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AUTONOMOUS SPACE PROCESSOR FOR ORBITAL DEBRIS (ASPOD)
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AUTONOMOUS SPACE PROCESSOR FOR ORBITAL DEBRIS ADVANCED DESIGN PROJECT IN SUPPORT OF SOLAR SYSTEM EXPLORATION

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Aerospace and Mechanical Engineering Department
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Abstract

This paper is regarding a project in the Advanced Design Program at the University of Arizona. The project is named the Autonomous Space Processor for Orbital Debris (ASPOD) and is a Universities Space Research Association (USRA) sponsored design project. The development of ASPOD and the students' abilities in designing and building a prototype spacecraft are the ultimate goals of this project. This year's focus entailed the development of a secondary robotic arm and end-effector to work in tandem with an existent arm in the removal of orbital debris. The new arm features the introduction of composite materials and a linear drive system, thus producing a light-weight and more accurate prototype. The main characteristic of the end-effector design is that it incorporates all of the motors and gearing internally, thus not subjecting them to the harsh space environment. Furthermore, the arm and the end-effector are automated by a control system with positional feedback. This system is composed of magnetic and optical encoders connected to a 486 PC via two servo-motor controller cards. Programming a series of basic routines and sub-routines has allowed the ASPOD prototype to become more autonomous. The new system is expected to perform specified tasks with a positional accuracy of 0.5 cm.

Introduction

The subject of orbital debris has been reaching the spotlight since SkyLab's degenerating orbit put the world on alert as to where the debris that survived reentry would touch down on Earth. These problems have not gone away and are currently affecting today's space missions, as was demonstrated when Discovery's crew in September of 1991 and Atlantis's crew in November of 1991 had to alter their orbits in order to avoid a piece of space junk that was on a trajectory that could possibly place the crew in danger. These events are a good indication of the growing trouble caused by orbital debris. Table 1 is a short outline of the types of problems caused by orbital debris [1].

Table 1: Several Problems with Orbital Debris

1. Loss or damage to satellites and spacecraft by collision with debris
2. Interference with astronomical observations on Earth and in orbit
3. Accidental reentry of satellites and other space hardware
4. Interference with scientific and military experiments
5. Spread of nuclear materials in orbit and on Earth
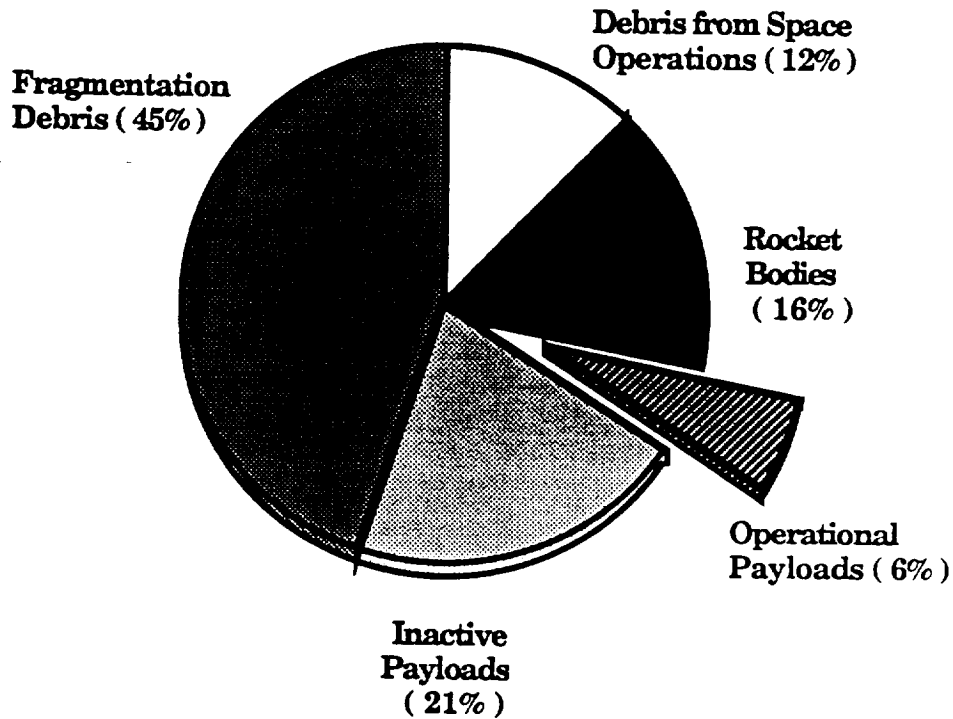6. Potential explosions of unused fuel

Presently there are over 7500 pieces of orbiting debris of sufficient size to cause a disaster similar to that of the Challenger. Furthermore, there are countless numbers of untraceable pieces of smaller debris that are capable of causing enough damage to a satellite to make it inoperable. The kinetic energy related to orbital debris is the significant problem. The table below is a representation of the possible effects from orbital debris collisions at a velocity of 10 km/s (22,369 mph) (i.e. kinetic energy) [2].

Table 2: Comparisons of Kinetic Energy of debris and Collision Effects

Particle Size (Diameter)	Effects
< 0.01 cm	Surface erosion
< 0.1 cm	Serious damage
0.3 cm at 10 km/s (32,630 ft/s)	Bowling ball at 60 mph (88 ft/s)
1.0 cm aluminum sphere at 10 km/s	400 lb safe at 60 mph

These small pieces of debris have also been responsible for small craters in the space shuttle's windows on several missions, thus requiring the windows to be replaced after each mission at a cost of approximately $50,000. Most recently, the new shuttle Endeavor received a small crater in one of it's windows which was determined to be caused by a small piece of debris. This is a direct result of placing satellites into orbit without considering what to do with them or their rocket boosters after their useful life has expired. Figure 1 is an illustration of the artificial orbital population [3].

Figure 1 Orbital Population (Dec. 1989)

Fragmentation
Debris (45%)

Debris from Space
Operations (12%)

Rocket
Bodies
(16%)

Operational
Payloads (6%)

Inactive
Payloads
(21%)

This figure shows that only 6% of all the artificial objects in orbit are functioning satellites. The rest of the objects are considered orbital debris. The table below shows the major elements of orbital debris [4].

Table 3: Elements of Orbital Debris

- Deactivated spacecraft or satellites
- Spent rocket stages
- Paint flakes
- Fragments of rockets and spacecraft
- Engine exhaust particles
- Spacecraft rocket separation devices
- Spent soviet reactors
- Intentional break-up of orbiting payloads

With the problems of orbital debris come many myths regarding the seriousness of the problems presented. Some such myths include:

1) The major problem posed by orbital debris is the inability to track accurately the trajectory of the smaller pieces. [This is in part true; the smaller pieces are the reason for concern. However, it must be

realized that the larger pieces through orbital collisions and explosions of excess propellant are the cause of the smaller pieces of debris.]

2) The problem of space debris will not be significant until the year 2000. [Why wait until the problem becomes serious in order to search for viable solutions? Furthermore, it can takes about 10 years to develop a space craft from conception to production, thus there is no better time to start than the present.]

3) The body of knowledge about orbital debris is not well defined; and thus more studies are needed to learn more about the problem. [This is an unfounded rumor. In fact, the majority of the larger pieces of debris are currently being tracked by the Space Surveillance Network (SSN) which is operated by Department of Defense. Also there are databases that have information about the large debris (i.e. trajectories, velocities, mass, geometry, etc.).]

Fortunately, students at the University of Arizona under the guidance of Dr. Kumar Ramohalli have been able to see through these myths and are now concerning themselves with a means to solve this problem. The concept of an Autonomous Space Processor for Orbital Debris is the answer to sweep up the problem of orbital debris. The two major goals of the ASPOD spacecraft are to deal with the orbital debris problem (by processing the trackable large pieces of debris before they have a chance of becoming small, untraceable projectiles that potentially could cause a lot of damage) and to utilize the resource (i.e. the debris) that is already in orbit (by using the materials from the debris to produce or build new device that will serve a propose). The goal of ASPOD is to process large pieces of debris. The following table shows the approximate number of objects and their total masses (see table 4) [5].

Table 4: Approximate Number and Size of Artificially-Made Orbital Debris

Object Size	Number of Objects	Percentage of Objects, %	Total Mass	Percentage by Mass, %
> 10 cm	7,000	0.2	3,000,00 kg	99.97
1 - 10 cm	17,500	0.5	1,000 kg	0.03
< 1 cm	3,500,000	99.3		

Although objects over 10 cm in size constitute less than 1% of the number of objects in orbit, they contribute to over 99% of the total mass of orbiting objects.

Another misconception is that in the vastness of space, it is virtually impossible to rendezvous with orbital debris and that the propellant requirements to do so are too great. This is not true. In fact a study conducted by the University of Arizona in 1989 identified several specific inclinations in which a majority of the large debris exist (see figure 2) [6].

Figure 2: Distribution of Orbital Inclinations
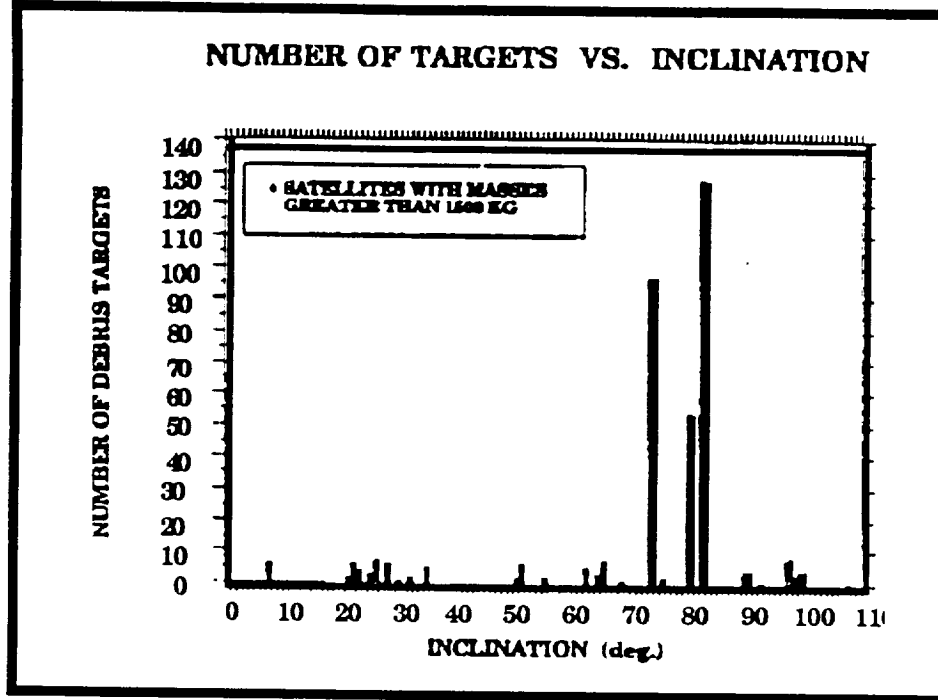
Mission feasibility studies have shown that one of the envisioned spacecraft could process at least five of the large pieces of debris with reasonable propellant requirements . This is accomplished by taking advantage of nodal regression differences and the use of classic Hohmann transfer [7].

ASPOD's Basic Mission Profile

The following is the overall mission scenario:

1. Launch from booster or Space Shuttle.
2. Use propulsion and programming to enter orbit and rendezvous with target debris.
3. Rendezvous with debris and use programming and one of two computer-controlled robotic arms to retrieve debris.
4. Programming selects the proper placement of second robotic arm to grip the piece to be cut off.
5. Both arms then move debris into the focal point of solar cutting device (solar cutter is an array of mirrors and Fresnel lenses).
6. After piece has been cut, the second arm places the piece in storage bin. The process (from 4 to 6) is repeated until whole debris is placed in storage bin.
7. Programming instructs ASPOD to rendezvous with next target debris (steps 3 to 7 are repeated until all target debris has been processed).
8. ASPOD has then three options depending on retrieved payload (i.e. orbital debris):

a) rendezvous with Space Shuttle where debris will be downloaded and return to earth. ASPOD will then be refueled and given new instructions and new target debris
b) rendezvous with future Space Station where debris will be downloaded and remanufactured for other uses
c) burnup on reentry into atmosphere.

This project was initiated in 1987 and has become an integral part of the Advanced Design Program at the University of Arizona over the past several years due in part to an increased interest in the problem of orbital debris and the continued funding of NASA/USRA. Moreover, the ASPOD project has been met with great support over the years from both the University of Arizona and the surrounding community, resulting in numerous appearances in both local and national newspapers and news broadcasts.

Progress

Since 1987, the ASPOD project has maintained a steady level of progress, each year enhancing the former years design along with incorporating necessary additional systems into the satellite to ensure that it will be truly be autonomous when completed. In this respect, the prototype (test-bed) has excelled from the basic concept of a debris retriever to that of an integrated machine capable of maneuvering a piece of debris with a robotic arm through a focal point of a solar array that has utilized a solar tracker to align itself with the sun in order to maximize its cutting potential.

Consistent with the USRA philosophy, a new group of undergraduates was involved with the ASPOD project this year. This years team consisted of 14 undergraduates and 2 graduate students with varying majors and interests. A complete list of these and past students can be found in the Appendix 1.

Arm

The ASPOD design group was tasked with designing a second robotic arm for the ASPOD satellite. Improvements that were required included a greater increase in reliability, a lighter structure, higher stiffness, drive system simplification, and a high degree of controllability. The arm's improvements must be accomplished while maintaining the original arm's degrees of freedom and rough link lengths.

The design group that undertook this project included Paul Chinnock, George Williams, Peter Wegner, and Curt Bradley. Paul Chinnock was responsible for the design of a light, rigid structure of high reliability, ease to manufacture. George Williams was charged with drive system design. The drive system was required to be light, consume low energy, be very reliable, and fulfill motivation needs for the loading conditions specified. Peter Wegner needed to engineer the control system with a closed loop feed-back control using encoders. In addition

the system needed to be light, very accurate, and to work in close conjunction with a remote computer for precise position control. Curt Bradley needed to design a support frame on which to mount the arm and straddle the mirror frame. Within the support frame design area, the arm's base needed to be positioned to maximize its usefulness.

The first semester consisted of brain storming and iterative paper-based design. The design (see figure 3 next page) was finalized and parts were ordered for manufacturing and assembling in the Spring semester. Throughout the manufacturing process, further simplifications were made to the individual pieces to shorten machining time. The entire two-semester project was packed with educationally rewarding experiences.

The arm is designed with linear ball screw-to-ball-nut drives for high efficiency, reduced stresses at the axles, simplicity, and lightness. The arm's structure is built of composite links and aluminum joints. The base is designed to travel a full 360 degrees of rotation and therefore uses a gear and chain assembly. Links are preloaded to increase stiffness. The arm's end has been designed to accept the arm end-effector.

The linear drives have preloaded ball nuts that eliminate play induced by wear and tear on the arm. The ball screw-ball nut linear actuator exceeds the first arm's drive system in reliability, reduced play, simplification, lightness, and reduced stresses. The arm's drive motors are DC brushless and offer torque for acceleration and deceleration for placement speed of 90 degrees per minute. The arm has been demonstrated at much higher speeds. Lagrangian dynamics was used to determine the torques required for all conditions. All three motors are the same and have 195 oz. of continuous torque.

The control system uses optical encoders to position the arm to an accuracy of 1 centimeter loaded with a 1 pound load and unloaded . A 486 computer with two three-channel control boards is used for control. The controller boards convert the computer's digital signals to analog signals for the motors. The boards' output signals are amplified to the DC motor's requirements for input by two amplifiers. The controller cards in addition to translating signals have built-in stability programming for set bandwidths. The channels on the boards each have position, velocity, and acceleration registers. The optical encoders offer 270,000 pulses for a joint's entire range of motion exceeding accuracy requirements.

The Base Support Frame has carbon-graphite composite links preloaded with centered bolts and joints made of aluminum. The structure exceeds strength requirements and stiffness specifications. The deflection under double the load requirement (2.2 lbs) and worst torque position is 6.35 mm including arm and base structure linked.
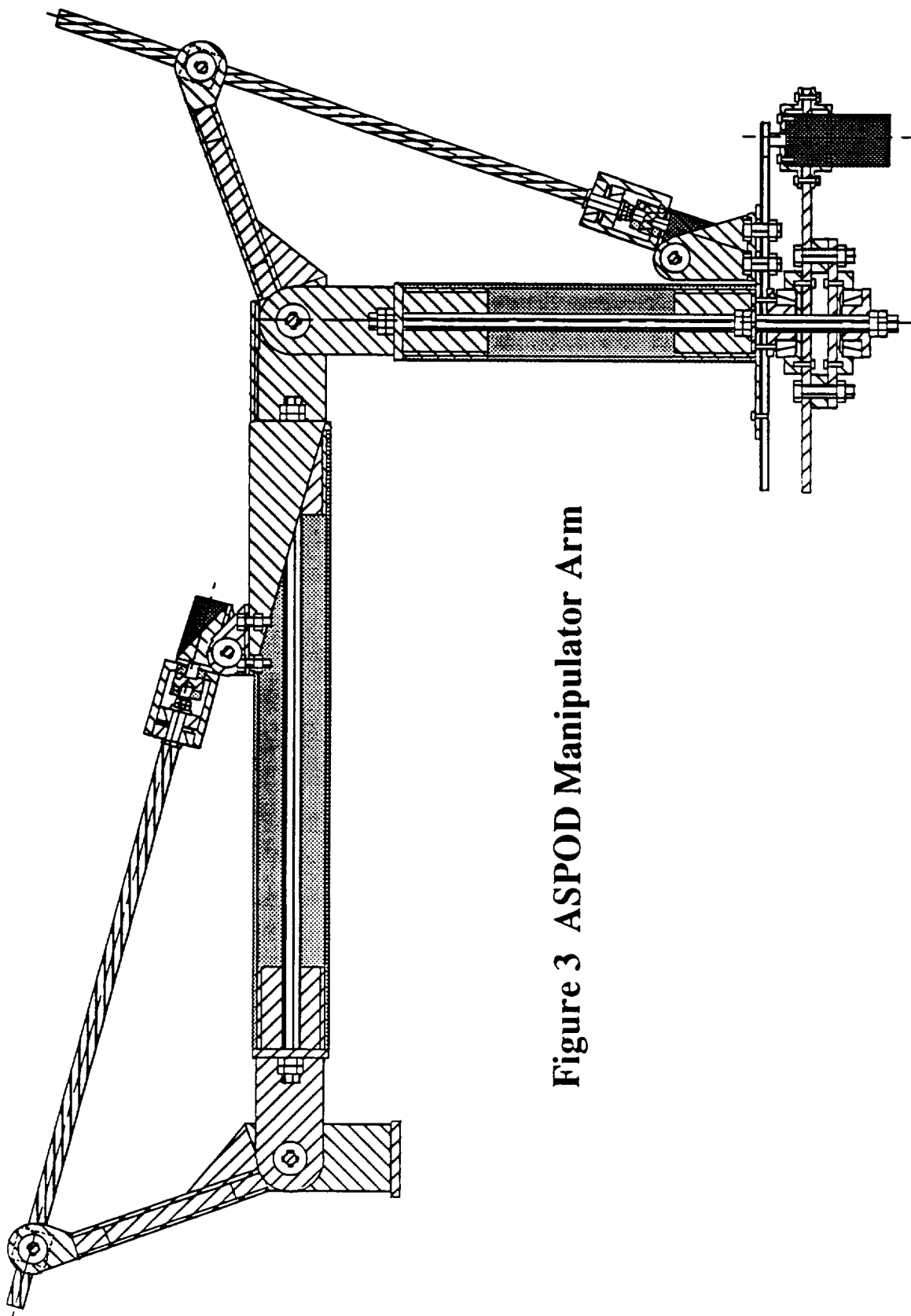
Figure 3 ASPOD Manipulator Arm

End-Effector

Operating in conjunction with the ASPOD arm is the end-effector. The end-effector was designed as part of the ground based working prototype for one of the twenty-first century's advanced space systems. The following were the original specifications to be met by the Autonomous Space Processor for Orbital Debris end-effector system.

GRIPPING ABILITY: The end-effector must be able to grip various sizes and shapes. It is proposed that it be able to pick up an object with a maximum weight of 1 lb. and that the jaws open up 5 inches.

DEGREES OF FREEDOM: The design will have three degrees of freedom. The gripper will open and close. The "wrist" joint will rotate and the "elbow" joint will be a pinned hinge joint.

MASS: A maximum total weight of 10 lbs has been set for the end-effector and its components. This will lower the torques it must overcome while being tested on Earth and decrease the weight that will need to be lifted to orbit.

SPEED: A suitable range for the operation of the effector will be from 1/16 to 3/16 (in/s). The wrist will rotate in the range of 2 to 8 revolutions per minute. The elbow joint will move as slow as necessary to keep acceleration at a minimum.

SENSORS: Encoders in joints will be used to relay rotation positions.

MOTORS: The end-effector and arm will be powered by 12-24V DC motors. Individual motor sizes will be determined by the torques they are required to produce.

COMPATIBILITY: The end-effector will be mounted on the robotic arm which is also under development. Cooperation with the robotic arm group will insure that the designs are compatible.

DRIVE SYSTEMS: A system of gears, drive screws and chains will be used to relay torques from motors to joints.

TOLERANCES: Because of the high degree of accuracy required, machining tolerances of 0.002 inches must be adhered to on all load bearing members.

Achieved Design Specifications
The exact specifications for the ASPOD end-effector system are shown below.

GRIPPING ABILITY: The end-effector is able to grip objects of various sizes and shapes. It produces a gripping force of approximately 8 pounds with a maximum opening range of 5 inches.

DEGREES OF FREEDOM: The end-effector design incorporates three degrees of freedom. The gripper opens and closes along a linear track. The "wrist" joint rotates more than 360 degrees in either direction. The "elbow" joint is a pinned hinge joint that moves through an angle of 220 degrees.

MASS: The end-effector weighs a total of 9.2 pounds. This meets the 10-pound limit set in the original design specifications.

SPEED: A suitable range for the operation of the hand will be from 1/16 to 3/16 (in/s). The wrist and elbow joints rotate between 6 and 8 revolutions per minute. This minimizes the inertial acceleration.

SENSORS: Magnetic encoders attached to the end of the motors are used to relay rotation positions.

MOTORS: The end-effector is powered by three motors. A 360 oz-in 12-V DC motor powers the elbow joint. The rotational joint is run by a 670 oz-in 12-V DC motor. And a 200 oz-in 24-V DC motor powers the gripper.

COMPATIBILITY: The end-effector is attachable to the parent robotic arm, which in turn works with the rest of the systems on the ASPOD vehicle.

DRIVE SYSTEMS: For all three degrees of freedom, power is transferred from the gear motor through shaft couplers and drive shafts. For the gripper and bending joints, a series of gears is used to relay power. But the rotational motor transfers torque by direct drive.

Beyond the basic quantitative constraints, the design team also followed a set of qualitative constraints or goals. The main concepts adhered to the design are efficiency, reliability and flexibility. To make the design "efficient" the prototype is representative of an uncluttered "common sense" assembly. The reliability of the end-effector components implies protection from failure and accidents, but also easy repair if an accident should occur. Finally, since the ASPOD system is still in the optimization stage of development, the end-effector is designed to be flexible with respect to changing performance needs. The result of careful design and analysis is shown in Figure 4 on the following page. From this figure several general design features are can be seen as examples of efficiency, reliability, and flexibility.

Notice the efficient layout of the components of the design. The twisting joint is situated before the bending joint. This arrangement better utilizes the capabilities of the bending joint. If the position of the joints were reversed, the bending joint would be redundant with the rest of the arm joints. Also the selection of compact, high torque gear motors manufactured by "Micro Mo" allowed the designers to place the motors at each joint inside the aluminum support tubing. The internal motors are protected from the environment, while the short distance to the applied joint eliminated the need for complex drive systems. Along with the motors, all of the gearing and most of the wiring are enclosed for protection. The result is an efficient, uncluttered design.

The design layout also contributes to high reliability. High precision fits and internal mountings reduce gear wear while protecting parts. Since the motors are mounted to the joints in assemblies of simple parts, the joints and parts are easily disassembled and repaired in case of a problem.

The design of the assemblies also allows for easy redesign or configuration changes. This flexibility reduces the need for major redesign iterations. The linear gripper utilizes removable fingers on the jaws. This allows jaw redesign and implementation in a matter of minutes rather than longer, more costly periods of time. In addition, since the motors are in single assemblies with their driven joints, switching from the twisting joint first, bending joint second configuration to the opposite arrangement is accomplished in half an hour.

Figure 4: ASPOD End-Effector
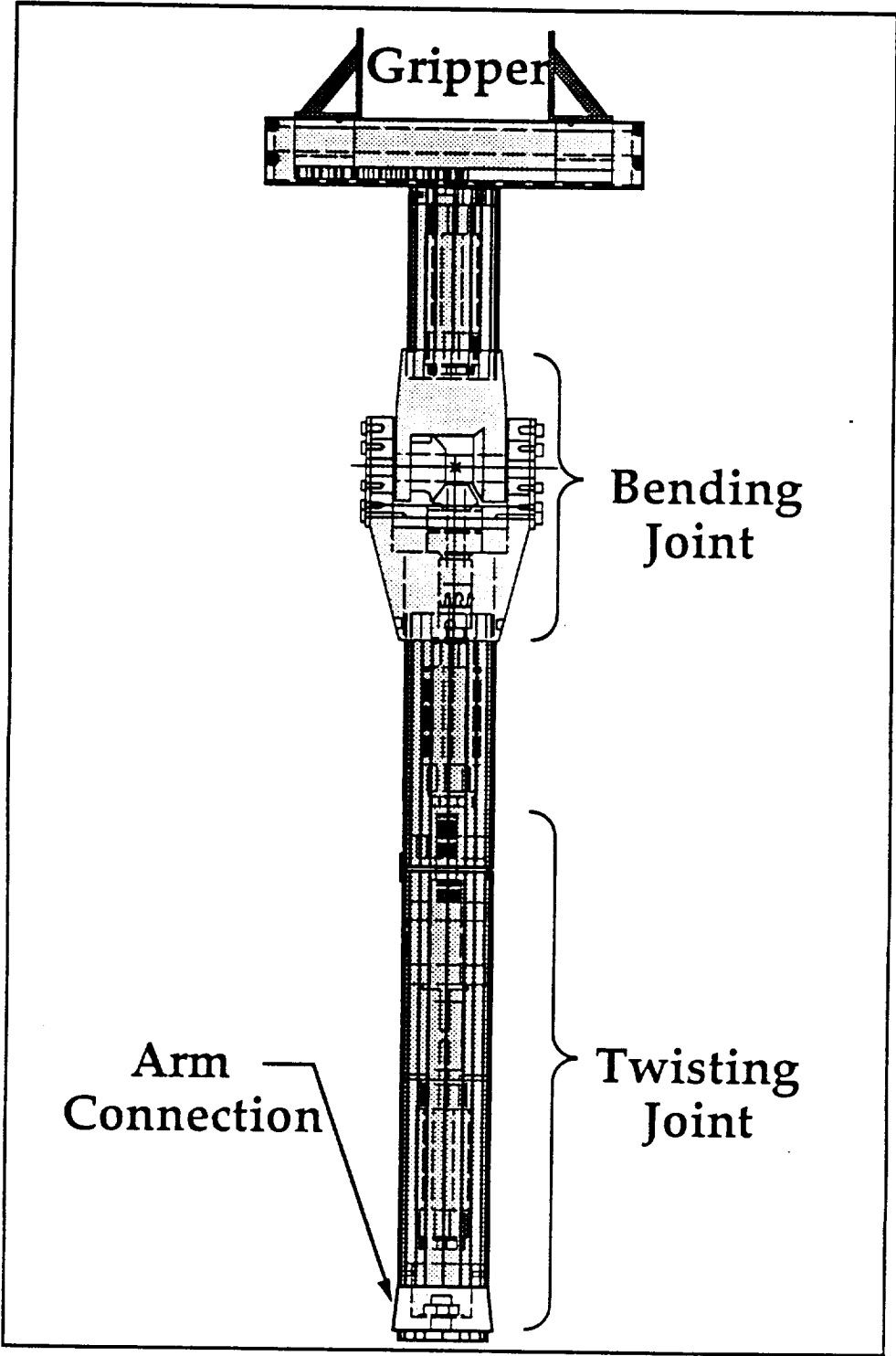
One of the most dramatic aspects of the flexible design is the control system. The control system allows the operator to program a desired output into the terminal. The computer-based control system then calculates the specific system requirements, provides the system commands, and moves the system to the desired state while checking for errors. This process starts at the computer terminal. The user specifies a move using one of the programming methods available. The controller card inside the computer converts the logical command to a voltage command and sends the command to the appropriate axis via the connection card. The power amplifier converts the output signal to an appropriate motor input command signal. While the motor is in a control mode, the controller card reads the encoder output, comparing the output to the desired position. The controller card will move the motor to the desired position and keep it there until another command is given. The major components used in the control system are the actuators, the feedback sensors, the interface hardware, the controller card, and the computer-based instructions.

