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MECHANICAL DESIGN OF AN EXPERIMENTAL PARALLEL ROBOT

by
Philip Song

A Thesis
Submitted to the Faculty of
New Jersey Institute of Technology
in Partial Fulfillment of the Requirements for the Degree of
Master of Science in Mechanical Engineering

Department of Mechanical Engineering

October 1997

ABSTRACT

MECHANICAL DESIGN OF AN EXPERIMENTAL PARALLEL ROBOT

by
Philip Song

OSCAR, or Operational Space Controlled Adjustable Robot, is a parallel-actuated manipulator, also known as Stewart Platform or platform manipulator. The apparatus consists of two platforms (base and top) and six prismatic actuators in between. The main advantage of a platform manipulator is the fact that it can out-perform serial manipulators in both load capacity and precision. However, there are disadvantages and weaknesses such as limited mobility. A platform manipulator has reduced workspace compared to serial manipulators. The problem of limited workspace is solved by enabling OSCAR to change its prismatic leg positioning about the base platform.

During the course of the research, the writer designed various parts of the platform manipulator to attend to particular needs using different computer-aided design packages. Once the design was completed and rendered feasible, the parts were actually manufactured and assembled. Some parts were designed to incorporate optical encoders. The feed-back information obtained from the encoders can be used to analyze the manipulator's forward kinematics. Since the forward kinematics is solved using matrices, singularities must be avoided at all times. Singularity found in matrix will suggest the jamming of the manipulator.

APPROVAL PAGE

MECHANICAL DESIGN OF AN EXPERIMENTAL PARALLEL ROBOT

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To my very supportive family, especially my older sister Susie
and my best friend Maria

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CHAPTER 1

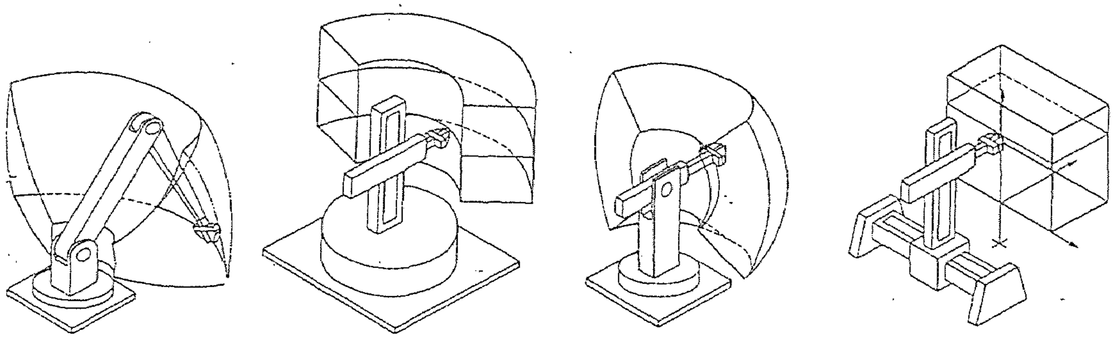
INTRODUCTION

1.1 Objective

It is the objective of this experimental research to carefully examine pre-existing platform manipulators. Based on knowledge acquired, it is the intent of the author to design, construct and possibly test a modular Stewart Platform. One very important aspect of this research is to further confirm and observe the workspace limitations in a parallel actuated robot. The manipulator actuators, in this particular case, will be modular, meaning that the legs can be repositioned at the base and at the platform at predetermined coordinates. Changes in the "root" positions will have a direct impact on the extent of reach in workspace. Making usage of simulation packages available in the market, and incorporating forward and inverse kinematics of the manipulator, it is possible to further observe the limitations of workspace. Furthermore, an optimum piston stroke length and positioning about the plates for any specific task can be found in future studies. The completed manipulator will furnish future researches with valuable design and planning issues related to reconfiguration of parallel manipulators.

1.2 Research Information

Robots used in present industries can be categorized into two distinctive linkage types - serial and parallel. The serial linkage has unsurpassed advantages over the parallel actuated manipulators in terms of mobility and dexterity. Serial robots are capable of performing flexible tasks, and its workspace can be defined without much complexity. Depending on what kind of joints involved, it is possible to predict the workspace of a serial robot (Figure 1.1).



(a) Anthropomorphic Robot (b) Cylindrical Robot (c) Spherical (Polar) Robot (d) Cartesian Robot

Figure 1.1 Serial robots and the associated workspace[2]

The end effector in a serial linkage manipulator travels at high speeds, which is quite desirable when performing multiple tasks of the same function such as in an assembly line. The basic design of a serial robot can be described as being a series of cantilever beams bound together by either rotary pivots or prismatic actuators at beam junctions (Figure 1.2).

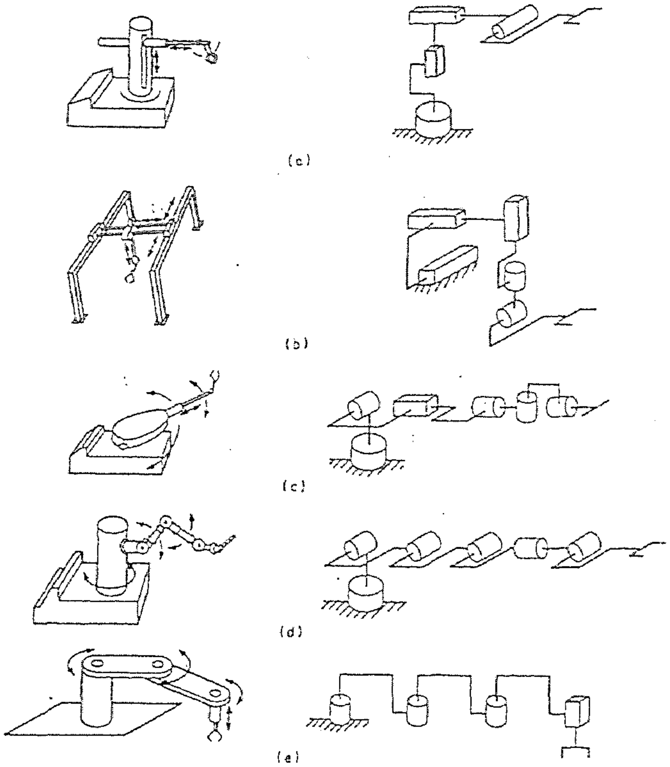


Figure 1.2 Examples of different kinematic designs of serial robots[1]

Major disadvantages in a serial robot is that the structure itself has poor mechanical stiffness and accuracy, thus rendering it inappropriate for heavy-duty, high-precision applications. Although the forward kinematics is very easy to solve, the servo joints will inherently cause positioning inaccuracies at the end effector by accumulating errors along every rotary joint or prismatic translator. Interestingly enough, the inverse kinematics of a serial robot is difficult to solve. Forward kinematics refers to computation of position and orientation of the end effector in relation to a stationary base. If the relative angles and arm lengths are known, the end effector can be located in a couple of mathematical steps. On the other hand, the inverse kinematics deals with knowing the position and orientation of the end effector and computing for angles at each joints and arm lengths that would yield the location of the end effector. Inverse kinematics can lead to more than one answer. Figure 1.3 shows that although the arms are at set lengths the joint angles can be different to achieve the same result. Multiple answers are desirable when circumventing obstacles between the end effector and its objectives.

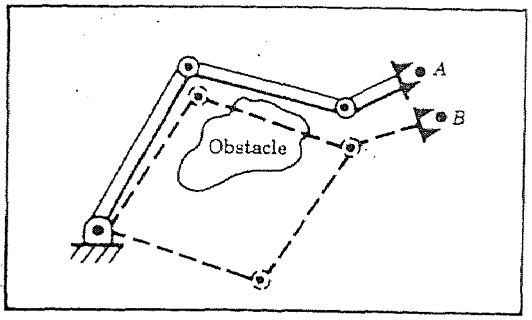


Figure 1.3 Multiple solutions for serial robots[6]

In contemporary industries, it is very likely to encounter operations where heavy objects are maneuvered during assembly, disassembly, machining and motion simulation processes. In these particular applications, the usage parallel linked robots is desired since the serial ones are not capable of withstanding the weight load. Parallel robots, compared to serial ones, have the best weight - load ratio. In comparison with the serial robot, a parallel robot of similar size and weight is capable of applying forces twice the magnitude. Capable of handling extremely heavy loads, and still maintaining precision and accuracy, parallel robots would be the ideal manipulator for various tasks if not for one particular limitation - mobility. [In a platform manipulator, all prismatic joints are fastened to a base, and since one leg is dependent on others to move, they are all inter-connected, thus compromising its mobility.]

The automation industries, in the past, used to build robots to perform one specific task repeatedly, such as in an assembly line, where the robot would produce many numbers of one particular part. In present industries, more and more "flexible" manufacturing is being experienced globally. Flexible robots are used to produce a small number of parts and once that task is completed, the robot is reconfigured to produce a different part in particular number and so on. In this manner, one manipulator can handle different jobs, saving time and money in building one robot per task. Our experimental robot presents two forms of increasing flexibility in a parallel manipulator - a) change the position of the legs at the base where they are fastened, and b) change the position of the legs at the platform where they are fastened. There might also be another option of increasing the stroke length of the prismatic joint to increase range of motion.

CHAPTER 2

CONCEPTUAL DESIGN

2.1 Design Constraints

It is undeniable that obtaining an optimum design is a very difficult task to accomplish. The functions of the apparatus in question will determine its final design. Based upon the function or functions that the machinery will perform, the designer will be compelled to modify the dimensions, shapes and building materials of the apparatus. There are several design constraints that must be set in order to obtain an optimum design. The constraints can be thought of being small barriers that will have to be overcome to reach the final design that meets predetermined parameters.

One of the most important features in any machinery is reliability. Once the design and construction are complete, the apparatus must perform its duties as planned. Reliability and repeatability in essence should be regarded as being complementary constraints. The platform manipulator must be able to repeat its task numerous times with same results. Durability of the platform manipulator will depend mainly upon the material selection of the parts and the dimensional tolerances. It is imperative that the manipulator's functions are not compromised by its physical integrity, the parts must be built to last for a certain period of time. In present industries, even the best of the design might be rendered useless due to high costs. The apparatus might be predicted to outperform any other machines in the same class, but if it is too expensive to construct, there will be a compromise on cost and performance. Cost plays a great role in design - performance will be sacrificed for a lower-cost machine. Depending on the complexity to design and actually build a part, a less expensive measure will be taken. Complex components will lead to very expensive machining times and procedures. Aesthetics is sometimes stated to be a less important issue in design. Interestingly enough, the previous argument might not be true in all cases. In the event of marketing any product, the appearance must be appealing to the consumer. In some cases, appearance can be judged to precede in importance than functionality. Fortunately, appearance is not an important issue in the design of this particular experimental robot.

There are particular design specifications that are defined for manipulators:

* Payload - determines the maximum weight capacity of a manipulator.
* Precision - ability of a manipulator to place its end effector at a desired location multiple times and/or as commanded.
* Speed - velocity at which the end effector travels
* Reach - overall range, how far the end effector can be moved
* Stiffness - ability for a manipulator to resist bending, buckling, torquing and other external/internal forces while in motion and rest.

There are various tradeoffs with which a designer might have to settle. For example, it is unexpected that heavy weight can be moved at high speeds nor with accuracy. High-precision machinery has low tolerance to wear and tear. Hence, the choice between precision and long machinery life must be made. A manipulator that can handle heavy loads generally implies that its building blocks are rigid, which inherently may cause problems with high natural frequencies due to vibrations while in motion. Sophistication in design may lead to difficulty in maintaining and servicing the machine. Simplicity is sometimes the key for a good design. The designer must recognize that strengthening one attribute can lead to a decreased performance in another.

Bearing all the constraints in mind, many different conceptual designs can be created. It is the personal choice of the designer to assign different importance to different constraints and prioritize which is more vital for the functions sought. For instance, if the weight of the manipulator is a concerning physical issue, lighter materials must be employed to decrease the overall weight. Lighter materials might lead to more expensive metal alloys or composites, which in turn will increase the projected cost.

2.2 Design Parameters

It was briefly mentioned before that the lengths and positions of the prismatic joints will be a direct cause to limit the motion of a platform manipulator. Due to their physical constraints, the platform is unable to "spin freely", and the end-effect's output angles are very limited. To raise and lower (strictly vertical translation) any end-effector (such as tools and grippers), all the six joints must be actuated simultaneously to avoid tilting of any sort in any side. Due to the fact that the end-effector is located by 6 coordinate axis - x, y, z, α, β, γ (three translational and three rotational) all the six joints must function in unison to perform one single task. All the joints are inter-related and dependent of each other. Changing the length of only one link, might cause not only rotation, but also translation. Assuming that the local coordinate axis of the mobile platform has been chosen so that the z-axis points perpendicular to the flat surface, the Stewart Platform has the inability to rotate fully about that z-axis. That particular motion is restrained by the actuators and the joints simulating two and three degrees of freedom.

