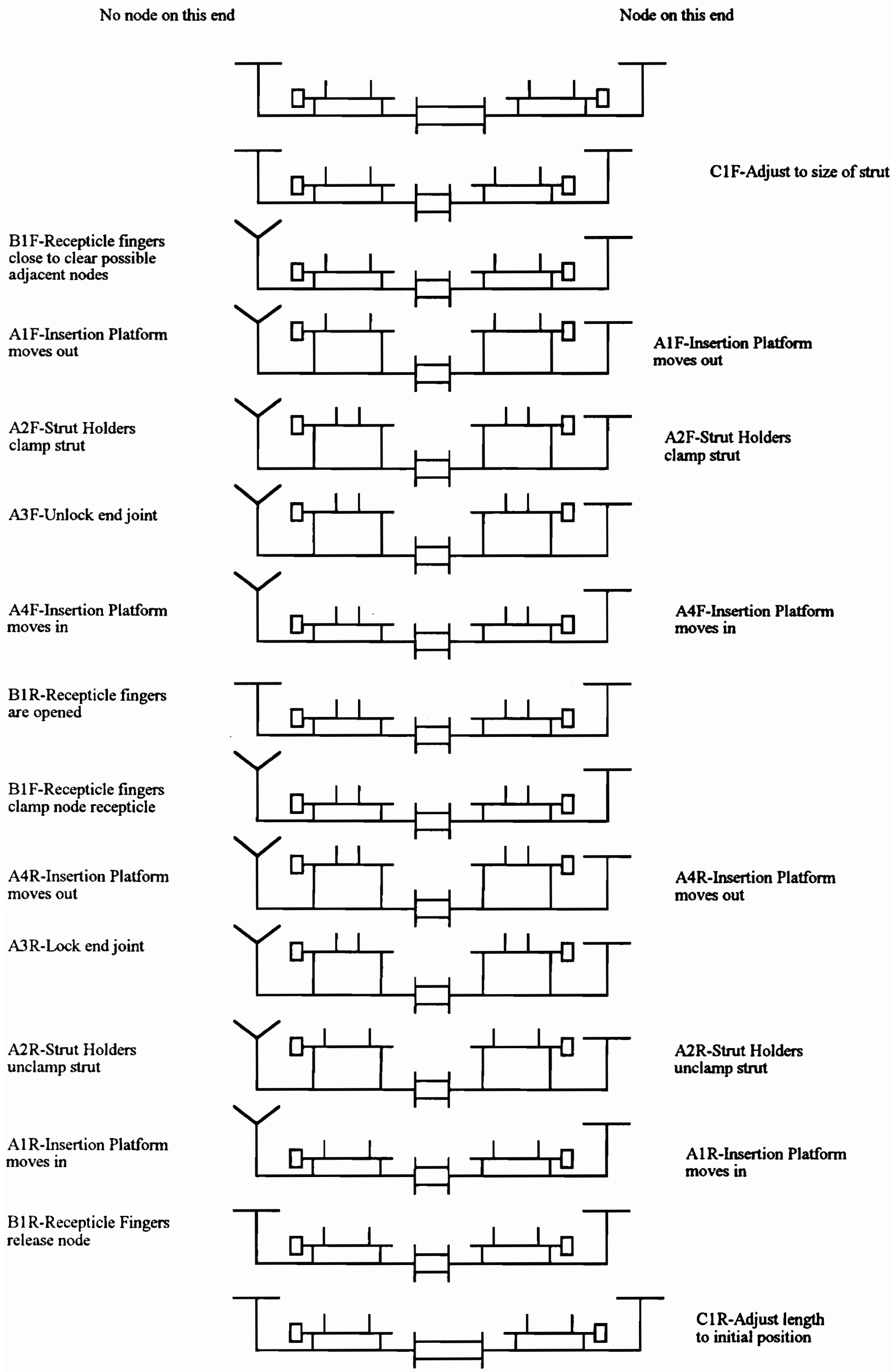
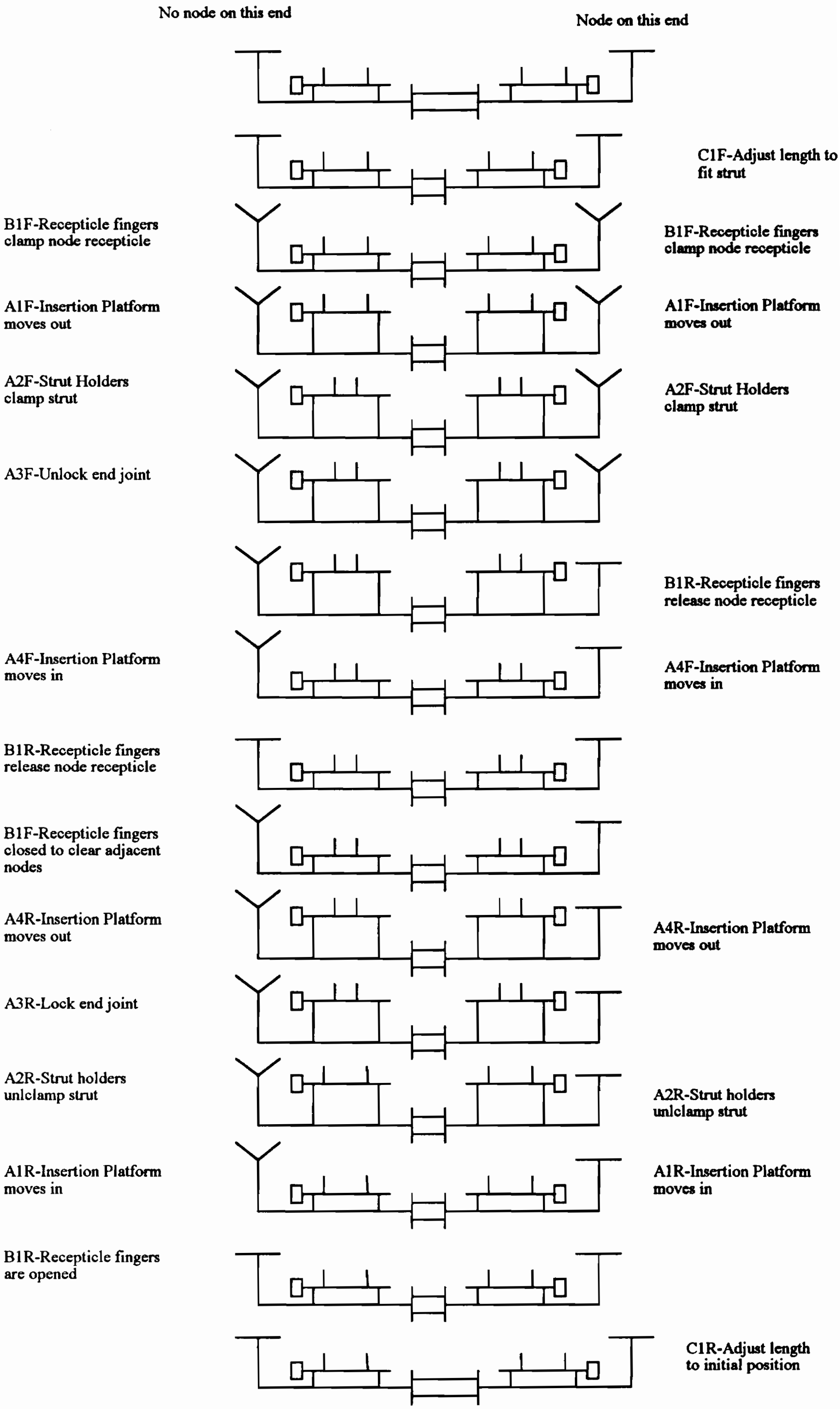


Figure 5-5b. Strut Removal (Organized into sets of reversible steps)



which moves in the same direction as the sleeve. This type of strut-holding mechanism would eliminate some of the complexity. An insertion platform lifting mechanism which moved in the same direction was also designed.

The sliding grip, which slides like the sleeve, has sloped hexagonal-shaped grippers (or another shape which will not permit rotation) which meshes with sloped hexagonal-shaped interfaces. This would slide along the strut axis to grip the strut. The reason this idea came about, was because the gripping motion could be used to pull back the joint operating collar during locking and unlocking. But it was also thought that, since this moved in the same direction as the internal helical sleeve, this could be used in combination with the internal helical sleeve to simplify the design. Since both are moving in the same direction, if one motor drove both of them, connecting there motion may be easier.

The mechanism which drives the insertion platform must lift the platform, operate the sleeve, operate the strut holder and then lower the platform. Using the sleeve and the sliding gripper this would mean that a square shaped output curve would be desired. This square shaped output would first lift the insertion platform while holding the sleeve and strut holder stationary, then, while holding the platform stationary, the sleeve and strut holder could be actuated. This square shaped output would then allow the insertion platform to be lowered while holding the sleeve and strut holder stationary. Now different methods of developing square shaped output curves will be investigated.

A simple rotating crank is close to the square motion desired, since it produces a circular output. This does not approximate a square very well, but due to its simplicity it was considered for use. A possible way to more accurately make a square with a mechanism was developed and is shown in Figure 5-6a, b and c. This is based on a scotch-yoke mechanism. A crank on this mechanism moves a profiled follower. The end of the crank is also attached to a flat follower in a groove on the first follower. As the crank rotates, the second follower moves in a circular pattern like the end of the crank. When the crank reaches the curved part on the first follower, this follower remains stationary since the radius on this follower matches the radius of the crank. But as the crank continues to turn the second follower goes along a straight line until the crank reaches the flat area of the first follower again. At this point the second follower follows a circular pattern again.

The receptacle fingers could not easily be operated by a motor which also ran another mechanism, so the proven design of the NASA LaRC developed receptacle fingers was used.

For the second design the following items will be combined. The sleeve will be used with the sliding strut holder. The mechanism discussed above which approximates square motion will be used to lift the insertion platform and actuate the sleeve and strut holder.

The first approach to the design of mechanism A is shown in Figure 5-7a,b,c,d and e. This figure shows the sleeve and the strut holder, which slides on two shafts.

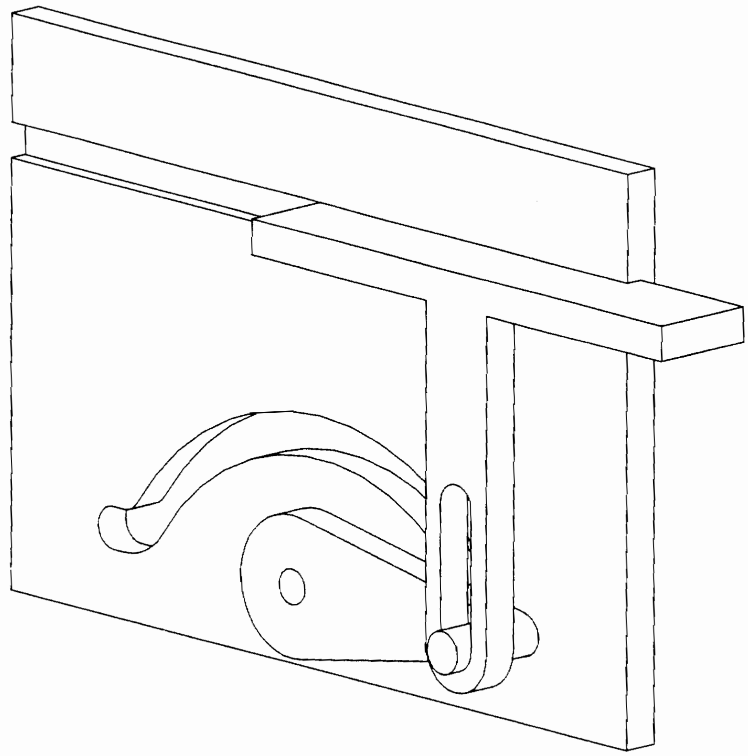


Figure 5-6a. Crank and Follower Mechanism.

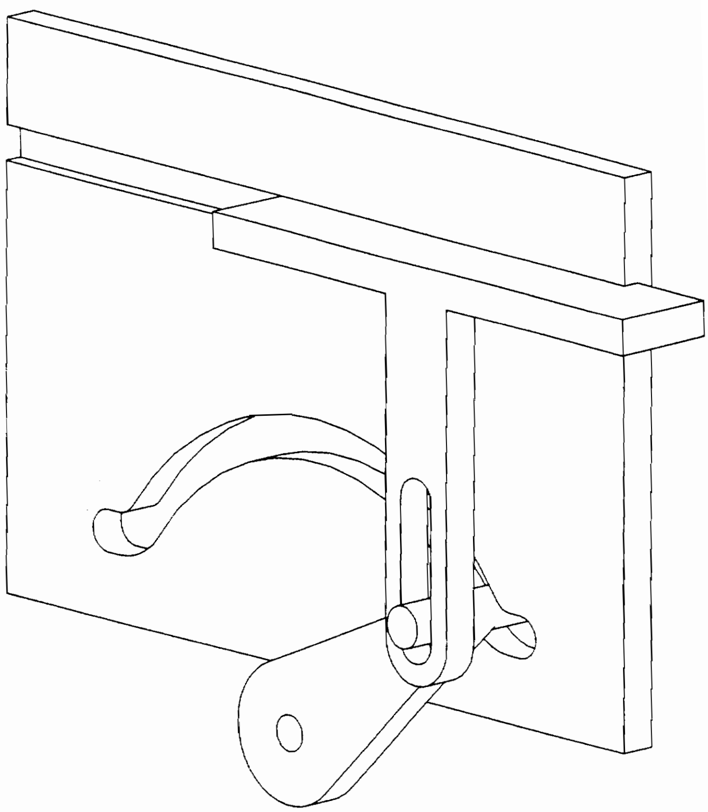


Figure 5-6b. Crank and Follower Mechanism.

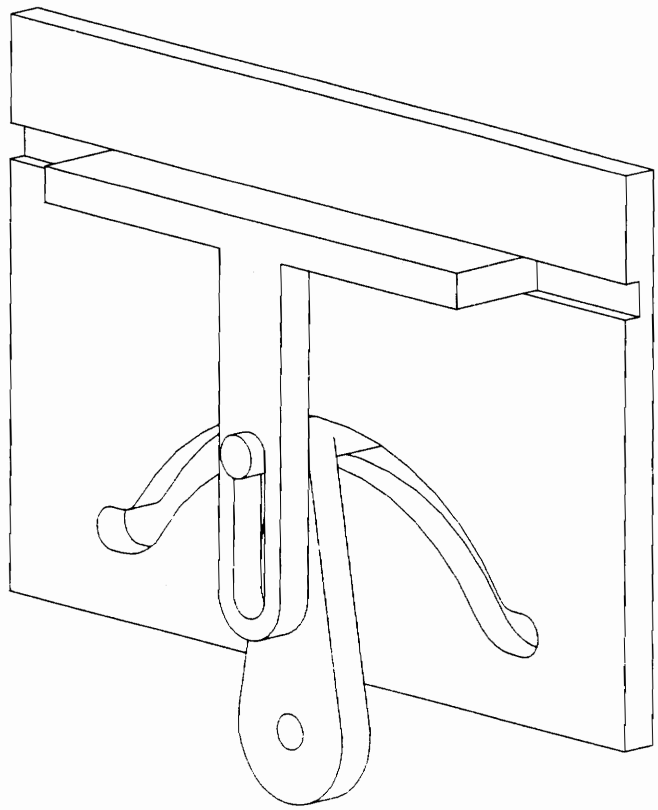


Figure 5-6c. Crank and Follower Mechanism.

