

DESIGN OF A ROBOTIC END-EFFECTOR
FOR AUTOMATED BOLTING

by

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Submitted to the Department of Mechanical Engineering
on May 10, 1985 in partial fulfillment of the
requirements for the Degree of Master of Science in
Mechanical Engineering

ABSTRACT

The goal of this thesis is to expand the manufacturing and assembling capabilities of today's robots. Most industrial robots are restricted to tasks that involve little interaction between the manipulator and the workpiece. In contrast, in this project interaction forces will be deliberately generated and used. Specifically, the object of this thesis is to demonstrate that the careful use of interaction forces generated between robot and workpiece can facilitate an assembly task, putting a bolt in a threaded hole.

A design for a special-purpose robotic end-effector for bolting is presented. A feature of this tool is its deliberate use of interaction forces. An investigation of the bolting process is presented, showing that cross-threading can occur even when the misalignment of bolt and hole is small. By using interaction forces to reduce misalignment of the parts to be assembled, this new tool will reduce the probability of cross-threading. The new tool design is evaluated by comparing it with an earlier prototype.

Thesis Supervisor: Neville Hogan

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To Julie

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CHAPTER ONE

INTRODUCTION

This thesis is part of a project designed to expand the manufacturing capabilities of today's robots. Most industrial manipulators are restricted to tasks that involve little dynamic interaction between manipulator and workpiece. These tasks include spray painting, welding, pick and place tasks and tasks in unsafe environments. The exchange of energy between the robot and workpiece has usually been kept to a minimum due to alignment and accuracy problems. For similar reasons, up until now, assembly tasks have been performed by hard automation or people. The thrust of this thesis is to demonstrate that an assembly task can be performed by manipulators with the careful use of interaction forces generated between robot and workpiece.

1.1 A New Approach to Assembly

A new approach to the assembly problem that focuses on the interaction between manipulator and workpiece has been termed impedance control [3,4]. Mechanical impedance is a generalization of mechanical stiffness which includes possible dynamic effects such as viscosity, inertia, etc. In more general terms, the impedance of the manipulator dictates how the manipulator will respond when displaced by any workpiece. Conversely, the admittance of the workpiece (the dual or inverse of impedance) dictates how it will respond when pushed upon by any manipulator. The control of the manipulator's impedance, and one motion variable (position, velocity, acceleration, etc.) at the point of interaction can dictate the behavior of both the manipulator and the

workpiece. For example, if a manipulator were approaching a rigidly held workpiece, the manipulator could change its impedance so that the contact between the robot and workpiece would not be a collision but a controlled connection.

The scope of the work presented here is a small part in the development of impedance control. The goal of this work is to demonstrate that impedance control can facilitate industrial assembly. To achieve this goal, the assembly task of bolting was chosen, where an unthreaded or through part is fastened to a threaded part with a gasket possibly inserted between the two. An unmodified bolt will be used. The reason for choosing the bolting assembly problem is because bolting is a widely used means of assembly.

This bolting operation will be performed using a specially designed bolting tool. It is the second attempt at such a tool and will therefore be appropriately labeled Mark II, with its predecessor being Mark I. [7] The bolting tool design presented here will be mounted as the last link of a manipulator. A major feature of the tool is that it will brace against the workpiece while the bolting operation is being performed. It will be compliantly supported with an adjustable impedance between the tool and manipulator. The compliance will allow the tool to align itself with respect to the workpiece and also allow the connection between tool and workpiece to be a controlled one. More specific requirements of the tool will be given later.

1.2 Bolting Tool Requirements

At the outset of this project, it was decided that the bolting tool should be designed with a specific bolting operation in mind to

highlight the practicality of an impedance controlled device. The task is represented in Figure 1.1 where a manipulator is delivering a bolting tool whose function is to fasten the headcover of an engine to the engine block with a gasket included.

As shown, the bolts to the headcover have limited vertical access, therefore the manipulator must approach the hole from the side. Note also that the headcover has eight fastening locations, four on each side that must be bolted in a particular sequence. Usually all eight bolts would be started to align the headcover, then they would all be pretightened to ensure the gasket is sealed with equal pressure at all points, and then the bolts would be tightened to their final torque.

More specifically the bolting tool has to meet several requirements. The tool will be mounted as an end-effector on a robot comparable to a General Electric P50. The tool must accommodate the workpiece and compensate for the misalignments, both angular and translational, of the endpoint location of the manipulator. The tool will be designed as a special purpose device for threading M8 metric bolts. It is also assumed that the vertical access to the threaded hole is limited. Ideally, the tool should be self-contained and modular; for example, it should be mountable on any robot of comparable size and should require no feedback to the manipulator for repositioning purposes during the bolting process. The robot's only function is the delivery of the tool to the threaded hole location within its own specified accuracy tolerances.

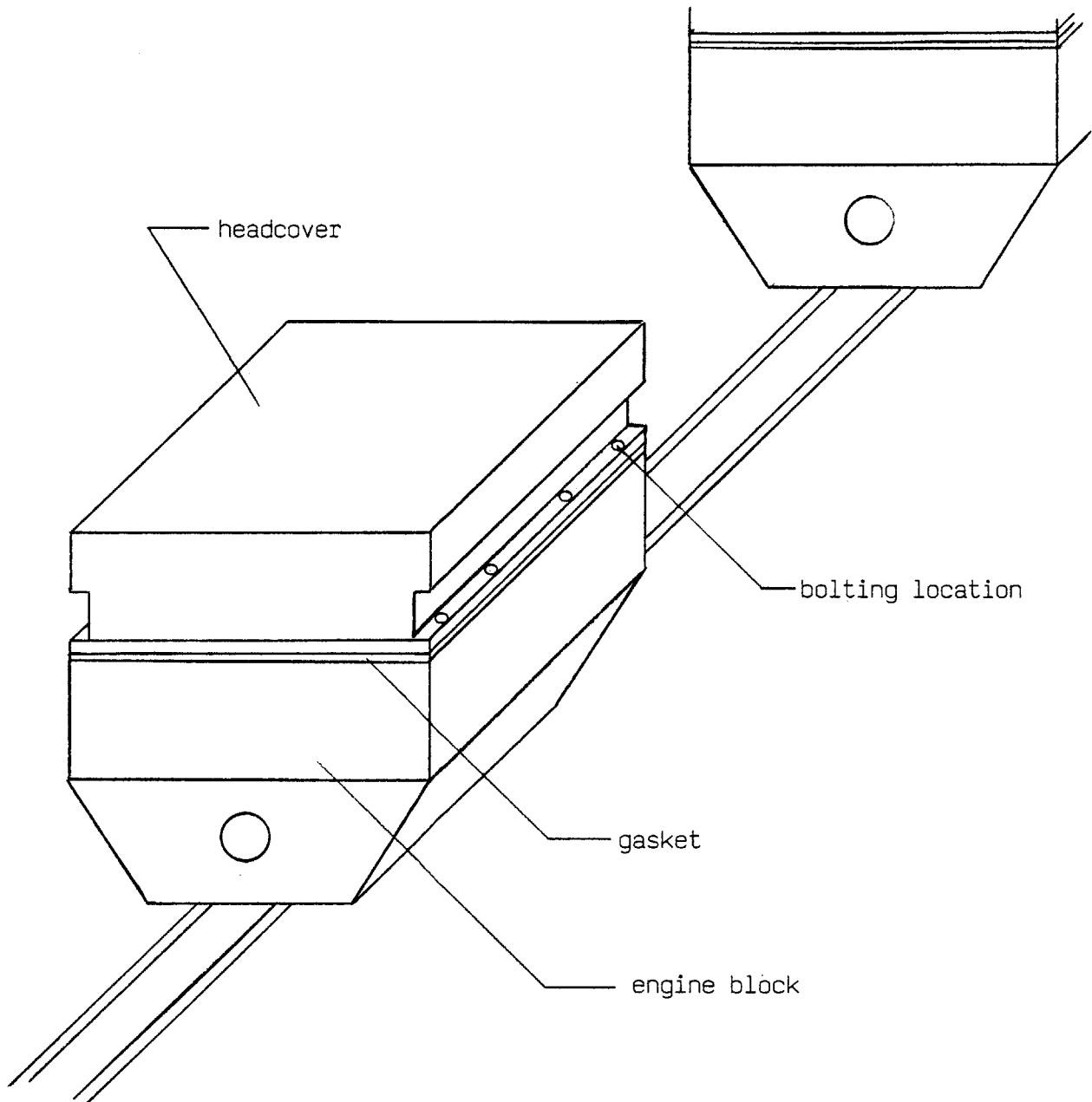


Figure 1.1 Schematic of a Specific Bolting Task

1.3 Thesis Objective

The objective of this thesis is to demonstrate the feasibility of impedance controlled assembly machines through the specific design of a self-aligning end-effector with variable impedance that will start M8 bolts.

1.4 A Summary of Following Chapters

The next chapter is an evaluation of the first bolting tool designed, the Mark I. In Chapter Three the results of a bolting investigation are discussed. In Chapter Four design issues that evolved during the design course are discussed. In Chapter Five design proposals for a new bolting tool are discussed and, then in Chapter Six a final tool design is presented. In the final chapter, an evaluation based on the first bolting tool is done and recommendations for further work in this area are given.

CHAPTER TWO

EVALUATION OF MARK I

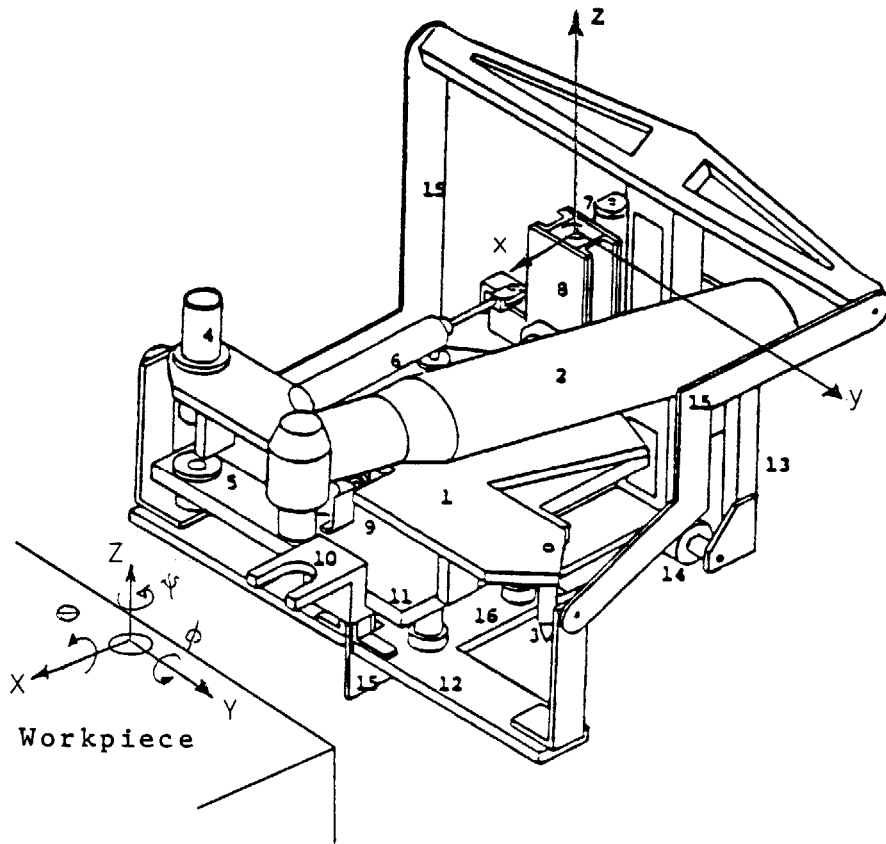
As mentioned previously, the bolting tool design presented here is the second generation tool in this project. The first tool, Mark I (shown in Figure 2.1), was designed and built by R. Dirk Taylor. [7] This design was an excellent first prototype and provided much insight into the task of bolting and provided the author with a good base from which to begin his own design. Before evaluating the Mark I tool's performance, a complete sequencing routine is provided.

2.1 Mark I Bolting Sequence

The bolting sequence for the Mark I has eight operational steps. Local (x, y, z) and ground (X, Y, Z) coordinate systems are shown in Figure 2.1 to facilitate explanations. Rotation about the x-axis, the θ direction will be referred to as the roll of the tool and rotation about the y-axis, the ϕ direction will be considered the pitch of the tool. To make the system complete, rotation about the z-axis, the ψ direction will be considered the yaw of the tool. Finally, any parts mentioned in the explanation will be followed by a number in parenthesis to make cross-referencing with Figure 2.1 easier.

2.1.1 Bolting Tool Delivery

A manipulator given the coordinates of the threaded hole with respect to the ground reference frame delivers the Mark I tool to the workpiece. In the process of the tool traveling to the hole location, a bolt is fed through the bolt delivery tube (4) and falls into the bolt holding station (5). The anchor (10) is the first part of the tool to contact the workpiece. During this connection a rotational



- | | |
|---|---|
| 1. Indexing Table | 10. Anchor |
| 2. Pneumatic Nutrunner | 11. Floating Plate-
Horizontal Compliance |
| 3. Probe | 12. Floating Base-
Rotational Compliance |
| 4. Bolt Delivery Tube | 13. Backplate and Slide-
Vertical Compliance |
| 5. Bolt Holding Station | 14. Spring-
Vertical Compliance |
| 6. Pneumatic Cylinder-
Table Rotation | 15. Rotational Compliance Links |
| 7. Pneumatic Cylinder-
Table Elevation | 16. Horizontal Compliance-
Shear Pads |
| 8. Vertical Slide-
Table Elevation | |
| 9. Bolt Retaining Fingers-
Pneumatic Actuation | |

Figure 2.1: The Mark I Tool

bearing in the rear of the tool (not shown) allows the tool to adjust its roll position and the four-bar linkage design (15) allows the tool to adjust its pitch position. Therefore once the tool has contacted the workpiece securely, it has been aligned properly in both angular positions.

2.1.2 Clockwise Rotation

The next step in the bolting sequence is the clockwise rotation (negative ψ direction) of the indexing table about the z axis, accomplished by the table rotation pneumatic cylinder (6). This step accomplishes two things. First, it moves the socket attached to the pneumatic nut-runner (6) over the bolt in the bolt holding station (5), and it also aligns the probe (3) over the threaded hole.

2.1.3 Downward Translation (#1)

The third step in the bolting sequence is the downward movement of the indexing table forced by the table elevation pneumatic cylinder (7). Due to this actuation the bolt is forced into the socket of the nut-runner (2) at the bolt holding station (5), and the probe (3) is forced to align the through part and the gasket with the threaded hole. The probe also aligns the tool in both lateral x and y directions with respect to the workpiece. The shear pads (16) provide the tool with the lateral compliance needed to adjust. Therefore at this point the tool is aligned in all directions, and the shear pads are in a stressed state.

2.1.4 Bolt Retention

The fourth step of the sequence involves retaining the bolt inside the socket. This task is accomplished by the use of the bolt retaining fingers (9) positioned directly under the nut-runner (12). The

fingers (9) are engaged using a small pneumatic cylinder (not shown). Therefore, at this point in the process, the probe (3) is still in the threaded hole, and the bolt is locked into the socket by means of the bolt remaining fingers.

2.1.5 Upward Translation

The fifth step in the bolting sequence is the upward movement of the indexing table forced by the table elevation-pneumatic cylinder (7). Due to this actuation the bolt is lifted out of the bolt-holding station, and the probe is lifted out of the threaded and through parts. Since the probe (3) has been lifted out of the threaded hole, the downward normal force due to the anchor (10) should keep the tool aligned.

2.1.6 Counter-Clockwise Rotation

The sixth step in the bolting sequence is the counter-clockwise rotation (positive ψ direction) of the indexing table about the z-axis, accomplished by the table-rotation pneumatic cylinder (6). These steps accomplish two things. It moves the probe (3) out of the way and moves the bolt into position over the threaded hole. At this point in the process, the tool is ready to begin the actual threading process.

2.1.7 Downward Translation (#2)

The seventh step is the second of two downward movements of the indexing table forced by the table elevation cylinder (7). When the indexing table (1) reaches its lower limit, the bolt in the socket should be aligned with respect to the threaded hole and ready to be rotated. Note also that at this time in the process, a second bolt would be fed through and held at the bolt-holding station (5).

2.1.8 Bolt Rotation

The final step of the bolting sequence is when the bolt is actually rotated by the pneumatic nut-runner (2).

2.2 Assets of the Mark I Tool

The Mark I tool achieved many of the goals set forth in this project. It proved the necessity of several critical components in the design. These components include the probe, the anchor and the Tool Impedance Isolator (TII), a modified form of the Remote Center of Compliance (RCC) [2]. The probe that the Mark I tool utilizes proved to be an effective means of mechanically referencing the threaded hole. The probe coupled with the TII required no feedback to the robot, one requirement set forth in the project. The probe used in the Mark I tool was only responsible for aligning the tool in the lateral x and y directions; yet, if desired it could also eliminate angular misalignment.

Another successful component, the anchor, served two purposes in the Mark I design. It was responsible for aligning the tool in two angular directions (θ and ϕ) and for providing mechanical interaction forces due to friction between the tool and the workpiece. Finally, the TII design used to kinematically locate the center of rotation of the tool at the center of the anchor allowed the probe to be inserted without jamming or wedging.

2.3 Weaknesses of the Mark II Tool

As shown in Figure 2.1, the bolt-driver dictates the shape and size of the tool. If it were eliminated the tool could be much smaller and lighter, thereby ameliorating problems due to build-up of backlash.

Secondly, the Mark I's anchor assumes an ideal workpiece, one that has a generous flat surface surrounding the threaded hole, located on an edge. Thirdly, the four-bar linkage providing the Mark I rotational accomodation possesses no springlike members to provide it with an equilibrium position. As a result the tool introduces a substantial uncertainty in the location of the probe with respect to its nominal position determined by the robot. Fourthly, the Mark I tool does not allow for bolting at an arbitrary distance from an edge. Fifthly, the tool allows for misalignment along the axis of the bolt. This is an unnecessary complication. Finally, the Mark I tool adjusts itself by placing the anchor on the workpiece first and then inserting a probe. The subsequent removal of the probe may allow misalignment to reappear. To prevent this the probe should be inserted first to eliminate all misalignment. Then the tool should be braced with respect to the workpiece to preserve this alignment.

The evaluation of the Mark I tool was an important first step in the design procedure. By evaluating it, the author eliminated the possibility of duplicating his work and was able to begin his design on a higher level. Finally, the Mark I tool brought the underlying problems in a bolting operation to the surface and singled out each required step in the bolting sequence.

CHAPTER THREE
BOLTING INVESTIGATION

In order to develop a second prototype tool which was an improvement over the Mark I tool, it was first necessary to establish some quantitative design specifications. For example, what is the maximum angular and translation misalignment the tool has to accomodate? What is the magnitude of the angular and translational correction the tool must make? (i.e. what is the angular and translational misalignment the bolting process can tolerate?) Should the bolt be stationary or moving on insertion? How does the tolerance class of bolt and hole influence the bolting process? How does the rigidity of the manipulator affect the bolting process? To address these questions, the bolting process was investigated.

3.1 Prior Work

Part of the bolting investigation was an attempt to find reference material relevant to the bolting process. The material found was a short paper, "Reliable Automatic Starting of Threaded Parts," by a Russian author, I.E. Blaer [1], and an M.I.T. Bachelor's thesis by Paul Ranyak [6] who based most of his work on Blaer's paper. The central concern of both of these works is cross-threading.

Ranyak in his thesis described two types of cross-threading. The first type was angular cross-threading where one tries to start the bolt relative to the nut one full thread out of phase. To do this with an M8 nut and bolt, the bolt would have to be tilted at almost 15 degrees, unlikely in automated assembly. The second type of cross threading that Ranyak described was parallel cross-threading, where the

beginning threads of the bolt and hole overlap when contact is initially made, and then are crushed together when rotation occurs. The beginning of the threads for both the bolt and hole must be in phase with each other for parallel cross-threading to occur. If they are out of phase (e.g. by 180 degrees) parallel cross-threading will not occur.

In the design of the Mark I tool, the issue of cross-threading was also considered. Taylor [7] performed a series of experiments in which a metric M8 bolt was placed in the collet, and an M8 nut was clamped to the x-y table of a Bridgeport milling machine. In this apparatus (which is almost perfectly rigid), it was determined that the bolt must be aligned angularly to within one degree and translationally to within .005" to guarantee successful thread starting. Note that in this series of experiments, when the bolt first made contact with the nut, it was stationary.

3.2 Experimental Investigation

To provide a more realistic quantitative basis for the new design, and to familiarize the author with the bolting process, a short series of experiments were performed. The experimental apparatus shown in Figure 3.1 included a GCA manipulator with a pneumatic nut-runner mounted as its last link. M8 bolts were threaded into a one-inch block of steel that had several chamfered (59°) and threaded holes. The steel block was placed on a magnetic chuck that was mounted on a sturdy wooden table as shown in Figure 3.1. The position of the bolt relative to the hole was measured using a precision parallel block and dial indicators.

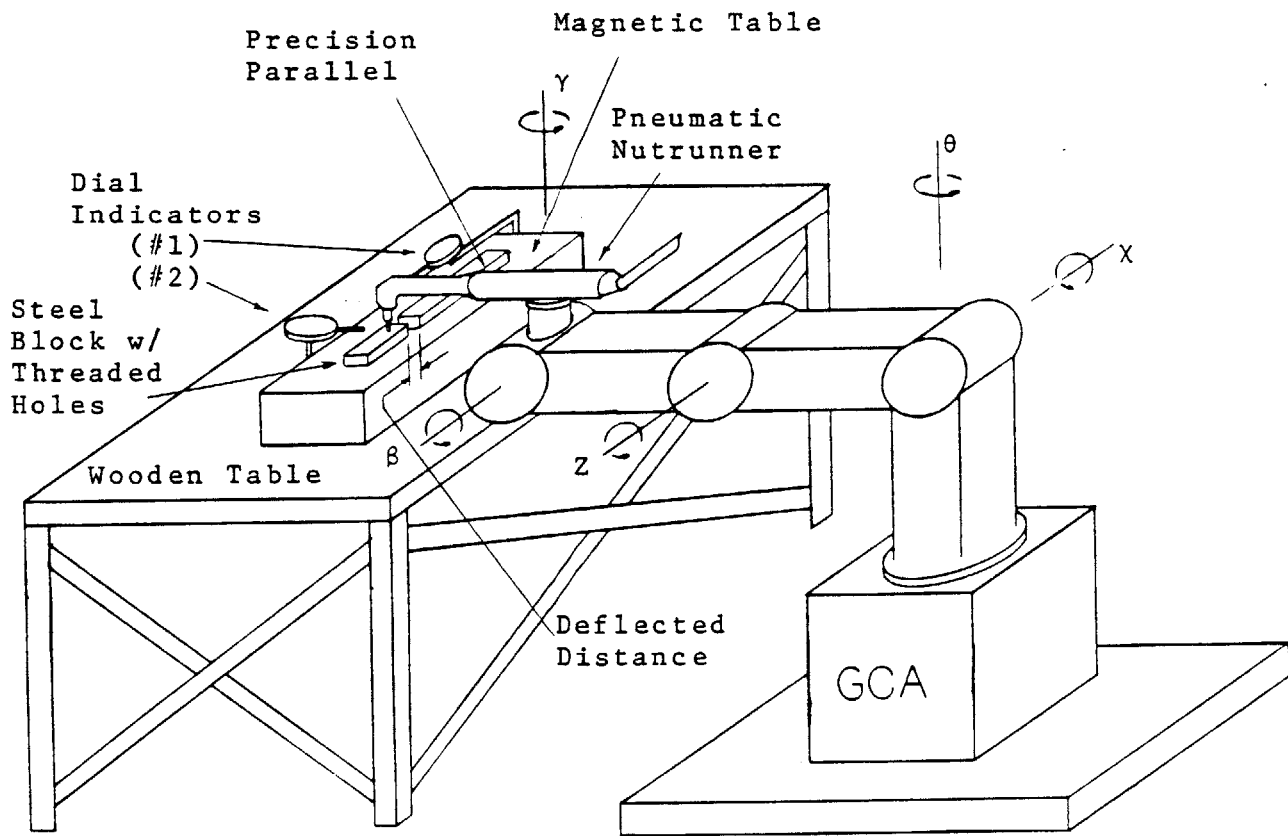


Figure 3.1 Experimental Apparatus

In the bolting experiments performed by Taylor, the bolt was not rotating when it initially made contact with the M8 nut, and the apparatus used was very stiff. In this investigation the opposite extremes were taken for comparison purposes; the bolt was rotating when it made contact with the threaded hole, and the manipulator used was very compliant when compared to other manipulators (such as the GE P50). The procedure for this investigation was divided into two parts - the first part was an experiment involving translational misalignment, and the second involved rotational misalignment.

3.2.1 Translational Experiment Procedure

The procedure for the translational experiment involved the following steps. Note that this procedure was repeated on the same bolt until that bolt crossthreaded.

1. Take a new bolt and measure major diameter.
2. Insert into socket of nut-runner.
3. Step the GCA up to a position where the bolt is directly above the hole.
4. Slide the dial indicator (#1) over against the bolt-runner and zero it.
5. Turn on the bolt-driver.
6. Lower the spinning bolt into the hole.
7. Record the maximum and average deflection of the robot, using the .001 dial indicator (#1).
8. Return the GCA to the home position.
9. With the bolt in the threaded hole record the maximum deflection of the head of the bolt in the +x and -x direction using a 0.0001" (#2) dial indicator. Call this deflection R.