The kinematic structure of the experimental platform in question is similar to other fully parallel platform manipulators. It consists of a base, a mobile platform on which tools (end effectors) or equipment (loads) are mounted, and six parallel-actuated extendible legs between the mobile platform and base. Previous study on design parameters in the platform manipulators has shown that the moving range of the legs as well as the placement of the legs has great effect on the shape and size of workspace. Therefore the reconfiguration should be achieved through modular design such that any of the leg modules can be easily replaced by another with different range of motion, and can be placed on the mobile platform and as well as the base at any predetermined location and orientation.

The first feature to be designed is one of the six legs. The leg consists of two joints in each end and a variable length joint in the middle (Figure 2.1). The prismatic joint is actuated via power screw which is attached to an electric motor. To the other extremity of the motor's main shaft, an optical encoders is placed. The joint that is supposed to be attached on the base requires two degrees of freedom. It is imperative that the other joint possesses three degrees of freedom to simulate a socket ball joint.

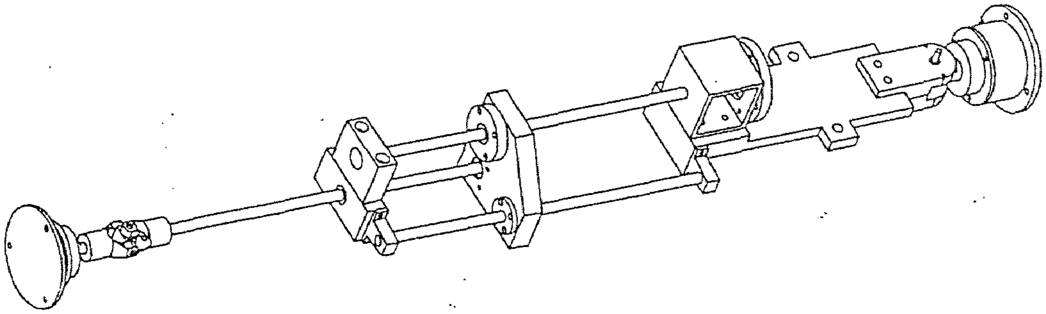


Figure 2.1 Modular Leg

CHAPTER 3

BOTTOM JOINT

3.1 Two Degrees of Freedom Requirement

In order to describe the position and orientation of a rigid part, it requires a unique combination of six parameters. Three of the parameters describe the position with respect to a specific reference - x, y, and z positions in Cartesian coordinates. The other three describe orientations such as pitch, yaw, and roll - α, β, and γ respectively. All the six parameters combined will govern the degrees of freedom (DOF) of any part. One specific parameter is considered to be one DOF. For example, a rotary joint will have one DOF because it needs only one angular orientation to describe its motion. Two DOF can be achieved in three different ways. By conjuring both rotary and prismatic joints, the following combination can be achieved - one rotary and one prismatic; both rotary; and both prismatic. In case of our experimental manipulator, a prismatic joint was unnecessary during the bottom joint design, for it had a prismatic leg attached to it. Eliminating any possiblity of using prismatic joints, the only option remained is having two rotary joints. Having the bottom plate as a stationary base with a default Cartesian coordinate axis having the z-axis pointing up, the bottom joint needed to have one DOF to spin about the z-axis and one DOF to spin perpendicularly to z-axis, thus in any direction along x-y plane. In the next section, it will be more apparent where each DOF is found as it is explained which component serves to which function.

The entire bottom joint consists of nine parts - five obtained after-market and four designed (Figure 3.1 and 3.2).

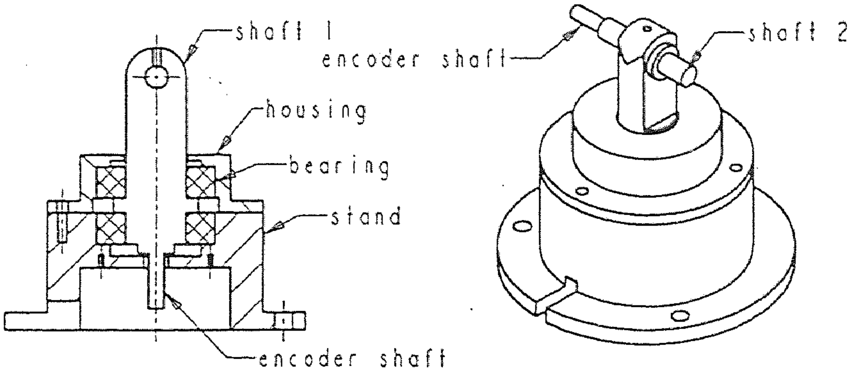


Figure 3.1 Bottom Joint (Section View)

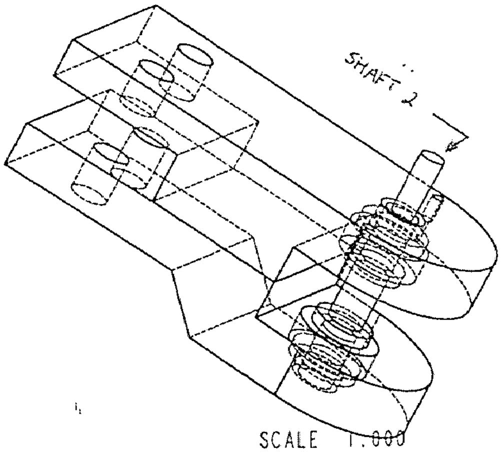


Figure 3.2 Fork (Cutaway View)

The bottom joint, by itself, is not modular. The housing and the stand must be in matching dimensions. The bearings and shaft 1 must also be in predetermined dimensions. The modularity will be apparent later on in the report in chapter 6 where assembly is discussed with more detail.

3.2 Design description

In essence, the bottom joint, with two DOF, was constructed by using a rod and two thrust bearings. Each leg undergoes compression or tension, therefore the usage of two thrust bearings - one bearing for each direction of force - is well justified. The two bearings were "slipped" into the rod, one on each extremity and two housing halves clamped the bearings in place, thus securing shaft 1. The housing is attached to the stand via three screws that are placed 120 degrees apart from each other on the x-y plane orientation. Shaft 1 has one DOF by itself, rotating about the axis that goes through the center of shaft 1. Two holes were drilled on the underside of the base in order to accommodate a pre-assigned optical encoder. The encoder measures and outputs the rotary displacement of shaft 1. To shaft 1, a hole is created. A horizontal rod (shaft 2) is inserted in the hole created in the shaft 1. In relation to shaft 1, shaft 2 is positioned perpendicularly, thus yielding the second DOF (Figure 3.1). One minor difficulty for future assembly revealed itself during the conceptual design of shaft 2. Shaft 2 presented itself as a problem due to the fact that it had to be inserted through the hole in shaft 1 from one extreme. That meant that a separate bushing had to be purchased. It can be seen in Figure 3.3 that one of the bushings has been already incorporated in the construction of the rod.

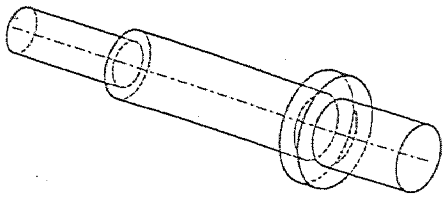


Figure 3.3 Shaft 2 (Cutaway View)

The dimensions and the placement of the bushing had to be selected in accordance with the selection of bearings that would support the fork on shaft 2. The fork would clamp in the two bearings on the rod (Figure 7) and the bushings would provide clearance for the bearings not to come in contact with shaft 1 and create unnecessary friction. Notice that the bottom section of the fork is round. Although the extra step in machining would incur a higher cost, it was necessary in order to provide enough clearance so that the fork would not come in contact with the housing while pivoting. Shaft 2 is fixed on shaft 1 via a set screw, and the fork revolves around shaft 2. An optical encoder is attached to the fork. The relative rotational displacement between the fork and shaft 2 is measured in the encoder

The manipulator being designed is capable of supporting a payload of 2000 pounds, which means that each leg should withstand at least one sixth of the 2000 pounds - approximately 340 pounds. In case of shaft 1, thrust bearings were selected according to the load it could endure. It must be born in mind that the less the stock material used, the lower the cost and weight of the resulting product. Thus, smallest bearing which would satisfy the load requirement was selected and the dimensions of shaft 1, housing and stand were incorporated in the design accordingly. In the case of shaft 2, the 340 pound load would manifest itself differently due to the orientation of the shaft. Shaft 1 required thrust bearings, but shaft 2 would require a bearing that could take axial loading. To meet the precision requirements during motion, heavy duty and high precision needle bearings were selected.

The modularity in the bottom joint is governed by one piece - the base. There are three 0.3 inch diameter holes drilled at 2.15 inches away from the main central axis set at 120 degrees apart (Figure A1). These holes are to be aligned with the pattern of holes in the base plate (Figure 3.5). Six possible combinations can be achieved while matching the holes in the base to the holes in the base plate.

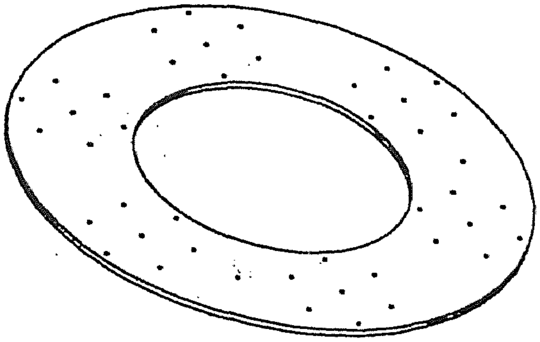


Figure 3.4 Base Plate

CHAPTER 4

PRISMATIC ACTUATOR

4.1 Stability Under Loads

The prismatic joint was built by unifying three distinctive "rods" to perform one single function - pure translation. As it can be seen in Figure 4.1, the guide is attached to the piston which is attached both to the power screw and the linear guide. When the power screw is activated, linear motion is achieved.

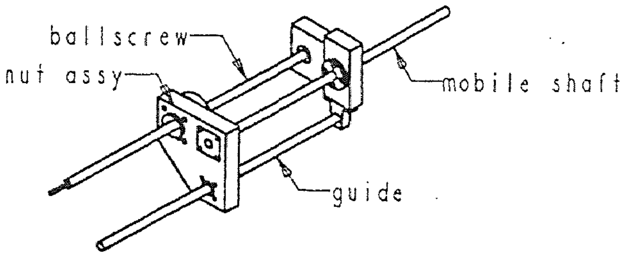


Figure 4.1 Linear Actuator

One of the problems that might occur is when pure bending or torsion is encountered along the piston rod. At a standpoint of statics, pure bending or torsion will not occur in the leg. This prismatic joint, by being supported by "pin" joints at both extremities, will only undergo tension or compression. Moment or torque will be found at the joints if and only if the joint resembles a fixed support. In order to ensure that there is no unbalance of reaction forces which would create undue couple moments, the piston rod was placed in such a way to align with the central axis of shaft 1 in the bottom joint. This feature will further be discussed in the next section during design phase. The preceding analysis is based solely on the fact that the weight of the prismatic joint is negligible. In reality this is highly desirable but untrue. The prismatic joint incorporates an electric motor that weighs approximately 15 pounds. This load might be enough to create minor deflection at the weakest part of the actuator, especially when it is fully extended. To avoid deflections or extreme bending forces caused by the actuator's weight, a triangular configuration of rods was chosen. In order to "deliver" accuracy and precision while the platform is under load, stability becomes a great concern while designing the actuator.

4.2 Design Description

Several possibilities were considered in regards to the positioning of the ball screw, supporting rod and actuating piston. Each linearly translating rods would glide back and forth via linear bearings. The ideal positioning would be such that the rods, seen from the front would form the vertices of an equilateral triangle. This feature could not be achieved because the after market parts would not allow flexibility in design, so the design had to be adjusted to accommodate the parts, but still having a triangular configuration.

The proximity of one shaft to another is governed by the design of piston block (Figure 4.2). In order to minimize internal torsion that might occur, it is the intention of the designer to place the shafts as close as possible to each other. Since all the shafts must be fixed on the piston block by usage of screws, enough distance must be given so that the holes do not overlap on each other. The piston block is designed to accommodate one linear bearing, the piston shaft support and the ball-screw assembly.