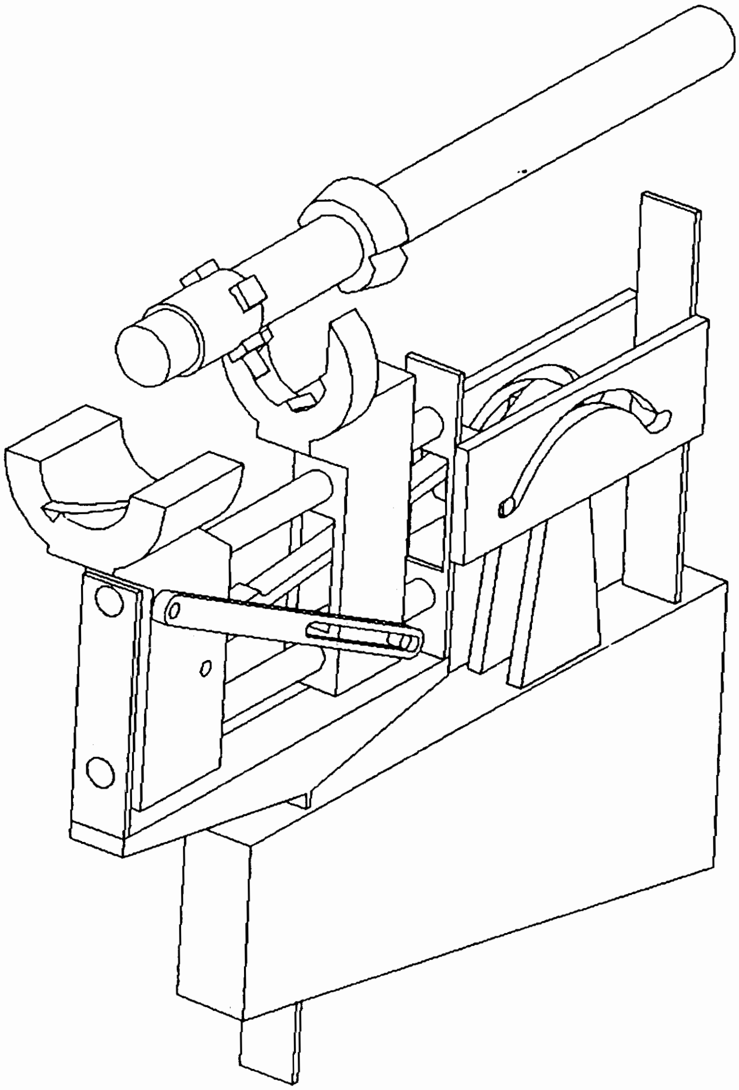


Figure 5-7a. Mechanism "A" Initial Position.

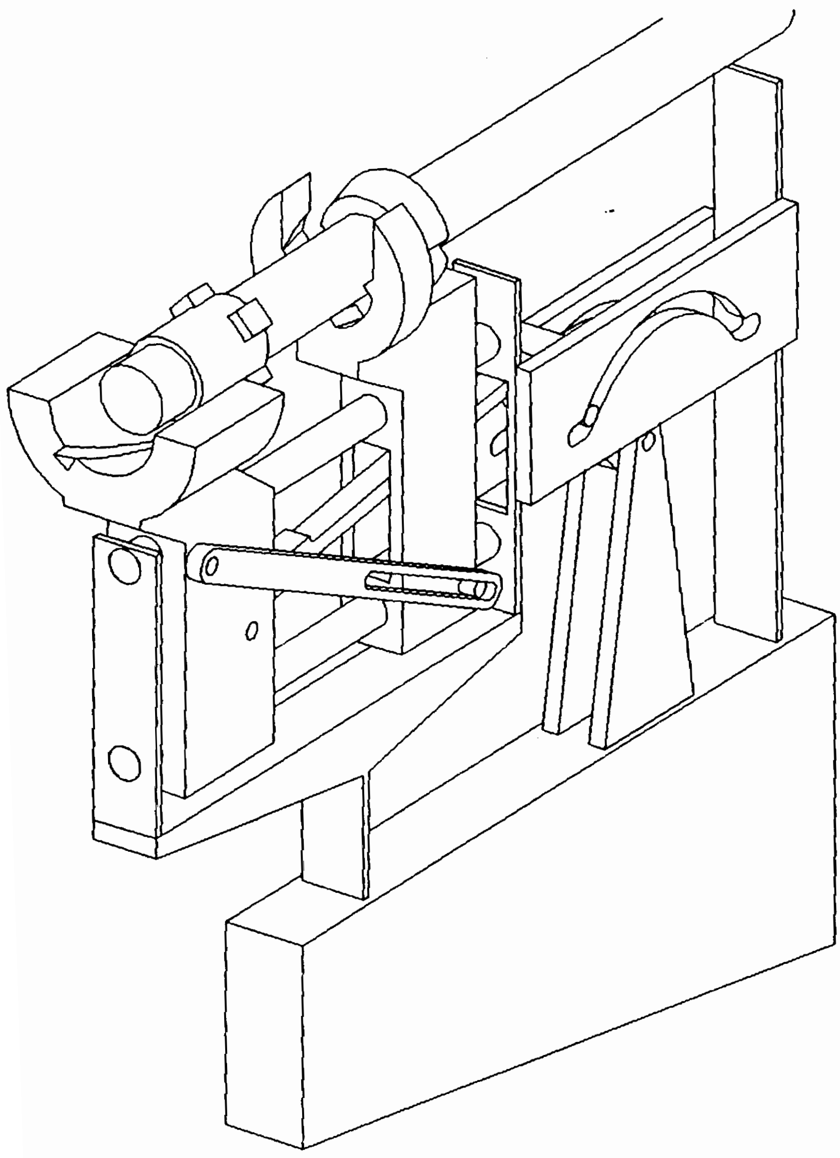


Figure 5-7b. Mechanism "A" Step 1.

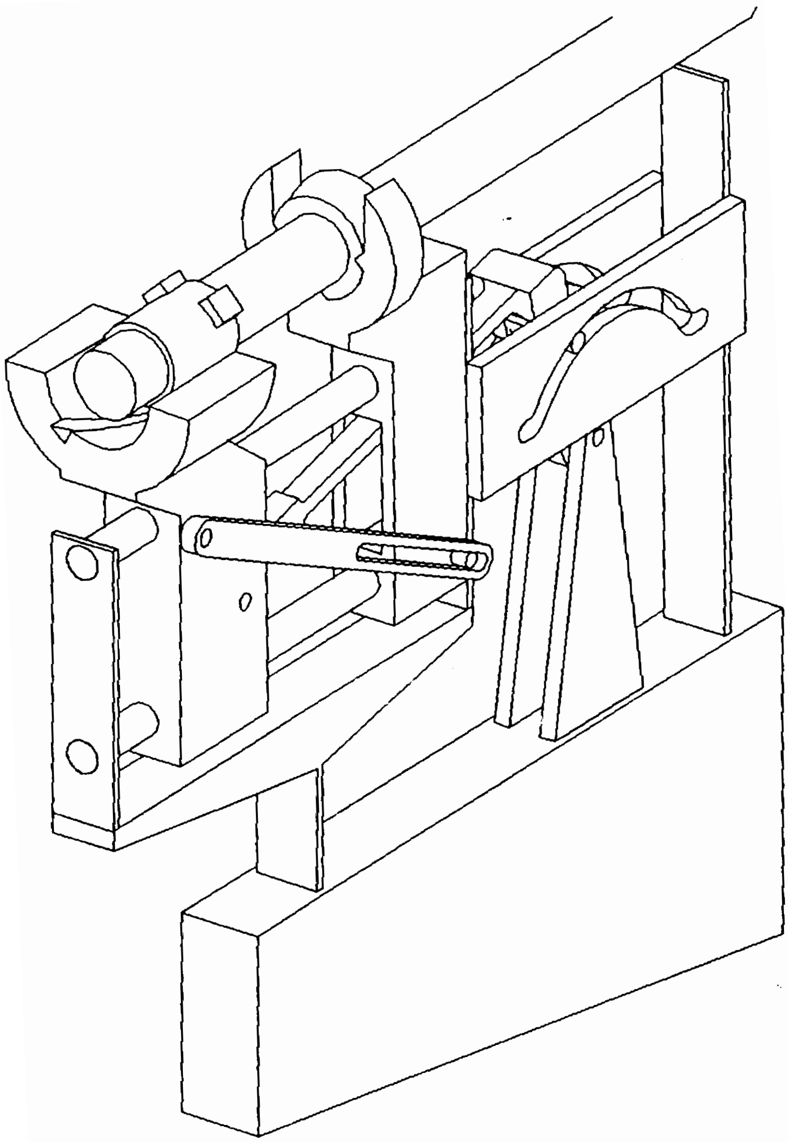


Figure 5-7c. Mechanism "A" Step 2.

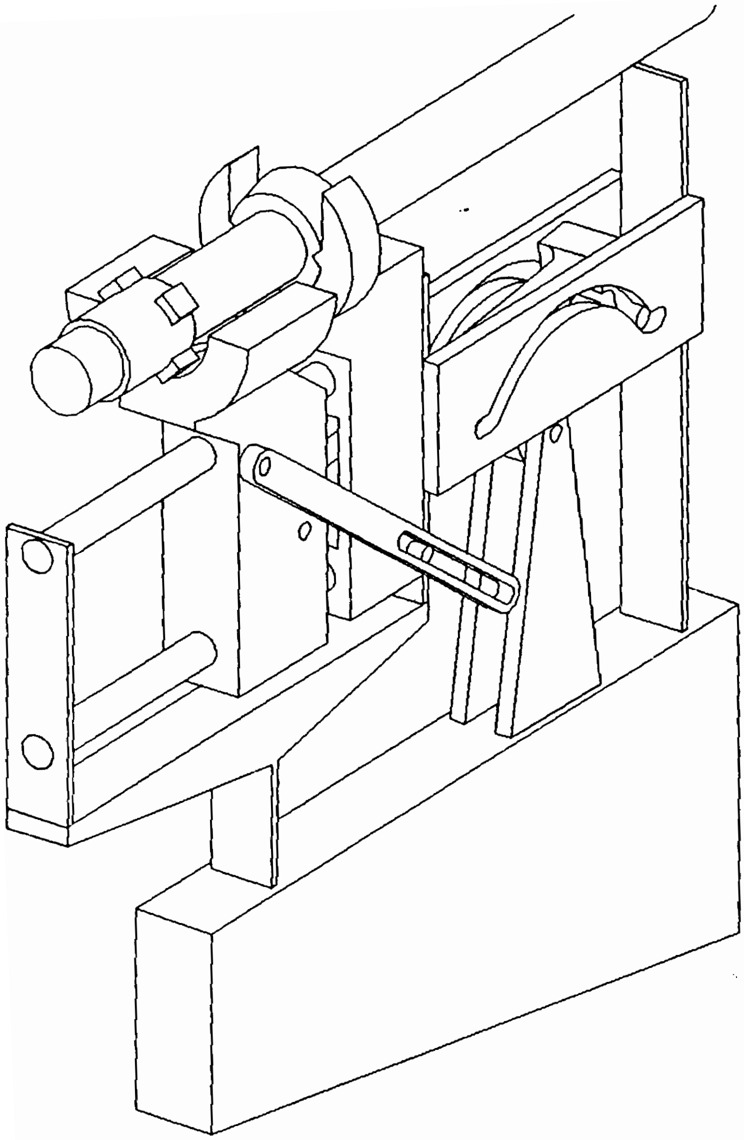


Figure 5-7d. Mechanism "A" Step 3.

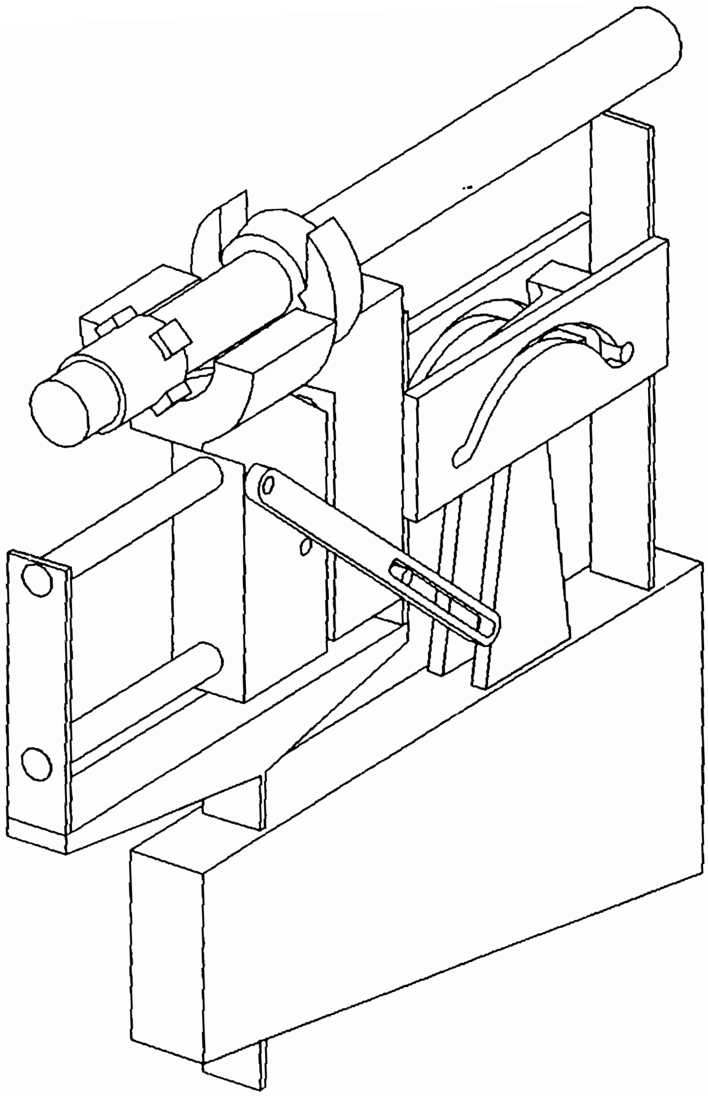


Figure 5-7e. Mechanism "A" Step 4.

These components are attached by a link which can slide on the pin located on the strut holder. The sleeve and strut holder would be resisted from sliding together by a spring between the pin on the strut holder and the linkage, although this spring is not shown. The sleeve is actuated by the rod which is attached to a crank. The crank also slides in a slot which controls the up and down motion of the insertion platform. The crank will be coupled to a motor for actuation of the mechanism.

The strut holder, shown in Figure 5-7, is circular shaped and tapered with three protrusion to stop rotation of the strut. The tapering is so that the strut will be positioned as it is grasped. The shape which accepts the strut holder is the inverse of the shape inside the strut holder with a hole in the center so that it can be slid over the strut. Once this is slid over the strut it is bonded in place with epoxy.

The crank and slot assembly, shown in Figure 5-7, is used to lower and raise the insertion platform assembly. This insertion platform is raised while the crank is on the flat part of the slot. When the crank reaches the curved part of the slot, whose radius equals the radius of the crank, the insertion platform stops and the crank actuates the sleeve and strut holder. The proper actuation of the sleeve and strut holder is controlled by the link and the attached spring.

As the sleeve is pulled by the rod, the strut holder moves along with it until it contacts the strut. At this point, as seen in Figure 5-7c, the sleeve continues to move unlocking the strut. While this is happening, the spring on the link is being compressed, applying a near constant force to the strut holder.

Once the strut is unlocked, the crank continues to move pulling the sleeve with it. As it continues to rotate around it pulls the insertion platform back down.

5.2.1 Problems with Second Design

Some of the problems with this mechanism are as follows. As seen in Figure 5-8, the sleeve must start in front of the joint; this causes a clearance problem because, during assembly, the strut may be attached to a joint which may have other end joints attached to it. This sleeve in the position shown would interfere with other struts. Also, receptacle fingers must be added to this end effector, and the position of the sleeve would interfere with any type of grippers used to grasp the joint receptacle. Another problem is with the spring between the sleeve and the strut holder. If one end joint had a node attached, while the opposite end was trying to unlock the joint operating collar, this would push the strut and the strut holder attached to it or could load the receptacle fingers. If both ends were unlocking the joint, these forces would tend to counteract each other, but most likely the strut would tend to move axially back and forth, since its only resistance to motion in that direction is a spring. After reviewing the problems associated with this mechanism it was determined that it was necessary to develop a new mechanism to take the place of the link and spring.