10. Remove the bolt and record the number of revolutions required, N.
11. Step the GCA back to the position nominally above the hole (as in step 3) and measure any residual deflection of the robot due to the bolting operation.
12. Misalign the threaded hole laterally by a known incremental amount and repeat steps 3-12 using the same bolt.

3.2.2 Rotational Experiment Procedure

The procedure for the angular experiment involved the following six steps. Note that it was carried out on a new bolt and hole each time.

1. Using a new bolt and threaded hole, thread the bolt up to five threads.
2. Record dimension R (step 9 in section 3.2.1) and remove the bolt.
3. Insert the same bolt into the socket of the nut-runner.
4. Step the GCA up to the position where the bolt is directly above the hole.
5. Misalign the bolt angularly by rotating the β axis of the manipulator (see Figure 3.1). Measure this angular misalignment to within $.5^\circ$ using an adjustable triangle.
6. Start the nut-runner. Lower the spinning bolt into the threaded hole at constant velocity.

3.2.3 Diametral Clearance Measurement

An important parameter of the bolting process is the diametral clearance between bolt and threaded hole. Measuring the diametral clearance is not trivial. An approximation was made by measuring the

deflection at the head of the bolt (the recorded distance R) using a ten-thousandths inch dial indicator and recording the number of threads the bolt entered the hole (N). These numbers were then substituted into Equation 1 (which is based on simple geometry) to provide an estimation of the diametral clearance.

$$\text{Diametral Clearance} = \sin \left[\tan^{-1} \left(\frac{R}{1.826 - .04921N} \right) \right] .04921N \quad (1)$$

3.3 Experimental Results

The first concern of the experiments was to estimate the maximum angular and translational misalignment which could be tolerated without compromising the reliability of the bolting process.

3.3.1 Translational Misalignment

Given a specified translational misalignment, first - will this misalignment error allow the bolt tip to seat in the threaded hole, and second - will this misalignment error prompt cross-threading?

The answer to the first question depended strongly on whether the bolt was stationary or rotating when it first made contact with the workpiece. If the bolt was not rotating, then the problem became a simple chamfered peg-in-a-hole problem. As shown in Figure 3.2 the maximum tolerable misalignment (determined geometrically), to permit successful assembly was .026".

If the bolt was rotating, determining the maximum tolerable misalignment which would allow the bolt to seat was much more complicated. The first part of the bolting investigation addressed this issue. Experimentally the bolt could be misaligned by approximately 0.160 in translation and it would still find the hole

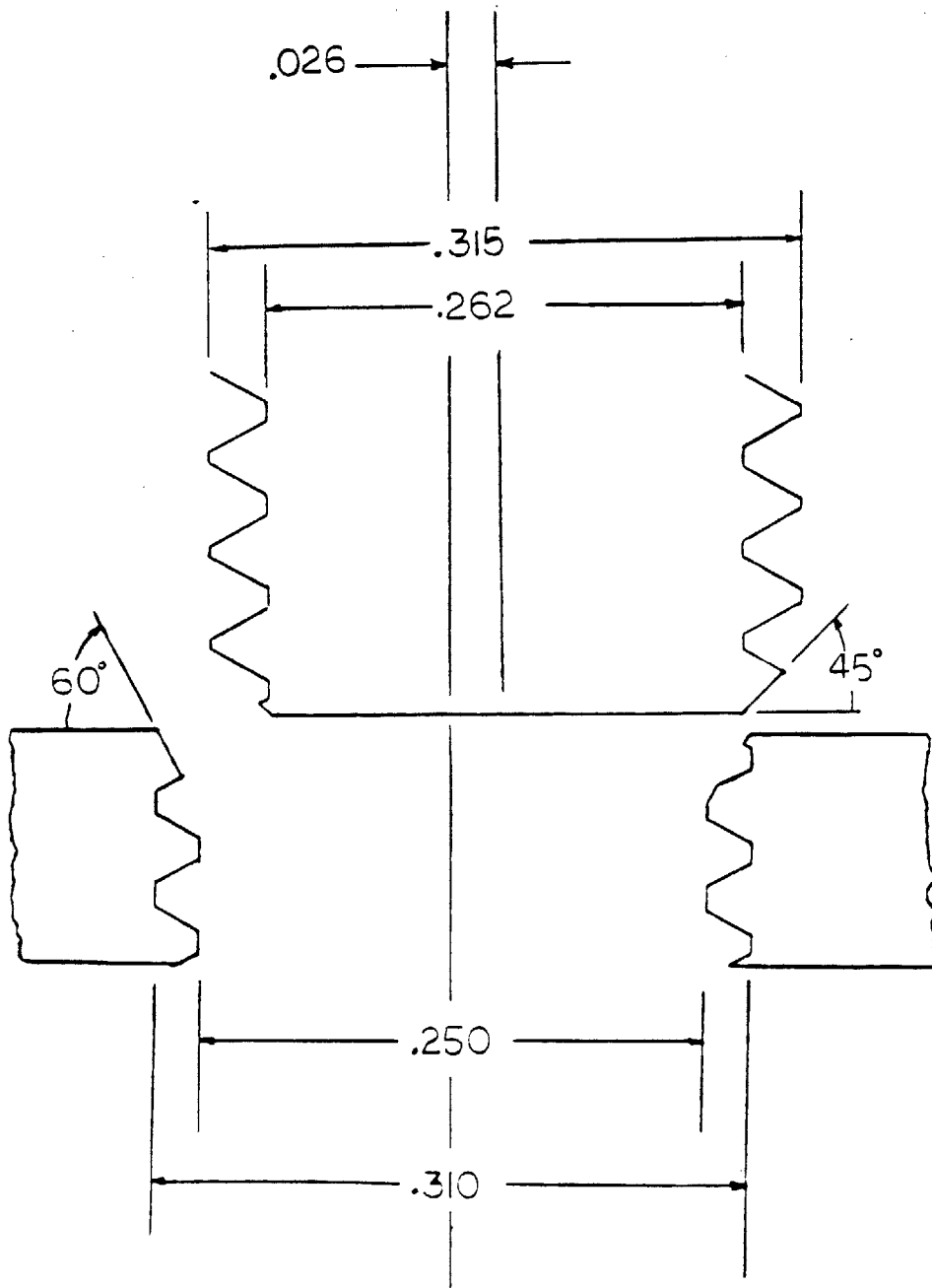


Figure 3.2 Translational Misalignment

essentially by "walking" or spinning around the hole until it seated. The experimental observations are provided in Table 3.1, 3.2 and 3.3.

The second question was, once the bolt tip was seated, would the specified translational misalignment cause the bolt to cross-thread? The first part of the investigation also addressed this question for three tolerance classes of bolts and threaded holes, though only for the case in which the rotating bolt approached the hole.

Experimentally, translational misalignments of up to .150" were tolerated without cross-threading. (see Tables 3.1, 3.2 and 3.3)

How can the bolting process tolerate such large misalignments? Unlike Taylor's experiments, in this work the manipulator was compliant and in addition the bolt head could swivel inside the socket of the nut-runner. (In Taylor's experiments it was clamped in a milling chuck.) These two factors combined to allow the rotating bolt to tilt until its tip seated in the hole; then the bolt pulled the manipulator so as to reduce the translational misalignment. This deflection of the manipulator while threading was substantial (see Tables 3.1, 3.2 and 3.3) and effectively reduced the misalignment to between 0.020" and 0.040", which is within the diametral clearance between bolt and hole.

Note in passing that this experiment also provided data on the repeatability of the manipulator under these reacting conditions. Errors of up to 0.026" were frequently observed.

3.3.2 Angular Misalignment

Given a specified angular misalignment, will this misalignment prompt cross-threading? In this part of the investigation, a new bolt and threaded hole was used in each trial and the bolt was rotating when it first made contact with threaded hole. The results are shown in

Deflection (in)	End Point Deflection from Previous Bolt (in)	Deflection while Threading		Recorded Distance R (in)	# threads inserted	Diametral Clearance (in)	Non-Insertion (X) or # of Revolutions Before Insertion
		Avg. (in)	Max. (in)				
.000	.000	.000	.002	.0050	4.5	.0007	0.0
.040	-.004	.020	.030	.0075	4.75	.0011	0.0
.080	-.010	.045	.065	.0070	4.75	.0010	0.0
.120	-.013	.060	.090	.0080	4.00	.0010	1.0
.130	-.015	.080	.100	.0080	4.50	.0011	0.5
.140	-.020	.090	.110	.0090	4.0	.0011	1.5
.150	-.023	-	-	-	-	-	X
.145	-.015	.095	.115	.0090	4.75	.0013	0.0
.150	-.026	-	-	-	-	-	X

Table 3.1: Lateral Misalignment Observations (Close Tolerance)

Deflection (in)	End Point Deflection from Previous Bolt (in)	Deflection while Threading		Recorded Distance R (in)	# threads inserted	Diametral Clearance (in)	Non-Insertion (X) or # of Revolutions Before Insertion
		Avg. (in)	Max. (in)				
.000	.000	.000	.005	.0270	5.0	.0042	0.0
.020	+.006	.010	.020	.0270	5.0	.0042	0.0
.040	-.002	.010	.030	.0245	5.5	.0043	0.0
.060	-.005	.030	.050	.0245	5.5	.0043	0.0
.080	-.005	.040	.065	.0260	5.5	.0045	0.0
.090	-.007	.050	.080	.0250	5.5	.0043	0.0
.100	-.009	.060	.090	.0265	5.5	.0046	0.0
.110	-.011	.060	.090	.0250	5.5	.0043	0.0
.120	-.012	.080	.100	.0250	5.5	.0043	0.0
.140	-.013	.090	.115	.0250	5.5	.0043	0.0
.150	-.014	.110	.130	.0200	7.0	.0046	1.0
.160	-.016	-	-	-	-	-	X

Table 3.2: Lateral Misalignment Observations (Normal Tolerance)

Deflection (in)	End Point Deflection from Previous Bolt (in)	Deflection while Threading		Recorded Distance R (in)	# threads inserted	Diametral Clearance (in)	Non-Insertion (X) or # of Revolutions Before Insertion
		Avg. (in)	Max. (in)				
.000	.000	.000	.003	.0300	4.25	.0039	0.0
.040	-.002	.005	.007	.0300	4.00	.0036	0.0
.080	-.008	.015	.025	.0320	4.00	.0039	0.0
.120	-.018	.045	.055	.0270	4.25	.0035	0.0
.130	-.202	.050	.070	.0280	4.25	.0036	0.0
.140	-.024	.050	.070	.0290	4.25	.0037	0.0
.150	-.025	.055	.080	.0300	3	.0026	1.0
.160	-.026	-	-	-	-	-	X
.155	-.020	.065	.085	.0350	3.5	.0036	1.5

Table 3.3: Lateral Misalignment Observations (Loose Tolerance)

Table 3.4. Even given these few observations, it is clear that the maximum tolerable angular misalignment is 3° or even less. Note that this is almost an order of magnitude less than the angular misalignment corresponding to angular cross-threading (see Section 3.1).

Trial	Angle	Recorded Distance R(in)	# of Threads (N)	Diametral Clearance (in)	Threaded?
1	5°	.0159	5	.0025	yes
2	5°	.0205	5	.0032	yes
3	5°	.0061	5	.0009	no
4	5°	.0255	5	.0040	yes
5	3°	.0065	5	.0021	yes

Table 3.4: Angular Misalignment Observation

3.3.3 Cross-threading Versus Tolerance Class

From mechanical considerations it is clear that the likelihood of cross-threading may depend on the diametral clearance between bolt and hole. Diametral clearance may be determined from the tolerance class of the bolt and hole. The tolerance class for a standard M8 bolt and nut is 8M x 1.25 x 6H6h where "6H" and "6h" designate the tolerance class for the nut and bolt respectively. Because data could not be found specifying the tolerances on drilled and tapped holes it was assumed that the tolerance class for an M8 nut was the same for an M8 tapped and threaded hole. As shown in Figure 3.3, this tolerance class of nut and bolt could provide a tight fit of .000" diametral clearance and on the other extreme a loose fit of .0108" diametral clearance. [5]

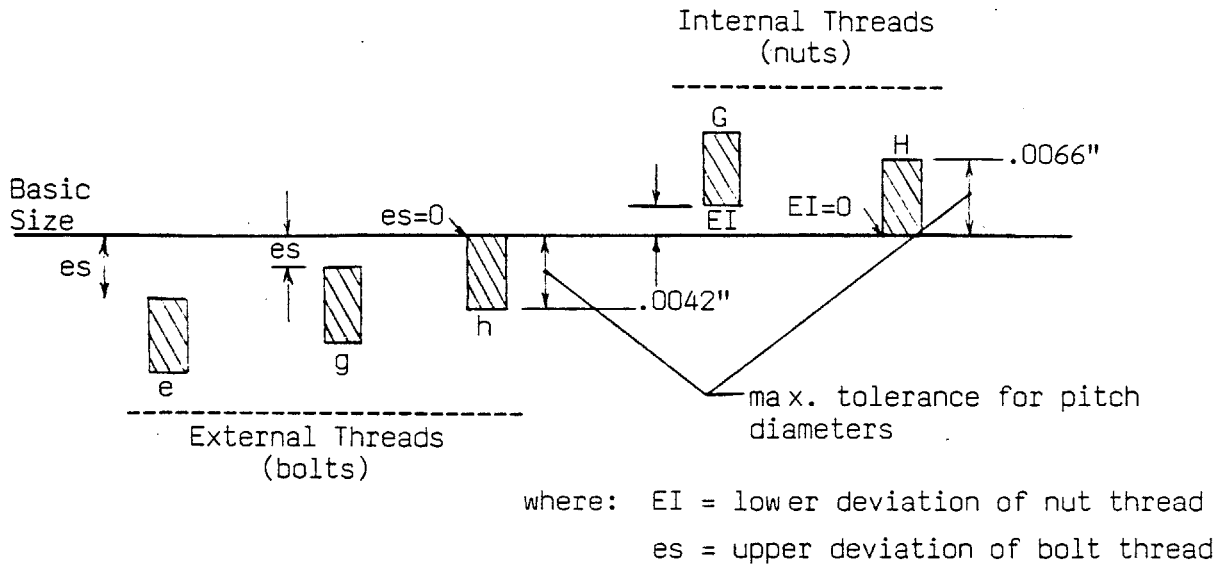


Figure 3.3 Tolerance Class for a 8M x 1.25 x 6H6h Nut and Bolt

It is not clear that a bolt and nut with 0.000" diametral clearance can be assembled. After consulting with Bossard International, a leading manufacturer of metric fasteners, it was learned that bolts and nuts are produced in large batches, and with every batch a quality control analysis is performed that provides an estimate of the range of tolerances for that particular batch. For any given batch of nuts and bolts, the clearances would be expected to be distributed statistically between the two specified extremes. If the distribution were Gaussian and it is assumed that 99% of the batch have clearances between the limits of 0.000" and 0.0108", then the standard deviation would be 0.0018"; therefore 95% of the batch would have clearances between 0.0018" and 0.009". Clearly, a design which accommodates the full clearance range of 0.000" to 0.0108" would be overly conservative.

What clearance range is likely to be encountered in practice? The diametral clearance between the threaded hole and bolt was measured (using the method previously outlined) in both parts of the experiment. In the investigation of translational misalignment, no reliable conclusions about the influence of diametral clearance on cross-threading can be drawn from the data because the same bolt was used repeatedly (almost ten times) until the bolt cross-threaded. The repetitious use of a bolt in this manner is not representative of manufacturing processes in which a new bolt and threaded hole are used every time. In the investigation of angular misalignment, a new bolt and threaded hole were used for every trial. Diametral clearances as low as 0.0008" were observed. Furthermore, it is clear that low diametral clearance can promote cross-threading. At 5° one bolt cross-threaded with a diametral clearance of .0008", while three other bolts with clearances of .0025", .0032" and .0040" did not.

Because angular cross-threading, in which the bolt and nut are one full thread out of phase would require 15° of angular misalignment, the observation of cross-threading at 5° is probably due to a different phenomenon, most likely that which governs parallel cross-threading. However, in our experiments parallel cross-threading was not observed when bolt and hole were perfectly aligned.

3.4 Summary

Because of the difficulty of duplicating a manufacturing process in a laboratory environment, the experimental results reported here should be interpreted with caution. However, they provide a basis for establishing design specifications for the Mark II tool. The data

indicate that cross-threading is more likely to occur when the diametral clearance is small, and they also indicate that to eliminate cross-threading the tool should align the bolt and threaded hole to within at least 3° of perfect angular alignment and to within at least 0.026" of perfect translational alignment; closer alignments will probably yield better performance.

Finally, what is the maximum angular and translational misalignment (due e.g. to robot or sensor inaccuracies) the tool must accommodate? No experimental procedure to determine these numbers was evident. From anecdotal observations, angular errors greater than 7° are unlikely. Using a probe to find the hole, translational errors of half a hole diameter, 0.165", are easily accommodated.

CHAPTER FOUR
DESIGN ISSUES

At this point in the design process several issues had become clear. These issues were addressed and resolved before specific proposals were considered for the new bolting tool design. Once these issues were resolved, a new set of tool requirements were outlined and included as a summary to this chapter.

4.1 Parallel Cross-threading

The first issue (discussed in the last chapter) is the problem of parallel cross-threading which may occur even when the axis of the bolt and threaded hole are perfectly aligned. It occurs when the starting threads of the bolt and hole line up with each other as the bolt makes contact with the threaded hole. The weakened sections of the starting threads are then twisted into each other when rotation occurs. This effect is accentuated by the 45° and 60° chamfers of the bolt and threaded hole respectively.

A solution to the problem of parallel cross-threading is "reverse-threading" - to reverse the normal direction of rotation of the bolt until the ends of the helical threads cross; then the starting thread of the bolt will fall one thread in depth onto a full thread section of the threaded hole. At this point the rotation of the bolt should be reversed and the bolt threaded. This strategy of reverse threading will ensure that the starting thread of the nut will be about 180° out of phase with the starting thread of the bolt, thereby eliminating the possibility of parallel cross-threading.

In the investigation presented in Chapter Three, parallel cross-threading was not observed when bolt and hole were coaxial, and it is unclear how large a problem it represents. Therefore, the Mark II tool will be designed to accommodate the strategy of reverse threading; however, the strategy should not be employed until the tool has been tested in a manufacturing environment and the need for reverse threading has been determined.

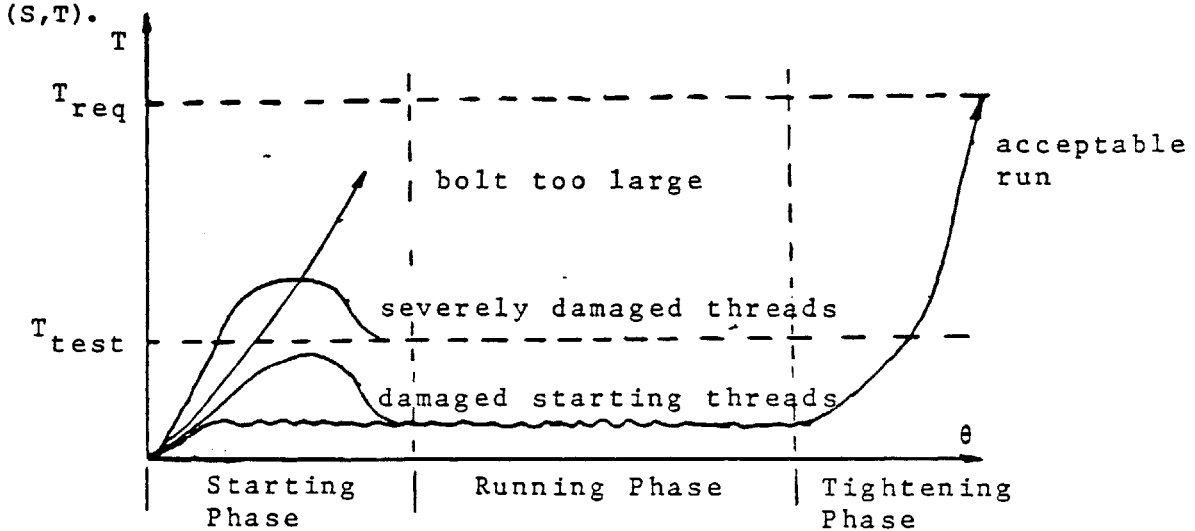
4.2 Starting Tool Versus Tightening Tool

The second issue is whether to separate the bolting process into two different processes using different tools. There are many advantages to this strategy. Discussion with several graduate students at M.I.T. who have worked in manufacturing and assembly environments indicated that many U.S. companies use commercially available tools to run and tighten bolts to prescribed torques, but few companies start bolts automatically.

Secondly, a nut-runner which must generate the high torques needed for tightening will be heavy and bulky. This was mentioned previously in the evaluation of the Mark I tool as it was primarily responsible for its size, weight and kinematic design of that tool. In contrast only low torque is required for starting a bolt. Thirdly, the tolerances required to start a bolt are much easier to achieve with a light dexterous tool. Also with a bolt already started, considerable clearance can be tolerated between the bolt head and the socket of a tightening tool.

Bolting may be described as having three different phases: the starting phase, the running phase and the tightening phase. All of

these are illustrated in Figure 4.1. To help decide this second issue, the following aspects of the bolting process were categorized as part of the starting and running (S) or tightening (T) process or both (S,T).



where: - T_{req} is the prescribed torque requirement of the bolt
 - T_{test} is the cutoff torque for threads that may present a problem

Figure 4.1 Three Phases of the Bolting Process

The tool design issues:

1. (S,T): Speed of the whole process and how the total process time is distributed among the operations
2. (S): Reliability of the process
3. (S): Ability to accommodate normal production tolerances
4. (S,T): Recoverability of the process (trade-off with reliability)
5. (S): Alignment of through and threaded hole
6. (S,T): Minimal access space (included in design)
7. (S): Detect incorrect assembly components (no gasket, wrong bolt, no gasket hole, no threads in hole or on bolt)
8. (T): Controlled axial loading

9. (S): Jamming/cross-threading
10. (S,T): Sensing and control requirements:
 - a. Force
 - b. Torque
 - c. Displacement
 - d. Angular Displacement

Of these 10 items, 9 may be addressed in the starting and running phases, while only 5 involve the tightening phase. Therefore the Mark II too will only perform the tightening and running phases of the process.

4.3 Anchoring

Another issue derived from the evaluation of the Mark I tool was the anchoring problem. Given a random set of workpieces with M8 threaded holes in various places, the only area on which to anchor common to all threaded holes is the small amount of flat area surrounding the threaded hole. This area must be able to accommodate an M8 socket wrench and is perpendicular to the axis of the threaded hole. As an M8 socket wrench is approximately 1" in diameter, the bolting tool's anchor should only require at most a circular area of 1 inch in diameter on which to stabilize the bolting tool.

4.4 Dynamic Loading of the Tool

A final issue that was also derived from the evaluation of the Mark I tool was the problem of dynamic loading of the bolting tool during the steps of its operation. A fundamental aspect of the bolting tool design was the fact that it used the threaded hole itself to align the bolting tool with respect to the workpiece. This alignment was

performed by the probe. Given this choice, the probe has to be removed before the bolt can be threaded.

The problem arises when the probe has been removed and the bolt is to be moved into place. The tool has been stabilized at this point in the process by a downward vertical force which creates a lateral frictional force. Excessive dynamic loading due to abrupt acceleration or deceleration during this movement can overcome this stabilizing force and cause the tool to return to its original misaligned position.

This problem was observed in the Mark I design which used an indexing table and an attached pneumatic nut-runner (see Figure 2.1). The pneumatic nut-runner had sufficient mass to cause the tool to misalign due to inertial forces generated during its movement.

The solution to this problem includes two parts. First of all, the net force of the moving probe or bolt should be directed downward if possible because the tool is essentially rigid in the z-direction. This movement should not, if possible, direct forces in the x or y directions or the θ and ϕ directions because the tool is compliant in these directions. Secondly, if the movement of the probe and bolt does direct forces in these directions, then a spring or damper element should be used to absorb the energy of this movement without generating excessive inertial forces.

4.5 Summary

From consideration of these design issues and previous requirements, the new bolting tool, the Mark II, should:

1. start M-8 metric bolts with the bolts fed to the tool directly.

2. have as low a profile as possible to meet its limited vertical access requirement.
3. use a probe as a mechanical reference between tool and threaded hole to align them to within at least 3° and $.026''$.
4. accomodate initial misalignments of 7° and $0.165''$.
5. utilize an anchor to generate interference forces between manipulator and workpiece. The anchor will be restricted to rest on the 1" diameter area immediately surrounding the bolt head.
6. utilize the strategy of "reverse threading" to prevent parallel cross-threading if this strategy is found necessary.
7. utilize springs and dampers to absorb the energy of moving parts during the transfer of probe and bolt.

CHAPTER FIVE
DESIGN PROPOSALS

This chapter presents some initial designs proposed for the Mark II tool. As in most design projects, ideas were not generated in any logical fashion but are presented here in a step by step fashion building on the few known details of the design that were derived from the evaluation of the Mark I tool. The design proposals were broken down into these five systems: the Anchoring System, the Delivery System, the Probe Activation System, the Bolt Rotation System and the Modified RCC Design. (Taylor's Tool Impedance Isolator)

5.1 The Anchoring System

The purpose of the anchoring system is to purposefully generate interference forces between the workpiece and the manipulator to stabilize the new position of the tool generated when the probe was inserted. The anchor must counter-balance the forces generated by the deflection of the spring elements in the modified RCC. Therefore the anchor must be able to support forces in the x and y directions and moments about the θ and ϕ directions.