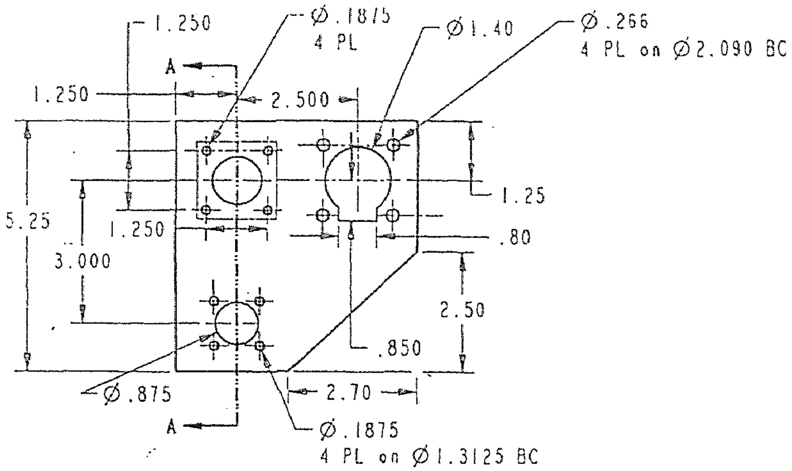


Figure 4.2 Piston Block (Front View)

The electric motor shaft is directly attached to the power screw shaft via step couplers. An attempt to attach the motor to the power screw support revealed that this step would require an additional part to act as a "liaison" between the support and the motor. The selected motor is about 15 pounds in weight, relatively large and long (Figure 4.3). In order to securely attach the motor to the power screw support, a motor plate was designed (Figure 4.4). The motor plate features a circular plate with a 1.5 inch diameter hole in the middle for the power screw shaft. The plate also has series of pre-dimensioned holes drilled in them. The holes are positioned in such a way that one set of holes aligns to pre-drilled holes in the power screw support, and the other set aligns to pre-drilled holes in the motor itself.

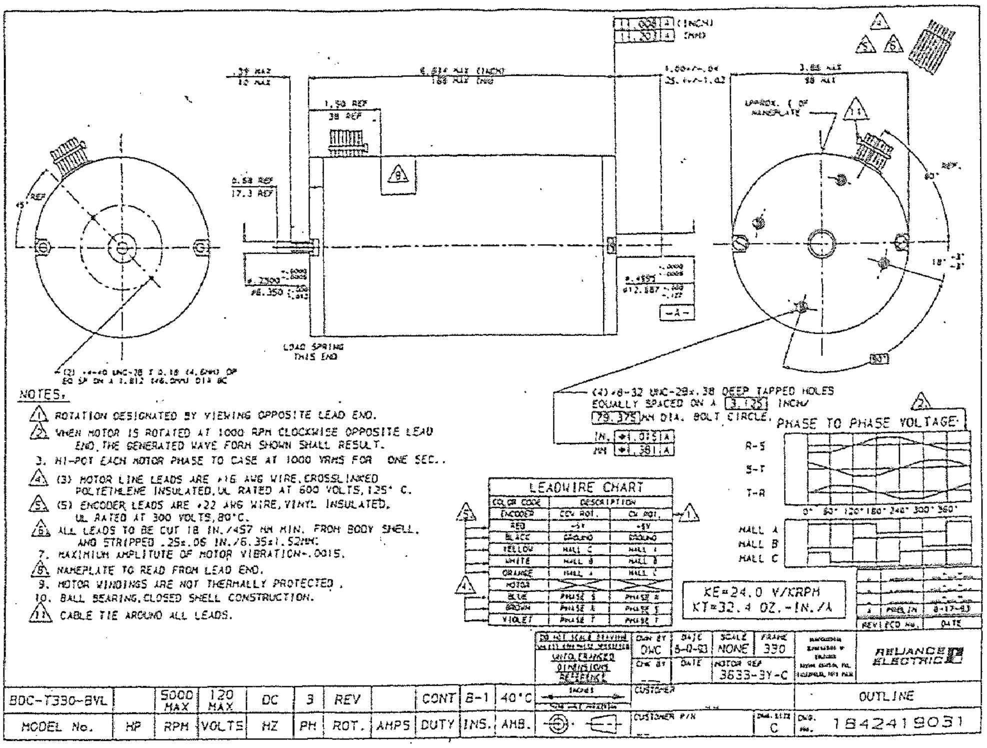


Figure 4.3 Motor Specifications

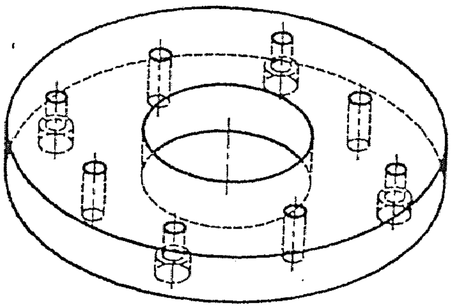


Figure 4.4 Motor Plate

Taking into account the 15 pounds inherent in the motor, only the motor plate would not be enough to securely hold the motor. A more sturdy support in form of a plate had to be made. The junction plate (Figure 4.5) provides abundant support for the following parts: power screw support, electric motor and fork.

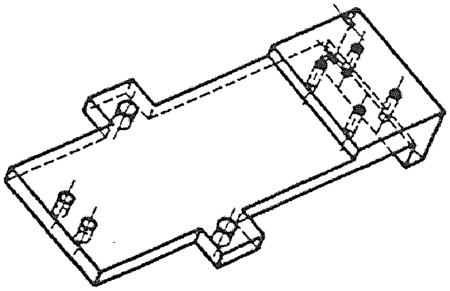


Figure 4.5 Junction Plate

The electric motor is tightly clamped on the junction plate by usage of a U-bolt readily available in the market. The prismatic joint is by far the most complex in number of separate parts. The entire ensemble of the actuator was designed so that the after market parts would fit together without compromising the expected performance. The motor is not only held in place by motor plate and the U-bolt, but also indirectly by the piston actuator assembly. The motor shaft has two extremities - one for the power screw shaft and one for an optical encoder. An encoder is attached to the other side of the motor so that any angular displacement made by the motor shaft can be registered. By knowing the pitch of the threads on the power screw, and the amount of rotation performed by the same, it is possible to calculate the linear displacement of the piston block, or the stroke length.

The actuator is the hardest portion to design due to its many parts and endless hours of thought involved in creating a feasible "match" between parts. It is not enough only to make the parts fit together, but also to make it meet or exceed its expected capabilities. The resultant design is a link between top and bottom joints with one single function - linear translation.

CHAPTER 5

TOP JOINT

5.1 Three Degrees of Freedom Requirement

The top joint is an interesting design challenge. It is required that the top joint possesses 3 DOF. A simple example of a 3 DOF joint is the socket-ball joint or a spherical joint (Figure 5.1). A socket-ball joint enables a link to gyrate in any orientation, but does not allow any form of translation in any direction, thus it can be regarded as a purely rotational joint.

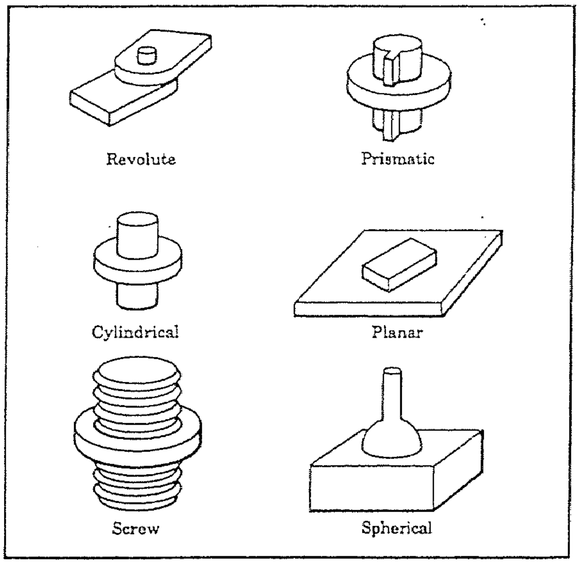


Figure 5.1 Different types of joints[6]

The available after-market socket-ball joints would not exceed more than 45 degrees inclination in any direction, and since OSCAR is still a prototype to be tested, it was rather unknown if OSCAR would require more 45 degrees inclination in the top joint. Having given the benefit of the doubt, it was decided to build a joint that would provide more than 45 degrees inclination. A universal joint, also readily available in the market in various sizes and types, holds 2 DOF. Setting a default Cartesian coordinate axis as an example, the universal joint can rotate about x and y axis, providing 2 DOF. A third DOF had to be added, enabling the universal joint to rotate about the z axis. The necessary third DOF was added by attaching the universal joint to a rotating rod, thus enabling the universal joint to revolve about its z axis.

5.2 Design Description

The design of the top joint resembles the one of bottom joint. It also consists of a base and a housing to clamp two thrust bearings with a rod in between (Figure 5.2). Again, the joint is going to experience both tensile and compressive forces, requiring one bearing for each direction of load force. By attaching the rod to a selected universal joint, top joint is created. One difference between the top joint and the bottom joint is manifested in the base. The base for the bottom joint had to be "roomy" enough to accommodate an optical encoder. In the case of the top joint, no encoders are necessary.

The interest of research is focused primarily on the position of each top joint. As it has been described in previous chapters, the bottom joint defines its two DOF by means of two encoders. The prismatic actuator defines its linear translation by usage of encoders as well. Compiling all the positions of at least three top joints, it is possible to define both the position and the orientation of the of the plane in which the end effector is present.

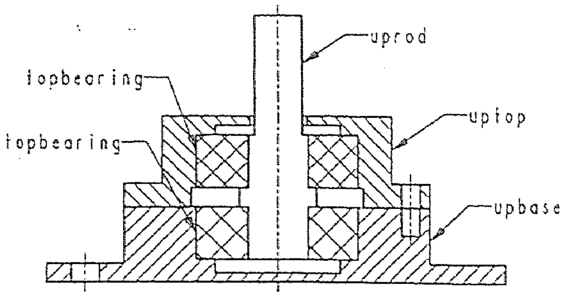


Figure 5.2 Top Joint (Section View)

CHAPTER 6

ASSEMBLY

6.1 Joints and Legs

The assembly procedure is quite simple if all the pieces are pre-categorized and sorted before the actual assembly. Starting from the bottom part of the entire apparatus and moving upwards, the bottom joint is the first setup to be assembled. One of the thrust bearings (the one supposed to support compression) is placed inside the base. Shaft 1 is oriented so that the hole for shaft 2 is in the upper portion, and it is inserted in the bearing. The second bearing, which will undergo tension is slipped in shaft 1. The housing is aligned with the holes in the base and fastened in place via screws. On the bottom of the base, a pre-selected encoder is inserted and attached in place with two small screws. To the hole in shaft 1, shaft 2 is inserted. Once shaft 2 is in place via tightening of a set screw in shaft 1, a bushing is inserted on shaft 2 from the open extremity. Two ball bearings are slipped from both ends and the fork finalizes the final clamping procedure. To one side of the fork, shaft 2 should be exposed. To this end the optical encoder is attached.

Prismatic actuator assembly is slightly more complex than either the top or the bottom joints. The simplest procedure in assembling the entire prismatic actuator is firstly to unite the ball nut in the piston block. To the piston block the piston rod must be attached, and finally the guiding rod should be placed in the linear bearing in the piston block. The guide will have to be attached simultaneously to the linear block and the motor support. The next step is to secure the power screw support to the motor support and the motor plate finalizes the assembly procedure.

The assembly of the top joint resembles the assembly procedures for the bottom joint. One thrust bearing is inserted in the base and the rod is inserted in the bearing hole. The other bearing is slipped on the rod and housing clamps the bearings and rod to the base. Universal joint is attached to the rod via a set screw.

Since the beginning of design phase, the connection between sections was thought of beforehand. There are two through holes in the fork. Similar dimension holes are also drilled in the motor support. The holes are aligned, and using bolts and nuts they are both secured in place, attaching the bottom joint to the prismatic actuator. The assembly between top joint and prismatic actuator is as simple as well. The diameter of the piston rod is 0.5 inches and the selected universal joint has 0.5 inch diameter holes. By placing the piston rod in the universal joint hole the entire assembly of one of the six modular leg is completed (Figure 2.1).

6.2 Platforms and Legs

The process to attach the legs to the platforms is very simple. As stated in one of the previous chapters, there are holes drilled on the top and base platforms. Before the legs are attached to the platforms, three specific foots must be placed under the base platform. The foot is used to elevate the base platform above the ground since the adjoining tools - i.e. bolts and nuts - will be protruding under the base platform. The holes in the bottom joint must be aligned to the holes in the base platform in the desired location. Once the base joint is aligned, it is fastened in place. This process is repeated until all the six legs are fixed in place. The top joints are attached to the top platform in the same manner as the bottom joint to base platform (Figure 6.1).