5.3 Latch Development

The link and spring replacement mechanism must allow the sleeve and the strut holder to move, lock, then the linkage would continue to move. One mechanism which was designed and is capable of accomplishing this is shown in Figure 5-9a,b

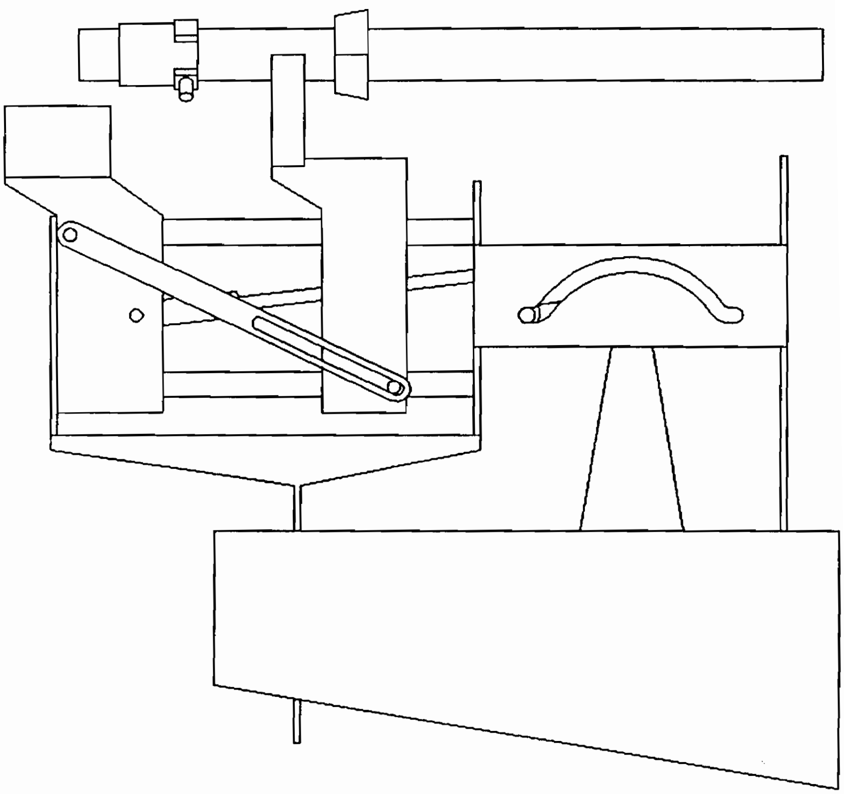


Figure 5-8. Side View of Mechanism A

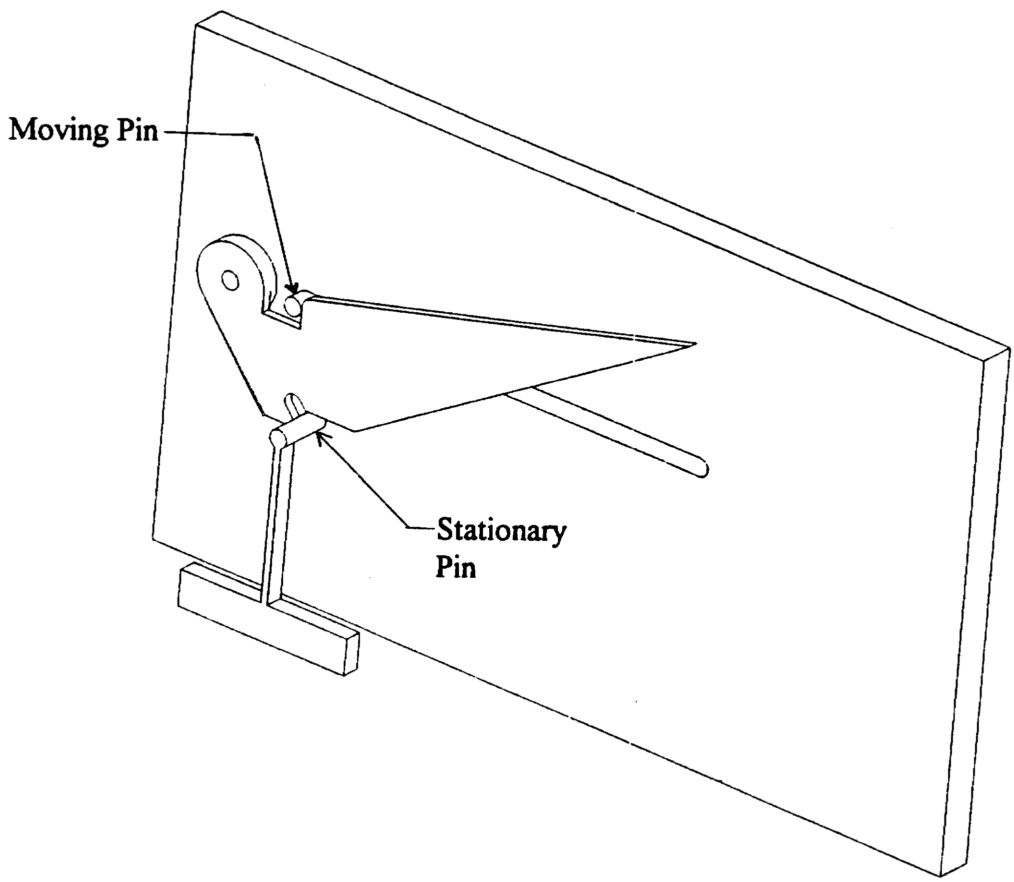


Figure 5-9a. Latch in Unlatched Position.

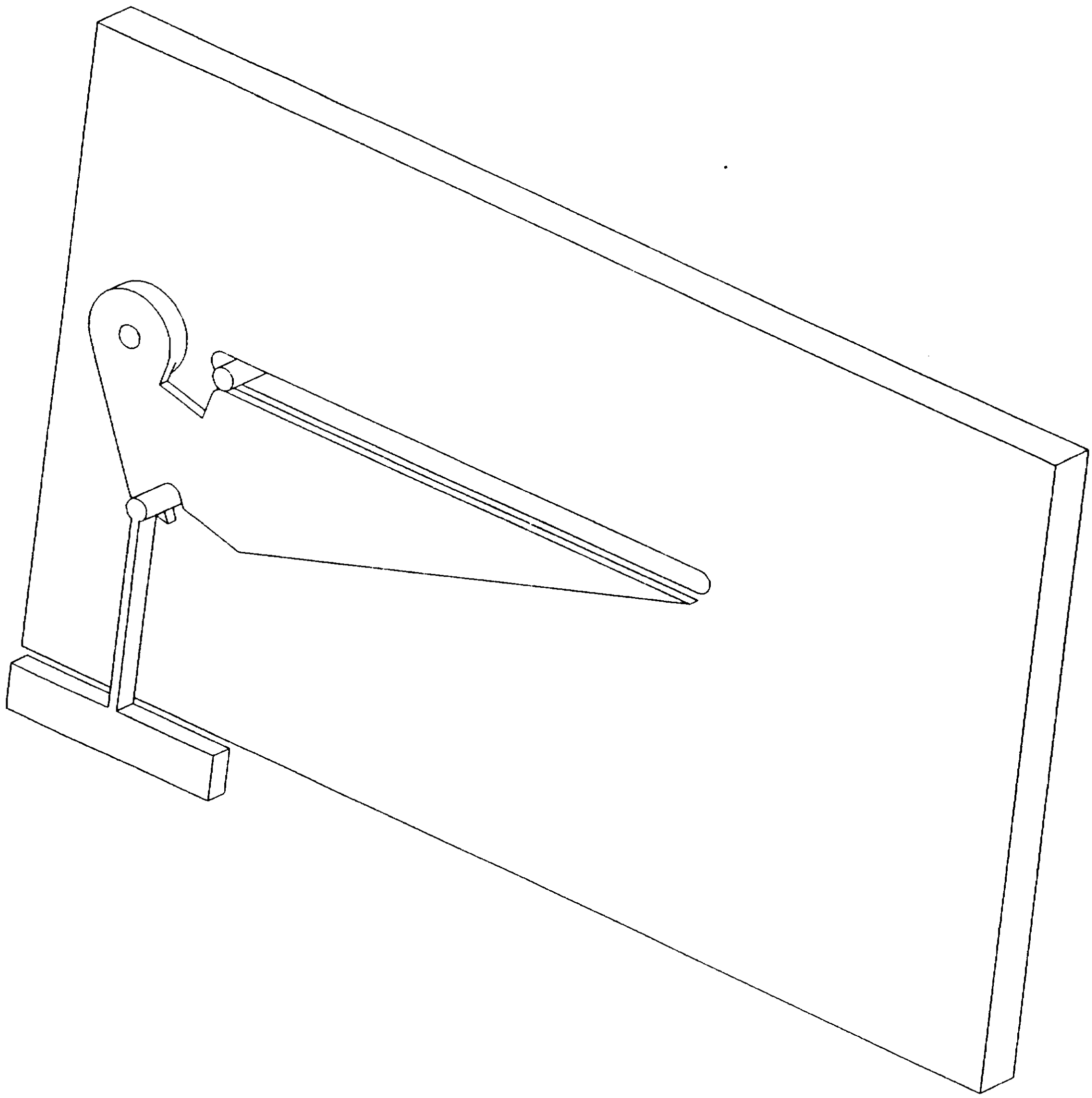


Figure 5-9b. Latch in Initial Latched Position.

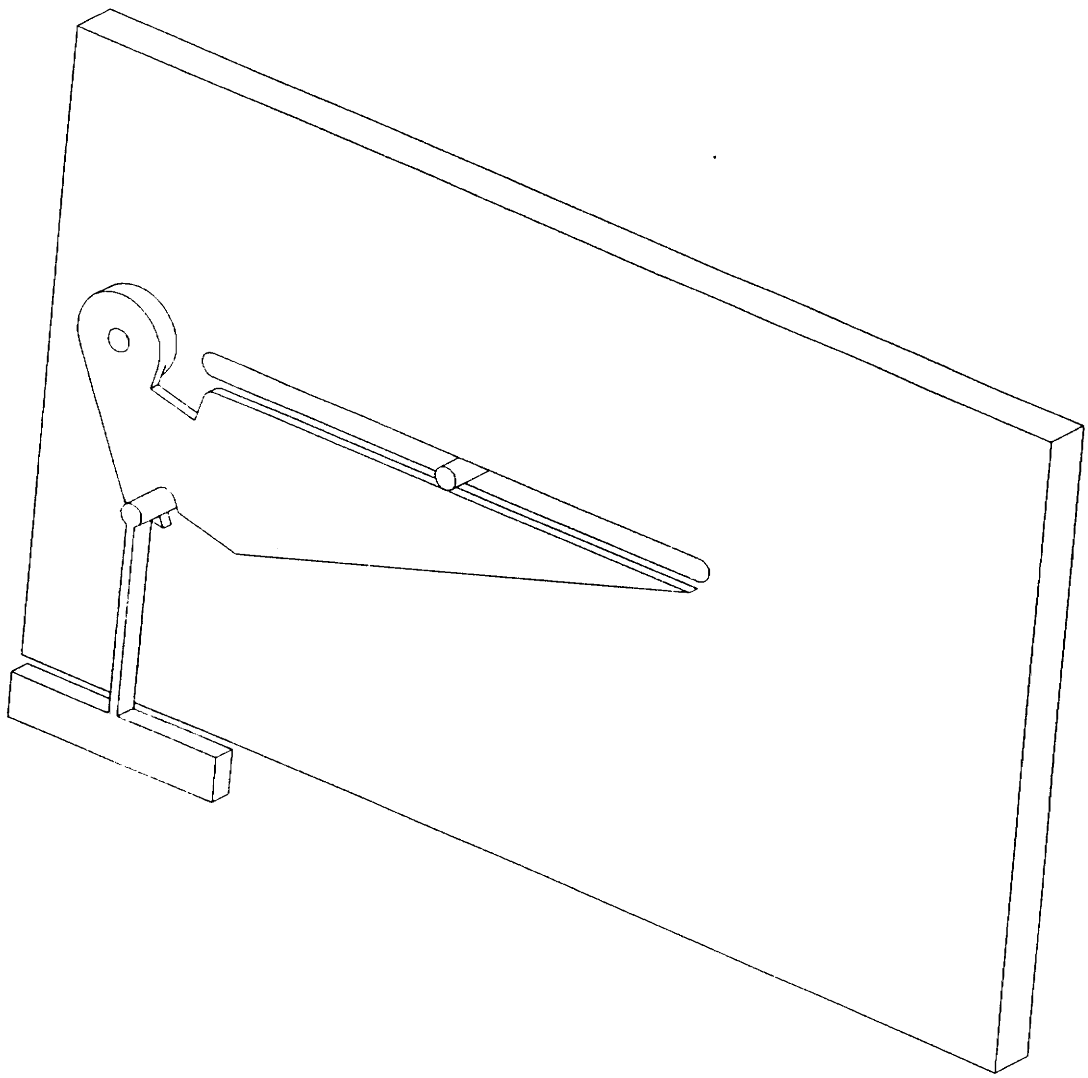


Figure 5-9c. Latch in Latched Position.

and c. This is a latch which is actuated by a stationary pin and a moving pin.

The latch starts in the unlatched position, a spring (not shown) holds the latch in position for the moving pin to move the latch along with it. The force applied by the moving pin is only to move the latch, no force goes into rotating the latch because the applied force is radial from the center of rotation of the latch. So the moving pin continues to move the latch, without any rotation of the latch, until the latch comes in contact with the stationary pin. At this point the latch begins to rotate. As the latch continues to rotate the pressure angle on the moving pin begins to move to a tangential direction, forcing the latch to rotate along with the stationary pin. Then when the moving pin gets to the flat area of the cam, the latch is latched and this moving pin can continue to move while holding whatever is attached to the latch stationary. The latch has two cam surfaces, one for actuation by the moving pin and one for actuation by the stationary pin. Refer to Appendix C for a detailed analysis of this latch.

5.4 Final Design

The final design will be very similar to the second design, but it does not have the linkage with a spring controlling the motion between the strut holder and the sleeve. The latches developed in the previous section will be used to replace this linkage. One latch will be used on the strut holder and one will be used on the sleeve. For a complete analysis of this final design refer to Appendix D.

A drawing of the final design is shown in Figure 5-10a and b. Since this crank is

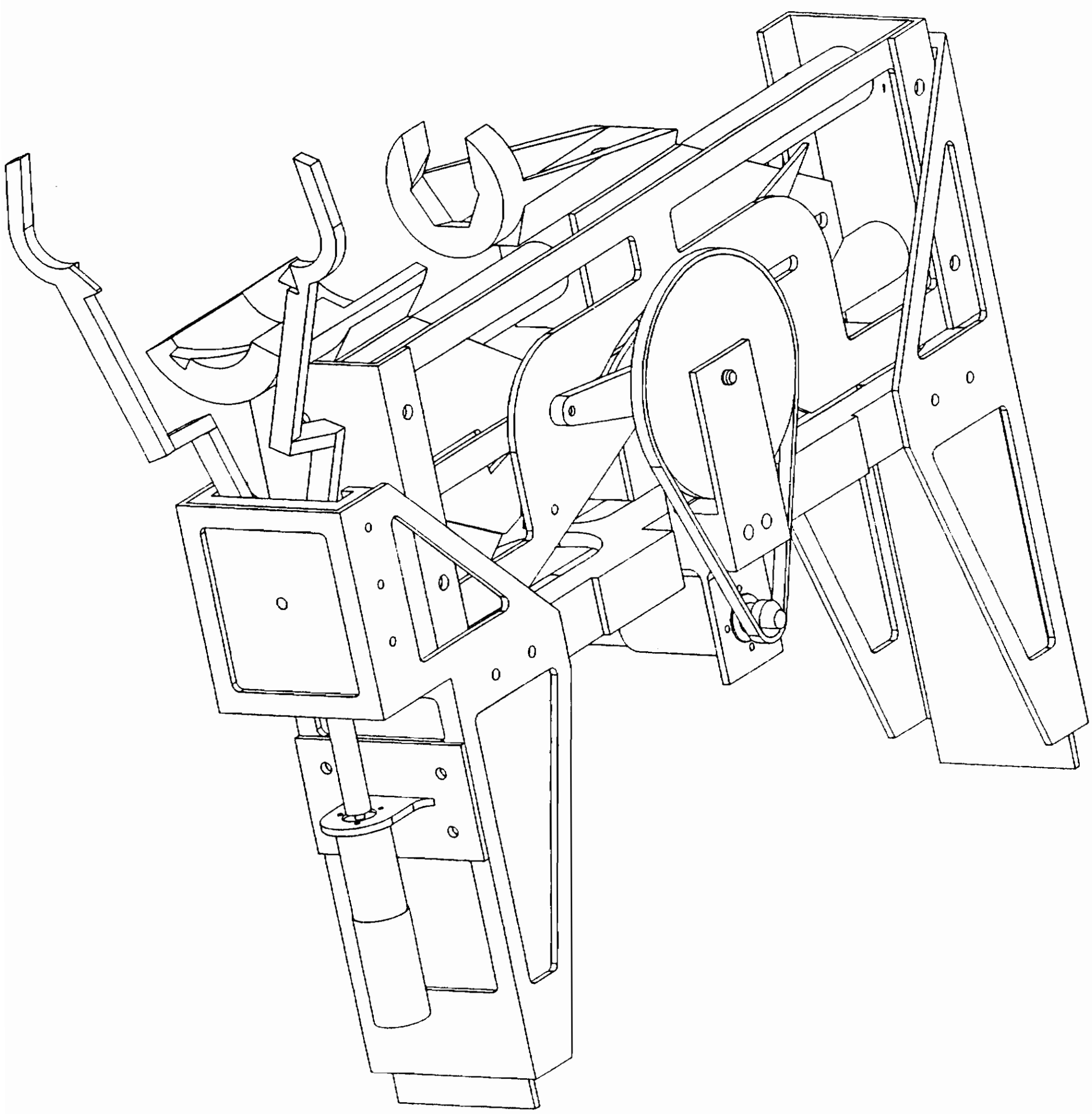


Figure 5-10a. Final Design (Mechanism "A" and "B").