The physical requirements of the anchor were outlined at the end of Chapter Four. The only surface area that the anchor can reliably utilize is the area immediately surrounding the threaded hole. This is the only surface that is guaranteed perpendicular to the axis of the hole. The second physical requirement is to design the anchor so that it is the lowest point on the tool. This prevents the tool from being restricted to bolting on edges only.

In the first design (shown in Figure 5.1) the anchor is a cylindrical sleeve driven by two pneumatic actuators. To meet the limited vertical access requirements a constrained flexible drive (similar to a bicycle brake cable) connects the two. There are several positive features of this design. First of all, it only requires the surrounding area of the threaded hole as specified. The second positive characteristic of the design is its use of cylindrical shapes, and this prompted the idea that the probe and bolt could be cylindrical cartridges which are loaded into the sleeve-like anchor. The biggest advantage to this approach is the fact that the anchor is never moved once the hole is located. To accomplish this the anchor would first be loaded with the probe cartridge and then this assembly inserted into the hole. Once the hole was located the probe would be removed leaving the anchor in contact with the workpiece at the same position. The bolt cartridge is then inserted into the sleeve.

A negative aspect of this proposal is its use of two actuators in such a limited space. This led to the second design (which was eventually adopted) in Figure 5.2. The anchor, as shown is compliantly supported in the z-direction by springs. In this design the manipulator forces the anchor against the workpiece; the resulting deflection of the springs generates the needed force in the z-direction without the use of actuators.

The cylindrical anchor generated the idea of using identical cartridges for the probe and the bolt. The need then arose for some means of delivering the bolt and probe cartridges (respectively) to the center of the anchor.

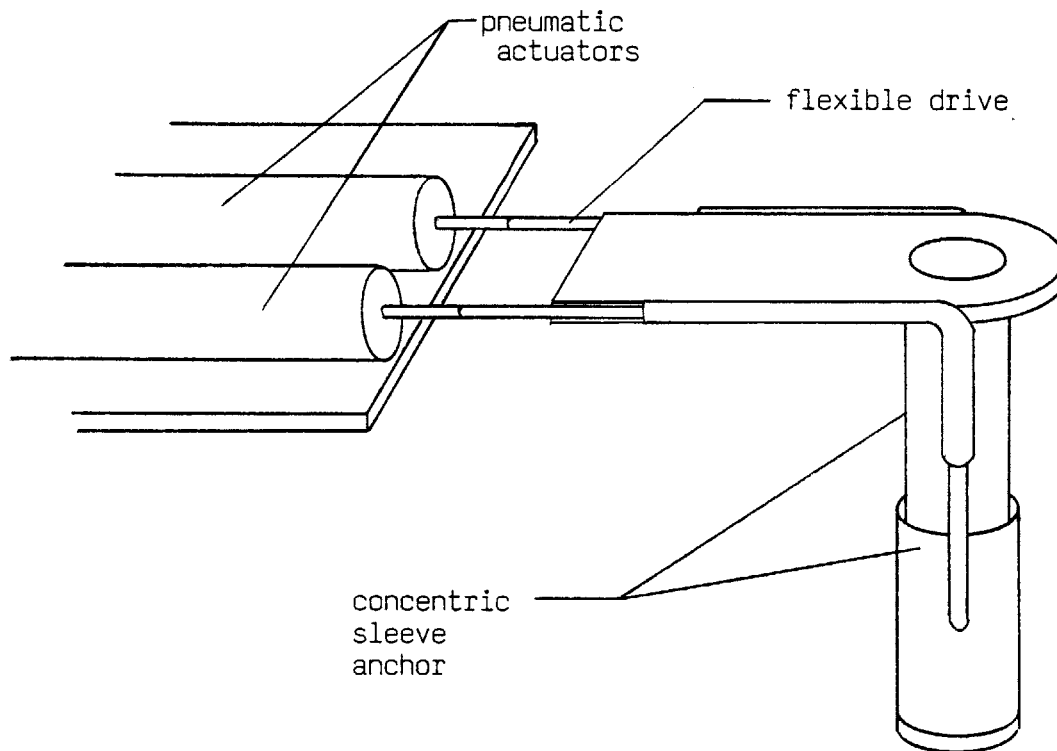


Figure 5.1 Initial Anchor Design

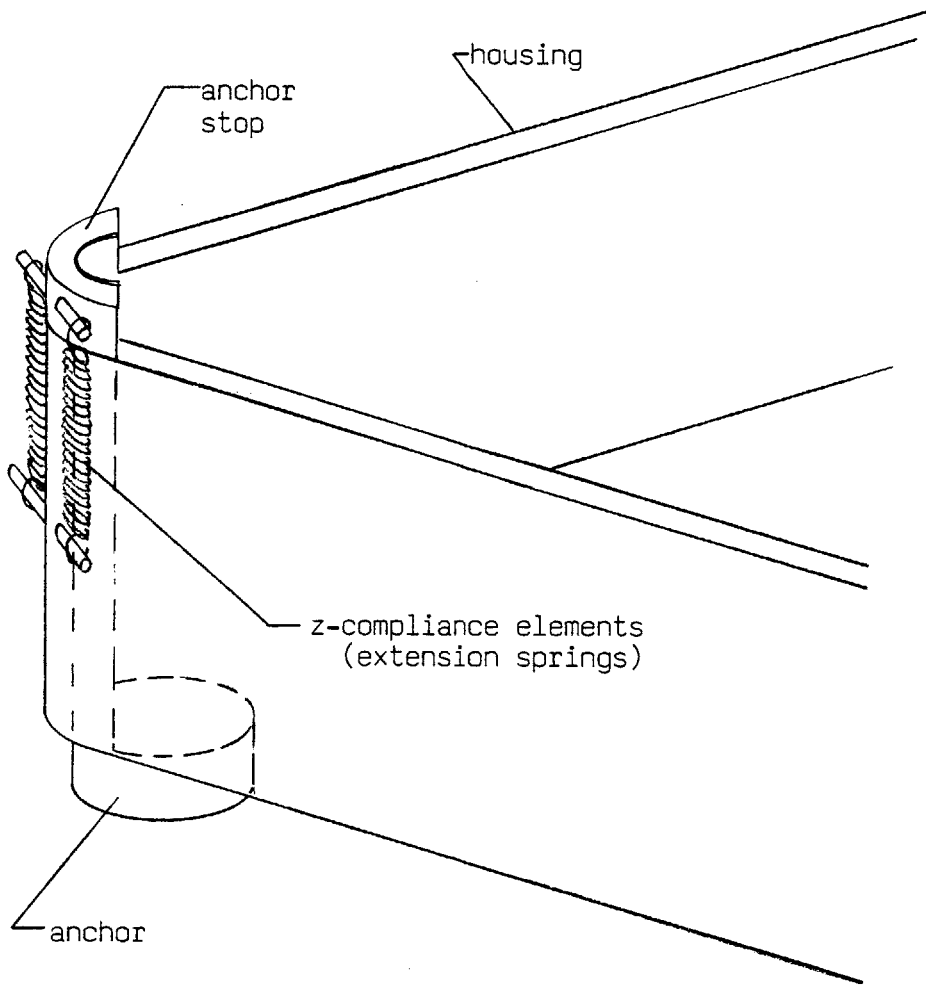


Figure 5.2 Final Anchor Design

5.2 The Delivery System

The purpose of the delivery system is the transportation of the bolt and probe from their resting place in the tool to the center of the anchor. This transportation involves four phases - two for each cartridge. The two critical phases are the removal of the probe and the delivery of the bolt. Dynamic loading of the tool during these two phases determines whether the tool will retain its corrected position.

The delivery system should have as low a profile as possible. There are several ways the bolt and probe cartridges could be delivered to the anchor location as shown in Figure 5.3. The design task is to implement one of these possibilities in as little space as possible. Another requirement for both cartridges is that the delivery system should transport the cartridge to the anchor, and at that point the cartridge should be in a perfectly vertical position. Furthermore, about the last quarter inch of this travel should be in the vertical direction to accommodate the deflection of the anchor without binding or jamming. A further requirement for the bolt cartridge delivery system is that it should permit the bolt to be loaded into it at some point.

The first design considered (shown in Figure 5.4) was the Sliding Cartridge Design. This design involved mounting the two cartridges in a V-shaped track and then loading them into the anchor sleeve. The biggest advantage of this approach is its low profile. Given the size of an M8 bolt the delivery system could not be much smaller. However, there are several problems with this design. The first problem is the fact that it requires two actuators to deliver the cartridges translationally and a third actuator to force it downward. Interfacing the cartridges with the anchor sleeve also presents a design problem.

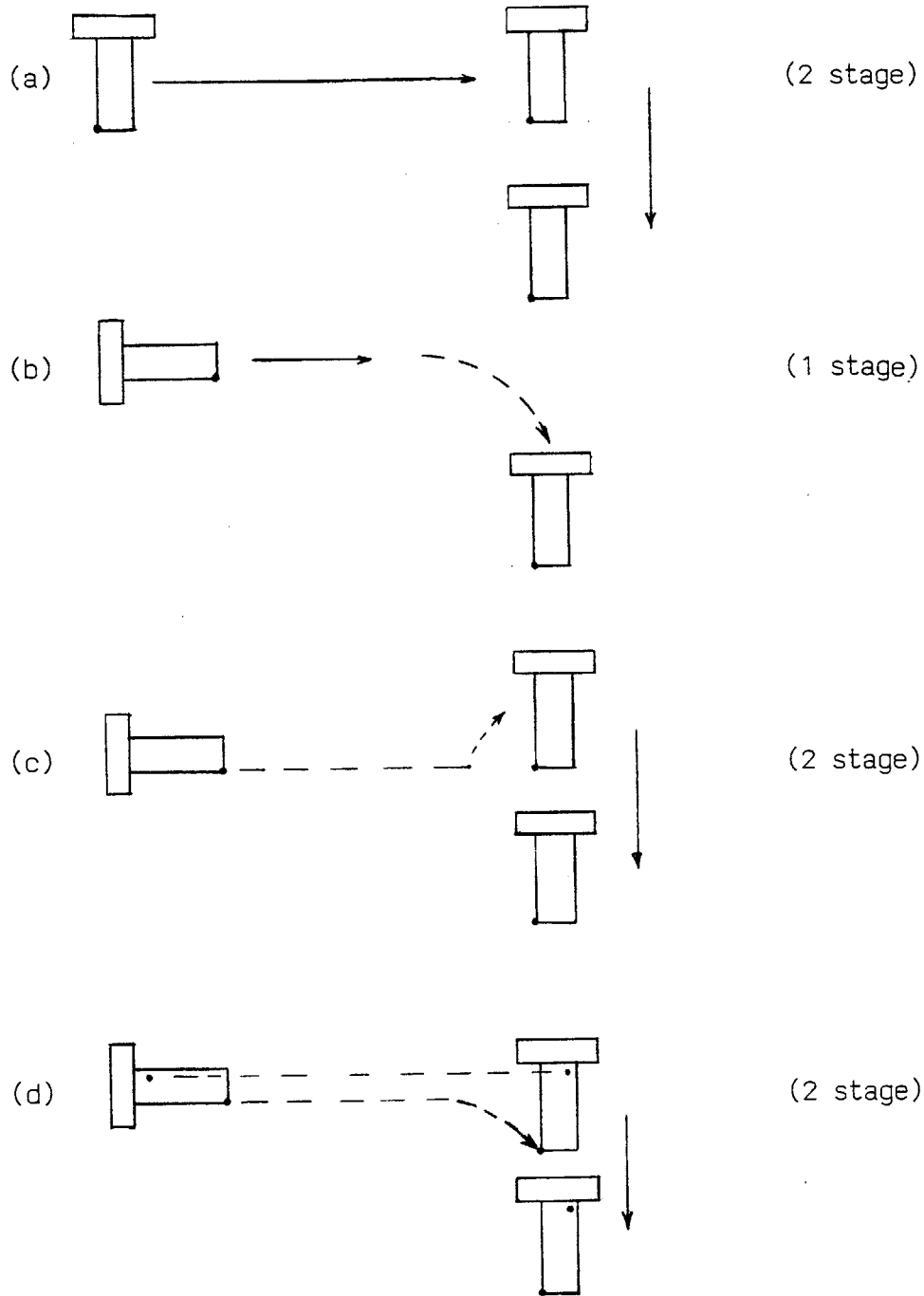


Figure 5.3 Possible Delivery Movements

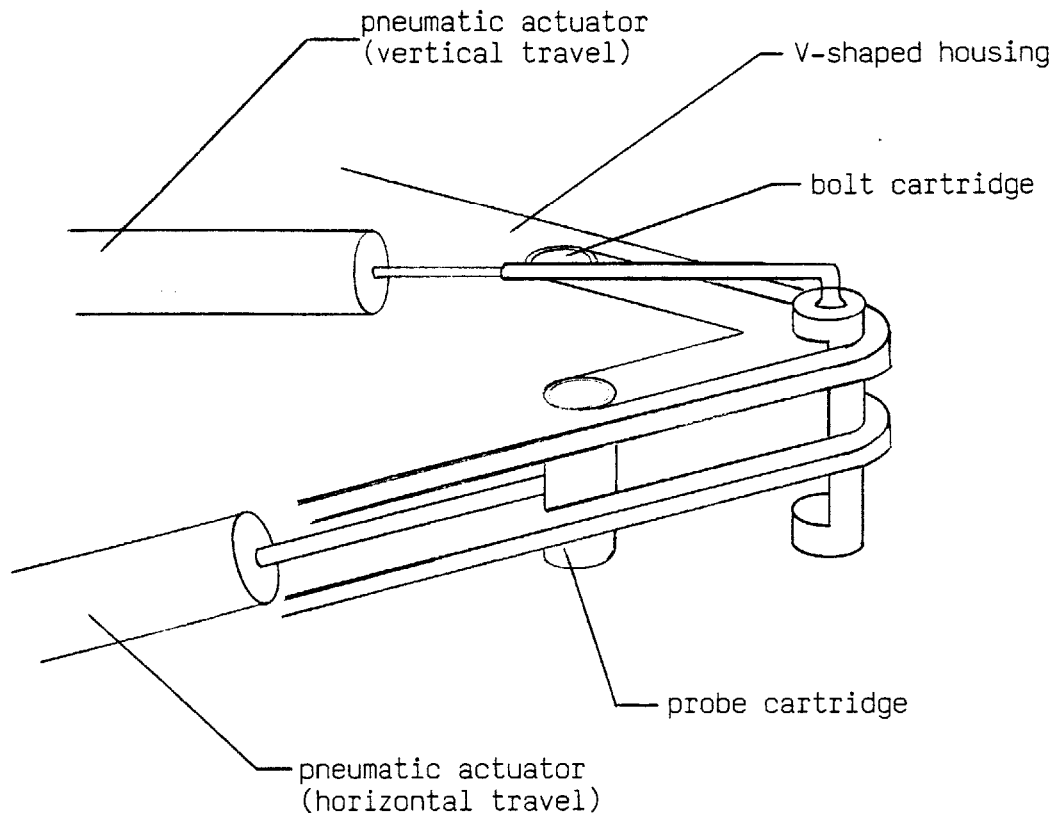


Figure 5.4 Sliding Cartridge Design

Therefore another design was pursued employing a different means of transporting the cartridges.

The second design considered (shown in Figure 5.5) was the Parallel Track Design. Two parallel tracks are mounted side-by-side. One track is designed for the bolt cartridge and the other for the probe cartridge. A pneumatic actuator drives each cartridge along its path until it is seated in the anchor. There were several advantages to this design. First of all the way the track is designed allows the bolt cartridge to turn up so that a bolt may be dropped into it head first - one of the requirements for the bolting tool. The second advantage to this design is the straight line travel of the cartridges at the tip of the tool. The biggest and most overwhelming problem is the design of the track for the cartridges to run along. The straight line travel at the end of the track could cause the cartridge to jam when the probe is to be pulled from the threaded hole. Given these complications, another alternative was sought, one which would provide the horizontal and vertical motion in one movement, as this design did, but one that was easier to implement.

A design that provides the same type of movement is the 4-Bar Linkage Design. It was eventually adopted in the Mark II tool. The 4-Bar Linkage Design shown in Figure 5.6 utilizes two small 4-bar linkages. The linkage should be mounted in a V-shaped housing so that the coupler of the linkage, or the cartridge, has the same final position at the center of the anchor, similar to the parallel truck design.

There are many advantages to a 4-bar linkage delivery system. Similar to the last design, the motion of the bolt cartridge linkage

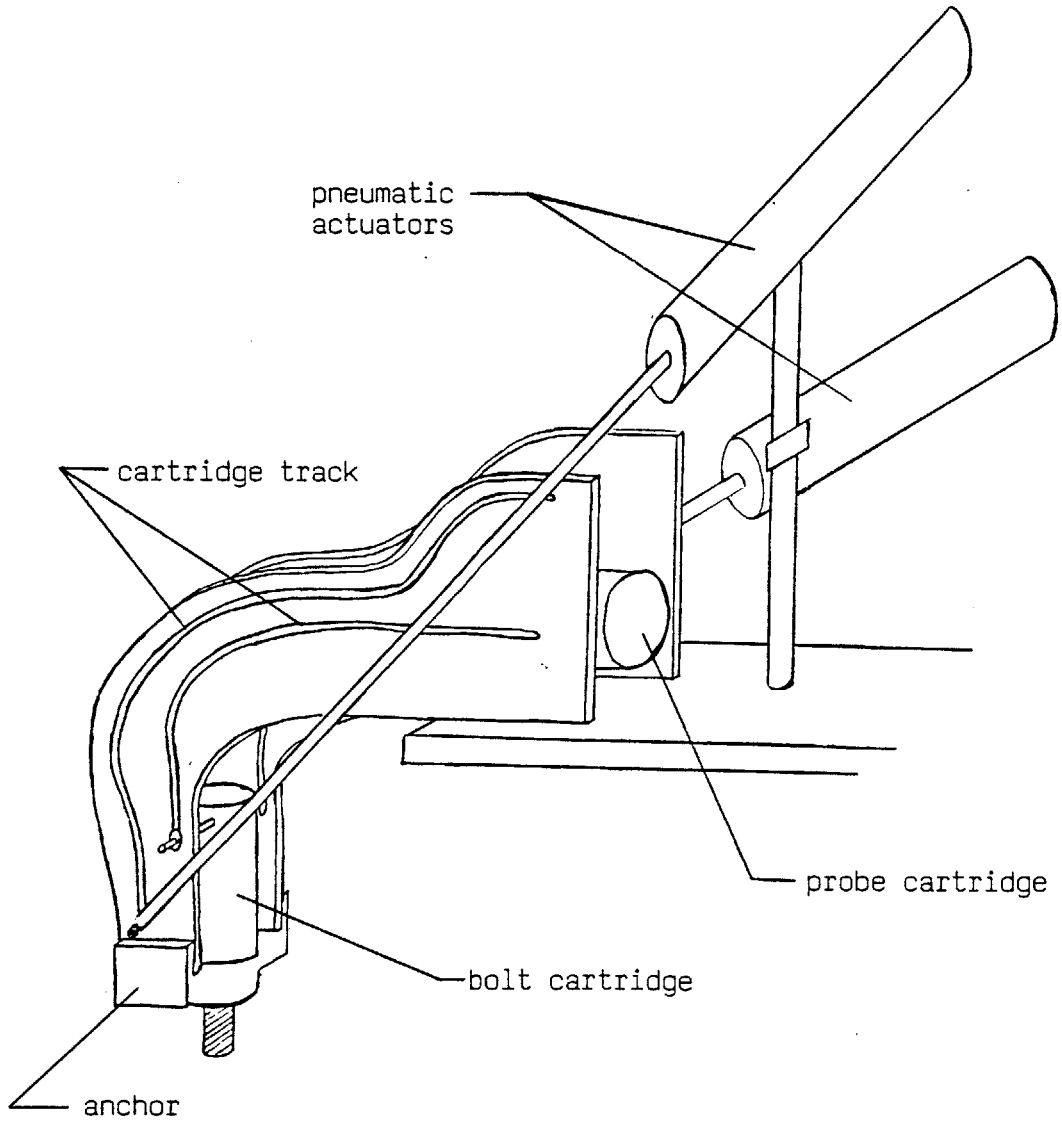


Figure 5.5 Parallel Track Design

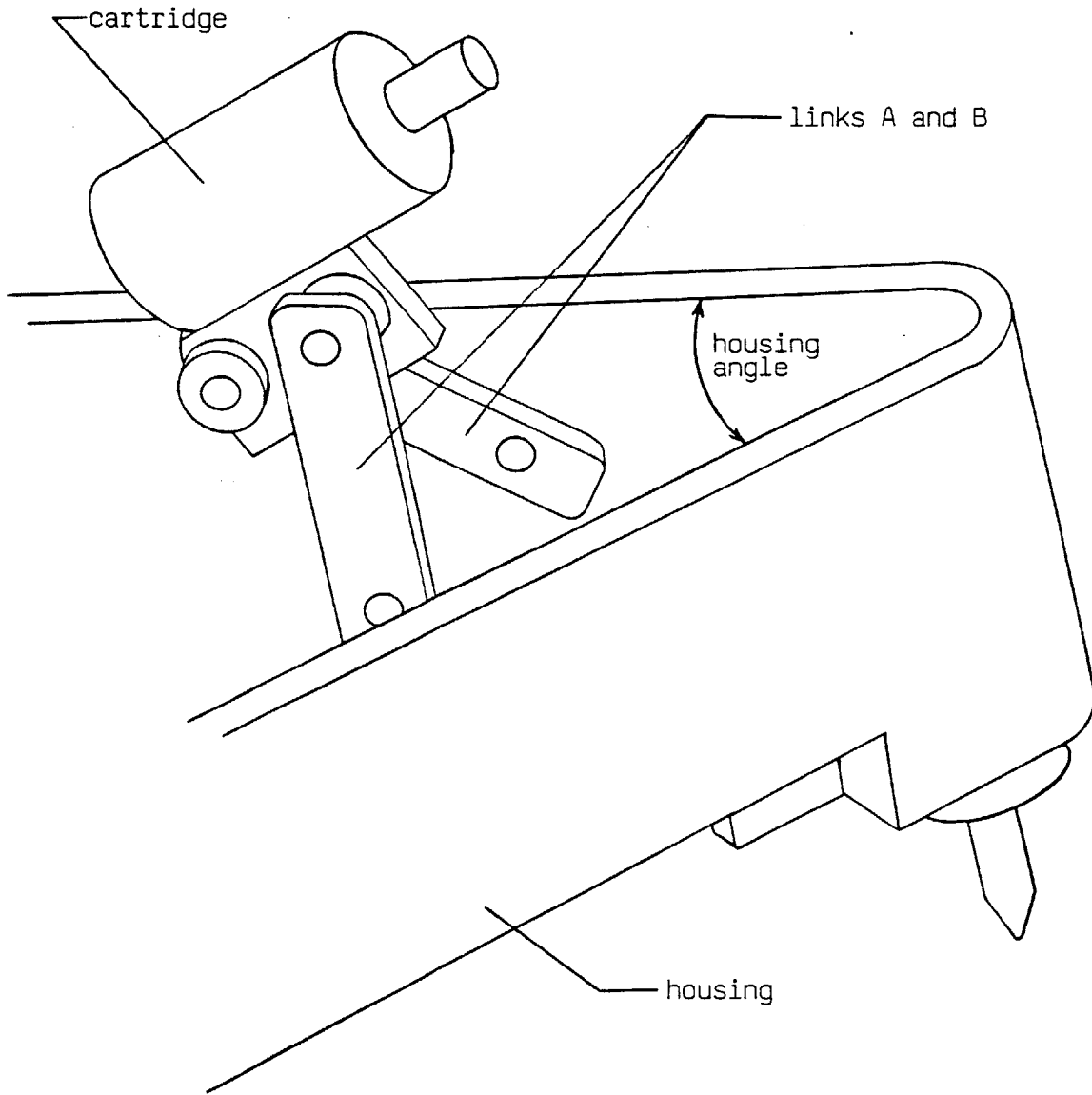


Figure 5.6 4-Bar Linkage Design

allowed the cartridge to be turned upward to accept a bolt head first. A second advantage was the compactness of the entire system and the fact that it met the requirement for low profile to a reasonable degree. A third advantage of the design is its symmetry. If the two linkages are designed identically then the accuracy with which the probe is removed and the bolt delivered should be within a few thousandths of an inch, with the use of precision bearings. The biggest advantage to the system is the fact that it is implementable without difficulty.

To implement this design for the delivery system it was necessary to locate the pivot point for the linkage given a desired trajectory of the cartridge. Using a simulation package, DRAM (Dynamic Response of Articulating Machinery), the pivot points were located to within .001" at positions that would allow the bolt cartridge to be turned upward at the end of the trajectory and vertically downwards at the anchor position, as shown in Figure 5.7. The probe's trajectory was identical to the bolt cartridge's except its path was shortened to stop with the probe in the horizontal position, because, unlike the bolt cartridge, it did not need to be loaded but only to be removed from the bolt cartridge's path as shown in Figure 5.8. A key feature of this design is that over the final 1/4 inch of travel, the deviation of the cartridge from a vertical path is within 0.003". This is clearly seen in the first two frames of Figures 5.7 and 5.8 which are drawn with the positions of the cartridge about 1/4" apart.