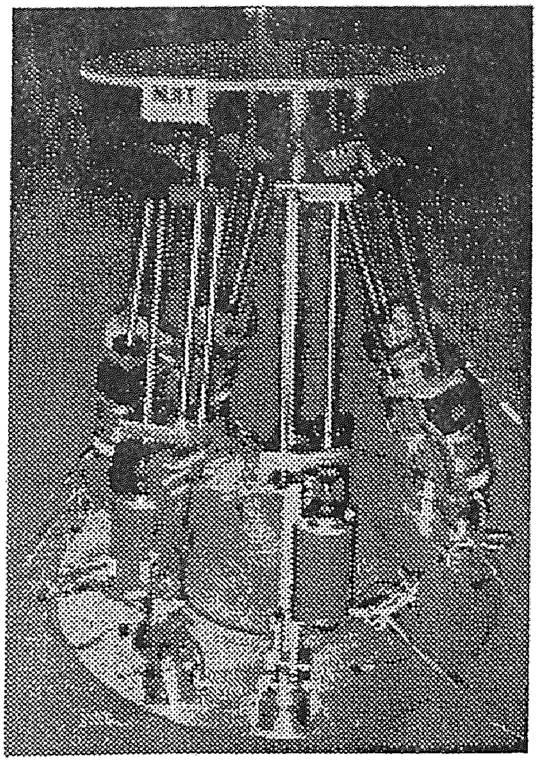


Figure 6.1 Experimental Parallel Robot (Completed)

CHAPTER 7

CONCLUSIONS AND RECOMMENDATIONS

7.1 Summary

In this research experiment, several different kinds of manipulators were cross referenced. Upon researching the existent manipulators, many different ideas on how to design OSCAR was obtained. During the process of design, it was observed that great part of the design is governed by after-market products available to the researcher. It is always less costly to purchase a product than building it. Therefore, after-market parts were used to the maximum allowable extent.

It can be observed that the geometric shapes of the designed parts are rather simple and rudimentary. Complex designs leads to expensive machining methods and extensive machining time, not to mention difficulty in maintenance and repairs. Simplicity in design is the key factor in OSCAR. The cost factor in machining was kept to its minimum by choosing simple geometric shapes to build.

Computer integrated manufacturing, or CIM was used to interface OSCAR's design concept into tangible parts. OSCAR was first designed in SDRC I-DEAS MS CAD package. Due to the user-friendly nature of this CAD package, the parts were created and assembled for clearance verification without difficulty. One particular problem arouse when the design was being passed from picture to actual parts. Discrepancies were found by the machine shop while trying to build the parts due to inadequate drafting capabilities of I-DEAS. The next step was to use any CAD package that would enable the user to obtain clear and self-explanatory drafting and provide CIM. Most of the design created in I-DEAS was redrawn in Pro-Engineer Release 18 from Parametric Technology Corporation. Pro-Engineeer offers a more flexible solid modeling due to the fact that all dimensions in any part can be modified at any time. It also has a direct interface with Fadal five axis milling machine. Once all the parts were assembled in Pro-E, each individual draft was obtained and the files were exported to Fadal for actual production. Most of the parts were made for aluminum to minimize the overall apparatus weight and in only critically loaded parts steel was used.

It is highly recommended that certain features are added to the finished OSCAR. In order to obtain a detailed analysis of OSCAR's performance, pressure sensors should be implemented at the junction between the piston rod and the universal joint. Pressure sensors would provide the user with a feed-back of how much load a particular leg is supporting at any given time. This information might be useful while performing motion simulations in order to avoid critical loads and to better understand the relationship between workspace (geometric configuration) and weight load. At present design state, there is no limiting switch for the prismatic actuator. In other words, when the leg is fully extended or retracted, if the user does not stop the motor, it will overdrive and create unwanted internal forces, and wear and tear that will damage the apparatus prematurely.

During the course of design, it was recommended to perform finite element analysis or FEA on the parts that were suspected to undergo severe loading. FEA was attempted using I-DEAS, but some problem was found while trying to implement the material selection. Aluminum was the material chosen for the part being analyzed, but I-DEAS would not perform the analysis with material properties that belonged to aluminum.

7.2 Modularity

There are many possibilities to utilize OSCAR's flexibility to maximize its advantage in favor of the user. It was mentioned before that the position of the bottom joint can be changed in relation to the base plate. It is also possible to purchase a different length ball nut-power screw assembly with same size support in both extremities in order to obtain a different stroke length of the prismatic joint. This would inherently require that the lengths of the piston rod and guide rod be changed accordingly, but longer legs infers broader workspace. Depending on the application, the stroke length can also be shortened as well.

A more immediate configuration change can be achieved by repositioning the leg about either the top or base platforms. Using different combinations of both leg length and positioning, extensive results in relationship between manipulator size and workspace can be found during simulations. Another form of rearranging the manipulator configuration is to increase or decrease the sizes of both the top and base platforms.

7.3 Simulation

A computer simulation program can be written by incorporating forward kinematic equations and optical encoder feedback to obtain the position and orientation of all the six legs. Forward kinematics of fully parallel manipulators has been known to be very complicated. Many publications have devoted to solve this problem. When the kinematic configuration of the manipulator changes, usage of one or two additional sensors to reduce the complexity of the problem has been studied[12,13]. The passive joint encoders, although they re not used only for this purpose, can easily be used to obtain the position and orientation of the mobile platform as follows. Figure 7.1 depicts the kinematic structure of the experimental platform, where Hooke joints on the base are denoted as B_i (i=1,...,6) and spherical joints on the mobile platform as M_i (i=1,...,6).

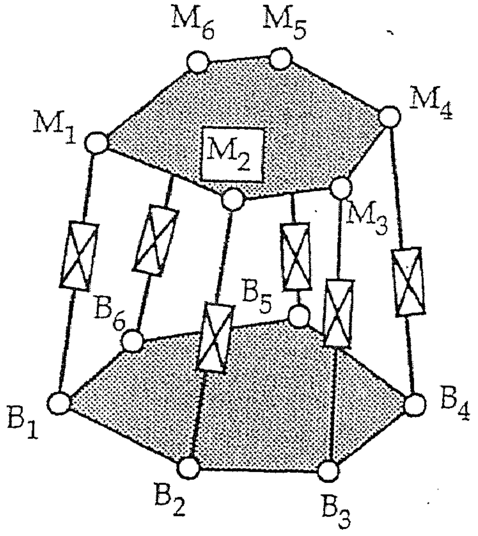


Figure 7.1 Kinematic structure of the experimental manipulator

A pair of passive-joint encoder, mounted on the foot of leg i can determine the orientation n_i of the leg. Combining n_i with the leg length l_i obtained with the encoder on the actuated linear joint, the position of joint M_i can now be found as

$$\bar{P}M_i = \bar{P}B_i + l_i\, n_i \tag{1}$$

where $\bar{P}B_i$ is the position of joint B_i.

Since the position and orientation of a rigid body can be uniquely determine by three non-degenerating point (not on the same line), any combination of three $\bar{P}M_i$ can be used to produce the orientation matrix R of moving frame $\{M\}$ in fixed frame $\{B\}$ and the position vector $\bar{P}0$ of the moving frame origin. Lets suppose legs i, j and k are used in the determination and the position vectors o M_i, M_j and M_k in $\{M\}$ are, respectively, ${}^{\mathrm{M}}\bar{P}M_i$, ${}^{\mathrm{M}}\bar{P}M_j$, and ${}^{\mathrm{M}}\bar{P}M_k$. We have

$$\begin{aligned} \bar{P}M_i &= \mathrm{R}^{\mathrm{M}}\,\bar{P}M_i + \bar{P}0 \\ \bar{P}M_j &= \mathrm{R}^{\mathrm{M}}\,\bar{P}M_j + \bar{P}0 \\ \bar{P}M_k &= \mathrm{R}^{\mathrm{M}}\,\bar{P}M_k + \bar{P}0 \end{aligned} \tag{2}$$

Let

$$\begin{aligned}
\vec{v}_{ij} &= \vec{P}M_i - \vec{P}M_j = R({}^{\mathrm{M}}\vec{P}M_i - {}^{\mathrm{M}}\vec{P}M_j) = R\vec{u}_{ij} \\
\vec{v}_{jk} &= \vec{P}M_j - \vec{P}M_k = R({}^{\mathrm{M}}\vec{P}M_j - {}^{\mathrm{M}}\vec{P}M_k) = R\vec{u}_{jk} \\
\vec{v}_{ki} &= \vec{P}M_k - \vec{P}M_i = R({}^{\mathrm{M}}\vec{P}M_k - {}^{\mathrm{M}}\vec{P}M_{\;k}) = R\vec{u}_{ki}
\end{aligned} \tag{3}$$

or

$$[\vec{v}_{ij} \quad \vec{v}_{jk} \quad \vec{v}_{ki}] = R[\vec{u}_{ij} \quad \vec{u}_{jk} \quad \vec{u}_{ki}] \tag{4}$$

Therefore

$$R = [\vec{v}_{ij} \quad \vec{v}_{jk} \quad \vec{v}_{ki}]\,[\vec{u}_{ij} \quad \vec{u}_{jk} \quad \vec{u}_{ki}]^{-1} \tag{5}$$

and

$$\vec{P}0 = \vec{P}M_i - \mathrm{R}^{\mathrm{M}}\vec{P}M_i \tag{6}$$

Equations (5) and (6) completely defines the position and orientation of moving frame $\{M\}$ in fixed frame $\{B\}$. This approach is only for real-time forward kinematics because of the dependence on the encoder information. It is therefore different form the pure kinematic sense of forward kinematics solution, where only leg lengths are used to obtain the solution.

APPENDIX A

COMPONENT LAYOUT

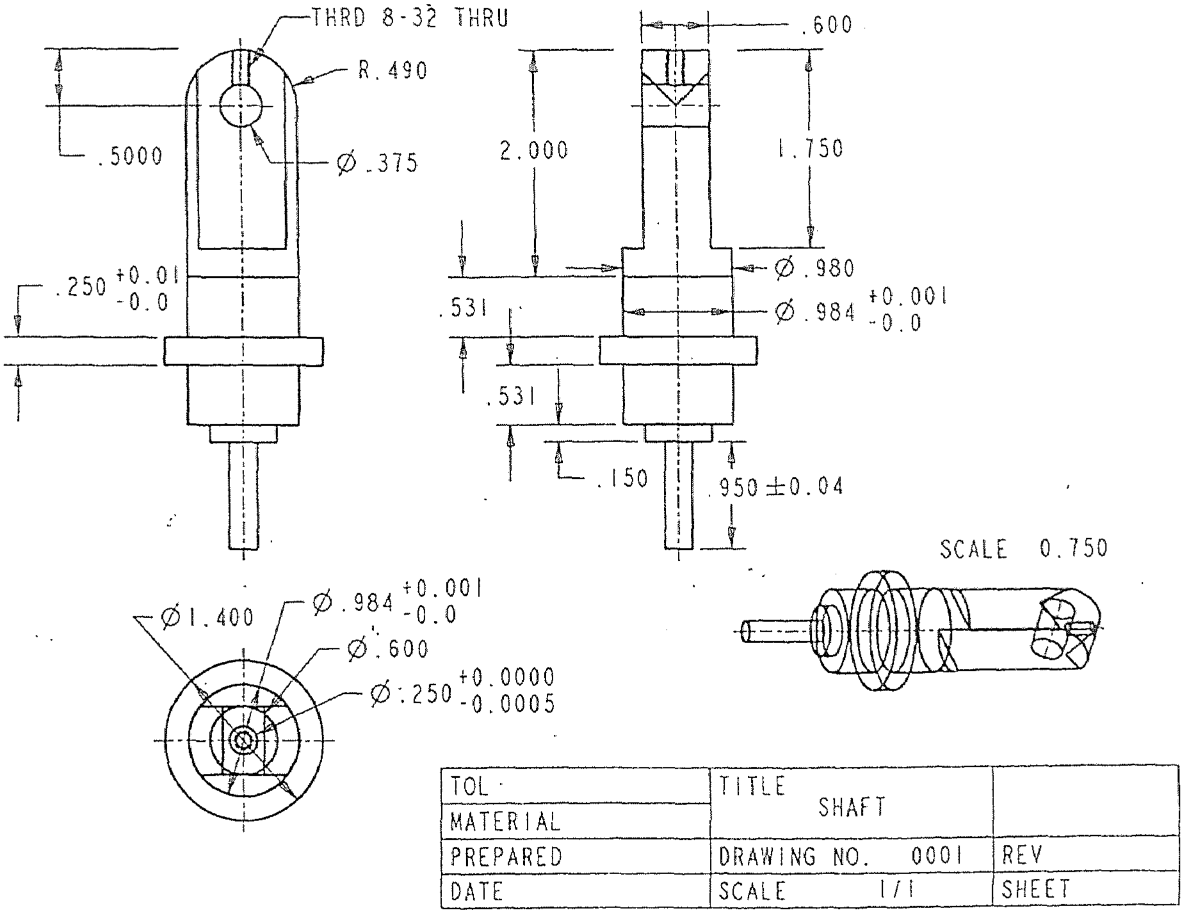


Figure A1 Shaft 1 - Main shaft in the bottom joint, used to support the entire leg and platform