The actuators used for the arm and end-effector are Pittman and Micro Mo high torque gear motors. The motors used for the bending and the twisting joint require a twelve volt power output, while the gripper and arm motors require twenty four volts. The controller card offers a convenient method for adjusting the output signal. Gain and offset potentiometers are supplied for each axis and can be adjusted for a desired output.

In the ASPOD Arm-Effector design, the actuators are all DC motors requiring an analog output from the controller card. Attached to the motors are the feedback sensors. In the case of the three Micro Mo motors, the feedback sensors are magnetic encoders. Magnetic encoders were chosen because they were cheaper and more readily available as an integral package from the manufacturer. The Pittman motors utilize BEI optical encoders reading off the output shaft. The encoders provide two square wave signals 180 degrees out of phase which are decoded in to a number of counts per motor revolution. The position of each joint is then determined from a reference. This information is then used to command the motor.

In the control system the encoders and the motors do not interface directly to the controller card. First, the controller connects to a wiring interface card which in turn connects to the power amplifiers and the encoders. The interface card was supplied by Servo Systems with the controller card. The power amplifier circuits were constructed by the design team.

The power amplifier circuits were designed around a National Semiconductor LM12C operational amplifier. The circuit involves two power supplies powering a common bus. Each power amplifier circuit draws power off the bus to distribute to the appropriate motor. Each power amplifier circuit is interfaced between a motor and a control axis on the controller card.

The controller card is the main processor of the control system. The Omnitech Robotics MC-3000 card is a 3-axis controller card designed around three Hewlett

Packard HCTL-1000 motion controller IC chips. Two MC-3000's are sufficient for the six axes of control required for the arm and end-effector. Although several control modes are available, the trapezoidal profile mode is being used. Trapezoidal mode is ideal for robotic applications because it offers reasonable velocity and acceleration control with positioning control. An acceleration / deceleration and a maximum velocity are specified by the user. When the card receives a position command, it accelerates the motor until maximum velocity is reached or until the motor is halfway to the desired position. Then the motor is decelerated at the programmed deceleration. After the motor is decelerated, the card checks for position, and adjusts to the programmed value.

Although a decoding program was provided by Servo Systems, a better user interface was desired. A goal was to have a program that fulfilled three objectives. The program should be easy to use, powerful, and, of course, should be able to run the robot arm through fixed routines. Originally the "C++" programming language was chosen for the program. However, it was later decided to use "Turbo Pascal 6.0". Turbo Pascal is easier to learn and compiles more quickly significantly lessening development time. Turbo Pascal also came equipped with extra libraries for windows and mouse interface programming. These libraries were not included with C++.

To make the control program easier to learn and use, the program was designed to be menu; windows; and mouse-driven. A windows-based menu-driven program arranges methods and commands in a logical system. This interface allows new users with little or no computer experience to learn program basics in less than an hour. In the case of the menu commands, pressing the "Alt" key and the highlighted letter will open that sub-menu. Once the sub-menu is open, a command in that sub-menu may be executed by pressing the key corresponding to the highlighted letter. An alternate, easier method for choosing commands is by using the mouse. With this method, the mouse is used to move the cursor to the desired sub-menu, the right mouse button is "clicked" (depressed and released) opening the sub-menu. Then the right mouse button is clicked while the cursor is over the desired menu item. This procedure will execute the desired menu command. Some commands offer yet an additional method for their use. When each sub-menu is open, some of the commands have key sequences adjacent to them against the right hand side of the box. These key sequences are known as "Hot-Keys". By executing the Hot-Key sequence on the keyboard, the desired command can be effected without having to use the menus. Within this structure, three general control methods are available to adapt to the varying needs of the operator. These methods are a menu-executed trapezoidal command, a programmed set of routines, and direct keyboard or "hand " control.

By using the mouse or keyboard commands to go through the menus the operator can executed trapezoidal command. Trapezoidal command implies that the maximum velocity and the acceleration / deceleration are specified by the user. When this method is used the position versus time profile is in the shape of a trapezoid. The menu-executed trapezoidal command is advantageous when testing moves in order to build a routine. To see what will happen when a command is executed, enter the test values and execute. If the effect is not

desired, return the arm to the original position and try again. By testing commands like this the user can come up with a programmed routine.

Once the user compiles enough commands, the full featured file editor can be used to construct a command file. A command file is constructed by placing the necessary commands (one per line) in a list with any needed values on the line following. To show how these commands might be used, an example routine is shown below.

```
set_base
776
reset
clr_act_pos
set_gain
10
set_zero
240
set_pole
40
set_timer
40
set_max_vel
127
set_accel
70
set_final_pos
10000
trap_mode
delay
2000
set_base
778
dac
255
delay
2000
dac
127
reset
set_base
776
reset
quit
```

The routine shown above operates the twisting joint of the end-effector and the gripper. After setting the zero, pole, gain and other parameters, the twisting joint will turn 10,000 encoder counts at max velocity while the program delays for 2000 units (about 400 units per second). Then the gripper will close at full voltage for another 2000 units of delay. Finally the gripper voltage will be set back to zero,

and both axes will receive a hard reset. Routines like this are easy to design and test using the file editor inside the controller program.

A final alternate to trapezoidal commands and command routines are the straight keyboard commands. Occasionally, the trapezoidal command mode is not the most convenient method for moving the arm. For this reason a set of "Hot-Keys" has been assigned to positive, negative, and zero voltage out commands for each axis. A list of these commands is located under the <u>Commands</u> menu. To move an axis, the user hits the "escape" key until the "All axes have been reset" message is displayed. Then the Hot-Key sequence corresponding to the desired motion is hit. The joint should move. Once the axis has moved to the desired point, the user hits the home key to stop the motion. The home key will only stop the last axis to be activated by a voltage out command.

Figure 5: Robotic Arm, Support Frame, and End-Effector Configuration

Arm

End-Effector

Support Frame

Mirror Array
and Frame
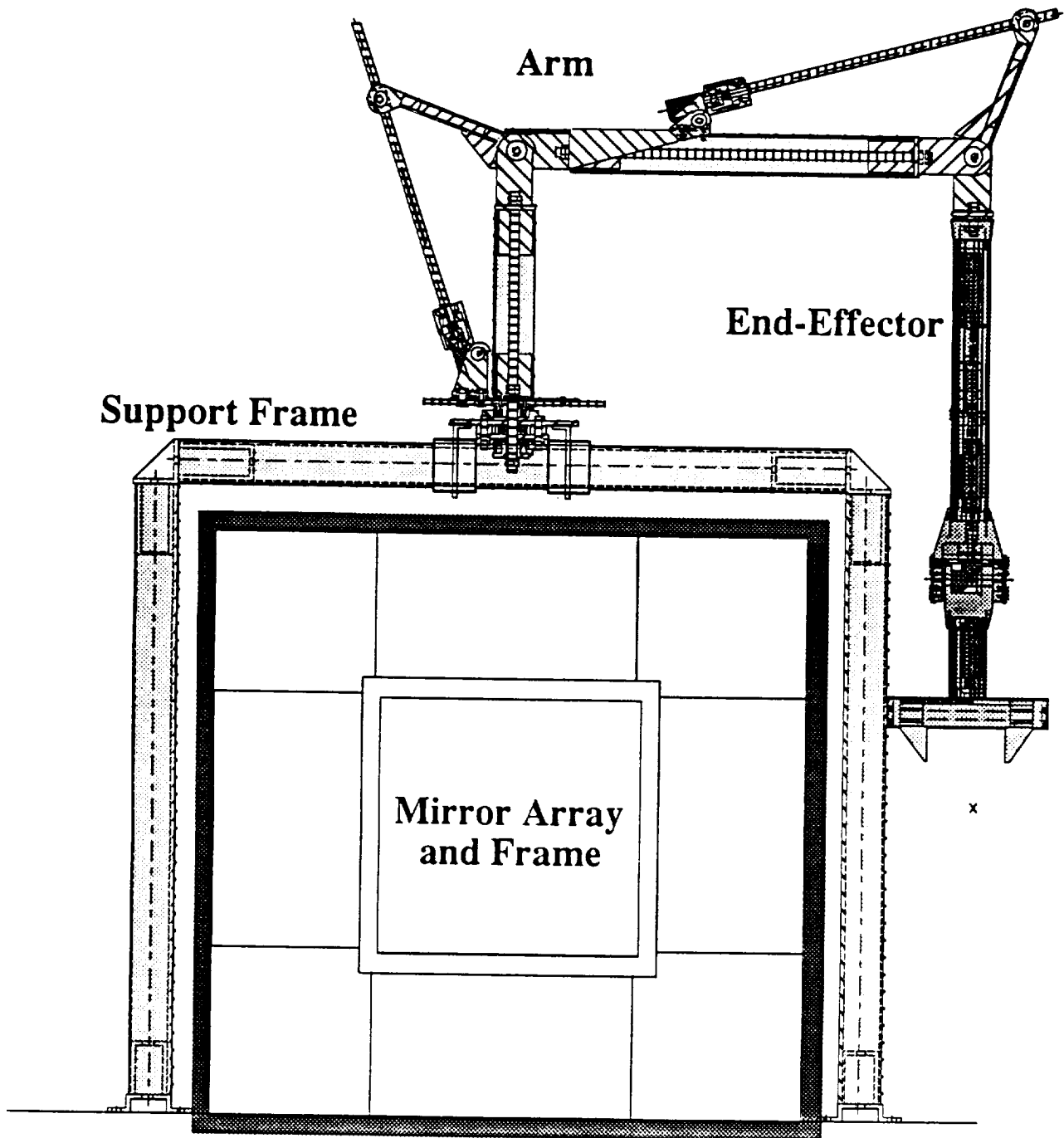
Conclusion

The progress of ASPOD is highly encouraging with several large steps made in both the integrated system and the overall design approach. One major advancement in the development is an additional robotic arm which is capable of working with the existing arm in order to accomplish the tasks that are needed in the removal of orbital debris. This arm is built with a more stable linear drive system and the use of composites as an effort to decrease weight of arm itself. The main characteristic of the end-effector design was that it incorporated all of the motors and gearing internally, thus not subjecting them to the harsh space environment. Furthermore, a control system was developed in order to control the arm and end-effector. The total configuration of the arm, support frame, and end-effector are on the previous page (see Figure 5). More detail information on the arm configuration and the end-effector configuration can be found in appendix 2 and 3 respectively.

The future plans are to control both arms in tandem from a computer in order to move the debris into the focal point of the solar cutter. In this respect, a computer code is being written such to tell the arms to perform certain functions with a single command from comm-linked operator.

References

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3. Orbiting Debris, A Space Environmental Problem, Office of Technology Assessment, September 1990, p2.

4. Orbiting Debris, A Space Environmental Problem, Office of Technology Assessment, September 1990, p2.

5. Space Debris a Potential Threat to Space Station and Shuttle, General Accounting Office Report, April 1990, p9.

6. Ramohalli, Kumar, et al., Advanced Design For Orbital Debris Removal in Support of Solar System Exploration, USRA Summer Conference, June 1991, p2.

7. Ramohalli, Kumar, et al., Advanced Design For Orbital Debris Removal in Support of Solar System Exploration, USRA Summer Conference, June 1991, p2.

Appendix 1

From Sept. 1987 to June 1992
> 60 - students, ranging from high school to graduate students have participated in the ASPOD program at University of Arizona.

Student Participation:

1987 - 1988

Graduate Students: David Campbell, Scott Reid

Undergraduate Students: Donald Barnett, Bryan Cindrich, Steve DiVarco, Catherine Dodd, Velda Dykehouse, Robert Flori, Reid Greenberg, Joseph Manning, Jim Matison, Ruzila Mohkhirhadi, James Poon, and Zenophen Xenophontos.

1988 - 1989

Graduate Student: David Campbell

Undergraduate Students: Jeff Brockman, Bruce Carter, Leslie Donelson, Lawrence John, Micky Marine, Dan Rodina.

1989 - 1990

Graduate Student: David Campbell

Undergraduate Students: Dan Bertles, Micky Marine, Ramon Gutierrez, Joseph Huppenthal, David Nichols, Mohamed Saad, Carlos Valenzuela.

1990 - 1991

Graduate Student: Micky Marine

Undergraduate Students: James Bartos, James Colvin, Richard Crockett, Kirby Hnat, David Ngo, Jennifer Putz, James Shattuck, Lee Sword, Sheri Woelfe.

Pre-University Students: Angela Mcfadden, Jennifer Hamilton, Brenda Lundt.

1991 - 1992

Graduate Students: Dominique Mitchell, Brett Taft

Undergraduate Students: Curt Bardley, Sheila Caoile, Paul Chinnock, Greg Hart, Todd Jacobson, Bjoern Kutz, Dave Lye, Matt McCutchen, Angela Mcfadden, Ted Parvu, Mohamed Saad, Glen Sonnenberg, Peter Weginer, George Williams.

Pre-University Student: William Dalby.

Appendix 2

ASPOD MANIPULATOR ARM
FINAL DESIGN REPORT

For

The Autonomous Space Processor for Orbital Debris (ASPOD)

Submitted To:

Prof. Kumar Ramohalli

Prof. Karl Ousterhout

AME 412 Faculty and Senior Advisors

May 5th, 1992

<u>Group Members</u>

Project Leader: Paul Chinnock

Curt Bradley

George Williams

Peter Wegner
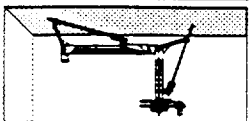
A.S.P.O.D.

APPENDAGE ENGINEERING INC.
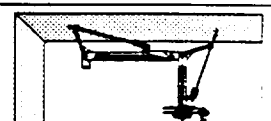
ASPOD Manipulator Arm

Table of Contents

A.S.P.O.D.

APPENDAGE ENGINEERING INC.

INTRODUCTION

Space debris has been increasing in quantity throughout the decades of space travel and has now begun to threaten future space development. According to a report by the General Accounting Office [2], space debris imposes a great threat to the future space station and continued space shuttle flights. The University of Arizona in 1989 found that there were 386 objects in Earth orbit that were 1500 Kilograms or larger in mass. The objects identified will maintain their orbits past the year 2000. Space debris includes dead satellites, rocket boosters, shielding and even human waste. These large pieces of debris will eventually fall to earth, but they will maintain their orbits for a long of time. If the orbital debris does fall, many pieces will not burn up upon reentry into the earth's atmosphere and will cause significant damage if they strike land. Because of the tremendous velocities involved, orbital debris of a small mass can cause catastrophic damage. A 25 gram object in orbit will have the kinetic energy of a 3000 lb automobile travelling at 60 mph [1]. The larger pieces of debris can be tracked by ground based sensors, but if two larger objects strike each other, the smaller debris resulting from the collision would be untrackable and therefore much more dangerous. The large pieces of debris that exist now must be processed soon, before the problem makes orbital flight too dangerous.
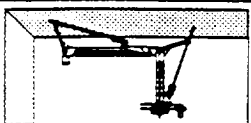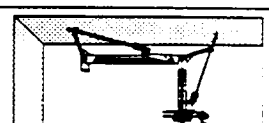
The Autonomous Space Processor for Orbital Debris (ASPOD) is designed to economically remove debris from orbit [3]. The robot arm this group has designed will grapple orbital debris and in conjunction with another arm will maneuver the object into the focal point of a solar powered cutting beam. The beam will cut the debris to more manageable sizes for possible use on the ASPOD satellite for additional light gathering capability or for such needs as increased power generation. Unrecycleable processed debris will be dealt with in one of three different manners; it will either be placed in a storage bin, sent into the atmosphere for safe burn up, or be placed into a ocean splash-down trajectory if the material will not burn up upon reentry.

The problems the design group solved include the challenge to make an arm with the same dimensions and degrees of freedom as that of the existing arm, to make the structure lighter, more reliable, maximize its usefulness by optimal base placement, meet all the specifications placed on the existing arm, and provide the capability to control the arm using computer software.

Reductions in the weight of the arm will increase the payload capacity for other desired hardware on the satellite. The position sensors will allow for remote operation or in the future, artificial intelligence control. Reliability will prevent the ASPOD from becoming another broken and dead satellite to avoid. The
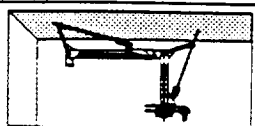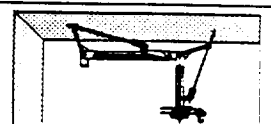
number of degrees of freedom and the general geometry of the new arm must stay the same or be similar to the old arm so that the amount of work needed for generating the control software is minimized and there is redundancy between the two arms so that the old arm can be replaced by the new if desired.

A successful solution to the orbital debris problem will greatly reduce the chances of orbital debris inhibiting space travel in the future.
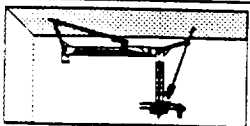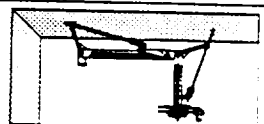
PROBLEM DEFINITION

The ASPOD Manipulator Arm Design Group has designed a robot arm that maintains the original arm's general linkage lengths and degrees of freedom while engineering in controllability, reliability, a lighter structure and optimal placement.

TECHNICAL SUBPROBLEMS

An efficient solution to the problem defined in this paper was addressed in the following technical areas;

1. Manipulator Arm Structure
2. Mounting and Positioning of Manipulator Arm
3. Control and Sensor Interface
4. Power System and Drive Mechanisms.

Each person from the group was responsible for one of these specific areas in developing the second manipulator arm for the ASPOD project.

The development of the manipulator arm structure was the responsibility of Paul Chinnock. The problem in this area was to design a strong and rigid arm structure that was as light as possible. This design included all the bearings, braces, and connections required to complete the manipulator arm. The weight was optimized to reduce the cost of orbital placement, because the launch cost for an object in orbit increases dramatically as the object's weight increases. Research was done in the area of material selection where the factors of weight, cost, reliability, and ease of manufacture were very important.

Curt Bradley concentrated on the problem of mounting and positioning of the arm. The arm is rigidly mounted to the ASPOD satellite in a position that will optimize the capabilities of the arm. The arm has to be able to reach out and grab a moving object and maneuver that object into the focal point of the mirrors. The arm is placed in such a manner that it will be able to attach a prespecified

piece of material onto the ASPOD satellite in order to improve it's own performance or it will place that object in a specified location for disposal. The mount or foundation frame is strong and reliable. The mount was optimized for light weight thereby reducing the overall weight of the satellite.

The design of the drive and power system was directed by George Williams. The problem was to design a system to drive the manipulator arm. The drive system had to be light weight. The drive system had to have a fairly low power requirement. The drive system must manipulate a 1500 kg satellite, at full scale operation. The drive system had to move at a rate that did not cause unacceptable stresses on the arm.

The control system of the manipulator arm is the responsibility of Peter Wegner. A closed loop servo system is used as the basis for stable control of the arm. This system uses digital control provided by motion control cards. Encoders are mounted as dictated by the control system requirements. These encoders are light weight and accurate. The control system enables the robot arm to be manipulated from computer without direct human intervention. This system moves the arm with smooth, precise movements.
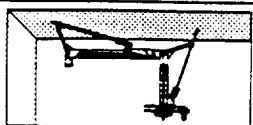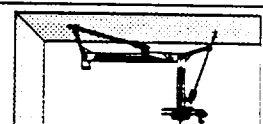
Milestone Chart, CPM Diagram, and Work Plan

DESCRIPTION OF MAJOR TASKS

A) <u>Define Need</u>: This is the problem to be solved

B) <u>Determine Limitations</u>: Determine the design restraints, cost considerations, weight, size, and time limitations.

C) <u>Develop Specifications</u>: Determine tolerances, torque needed, mobility of arm, strength of chassis, etc.

D) <u>Conceptualize Designs</u>: Suggest different solutions to the problem.

E) <u>Trade Off Studies</u>: Determine the advantages and disadvantages to each of the suggested designs.

F) <u>Stress Analysis</u>: Perform a stress analysis on each of the suggested designs.

G) <u>Feasibility Analysis</u>: Determine the designs that meet the required specifications and are within the limitations.

H) <u>Select Concept</u>: Select the final concept from the suggested concepts.

I) <u>Optimize Concept</u>: Improve upon the concept design.

J) <u>Develop Final Design</u>: Finalize upon the concept improvements.

K) <u>Design Freeze</u>: The design is no longer improved at this point.

L) <u>Make Detailed Drawings</u>: Produce drawings for fabrication and assembly of the prototype.

M) <u>Order Parts</u>: Raw material and specific parts are to be ordered.

N) <u>Fabricate Parts</u>: Use machine shop and other sources to produce parts that need to be customly made or modified.

A.S.P.O.D.

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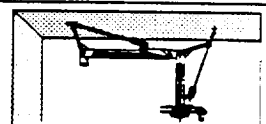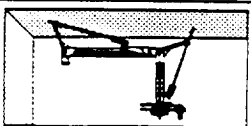
O) <u>Receive Parts</u>

P) <u>Assemble</u>: Begin assembly of the prototype.
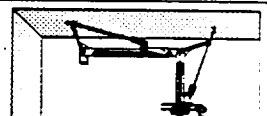
Q) <u>Test:</u> Perform tests on the assembled prototype to determine if it meets all required specifications and functions.

R) <u>Write Final Report</u>: Write up final designs and prototypes report. In the 2nd semester write up final report and prepare oral and visual presentation.

TABLE 1

SCHEDULE

MILESTONES	STEP	SEPTEMBER				OCTOBER				NOVEMBER				DECEMBER					JANUARY		FEBRUARY		MARCH			APRIL		MAY
		9	16	23	30	7	14	21	28	4	11	18	25	2	9	16	23	30	6	20	3	17	2	16	30	13	27	5
DEFINE NEED	A	◆																										
DETERMINE LIMITATIONS	B	◆																										
DEVELOP SPECIFICATIONS	C	◆			◆																							
CONCEPTUAL DESIGNS	D	◆			◇																							
TRADE OFF STUDIES	E		◆			◇	◆																					
STRESS ANALYSIS	F		◆			◇	◆																					
FEASIBILITY ANALYSIS	G		◆			◇	◆																					
SELECT CONCEPT	H						◆																					
OPTIMIZE CONCEPT	I						◆	◇					◆															
DEVELOP FINAL DESIGN	J						◆	◇	◇				◆															
DESIGN FREEZE	K							◇		◆																		
MAKE DETAILED DRAWINGS	L							◇						◆	◆													
ORDER PARTS	M							◆	◇		◇						◆											
FABRICATE PARTS	N							◆	◇	◇	◇													◆				
RECEIVE PARTS	O							◆		◇	◇							◇								◆		
ASSEMBLE	P										◇	◇														◇	◆	◆
TEST	Q										◇														◇	◆	◇	◆
WRITE FINAL REPORT	R											◆													◇	◆	◆	◆

Figure 1

CPM DIAGRAM
for
ASPOD Robot Arm
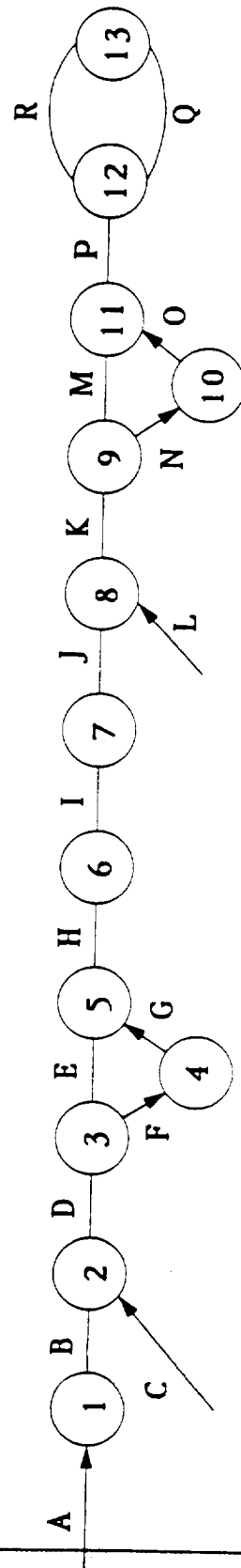
GEOMETRY AND

STRUCTURAL DESIGN

by

Paul Chinnock
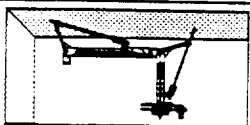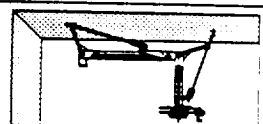
INTRODUCTION

The ASPOD arm structure needed to be both strong and light. The existing prototype arm made by last year's senior design team is a very heavy arm that has unduly high stresses at many joints. This arm has stripped one of its axles, because the entire weight of the arm and its coinciding torque was supported at a very small radius bolt. The arm configuration designed and built during the last two semesters has been engineered to rid the joints of moments and reduce the stresses that exist at the pivot points. The design has resulted in a highly reliable, clean in appearance and light arm structure.
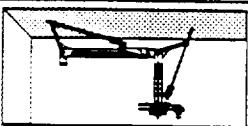
PROBLEM DEFINITION

The structure of the ASPOD arm had to be designed to be as light as possible, highly reliable, deflect less than 1 cm when under full load, be nearly identical in link dimensions, have the same degrees of freedom as the existing arm, and interface correctly with the end effector.
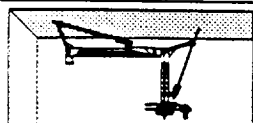
LIMITATIONS AND CONSTRAINTS

The arm was restricted by dimensions and degrees of freedom to be nearly identical to last year's design. The completed arm has link lengths very near the first arm's, with the first link being 14 inches from base to the first pivot point and the second link being 25 inches long. It was expressed by our graduate student managers that exact link lengths were not important constants, but degrees of freedom were. The third link was modified due to the length of the end effector to be only as long as a good transition joint required. The end effector is mounted directly to the third link elbow joint to keep the overall arm length as close as possible to the existing arm and to reduce the torque arm. The arm had to be lighter than last year's design and the arm is currently competitive in weight. Modifications to the arm are being carried out that will drastically reduce the weight while not reducing its structural integrity. The third linkage's design provided a very simple end for integration of the end effector.
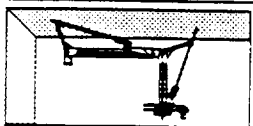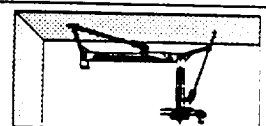
SPECIFICATIONS

The arm's structure allows it to work in unison with the drive system and control system to move to any given location with an accuracy of 1 centimeter carrying the end effector and over two pounds of load. The arm designed provides a reliable platform while being lighter and more rigid than the previous arm. The arm had to be manufacturable and in the final design individual pieces were made as easy to machine as possible. In the manufacturing stage, further simplifications were made to the design to accelerate the assembly.
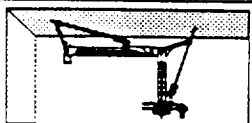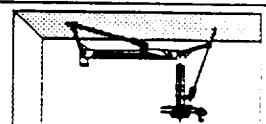
ARM DESIGN AND CONFIGURATION DETAILS

The design and configuration of the arm became an ever changing iterative process during the first semester. At the start, the design was built around a gear drive motivation scheme that became extremely bulky because of the many gear reductions required to obtain reasonable motor sizes and velocities needed. This configuration would have resulted in tremendous difficulties in control due to the backlash problems incurred by numerous gears. In addition, difficulties would have appeared in reliability. The design was also not very asthetically pleasing. After expressing our concerns to our class and faculty advisors, we decided that a linear drive motivated design would solve many of the previous design's problems. The linear driven design (see Figure 1 in Appendix A.1) provides the capability to rid the axles of torsion and load them with shear only. The design has become very clean and simplified.