The minimum angle between the vertical rises of the housing that would accommodate both cartridges without the two colliding was determined empirically by making a wooden model of the tool shown in

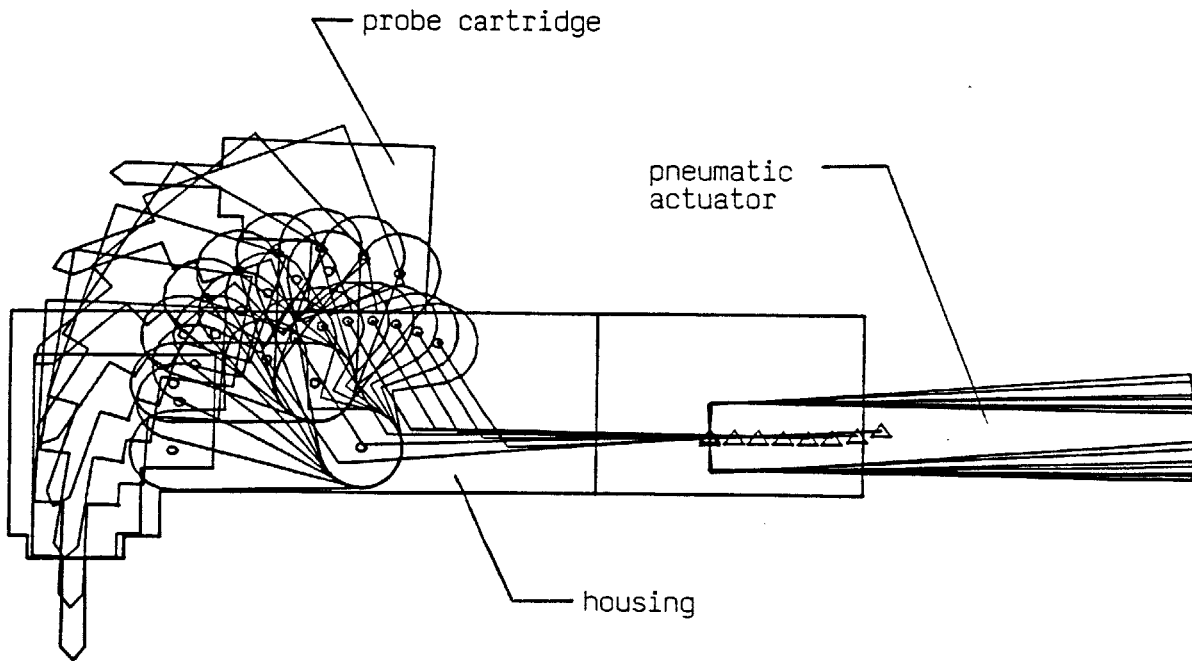


Figure 5.7 Probe Cartridge Trajectory

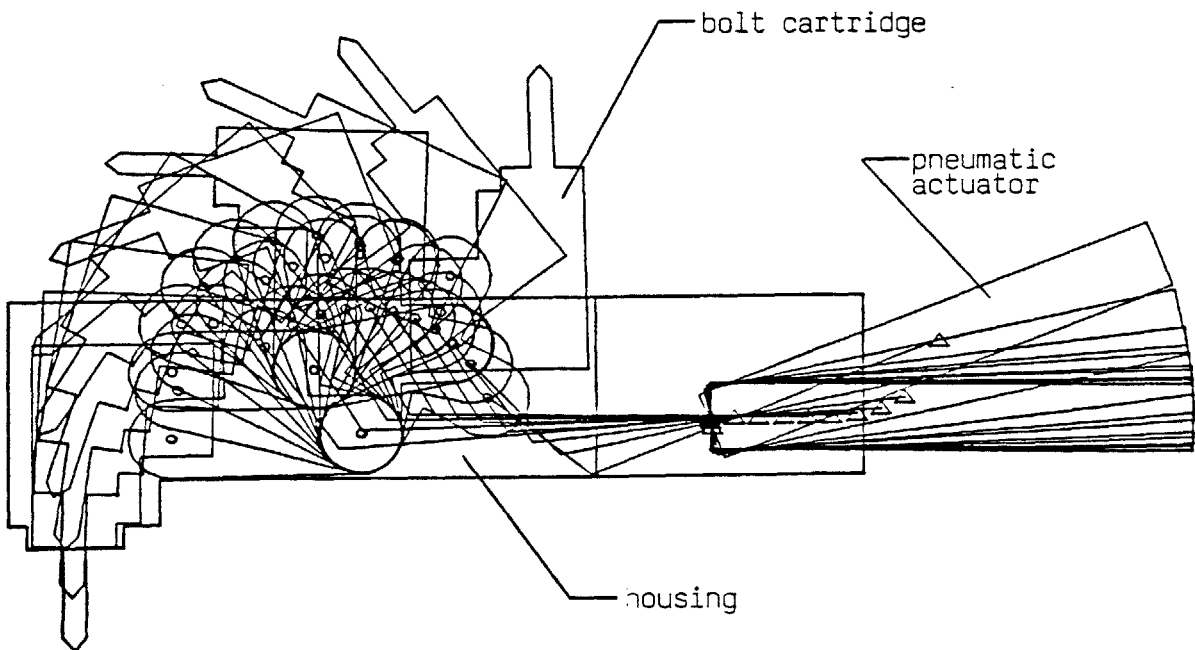


Figure 5.8 Bolt Cartridge Trajectory

Figure 5.9. The driving mechanism for the 4-bar linkages are pneumatic actuators mounted to the sides of the housing with pivoting mounts. The shafts of the actuators are connected to the longest link of the 4-bar as shown in Figures 5.7 and 5.8.

The 4-Bar Linkage Delivery System provided an acceptable means of delivering the cartridges to the anchor. The next step in the design process was to find some way to lock probe cartridge to the anchor so that when the probe is reoriented or realigned to a correct position it will also realign the tool.

5.3 The Probe Locking System

The system used to mechanically lock the probe to the anchor was a collet design. (see Figure 5.10) The collet is driven by a double acting pneumatic cylinder. When air is forced into Port II, the piston is forced upwards which drives the wedge-shaped cone in the base of the cartridge upwards and forces the split walls of the base outwards and against the inside wall of the anchor. To release the locking mechanism, air is forced into Port I.

By far the biggest advantage to this design is the fact that as the probe is inserted into the hole, any interference forces due to insertion move the wedge-shaped cone up so as to tighten the connection between the probe cartridge and the anchor. The biggest disadvantage is the complexity of the probe cartridge. The machining involved in constructing this part is considerable, but the advantages outweigh the disadvantages.

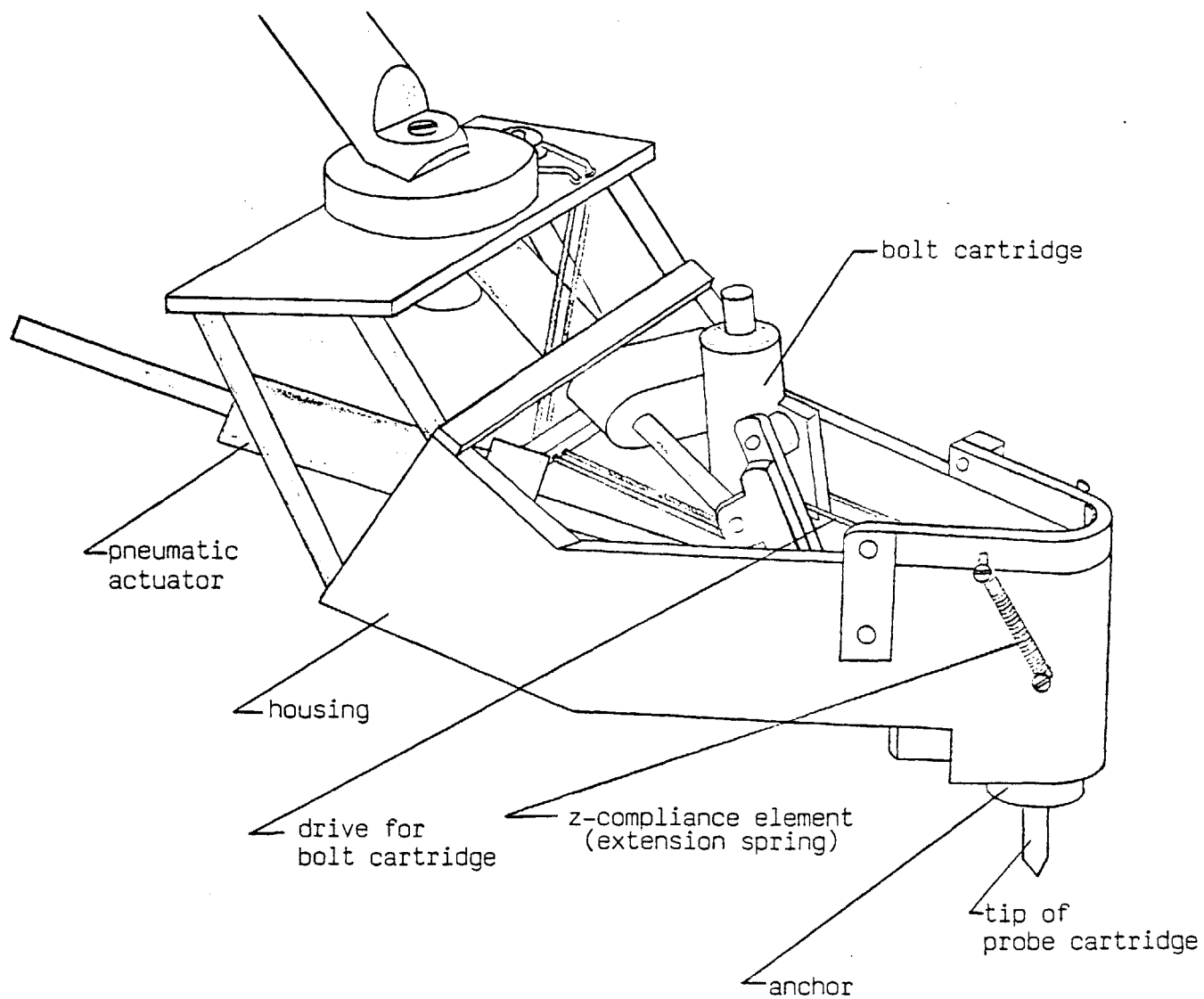
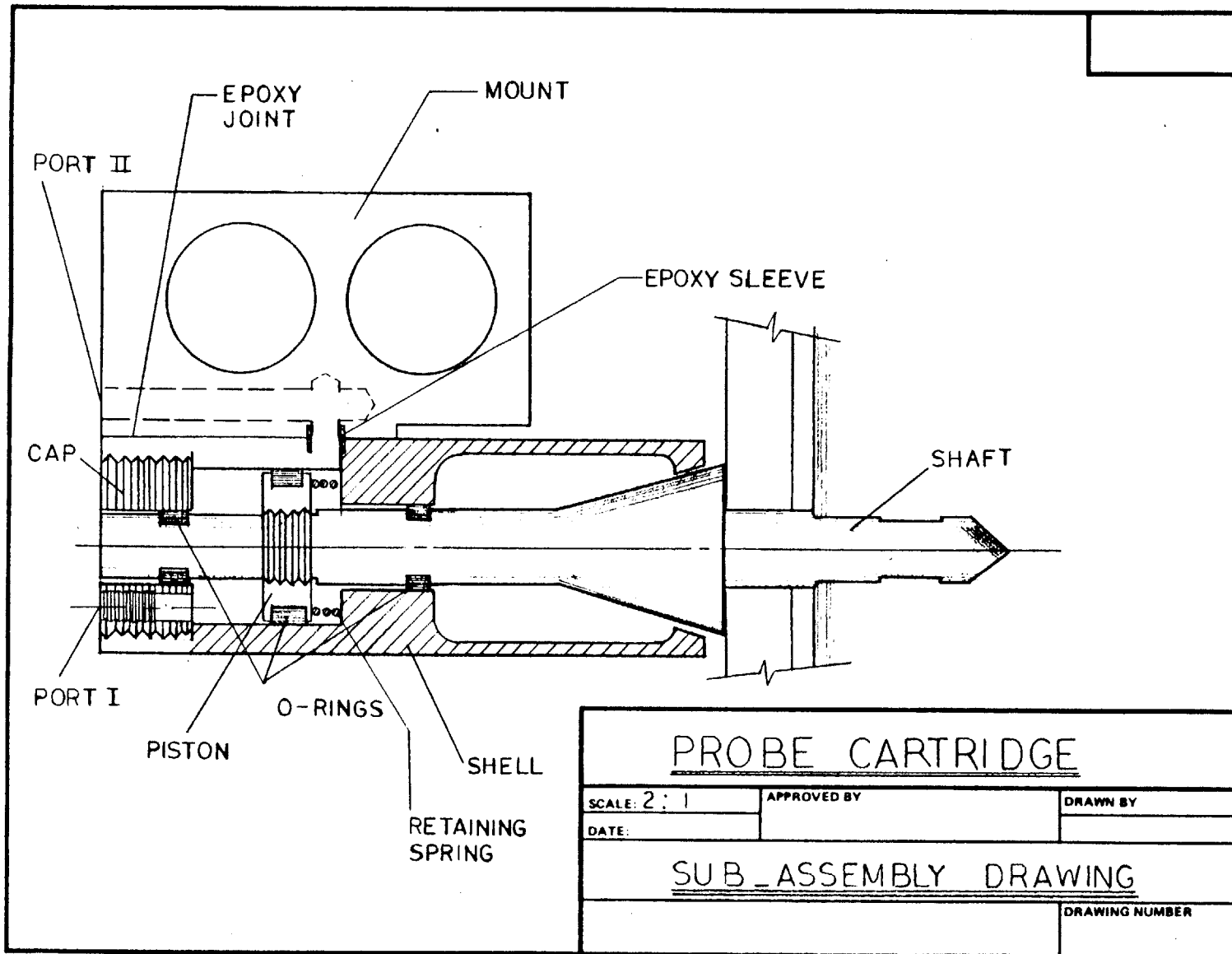


Figure 5.9 A Wooden Model of the Mark II Tool



DIETZGEN MASTER FORM 198MF

Figure 5.10: The Probe Cartridge

5.4 Bolt Rotation System

The purpose of the Bolt Rotation System was to rotate the bolt in two directions. As specified in Chapter Four, the reverse direction is required in case the strategy of "reverse-threading" proves to be necessary.

The bolt cartridge, shown in Figure 5.11, was designed using an M8 socket, with a spring-loaded magnet included that would deflect 1/4 inch and allow the head of the bolt to rest against the curved base in the socket. The socket was attached to the cartridge using a 1/4 diameter inch shaft secured with two 1/4 inch bore ball bearings.

Rather than mount the actuator for rotating the bolt directly on the cartridge, it was mounted on the tool housing. To accommodate the movement of the cartridge a flexible transmission using a beaded chain was used.

5.5 The Modified RCC Design

The purpose of the Modified RCC was to provide the bolting tool with a center of compliance about the tip of the probe when it was locked into place at the center of the anchor. The Modified RCC allows the tool to align itself with the workpiece under the action of interference forces generated at the tip of the probe during the insertion step, without the use of feedback to the manipulator.

There are several requirements for the Modified RCC design as outlined at the end of Chapter Four. First of all, the Modified RCC design has to accommodate translations in the x and y directions and rotations about the ϕ and ψ directions. The maximum misalignment that

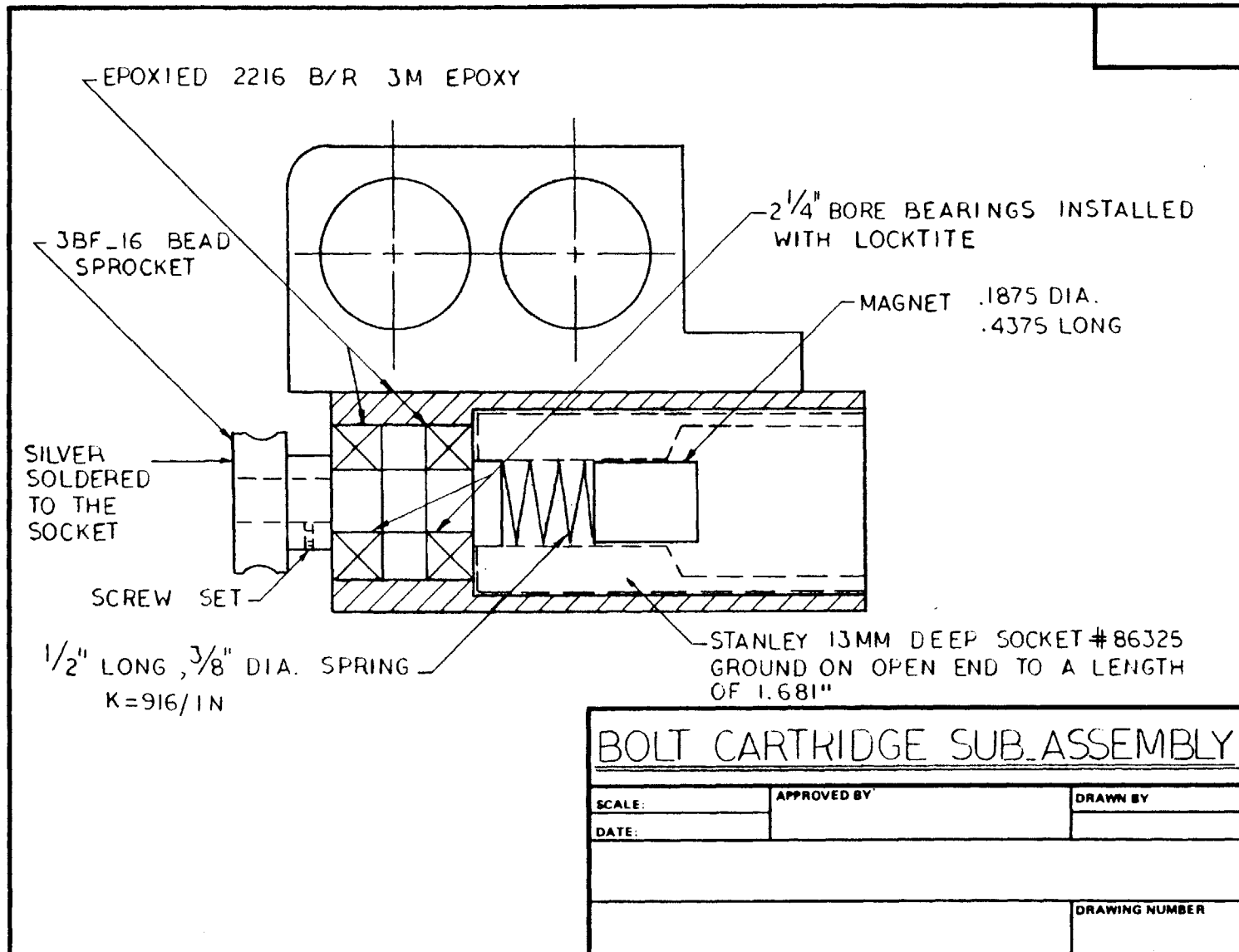


Figure 5.11: The Bolt Cartridge

the tool must be able to accommodate is 7° and $.165''$. It must reduce this misalignment to within 3° and $.026''$.

The RCC design was first developed by Samuel Drake [2] to allow a manipulator to place a round peg into a closely fitting chamfered hole. Conceptually, there are two parts that make up the RCC design - a kinematic linkage that provides the mechanism with a remote center of rotation and a spring-damper system that provides the linkage with an equilibrium position. A suitable kinematic system which involves two 4-bar linkages is shown in Figure 5.12. However this design would require vertical access to the hole.

Throughout this project it was assumed that vertical access to the hole was limited. Consequently a Modified Remote Center of Compliance device must be designed. The tool cannot approach the threaded hole from above and in fact the access space to the hole needs to be as small as possible. Given these conditions the first design is shown in Figure 5.13. This design utilized 7 elastomeric shear pads of the type used by Lord Corporation in their RCC designs. The elastomeric shear pads consist of several thin metal disks stacked up and held together with an elastomeric coating. The pads are very stiff in the axial direction, stiff in bending and compliant in the shear directions and the axial torsional direction. In the modified RCC shown in Figure 5.13 four pads are mounted between two flat surfaces. These provide translational compliance. Three are mounted to points on an imaginary spherical surface with its center at the tip of the probe. These provide rotational compliance about the tip of the probe.

This design provided some insight into the role of the spring elements needed in the modified RCC. The springs had to be stiff

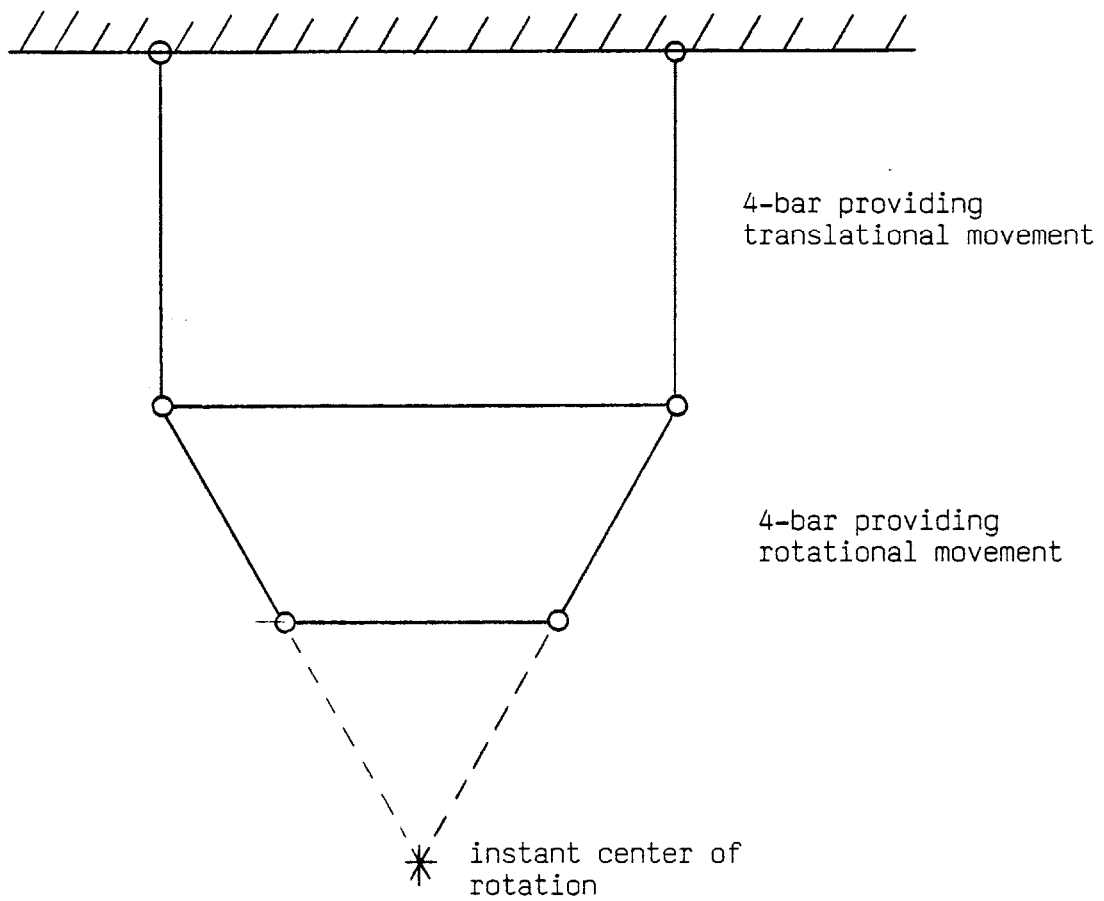


Figure 5.12 Conceptual Kinematics of the RCC

3 elastomeric pads responsible
for rotational accomodation

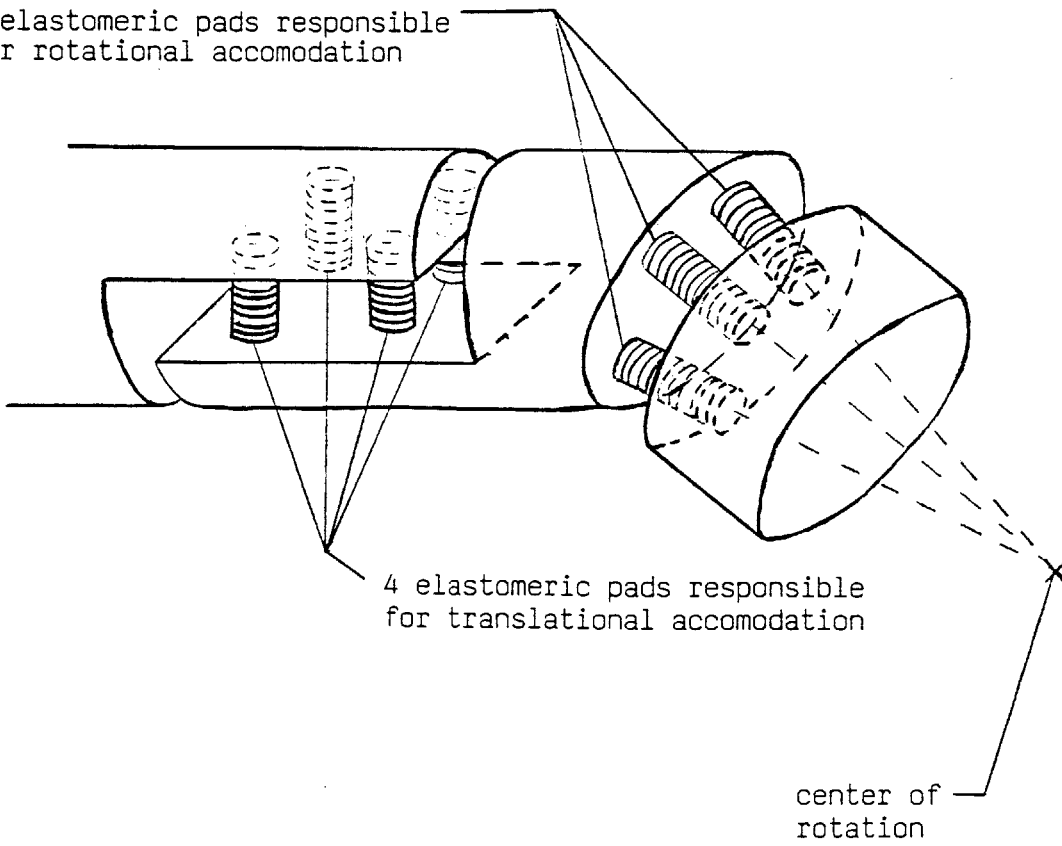


Figure 5.13 First Modified RCC Design

enough to support the weight of the tool and provide it with an accurate equilibrium position yet compliant enough to prevent them from overcoming the forces and moments generated by friction between the anchor and the workpiece.