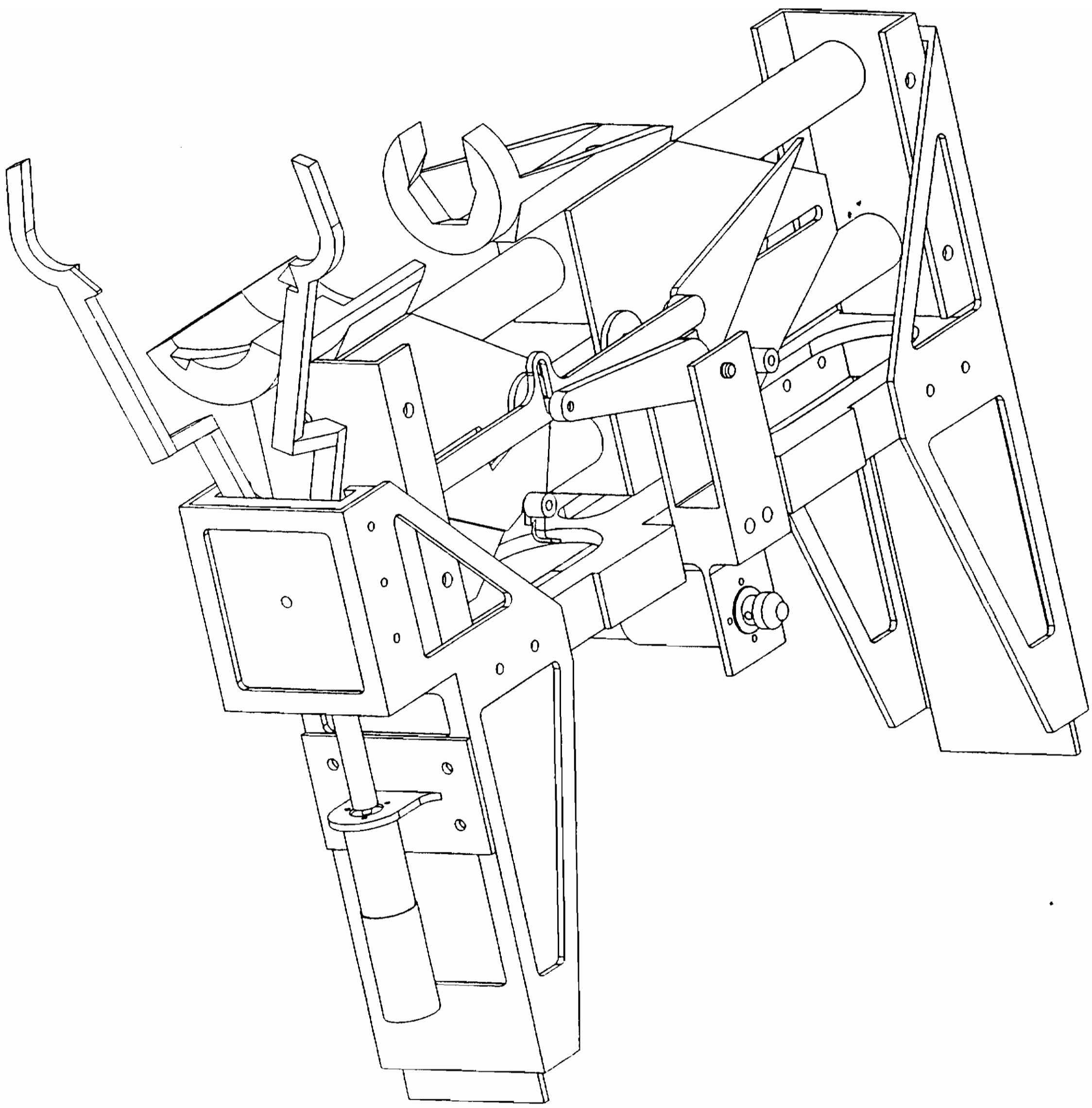


Figure 5-10b. Final Design (Crank Follower Removed)

longer than the crank on the second design and the travel distances for the linkage driving the sleeve and strut holder are longer, it was necessary to rearrange the components of the end effector from the previous design. For the final design, the crank and follower are in front of the sleeve and strut holder to save space. The sleeve and strut holder are operated by a linkage, which in turn is operated by the crank.

Figure 5-10b shows the end effector with the crank and follower removed to show the linkage, the sleeve slot, the strut holder slot and the latches. The moving pins on the latches are on the linkage and the stationary pins are mounted on the slotted follower which the crank rides in.

The sleeve overhangs the left side of the insertion platform so that a vision system can be added to the end effector. The vision system is not shown but would be placed under the receptacle fingers. This position would allow the system to view the targets, which would be mounted on the node receptacle, while the end effector is in the position to grasp the node receptacle.

This one end of the end effector has two motors. One motor is mounted under the base and this motor actuates the insertion platform, the sleeve and the strut holder. The other motor is mounted under the receptacle fingers and operates the receptacle fingers. This end effector would have a total of five motors, two on each end and one in the middle to adjust for different length struts.

The operation of the final design is similar to the second design. As the crank rotates, the insertion platform is raised and the strut holder moves to grip the strut until the pin in the end of the crank reaches the curved part of the follower. As the crank continues to rotate, the strut holder grips the strut and the strut holder latch is locked. Then the sleeve latch is unlocked allowing the sleeve to unlock the end joint. Once the end joint is unlocked, the pin in the crank reaches the flat portion of the follower and begins to lower the insertion platform and the sleeve continues to move with it. The crank is operated by a chain drive system, which is driven by an electric motor. The motor has an encoder to verify the position of the crank.

A model has been made of the insertion platform with the latches, sliding sleeve support and strut holder support. This model was made of wood to verify the operation of the latches. When this model was first assembled, the operation of the latches was not very smooth and required excessive force to unlock. This problem was alleviated by lubricating the cam surfaces of the latches. Now the latches work smoothly and hold position well when locked. This model shows that these latches will work extremely well, especially when low friction materials are used.

Chapter 6
Advantages and Disadvantages of Final Design

The biggest advantage of this final design, compared to previous designs, is less computer control and less required feedback. For strut installation, when the end effector is moved over to the strut and the end effector has been positioned with the receptacle fingers, one motor can be operated to grab the strut and remove it from the structure. This will only require that the motor be commanded to rotate through some angle. The old method would have involved four commands.

This final design requires four binary sensors and one analog sensor on each end of the end effector. Another analog sensor would also be required for the length adjustment of the end effector. Therefore, this end effector would require a total of eight binary sensors and three analog sensors. This end effector has less feedback sensors than any end effector previously designed. A double-ended end effector, similar to the LaRC tested end effector, capable of assembling variable length struts would require nine motors, sixteen binary sensors and six analog sensors. By reducing the number of sensors, this final design would be less complicated to operate.

The weight of one side of this end effector is approximately twelve pounds. This is heavier than the NASA LaRC designed end effector designed for the same task. As discussed earlier, one end of this end effector weighed approximately seven pounds. This final design has not been optimized, but by adding lightening holes and redesigning some of the items, the weight could be reduced significantly. One way to look at the weight advantage of this final design is to compare the weight of using the latches over installing a motor for each latch. The weight of each motor would be .23 pounds. The weight of the latches are .08 and .06 pounds. There is a clear weight advantage to use the latches instead of separate motors for the sleeve, strut holder and insertion platform.

By reducing the number of motors the chances of a motor failure has been reduced. Also, with this new type of design, a backup motor could be added if necessary without adding too much complication to the end effector. With previous designs, placing a backup motor for each motor would be a major task.

The biggest disadvantage to this design method is that in development it requires more time than previous designs and changes to the design after the parts are made would be extremely costly. For example if the final end effector was made and a smaller pressure angle was needed on the sleeve, the sleeve length would need to be extended. This change would mean redesigning the entire end effector since many of the dimensions are dependent on the sleeve slide length. The added cost of development could be outweighed when assembling a large quantity of items.

From the beginning of the design a problem that needed to be solved was the ability for the end effector to back out of any situation. With the first design, if the joint jammed while the strut holder gripped the strut and the joint was unlocked, there was no way for the end effector to release the strut. This final design does allow the end effector to release the strut in this event. The strut can be released in these circumstances by increasing the length of the end effector and rotating the crank to move the sleeve toward the center of the strut. If the end effector was not able to release the strut, this design would have a major disadvantage. Using the first design, if one of the joints jammed, the end effector would be stuck holding a strut and not be able to continue assembling the structure.

This design method developed for this thesis is clearly advantageous from a control and feedback point of view. It does not appear that any significant weight reduction could be achieved using this method, but it does seem possible to design without any additional weight penalty. The weight issue would need to be studied further to develop weight reduction techniques. The biggest disadvantage of this final design is in the design time and redesign time. The design time could be reduced if there were a database available with many different types of mechanism which have intermittent output.

Chapter 7
Conclusions

The design methodology developed in this thesis clearly has some advantages over previous and current design methods. The biggest advantage is the control and feedback required is less than most other design methods. The biggest disadvantage is the extra design and redesign time required. The redesign time required is inherent in the method and cannot be reduced. The design time could be reduced if a database were available with many different types of intermittent output mechanisms. There are not many of these mechanisms developed or documented, so a data base would reduce the amount of ground up designing required.

The design became much simpler when the idea of developing systems to move in the same direction was applied for items operated by one motor. For example when the strut holder was designed to move in the same direction as the sleeve, the design was simplified. Then the crank and follower was developed to move in this same direction also. This idea was very helpful in the design process and should be added to the design method. If this idea had been used from the beginning of the design a lot of time could have been saved.

The idea of maximizing reversible processes to direct the design does appear to be a viable design method for complex end effectors. There may be other ways to group the assembly steps, but this method works, giving a simple, easy-to-control end effector. The method is not limited to end effectors. It could be used for many kinds of complex mechanisms. This method should be considered for any system which uses many motors to operate latches or position items.

One idea for future work is to develop a mechanical "assembly language" to design control systems using this design methodology. Mechanisms, like the latch developed in this thesis, could be combined to control systems mechanically using the developed method of grouping the operating steps. By having a general method of grouping the steps, many different systems could then be operated by standard mechanical components assembled together.

Section 7.1 Commercial Applications

A packaging plant was visited to see what machines are used in industry and find examples to apply this design methodology. The information in this section was obtained from Ray Philbates (1994) on a tour of the Philip Morris cigarette plant in Richmond Virginia. Most of the machines at this facility use mechanical control. One machine which uses electronic control is the Sasib Alpha Packer cigarette packaging machine. This machine performs the same function as the G.D. X-1 cigarette packaging machine, but the Sasib machine uses approximately 30 motors while the G.D. machine uses only two motors. There have been a lot of mechanical failures with the Sasib machines according to Ray Philbates (1994), so Philip Morris is going to replace these Sasib machines with mechanically controlled G.D. machines.

Another application of this method will be discussed with an example that was found at the Phillip Morris plant. The machine for this example is a Vertical Tray Filling (VTF) machine, which stacks cigarettes in trays. This machine was investigated to see if the number of motors could be reduced using the methodology developed in this thesis. This machine performs several different operations, but to keep things simple, only the operation of the tray positioner, cigarette holding platform and the plunger will be discussed. Figure 7-1 shows a schematic representation of these components. Figure 7-2 shows the current sequence of operations of this VTF machine. These schematics are labeled the same way the schematics in Chapter 4 were labeled. This system uses two motors and one of the motors performs multiple tasks. The motor that performs many tasks is designated mechanism B. Mechanism B also performs two steps (both labeled B2F) at once, which are moving the plunger in and lowering the tray positioner. In this sequence there is not a way to organize these steps into reversible sets of steps, so this sequence was modified. Figure 7-3 shows these steps reorganized reversibly to allow one mechanism (mechanism P) to operate everything. In order to make the sequence reversible, the second part of step B2F (lowering tray positioner) was moved from before step A1R to after step A1R. The mechanisms to perform this sequence of