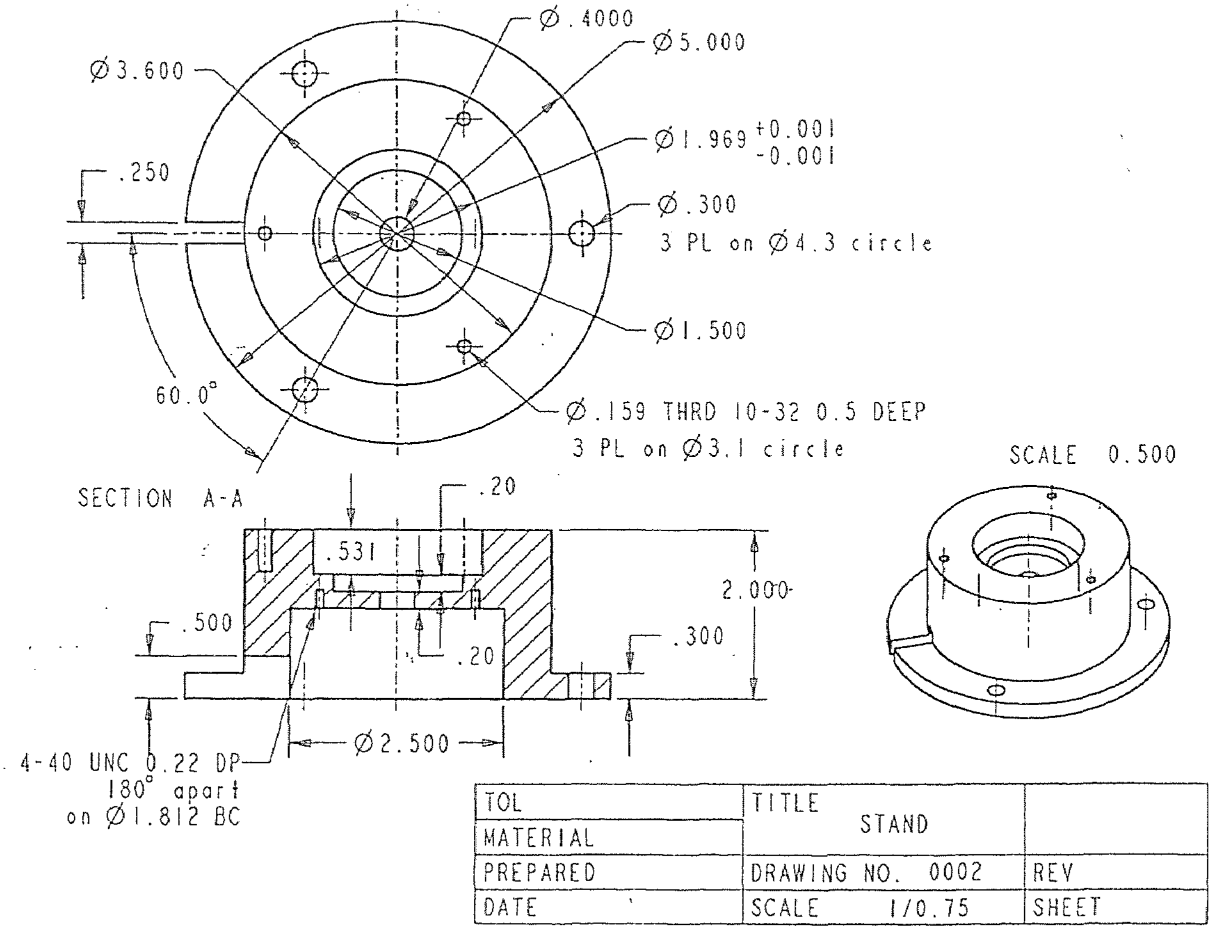
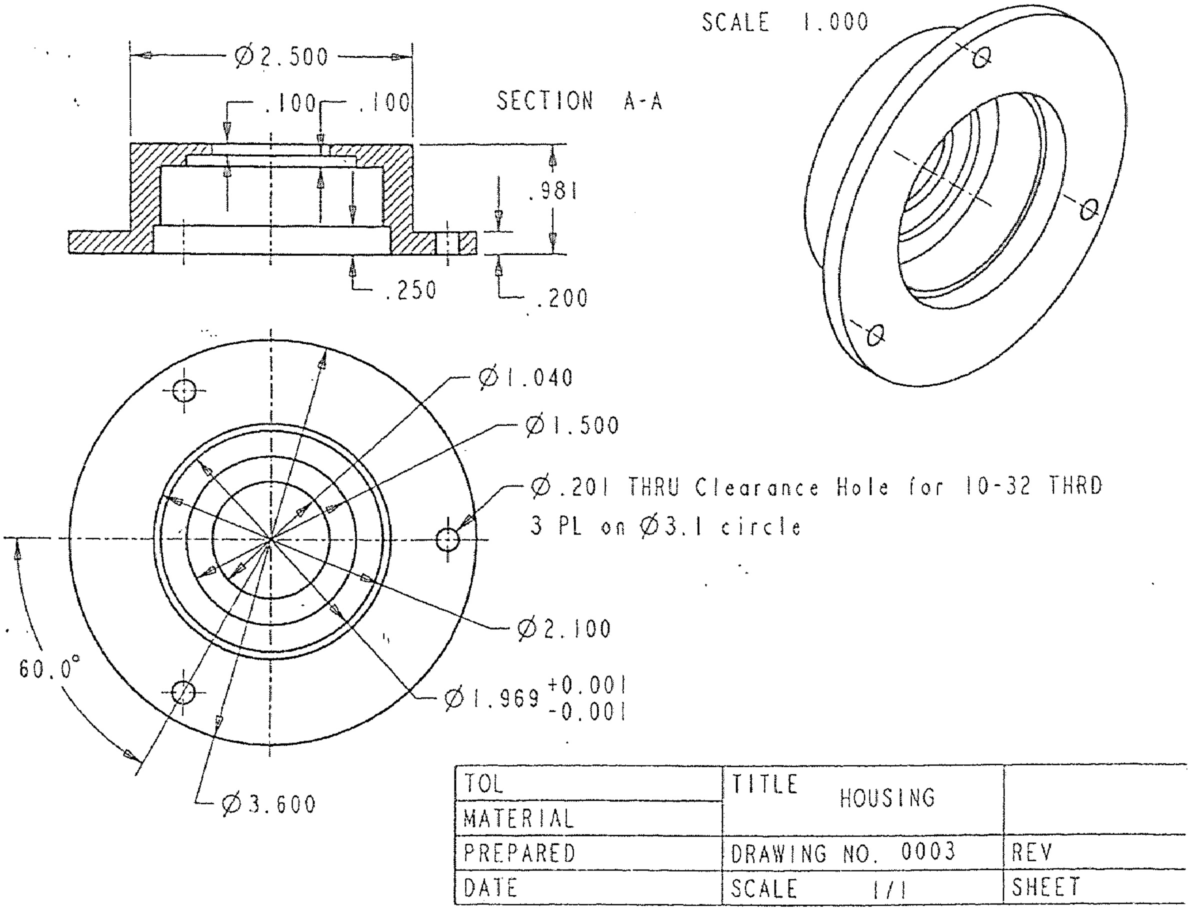
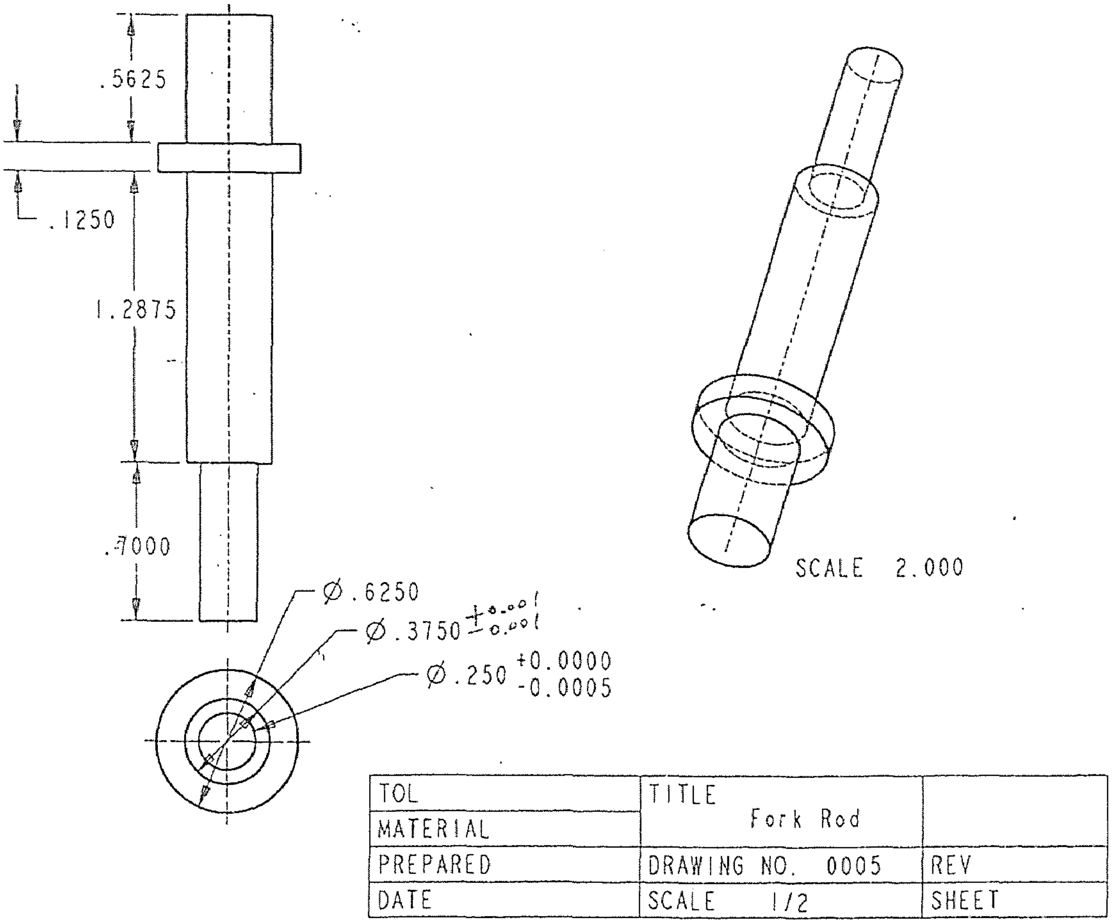


Figure A2 Bottom Joint Base - Note the spaces on the top and bottom to accommodate bearing and encoder, respectively



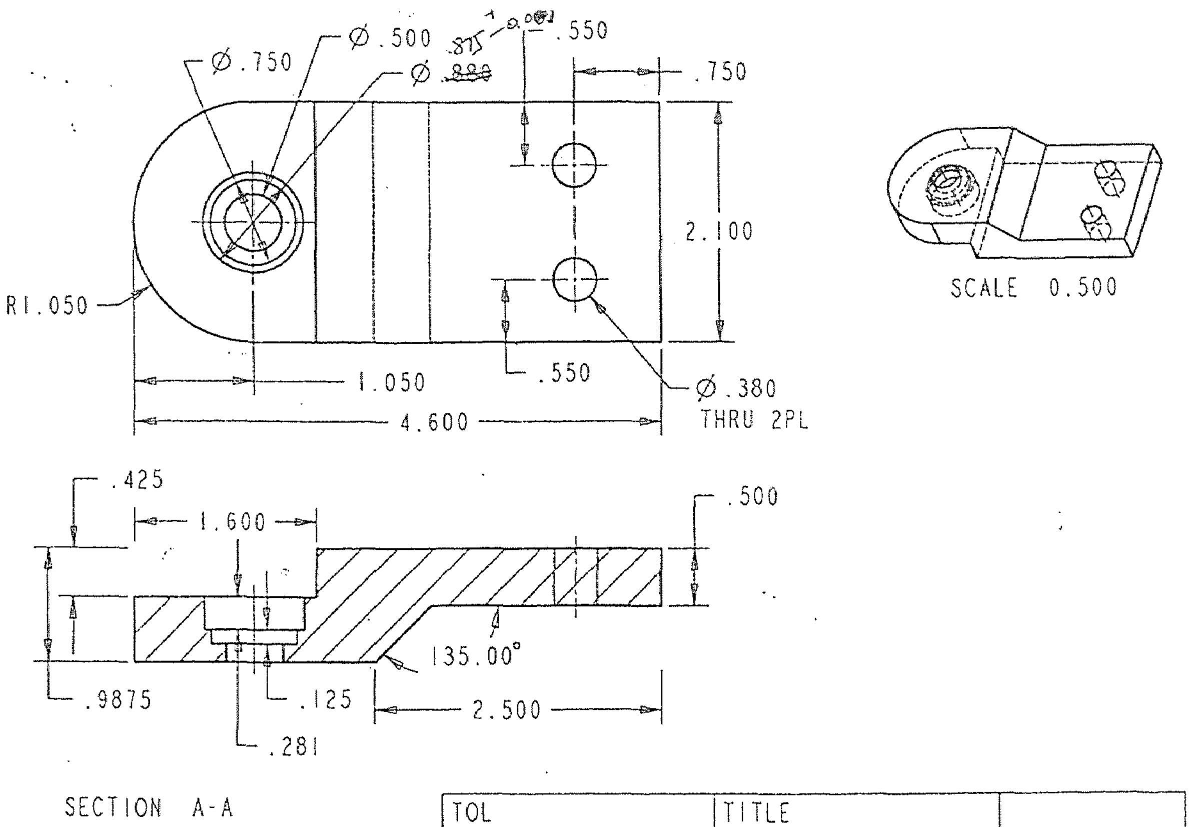
TOL	TITLE HOUSING	
MATERIAL		
PREPARED	DRAWING NO. 0003	REV
DATE	SCALE 1/1	SHEET