A. CONFIGURATION MATERIALS

Each link is built around a composite tube of carbon graphite construction. The composite tubing has a good strength to weight ratio, high stiffness and relatively good abrasion resistance. Through each link is located a 1/2" threaded rod that provides preloading in the each link and holds the ends together for each link in the prototype phase. If the links did not require dissassembly the 1/2" rods could be removed for all, but the base to reduce weight. The rest of the structure is made of aluminum. Aluminum provides easy
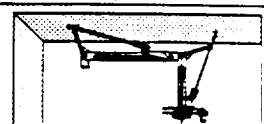
machining, a fairly good strength to weight ratio, weldability and a fairly low cost. The base bearing sleeves (see Figure 2 in Appendix A.2) required steel to be used to provide good strength between the 1/2" rod and the bearing. The materials chosen provide a structure that is lighter than last year's design when combined with the simplicity of the drive system.

B. STRUCTURE DETAILS

Throughout the design, individual pieces (see Figures Appendix A.2) were kept as simple as possible to minimize the amount of machine work. The joints were made identical to make machining as easy as possible and to reduce the work needed for motivation analysis. The aluminum joints are standardized into male and female parts that will be relatively easy to machine. In the female joints machine screws were used to reduce milling time. The male joints were greatly simplified to two pieces welded together that proved to be strong enough without additional strengthening pieces. The height of the first joint above the base allowed room for only an eight inch torque arm to be used, because of the space restrictions of placing a motor, transition section and torque arm at full pivot within the length of the link. The first torque arm's length was further reduced due to the angle limitations introduced by a large motor. The torque arm is angled 20 degrees above the horizontal when the connected arm is horizontal. The reason this was done was to provide the capability to move the arm from in line with the previous link to 140 degrees counter-clockwise from there and still provide a minimum torque arm for the linear drive of 2.73 inches
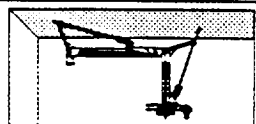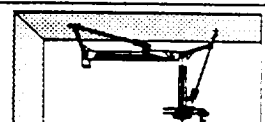
corresponding to an eight inch torque arm. The second link is still easily movable under all load conditions due to above requirement motors used. Motor position on the second link had to be far enough out to provide clearance from the drive screw driving that link.

Each link has an aluminum plug fitting snugly internal to the composite. The tubing is connected to the male joint pieces by welds that the composite unevenly fit against. Collars were machined to straddle these welds and provide a uniform surface to compress the composite onto. The plugs provide shear strength and moment resistance. The plugs form the connection point to each joint base.

Motor mounts and motor to linear drive screw transition sections are made from aluminum. The transition from the motor to screw is done with a flexible coupling to make up for any innacuracies in the center of rotation locations. The joint axles and motor mount axles are supported by standard ball bearings while the linear drive screws and the base are supported by tapered roller bearings.

All the individual pieces were drawn and configured for machining (see Figures, Appendix A.2). Even though the drawings were done with the utmost effort in trying to ease machining requirements, during the machining process further simplifications were carried out. One such simplification resulted in reducing the amount of milling time required by a single complex piece by producing many simple pieces machine screwed together.

The entire arm is supported by a 1/4 inch plate of aluminum that is flanked top and bottom by the arm supporting tapered roller bearings. The bearings are held between their brackets and sheaths
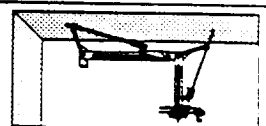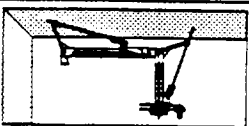
by preloaded a 1/2 inch bolt that runs through the center of the link and the base. The first link's motor is mounted on the base gear that acts as a rotating foundation.

All bolts were chosen to be as large as possible within reason and space limitations. This was done to make sure that our design would not fail due to fastener failure.

C. ANALYSIS

Some simple analysis was done (See Appendix A.5) on parts where concern about failure or large deflections was focused. The I-Beam that was a large part of the torque arm for each joint was analyzed as if it was the only moment supporting member in the joint. The simple analysis that was done revealed that the torque arm's deflection at maximum load conditions would result in end of manipulator arm deflection well within tolerances. The maximum stress would result in a safety factor near two for 2011 Aluminum alloy. The highest stress area in the base was in the top bearing sheath. The steel sheath was analyzed with assumptions made that would make the situation far worse than in actuality. The mounting bolts could easily carry the loads induced with factors of safety above three. If the center 1/2 inch bolt were preloaded the tensile and shear forces in bearing sheath's bolts were further reduced. An analysis was done on the maximum shear force that could be imparted on the base if only three of the sheath bolts were resisting the force and without the center bolt. The force calculated with very low shear strengths used in each bolt and very low friction coefficients between the sheath and the base gear assumed, resulted
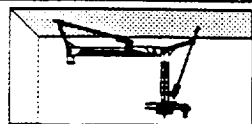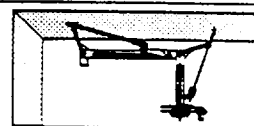
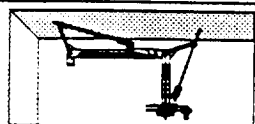in over 500 pounds. In conclusion, areas of concern were analyzed and they easily met max load conditions.
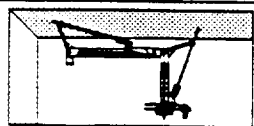
PARTS AND SUPPLIER INFORMATION

An item list (see Appendix A.3) was made and was very helpfull in ordering parts. Suppliers of bearings and couplings are identified in Appendix A.4.

PROJECT RESULTS AND MODIFICATIONS

The arm's assembly was a long drawn out process were simplifications to the orriginal drawings were done at every chance to allow us to complete the project on time. Simplifications included, as discussed earlier, using machine screws were possible to assemble complex pieces from a few simple ones. George became very adept at drilling and tapping #8 and #10 machine screws. In the summer further weight reduction to the arm, that was not allowed due to time restrictions, will be carried out. The structure met all specifications required of it. The arm has shown a very high degree of reliability by being transported and banged numerous times and being operated at speeds well in excess of its design velocities. The arm has shown a deflection with gripper attached and a 2.2 pound load of less than 6.5 millimeters. The result of our labor has turned out to be a very clean design with a minimum of complexity. The arm proved be tough to manufacture, but we completed it with many long hours of work. Most important of all, our graduate managers have said that we have met all their requirements for the arm. The USRA budget was not known by the team member's, but our arm was relatively cheap compared to the controlling computer. The linear drives and composite tubing was by far the most expensive with a cost of approximately $600 for both types of hardware. Second most expensive where the bearings and where close to $150 . The motors were $25 dollars apiece and raw materials and bolts were quite innexpensive also.
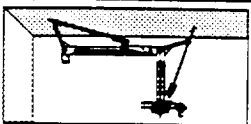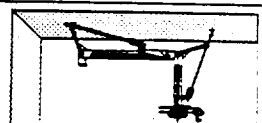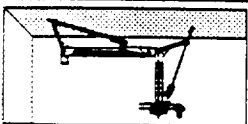
DRIVE SYSTEMS

b y

George   Williams

BACKGROUND:

The drive systems of the robotic were a subproblem of this project simply because the previous design was unsatisfactory in the areas of weight, precision movement and reliability. Therefore, this design was to optimize the previous design in these areas while fulfilling performance specifications.

PROBLEM DEFINITION:

To design a drive system for the robotic arm that will manipulate the arm through all 3 degrees of motion with fluid, precise, controllable movements.

PROJECT LIMITATIONS/CONSTRAINTS:

The following are limitations and constraints on the ASPOD ROBOT ARM project (1/5 scale). Each limitation and constraint must be met in accordance with the previous teams specifications but will hopefully be surpassed through optimization of the design. Following the list is a brief summary of what each limitation/constraint means.

1) Time - Working prototype by May 1, 1992.
2) Weight - Arm must weigh less than current arm.
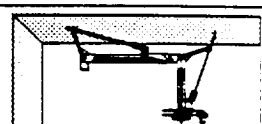
3) <u>Deflection</u> - Must be less than 1 cm between the
loaded and unloaded conditions.

4) <u>Degrees of freedom</u> - Arm must have 6 D.O.F.

5) <u>Earth based design</u> - Related problems

6) <u>Loading conditions</u> - Arm must be able to handle
and move a specified mass.

7) <u>Arm span</u> - The arm must extend 4.0 feet in
any given direction.

<u>Descriptions:</u>

1) The time given to design and develop a prototype is
only one semester. The following semester will be
spent on further optimization and construction of the
design.

2) The goal of the project is to minimize the weight of the
robotic arm (thereby decreasing the overall weight of
the satellite) through optimization of the existing arm.

3) The design of the arm should be should be such that
there be less than 1 cm deflection between the loaded
and unloaded condition. This is in consideration of the
dynamic loading effects on the arm and the material it
is made of.

4) The arm must be able to translate as well as rotate in
the x-y-z spatial coordinates in order to handle the
precise positioning of debris required for the cutting
procedure.

5) The design of this robotic arm takes place on earth
where gravity exists while it is to function in space
where gravity does not exist. On earth, the predominate
acceleration is gravity while in space the predominate
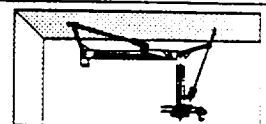acceleration will be angular acceleration. It is this
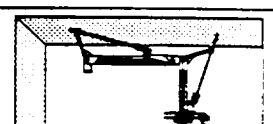
unavoidable fact that makes using the Langrangian Equation for torque difficult.

6) The mass of the load, for application in space, will be 1500 kg or greater. The mass the 1/5 scale prototype must handle is 2 lb.

7) The length of the robotic arm is to be 4.0 feet in extended length.
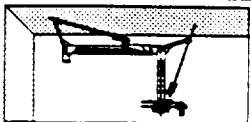
SOLUTION:

The first proposed solution for the robot arm drive systems is shown in Figures 2, 3 and 4. The robot arm was to be driven with sprocket-chain assemblies with specific gear train values designed to meet both torque and speed requirements. This proved to be a very simple design and it met all of the operating conditions. However, this design was eventually discarded for several reasons. First, this design introduced high localized stress concentrations at all of the axis of rotation. Second, these types of systems are inherently difficult to control due to the inherent "play" characteristics that exist within them. Finally, this design was deemed to be unappealing to the eye due to its bulky appearance. For these reasons a new design was proposed and is shown in Figure 5.

The introduction of the ball screw-ball nut linear actuator proved to be a much better design when compared to the sprocket-chain assembly due to three major improvements. First, the linear actuator is a very efficient device, on the order of 95%, in power transmission. Second, the ball nut of this system can be preloaded so as to negate any effects of play that may exist within the system. Finally, this design is much more appealing to the eye due the streamlined appearance the linear actuators create. However, it must be noted that a modified version of the sprocket-chain assembly has been retained as the drive system for the base for the following reason. The motion requirement for the base is that it must be able to rotate through 360 degrees, a condition that is best met with the application of the sprocket-chain assembly system. The
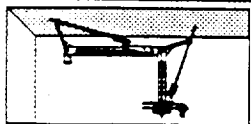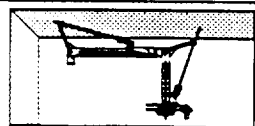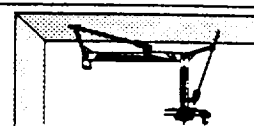
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problems previously mentioned with using this type of system have been compensated for by applying a preload to the chain so that any detrimental effects will be minimized.

Due the improvements that have been noted, the design shown in Figure 5 was chosen as the final design to be implemented as the mechanical drive system for the robotic arm.

GEAR TRAIN VALUE e=0.0078125 (128:1)
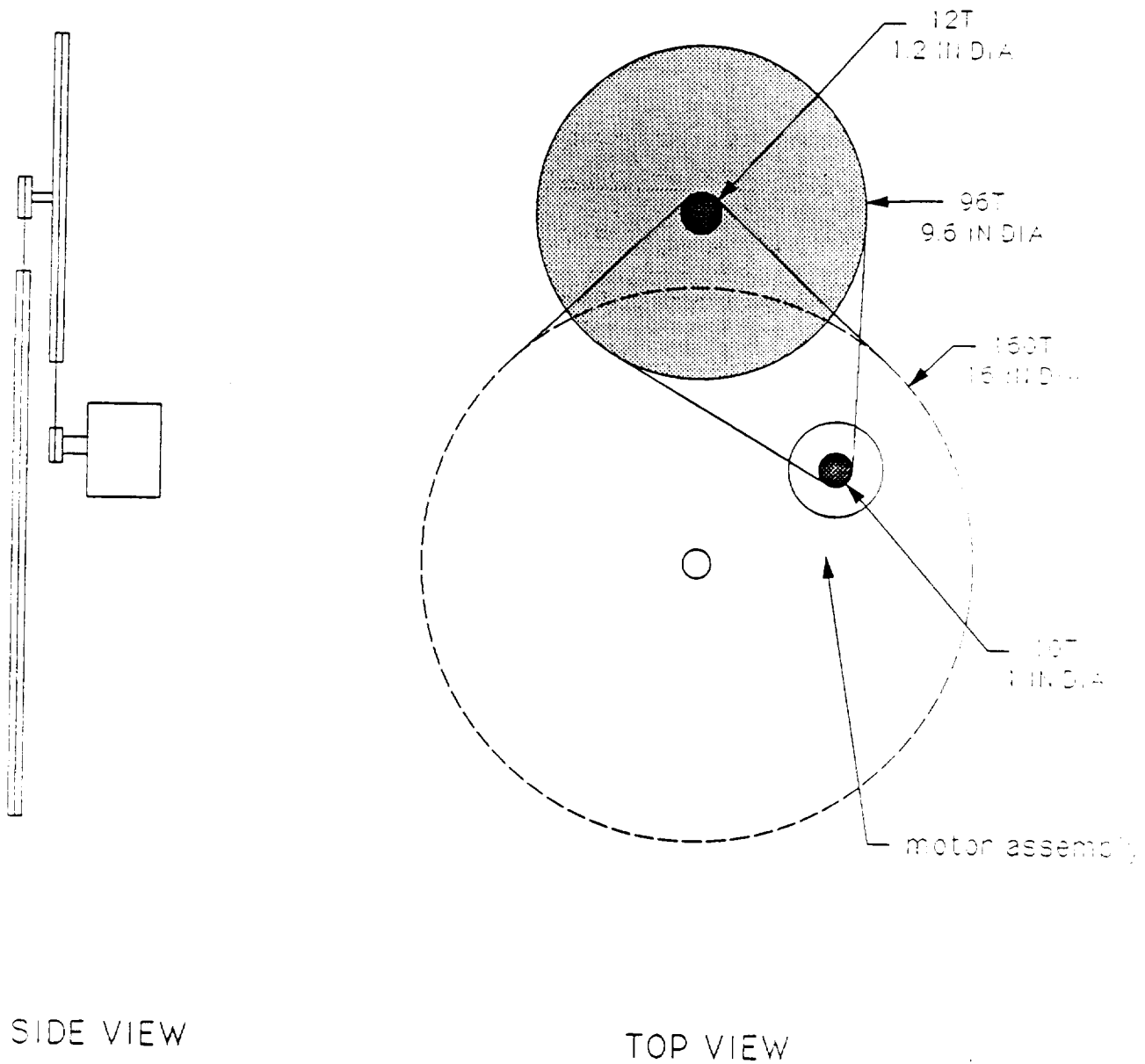DIAMETRIAL PITCH = 10T/IN

12T
1.2 IN DIA

96T
9.6 IN DIA

160T
16 IN DIA

16T
1 IN DIA

motor assembly

SIDE VIEW

TOP VIEW

Figure 2

Figure 3

GEAR TRAIN VALUE: e=0.0078125
DIAMETRIAL PITCH= 16T/IN

STRESS REDUCTION BOLTS

160 T
10 IN DIA.

96T
6 IN DIA.

12T
0.75 IN DIA.

10T, 0.625 IN DIA.

MOTOR

16"

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60 T
6 IN DIA.

12T
1.2 IN DIA.

10 T
1 IN DIA.

10T
1 IN DIA.

MOTOR ASSEMBLY

40T
4 IN DIA.

64T
6.4 IN DIA.

16"

STRESS REDUCTION BOLTS

GEAR TRAIN VALUE: e=0.0078125 (128:1)
DIAMETRIAL PITCH= 10T/IN

Figure 4

A.S.P.O.D.
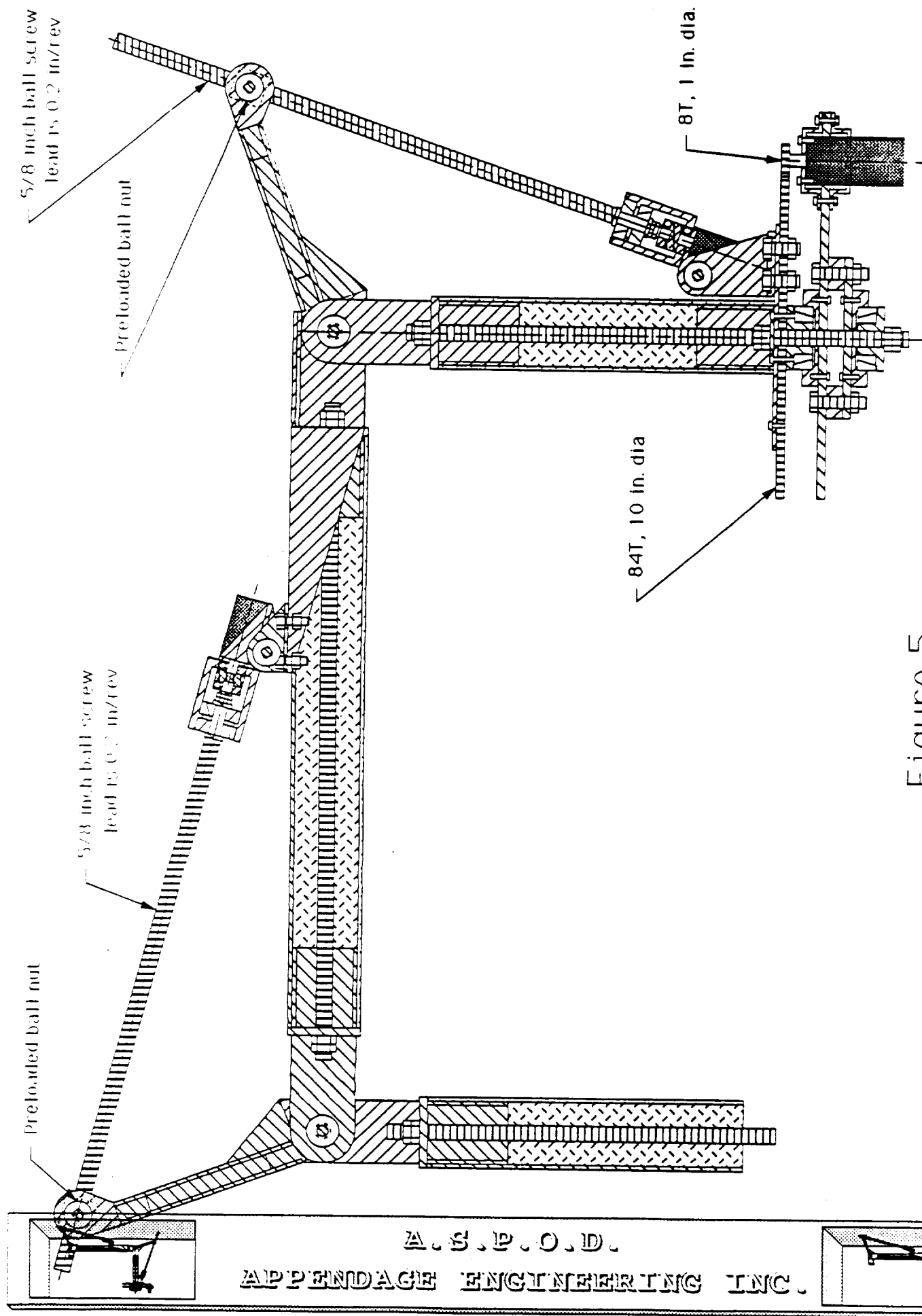APPENDAGE ENGINEERING INC.

5/8 inch ball screw
lead is 0.2 in/rev

Preloaded ball nut

8T, 1 in. dia.

84T, 10 in. dia

5/8 inch ball screw
lead is 0.2 in/rev

Preloaded ball nut

A.S.P.O.D.

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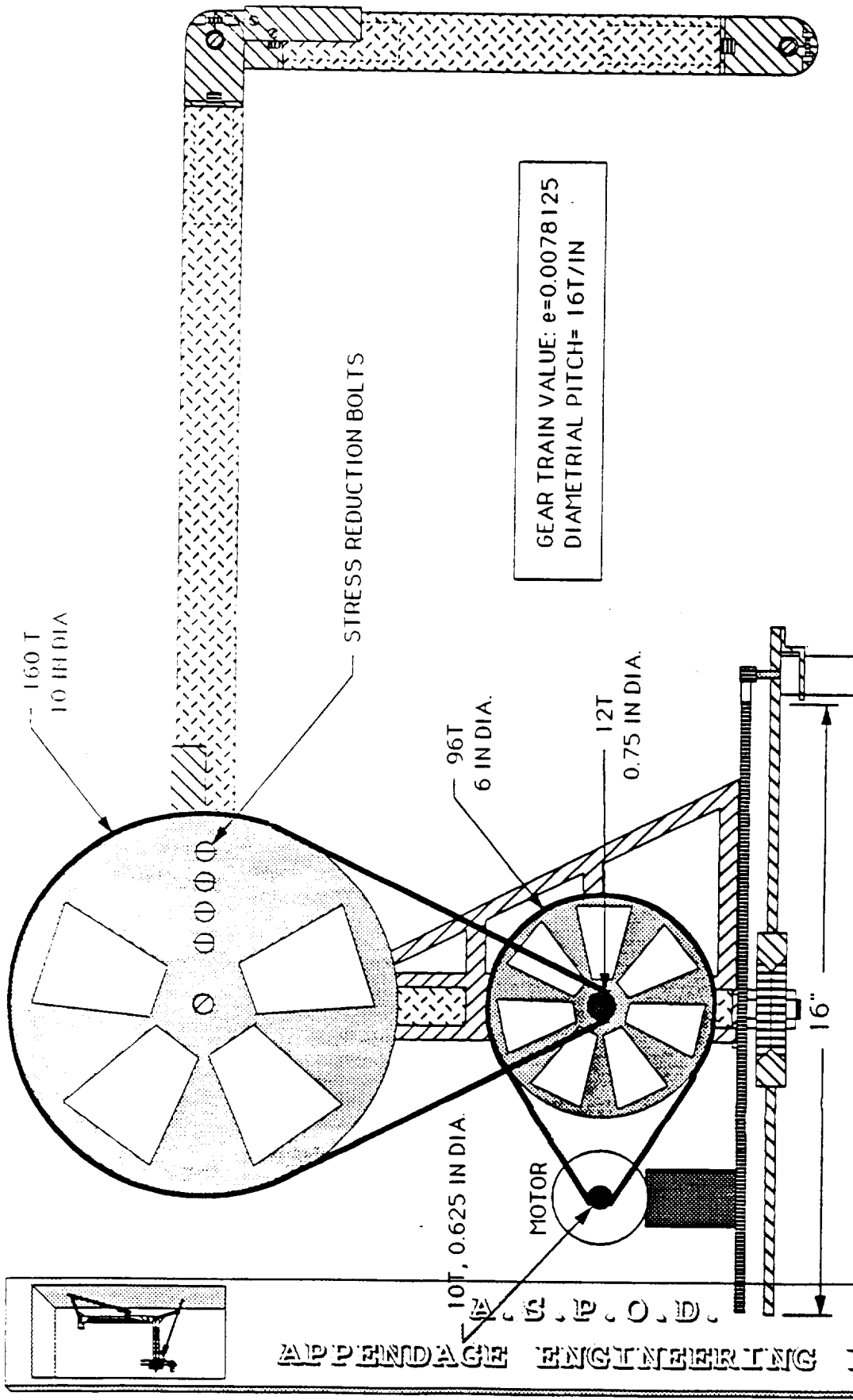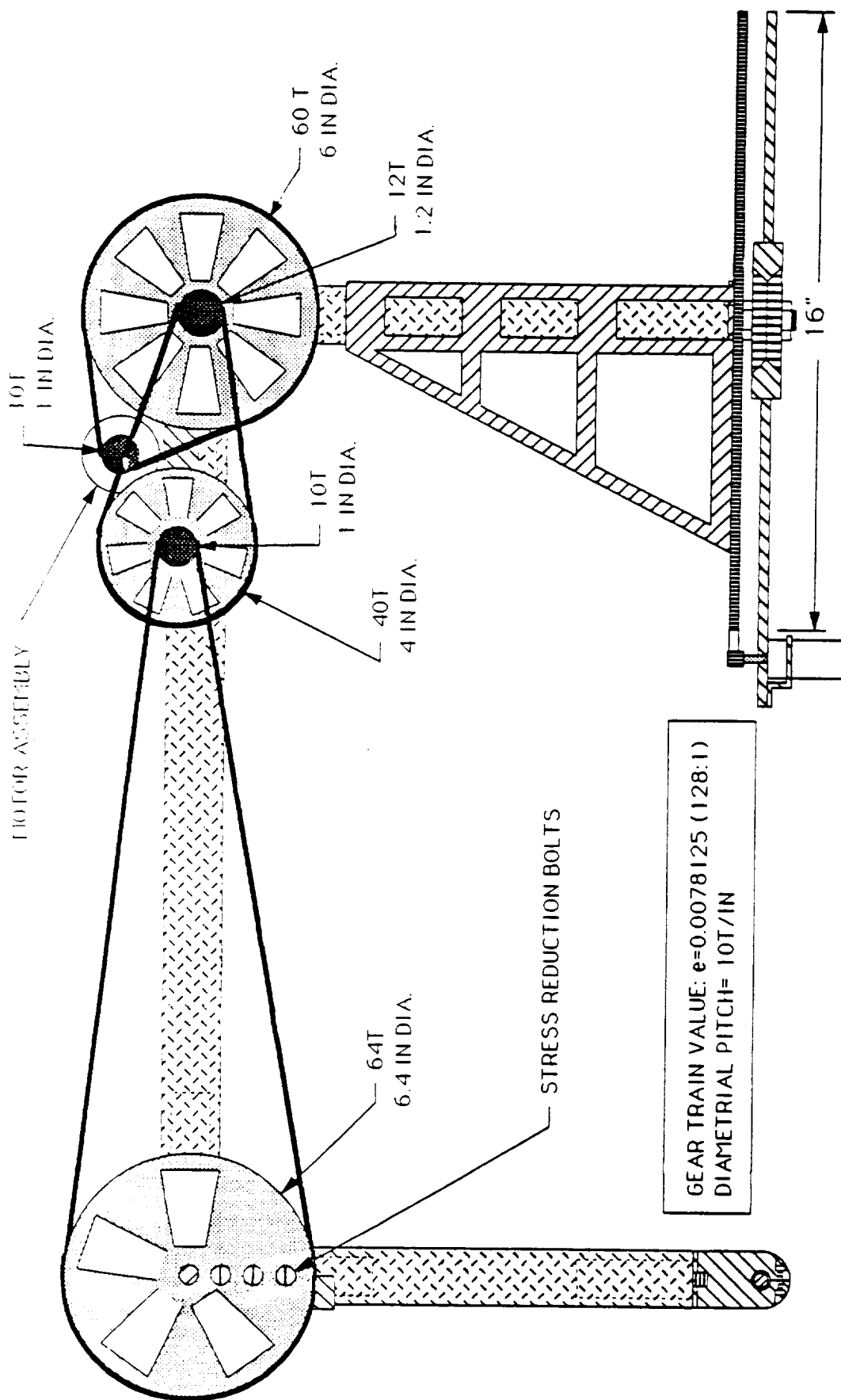
Figure 5

<u>ANALYSIS:</u>

The analysis of the arm was subject to several parameters. First, the analysis was performed with the assumption that the applied load is twice as heavy as the actual load so that all calculations would meet the required factor of safety of 1.5. Second, the angular velocity of each link was specified to be 90 degrees/minute (0.25 rev./min), defined by the desire for uniform velocities between links and also from the knowledge that fast operating speeds are neither required nor desired. Third, the angular acceleration of each link was specified to be 0.0436 radians/sec^2, defined by accelerating to the specified angular velocity in 2 seconds while traveling through 5 degrees. This value of acceleration was chosen because a greater acceleration would require greater torque from the motors, while a slower acceleration would make demonstration practices time consuming. Therefore this acceleration is a middle ground and is uniform for all links. Finally, an analysis using Lagrangian dynamics was performed so that the motors would be accurately sized for the condition of all links being in motion at the same time.