To determine the stiffness of these spring elements the magnitude of the frictional forces generated during probe insertion are required. However, these forces are unknown and furthermore, they depend on the stiffness of the spring elements in the RCC. In fact, if it were not for the need to maintain an equilibrium position for the tool, the ideal stiffness of these springs would be zero. Unfortunately, zero stiffness would be completely inappropriate during the phase in which the tool is transported to the workpiece. In fact, this highlights the need for a variable impedance during the bolting process.

As no analytical method for determining the stiffness of the spring elements was evident, an empirical approach was adopted: All of the spring elements are extension springs and provision has been made so that they may easily be interchanged.

The kinematics of the modified RCC design were provided as follows: Two cross-roller ways by IKO Industries are mounted at right angles in the horizontal plane to provide translational accommodation. A 4-bar linkage design is used to provide the tool with rotational accommodation in the pitch direction. Rotational accommodation in an orthogonal direction is provided by a ball bearing mounted in the coupler of the linkage with its axis passing through the probe tip.

This Modified RCC design along with the other four systems comprised an acceptable and viable strategy for the final tool design that is presented in the next Chapter.

CHAPTER SIX
FINAL TOOL DESIGN

The five systems outlined in Chapter Five comprised the essential components of the Mark II tool. Time did not permit the author of this design to construct the hardware and test it. However, a complete set of detailed machine drawings, assembly drawings and instructions were made.

An assembly drawing is shown in Figure 6.1. Note that a parts list is included with the vendor of each part listed in the last column. The vendor and address corresponding to the letter listed in Figure 6.1 can be found in the Appendix. Any parts referred to in the explanation of the final tool design will be followed by the part number to facilitate referencing to Figure 6.1. The parts of the tool are best categorized into two groups - The Bolting Mechanism and the Modified RCC Design.

6.1 The Bolting Mechanism

The bolting mechanism consists of the bolting apparatus located in front of the Modified RCC. For description purposes the bolting mechanism will be presented in five parts: the Probe Cartridge, the Bolt Cartridge, the Delivery System, the Anchoring System and finally the Bolt Rotation System.

6.1.1 The Probe Cartridge

The function of the probe cartridge is to provide the tool with the means to mechanically locate the threaded hole. This is done by inserting the probe into the threaded hole. The assembly drawing for

the probe cartridge is shown in Figure 6.1. The machine drawings for the probe cartridge are shown in Figure 6.2 through 6.8.

The two major parts of the probe cartridge are the shaft (67) shown in Figure 6.4 and the shell (70) shown in Figure 6.7. Note in plan view of the tool in Figure 6.1 and in Figure 6.7, that the walls of the shell are split along part of their length. These split walls allow the bolt cartridge to lock itself to the cylindrical anchor (29). This locking action occurs when the probe cartridge's wedge-shaped shaft (67) is forced upward by feeding air via Port II to the bottom side of the piston (66) shown in Figure 6.3. To release the probe, air is fed to the top of the piston via Port I. The air chamber is sealed at the top using the Probe Cartridge Cap (68), shown in Figure 6.5. The cap is drilled and tapped at one point to accommodate a 10-32 port. Also two small holes are included in the cap design to facilitate tightening.

The mount (65) shown in Figure 6.2 couples the probe cartridge to the 4-bar linkage delivery system. It is epoxied to the shell (70) using Tra-Bond 2101 from TraCon Inc. (71). This is a common adhesive for aluminum parts. The mount includes the airway for port II. An epoxy sleeve (69), shown in Figure 6.6 is used between the shell (70) and the mount (65) to prevent clogging the port during assembly. The mount also houses the 1/4" bore ball bearings used in the linkage.

Finally, O-Rings (72,73,74) are used to seal the various sections of the air chamber. Groove details for each O-Ring are shown in Figure 6.8. To prevent the piston from closing the chamber at the extreme downward position, a retaining spring (75) is used. For the extreme

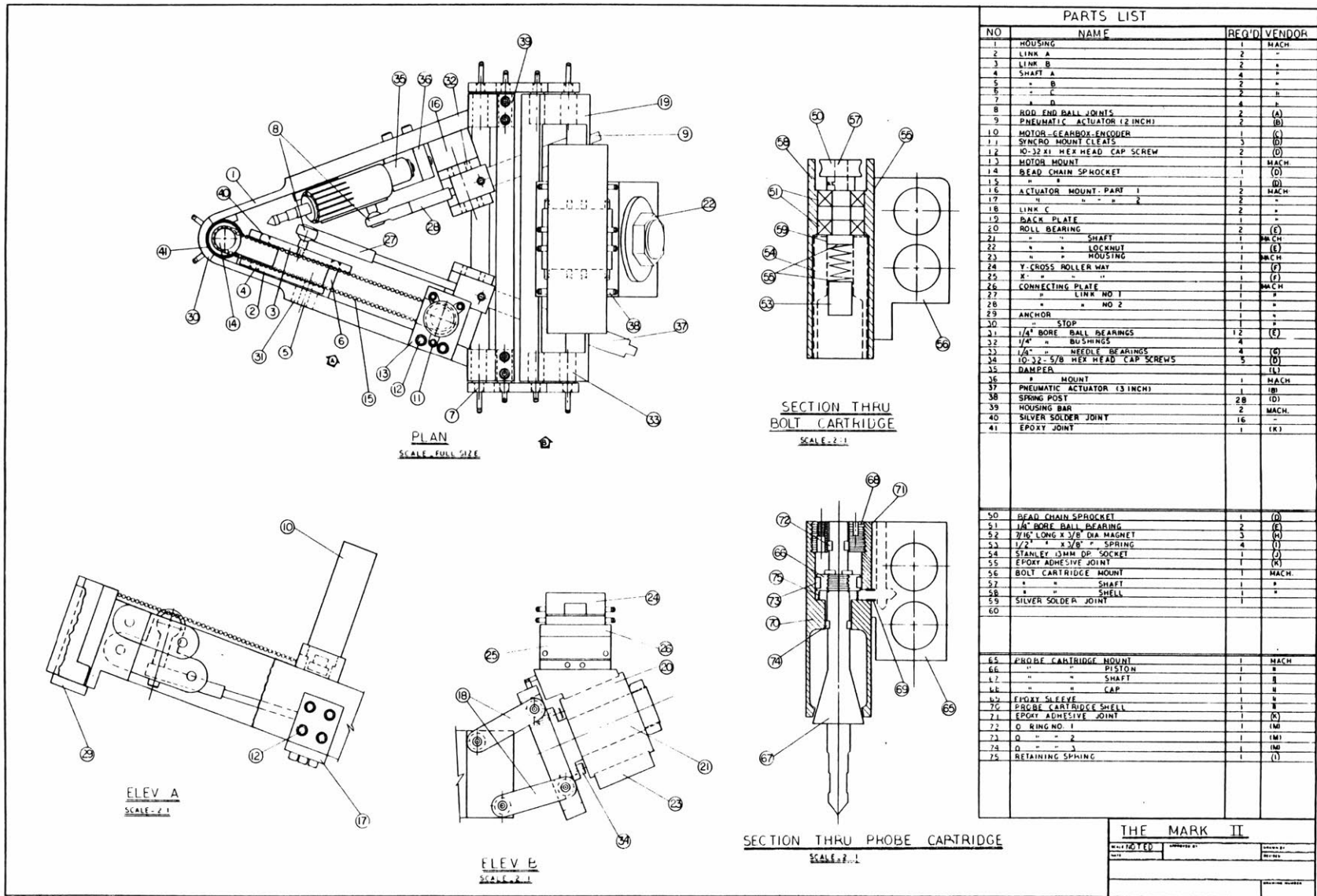
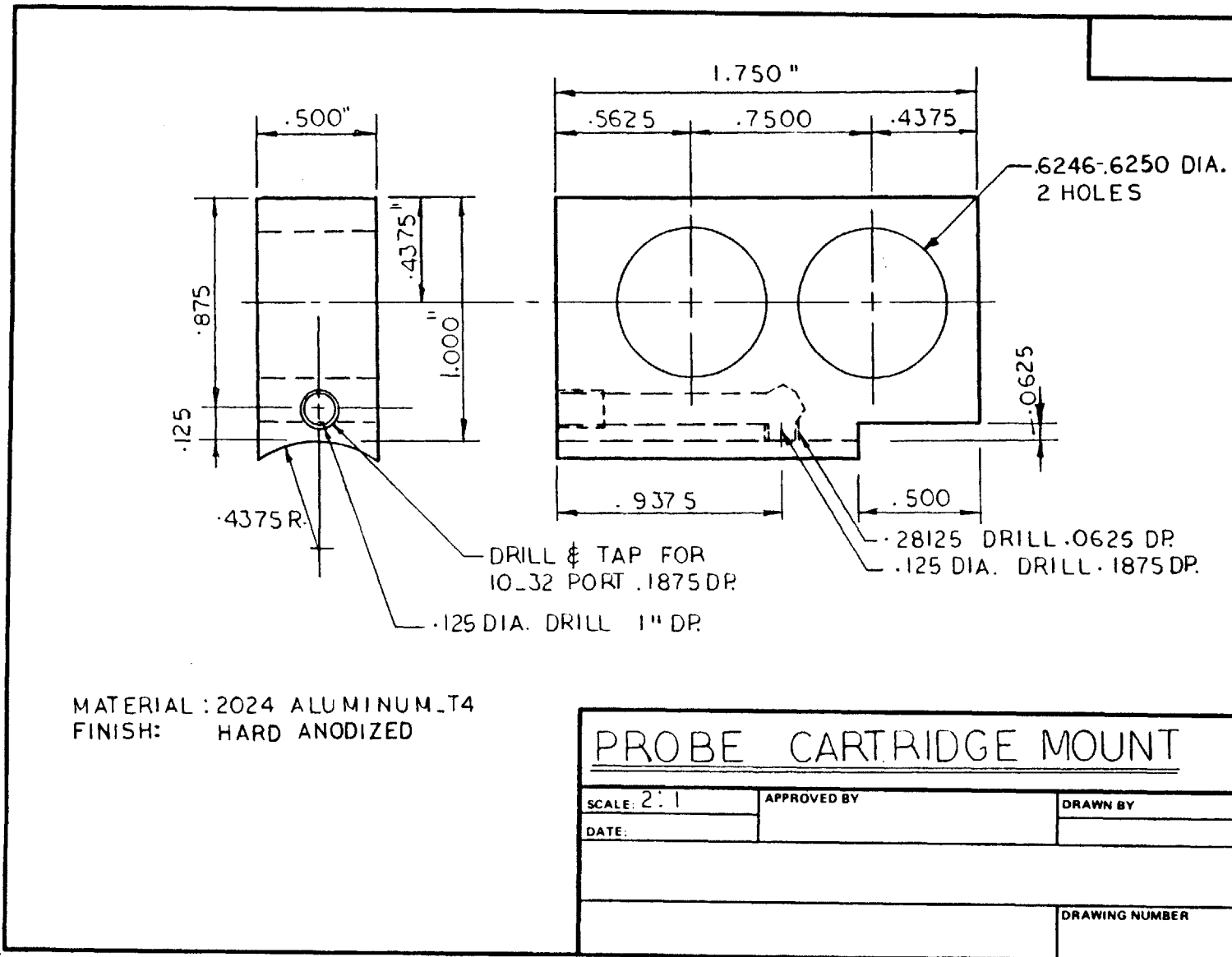
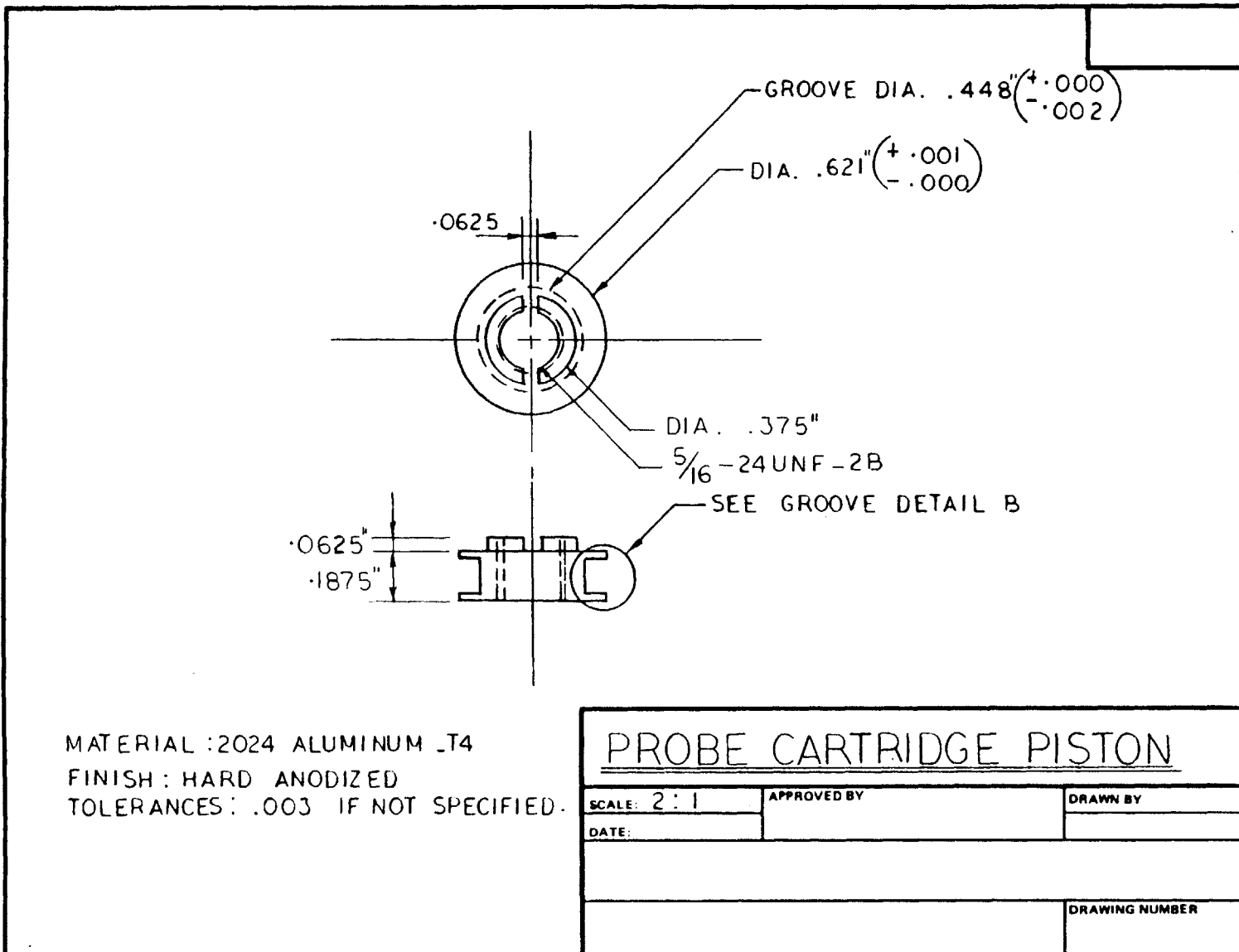