Figure A3 Bottom Joint Housing



TOL	TITLE Fork Rod	
MATERIAL		
PREPARED	DRAWING NO. 0005	REV
DATE	SCALE 1/2	SHEET

Figure A4 Shaft 2 - is inserted in Shaft 1 and connected to the fork



TOL	TITLE Fork	
MATERIAL		
PREPARED	DRAWING NO. 0006	REV
DATE	SCALE 1/1	SHEET

Figure A5 One side of the fork where the encoder is <u>not</u> attached

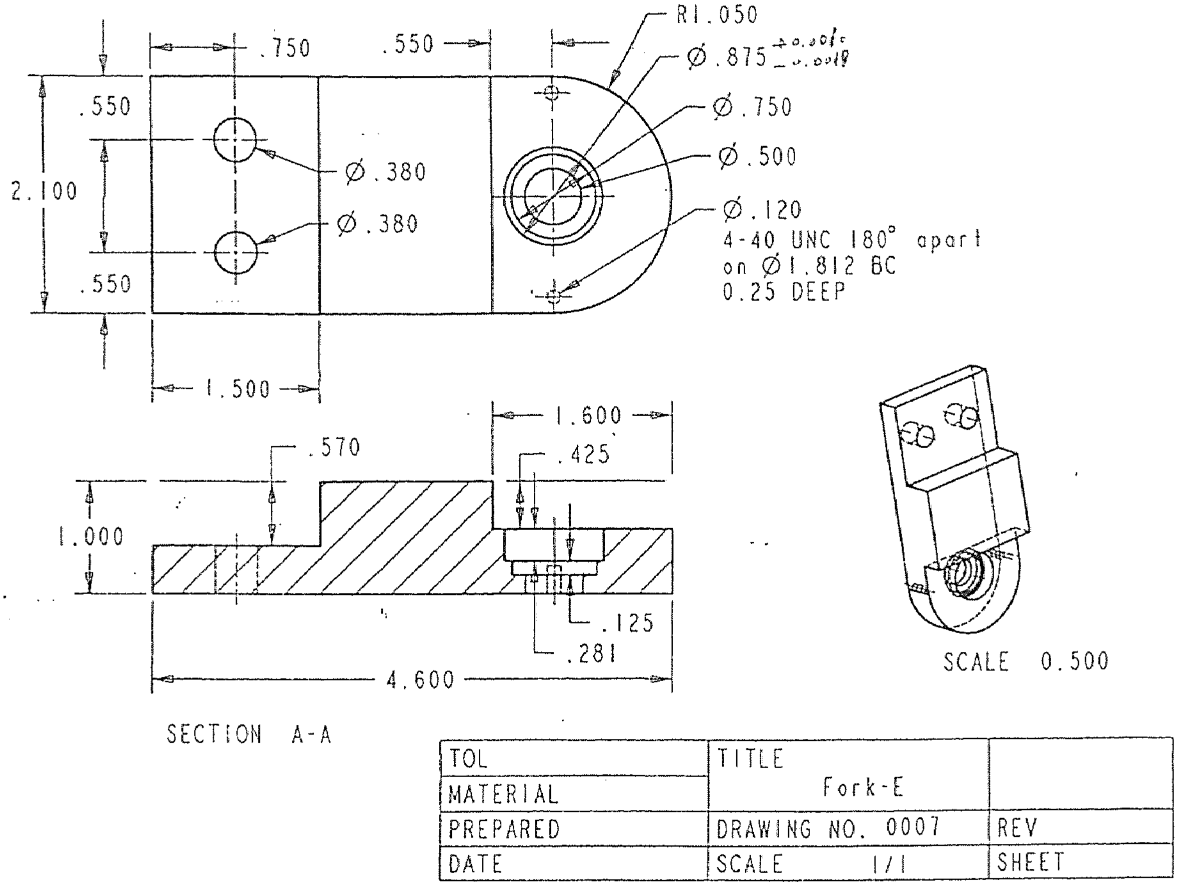
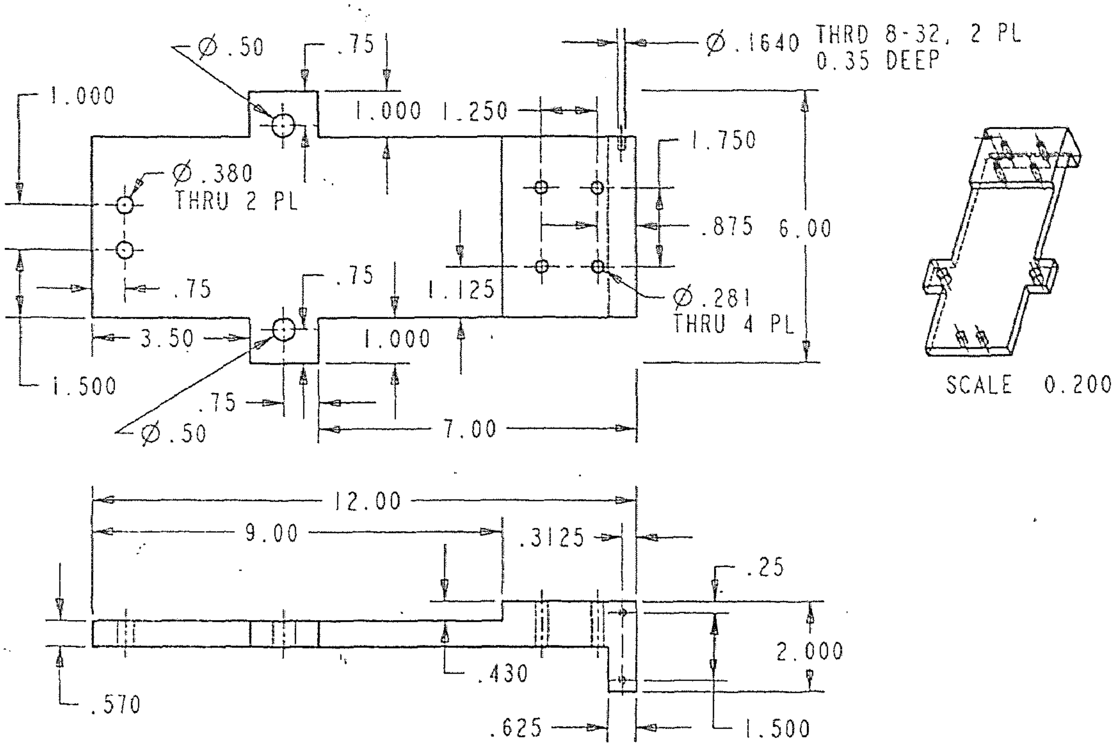
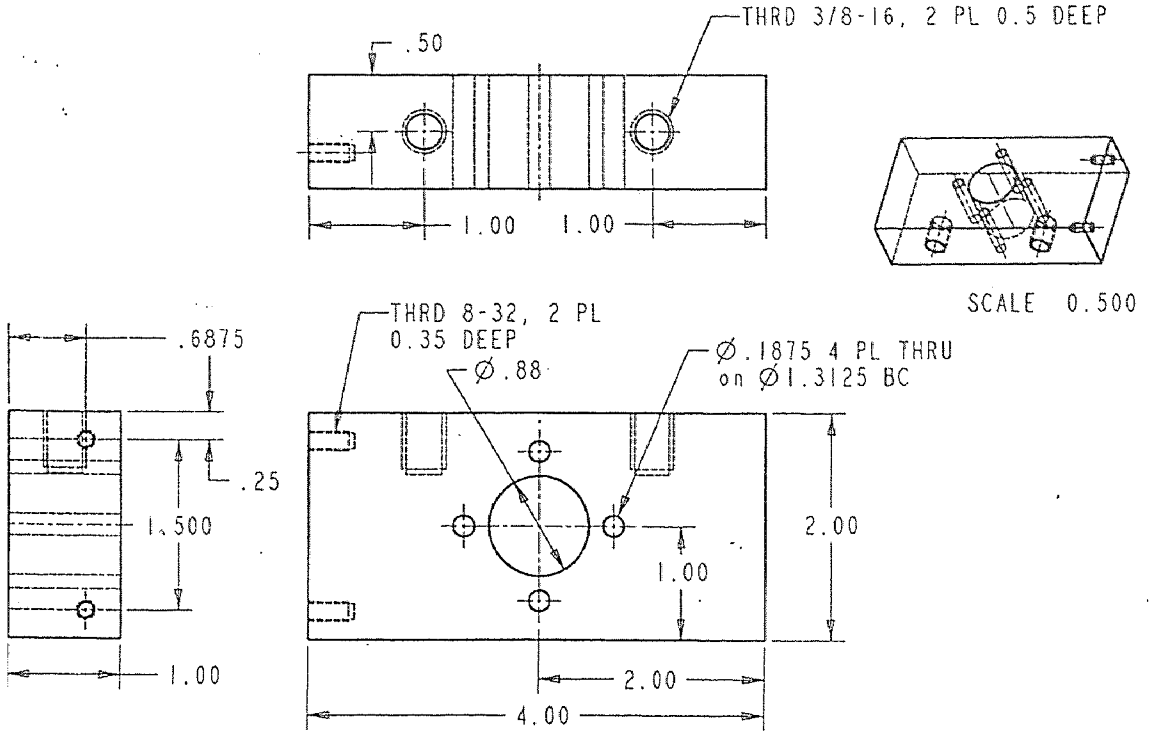


Figure A6 Side of fork where the encoder is attached



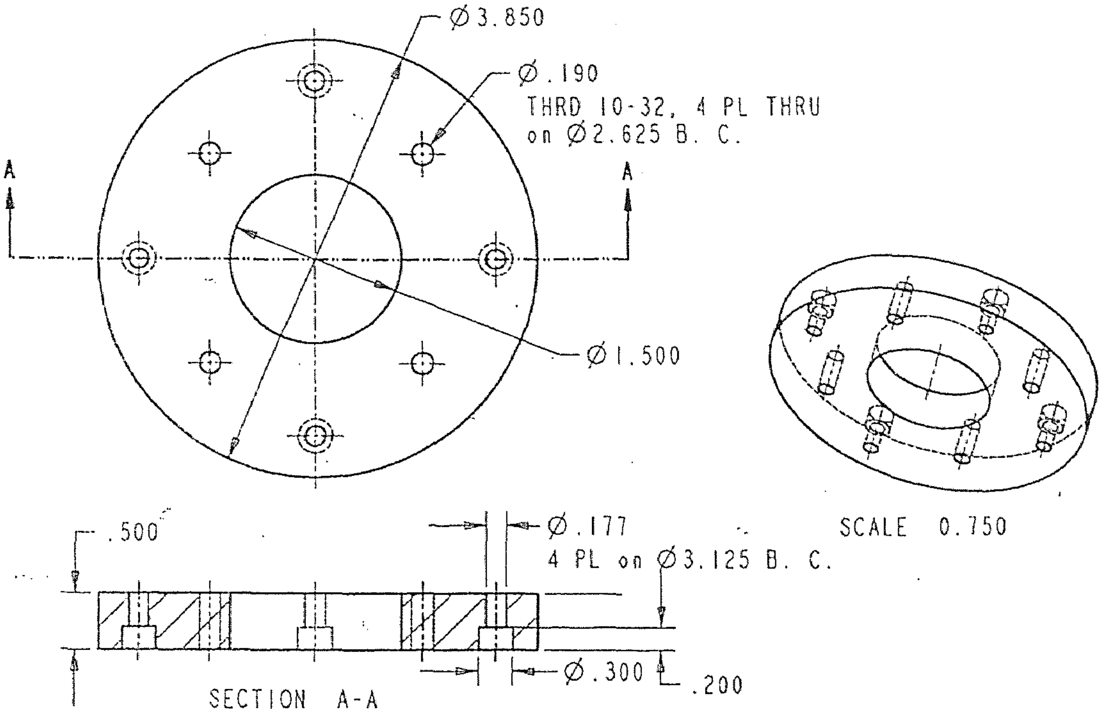
TOL	TITLE Junction	
MATERIAL		
PREPARED	DRAWING NO. 0008	REV
DATE	SCALE 1/0.4	SHEET