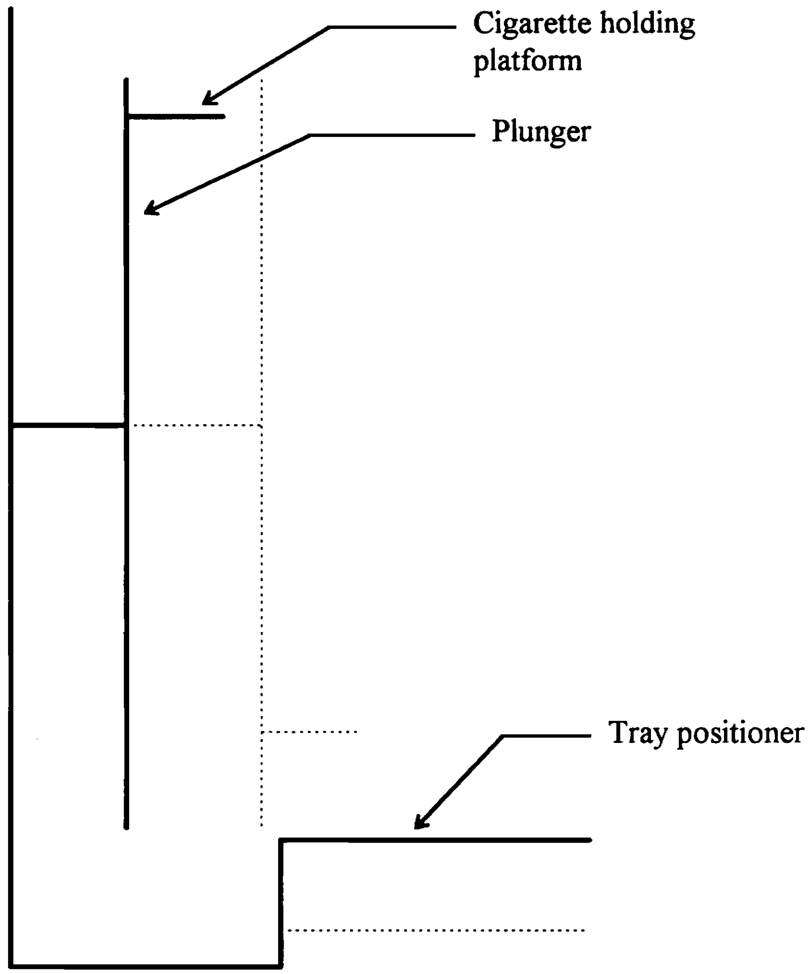


Figure 7-1. Vertical Tray Filler Schematic

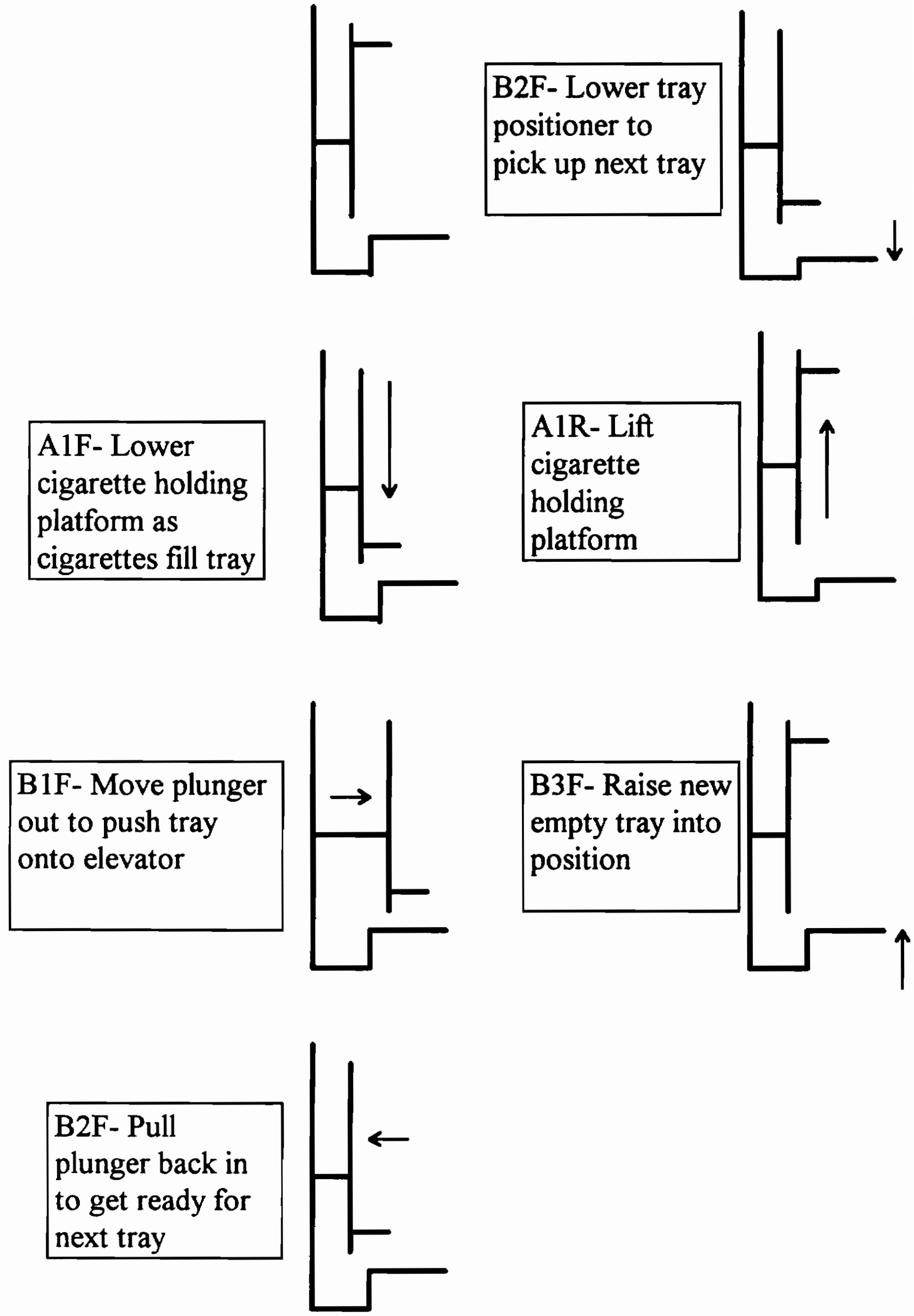


Figure 7-2. Vertical Tray Filler Operations

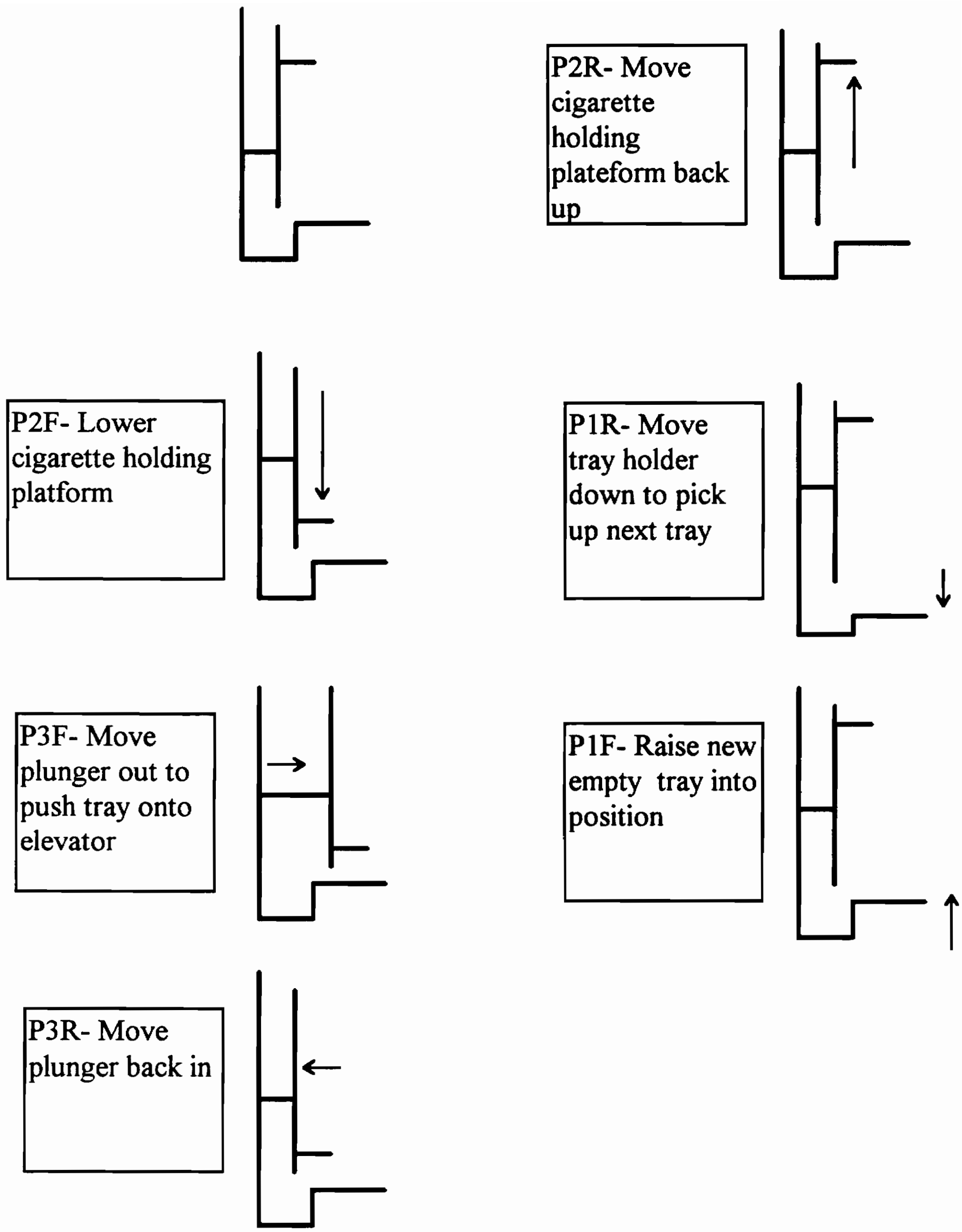


Figure 7-3. Vertical Tray Filler Operations Organized to Operate Reversibly

operations were not designed, but this does show an application of this design methodology.

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Appendix A
General Equations for Internal Helical Groove

The following general method was developed to analyze the pressure angle of the follower within the helical groove which actuates the end joint. To insure smooth motion and to control the pressure angle, Kloomok and Muffley (Mabie and Reinholtz, 1987) curves were used to create the motion specifications for these internal helical grooves. These curves were chosen because they are commonly used in cams to reduce jerk and minimize discontinuities.

Harmonic and cycloidal curves developed by Kloomok and Muffley (Mabie and Reinholtz, 1987) are used to change rotary motion into linear motion. The use of these curves for changing linear motion into rotary motion will be developed. An example of the use of this technique is shown in Figure 5-1a and 5-1b. The mechanism shown has a linear relationship of angle of the shaft versus displacement of the sleeve. For ease of analysis this simple relationship will be analyzed and the results will be expanded to include the other more complicated curves.

The harmonic and cycloidal curves must be changed slightly in order for the curves to be used to change translation into rotation. The curves must be mapped onto a cylinder. First we will start with a linear relationship between angle and displacement to show how this curve can be mapped onto a cylinder, then it can be done similarly for other curves. A linear curve is shown in Figure A-1a. The equation for this curve is:

$$S=\frac{L}{\beta}\theta \qquad \text{A.1}$$

where:

S = Translation of follower

L = Final translation of follower

β = Total angle change of cam

θ = Angle change of cam

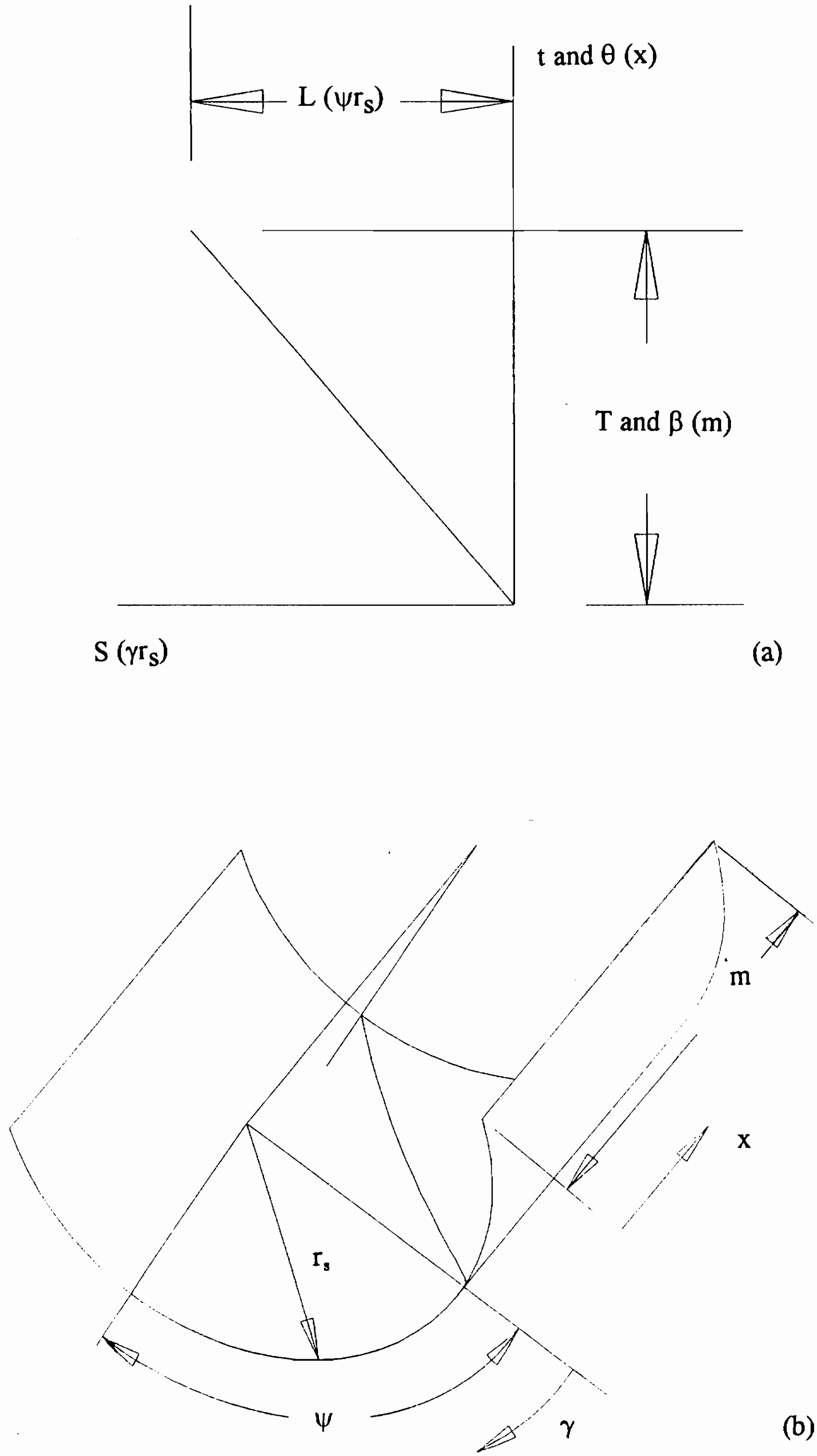


Figure A-1. Linear Curve Placed on Cylindrical Surface

Time or θ is plotted on one axis and displacement is plotted on the other. In order to map this linear curve on a cylindrical surface as shown in Figure A-1b we must make the following substitutions.

$$S=\gamma r_s$$

$$L=\psi r_s$$

$$\frac{\theta}{\beta}=\frac{t}{T}=\frac{x}{m}$$

Where :

S,L,β and θ are as defined in previous equation

t= time

T= Final time

r_s=Radius at which roller contacts groove

γ= Angular displacement of the follower

ψ= Angle of follower at time T

x= Displacement of sleeve

m= Displacement of sleeve at time T

With these substitutions the linear equation becomes,

$$\gamma r_s = \psi r_s \frac{x}{m} \qquad \text{A.2}$$

Cancelling r_s on both sides we obtain

$$\gamma = \frac{\psi}{m} x \qquad \text{A.3}$$

These substitutions can also be made for all the harmonic and cycloidal Kloomok and Muffley (Mabie and Reinholtz, 1987) curves as shown in Figures A-2 and A-3. Figure A-4 has all the variables labeled on a diagram of the mechanism.

It is relatively easy to calculate the pressure angle on this type of mechanism. The pressure angle as shown in Figure A-5 is simply:

$$\phi = \arctan \frac{d(\gamma r_s)}{dx} \qquad \text{A.4}$$

Where:

ϕ = Pressure angle

γ = Angular displacement of follower

r_s = Radius at which roller contacts groove

x = Displacement of sleeve

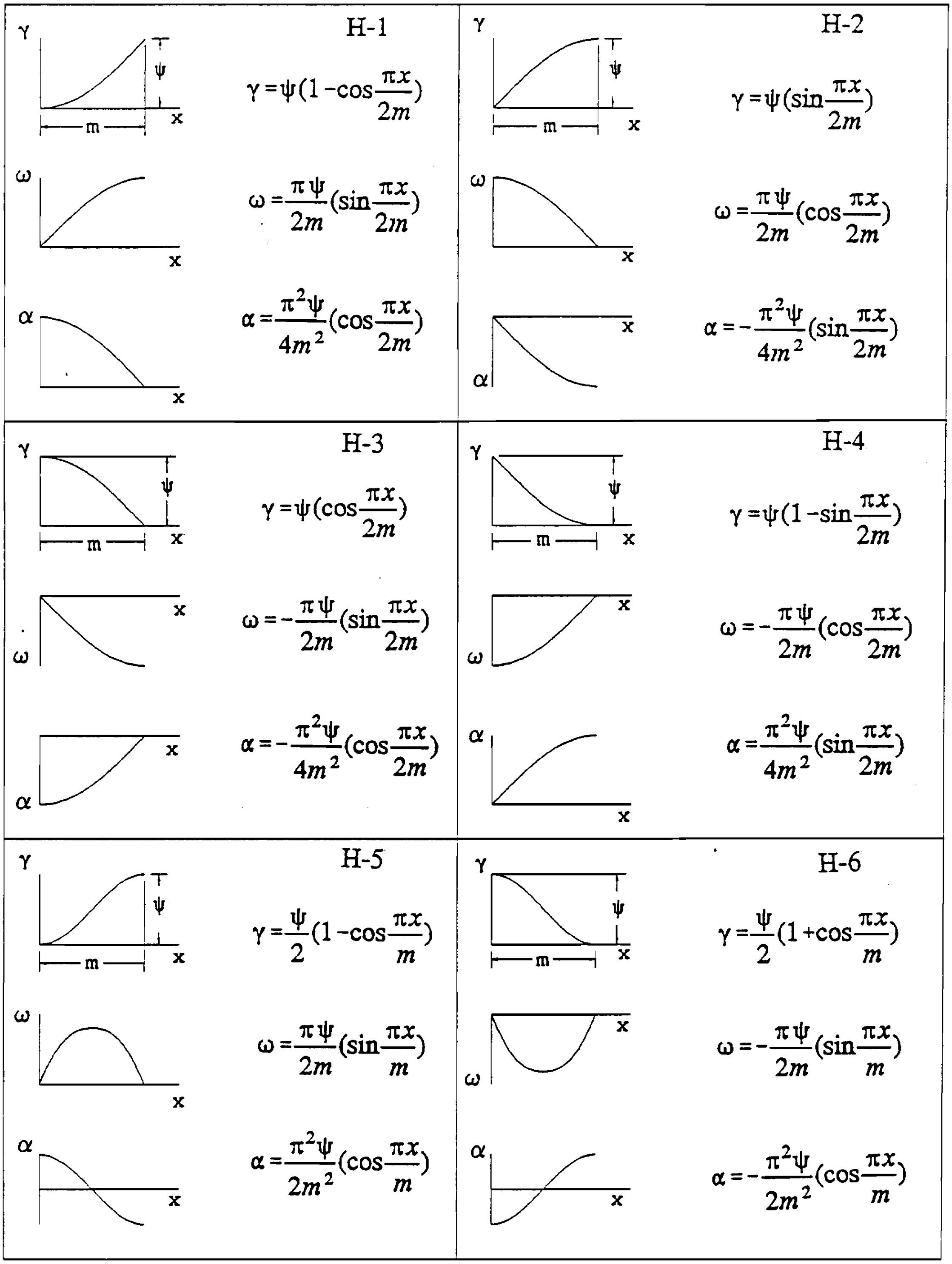


Figure A-2. Transformed Kloomok and Muffley Curves

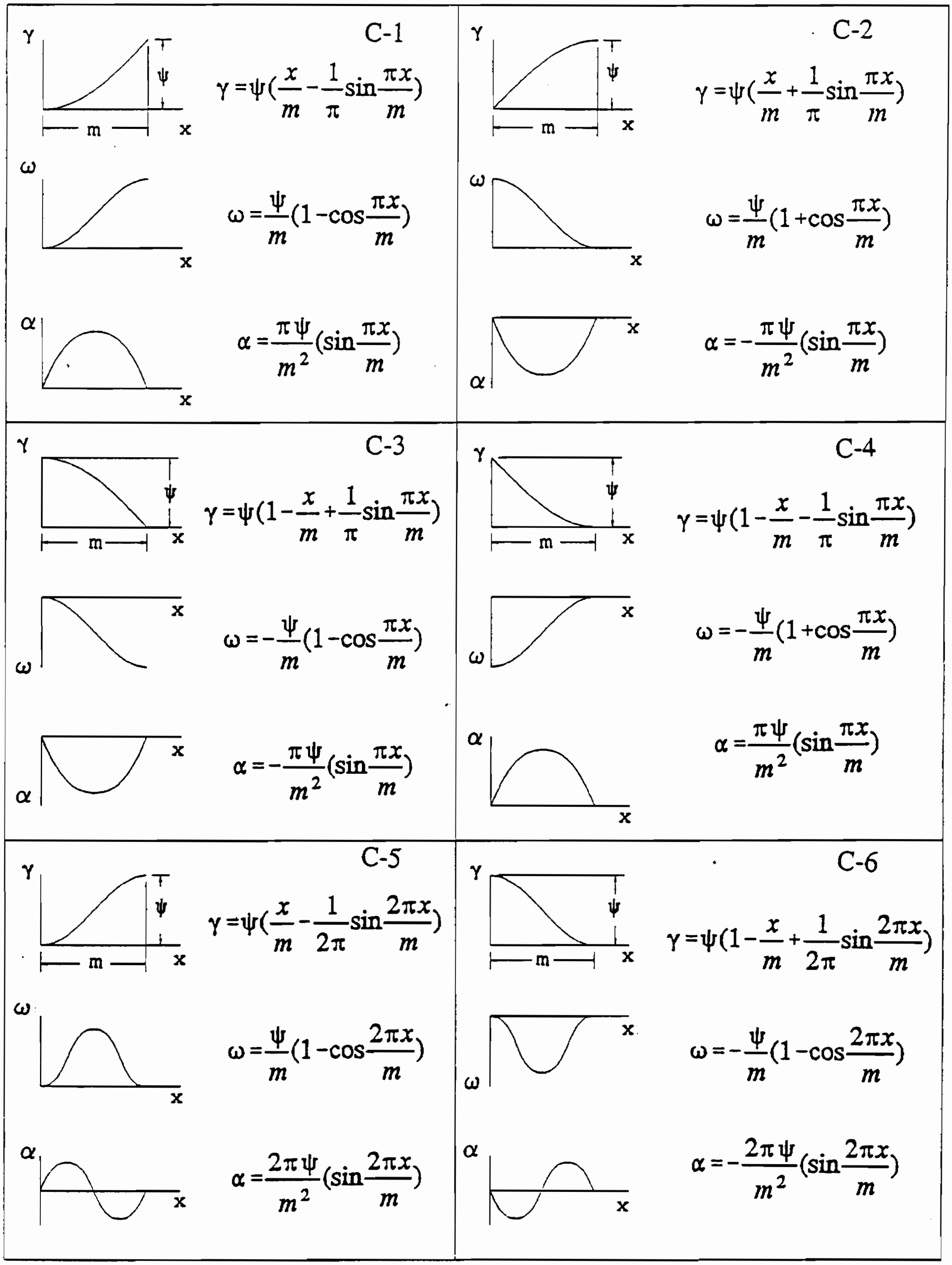


Figure A-3. Transformed Kloomok and Muffley Curves

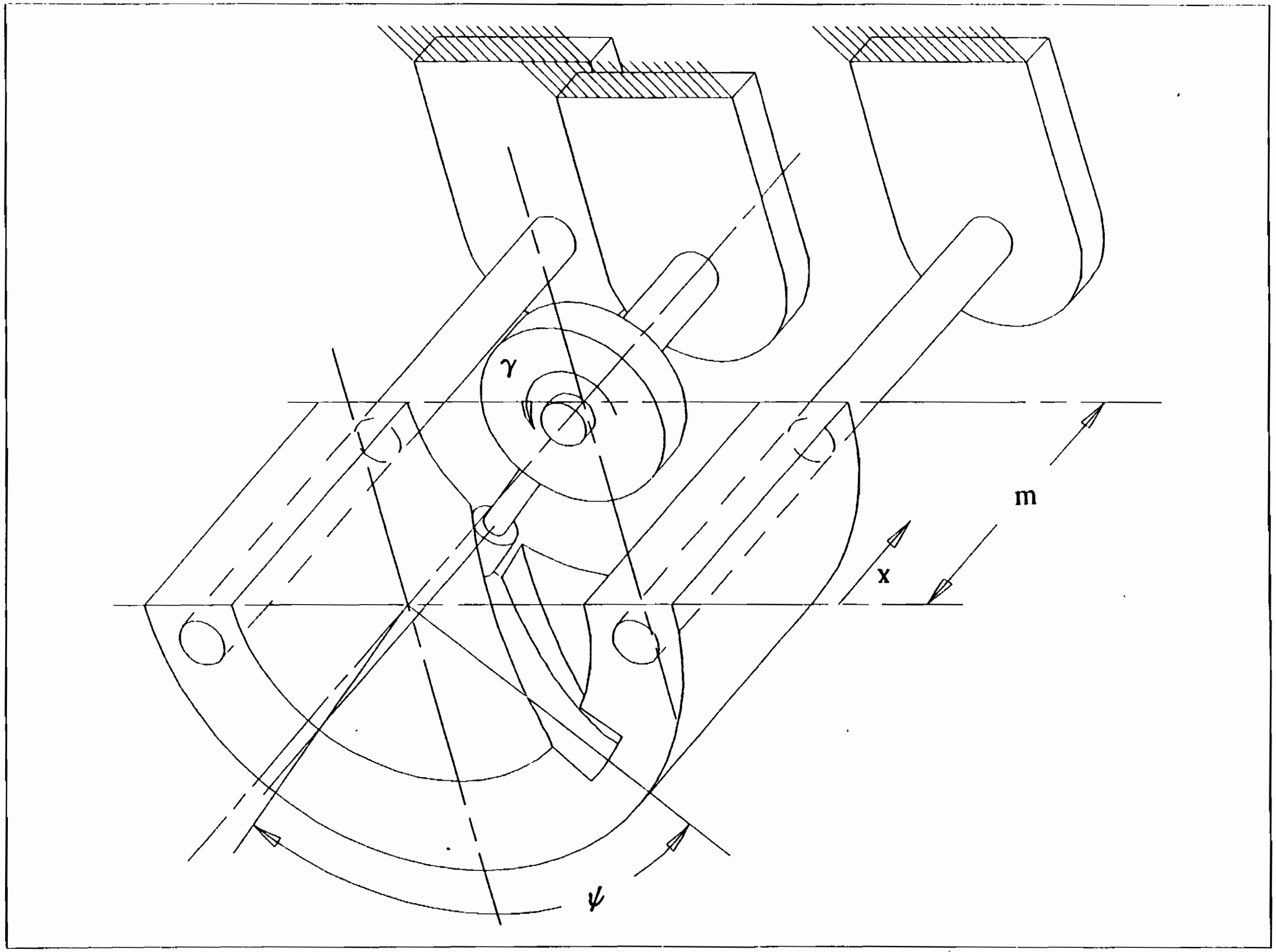


Figure A-4. Labeled Internal Helical Groove Mechanism

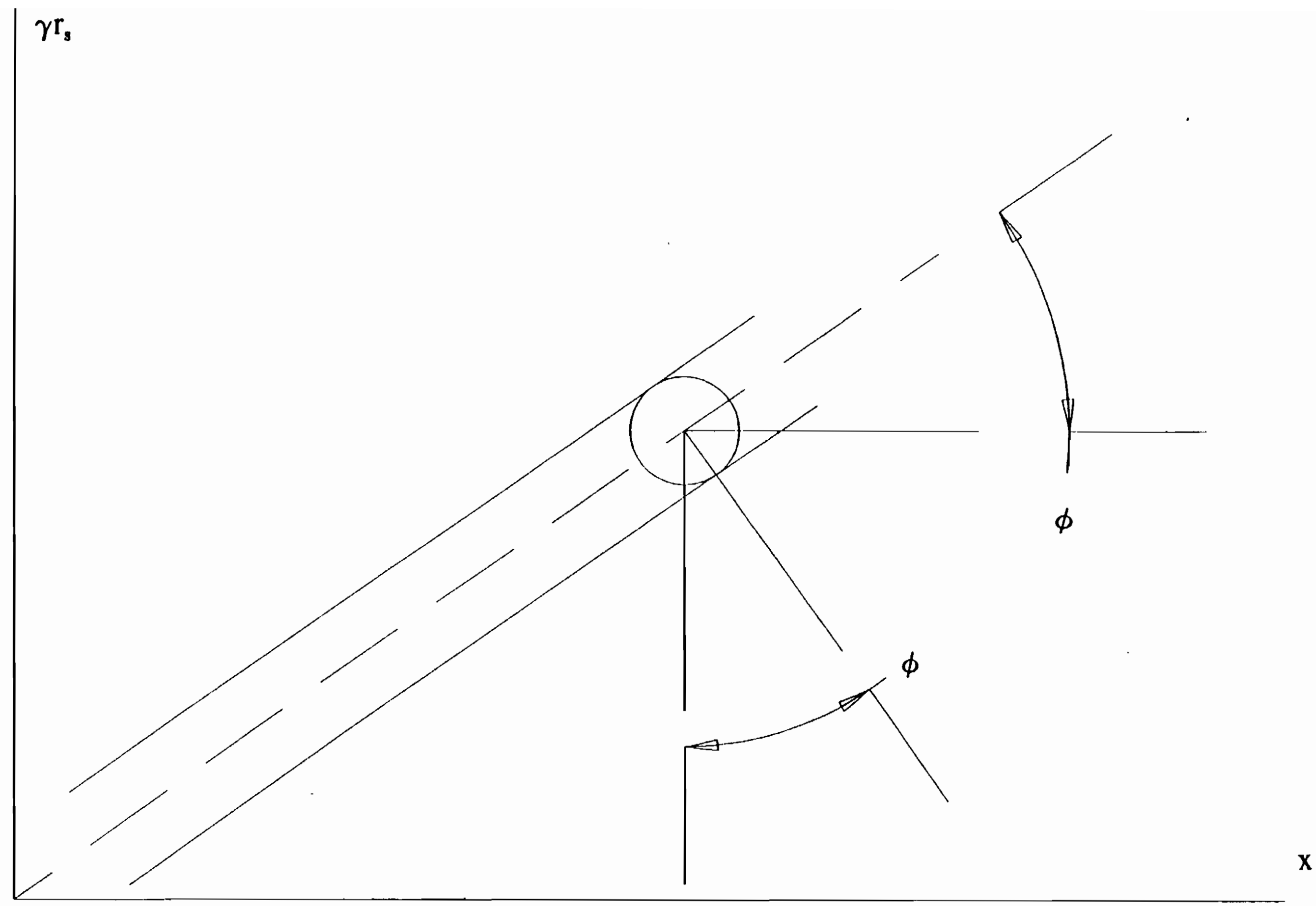


Figure A-5. Pressure Angle

The following steps show how the pressure angle can be determined from equation A.3. Multiplying both sides of equation A.3 by r_s:

$$\gamma r_s = \frac{\psi r_s}{m} x \qquad \text{A.5}$$

Taking the derivative of both sides:

$$\frac{d(\gamma r_s)}{dx} = \frac{\psi r_s}{m} \qquad \text{A.6}$$

Substituting equation A.6 into equation A.4 we obtain:

$$\phi = \arctan\left(\frac{\psi r_s}{m}\right) \qquad \text{A.7}$$

As can be seen from this equation, the pressure angle changes with r_s. As r_s increases the pressure angle increases since the pressure angle must be between 0 and 90 degrees by definition. This means that you must check the pressure angle at the furthest point of contact in order to get the worst case of pressure angle.

Pressure angle equations can also be derived for harmonic and cycloidal Kloomok and Muffley (Mabie and Reinholtz, 1987) curves, as follows;

H-1 and H-3

$$\phi=\arctan\left(\frac{\pi\psi r_s}{2m}\left(\sin\frac{\pi x}{2m}\right)\right) \qquad \text{A.8}$$

H-5 and H-6

$$\phi=\arctan\left(\frac{\pi\psi r_s}{2m}\left(\sin\frac{\pi x}{m}\right)\right) \qquad \text{A.9}$$

H-2 and H-4

$$\phi=\arctan\left(\frac{\pi\psi r_s}{2m}\left(\cos\frac{\pi x}{2m}\right)\right) \qquad \text{A.10}$$

C-1 and C-3

$$\phi=\arctan\left(\frac{\psi r_s}{m}\left(1-\cos\frac{\pi x}{m}\right)\right) \qquad \text{A.11}$$

C-5 and C-6

$$\phi=\arctan\left(\frac{\psi r_s}{m}\left(1-\cos\frac{2\pi x}{m}\right)\right) \qquad \text{A.12}$$

C-2 and C-4

$$\phi=\arctan\left(\frac{\psi r_s}{m}\left(1+\cos\frac{\pi x}{m}\right)\right) \qquad \text{A.13}$$

These harmonic and cycloidal curves can be combined in much the same way as they are combined when used in their standard form. An example of this will now be discussed to show how it can be performed.

For this example we will combine a C-1 and H-2 curve.

Example:

Given: It is necessary to go from a dwell to $\pi/4$ radians for 1.000 inches (25.40 mm) of sleeve travel using a C-1 curve, then rotate another $\pi/4$ radians using an H-2 curve.

Find: Determine the displacement and velocity equation for these C-1 and H-2 curves. Also determine the pressure angle at a displacement of 1.000 inches (25.40 mm) using r_s = 0.450 inches (11.43 mm).