Figure 6.1 Assembly Drawing of the Mark II Tool



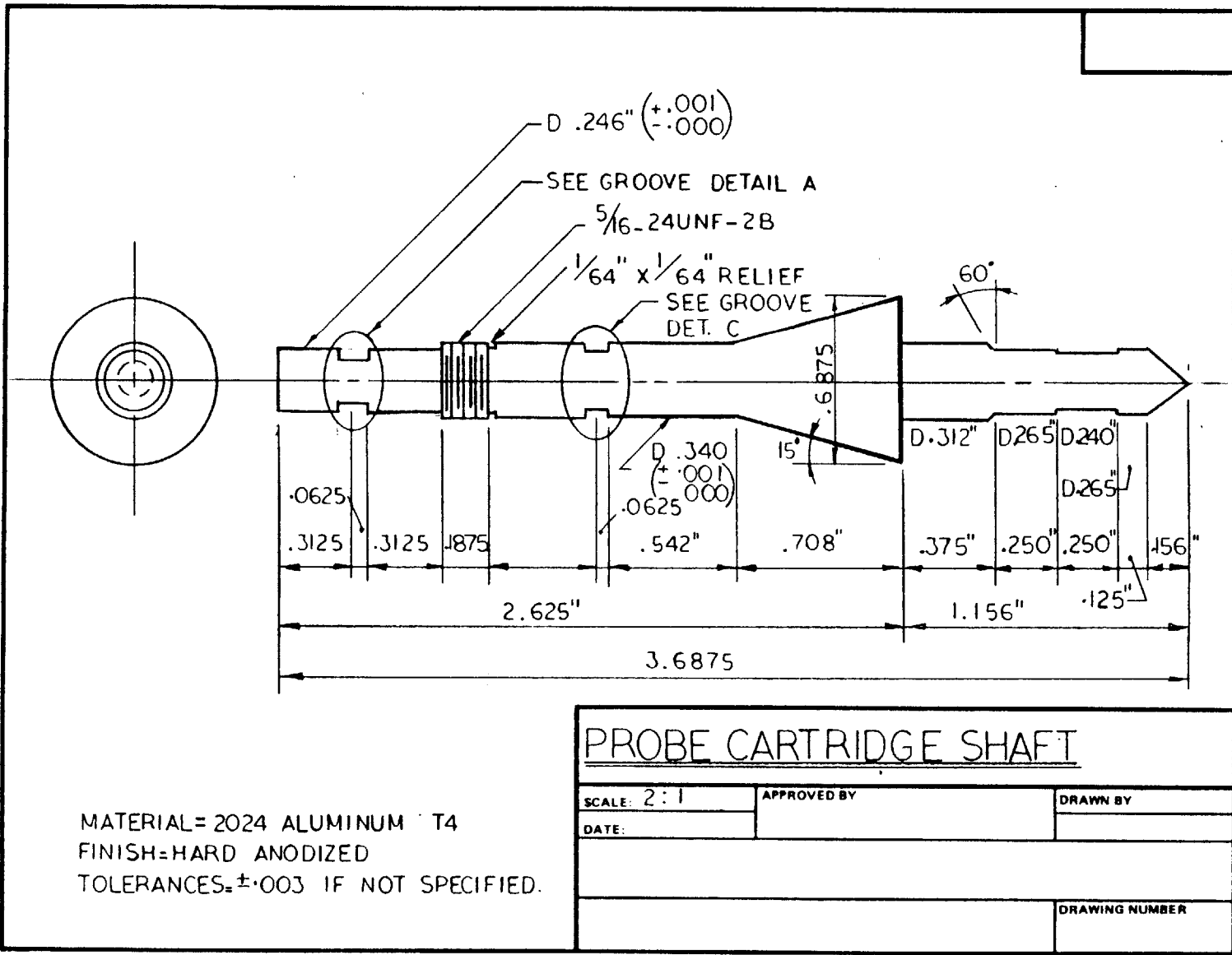
DIETZGEN MASTER FORM 198MF

Figure 6.2



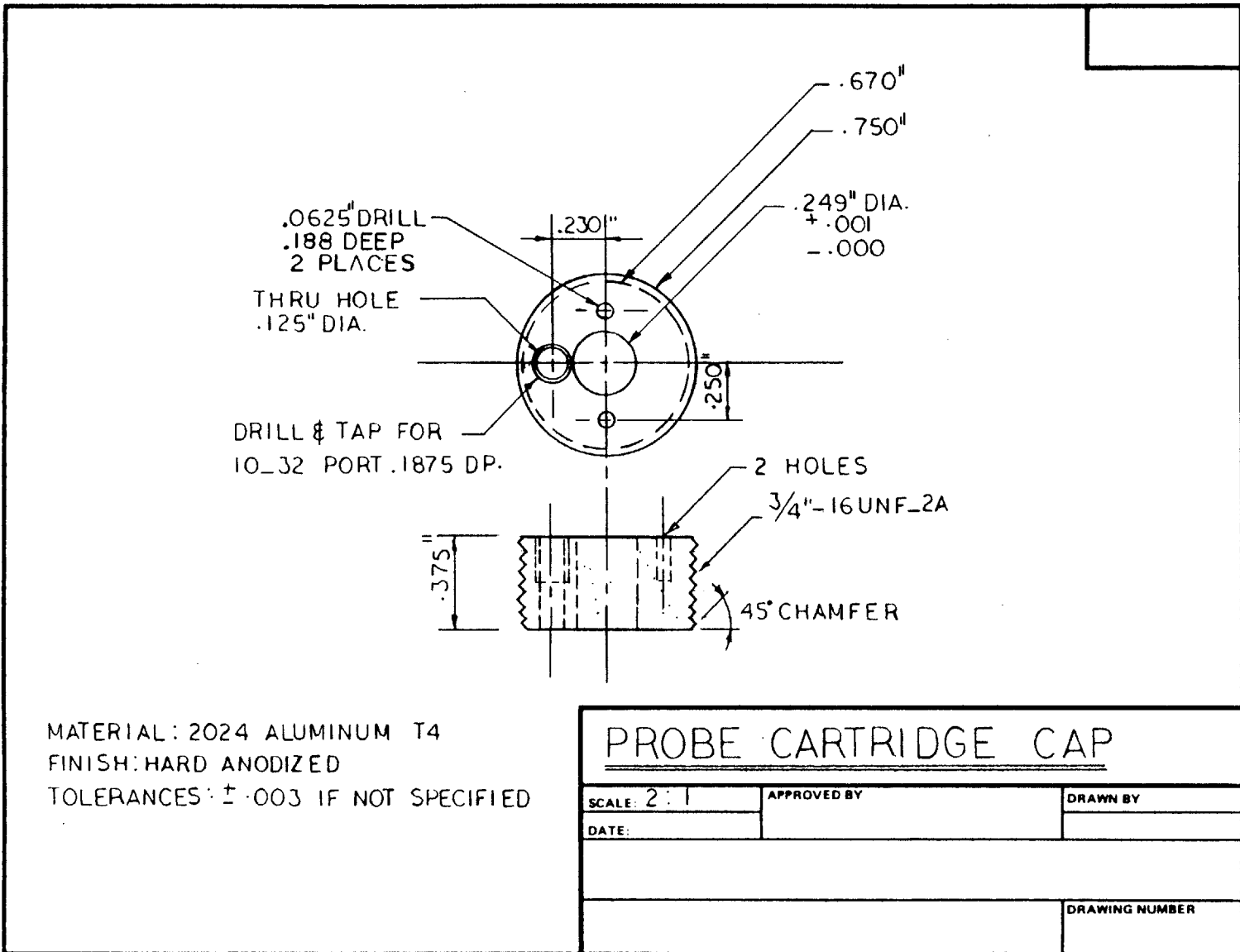
68

Figure 6.3



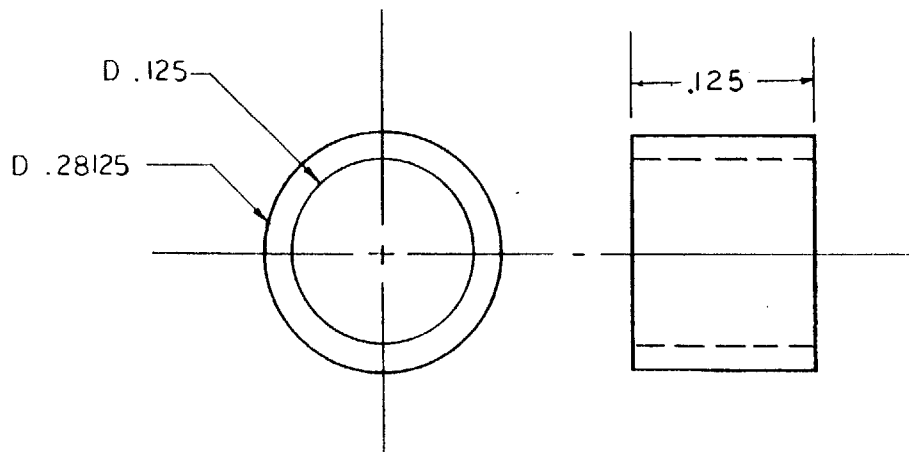
DIETZGEN MASTER FORM 198MF

Figure 6.4



DIETZGEN MASTER FORM 198MF

Figure 6.5



MATERIAL: 2024 ALUMINUM T4

EPOXY SLEEVE

SCALE: 10:1

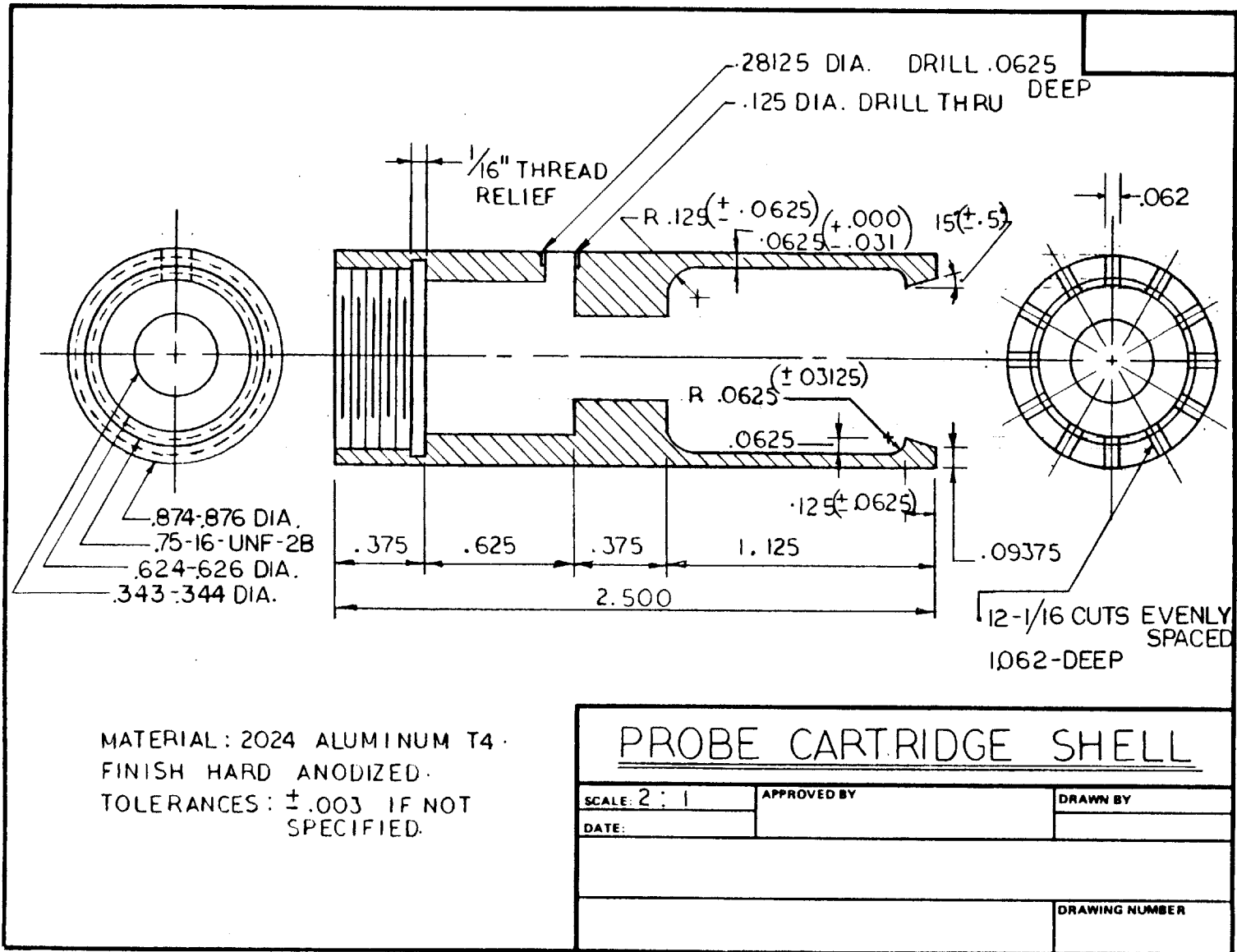
APPROVED BY

DRAWN BY

DATE

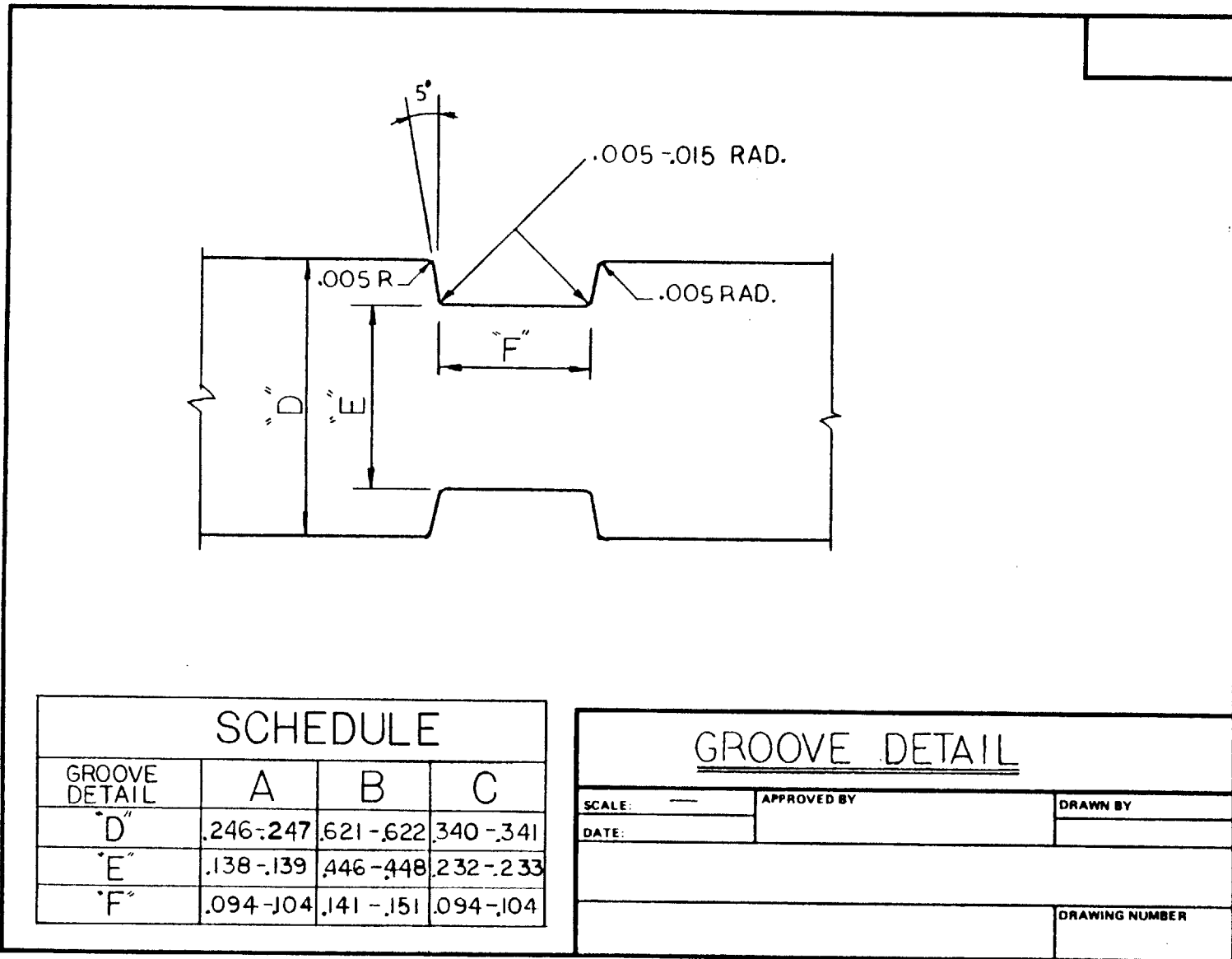
DRAWING NUMBER

Figure 6.6



72

Figure 6.7



DIETZGEN MASTER FORM 198MF

Figure 6.8

upward position, a lip, shown in Figure 6.3, is included in the piston design (66).

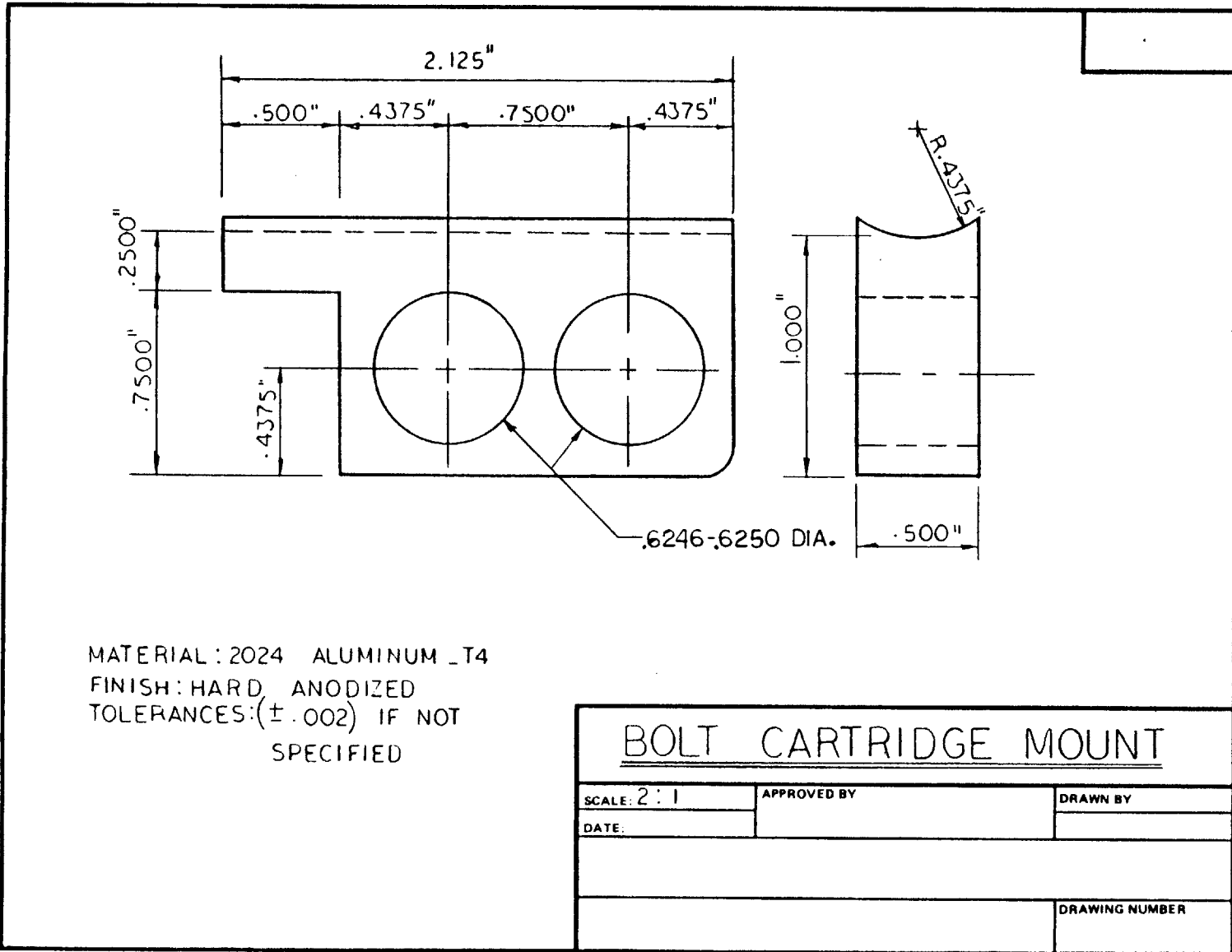
6.1.2 The Bolt Cartridge

The function of the bolt cartridge is to securely hold the bolt and accommodate a transmission system that can rotate it. The assembly drawing for the bolt cartridge is shown in Figure 6.1 and the machine drawings are presented in Figures 6.9 through 6.11.

The bolt cartridge consists of a shell (58), shown in Figure 6.11, with a mount (56), shown in Figure 6.9, to couple the cartridge to the 4-bar linkage delivery system. Note that the mount includes a stop near the bottom of the cartridge that will rest against the anchor (29) when the cartridge is in the vertical bolting position. Inside the shell (58) is a shaft that connects the interior members of the cartridge. At one end of the shaft, a 13mm deep socket (54) is connected using a silver soldered joint (59). At the opposite end a beaded chain sprocket (50) is attached using a set screw. The shaft (51) is supported in the shell using 2 1/4" bore ball bearings (51); the bearings are installed using "Loctite". Finally, a magnet (52) and spring (53) are epoxied in the socket to contain the bolt and provide an initial axial force to the bolt when starting. Note that the magnet recesses completely into the socket when the cartridge is deployed, and thus allows the head of the bolt to seat against the curved roof of the socket during the starting process.

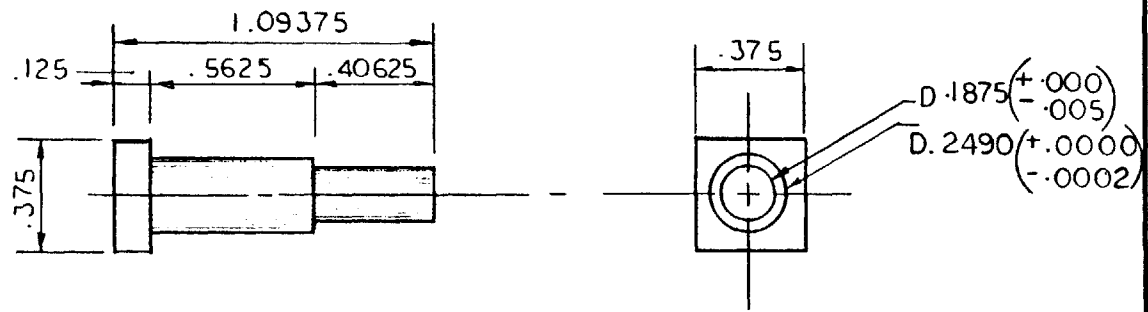
6.1.3 The Delivery System

The function of the delivery system is to provide a means of moving the bolt and probe cartridges from their resting positions in the tool to the center of the anchor. One of the main parts of the



DIETZGEN MASTER FORM 198MF

Figure 6.9

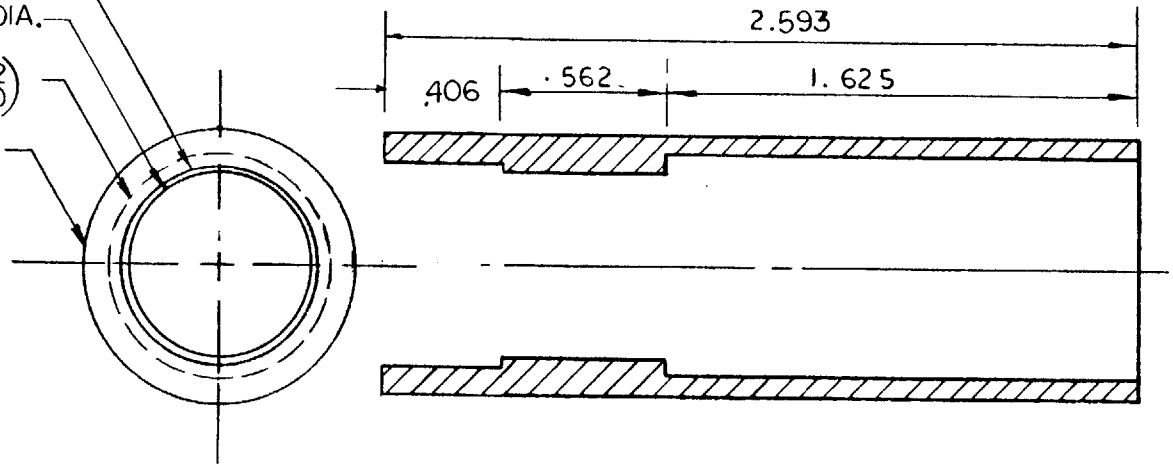


MATERIAL: 2024 ALUMINUM -T4
 TOLERANCES: ($\pm .002$) IF NOT
 SPECIFIED

<u>BOLT CARTRIDGE SHAFT</u>		
SCALE: 2:1	APPROVED BY	DRAWN BY
DATE:		
		DRAWING NUMBER

Figure 6.10

.686-.690 DIA.
 .6246-.6250 DIA.
 D .750 ($\pm \frac{.002}{.000}$)
 D .875 ($\pm .002$)



MATERIAL: 2024 ALUMINUM - T4
 FINISH: HARD ANODIZED
 TOLERANCES: ($\pm .003$) IF NOT SPECIFIED

<u>BOLT CARTRIDGE SHELL</u>		
SCALE: 2:1	APPROVED BY	DRAWN BY
DATE:		
		DRAWING NUMBER

Figure 6.11

tool and delivery system is the housing (1), shown in Figure 6.12, which structurally supports the tool and its delivery system. Bars (39), shown in Figure 6.13, are attached at the rear of the housing to add additional structural rigidity.

The actuating elements for the probe and bolt cartridges are 2 and 3 inch pneumatic cylinders (9,37) respectively, with front trunnion mounts. A longer actuator is required for the bolt cartridge because it has to travel through a greater distance. The pneumatic actuators are mounted to the side walls of the housing (1) using machined actuator mounts (16,17), shown in Figure 6.14. Bushings with 1/4" bore (32) are used between the trunion pins of the actuators and the actuator mounts.

Two identical 4-bar linkage systems are used to deliver the bolt and probe cartridges to the center of the anchor (29). The housing (1) acts as the ground link and the driving member is Link B (3), shown in Figure 6.15. The coupler is the cartridge, and the follower is Link A (2), also shown in Figure 6.15. The linkage configuration is best shown in Figure 6.1 - Elevation A. The rods of the pneumatic actuators are joined to the driving link B (3) using rod end ball joints (8) mounted at right angles to the Connecting Links 1 and 2 (27,28), shown in Figure 6.16.

The rotary joints between the links use 1/4" bore ball bearings (31), and 1/4" shafts with shoulders (4,5,6), as shown in Figure 6.17. The bearings are installed using "Loctite" and the shafts are silver soldered (40) to their respective links as shown in Figure 6.1.

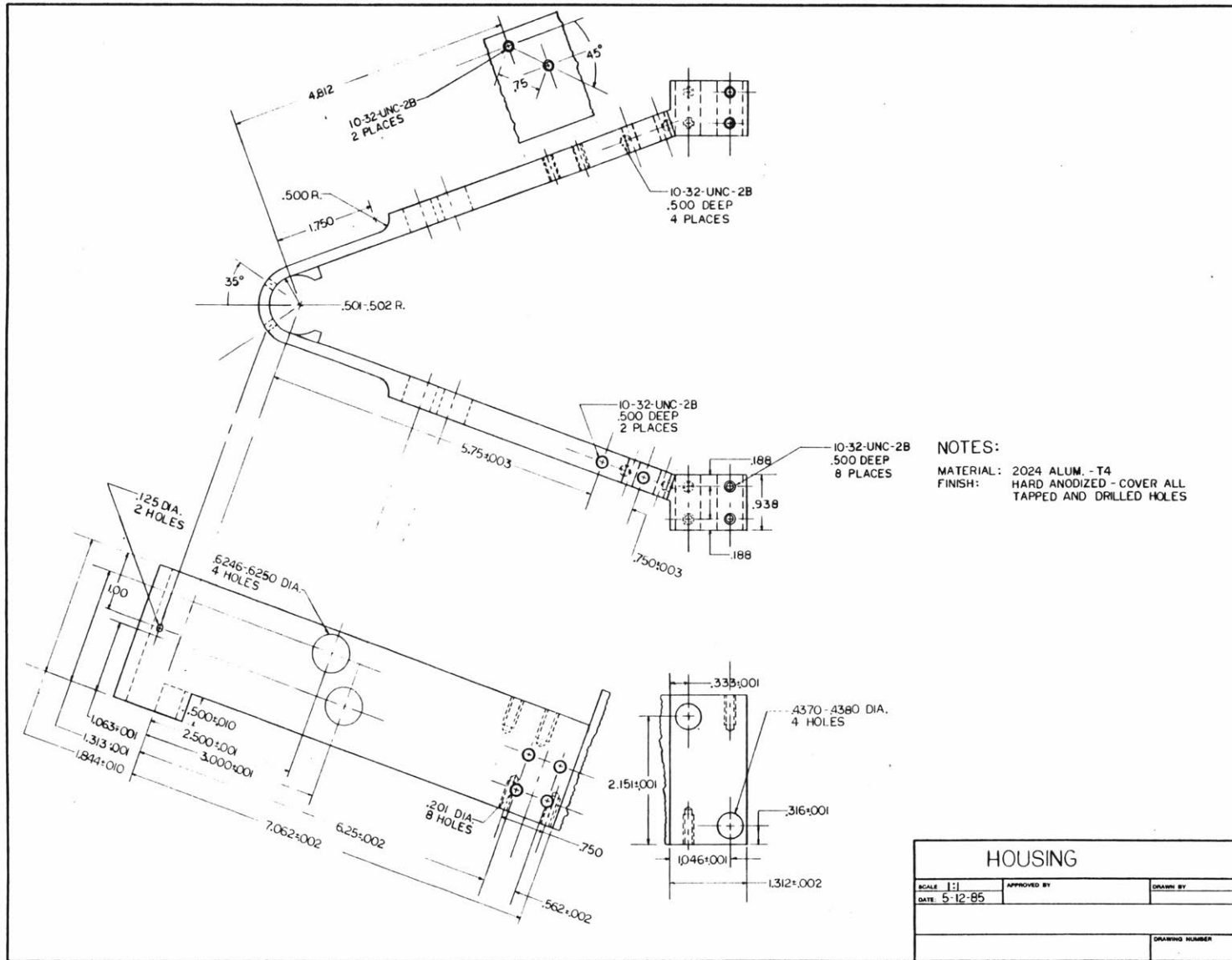
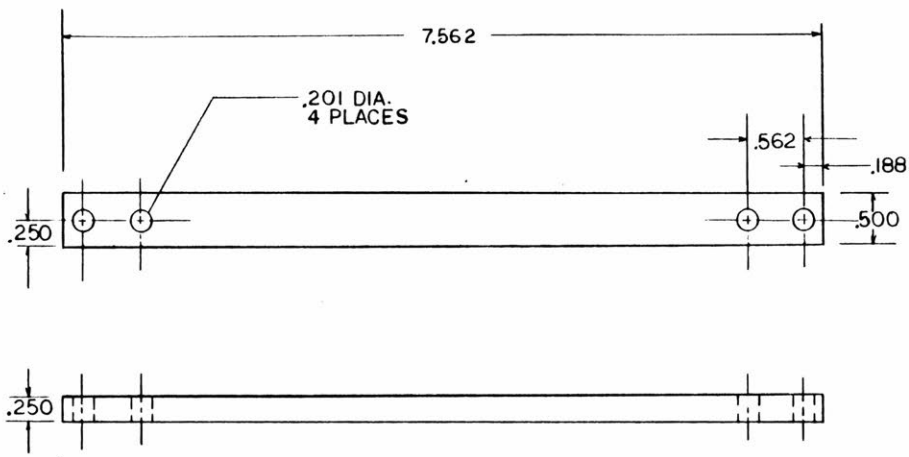