...
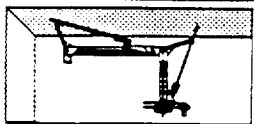
MOTOR SIZING:

<u>Base Motor</u>: The base motor will be driving a 8 tooth, 1 inch diameter, 1/8 inch thick steel pinion which will transmit its motion through a chain to the 84 tooth base plate gear which is 10 inches in diameter, 1/8 inch thick steel. The pinion is preloaded in one direction so as to negate the effects of backlash within the system. The base motor was sized using a dynamic analysis only since the base motor must only overcome frictional forces during static operation. The dynamic analysis was performed using a computer program that reflected the inertias of the extended links and the load back to the vertical z axis for all possible geometries of the arm so that the dynamic torque (the torque required to accelerate and decelerate the arm from and to a dead stop) could be determined from equation 1.

$$T = I\alpha \qquad (1)$$

The dynamic torque at the worst case was found to be 104.78 oz-in, which correlates to 10.47 oz-in at the motor. Thus the base motor was sized at 12.0 oz-in at continuous duty (see note).

<u>Note</u>: An additional 10% has been added to each motor torque calculation in compensation of frictional losses. The complete analysis is located in Appendix B.
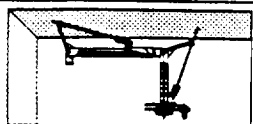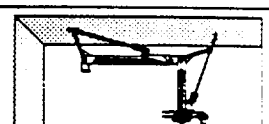
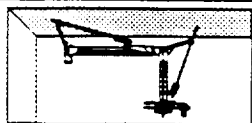A.S.P.O.D.
APPENDAGE ENGINEERING INC.
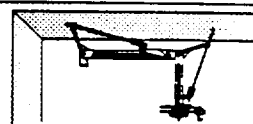
Second Link Motor: The second link motor will be driving a 5/8 inch stainless steel ball screw through a compatible pre-loaded stainless steel ball nut. The ball nut is to be pre-loaded so as to negate the effects of backlash within the system. A static analysis was performed on an Excel spreadsheet for all possible arm geometries so that the worst case could be easily obtained. The worst case was found to be when the arm is fully extended and 50 degrees below horizontal. The static torque at worst case was found to be 242 oz-in. A dynamic analysis was then performed and it was predetermined that the worst case would not be dependant on the angle of the arm relative to the horizontal, only that it was dependant on the degree of extension of the arm. The worst case was found to be at full extension and the dynamic torque was found to be 78.17 oz-in. Thus, in order to accurately size the motor the motor must provide both the static and dynamic torque at the same time. Therefore, the second link motor must provide 360 oz-in at continuous duty.
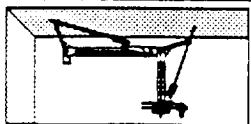
Third Link Motor: The third link motor will be driving a 5/8 inch stainless steel ball screw through a compatible pre-loaded stainless steel ball nut. The ball nut is to be pre-loaded so as to negate the effects of backlash within the system. A static analysis was performed on an Excel spreadsheet for all possible arm geometries so that the worst case could be easily obtained. The worst case was found to be when the arm and the load are fully extended relative to one-another. The static torque at worst case was found to be 102.7 oz-in. A dynamic analysis was then performed. It was predetermined that the worst case would not be dependant on the angle of the arm relative to the horizontal, rather that it was dependant only on the degree of extension of the arm. The worst case was found to be at full extension and the dynamic torque was found to be 71.9 oz-in. Thus, the second link motor must provide 192 oz-in at continuous duty.
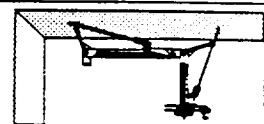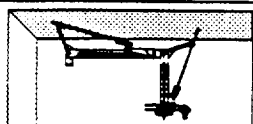
CONTROL SYSTEM

b y

Peter   Wegner

A.S.P.O.D.

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INTRODUCTION

A. Background

The goal of the US RA funded research project for the 1991-92 school year has been to develop a second robotic arm for the debris collecting satellite. This arm, in conjunction with the arm developed by the previous years design team, will serve as a proof of concept for the Autonomous Space Processor for Orbital Debris. The arm must demonstrate that autonomous retrieval of space debris is possible and feasible.

B. PROBLEM DEFINITION

A control system for the manipulator arm must be designed so that the arm can demonstrate autonomous movements. The control system must provide reliable, stable, and simultaneous movements for all six degrees of freedom on the arm. This movement must be repeatable and alterable.

C. LIMITATIONS AND CONSTRAINTS

The control system must meet the above criteria in such a way that cost is minimized. The weight of the arm must be reduced below that of last years design. The control system should have an accuracy of +/-2.5 cm at the full extension of the arm. The control system must be designed so that the end affector and the first 3 degrees of freedom (DOF) of the arm can be combined into one system. The arm must be capable of varying velocities and accelerations so that the arm can perform a reasonable demonstration. In order to do this the arm must be
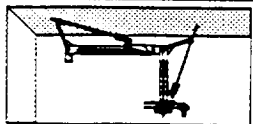
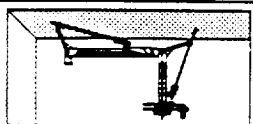A.S.P.O.D.

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capable of moving a 2# load as slow as 2.5 cm/min and fast enough that the arm will move through a 90 degree rotation in 1 minute.
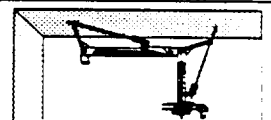
FINAL DESIGN

A. OVER-VIEW

The system used to control the arm is shown in figure 6. A personal computer with a 486 micro processor is used to power the control software and provide processing power. Two control cards installed in the computer are used to convert the digital motor commands required for proper positioning commands to analog signals that are used by the motors. These cards perform the time intensive tasks of motion profiling, compensation filtering, and encoder decoding. Connector boards as shown in figure 7 are used to connect amplifier, encoder, motor, and computer wiring in a simple manner. Signal amplifiers as shown in figure 8 are used to amplify the motor signals coming from the computer at +/-10VDC to +/-24VDC as required by the motors. Power supplies shown in figure 6 are used to supply current to the motors as required to move the applied loads. Optical encoders mounted as in figure 9 are used to provide position feedback to the computer. The control cards are programmable so that the arm can autonomously move through a given motion. This programming is accomplished using a series of supplied functions provided with the control cards.
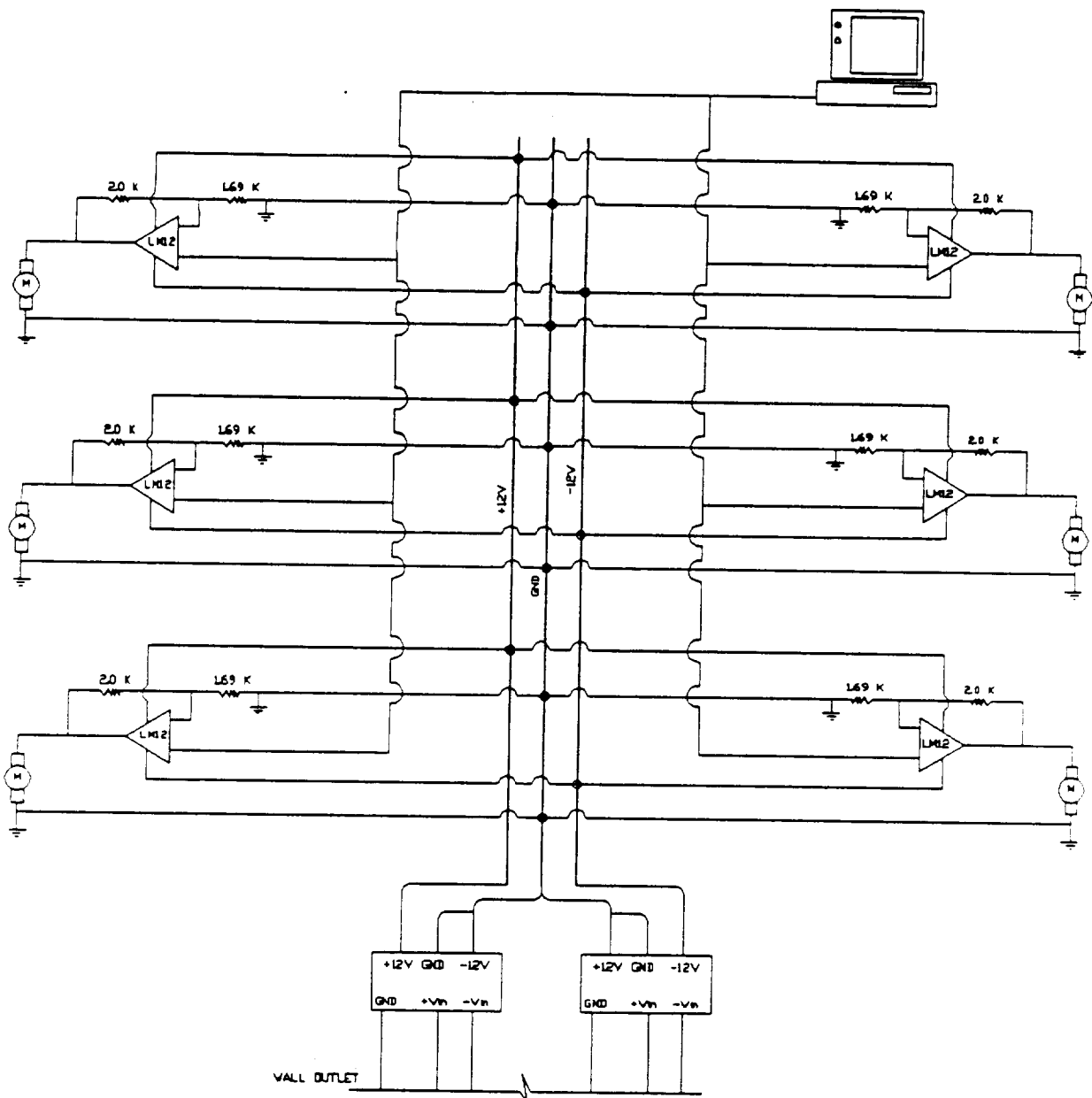
AME 412b   ASPOD ARM
POWER SUPPLY WIRING DIAGRAM
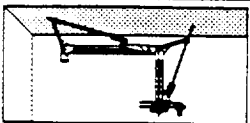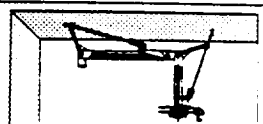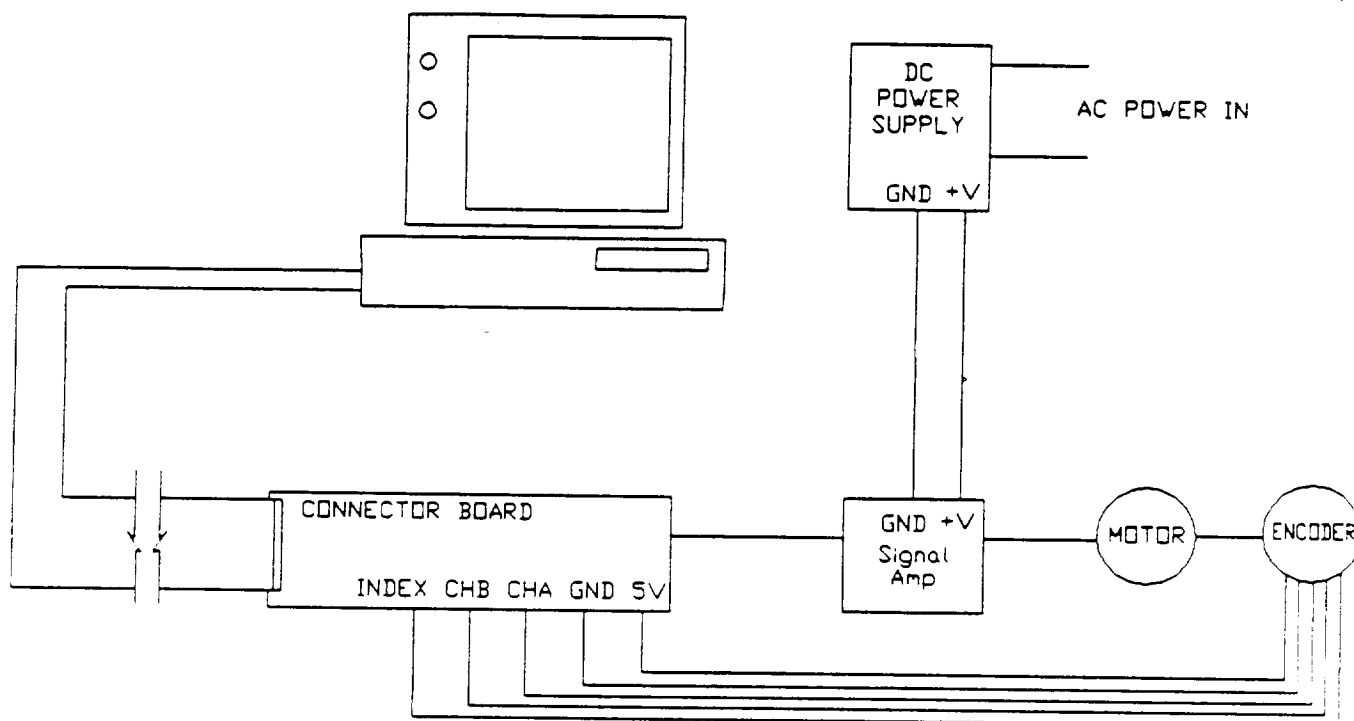
Fig 6

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DC POWER SUPPLY

GND +V

AC POWER IN

CONNECTOR BOARD

INDEX CHB CHA GND 5V

GND +V
Signal
Amp

MOTOR

ENCODER

AME 412B ASPOD ARM

Fig 7

ENCODER PHASING

+30V

250microF

MR 752

1.69 K

2.0 K

LM12

+/-10V INPUT

MR 752

MR 752

M

250microF

-30V
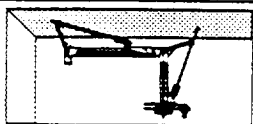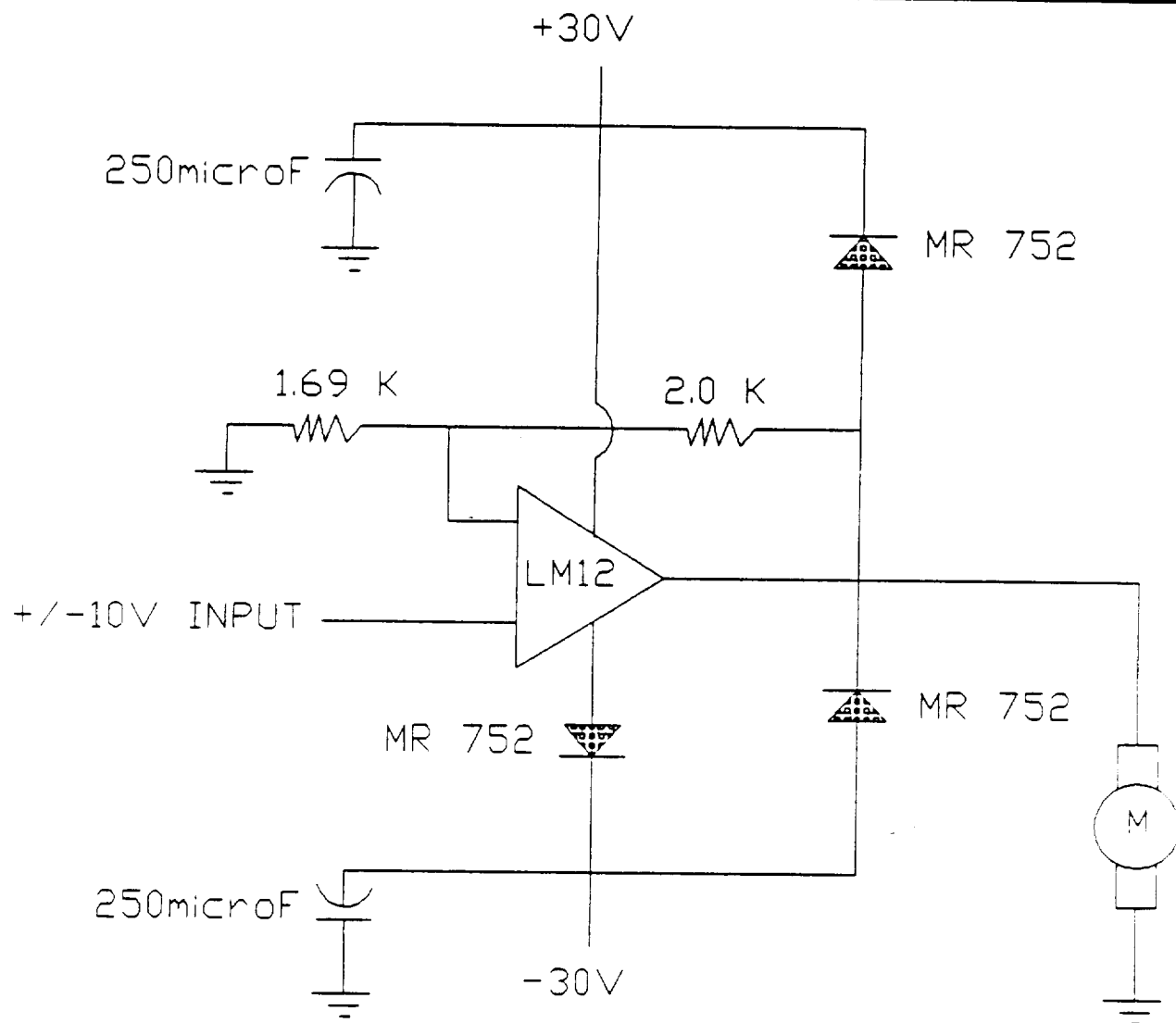
AME 412b

Fig 8 SIGNAL AMPLIFIER

Optical Encoder
BEI Model # E113-900-11

Flexable Coupling

Lead Screw

DC Motor
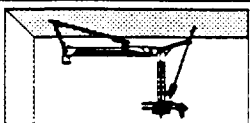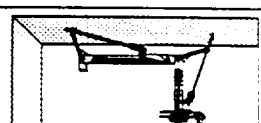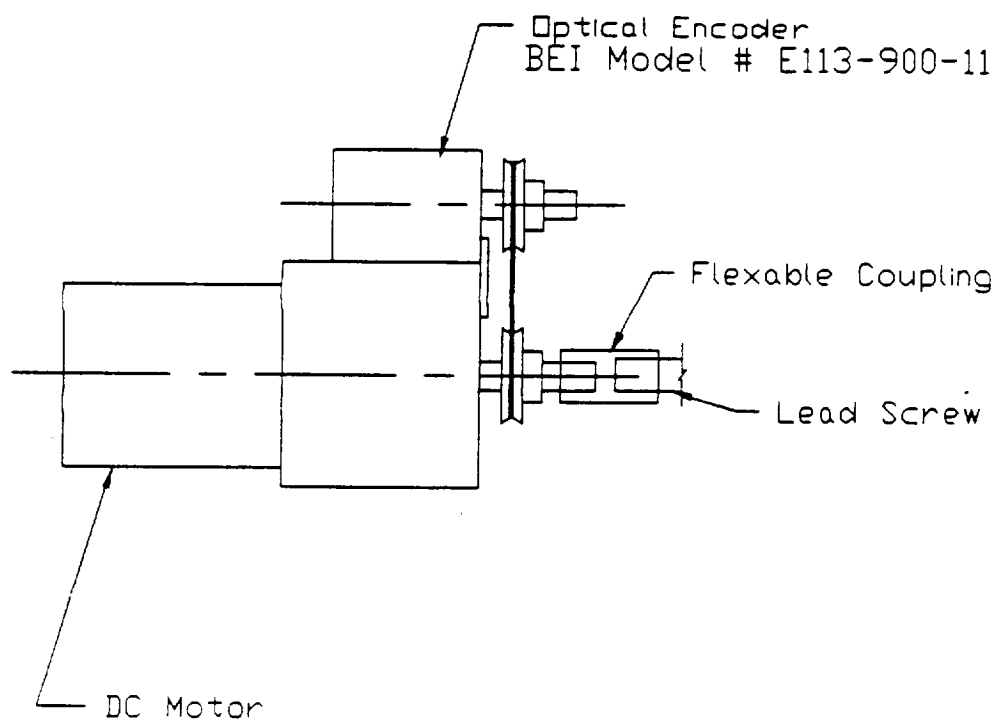
AME 412b ASPOD ARM

Fig 9 | ENCODER MOUNTING
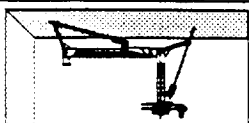
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PARTS LIST

QTTY	ITEM	DESCRIPTION	PRICE
1	Personal Computer	486 processor	N/A
2	Control Cards	Omintech MC-3000	$1500.00
2	Connector Boards	Omintech Robotics	$300.00
2	Computer Cable	Omintech Robotics Cable Set	$100.00
3	DC Motors	Pittman DC Gear-head motor 24VDC, 91RPM @ 200mA with 175 Oz-in load, #GM9434E616	$67.50
3	Encoders	BEI #E113-900-11, 900PPR, 5VDC @ 100mA	$157.50
2	Power Supplies	ACME Electric #PS59134, 24VDC @ 6 A, Ripple less than 1mV	$73.00
6	Op-Amps	National Semiconductor, LM12ClK, 150W operational amplifier	$147.00
12	Capacitors	250 micorFarad capacitors, electrolytic	$5.00
12	Resistors	1.69Kohms	$5.00
12	Resistors	2.0Kohm	$5.00
18	Diodes	Motorola #MR752	$10.00
3	Wiring Boards	EXP 300 Experimental Boards	$30.00
6	Heat Sinks	Aluminum Heat Sinks	N/A
		Assorted wiring and hardware including 18Ga wire and solderless connectors	

TOTAL COST= $2400.00

B. DETAILED DESCRIPTION & DESIGN DECISIONS

MOTOR SIZING

Sizing of the motors was accomplished through the use of a full 3-dimensional dynamic analysis. The general equations for a 3 degree-of-freedom arm with the same configuration as this years design have been derived by Eguene Irven (Irven, pg102). These equations are given in figure 10. A spreadsheet program was written in which the arm parameters could be varied. This spreadsheet is listed in Appendix C, see figure 1. Last years completed arm was used as a data base for this spreadsheet. The joints of this years arm were initially designed to be the same length as the previous years design. One of the design criteria for this years design was that it must be lighter than last years. If the motors were sized for last years arm then they would work very well for the present arm.

Using this spreadsheet program the velocity and accelerations were varied in many configurations until the maximum required torques were determined. The maximum torque was required when a 20# load was applied to the end of the arm with an acceleration of 0.04363 rad/s (this will accelerate the arm through 5 degrees in 2 sec) and a velocity of 0.288 rad/s (this will move the arm through 90 degrees in 1 minute). Under these conditions the maximum torque was calculated to be 143 oz-in at the shoulder joint. The base motor required 1.3 oz-in of torque and the elbow motor required 38 oz-in of torque at the maximum load.

Using a safety factor of 1.5 the maximum torque required is 214 oz-in. The Pittman Model #GM9434E616 Gearhead Motor has a
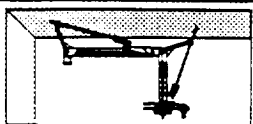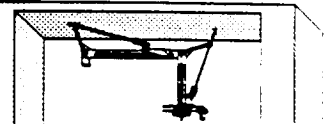
$$T_0 = T_{00} + T_{01} + T_{02} = \{I_0 + (m_1 l_{1c}^2 + I_1) \cos^2 \theta_1$$

$$+ m_2 l_1 [l_1 \cos \theta_1 + 2 l_{2c} \cos (\theta_1 + \theta_2) \cos \theta_1]$$

$$+ (m_2 l_{2c}^2 + I_2) \cos (\theta_1 + \theta_2)\} \ddot{\theta}_0 + 2 \{m_1 l_{1c}^2$$

$$+ I_1) \sin \theta_1 \cos \theta_1 + m_2 l_1 [l_1 \sin \theta_1 \cos \theta_1$$

$$+ l_{2c} \sin \theta_1 \cos (\theta_1 + \theta_2)] + (m_2 l_{2c}^2 + I_2) \sin (\theta_1 + \theta_2)$$

$$\times \cos (\theta_1 + \theta_2)]\} \dot{\theta}_0 \dot{\theta}_1 + 2[m_2 l_1 l_{2c} \cos \theta_1 \sin (\theta_1 + \theta_2)$$

$$+ (m_2 l_{2c}^2 + I_2) \sin (\theta_1 + \theta_2) \cos (\theta_1 + \theta_2)] \dot{\theta}_0 \dot{\theta}_2$$

$$T_1 = T_{11} + T_{12} + T_{1\ell} = (m_1 l_{1c}^2 + I_1 + m_2 l_1^2$$

$$+ 2 m_2 l_1 l_{2c} \cos \theta_2 + m_2 l_{2c}^2 + I_2) \ddot{\theta}_1$$

$$+ (m_2 l_1 l_{2c} \cos \theta_2 + m_2 l_{2c}^2 + I_2) \ddot{\theta}_2$$

$$- \{(m_1 l_{1c}^2 + I_1) \sin \theta_1 \cos \theta_1 + m_2 [l_1^2 \sin \theta_1 \cos \theta_1$$

$$+ l_1 l_{2c} \sin \theta_1 \cos (\theta_1 + \theta_2) + l_{2c}^2 \sin (\theta_1 + \theta_2)$$

$$\times \cos (\theta_1 + \theta_2)] + I_2 \sin (\theta_1 + \theta_2) \cos (\theta_1 + \theta_2)\} \dot{\theta}_0^2$$

$$+ (m_2 l_1 l_{2c} \sin \theta_2) \dot{\theta}_2^2 + (2 m_2 l_1 l_{2c} \sin \theta_2) \dot{\theta}_1 \dot{\theta}_2$$

$$+ g \{m_1 l_{1c} \cos \theta_1 + m_2 [l_1 \cos \theta_1 + l_{2c} \cos (\theta_1 + \theta_2)]\}$$

$$T_2 = T_{22} + T_{2\ell} = (m_2 l_1 l_{2c} \cos \theta_2 + m_2 l_{2c}^2 + I_2) \ddot{\theta}_1$$

$$+ (m_2 l_{2c}^2 + I_2) \ddot{\theta}_2$$

$$- \{m_2 [l_1 l_{2c} \cos \theta_1 \sin (\theta_1 + \theta_2)$$

$$+ l_{2c}^2 \sin (\theta_1 + \theta_2) \cos (\theta_1 + \theta_2)]$$

$$+ I_2 \sin (\theta_1 + \theta_2) \cos (\theta_1 + \theta_2)\} \dot{\theta}_0^2$$

$$- (m_2 l_1 l_{2c} \sin \theta_2) \dot{\theta}_1^2$$

$$+ g [m_2 l_{2c} \cos (\theta_1 + \theta_2)]$$

FIGURE 10

continuous rating of 195 oz-in. This is slightly less than the calculated torque required. However, after considering the affects of counterbalancing achieved by the torque arm and lead screw design (a total weight of 3# was used as a counterbalance) the maximum torque required was determined to be only 183 oz-in. This motor was used in all three joints of the arm for ease of manufacturing. This motor has operating characteristics as shown in appendix C, figure 2. The motor is available from Servo Systems Inc. for $22.50 each.