Figure A7 Junction Plate



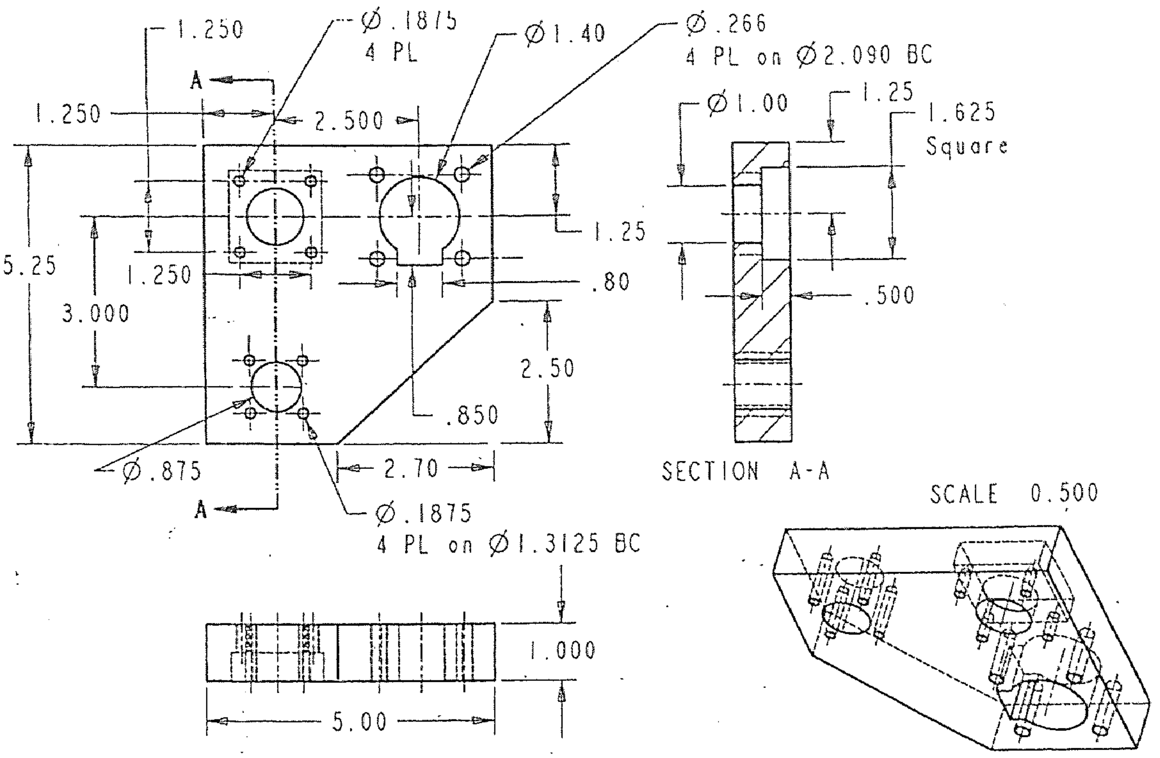
TOL	TITLE Block	
MATERIAL		
PREPARED	DRAWING NO. 0010	REV
DATE	SCALE 1/1	SHEET

Figure A8 Bearing Support - used to hold linear guide support and power screw support



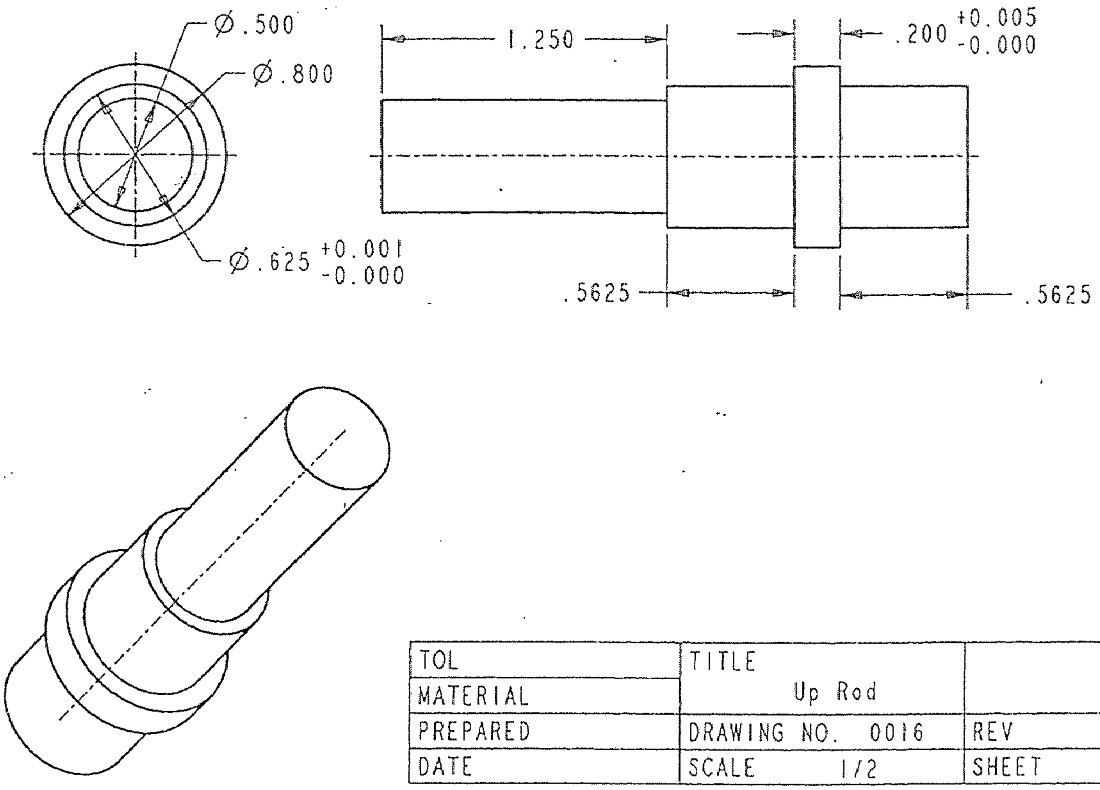
TOL	TITLE Motor Plate	
MATERIAL		
PREPARED	DRAWING NO. 0012	REV
DATE	SCALE 1/1	SHEET

Figure A9 Motor Plate - used to create a "hold" between the motor and power screw support



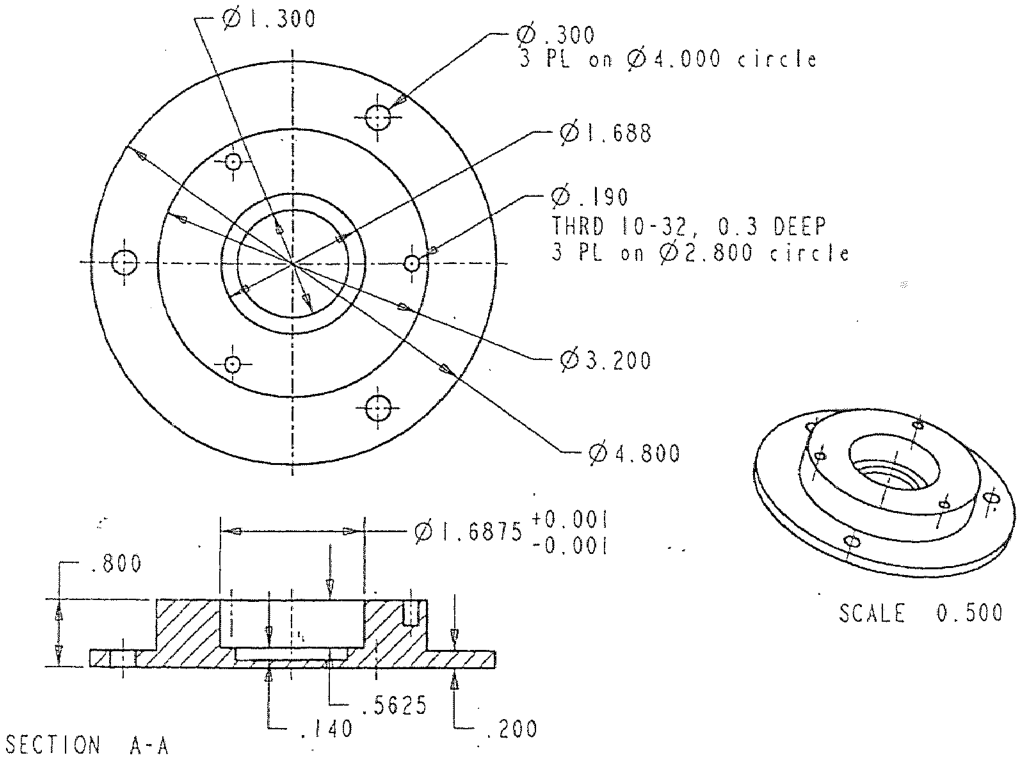
TOL	TITLE Piston Block	
MATERIAL		
PREPARED	DRAWING NO. 0011	REV
DATE	SCALE 1/0.5	SHEET