Figure 6.12



NOTES:
 MATERIAL: 2024-ALUM -T4
 FINISH: HARD ANODIZED
 COVERALL HOLES

HOUSING BAR		
SCALE: 1" = 1"	APPROVED BY	DRAWN BY
DATE:		
		DRAWING NUMBER

80

Figure 6.13

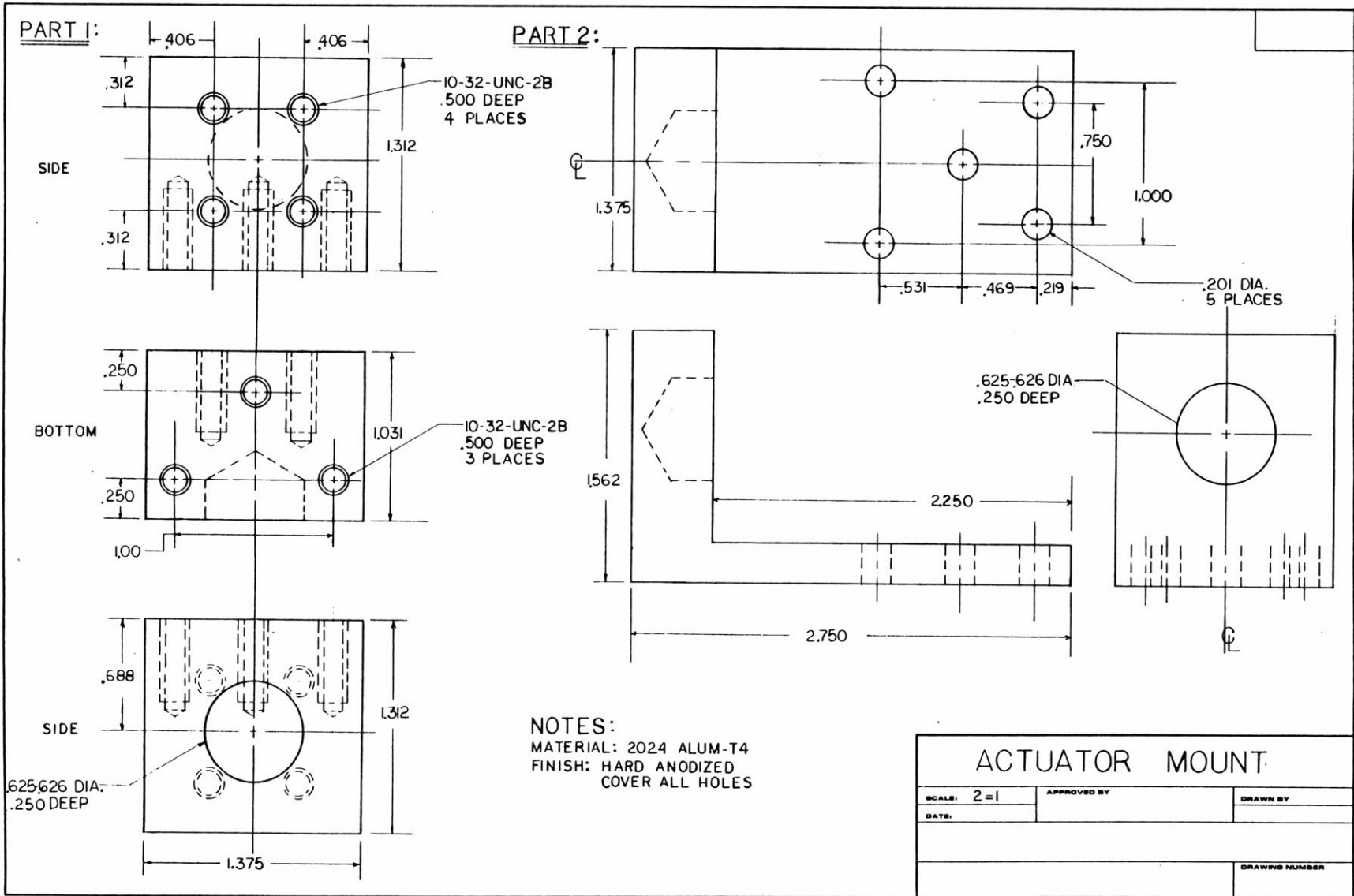
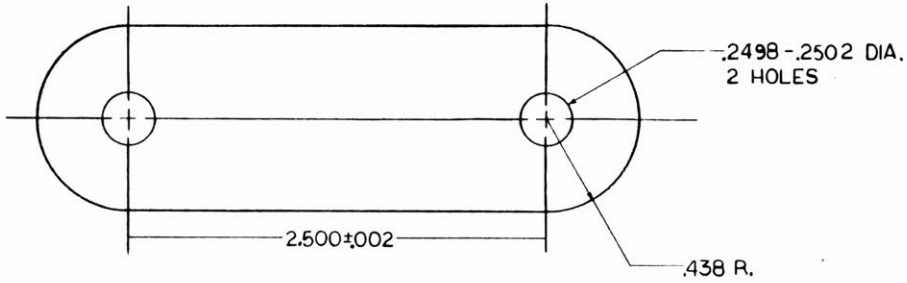
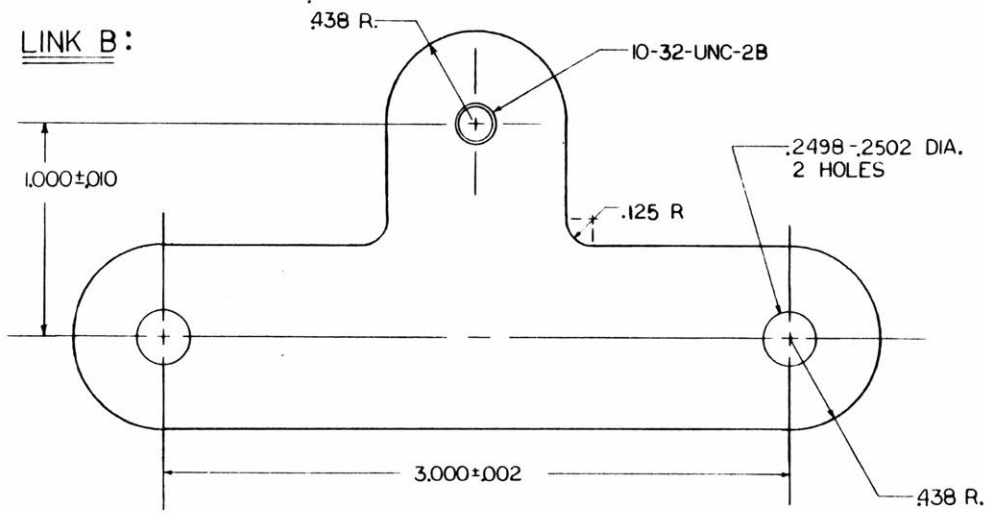


Figure 6.14

LINK A:



LINK B:

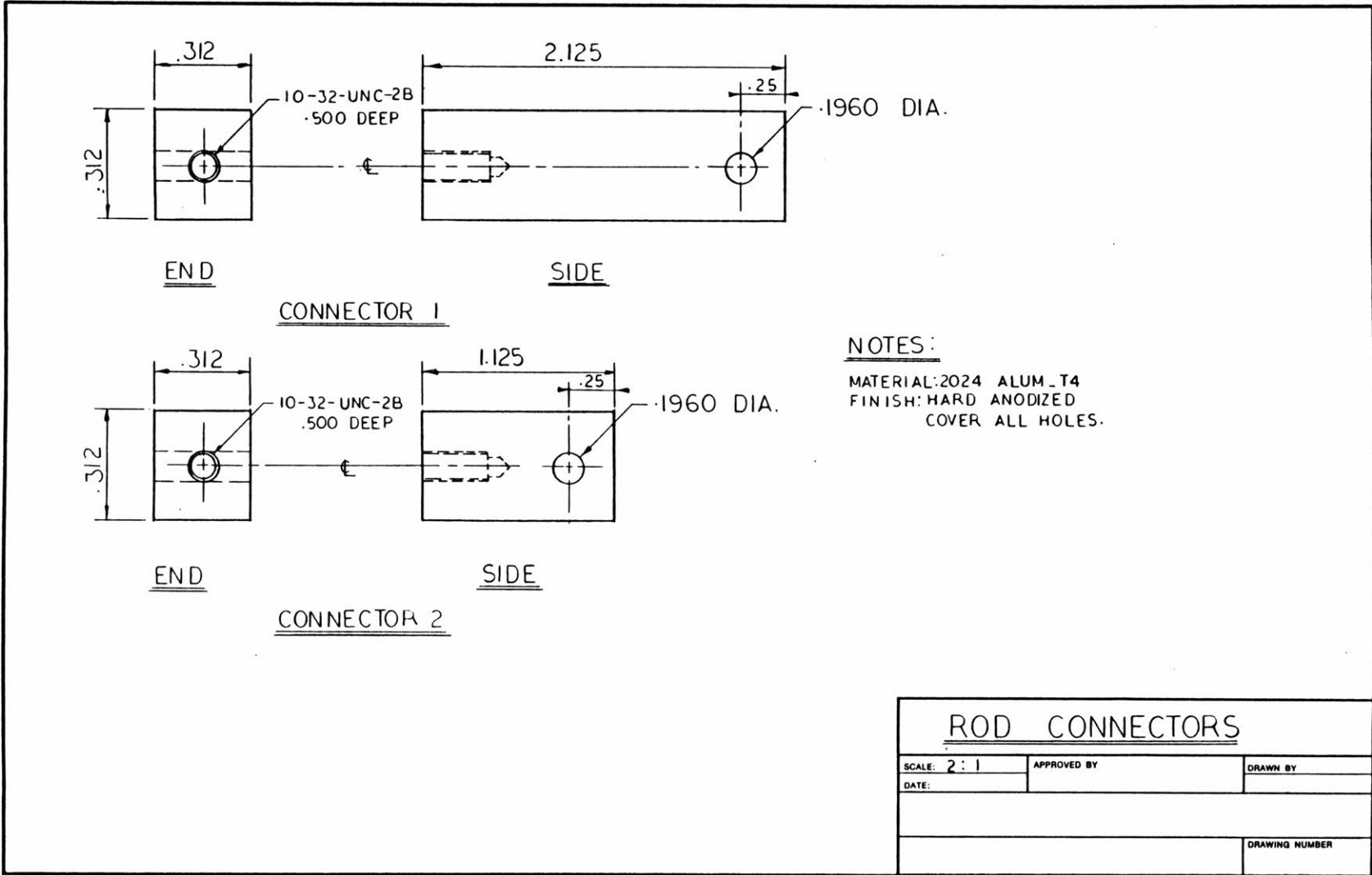


NOTES:

MATERIAL: 2024-ALUM.-T4
 THICKNESS: .438
 FINISH: HARD ANODIZED - COVER ALL HOLES

LINKS A ANB B		
SCALE: 2=1	APPROVED BY	DRAWN BY
DATE: 5-13-85		
		DRAWING NUMBER

Figure 6.15



83

Figure 6.16

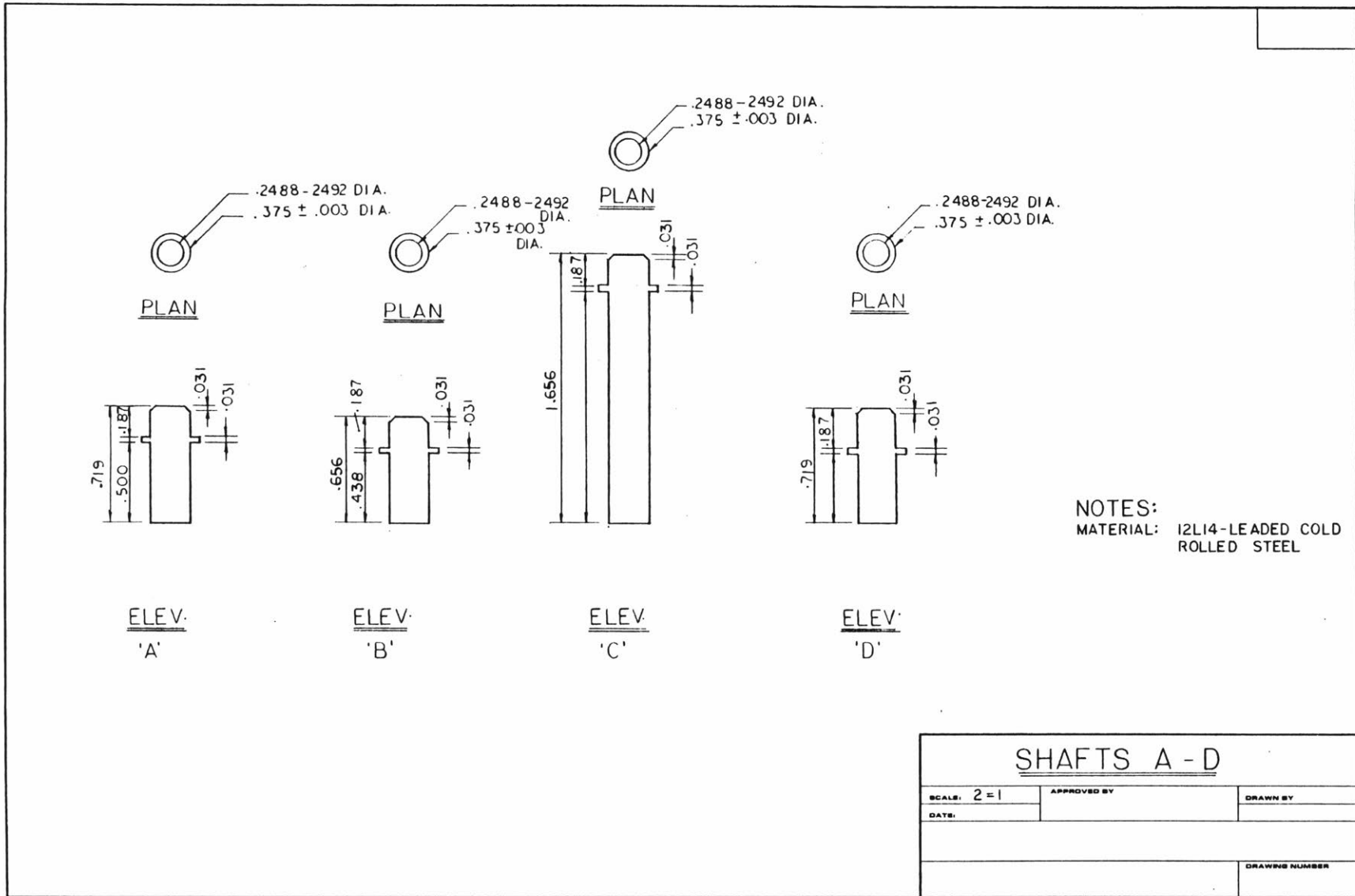


Figure 6.17

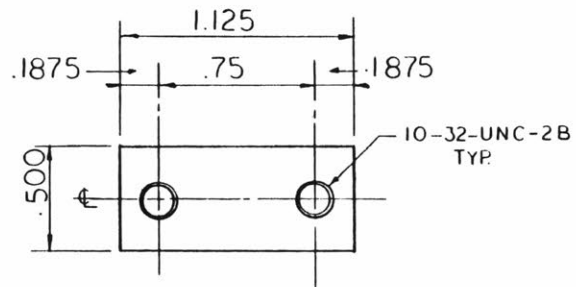
Finally, dampers were included in the design to absorb any impact due to the delivery process. A small damper (35) is located at the resting position of the probe. It is held in place using the damper mount (36), shown in Figure 6.18.

6.1.4 The Anchoring System

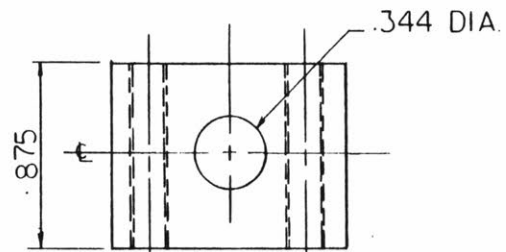
The function of the anchoring system is to generate interference forces between the tool and the manipulator which will stabilize the tool's corrected position. This task is achieved using the cylindrical anchor (29), shown in Figure 6.19; two extension springs (not shown); four spring posts (38); and an anchor stop (30), shown in Figure 6.20. The anchor is a cylindrical stainless steel tube with a large slit in it to allow the linkage to insert the cartridges. The bottom of the tube is complete for 1/4" to provide a surface for the probe cartridge to push against. First, the anchor stop is fastened to the top of the anchor using Tra-Bond 2101 epoxy (41). Then spring posts (38) are mounted in the housing (1), and also in the anchor stop (30). Next, extension springs are stretched between the posts to provide the needed stiffness in the z-direction capable of generating sufficient interference forces.

6.1.5 The Bolt Rotation System

The function of the Bolt Rotation System is to provide sufficient torque to start the bolt. Bolt rotation is provided by a DC servomotor (10) with integral gear reducer and optical encoder, rated at an output torque of 57 oz-ins, (intermittent) and 14.2 oz-ins (continuous). The motor is attached to the housing (10) using a motor mount (13), shown in Figure 6.21, and three synchro mount cleats (11). The transmission system is a beaded chain (15). Its length is chosen such that when the



PLAN

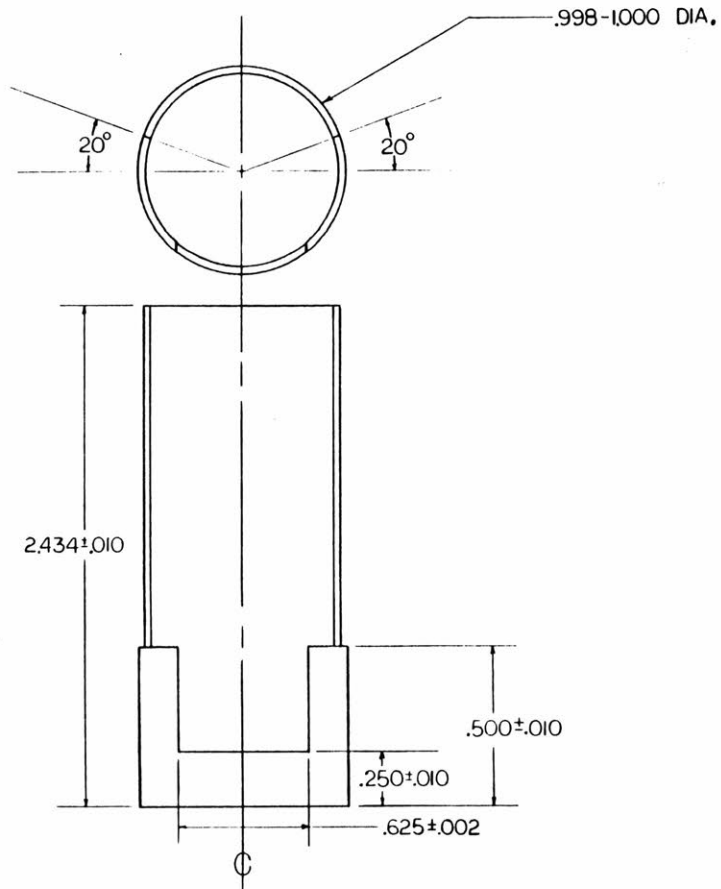


ELEVATION

NOTES:
 MATERIAL: 2024-ALUM.-T4
 FINISH: HARD ANODIZED
 COVER ALL HOLES

<u>DAMPER MOUNT</u>		
SCALE: 2:1	APPROVED BY	DRAWN BY
DATE:		
		DRAWING NUMBER

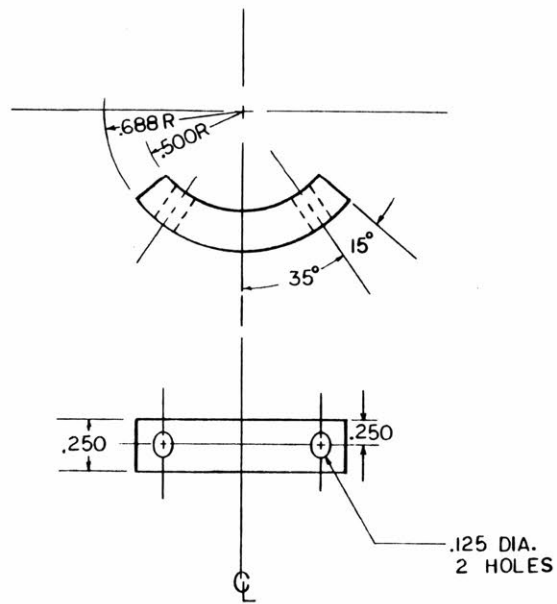
Figure 6.18



NOTES:
 MATERIAL: 1 INCH STAINLESS STEEL TUBE
 FINISH: DEBUR ALL EDGES

ANCHOR		
SCALE: 2 = 1	APPROVED BY	DRAWN BY
DATE: 5-12-85		
		DRAWING NUMBER

Figure 6.19



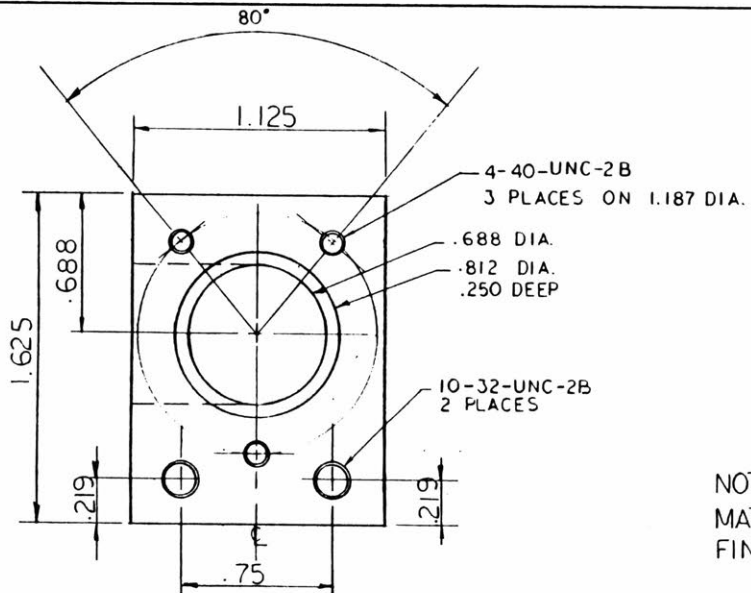
NOTES:
 MATERIAL: 2024-ALUM-T4
 FINISH: HARD ANODIZED
 COVER ALL HOLES

88

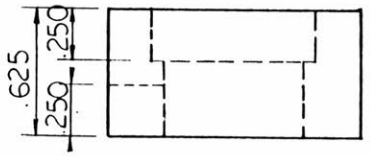
ANCHOR STOP		
SCALE: 2=1	APPROVED BY	DRAWN BY
DATE:		
		DRAWING NUMBER

DIETZEN NO 1897 AGEPROOF MASTER FORM

Figure 6.20



PLAN



ELEVATION

NOTES:
 MATERIAL: 2024_ALUM_T4
 FINISH: HARD ANODIZED
 COVER ALL HOLES

<u>MOTOR MOUNT</u>		
SCALE: 2:1	APPROVED BY	DRAWN BY
DATE:		
		DRAWING NUMBER

Figure 6.21

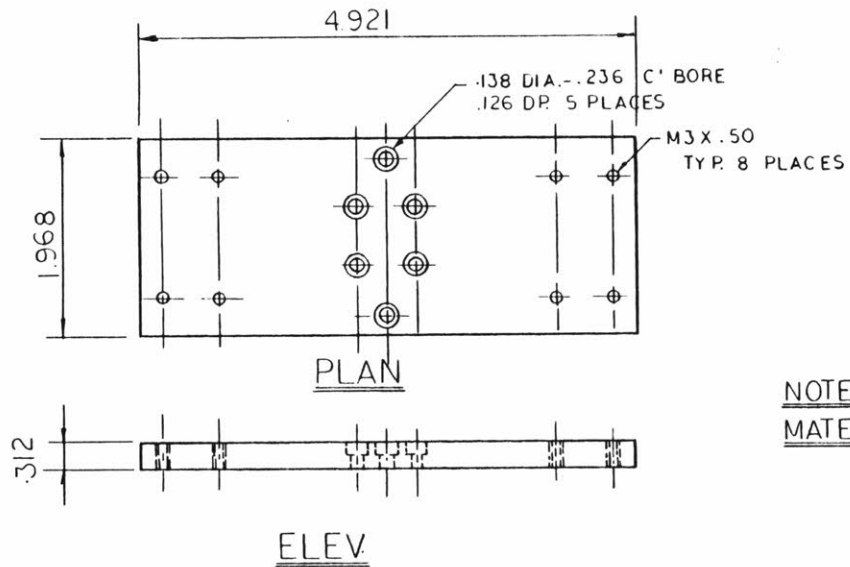
bolt cartridge is fully deployed, the beaded chain is taut. For any other position of the bolt cartridge, the beaded chain is slack. It is retained in position on the sprockets (14,50) at the bolt cartridge and the servomotor by means of two shrouds surrounding the sprockets, as shown in Figure 6.1.

6.2 The Modified RCC

The function of the Modified RCC was to kinematically provide the tool with a remote center of rotation at the tip of the probe, and maintain the tool at an equilibrium position when no external forces are being applied.

The kinematic part of the Modified RCC consists of four elements. Each element is responsible for accommodating a particular degree of freedom - x , y , θ , ϕ . The x and y translational directions are accommodated using a set of crossed roller ways (24,25). The crossed roller ways are mounted perpendicular to each other using the connecting plate (26), shown in Figure 6.22.

The angular part of the Modified RCC also has two components. First, to accommodate the pitch or θ direction, a 4-bar linkage is used which has its instant center of rotation at the tip of the probe. The dimensions provided in the machine drawings were determined geometrically. Two links of equal length, Link C (18), shown in Figure 6.23, are used in the design. The coupler link or the Backplate (19) is shown in Figure 6.24. The rotary joints between the links utilize 1/4" bore needle bearings (33), and 1/4" diameter shafts with shoulders (7), shown in Figure 6.17. As shown, the holes in the Backplate allow the pneumatic actuators (9,37) to protrude past the end of the housing (1).

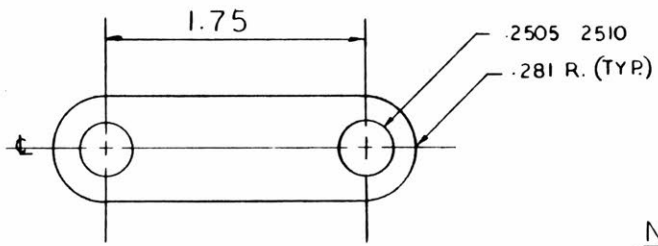


NOTES:
 MATERIAL: 2024 ALUM. T4
HARD ANODIZED
COVER ALL HOLES.