Equations for C-1 from Figure A-3:

$\psi_{C-1} = \pi/4$

m_{C-1} = 1.000 inches (25.40 mm)

$$\gamma_{C-1}=\frac{\pi}{4}\left(\frac{x}{1}-\frac{1}{\pi}\sin\frac{\pi x}{1}\right)=\frac{\pi}{4}\left(x-\frac{1}{\pi}\sin\pi x\right) \qquad \text{A.14}$$

$$\omega_{C-1}=\frac{\pi}{4(1)}\left(1-\cos\frac{\pi x}{1}\right)=\frac{\pi}{4}(1-\cos\pi x) \qquad \text{A.15}$$

Equations for H-2 from Figure A-2:

$\psi_{H\text{-}2} = \pi/4$

$m_{H\text{-}2} = ?$

$$\gamma_{H\text{-}2}=\frac{\pi}{4}(\sin\frac{\pi x}{2m_{H\text{-}2}}) \qquad \text{A.16}$$

$$\omega_{H\text{-}2}=\frac{\pi^2}{8m_{H\text{-}2}}(\cos\frac{\pi x}{2m_{H\text{-}2}}) \qquad \text{A.17}$$

Set angular velocities equal to each other to find $m_{H\text{-}2}$:

$$\omega_{C\text{-}1,x=1}=\omega_{H\text{-}2,x=0} \qquad \text{A.18}$$

$$\frac{\pi}{2}=\frac{\pi^2}{8m_{H\text{-}2}} \qquad \text{A.19}$$

$$m_{H\text{-}2}=\frac{\pi}{4}=.785''(19.94mm)$$

The H-2 equations then become:

$$\gamma_{H-2}=\frac{\pi}{4}(\sin 2x) \tag{A.20}$$

$$\omega_{H-2}=\frac{\pi}{2}(\cos 2x) \tag{A.21}$$

In order to find the pressure angle at the joining point of the two curves either the equation for C-1 or H-2 can be used. For this analysis the equation for C-1 will be used.

$$\psi=\frac{\pi}{4}$$

$$m=1.000''(25.40mm)$$

$$x=1.000''(25.40mm)$$

$$r_s=0.450''(11.43mm)$$

$$\phi=\arctan\left(\frac{\pi(0.450)}{4(1.000)}(1-\cos\pi)\right) \tag{A.22}$$

$$\phi=\arctan(.707)=35.3° \tag{A.23}$$

A pressure angle of 35.3 degrees is small enough that this mechanism should work relatively well. If it were necessary for the radius r_s to be larger, then the

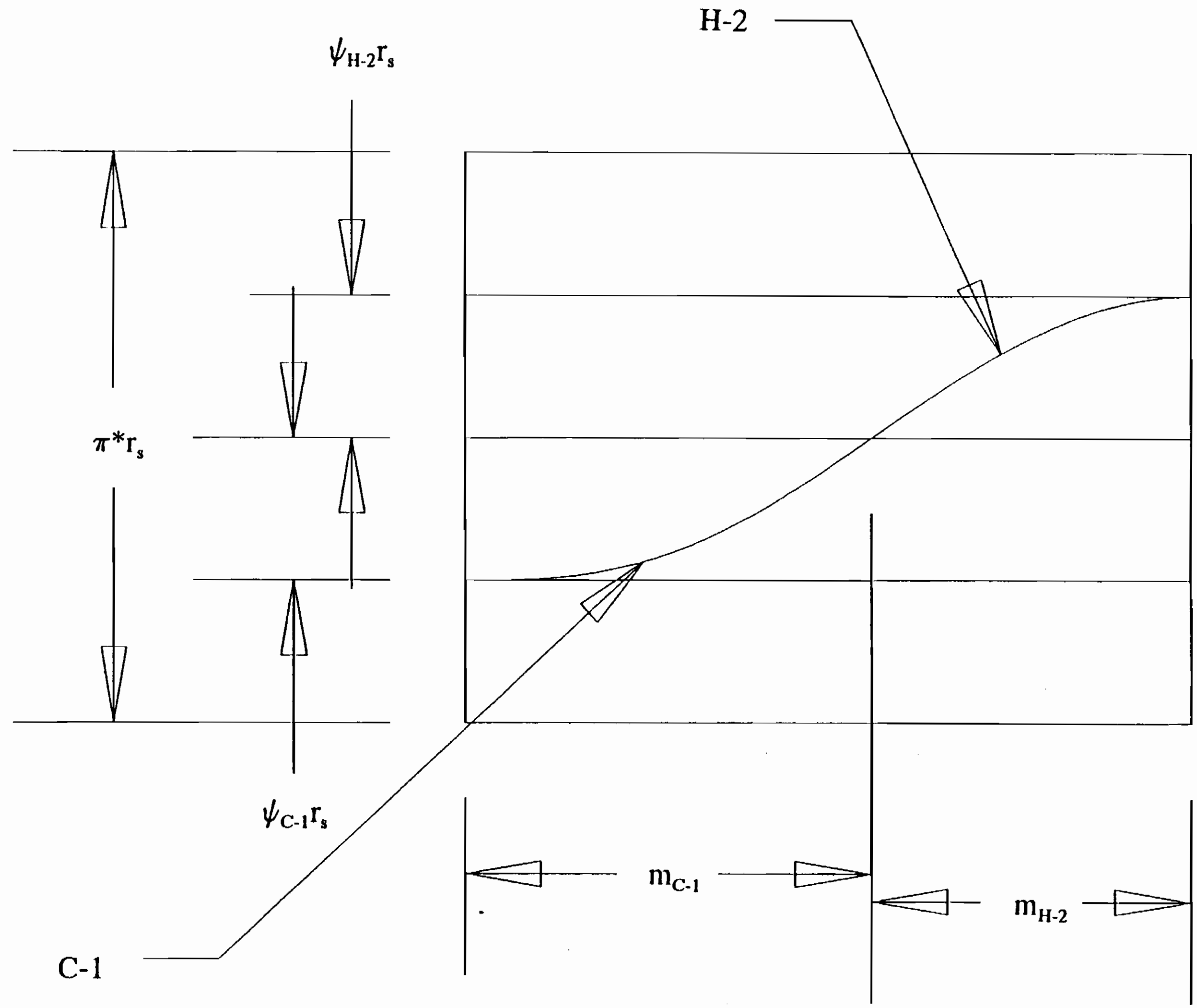


Figure A-6. Combined Curves

pressure angle may become too large. If this is the case, the length of travel m would have to be increased or the angle of travel ψ must be decreased. It is important to note that this r_s must be measured at the deepest point of contact in the groove in order to obtain the worst case pressure angle.

These curves can be laid out on the surface of the sleeve as shown in Figure A-6. The height of the rectangle enclosing the curve is equal to r_s times the angle from one end of the sleeve to the other. For this example the sleeve is 180 degrees. So the height of the rectangle is $\pi * r_s$. The length of the rectangle is the length of the sleeve, $m = m_{C-1} + m_{H-2}$. In order to draw the curve on the surface of the sleeve the equations for C-1 and H-2 must be put in cartesian form by multiplying both sides of equations A.14 and A.20 by r_s:

$$\gamma_{C-1} r_s = \frac{\pi}{4} r_s (x - \frac{1}{\pi}\sin\pi x) = \frac{\pi}{4} 0.45 (x - \frac{1}{\pi}\sin\pi x) \qquad \text{A.24}$$

$$\gamma_{H-2} r_s = \frac{\pi}{4} r_s (\sin 2x) = \frac{\pi}{4} 0.45 (\sin 2x) \qquad \text{A.25}$$

Sleeves with internal grooves can be cut on an NC Lathe provided the sleeve geometry does not interfere with the cutting tool. The method of cutting this groove would be to translate the cutter and rotate the sleeve simultaneously. The equations of Figures A-2 and A-3 would be used to calculate the coordinates, which could be input into the NC Lathe. The equations from the Kloomok and Muffley harmonic and cycloidal curves to create rotation from translation have been developed. The use of an internal groove on a sleeve to produce this motion has been discussed and equations to calculate the pressure angle on this mechanism were developed. These same ideas could be used for other mechanisms such as an external helical groove on a cylinder with a roller follower.

Appendix B
Internal Helical Groove Analysis

Now that general design equations have been developed in Appendix A, the dimensions selected for the final design will be discussed. The internal radius of the sleeve should be .875 inches (22.23 mm) to match the outer radius of the protrusions on the joint operating collar. For this design a follower radius of .125 inches (3.18 mm) was used. The joint must be rotated 90 degrees, so ψ in equation 5.7 becomes 90 degrees. The maximum length of the sleeve is 2 inches (50.8 mm) in order that it not interfere with the operation of the node receptacle. The longer the sleeve, the smaller the pressure angle, so the longest possible sleeve will be used. In equation 5.7, m is the final displacement of the sleeve, but this is for a groove which continues past the position of the follower. If the sleeve were cut perpendicular to its axis, at a distance m, one edge of the follower would not touch the groove at the end of travel. This can be seen in Figure B-1, which also shows the additional material needed on the end of the sleeve to make the follower rotate the required amount as the sleeve slides by the follower. The meaning of the variables are as follows:

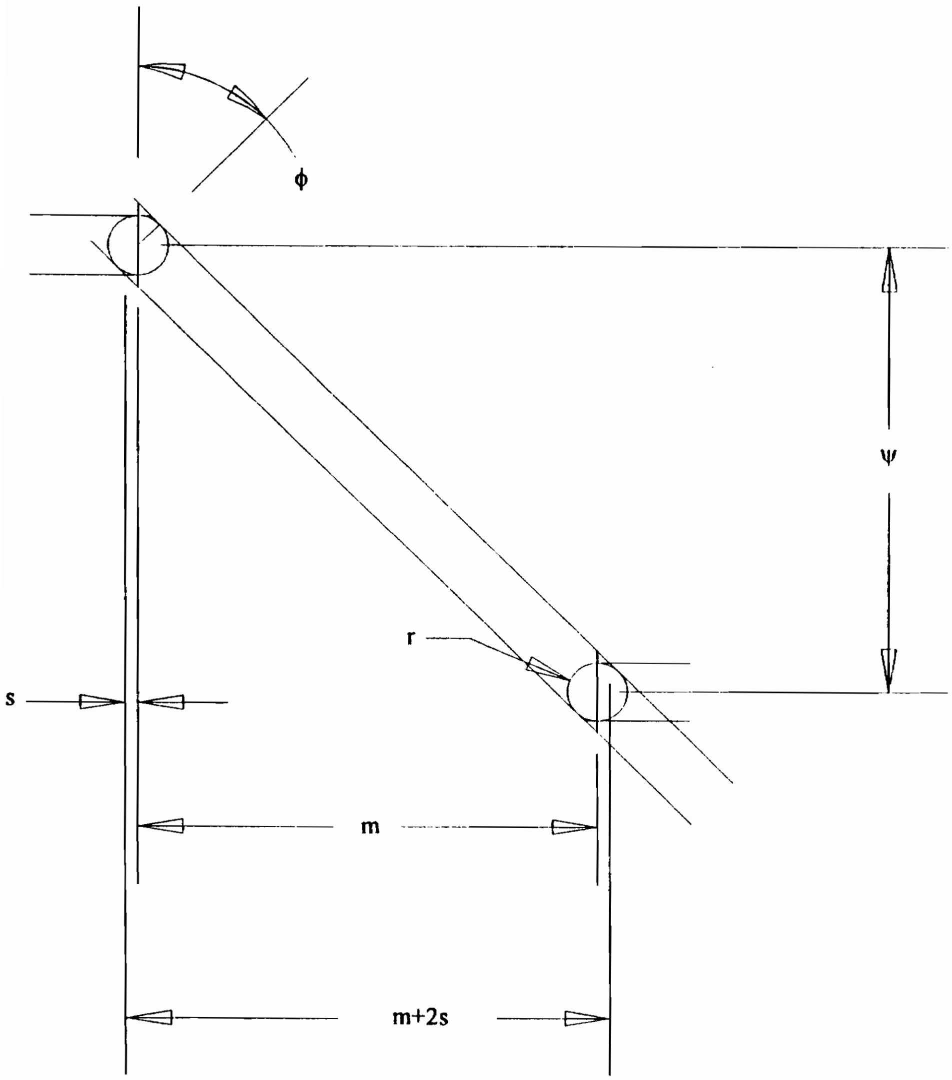


Figure B-1. Additional Sleeve Length Needed s=additional travel required if roller leaves the sleeve parallel to the sleeve axis

r=radius of the roller

ϕ=pressure angle

ψ=final angle of follower

r_s=Radius at which roller contacts groove

m=Final displacement of sleeve for continuous groove

The following equations can be developed from Figure B-1:

$$s=r\sin\frac{\phi}{2} \qquad \text{B.1}$$

$$\phi=\arctan\left(\frac{\psi r_s}{m}\right) \qquad \text{A.7}$$

Since the length of the sleeve is to be 2 inches (50.8 mm) then m+2s=2.

This becomes:

$$s=\frac{2-m}{2} \qquad \text{B.2}$$

Substituting Equations B.2 and A.7 into equation B.1 we obtain:

$$m=-2r\sin\frac{\tan^{-1}\frac{\psi r_s}{m}}{2}+2 \qquad \text{B.3}$$

Solving equation B.3 iteratively, m is found to be:

$$m=-2(.125)\sin\frac{\tan^{-1}\frac{(\frac{\pi}{2})(.875)}{m}}{2}+2=1.924''(48.87mm)$$

Setting m=1.924 inches (48.87 mm), ψ = 90 degrees and r_s = .875 inches (22.23 mm), and substituting into equation A.7 as follows:

$$\phi=\arctan(\psi\frac{r_s}{m})=\arctan(\pi/2\times\frac{.875}{1.924})$$

ϕ is found to be:

$$\phi=35.5^o$$

A pressure angle(ϕ) of 35.5 is relatively high, but it is low enough that this mechanism should work. This is the lowest achievable pressure angle due to the constraints of this problem. This pressure angle was calculated at the inside edge of the sleeve, so the follower will have to be conical shaped and contact at only the inside edge.

Appendix C
Latch Analysis

First the cam surface actuated by the moving pin will be discussed. A diagram of this surface is shown in Figure C-1 with the roller in two positions. The first is when the cam is at 0 degrees and the second position is shown as the roller just engages with the flat portion of the cam for the full locked position. The meaning of each variable is as follows:

θ=angle of the latch when the latch is locked

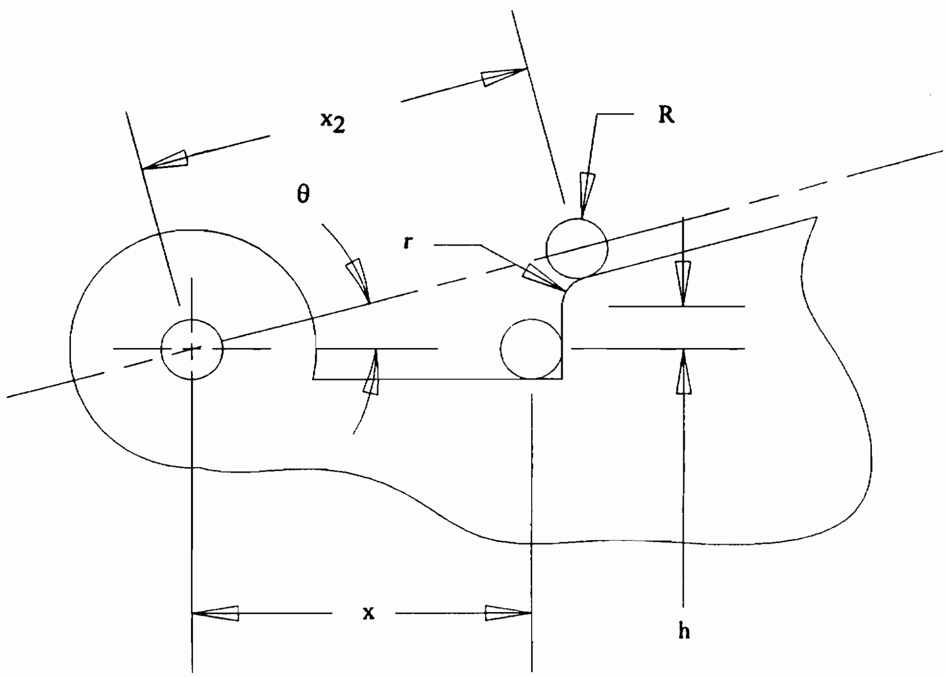
r=radius between the two flat surfaces of the cam

h=height above the center of rotation of the latch that the radius r begins.

R=radius of the roller

x=distance from the center of rotation of the latch to the initial position of the roller.

x_2=distance from the center of rotation of the latch to the locked position of the roller.