Figure A10 Piston Block



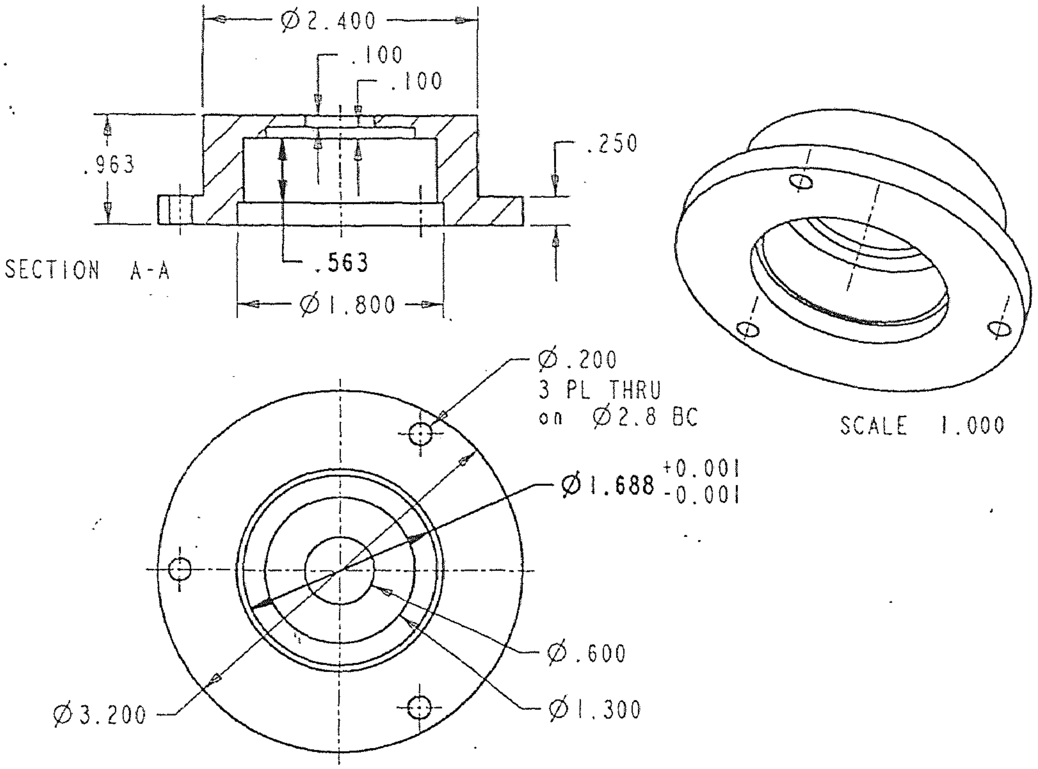
TOL	TITLE Up Rod	
MATERIAL		
PREPARED	DRAWING NO. 0016	REV
DATE	SCALE 1/2	SHEET

Figure A11 Top Joint Rod



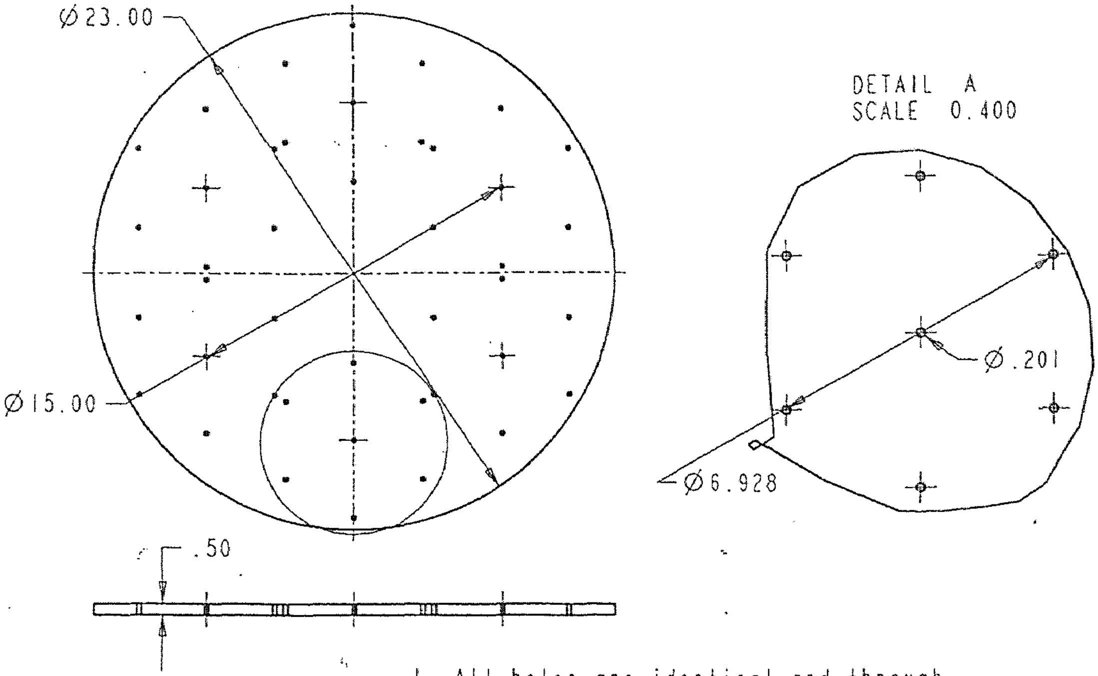
TOL	TITLE Up Base	
MATERIAL		
PREPARED	DRAWING NO. 0017	REV
DATE	SCALE 1/0.75	SHEET

Figure A12 Top Joint Base



TOL	TITLE Up Top	
MATERIAL		
PREPARED	DRAWING NO. 0015	REV
DATE	SCALE 1/1	SHEET

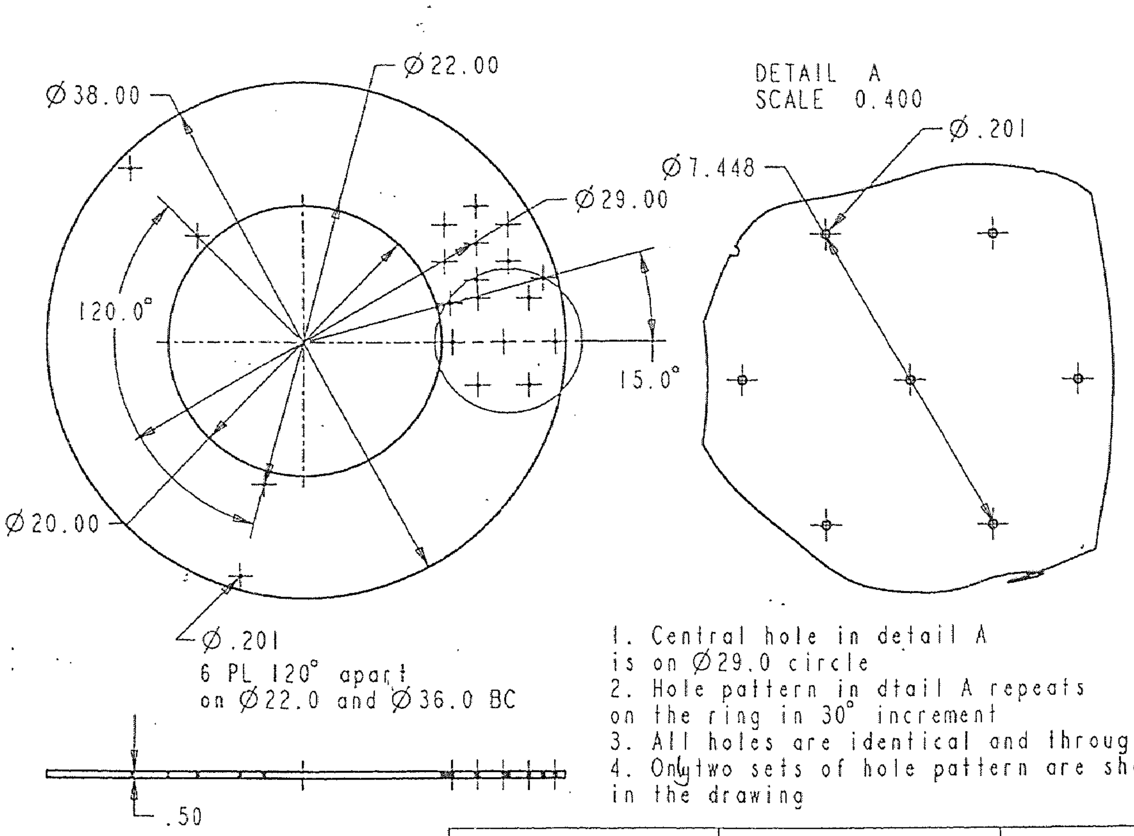
Figure A13 Top Joint Housing



1. All holes are identical and through
2. Central hole is detail A is on Ø15.0 circle
3. Hole pattern in detail A repeats in 60° increment

TOL	TITLE Top Plate	
MATERIAL		
PREPARED	DRAWING NO. 0020	REV
DATE	SCALE 1/0.2	SHEET

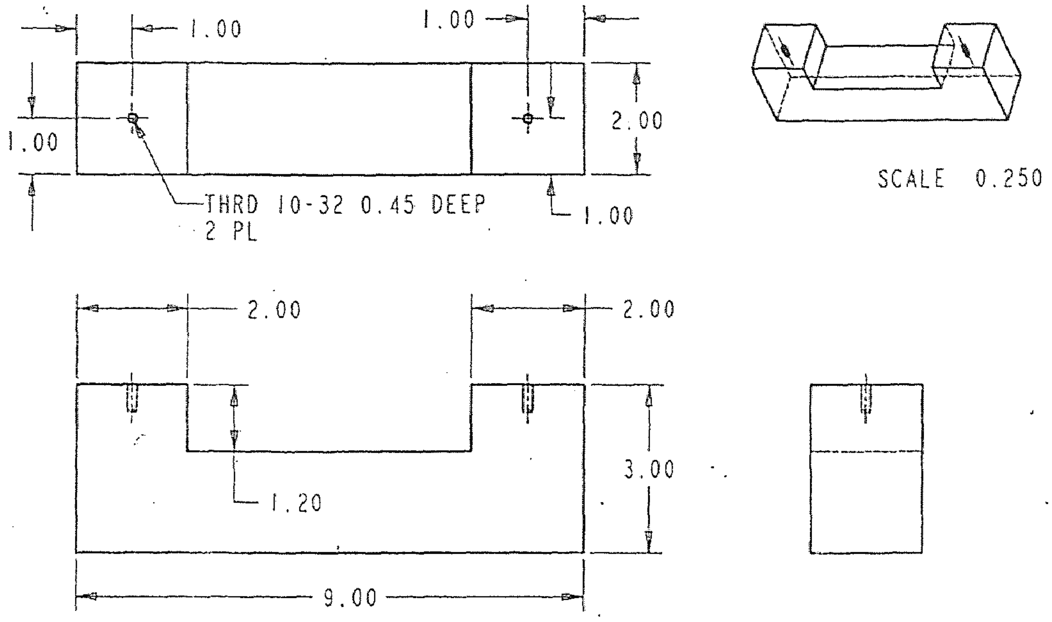
Figure A14 Top Platform



1. Central hole in detail A is on Ø29.0 circle
2. Hole pattern in dtail A repeats on the ring in 30° increment
3. All holes are identical and through
4. Only two sets of hole pattern are shown in the drawing

TOL	TITLE Base Plate	1 pc
MATERIAL		
PREPARED	DRAWING NO. 0019	REV
DATE	SCALE 1/0.12	SHEET

Figure A15 Base Platform



TOL	TITLE Foot	
MATERIAL		
PREPARED	DRAWING NO. 0021	REV
DATE	SCALE 1/0.5	SHEET

Figure A16 Base Platform Foot

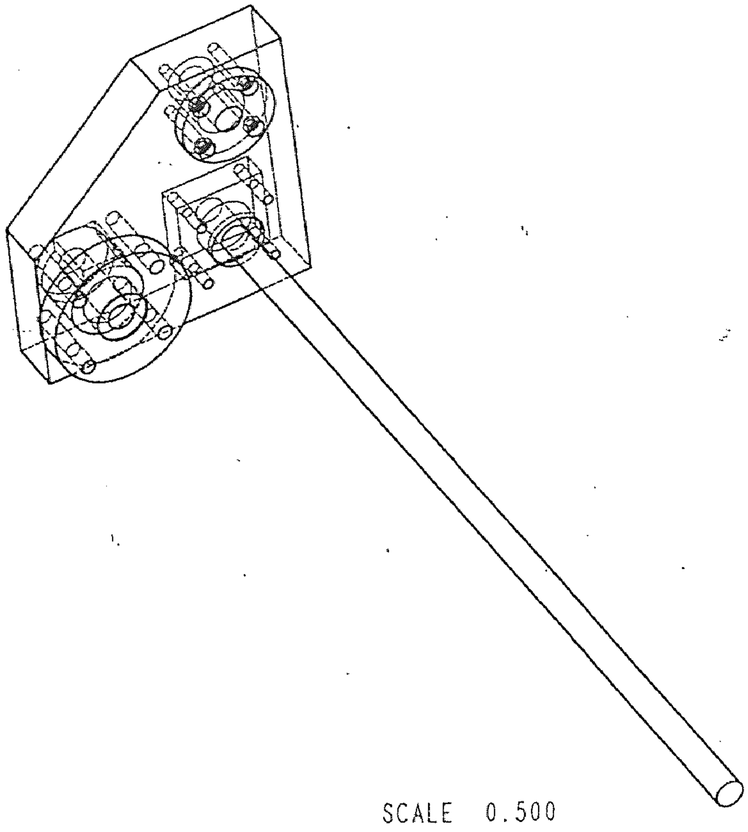


Figure A17 Piston Block Assembly

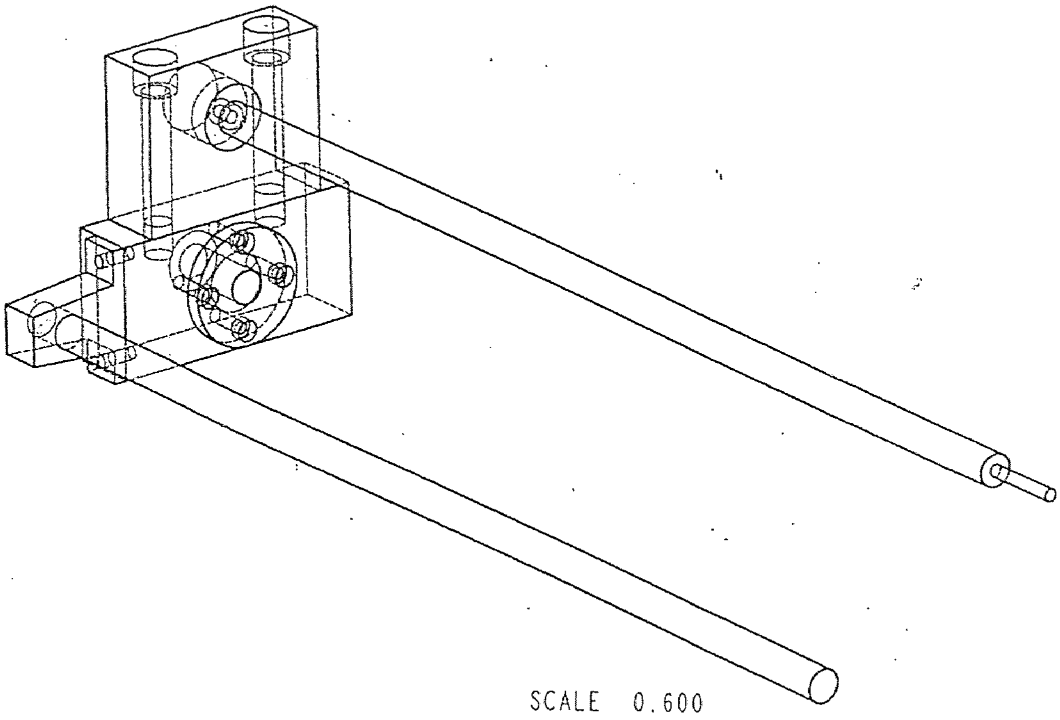


Figure A18 Bearing Support Assembly

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