91

CONNECTING PLATE		
SCALE: 1:1	APPROVED BY	DRAWN BY
DATE:		
		DRAWING NUMBER

Figure 6.22



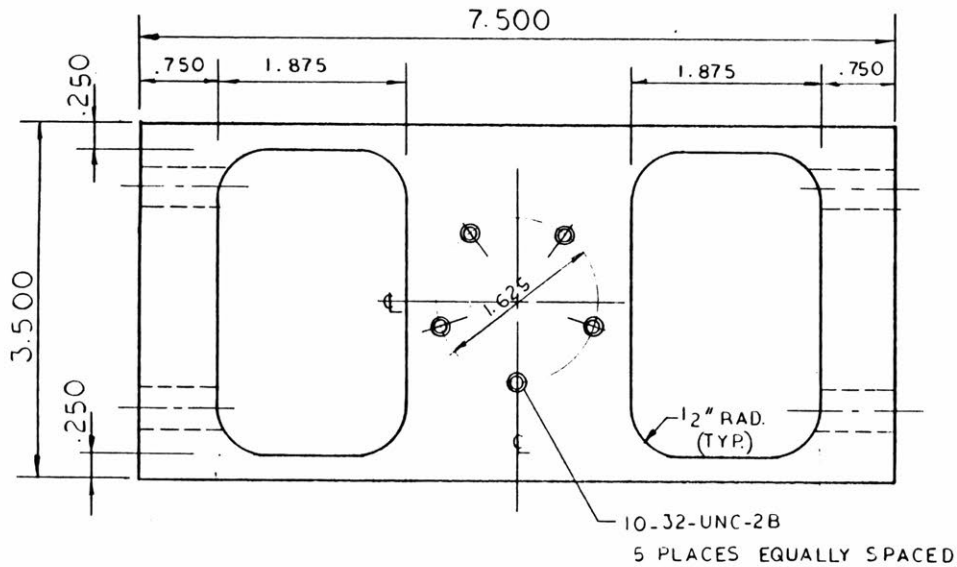
PLAN

NOTES:

MATERIAL: 2024 ALUM. T4
 THICKNESS: .250
 FINISH: HARD ANODIZED
 COVER ALL HOLES

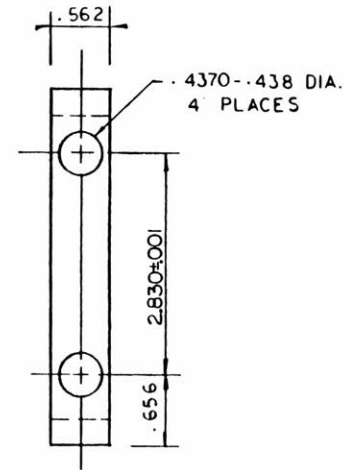
<u>LINK 'C'</u>		
SCALE: 2:1	APPROVED BY	DRAWN BY
DATE:		
		DRAWING NUMBER

Figure 6.20



PLAN

NOTES:
 MATERIAL: 2024 ALUM_T4
 FINISH: HARD ANODIZED
 COVER ALL HOLES



END

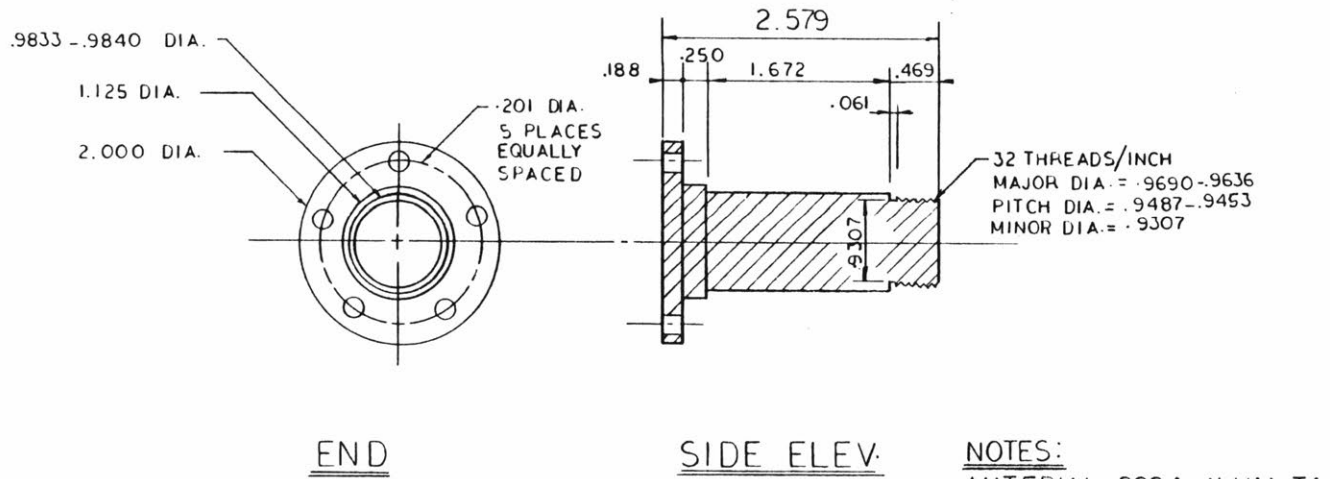
BACKPLATE

SCALE: 1:1	APPROVED BY	DRAWN BY
DATE:		
		DRAWING NUMBER

Figure 6.24

The remaining element of the Modified RCC must accommodate the ϕ or roll direction of the tool. This direction is accommodated by attaching a precision shaft (21), shown in Figure 6.25, to the back plate with its center directed at the tip of the probe as shown in Figure 6.1, and mounting on that shaft a Roll Bearing Housing (23), shown in Figure 6.26. The Roll Bearing Housing is mounted using 2 .9843" diameter, flanged ball bearings (20). The bearings are preloaded using a locknut (22) tightened at the end of the Roll Bearing Shaft. As shown in Figure 6.26, the Roll Bearing Housing was designed so that the crossed roller ways would move in the x-y plane while the axis of the Roll Bearing Shaft would intersect the tip of the probe.

These four elements kinematically provide the tool with a remote center of rotation at the tip of the tool. To maintain this center of rotation, spring posts (38), were added at specific points in the Modified RCC (see Figure 6.1), which allows one to attach extension springs to maintain the tool at equilibrium.



NOTES:
MATERIAL: 2024 ALUM_T4

<u>ROLL BEARING SHAFT</u>		
SCALE: 1:1	APPROVED BY	DRAWN BY
DATE:		
		DRAWING NUMBER

Figure 6.25

DIETZEN NO. 1887F AGEPROOF MASTER FORM

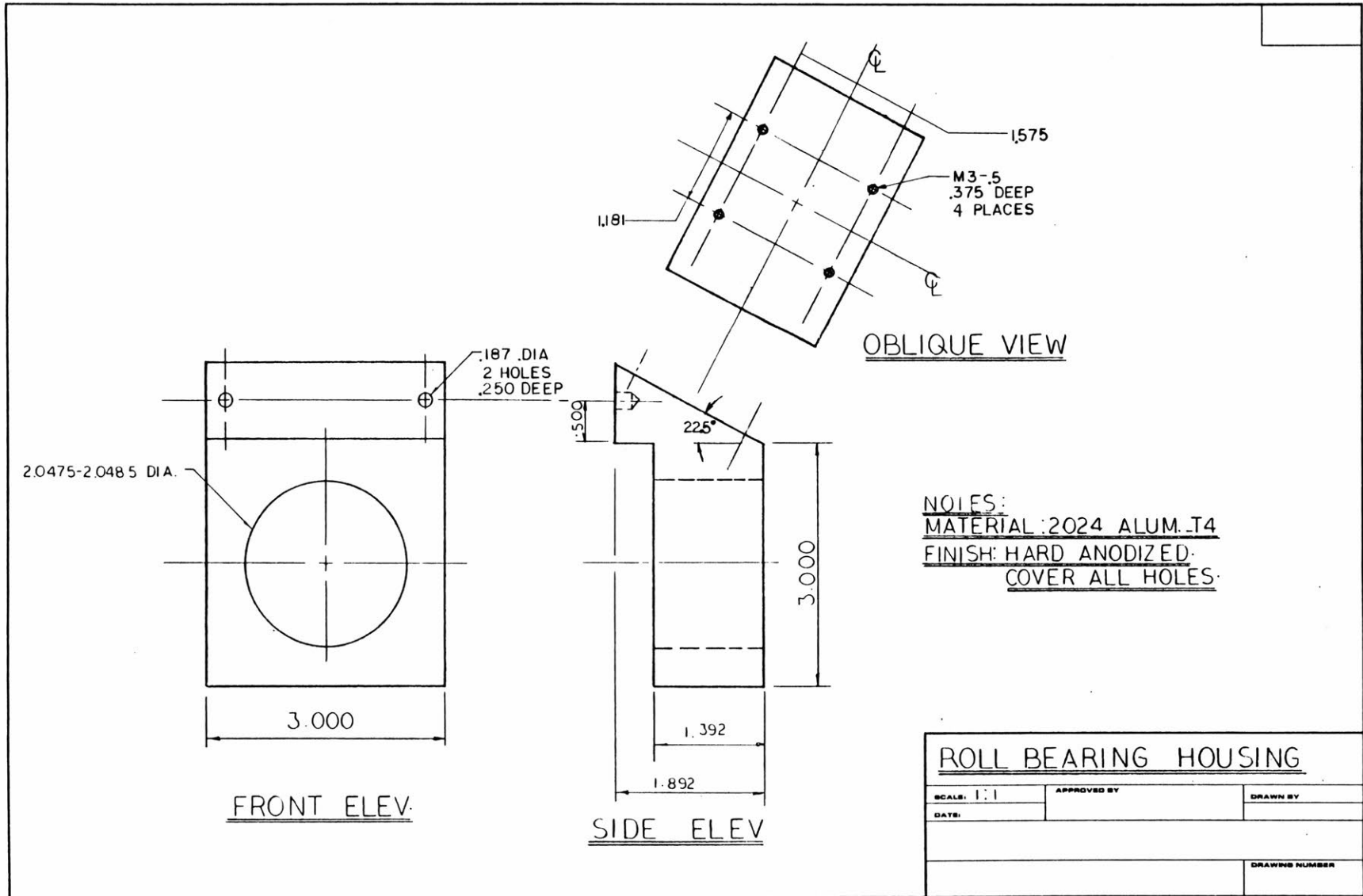


Figure 6.26

DESIGNER NO. 198MP AGEPROOF MASTER FORM

CHAPTER 7

EVALUATION AND RECOMMENDATIONS

The purpose of this thesis is to demonstrate that the careful use of interaction forces generated between robot and workpiece can facilitate an assembly task - putting a bolt in a threaded hole. This task is accomplished through the specific design of a self-aligning end-effector with a changeable stiffness that will start M8 bolts. The tool has to perform the following acts, given the restriction of limited vertical access.

1. The tool has to accept a M8 bolt from a tube of bolts fed from above.
2. Given the bolt, the tool has to align the through hole and gasket with the threaded hole, and align the tool with respect to the workpiece to minimize the possibility of cross-threading.
3. Once the tool and parts are aligned the bolt has to be delivered to the threaded hole and started.

In this chapter the new tool design is evaluated by comparing it with an earlier prototype. The design strategy is then reviewed and future work is recommended.

7.1 Evaluation of the Mark II Tool

The Mark II tool had not been built at the time of writing. However, a model was built (as noted earlier) during the design process and is shown again in Figure 7.1. A step-by-step evaluation of the Mark II tool follows which compares the Mark I tool with the Mark II tool based on the model. In this evaluation the bolting process is

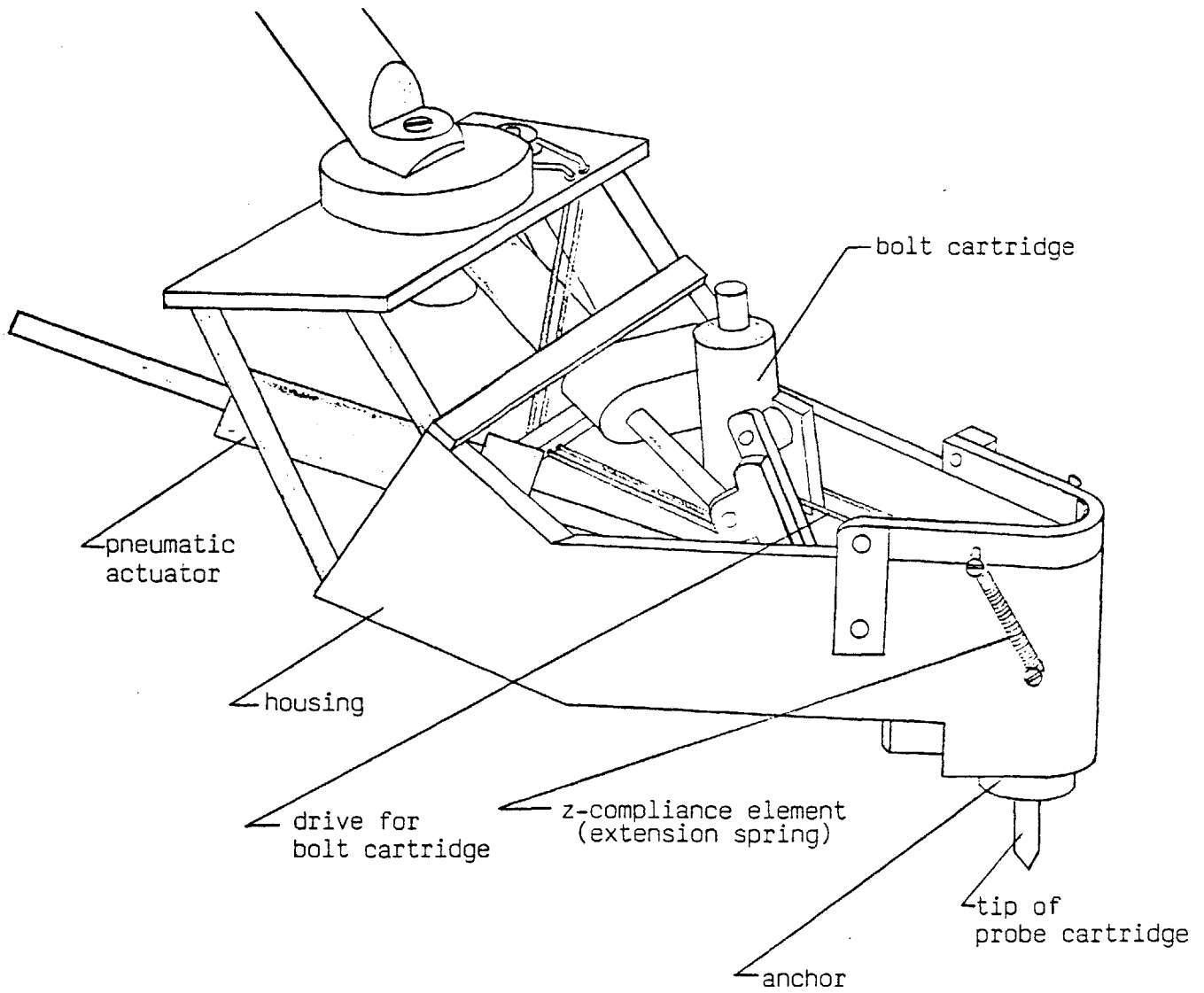


Figure 7.1 A Model of the Mark II Tool

considered in five steps: Pre-bolt Delivery, Part and Tool Alignment, Tool Stabilization, Probe Removal and Bolt Delivery and Bolt Rotation.

7.1.1 Pre-bolt Delivery

This step in the bolting sequence was not addressed specifically in this design. Nevertheless, a bolt must be delivered from some storage bin and placed in the tool. The most efficient manner to feed the bolts would be to allow the manipulator to carry around a tube of bolts, fed from above, positioned over the socket. Note that the manipulator should support the weight of the bolts and not the tool. This would eliminate alignment problems that could possibly be caused by the modified RCC having to support the tool and the weight of several bolts. In the Mark I tool the bolt was accepted tip first and provisions were made to accommodate tube-fed bolts. In the Mark II design provisions were made that allows the tool to accept a bolt head first into a socket and be held there magnetically as shown in Figure 7.1.

7.1.2 Part and Tool Alignment

This is essentially the first step in the actual bolting operation. It involves two different alignment tasks that are accomplished by one piece of hardware in both designs - the probe. The probe proved itself in the Mark I tool and was therefore adopted in the Mark II design. Before the probe can be utilized for alignment purposes, it must first be delivered to the proper position in the tool and held there. Once this is done the probe can be inserted and in doing so align the parts to be bolted together and align the tool with

respect to the workpiece. The evaluation of each of these tasks are addressed separately in the following subsections.

7.1.2.1 Probe Delivery

This step involves the transferal of the probe from its resting place in the tool to the point at which it will be used. There are many ways to achieve this movement. The Mark I uses a two-step approach where the probe is first swung into place directly above the hole using a rotating indexing table; then the probe is forced into the hole by forcing the indexing table downward. The Mark II tool allows the manipulator to force the probe into the hole, not an actuator. In Figure 7.1, the probe is shown delivered to the center of the anchor.

7.1.2.2 Probe Activation

The Mark II design, the probe is locked to the bolting tool, using air actuation, before the probe is inserted into the threaded hole. This eliminates all movement between probe and tool during insertion. This step was not included in the Mark I design because the probe was not locked to the bolting tool.

7.1.2.3 Probe Entry

Once the probe has been delivered to its insertion position and locked into place, the next step is for the manipulator to force the probe into the threaded hole. In the process of the manipulator forcing the probe into the hole, two entirely different alignment processes occur.

The first alignment task of the probe is the alignment of the through hole and the gasket with the threaded hole. Both designs use the probe to align the parts but in a different way. The Mark I tool initially places the anchor on the part with the through hole before

the probe is inserted as described in Section 2.1.1. This action generates a large normal force in the z-direction. When the probe is then forced downwards, it must overcome large frictional forces if it is to move the parts laterally relative to one another. In contrast, the Mark II tool does not brace against the workpiece or generate z-directional forces until the parts are aligned.

The second alignment task performed by the probe is the alignment of the tool with respect to the workpiece. The probe should align the tool in the lateral (x and y) directions and the angular θ and ϕ directions. Note in the Mark I tool the anchor is responsible for aligning the tool in the angular directions, and the probe is responsible for the lateral directions. In the Mark II design, the probe is responsible for all four directions of misalignment.

The fact that the probe is not mechanically locked to the Mark I tool does not influence its performance in its first task, part alignment, but it does make a substantial difference in the second. If the Mark II tool were to operate as the Mark I, the probe cartridge would be deployed and held there by its pneumatic actuator. Instead it is deployed and then locked in place using the wedging action of the probe cartridge. In fact, the probe cartridge has been designed so that the fit between the probe and the anchor improves as the insertion forces in the z direction increase.

In both designs, a modified RCC is used (the TII in the Mark I tool) to allow the tool to adjust with respect to the manipulator when the probe is inserted. Both designs use a 4-bar linkage to provide for misalignments in the θ or pitch direction. In the Mark II tool bearings are used at the pivot points instead of the bushings used in

the Mark I design. The 4-bar linkage in the Mark II tool is considerably smaller which should reduce the detrimental effects of clearance in the joints. Both designs use a large bearing to accomodate misalignments in the ϕ or roll direction. The difference between the two designs is that the axis of the bearing in the Mark II design is angled 22.5° with respect to the horizontal so that it intersects the tip of the deployed probe without protruding below the base of the tool. In contrast, the Mark I's roll bearing is horizontal, but the tool protrudes considerably below the line of the anchor, thereby restricting its operation so bolting near an edge.

The Mark I tool did not have any spring-like elements to provide the tool with an equilibrium position in the rotational degrees of freedom. The Mark II design includes spring posts at various places to which extension springs can be attached to equilibrate the tool's 4-bar linkage so that its center of rotation is at the tip of the probe and to hold the probe in its vertical position.

For accomodation in the translational directions, the Mark I tool uses the elastomeric pads (Lord Corporation) described earlier. The Mark II design uses crossed roller ways (IKO Industries) with springs attached to equilibrate the tool at the center position.

Note that the Mark II tool has been designed so that its spring and damper elements are easily removed and changed. This is to facilitate empirical determination of the optimum value of these elements.

7.1.3 Tool Stabilization

During this phase of the bolting operation, large interaction forces are purposely generated between the manipulator and workpiece to

stabilize the corrected position of the tool that was generated by probe insertion. This step essentially "freezes" the realigned tool relative to the workpiece, allowing the probe to be removed from the threaded hole and the bolt to be moved into position.

This act of stabilization is performed by the anchor in both designs. In the Mark I tool a "finger"-like anchor is used that can only be placed on the edge of a workpiece. In the Mark II design the anchor is a cylindrical tube that requires less area surrounding the hole and does not require a workpiece edge because the anchor is the lowest point on the tool as shown in Figure 7.1.

The anchor in the Mark II design is a mechanical referencing device. The probe attached to the anchor locates the hole. The probe is then removed leaving the anchor in an aligned position. Then the bolt cartridge is inserted into the anchor. Using the anchor as a referencing device that doesn't move during the bolting process eliminates errors, because the tool would otherwise have a tendency to move when interchanging the bolt and the probe. This is the single most important improvement over the Mark I design.

7.1.4 Probe Removal and Bolt Delivery

Once the tool has been stabilized, the probe must be removed and then the bolt delivered. These actions are the two movements during the bolting process that could cause the anchor to slip or lose its point of reference due to the acceleration or deceleration of moving parts.

In the Mark I tool, problems did arise due to the deceleration of the pneumatic nut-runner during these two movements. The forces generated caused the anchor to slip and misalign the tool. In the Mark

II design this problem has been corrected by using a 4-bar linkage delivery system. The forces generated due to acceleration or deceleration of the cartridges are directed downward (in the z-direction), and the tool is essentially rigid in this direction. Also, to prevent the effect of impacts, a damper is positioned behind the probe cartridge to absorb the kinetic energy of the retracting probe. Furthermore, a spring is placed on top of the bolt which should help to absorb the kinetic energy of the bolt cartridge when it is deployed.

7.1.5 Bolt Rotation

The final step in the process is the rotation of the bolt to actually thread it. The Mark I tool uses a pneumatic nut-runner positioned on an indexing table. The Mark II design uses a socket inside a bolt cartridge which is driven by a beaded chain coupled to a small servomotor. The major difference between the two designs is that the nut-runner used in the Mark I tool is a high-torque device capable of tightening the bolt as well as starting and running it whereas the Mark II tool will only start and run the bolt. The nut-runner is considerably larger and heavier than the servomotor used in the Mark II tool, which is therefore lighter and more compact than the Mark I tool. Tightening will therefore be treated as a separate part of the bolting process.

7.2 Strategy Review

A review of the design strategy allowed the author to look back and see how the design course could have been changed to improve on the results of the work. The most important change would be the

interaction that the author had with industry. A visit should have been made at the outset of the project to an assembly plant to see first hand how the bolting operation affects the assembly process. This would have allowed the author to address the issue of tolerances between bolt and hole directly and to document the restrictions on the tool from the beginning.

The only other change in the design process that the author would have initiated is to have spent more time on the bolting investigation. The biggest problem with doing a full scale experiment is the time that is required to chamfer, drill and tap threaded holes. Nevertheless, to understand what is required to prevent cross-threading a large number of trials should be performed. Furthermore, before this is done the investigator should understand how holes are tapped in a typical manufacturing process and try to duplicate that process in the laboratory.

7.3 Future Work

The bolting mechanism that was proposed in this project is an acceptable solution to the bolting problem given the desired specifications. Future work is required on the modified RCC design. The first step would be to build the current Mark II tool and determine the requirements of the modified RCC through testing. With the Mark II's modified RCC, the proper stiffness and damping can be determined by interchanging the extension springs on the tool. Once the proper stiffness and damping has been determined, a more robust design can be implemented.

In joining this project and designing the Mark II, the author has learned a great deal about the design process and the mechanics of bolting. The author hopes the Mark II tool will be built, tested and proved to be an important link in the final design of an ideal bolting tool used for automated assembly.

APPENDIX
VENDORS LIST

Vendor Letter	Company Name & Address	Part List #	Part Name	# Required	Catalog #
A	Superior Linkage Division 2110 Summit St. New Haven, Indiana 46774	8	Rod End Ball Joint	2	SPF-3S
B	Bimba Monee, Illinois 60449-0068 Ph: 312-534-8544	9	Pneumatic Actuator (2 inch)	1	BFT-012-D
		37	Pneumatic Actuator (3 inch)	1	BFT-013-D
C	Micro Mo Electronics, Inc. 742 Second Ave. S. St. Petersburg, FL 33701 Ph: 813-822-2529	10	Motor Gearbox Encoder	1	Motor-2233 Gearhead-22/2:97.3-1 Encoder-Series 09A
D	Berg 499 Ocean Ave. East Rockaway, NY 11518	11	Synchro Motor Cleats	3	SM-25
		14	Bead Chain Sprocket	2	3BE-16
		15	Bead Chain	1	3BEC-
		38	Spring Posts	28	CL-1
E	New Department Hyatt 2509 Hayes Ave. Sandusky, OH 44870	20	Roll Bearing	2	20205
		22	Roll Bearing Locknut	1	N-05
		31	1/4" Bore Bearings	12	Z97R4

Vendor Letter	Company Name & Address	Part List #	Part Name	# Required	Catalog #
F	Iko International P.O. Box 809/26-F Chapin Rd. Pine Brook, NJ 07058 Ph: 201-882-0120	24	Y-Cross Rollerway	1	CRWU 40-125
		25	X-Cross Rollerway	1	CRWU 40-50
G	Torrington Bearings 260 Cochituato Rd. Framingham, MA 01701 Ph: 617-579-3775	33	1/4" Needle Bearing	4	MJ-471
H	Bunting Magnets P.O. Box 739 Morristown, NJ 07960-0739 Ph: 201-540-8967	52	1/2 x 3/8 DIA Magnet	1	BM-1071
I	Lee Spring 1462 62nd St. Brooklyn, NY 11219 Ph: 212-236-2222	53	1/2" x 3/8" DIA Spring	1	LC-026E-1
		75	Retaining Spring	1	
J	Plus Industries 1206 River St. Boston, MA 02136 Ph: 617-631-2200	54	Stanley Socket 13M x 3/8 drive Dp. Socket	1	
K	TraCon, Inc. 55 North St. Medford, MA 02155	41	Epoxy Joint	1	Tra-Bond 2101
		55	Epoxy Joint	1	Tra-Bond 2101
		71	Epoxy Joint	1	Tra-Bond 2101
L	Ace Controls, Inc. P.O. Box 71 Farmington, MI 48024	35	Damper	1	FA-0712C-1

Vendor Letter	Company Name & Address	Part List #	Part Name	# Required	Catalog #
M	Parco 2150 Parco Ave. Ontario, CA 91761 Ph: 714-947-2000	72	O-Ring #1	1	PRP-568-006
		73	O-Ring #2	1	PRP-568-111
		74	O-Ring #3	1	PRP-568-009

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