CONTROL CARDS

The control cards solve the differential equations of motion for each motor on a real time basis. They also decode the encoder feedback and determine the compensation filtering to provide system stability. This frees the PC for higher level applications. Using this motor control card the components required to build a servo control system are the DC motor, an incremental encoder, and a power amplifier (see figure 7).   The control card that will be used for this system is the MC-3000 motor control card from Servo Systems Inc. This is a three axis control card, i.e. one that can simultaneously control three motors. The controller card has 32-bit position, velocity, and acceleration registers.   The control card contains a full PID controller which will stabilize the system within a given bandwidth. It can be shown through classical control methods that a system can be stabilized within a certain operating range by the proper choice of feedback gain parameters in a PID controller [Grantham & Vincent, 1991, pp 6.1-6.60].
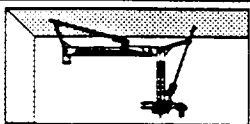
POWER SUPPLY SELECTION

At maximum load these motors will draw about 900 mA. The end affector group selected motors that would draw less than 1 amp at the maximum load. The power supplies were sized so that 6 amps of current is available. This means that all 6 motors can be operating at the maximum loading case simultaneously with available current left over if a stall condition should occur. The power supplies are wired as in figure 6. This was done because the power supplies output +24VDC. With this wiring configuration the system is supplied with +24VDC as well as -24 VDC at 6 amps. The power supplies were purchased from Servo Systems Inc. for $36.50 each.

SIGNAL AMPLIFIERS

The signal amplifiers are built around an LM12CLK op-amp from National Semiconductor. These were purchased from Anthem Electronics for $25.40 each. The op-amps were wired with protection circuits as shown in figure 8. The capacitors smooth ripples in the power supply. The diodes keep current from going back into the op-amp and destroying the op-amp. The resistors provide a gain factor for the amplifier of 1.18. These circuits are wired to bread boards as shown in figure 11.

The op-amps were mounted to heat sinks as shown in figure 6. The heat sinks must be able to dissipate 80 Watts of power from the op-amp and keep the center of the op-amp from exceeding 70 degrees Celsius. Initially a heat transfer analysis was performed for a fin dissipating this energy (Reynolds, p 568). The calculations are shown in Appendix C. These calculations

250microF

250microF

1.69K

GND BUSS

MR752

MR752

MR752

+30V

+10V

-30V

M

Horizontal sectors are connected
in a common buss

Common GND buss
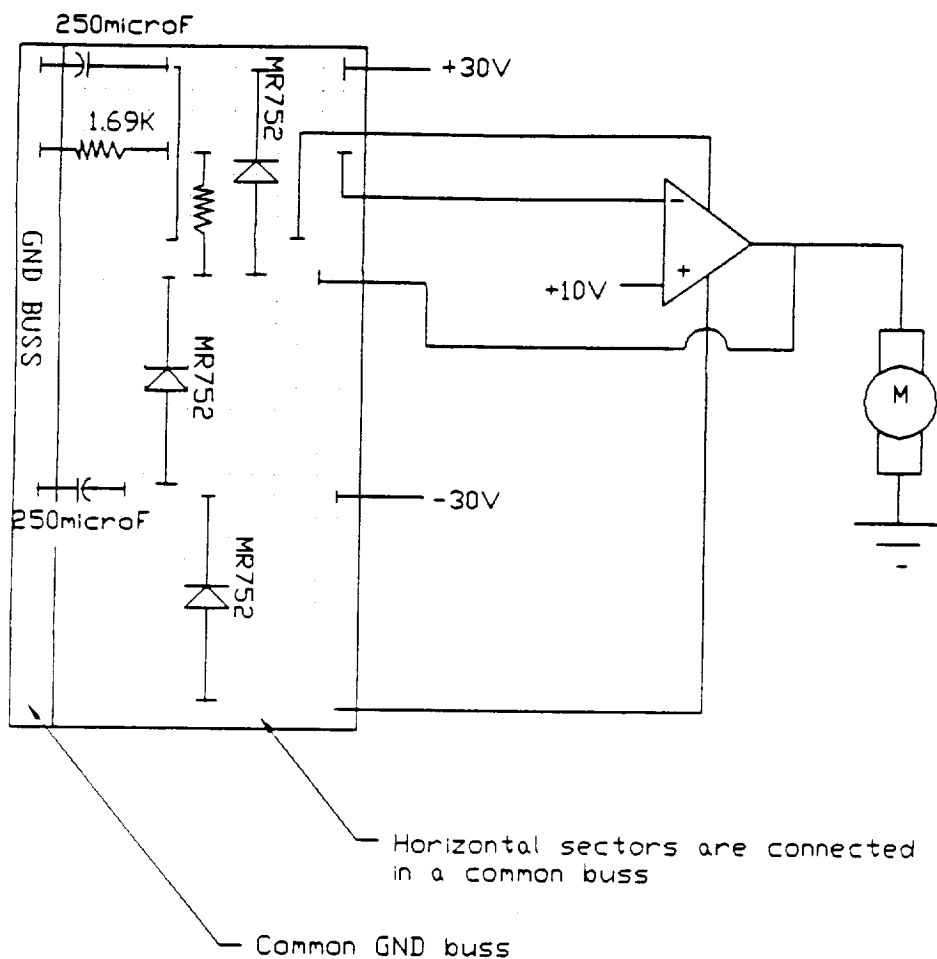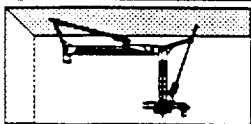

Fig 11 | AME 412b ASPOD ARM
BREAD BOARD WIRING DIAGRAM

A.S.P.O.D.
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Plywood 3/4"

2"

Aluminum 1/4"

6"

8"
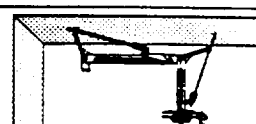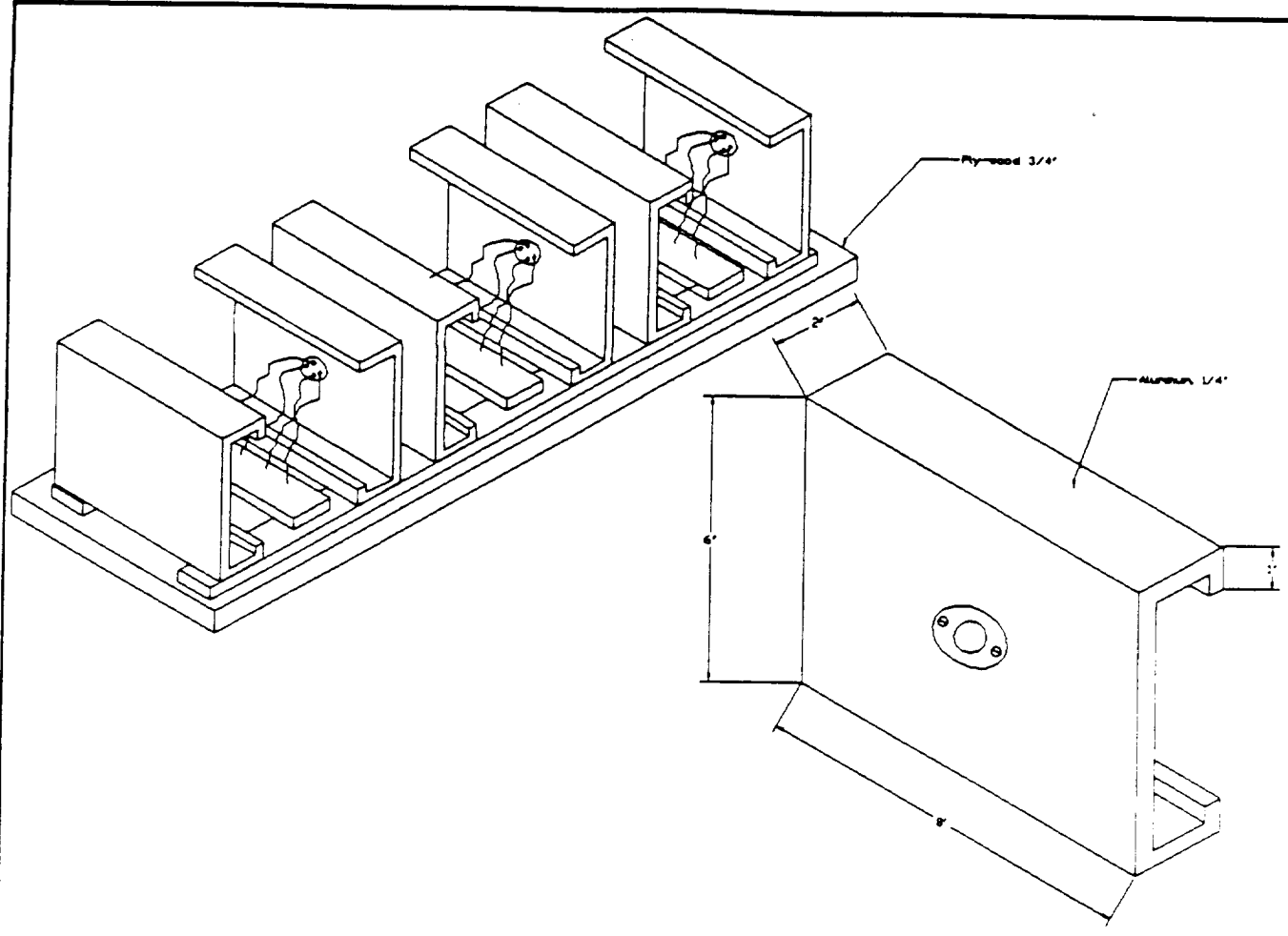
AME 412b ASPOD ARM
HEAT SINKS- MOUNTING CONFIGURATION

Fig 12
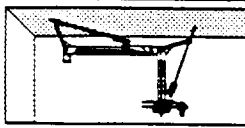
A.S.P.O.D.

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were written into a spreadsheet as shown in Appendix C, figure 3.
This analysis showed that each op-amp would require a fin 20cm x
15 cm x 2.5 cm. To check these calculations the heat sinks were
sized using procedures given in a Thermalloy Catalogue. This
analysis determined that a plate 13cm x 13cm x 2cm would
adequately cool the op-amps. Finally, a chart provided by
National Semiconductor was consulted. This chart showed that
each op-amp would require 50 square inches for adequate cooling.
ENCODERS

As previously noted, in order to complete the servo-system
design the controller card must be supplemented by an optical
encoder. An optical encoder is a device capable of counting the
angular distance that a given shaft is rotated. The encoder used
in this design is the BEI Model #E113-900-11. This encoder
operates on 5VDC at 100mA. The output is on 2 channels in
quadrature with an index channel. This means that the encoder
indicates direction of rotation as well as absolute position of
the arm.

The resolution is increased substantially by the control card.
The control card has the capability of reading the encoder output
in quadrature. The controller counts every time the encoder
signal changes direction, which happens four times for every
pulse. Essentially the controller card increases the resolution
of the encoder by a factor of four.

It was determined that if the encoder emits 360 pulses
during the entire range of motion of the arm the position of the
end affector could be determined to within +/- 2 centimeters.

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The encoder selected emits 900 pulses per revolution, which is equivalent to 3600 PPR in quadrature. The encoder will be directly driven at a 1:1 ratio by the motor shaft using a small pulley and belt as shown in figure 9. This configuration will keep backlash between the arm joints from entering the controller and creating a cyclic affect. Mounting the encoders in this manner will also increase the length of travel of the torque arm on the lead screw.

It was determined that the maximum change in length for either of the lead screws was 15 inches, the lead screws selected have a lead of 0.2 inches per revolution. The motor must turn 75 times to obtain this change in length. This means that the encoder will emit 270,000 pulses during the full range of motion of either joint. The base motor will turn 10 times during one revolution of the manipulator base. The encoder attached to this motor will emit 36,000 pulses during this motion. Thus it is apparent that in the absence of backlash in the system this encoder would easily meet the accuracy requirements.

The controller card that will be used has a 32 bit position register. This means that the card can store 2.1×10^9 pulses on each channel. This is far more than are required for the complete range of motion of the arm.

The encoder selected operates at 100KHz. If the motor turns at 63 RPM, which will cause the arm to move 90 degrees per minute, the encoder will be sending 3.8×10^3 pulses per second. This speed is well within the operating resolution of the encoder. This will ensure that the encoder does not miss any
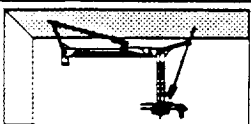
counts during operation. The controller cards selected will operate with an encoder of up to 750 Khz. Thus, there is a good match between the controller cards and the encoders to ensure that this combination accurately measures the arms position.

CONTROLLER PROGRAM

The controller program is written in a text file in which pre-programmed commands are recalled and used from the controller card's memory. These commands tell each axis how many encoder counts to rotate through as well as the speed and acceleration requirements. The manipulator arm initially is programmed with only one trajectory. The program tells the arm how many revolutions of each motor are needed as well as the velocity and acceleration required for each motor. This initial program completes a good demonstration of the arm. It moves each joint individually, then proceeds through a series of simultaneous movements. This program is listed in Appendix C, figure C.4.

A spreadsheet program was developed that calculates the number of turns of each encoder required for a one degree turn of the corresponding joint, see Appendix C figure c.5. A 3-D AutoCad drawing of the arm was used to visualize the proper angles to rotate each joint, this drawing is shown in Appendix C, figure c.6.
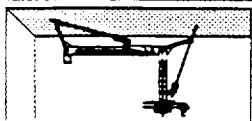
A.S.P.O.D.

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C. CONCLUSION

The design presented in this report has been completed and tested. The system is able to place a 2# object with an accuracy of 2.5 cm, this has been tested by measuring the repeatability of the arm motions with a 2# object.

This project has been a very valuable lesson to the people involved. The knowledge gained from this experience is far superior to that obtained in any previous courses. The author's knowledge of control systems, electricity, and electronics, as well as team work and the design process have been increased tremendously. The author is very grateful to the people who made this project possible through their advice and guidance.
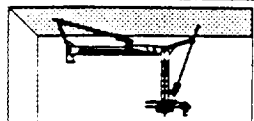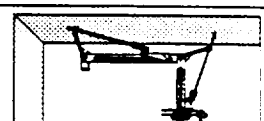
MOUNTING AND POSITIONING
OF MANIPULATOR ARM

By

Curt   Bradley
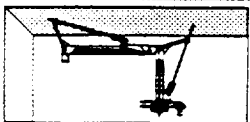
INTRODUCTION

One of the functions of ASPOD is to dissect large pieces of debris into smaller more manageable parts. These smaller pieces, if useful, can then be stored on the ASPOD craft itself. Or, if the piece is unwanted junk, it can be sent into a lower orbit that will speed it's reentry into the earth's atmosphere. It is during the cutting operation that two robotic arms are necessary. One of the arms will be used to position the debris in front of the solar cutter, the other will be needed to prevent the material from swinging forward into the solar mirror array or any other vital instruments on the craft. Also, a second arm placed at an optimal distance from the first, will offer a larger area of accessibility. What this means is that if a desirable piece of material is separated from its parent satellite, there will be a need to store this piece somewhere on the craft. The second arm, positioned correctly, could place this useful part, possibly near the solar mirror array. If the useful part happened to be reflective in nature it could be positioned in such a way to increase the effectiveness of the solar mirror array.

It is my specific task to position the second robotic arm and design a frame to hold it in place. The second arm needs to be placed near enough to the first so that both arms can grab the same object, but it also needs to be placed close to the solar mirror array so that it has access to the rear of the craft. The frame that supports the second arm must be connected to the frame of the spacecraft itself and not any external members, such as the frame of the solar mirror array. This constraint was created to allow flexibility in the design of the solar mirror setup. If the design for the solar mirrors were to change, the frame for the second arm would not need to be. Because of this uncertainty, there must be sufficient clearance
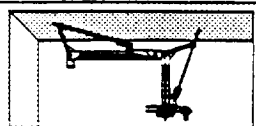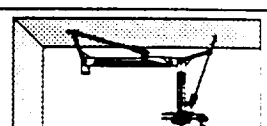
between the robotic arm frame and the frame for the mirrors. The frame must be made of a material strong enough to be able to support the weight of the robotic arm and any moments it will encounter. It should be made of a material stiff enough to keep the total deflection of a fully extended arm loaded with a two pound weight to less than 1.0 cm. Also, the frame placement must be such that it doesn't interfere with the functioning of the first robotic arm or the solar cutter. Weight must be taken into consideration because of the high cost of sending any mass into orbit.

FINAL DESIGN

My proposed frame design is shown in Appendices D.1, D.2, D.3, and D.4. Appendix D.1 shows the three views of the assembled frame and its dimensions.

Appendix D.2 is a side view of the frame with the robot arm assembly, mirror frame, and the base of the ASPOD satellite. The dashed semicircle represents the area of accessibility of the fully extended robot arm positioned perpendicular to the mirror frame. This arc does not include the length of the end effector. The directions foreword and aft are used to describe positions on the satellite. When looking at the figure, foreword or front refers to the left part of the diagram, rearward or aft refers to the right. The focal point of the solar cutter lies along the horizontal dashed line that crosses through the center of the mirror frame. This is the point where the sun's rays will be concentrated in a similar manner as they are when they pass through a magnifying glass. From the figure it appears that the robot arm is not long enough to reach the focal point, but with the end effector attached, giving it an extra thirty inches, it is able to do so. One of the purposes of our designed arm is to hold objects in front of the
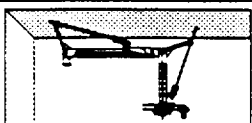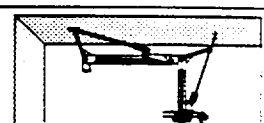
solar cutter in conjunction with the primary arm. The primary arm will be the same as the secondary arm except that it is mounted to a base that rotates about a point in the center of the base of the satellite. This point is represented by the vertical dashed line. When as object is to be cut, the piece will be held in position by the primary arm with the assistance of the secondary arm. If the cut part is then to be stored, the secondary arm will have access to any storage areas near the rear of the craft. As indicated on the drawing, the front mirror frame is two inches aft of the front of the robot arm frame. The frame was positioned here because it is the furthest aft it can be placed without the bottom brackets extending beyond the ASPOD base boundary. The frame can be moved slightly forward but is limited by the support track for the primary arm base. Clearance was given between the arm frame and mirror frame to allow for design changes in the latter.

Appendix D.3 is a front view of the frame and arm assembly surrounding the mirror frame. The dashed semicircle is the area swept out by the fully extended arm (excluding end effector) when it is positioned parallel with the front of the mirror frame. The crosshatch represents the focal point of the solar cutter.

Appendix D.4 is a top view of the arm frame with the satellite base and the mirror frame assembly. This figure includes the boundaries for the satellite and position of the support track for the primary arm base.

Appendices D.5, D.6, D.7, and D.8 are drawings of the individual parts of the support frame. When designing the brackets I kept three criteria in mind: strength and stiffness of the bracket, cost of the material, and ease of assembly. Because of these factors I chose to fabricate all three brackets out of aluminum, which is relatively cheap, has a high stiffness to

figure D.2). This would give the robot arm greater accessibility to points closer to the front mirror frame. But this tilt of sixteen degrees to the horizontal created a torque demand that was too large for the base motor, so the bracket design was changed to the present horizontal configuration. This bracket is made from 4" x 4" x .25" angle stock cut to the proper size. Through the stock two cylinders are attached using a compound called J.B. Weld. The two cylinders are machined so that they slide over the upper composite crossmembers. Presently, the center brackets are not fixed to the crossmembers, but can be by using epoxy. The arm base is connected to the center brackets by four bolts and mating nuts (not drawn).

Appendix D.8 is a drawing of the composite tubing and thread rods that are used. The composites are carbon graphite with a HMS 6 ply (the same as used for the arm). The frame is held together by the thread rods that compress the brackets into the composites. This is done to allow the frame to be disassembled and adjusted. To lower the weight of the frame the thread rods can be removed and the composites can be epoxied to the brackets. For this reason, concentric grooves were cut in the tube surfaces of the edge and bottom brackets. This was done to provide the epoxy with a larger surface area to bond to.

Aluminum rings are place around the tubes of the bottom and edge brackets to compensate for the weld bead that is present. Appendix D.9 is a drawing showing the placement of these rings with respect to the composite tubes. The rings slide over the aluminum tubes and butt up against the weld. This gives the composites a flat surface to compress upon. If the rings were not present the tubes would press up against the welds and cause stress concentrations and possible failure at their ends.
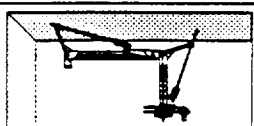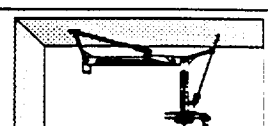
ANALYSIS

Before the frame was constructed a static analysis of the frame was performed. This was done to see if the designed frame was stiff enough to support the moments and weights of the arm, and to find the optimal placement of the thread rods. A finite elements modeling program called GIFTS was used to do this. By modeling the frame in different configurations, the best frame design was chosen.

Appendix D.10 is an isometric view of the modeled frame without the thread rods. Appendix D.11 is a front view of the same. Six models of the frame were made, each with different thread rod positions. The frames were modeled with all aluminum components because the exact characteristics of the composites were not known at the time. The frames were then loaded at four points corresponding to the loads and moments that these points would encounter if an arm were attached that was extended in a horizontal position with a ten pound weight at its end. Because these loads would change if the arm position were changed, several load cases were placed on each model. The symmetry of the arm gave deflection results that were similar but opposite in sign when compared to the opposite arm condition. For this reason the 270, 315, and 0 degree cases were the ones repeated for each load condition. When looking at Appendix D.4 (top view), the 270 degree case is where the arm is extended directly in front of the frame towards the center crosshair. This case is represented graphically in Appendix D.12. The 0 degree case is where the arm is extended towards the right mirror. Because of the unknown stiffness of the composites, all parts of the frame were modeled as aluminum.
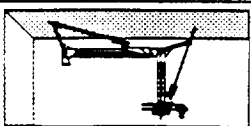
Appendix D.13 contains the model results. The first column describes the model. 'Standard' represents the model with the thread rods centered. 'Opposite Offset' represents the model with parallel rods in the same plane offset to s to each other. In other words the vertical rods in the fore members were offset to the inside and the vertical rods in the aft members were offset to the outside (inside refers to the center of the mirror frame). The fore horizontal member is offset to the bottom and the aft horizontal member is offset to the top. Column three to six contain the deflections and rotations of the point where the arm attaches to the frame. This point is labeled 'X' in Appendix D.10. From the rotations and deflections at this point, the total deflection of a fully extended arm can be calculated. This information is contained under column seven.

From this information, the standard orientation was chosen because of the small difference between the different models and the fact that this placement would be easier to fabricate.

PARTS LIST

ALUMINUM TUBING:

    41" of 2" O.D. x .125" wall thickness

    6" of 2" I.D. of .125" wall thickness (fabricated)

ALUMINUM ANGLE STOCK:

    30" of 1" x 1" x .25"

    18" of 2.5" x 2.5" x .25"

    20" of 4" x 4" x .25"

ALUMINUM PLATE:

    20" x 20" x .25"

COMPOSITE TUBING:

    4 x 34" x 2.0" I.D. x .050" wall thickness

    2 x 36.5" x 2.0" I.D. x .050" wall thickness

STEEL THREAD ROD:

    4 x 37" x .5" Dia.

    2 x 40" x .5" Dia.

STEEL BOLTS:

    12 x 3/8" x 1"

NUTS:

    24 x 1/2" coarse

    12 x 3/8" coarse

WASHERS:

    24 x 1/2" flat

    12 x 3/8" flat

    12 x 3/8" lock
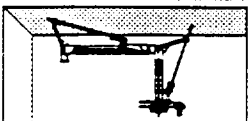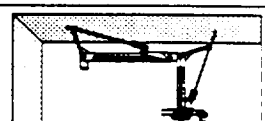
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APPENDIX A.1

OVERALL SCHEMATIC

ASPOD Manipulator Arm
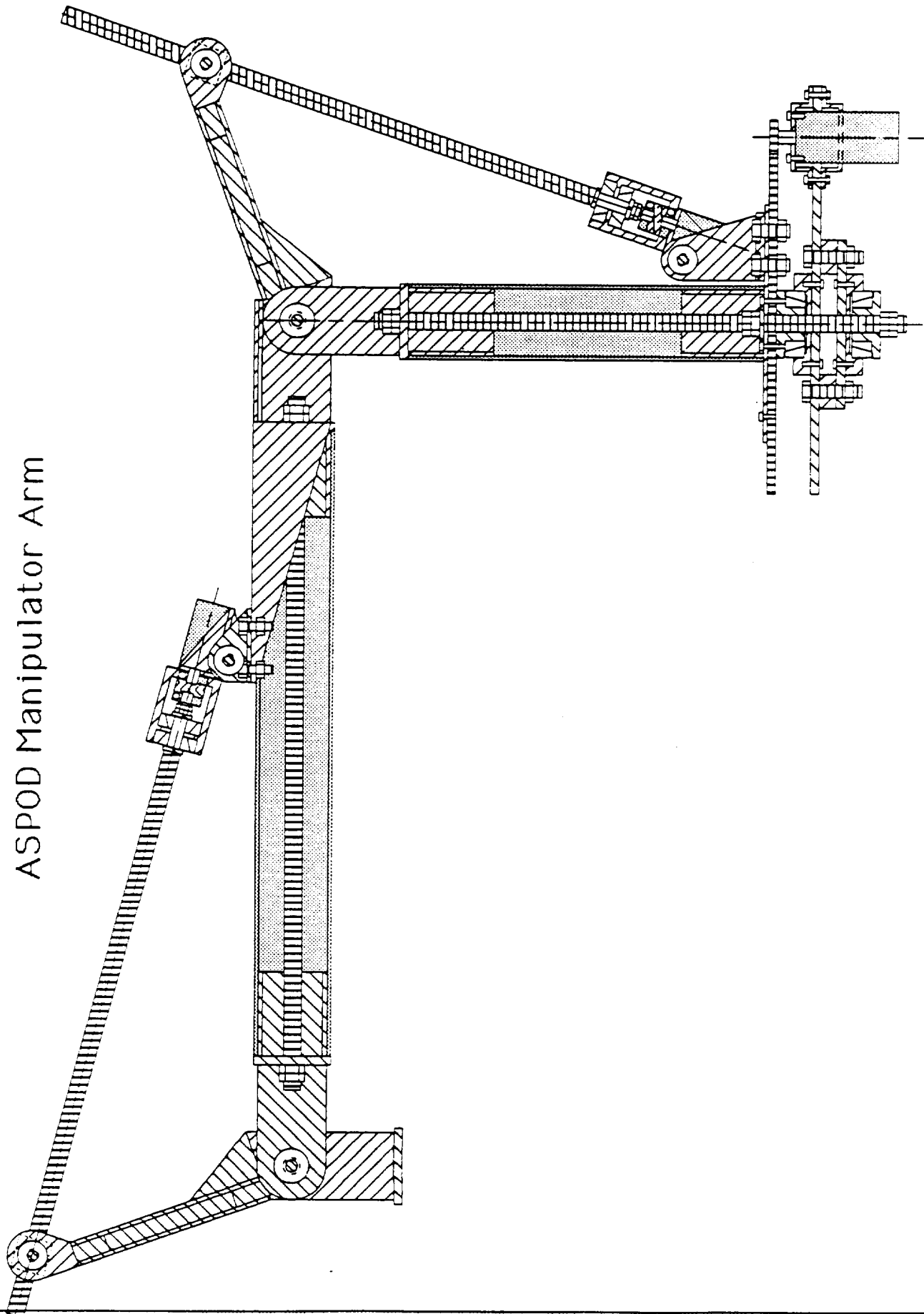
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APPENDIX A.2

INDIVIDUAL PIECE SCHEMATICS

2x

2 1/2"

1 3/4"

0.375"

1/16" gap

0.275" Dia inset

3/16" machine screw

0.5118" radius hole

3/4"

3 1/4"

1/4"