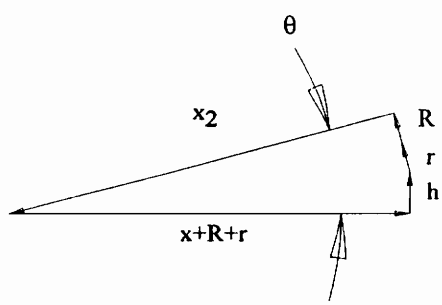


Figure C-1. Latch Cam Design

From Figure C-1 using loop closure methods the following equations can be obtained by summing the vectors:

$x+R+r-r\sin(\theta)-R\sin(\theta)=x_2\cos(\theta)$

$h+r\cos(\theta)+R\cos(\theta)=x_2\sin(\theta)$

Rearranging the first equation we obtain:

$$x_2=\frac{x+R+r-r\sin\theta-R\sin\theta}{\cos\theta} \qquad \text{C.1}$$

Rearranging the second equation we obtain:

$$h=x_2\sin\theta-r\cos\theta-R\cos\theta \qquad \text{C.2}$$

The cam of the latch actuated by the stationary pin will now be discussed, then the overall latch design will be discussed. A figure of this cam with the roller in the opened, intermediate and locked position is shown in Figure C-2. The intermediate position is shown so that the of the depth of stationary pin slot can be determined. The variables have the following meanings

d_1=direct distance of the roller from the rotation point of the latch just as it contacts the latch

d_2=direct distance of the roller from the rotation point of the latch in an intermediate position

d_3=direct distance of the roller from the rotation point of the latch in the locked

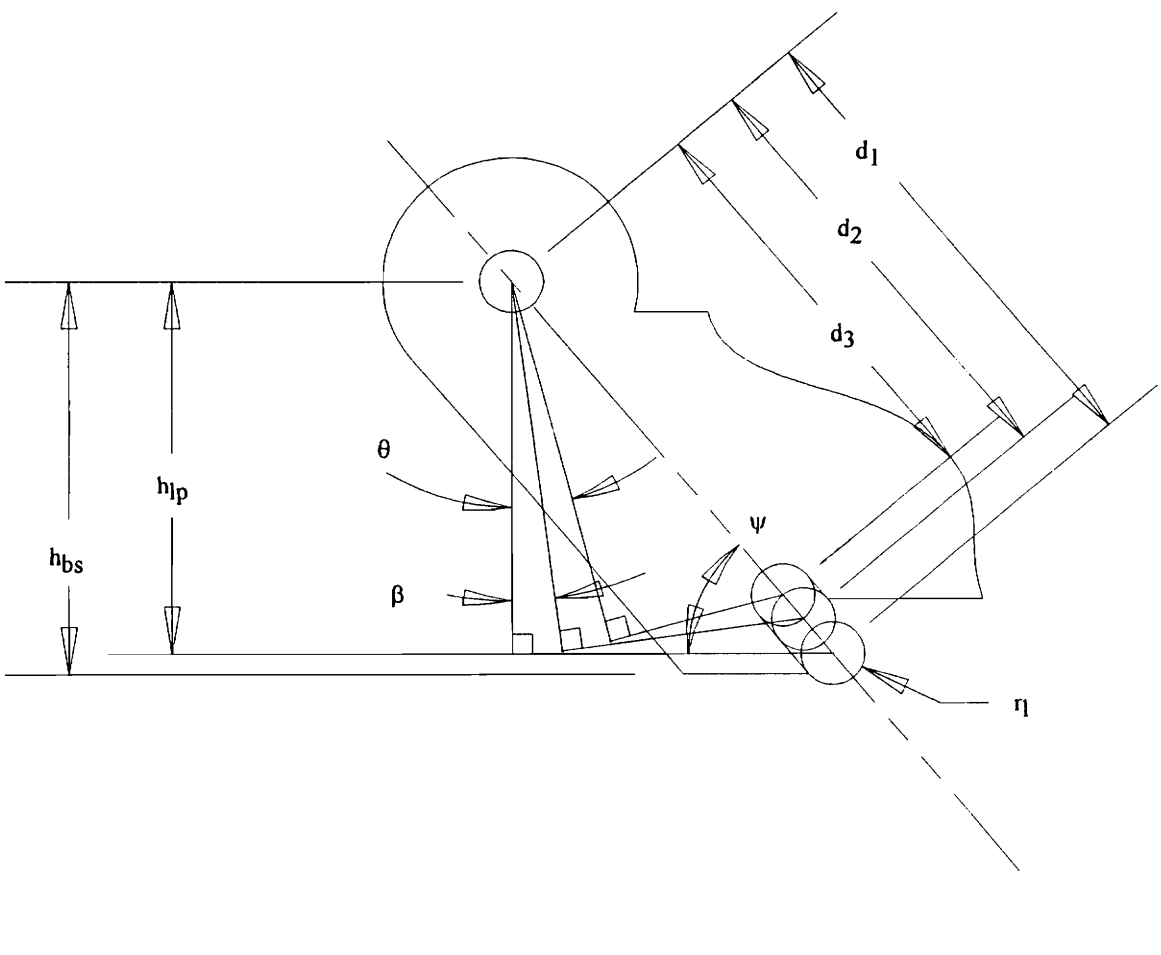


Figure C-2. Latch Cam Design

position

h_{lp}=vertical distance from the rotation point of the latch to the roller just as it contacts the latch

h_{bs}=the minimum distance which the actuating side of the latch must extend vertically below the rotation point of the latch

ψ=initial angle of the latching slot

β=intermediate rotation angle of the latching slot

θ=full rotation angle of the latching slot

r_l=radius of roller

The following equations were developed from Figure C-2.

$$d_1=\frac{h_{lp}}{\sin\psi} \qquad \text{C.3}$$

$$d_2=\frac{h_{lp}}{\sin(\psi+\beta)} \qquad \text{C.4}$$

$$d_3=\frac{h_{lp}}{\sin(\psi+\theta)} \qquad \text{C.5}$$

$$h_{bs}=h_{lp}+r_f\cos\psi \qquad \text{C.6}$$

The maximum radius is limited by interference with the flat surface to the right of the slot in Figure C-2. The equation for maximum radius is as follows:

$$r_l<r_f\cos\psi+(d_1-d_2)\sin\psi \qquad \text{C.7}$$

This becomes:

$$r_l < \frac{\left(\frac{h_{lp}}{\sin\psi} - \frac{h_{lp}}{\sin(\psi+\beta)}\right)\sin\psi}{1-\cos\psi} \qquad \text{D.8}$$

Appendix D
Final Design Analysis

Before the sizes of components can be found, various travel distances must be determined. The motion of the sleeve was set to be 2.4 inches (61.0 mm). This was chosen because the length of the sleeve in order to not interfere with the adjoining struts and the receptacle finger must be less than 2 inches (50.8). Allowing .2 inches (5.08 mm) on either side to engage and disengage with the roller on the joint operating collar gives a total of 2.4 inches (61.8 mm). The sliding gripper was chosen to be .6 inches (15.2 mm) thick in order for it to be strong enough to grip the strut and not allow it to deflect excessively. Travel for engagement with the strut was chosen to be .3 inches (7.62 mm), this gives a total of .9 inches (22.9 mm) of travel for this gripper.

The first step in the analysis of the final design is to size the latch. This result will be used to determine the sizes of various other components. In order for the stationary pin on the latch to hold the latch in position with as small a force as possible applied to both the stationary pin and the moving pin, it was necessary to set the final angle of the cam surface actuated by the stationary pin to be as close to 90 degrees as possible. By applying a smaller force to the moving pin, the friction forces will be lower therefore allowing for smoother operation. Also it was necessary that the stationary pin be engaged in the cam surface far enough to get a good grip. A good grip would definitely be accomplished if the pin traveled at least the diameter of the pin into the latch. For this latch a pin diameter of .25 inches (6.35 mm) was used so a travel of .3 inches (7.62 mm) was chosen. In order to have good strength in the latch, h_{lp} was set equal to 1.5 inches (38.1 mm). For θ, 15 degrees was used and β is half of that at 7.5 degrees. Then, keeping these values constant, ψ was changed to obtain a value of .3 inches (7.62 mm) of travel (relative to the latch) with a .25 inch (6.35 mm) diameter pin. The value of ψ turned out to be 50 degrees. With these values substituted into equations C.3 through C.6 the following values were obtained:

h_{bs}=1.596 inches (40.54 mm)

d_1=1.958 inches (49.73 mm)

d_2=1.779 inches (45.19 mm)

d_3=1.655 inches (42.04 mm)

The stationary pin travel relative to the latch is determined by subtracting d_3 from d_1 which gives a travel of .303 inches (7.70 mm).

After the θ was determined for the cam actuated by the stationary pin, then this same θ should be used for the cam actuated by the moving pin. For the moving pin, a pin diameter of .25 inches (6.35 mm) was chosen for strength. Next, keeping r as small as possible to reduce the distance travelled to latch, and trying to maintain smooth operation, r was set equal to .125 inches (3.18 mm). The value of 1.375 inches (34.93 mm) was chosen for x. Substituting these values into equations C.1 and C.2, the values for x, x_2 and h are as follows:

$x=1.375$ inches (34.93 mm)

$x_2=1.615$ inches (41.02 mm)

$h=.177$ inches (4.50 mm)

Subtracting x from x_2 gives a value of .240 inches (6.10 mm) which is the total travel of the moving pin relative to the slotted plate from initial engagement of the latch with the stationary pin until the latch is latched. The value of h is acceptable, since this shows there is a good distance between the contact point of the moving pin and the curved portion of the latch.

At this point, now that all the travel distances are known, using similar dimensional analysis performed with the previous design, it is possible to design the rest of the end effector. It is important to note that each component is dependent on other components in this type of design. Any changes in one part of the end effector can change many other parts. This will become more apparent as the discussion of this design is continued.

For this new design, one of the above latches would be used on the sleeve and one on the strut gripper. Each will have different length slots for the moving pin to slide in. The length of these slots will be determined after the crank length is determined.

Now that the travel distances are known, while the insertion platform is in the stationary up position, the crank and follower slot can be sized. In order to size the crank and follower, the travel distances for the operations while the platform is in the up position must be totalled. The following steps are performed at the up position of the insertion platform. The strut gripper grips the strut (.9 inches (22.86 mm)), the strut gripper latch is latched(.240 inches (6.10 mm)), the sleeve latch is unlatched(.240 inches (6.10 mm)) and the sleeve unlocks the joint(2.4 inches (61.0 mm)). This gives a total travel of 3.780 inches (96.01 mm). Looking at Figure D-1, this 3.780 inches (96.01 mm) represents the value L. All other values in Figure D-1 are as follows:

θ_p= largest pressure angle for holding the insertion platform in position.

θ_1= angle of the crank at which upward motion stops

H=vertical travel of the insertion platform

R=radius of the roller

r=radius between the flat and curved portion of the slot

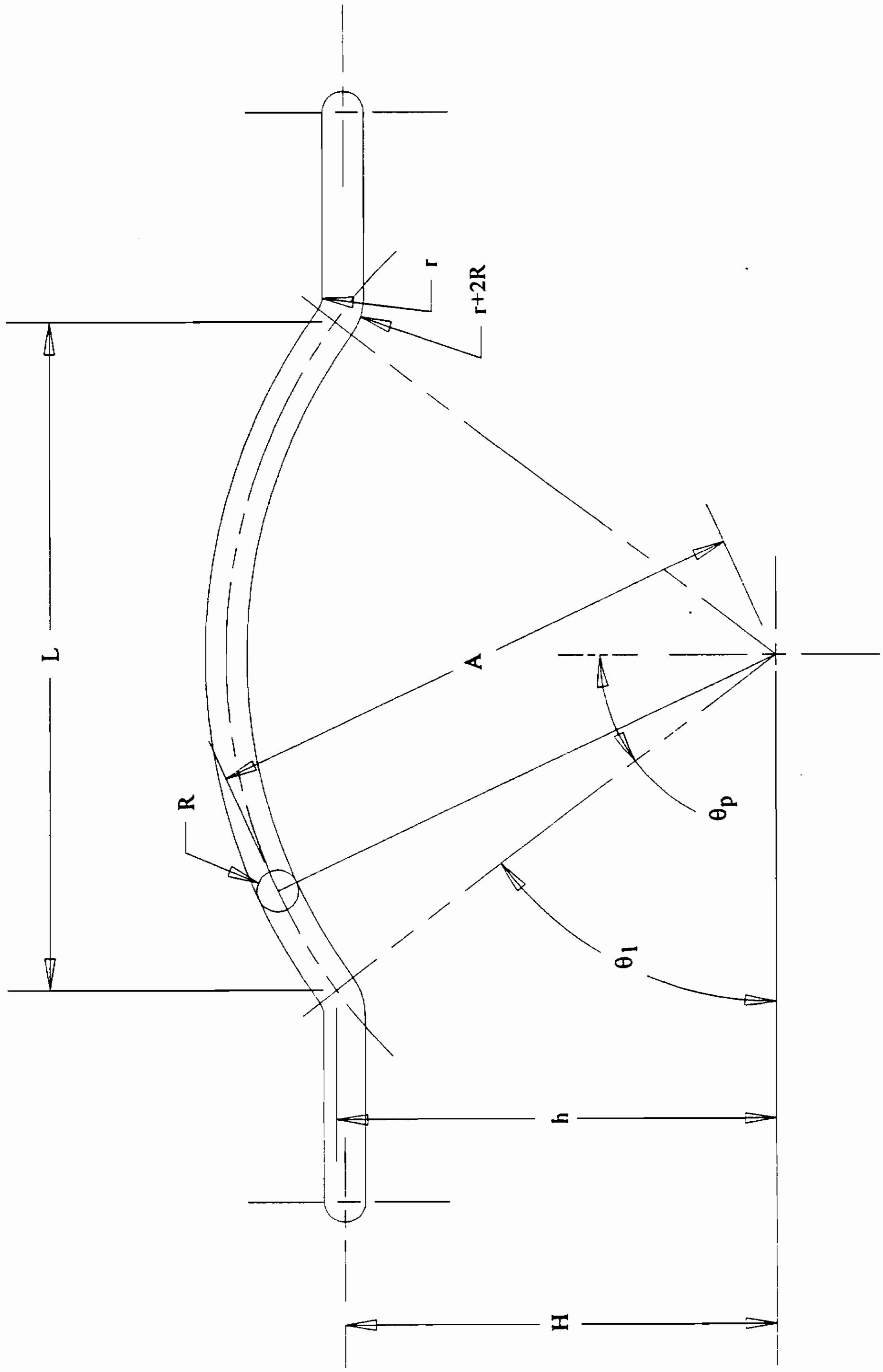


Figure D-1. Crank Follower Design

A=radius of the crank

The following equations can be obtained from this figure:

$$\theta_p = \arcsin(\frac{L}{2A}) \qquad D.1$$

$$\theta_1 = 90^o - \theta_p \qquad D.2$$

$$H = (A+R+r)\sin\theta_1 - R - r \qquad D.3$$

In order for this to operate smoothly, the pressure angle must be less than 40 degrees so that side forces will not bind the insertion platform. If A is equal to 3.3 inches (83.82 mm), the pressure angle is 34.94 degrees, which is acceptable. Using this value, θ_1 becomes 55.06 degrees. Using values of R=.125 inches (3.18 mm) and r=.125 inches (3.18 mm), H is found to be 2.660 inches (67.56 mm).

The total rise of the insertion platform must be 2 inches (50.8 mm) as discussed earlier, so if H is smaller or larger than 2 inches (50.8 mm), the rise of the insertion platform can be adjusted for by starting the crank below or above horizontal. The starting position can be calculated as follows. First subtract the difference between the H value found in the above equation and 2 inches (50.8 mm). This is the initial height above or below horizontal (positive is above and negative is below). The start angle of the crank is then calculated as follows:

$$\theta_i = \arcsin(\frac{H-2}{A}) = \arcsin(\frac{2.660-2}{3.3}) = 11.54^o \qquad D.4$$

The sleeve slot length and the strut gripper slot length can now be determined since the crank length and follower slot size has been determined. The sleeve slot length is determined by four values: the horizontal distance moved as the insertion platform is risen, the distance needed to grab the strut, the distance needed to lock the latch on the strut gripper and the distance needed to unlock the latch on the sleeve. The strut gripper slot length is determined by the distance traveled to lock the latch on the strut gripper, unlock the latch on the sleeve, distance traveled to unlock the joint and the distance traveled horizontally to lower the insertion platform. The distance needed to grip the strut is known to be .9 inches (22.86 mm), the distance needed to unlock and lock the latches is known to be .240 inches (6.10 mm). The distance needed to unlock the joint is 2.4 inches (61.0 mm) as determined earlier. The horizontal distance which the crank moves as it lifts the insertion platform is equal to:

$$A(\cos\theta_i - \cos\theta_1) = 3.3(\cos(11.54) - \cos(55.06)) = 1.343 \mathit{inches} (34.11 \mathit{mm})$$

The sleeve slot length is as follows:

1.343 + .9 + .240 + .240 = 2.723 inches (69.16 mm)

The gripper slot length is as follows:

.240 + .240 + 2.4 + 1.343 = 4.223 inches (107.26 mm)

Now all the co-dependent values in this end effector have been determined.

Vita

Todd C. Denkins was born in Newport News, Virginia on June 7, 1966. He earned a Bachelor of Science degree in Mechanical Engineering from Virginia Polytechnic Institute and State University in May of 1988. Immediately following graduation, he worked at Ethyl corporation in Baton Rouge, LA. In 1989, he left Ethyl corporation and went to work at NASA Langley Research Center where he currently works on the design and development of space systems. While at NASA, he attended off campus classes toward a Master of Science degree and his thesis work was performed in conjunction with job duties. He plans to continue to work at NASA Langley and earn another degree at a later date.