Symetrical around this line

1/2" hole
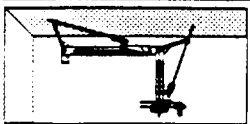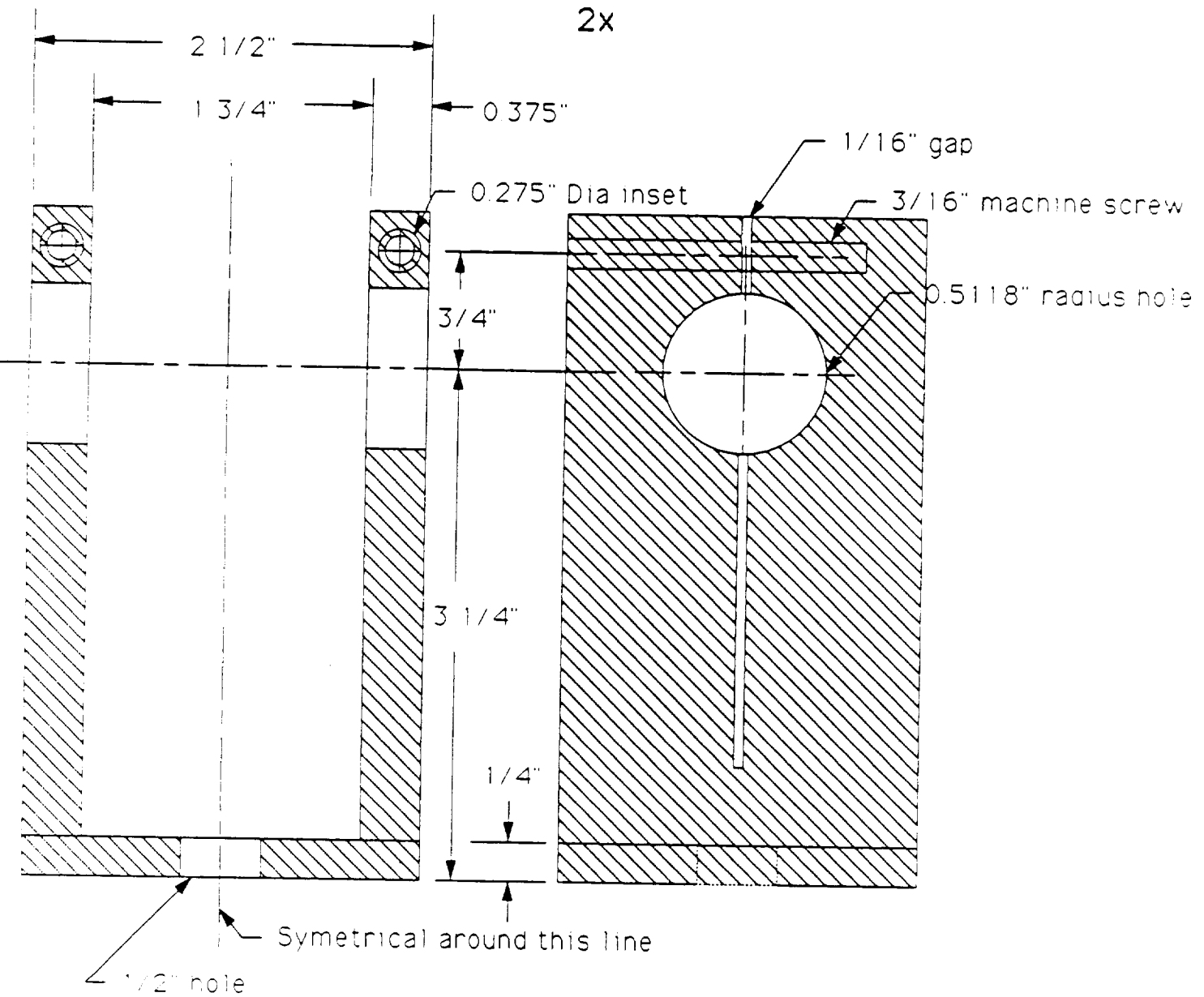
All pieces machine screwed
together using three #10
machine screws
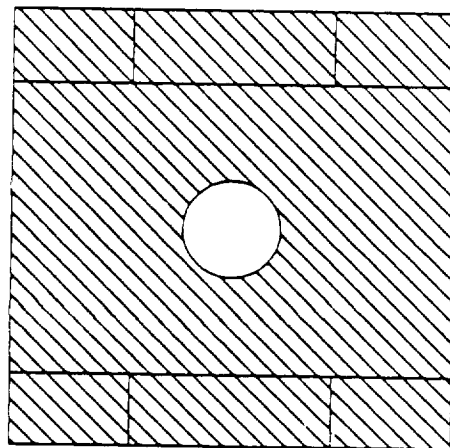
3.164 inches

A.S.P.O.D.

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3/16" Set bolt

1/2" Dia

3.60"

20.1°

2.0"

1.0"

1.5"

1.0"

4.33"

3.0"

2.5"

2 1/4"

1/2" Dia. Hole

2 1/4"

1/4"

A.S.P.O.D.

APPENDAGE ENGINEERING INC.

8661 Dia Hole

1 1/2"

1/2

3/4

1/4

1/2"

3/4

2 1/2

3

1/4"

1 0"

1 3/4 inches

3 3/4

3/8" Dia Holes

All pieces held together with #8
machine screws
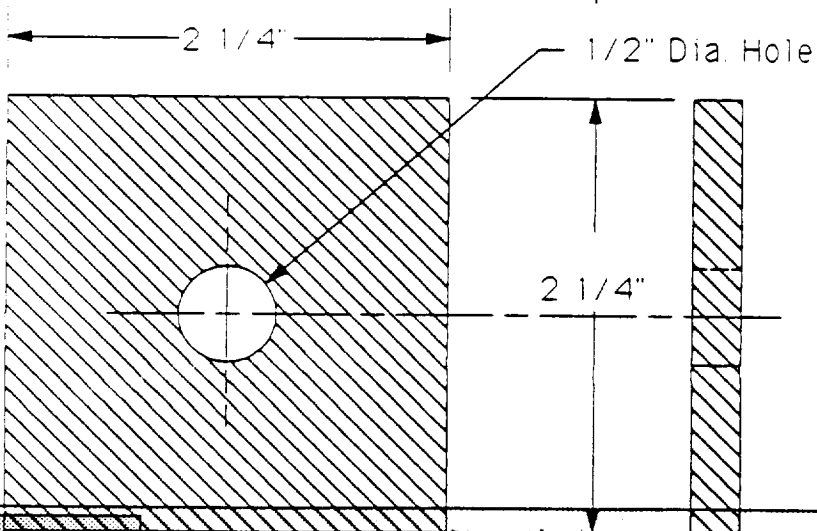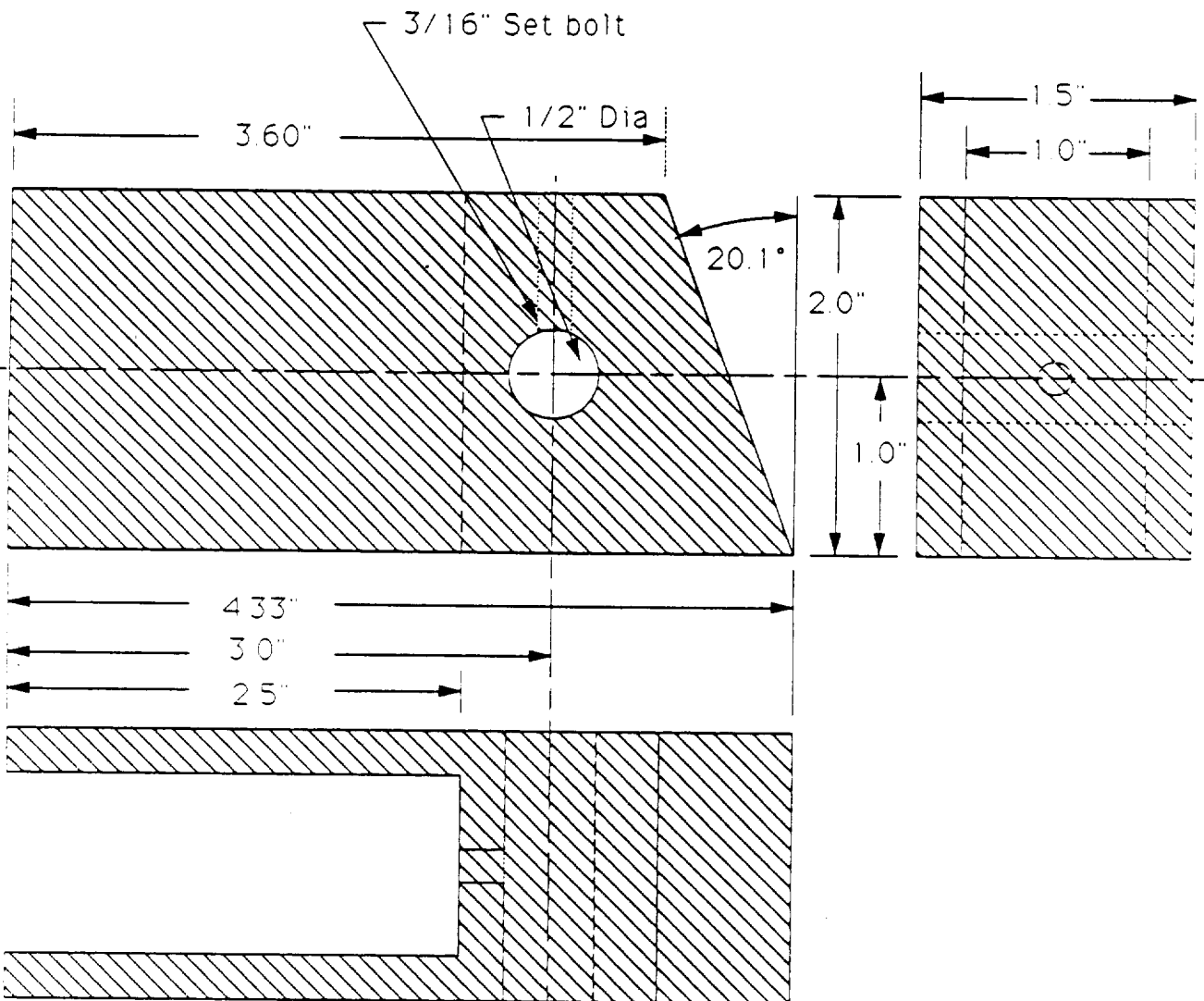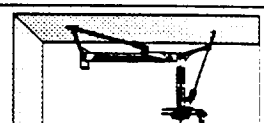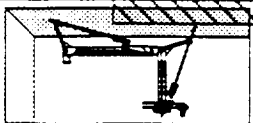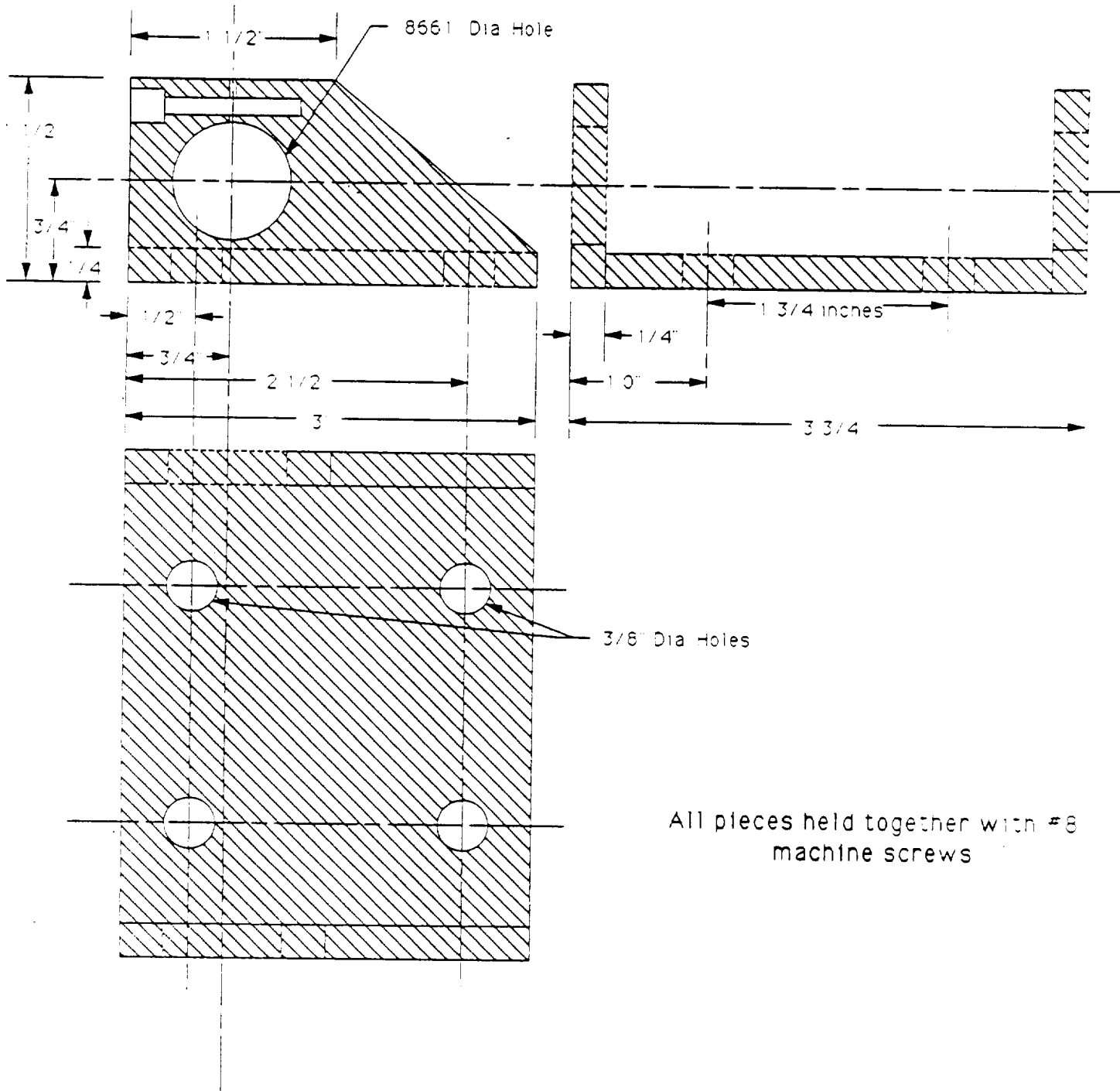
2nd Motor Support Frame
and 1st Motor Foundation

3/16" Dia Hole

3/8" Dia Holes

1/4" Dia Hole

0.866" Dia Hole

2 1/2"

2 inches

1/4"

1 1/2"

1.0"

1/2" Dia Hole

1/4" Dia Hole

2 1/8"

2 3/8"

1/8"

4 x

1/4"

1/2"

1/8"

2 1/2"

1 3/4

1 1/2

3/8" Dia. Hole

1/8
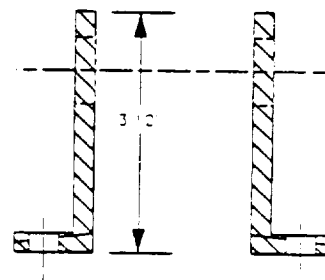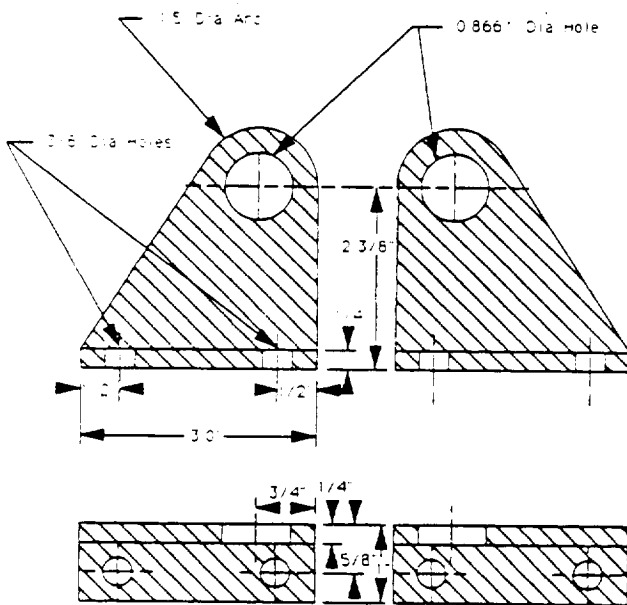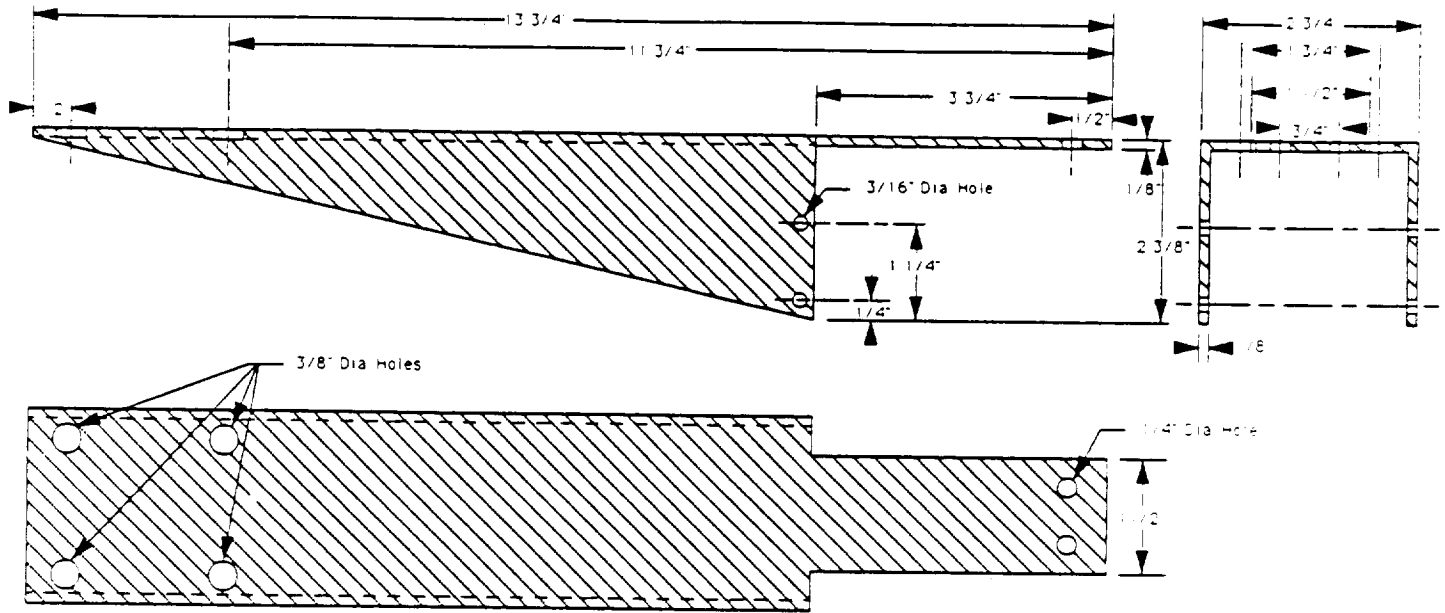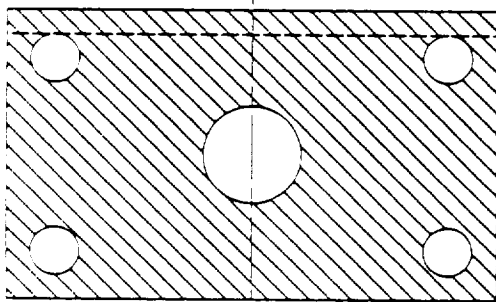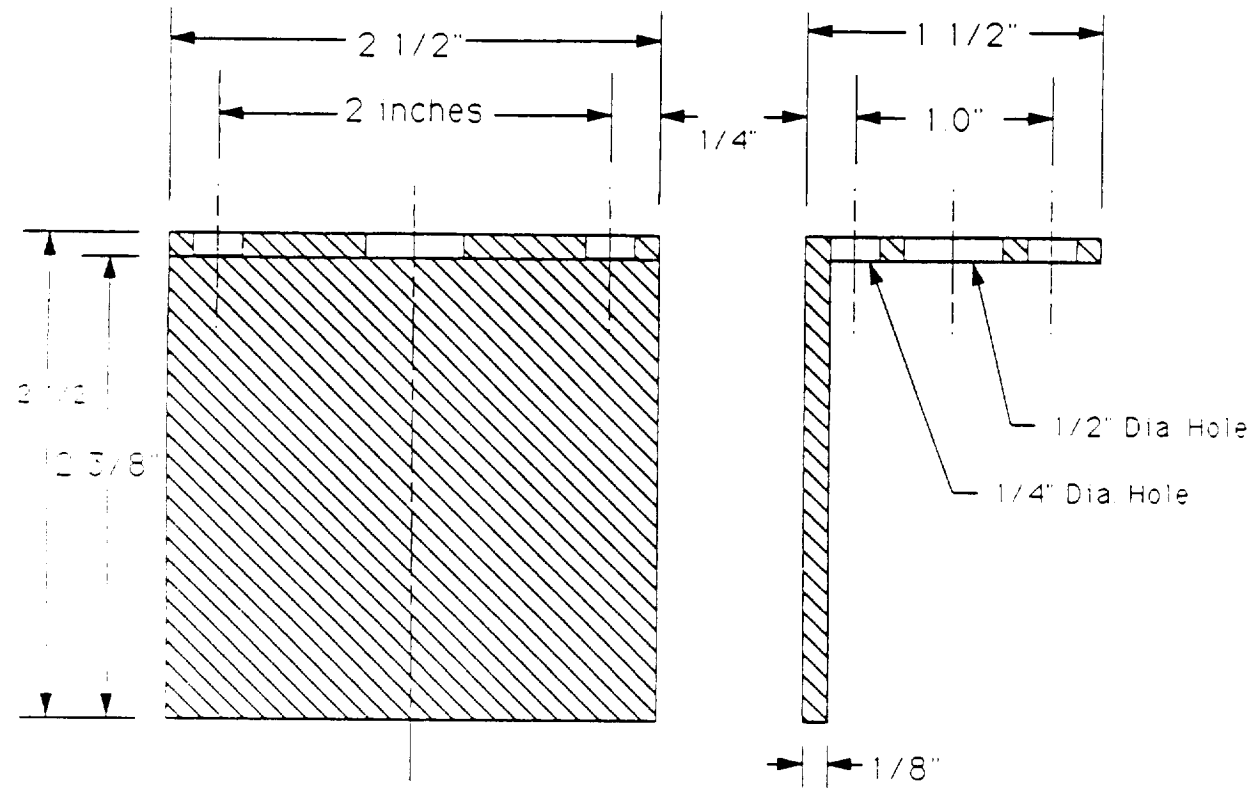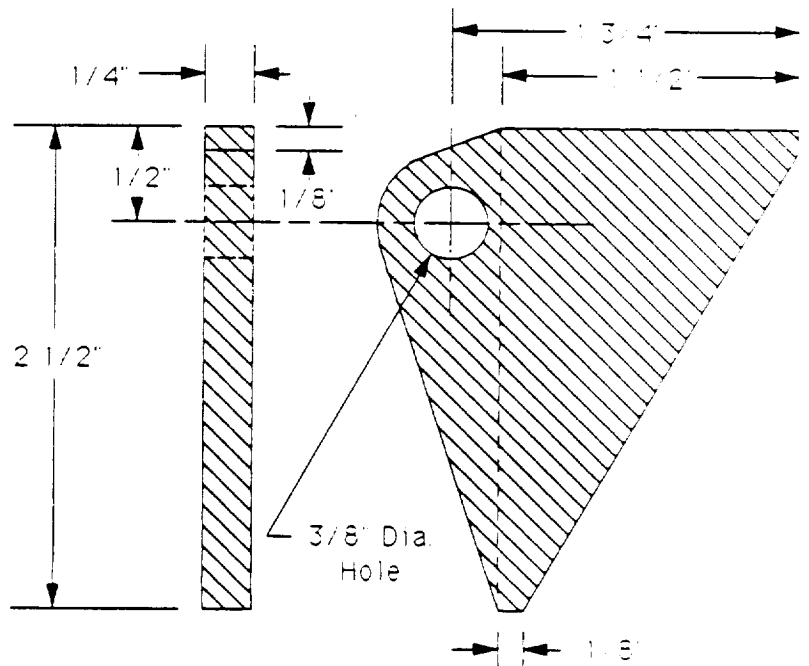
All pieces welded together

C-2

1 1/2"

0.745"

1/2"

3/8"

3"

2"

1/4"

1 1/2"

2"

5 9282"

4 9282"

0.8661" Dia Hole

2"

3/8"

1 5"
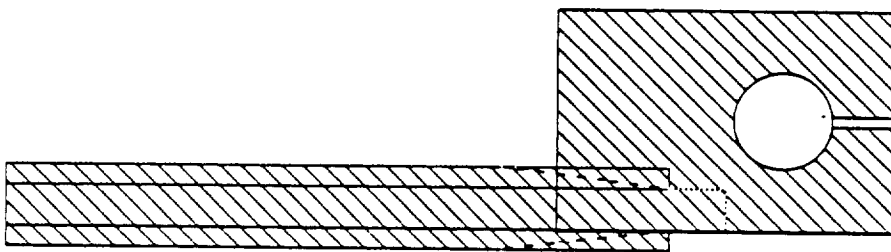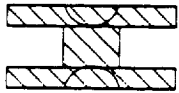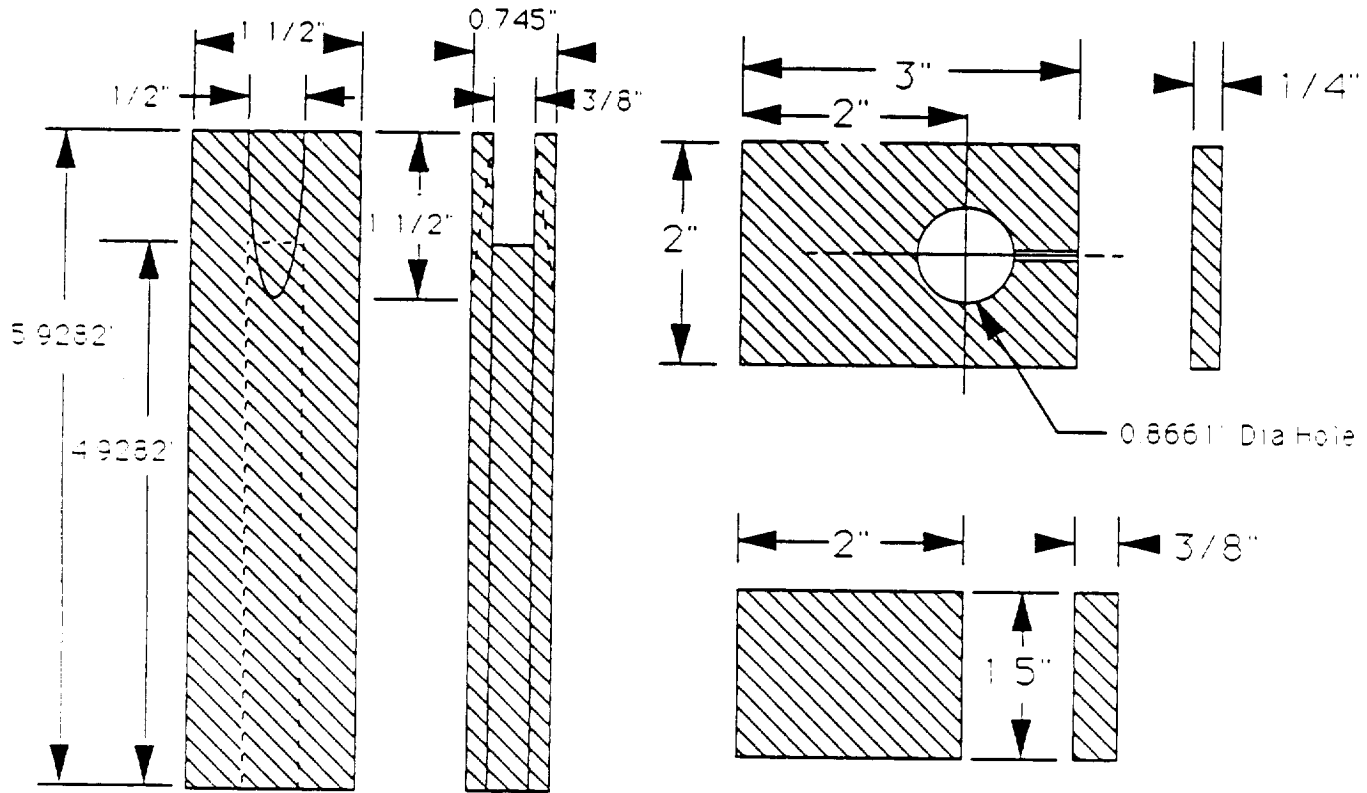
Shoulder Torque Arm 2" Shorter
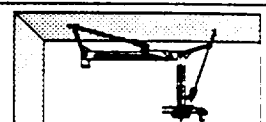
1.65"

1 1/4"

1.02"

0.395"

1/8"

2.295"

1/4"

1.00"

2 1/2"

2"

1/4" holes

1.65"

Flexible Coupling Access Slot
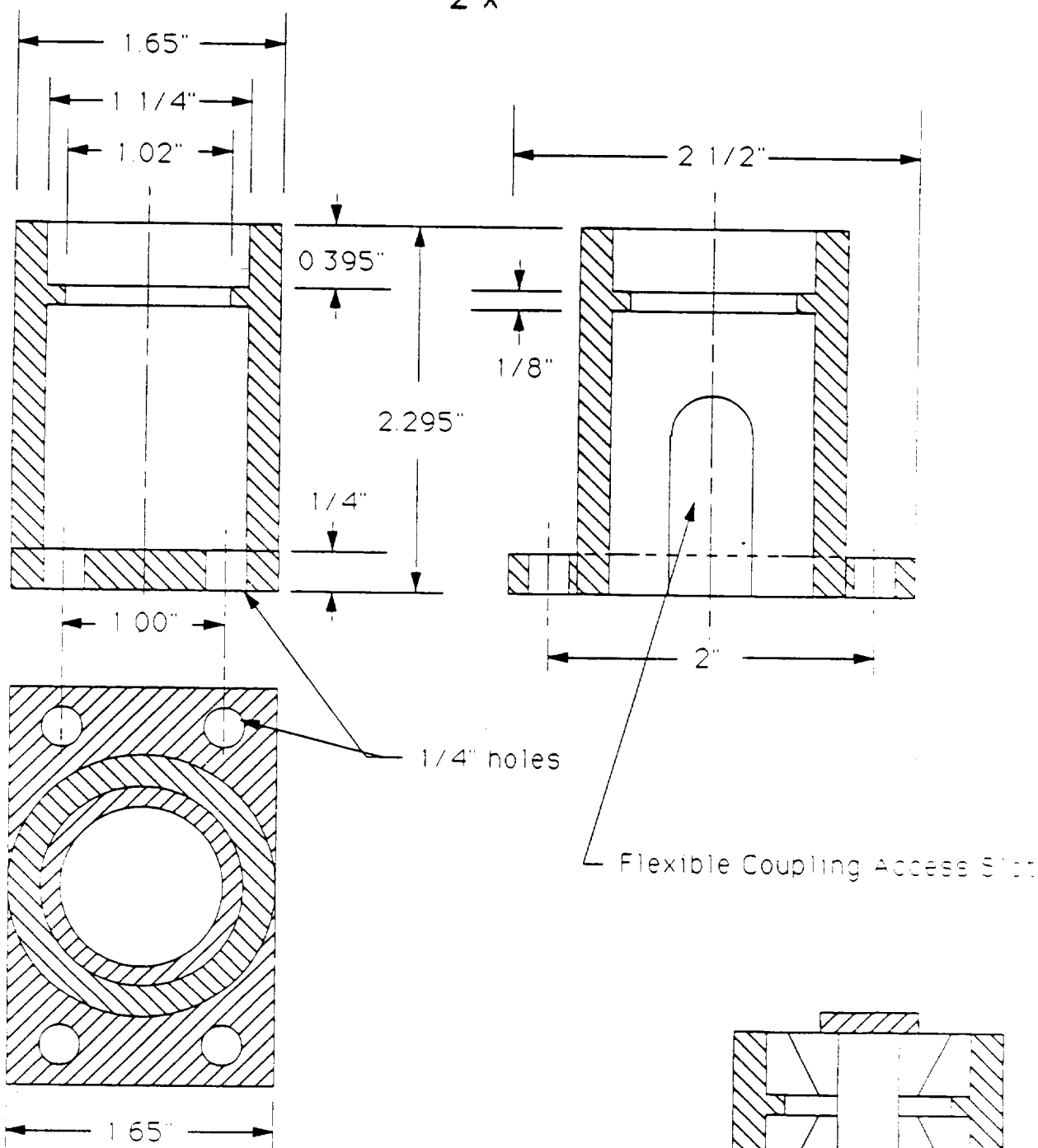
4 x

Grooves for Epoxy Adhesion
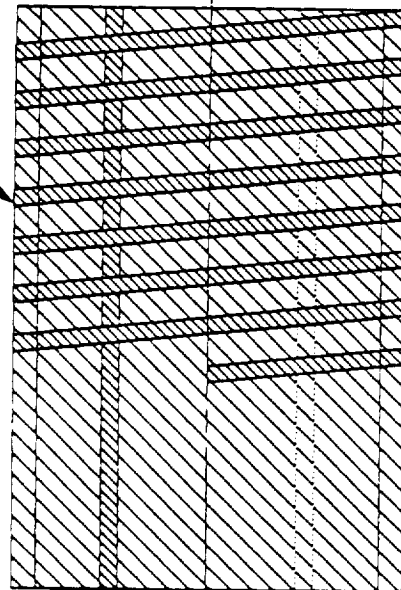
3 inches
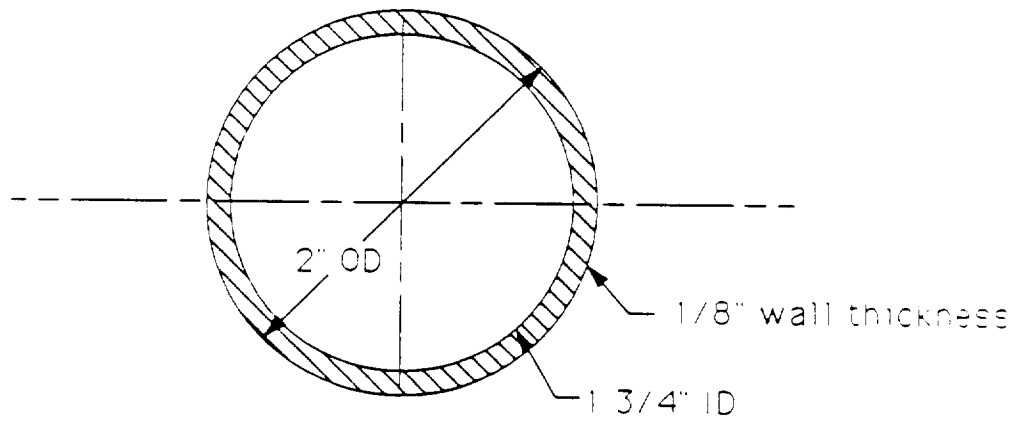
2" OD

1/8" wall thickness

1 3/4" ID

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2 1/4
20

1/2

9 3 4

8 1/2

12

20 1/2
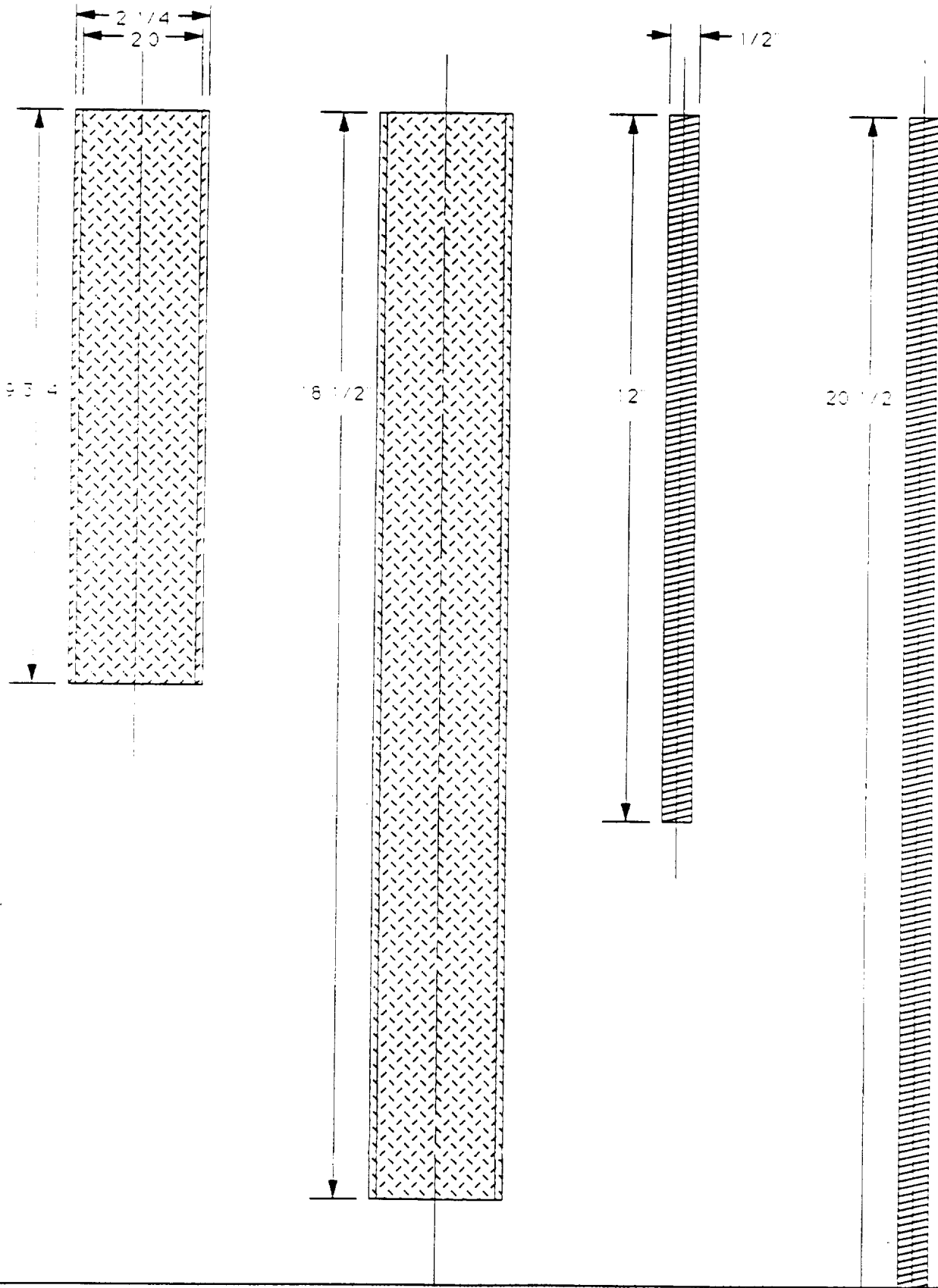
A.S.P.O.D.

APPENDAGE ENGINEERING INC.

Mounting Plate and Spacers
for Tapered Bevel Bearings

4*3/8" Dia. Holes
Arranged 2" Radius

8*1/4" Dia. Holes
Arranged 1 1/4" Rad.

3.5858"

5.0

6.4142

5

Two Motor
Mount Slots

0.55" Diameter Hole

10.0

1.5"

4 inches

7 inches

4 x

3/8" Dia Hole

1/2"

3/4"

3/4"

4*3/8" Dia Holes Arranged at 2" radius

4 inches

2.0 inch

2 inches

4 inches
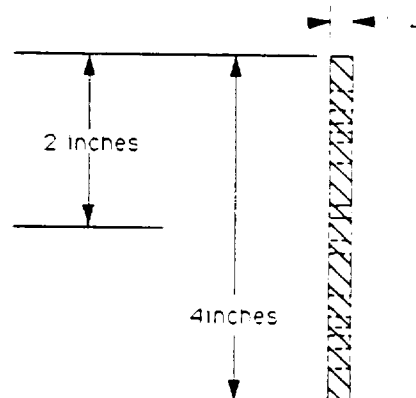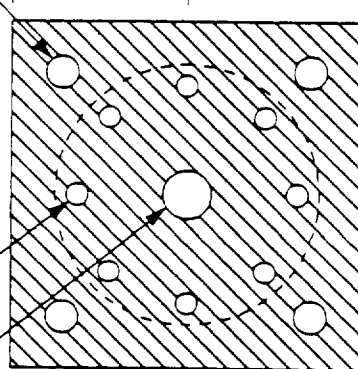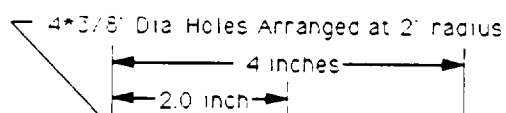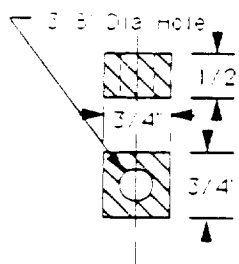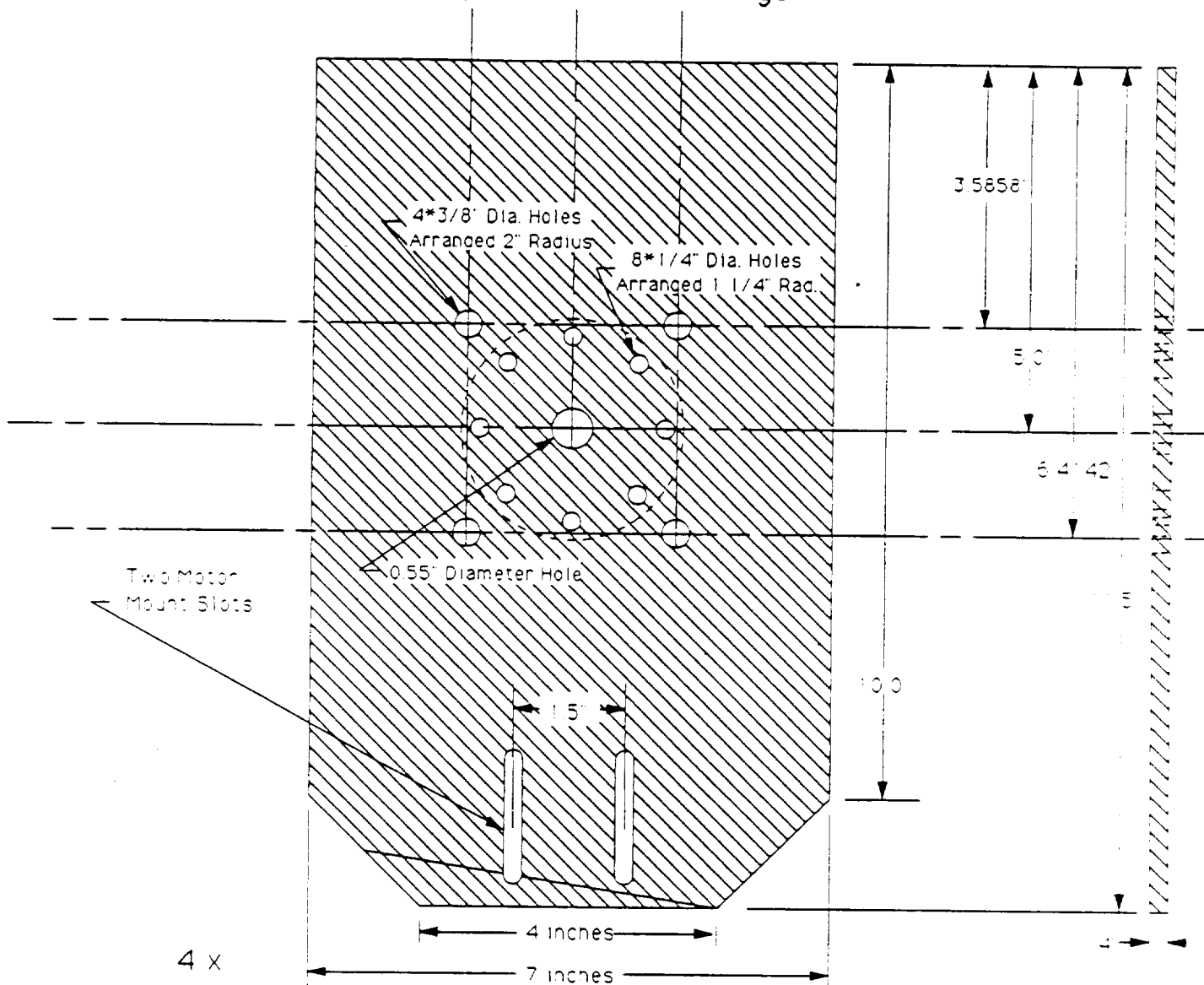
0.55" Dia Holes

8*1/4" Dia. Holes Arranged at 1 1/4" radius

3/16" Dia. Holes
11/16" Radius

1/2" Dia. Hole

3/8" Dia. Holes

2"

3 1/2"

5 1/2"

4 x 1/8"

5/8"

1/2"

5 11/16"

2 1/2"

6 3/4"

3

2 inches

4 1/2"

6"

1/8"

3/8" Dia. Holes

9 1/2" Dia Arc

1 1/16"

0.81"

0.6017"

0.56"

0.925

1/2

1/4

3/16-20 tap holes

0.8"

0.6017"

0.56

0.625

1/2

1/4"

3.0"
2 1/2"
1.98"
1 3/4"
0.55"

1/2"
0.31"
1/8"
3/8"

1/4"-20 Tapped Holes
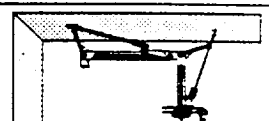
APPENDIX A.3

ITEM LIST

<u>ITEM LIST</u>

1) 2 ft by 2 ft by 1/4" sheet of aluminum
2) 2 ft by 2 ft by 1/8" sheet of aluminum
3) One 2 1/2" by 2 1/2" by 13" block of aluminum
4) Two 2" diameter by 1" long steel rod sections
5) One 2" by 1 1/2" by 9" block of aluminum
6) One 1 1/2" by 3/4" by 12" block of aluminum
7) One 2" OD aluminum tube of 1/8" wall thickness 16" long
8) Three carbon graphite composite tubes approximately 2" ID, 1/8" wall, 9 3/4" long, 10 3/8" long, and 18 1/2" long
9) Threaded Steel Bolts 1/2" Diameter 12" long, 15 1/2" long, 20 1/2" long
10) 26 1/4-20 bolts 1/2" length
11) 4 1/4-20 bolts 2" long with lock washers and nuts
12) 2 SKF Type TS Single Row Tappered Bearings D-1.98" Bore-1" Width-0.56"
13) 2 AC 087-10 Heli-Cal Flexible Couplings
14) 4 Timken Single Row Straight Bore A2037, A2126 Bearings Type TS D-1.2595" Bore-0.3750" Width-0.3940"
15) 8 SKF Single Row Deep Groove Ball Bearings Designation 608 Bore-0.3150" D-0.8661" Width-0.2756"
16) 4 SKF Single Row Deep Groove Ball Bearings Designation 6000 Bore-0.3937" D-1.0236" Width-0.3150"
17) 8 3/8" bolts 1" long with lock-washers and nuts
18) 4 3/8" bolts 2" long with lock-washers and nuts
19) 10 5mm bolts 10mm long
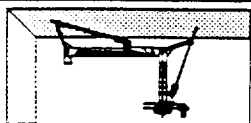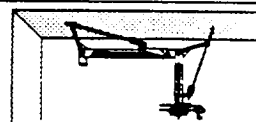
APPENDIX A.4

SUPPLIERS

SKF
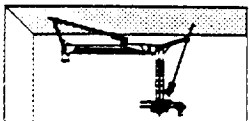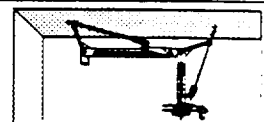
Product Service Guide

Atlantic ⬤ Tracy, Inc.
bearings & power transmission equipment

44 THIRD AVENUE
SOMERVILLE, MA 02143
617-666-3850

190-710
NOVEMBER 1985

Sales Offices
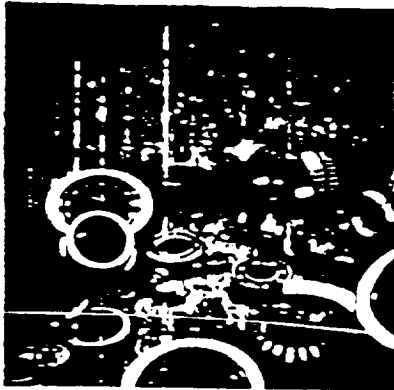
ATLANTA, GA
Suite 110 Bldg. 400
American Business Center
1395 Marietta Parkway
Marietta, GA 30067
Telephone—404 426 6853

*(Warehouse)
680A—Wharton Circle S.W.
PO Box 43545
Atlanta, GA 30336
Telephone—404 691 7755

BIRMINGHAM, AL
Suite 215
1 Riverchase Office Plaza
Birmingham, AL 35244
Telephone—205 988 4232

BUFFALO, NY
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331 Alberta Drive
Amherst, NY 14226
Telephone—716 837 5244

CHARLOTTE, NC
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5501 Executive Center Drive
Charlotte, NC 28212
Telephone—704 568 5500

CHICAGO, IL
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2 Crossroads of Commerce
Rolling Meadows, IL 60008
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7770 Cooper Road
Cincinnati, OH 45242
Telephone—513 793 1990

CLEVELAND, OH
Room 104
21403 Chagrin Blvd
Beachwood, OH 44122 5397
Telephone—216 491 9200

DALLAS, TX
Suite 208
14675 Midway Road
Dallas, TX 75244
Telephone—214 387 7977

DENVER, CO
Suite 210
7500 E Arapahoe Road
Englewood, CO 80112
Telephone—303 850 9431

DETROIT, MI
Suite 200
21650 W Eleven Mile Road
Southfield, MI 48076
Telephone—313 353 5255

HARTFORD, CT
Suite 102
750 Old Main Street
Rocky Hill, CT 06067
Telephone—203 529 6871

HOUSTON, TX
Suite 126
4420 FM 1960 West
Houston, TX 77068 3497
Telephone—713 440 3914

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32107 Lindero Canyon Road
Westlake Village, CA 91361
Telephone—818 991 9770

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5885 Hyatt Ridgeway Parkway
Memphis, TN 38119
Telephone—901 682 4323

MILWAUKEE, WI
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450 N Sunnyslope Road
Brookfield, WI 53005
Telephone—414 785 9920

MINNEAPOLIS, MN
Suite 546
Southtown Office Park
8120 Penn Avenue, South
Bloomington, MN 55431
Telephone—612 884 2402

MOBILE, AL
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Building B
3780 Dauphin Street
Mobile, AL 36606
Telephone—205 479 5484

NEW YORK, NY
118 North Avenue West
Cranford, NJ 07016
Telephone—201-272-9646

ORLANDO, FL
Suite 252
Essex Building
3101 Maguire Blvd
Orlando, FL 32803
Telephone—305-896-8571

PHILADELPHIA, PA
Suite 1109
996 Old Eagle School Road
Wayne, PA 19087
Telephone—215 688 7775

PHOENIX, AZ
Suite 15
Building A105
9830 N 32nd Street
Phoenix, AZ 85028
Telephone—602-971-0116

PITTSBURGH, PA
Suite 140
9800 McKnight Road
Pittsburgh, PA 15237
Telephone—412-931-2955

PORTLAND, OR
Suite 235
8835 S W Canyon Lane
Portland, OR 97225-3474
Telephone—503-297-8076

QUAD CITIES, IA
Suite 223
Brenton Bank Bldg
Davenport, IA 52803
Telephone—319-322-7105

RENO, NV
*(Warehouse)
300 Edison Way
PO Box 10303
Reno, NV 89502
Telephone—702 323 0311

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Suite 300-300A
Clayton Plaza Bldg
7750 Clayton Road
St Louis, MO 63117
Telephone—314 647 3444

SALT LAKE CITY, UT
Spring Run Executive Plaza
Suite 3H
969 East 4800 South
Salt Lake City, UT 84117
Telephone—801 268 6633

SAN FRANCISCO, CA
Suite 206
150 N Wiget Lane
Walnut Creek, CA 94598 2496
Telephone—415 943 1800

TULSA, OK
Suite 136
Osage Bldg
9726 E 42nd Street
Tulsa, OK 74146
Telephone—918 622 7330

YOUNGSTOWN, OH
*(Warehouse)
100 Victoria Road
PO Box Drawer D
Youngstown, OH 44515
Telephone—216 799 1561

AUTOMOTIVE SALES
Suite 375
6735 Telegraph Road
Birmingham, MI 48010
Telephone—313-540 0580

FLEET PRODUCT SALES
SKF Automotive Products Div
2320 Marconi Avenue
St Louis, MO 63110
Telephone—314 776 4800
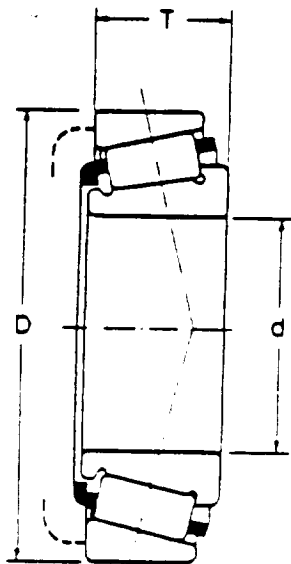
Bore d	Outside Dam D	Width T	Basic Load Rating C, lbf. N	Axial Load Factor Y	Cone	Cup
0.9835 24.981	2.0470 51.994	0.5910 15.011	5 290 23 500	1.50	07098	07204
0.9843 25.000	1.9687 50.005	0.5313 13.495	5 290 23 500	1.50	07097	07196
	2.0470 51.994	0.5910 15.011	5 290 23 500	1.50	07097	07204
1.0000 25.400	1.9687 50.005	0.5313 13.495	5 290 23 500	1.50	07100	07196
	1.9800 50.292	0.5600 14.224	5 740 25 500	1.60	L44643	L44610
	2.0470 51.994	0.5910 15.011	5 290 23 500	1.50	07100	07204
	2.4375 61.913	0.7500 19.050	9 290 41 300	1.70	15101	15243
	2.4375 61.913	0.7500 19.050	9 290 41 300	1.70	15100	15243
	2.4410 62.000	0.8125 20.638	9 290 41 300	1.70	15101	15244
	2.4410 62.000	0.8125 20.638	9 290 41 300	1.70	15100	15244
	2.4410 62.000	0.7500 19.050	9 290 41 300	1.70	15101	15245
	2.4410 62.000	0.7500 19.050	9 290 41 300	1.70	15100	15245
	2.5000 63.500	0.8125 20.638	9 290 41 300	1.70	15101	15250
	2.5000 63.500	0.8125 20.638	9 290 41 300	1.70	15101	15250X
	2.5000 63.500	0.8125 20.638	9 290 41 300	1.70	15100	15250
	2.5000 63.500	0.8125 20.638	9 290 41 300	1.70	15100	15250X
1.0300 26.162	2.4375 61.913	0.7500 19.050	9 290 41 300	1.70	15103S	15243
	2.4410 62.000	0.7500 19.050	9 290 41 300	1.70	15103S	15245
	2.4410 62.000	0.8125 20.638	9 290 41 300	1.70	15103S	15244
	2.5000 63.500	0.8125 20.638	9 290 41 300	1.70	15103S	15250
	2.5000 63.500	0.8125 20.638	9 290 41 300	1.70	15103S	15250X
1.0625 26.988	1.9800 50.292	0.5600 14.224	5 740 25 500	1.60	L44649	L44610
	2.4375 61.913	0.7500 19.050	9 290 41 300	1.70	15106	15243

*Bearing number consists of a cone number and a cup number
NOTE: Additional sizes available Consult your SKF representative

Single Row Deep Groove Ball Bearings

PLAIN

B

d · D

NO SHIELD

TYPE Z
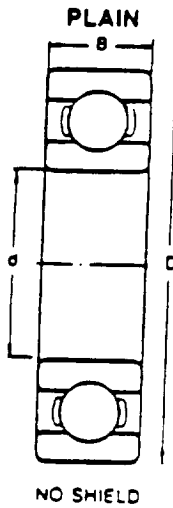
ONE SHIELD

Boundary Dimensions			Basic Load Rating C	Speed Limit [1]	Max Fillet Radius	Bearing Mass	Designation and Type				
Bore d	Outside Diameter D	Width B					Plain	One Shield	Two Shields	One Seal	Two Seal
mm in	mm in	mm in	N lbf	rpm	mm in	kg lbs		Z	2Z	RS	2 RS
3 0.1181	10 0.3937	4 0.1575	488 110	48 000	0.1 0.004	0.0015 0.0033	623	623 Z	623 2Z	—	—
4 0.1575	13 0.5116	5 0.1969	884 199	45 000	0.2 0.008	0.0031 0.0068	624	624 Z	624 2Z	—	—
	16 0.6299	5 0.1969	1 110 250	40 000	0.3 0.012	0.0054 0.012	634	634 Z	634 2Z	—	—
5 0.1969	16 0.6299	5 0.1969	1 110 250	40 000	0.3 0.012	0.0050 0.011	625	625 Z	625 2Z	—	—
	19 0.7480	6 0.2362	1 720 387	38 000	0.3 0.012	0.0090 0.020	635	635 Z	635 2Z	—	—
6 0.2362	19 0.7480	6 0.2362	1 720 387	38 000	0.3 0.012	0.0084 0.019	626	626 Z	626 2Z	626 RS	626 2RS
7 0.2756	19 0.7480	6 0.2362	1 720 387	40 000	0.3 0.012	0.0075 0.016	607	607 Z	607 2Z	607 RS	607 2RS
	22 0.8661	7 0.2756	3 250 731	36 000	0.3 0.012	0.013 0.028	627	627 Z	627 2Z	627 RS	627 2RS
8 0.3150	22 0.8661	7 0.2756	3 250 731	38 000	0.3 0.012	0.012 0.026	608	608 Z	608 2Z	608 RS	608 2RS
9 0.3543	24 0.9449	7 0.2756	3 710 835	36 000	0.3 0.012	0.014 0.031	609	609 Z	609 2Z	609 RS	609 2RS
	26 1.0236	8 0.3150	4 620 1 040	32 000	0.3 0.012	0.020 0.044	629	629 Z	629 2Z	629 RS	629 2RS
10 0.3937	26 1.0236	8 0.3150	4 620 1 040	34 000	0.3 0.012	0.0055 0.012	6000	6000 Z	6000 2Z	6000 RS	6000 2RS
	30 1.1811	9 0.3543	5 070 1 140	30 000	0.6 0.024	0.032 0.071	6200	6200 Z	6200 2Z	6200 RS	6200 2RS
	35 1.3780	11 0.4331	8 060 1 810	26 000	0.6 0.024	0.053 0.11	6300	6300 Z	6300 2Z	6300 RS	6300 2RS

[1] This refers to oil lubrication and moderate load. Consult SKF for lower limits applicable to grease lubrication
Series 61800 — 618/900, 16100 — 16101, 16002 — 16072, 6032 — 60/630, 61938 — 619/750 and 6740 — 6756 available from SKF TransAtlantic
Series 6700 through 6220 and 6303 through 6317 are also available as precision bearings (ABEC 5)

TIMKEN

REGISTERED TRADEMARK

TAPERED ROLLER BEARINGS

BEARING
SELECTION
HANDBOOK
REVISED - 1986
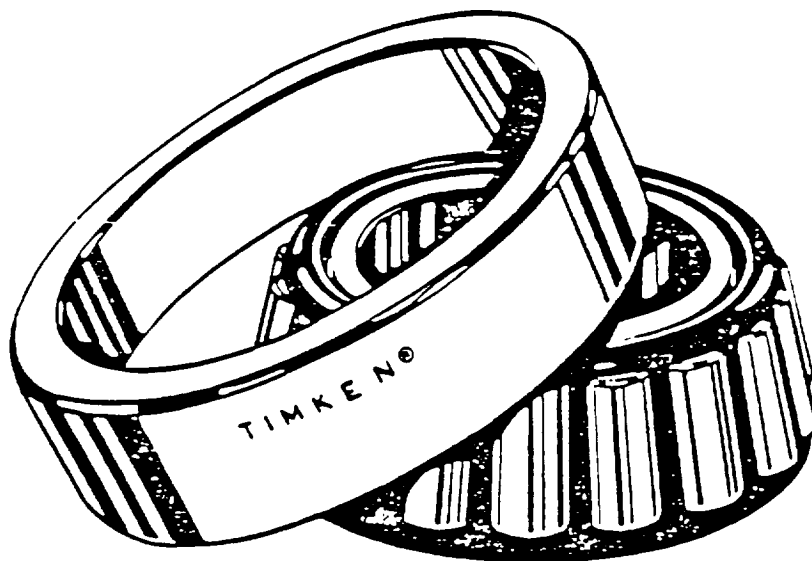
THE TIMKEN COMPANY

SINGLE-ROW STRAIGHT BORE

bore	outside diameter D	width T	rating at 500 rpm for 3000 hours L10 — one-row radial N/lbf	rating — thrust N/lbf	factor K	eff. load center aD	part numbers — cone	part numbers — cup	cone r	cone B	cone db	cone da	cup r	cup width C	cup Db	cup Da
9.525 / 0.3750	31.991 / 1.2595	10.008 / 0.3940	2750 / 618	1910 / 429	1.44	-3.0 / -0.12	A2037	A2126	1.3 / 0.05	10.785 / 0.4246	15.0 / 0.59	13.5 / 0.53	1.3 / 0.05	7.938 / 0.3125	26.0 / 1.02	29.0 / 1.14
†11.986 / †0.4719	31.991 / 1.2595	10.008 / 0.3940	2750 / 618	1910 / 429	1.44	-3.0 / -0.12	A2047	A2126	0.8 / 0.03	10.785 / 0.4246	16.5 / 0.65	15.5 / 0.61	1.3 / 0.05	7.938 / 0.3125	26.0 / 1.02	29.0 / 1.14
12.680 / 0.4992	34.988 / 1.3775	10.998 / 0.4330	3160 / 710	2450 / 550	1.29	-2.5 / -0.10	A4049	A4138	0.8 / 0.03	10.988 / 0.4326	17.5 / 0.69	17.5 / 0.59	1.3 / 0.05	8.730 / 0.3437	29.0 / 1.14	32.0 / 1.26
12.700 / 0.5000	34.988 / 1.3775	10.998 / 0.4330	3160 / 710	2450 / 550	1.29	-2.5 / -0.10	A4050	A4138	1.3 / 0.05	10.988 / 0.4326	18.5 / 0.73	17.0 / 0.67	1.3 / 0.05	8.730 / 0.3437	29.0 / 1.14	32.0 / 1.26
12.700 / 0.5000	38.100 / 1.5000	13.495 / 0.5313	5010 / 1130	2360 / 531	2.12	-5.1 / -0.20	00050	00150	1.5 / 0.06	14.072 / 0.5540	19.0 / 0.75	16.5 / 0.65	0.8 / 0.03	11.112 / 0.4375	33.0 / 1.30	34.0 / 1.34
†14.989 / †0.5901	34.988 / 1.3775	10.998 / 0.4330	3160 / 710	2450 / 550	1.29	-2.5 / -0.10	A4059	A4138	0.8 / 0.03	10.988 / 0.4326	19.5 / 0.77	19.0 / 0.75	1.3 / 0.05	8.730 / 0.3437	29.0 / 1.14	32.0 / 1.26
15.000 / 0.5906	42.000 / 1.6535	14.250 / 0.5610	8310 / 1420	3080 / 6930	2.05	-4.6 / -0.18	◆30302	◆30302	1.0 / 0.04	13.000 / 0.5118	20.5 / 0.81	18.0 / 0.75	1.0 / 0.04	11.000 / 0.4331	36.5 / 1.44	38.5 / 1.52
15.875 / 0.6250	34.988 / 1.3775	10.998 / 0.4330	3650 / 820	1990 / 447	1.83	-3.3 / -0.13	L21549	L21511	1.3 / 0.05	10.998 / 0.4330	21.5 / 0.85	19.5 / 0.77	1.3 / 0.05	8.712 / 0.3430	29.0 / 1.14	32.5 / 1.28
15.875 / 0.6250	39.992 / 1.5745	12.014 / 0.4730	3220 / 724	2900 / 653	1.11	-1.5 / -0.06	A6062	A6157	1.3 / 0.05	11.153 / 0.4391	22.0 / 0.87	20.5 / 0.81	1.3 / 0.05	9.525 / 0.3750	34.0 / 1.34	37.0 / 1.46
15.875 / 0.6250	41.275 / 1.6250	14.288 / 0.5625	5770 / 1300	3070 / 690	1.88	-5.1 / -0.20	03062	03162	1.3 / 0.05	14.681 / 0.5780	21.5 / 0.85	20.0 / 0.79	2.0 / 0.08	11.112 / 0.4375	34.0 / 1.34	37.5 / 1.48
15.875 / 0.6250	42.862 / 1.6875	14.288 / 0.5625	4510 / 1010	5430 / 1220	0.83	-1.3 / -0.05	11590	11520	1.5 / 0.06	14.288 / 0.5625	24.5 / 0.96	22.5 / 0.89	1.5 / 0.06	9.525 / 0.3750	34.5 / 1.36	39.5 / 1.56
15.875 / 0.6250	42.862 / 1.6875	16.670 / 0.6563	7550 / 1700	4280 / 962	1.76	-5.8 / -0.23	17580	17520	1.5 / 0.06	16.670 / 0.6563	23.0 / 0.91	21.0 / 0.83	1.5 / 0.05	13.495 / 0.5313	36.5 / 1.44	39.0 / 1.54
15.875 / 0.6250	47.000 / 1.8504	14.381 / 0.5662	6420 / 1440	3920 / 881	1.64	-4.1 / -0.16	05062	05185	1.5 / 0.06	14.381 / 0.5662	23.5 / 0.93	21.0 / 0.83	1.3 / 0.05	11.112 / 0.4375	40.5 / 1.59	42.5 / 1.67
15.875 / 0.6250	49.225 / 1.9380	19.845 / 0.7813	10300 / 2310	4680 / 1050	2.20	-9.1 / -0.36	09062	09195	0.8 / 0.03	21.539 / 0.8480	22.0 / 0.87	21.5 / 0.85	1.3 / 0.05	14.288 / 0.5625	42.0 / 1.65	44.5 / 1.75
15.875 / 0.6250	†53.975 / †2.1250	22.225 / 0.8750	11200 / 2510	11300 / 2540	0.99	-5.8 / -0.23	21063	21212	0.8 / 0.03	21.839 / 0.8598	29.0 / 1.14	26.0 / 1.03	2.3 / 0.09	15.875 / 0.6250	43.0 / 1.69	50.0 / 1.97
†15.987 / †0.6294	†46.975 / †1.8494	21.000 / 0.8268	9630 / 2170	9000 / 2020	1.07	-6.1 / -0.24	HM81649	HM81610	1.0 / 0.04	21.000 / 0.8268	27.5 / 1.08	23.0 / 0.90	2.0 / 0.08	16.000 / 0.6299	37.5 / 1.48	43.0 / 1.69
16.993 / 0.6690	39.992 / 1.5745	12.014 / 0.4730	3220 / 724	2900 / 653	1.11	-1.5 / -0.06	A6067	A6157	0.8 / 0.03	11.153 / 0.4391	22.0 / 0.87	21.0 / 0.83	1.3 / 0.05	9.525 / 0.3750	34.0 / 1.34	37.0 / 1.46
16.993 / 0.6690	47.000 / 1.8504	14.381 / 0.5662	6420 / 1440	3920 / 881	1.64	-4.1 / -0.16	05066	05185	1.5 / 0.06	14.381 / 0.5662	24.5 / 0.96	22.0 / 0.87	1.3 / 0.05	11.112 / 0.4375	40.5 / 1.59	42.5 / 1.67
17.000 / 0.6693	40.000 / 1.5748	13.250 / 0.5217	5190 / 1170	3060 / 689	1.69	-3.8 / -0.14	◆30203	◆30203	1.0 / 0.04	12.000 / 0.4724	22.0 / 0.87	21.0 / 0.83	1.0 / 0.04	11.000 / 0.4331	35.0 / 1.38	37.0 / 1.46

① These maximum fillet radii will be cleared by the bearing corners.
② Minus value indicates center is inside cone backface.
† For standard class ONLY, the maximum metric size is a whole millimetre value.
* For "J" part tolerances—see metric tolerances, page 73 and fitting practice, page 65.
◆ ISO cone and cup combinations are designated with a common part number and should be purchased as an assembly. For ISO bearing tolerances—see metric tolerances, page 73 and fitting practice, page 65.

REPRESENTATIVE
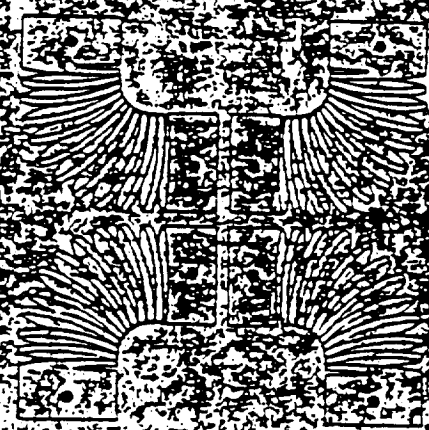
HELICAL
PRODUCTS COMPANY, INC.

HELI-CAL

ROTATING SHAFT FLEXIBLE COUPLINGS

FEATURES:
ALUMINUM ALLOY, ANODIZED
SHAFT ATTACHMENT
  INTEGRAL CLAMP
  SET SCREW
COMPONENT SHAFTS MAY BUTT
ANGULAR OFFSET
PARALLEL OFFSET
ONE PIECE CONSTRUCTION
NO LUBRICATION
NO BACKLASH
CONSTANT VELOCITY

INTEGRAL CLAMP ATTACHMENT
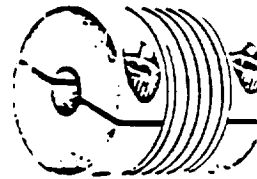
AC SERIES
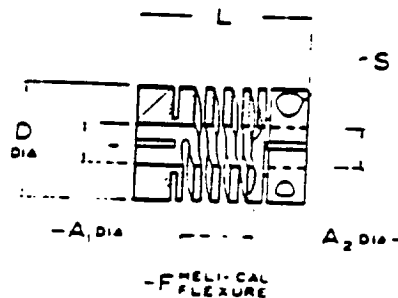
ACR SERIES
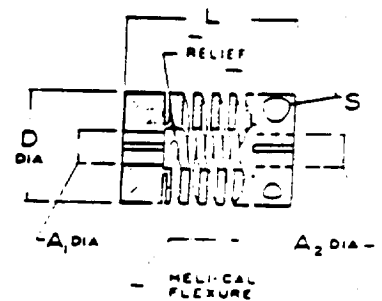
D DIA. inches	A₁ & A₂ DIA. +.002 / -.000 BORE CODE DASH NUMBERS & STANDARD SHAFT COMBINATIONS For use with Shaft Diameter of								(AC Model Number)	L Length ±.005"	S Cap Screw	F Flexure Space	(ACR Model Number)	L Length ±.005"	S Cap Screw
	1/2 .500	3/8 .375	5/16 .313	1/4 .250	3/16 .188	5/32 .157	1/8 .125	3/32 .094							
.50							-4	-3	AC 050 [ ] [ ]	.75	1-72	.25	ACR 050 [ ] [ ]	.75	1-72
.75				-8	-6	-5	-4		AC 075 [ ] [ ]	.90	4-40	.35	ACR 075 [ ] [ ]	.90	4-40
1.00		-12	-10	-8					AC 100 [ ] [ ]	1.25	6-32	.45	ACR 100 [ ] [ ]	1.25	6-32

> MAJOR SHAFT DIAMETER

Any combination of shaft bore can be furnished for any model up to major shaft diameter.

METRIC BORES AVAILABLE
SEE NOTE 6

To allow the bore with integral clamp attachment the minimum shaft length is increased. Consult factory for dimension.

INSTALLATION NOTES. For installation the coupling may slide on the major or minor shaft.

MINOR DIAMETER SHAFT MAY EXTEND INTO FLEXURE AREA
UNEQUAL DIAMETER SHAFTS

MAJOR DIAMETER SHAFT MUST CLEAR FLEXURE OPERATION

EQUAL DIAMETER SHAFTS

RELIEF COUPLINGS

UNEQUAL DIAMETER SHAFTS — RELIEF

MAJOR AND MINOR DIAMETER SHAFTS MAY ENTER FLEXURE AREA DURING OPERATION — RELIEF

EQUAL DIAMETER SHAFTS — RELIEF

HELICAL PRODUCTS COMPANY, INC.

APPENDIX   A.5

STRESS ANALYSIS
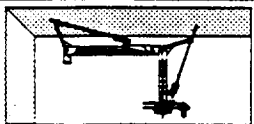
1 1/2"

0.1866"

1/2"   0.375"

0.1860"

5.9252"

226.67 lbs

226.67 lbs

21,500 oz·in or 1343.75 lb·in

Y_{max}

$E = 0.3$ Mpsi

$G = 3.8$ Mpsi

I-Beam weight = ...

I-Beam weight = 0.93 lbs
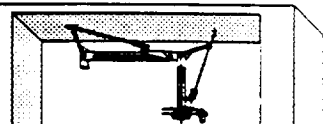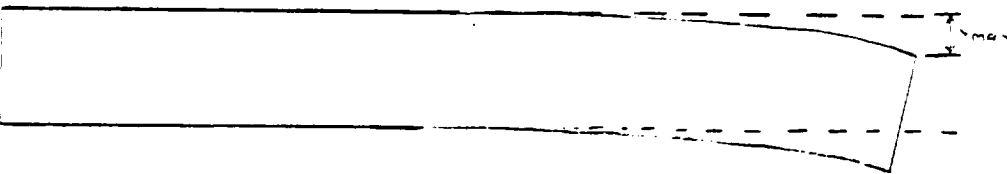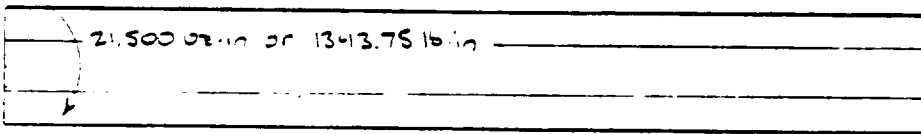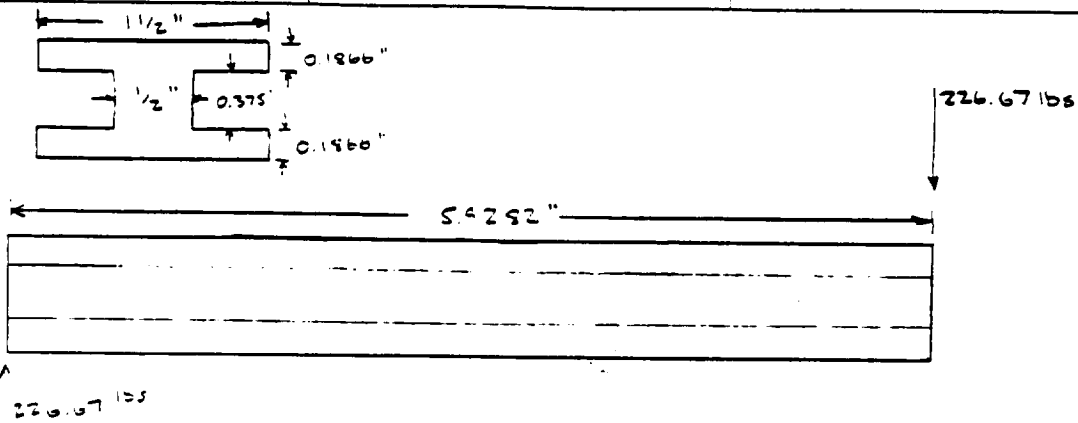
$$Y_{max} = \frac{-FL^3}{3EI}$$

$$Y_{max} = \frac{-226.67 \text{ lbs} (5.9252 \text{ in.})^3}{3(0.3 \times 10^6 \text{ psi/in}^2) I}$$

$I_{z_1} = I_{z_3} = 8.22 \times 10^{-4}$ in

$I_{z_2} = (.5)(.375)^3 = 3.197 \times 10^{-3}$ in

$I_z = (8.22 \times 10^{-4}) + 2.47 \times 10^{-3} + 0 + (.1866)(1.5)(\frac{.375 + .}{2})^2 \times 2$

$I_z = 7.790 \times 0$ in

$Y_{max} = 0.03.93$ in

$\sigma = \frac{My}{I}$ $\tau = \frac{F}{A}$

$\sigma = 5$ kpsi

$\sigma_{max} = \frac{1343.75 \text{ lb·in} (.375 - \frac{.}{2}) \text{ in}}{... }$

$\sigma_{max} = 13.121$ kpsi

$\tau = 353.3$ psi

$$\sum M_z = 0 \qquad 13.375 \text{ lb} \cdot \text{in} = [F_1 + F_2(.65625) + F_3 + F_4)(1.3.35)$$
$$+ F_5(1.6875)]$$

assuming ... for ... ...

$$\text{if } F_1 = F_2 = F_3 = F_4 = F_5$$

$$F_1 \rightarrow F_5 = 13.375 \text{ lb}$$

$$\sigma = \frac{F}{A} = \frac{13.375}{.05} = 267.5 \text{ psi}$$

Friction coefficient is small $\mu = 0.10$

Friction resistance
Shear Force
clamping Force

assuming 1 inch moment arm

Friction Force $= 13.375 \text{ lbf} (0.10)$
$$= 13.375 \text{ lbf}$$

Combining shear force $= 500 \text{ lbf} + 2(?) = \frac{(\text{lbf})^2}{2}$
$$= 3817 \text{ lbf}$$

Combining shear max shear force without ... of friction
$$= 516.1 \text{ lbf}$$

APPENDIX B

DRIVE SYSTEMS ANALYSIS
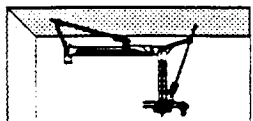
BASE MOTOR ANALYSIS

* EQUATION DERIVATION

* MATLAB PROGRAM

$$I_{zz} \left(\text{plate} \right) = \tfrac{1}{2} mr^2$$

$$I_{zz} = \tfrac{1}{2} mr^2$$

$$\left. \begin{aligned} I_{x m_2} &= \left[\tfrac{1}{4} mr^2 + \tfrac{1}{12} m l^2 \right] \cos \theta_2 \\ I_{z m_2} &= \left[\tfrac{1}{2} mr^2 \right] \sin \theta_2 \end{aligned} \right\} \quad I_2' = \left[\tfrac{1}{4} mr^2 + \tfrac{1}{12} m l^2 \right] \cos \theta_2 + \left[\tfrac{1}{2} mr^2 \right] \sin \theta_2$$

$$\left. \begin{aligned} I_{x m_3} &= \left[mr^2 + \tfrac{1}{12} m l^2 \right] \cos(\theta_2 + \theta_3) \\ I_{z m_3} &= \left[\cdots \right] \sin(\theta_2 + \theta_3) \end{aligned} \right\} \quad I_3' = \left\{ \left[\tfrac{1}{4} mr^2 + \tfrac{1}{12} m l^2 \right] \cos(\theta_2 + \theta_3) + \left[\cdots mr^2 \right] \sin(\theta_2 + \theta_3) \right\}$$

+ TRANSLATE BACK TO zz_1 AXIS

$$I_2'' = I_2' + m \left[\tfrac{L_2}{2} \cos \theta_2 \right]^2$$

$$I_3'' = I_3' + m \left[L_2 \cos \theta_2 + \tfrac{L_3}{2} \cos(\theta_2 + \theta_3) \right]^2$$

$$I_{m_1} = \tfrac{1}{2} mr^2 + m c^2$$

$$I_{x m_2} = \left\{ \tfrac{1}{4} mr^2 + \tfrac{1}{12} m l^2 \right\} \cos \theta_2$$

$$I_{z m_2} = \left[\tfrac{1}{2} mr^2 \right] \sin \theta_2 \qquad I_{m_2} = \left\{ \tfrac{1}{4} mr^2 + \tfrac{1}{12} m l^2 \cos \theta_2 - \cdots mr^2 \sin \theta_2 \right\}$$

$$I_{m_2}'' = I_{m_2} + m \left[L_2 \cos \theta_2 \right]^2$$

$$I_{x,4} = \left[\frac{1}{4}mr^2 + \frac{1}{12}ml^2\right]\cos\theta_2 \cdot \theta_3 \Bigg\}$$
$$I_{zz4} = \frac{1}{2}mr^2 \sin(\theta_2 \cdot \theta_3) \Bigg\} \quad I_4' = \left\{\left[\frac{1}{4}mr^2 + \frac{1}{12}ml^2\right]\cos(\theta_2 + \theta_3) + \left[\frac{1}{2}mr^2\right]\sin(\theta_2 + \theta_3)\right.$$

TRANSLATED:

$$I_4'' = I_4' + m\left[L_2\cos\theta_2 + (L_3 + E)\cos(\theta_2 + \theta_3)\right]^2$$

FULL EQUATIONS TRANSLATED BACK

LINK 1:
$$\qquad\qquad I = \frac{1}{2}mr^2 = \frac{1}{2} \text{ kg m}^2$$
$$I_1'' = \frac{1}{2}mr^2$$

LINK 2:
$$I_2'' = \left[(\tfrac{1}{4}mr^2 + \tfrac{1}{12}ml^2)\cos\theta_2 + (\tfrac{1}{2}mr^2)\sin\theta_2\right] + m_2 \cdot \left[\frac{L_2}{2}\cos\theta_2\right]^2$$

LINK 3:
$$I_3'' = \left[(\tfrac{1}{4}mr^2 + \tfrac{1}{12}ml^2)\cos(\theta_2 + \theta_3) + (\tfrac{1}{2}mr^2)\sin(\theta_2 + \theta_3)\right] + m_3\left[L_2\cos\theta_2 + \frac{L_3}{2}\cos(\theta_2 + \theta_3)\right]^2$$

EXT. 4:
$$I_4'' = \left[\tfrac{1}{4}mr^2 + \tfrac{1}{12}ml^2\cos(\theta_2 + \theta_3) + (\tfrac{1}{2}mr^2)\sin(\theta_2 + \theta_3)\right] + m_4\left[L_2\cos\theta_2 + (L_3 + E)\cos(\theta_2 + \theta_3)\right]$$

MOTOR 1:
$$I_{m_1}'' = \left[\tfrac{1}{2}mr^2 + m_n(\cdot)\right]^2$$

MOTOR 2:
$$I_{m_2}'' = \left[(\tfrac{1}{4}mr^2 + \tfrac{1}{12}ml^2)\cos\theta_2 + (\tfrac{1}{2}mr^2)\sin\theta_2\right] + m_{m_2}\left[D\cos\theta_2\right]^2$$

TOTAL $I'' = I_1'' + I_2'' + I_3'' + I_4'' + I_{m_1}'' + I_{m_2}''$

NOW, $T = I\ddot\theta$

```matlab
function f = TI(a,b)

ramp = 0;

%convert degrees to radians
a = a*pi/180;
b = b*pi/180;

%a=pi/180*[-50:1:90];
%a=a(:);
%[m,n]=size(a);

%db = 50/(m-1);

%b=pi/180*[0:-db:-50];
%b=b(:);

%Define the masses of the links (1-3) and motors(5-6) and extension(4)
%in (kg)
m1 = 11.33;
m2 = 4.082;
m3 = 4.082;
m4 = 9.071;
m5 = 0.4535;
m6 = 0.4535;

%Define the radius of links(1-3), extension(4), and motors(5,6) in (m)
r1 = 0.0254;
r2 = 0.0254;
r3 = 0.0254;
r4 = 0.0254;
r5 = 0.01905;
r6 = 0.01905;

%Define the lengths of the links in (m)
L1 = 0.3495;
L2 = 0.635;
L3= 0.37465;
L4= 0.414;
L6= 0.0762;


%Define the lengths of CG of motors(C,D) and extension (E) in (in)
D = 0.2032;
```

```
C = 0.0254;


% Translated mass moments of inertia (Kg-m^2)

I_1= 0.5*m1*r1^2;

I_2=((0.25*m2*r2^2+0.0833*m2*L2^2)*cos(ramp+a))+m2*((L2/2)*cos(ramp+a)).^2;

I_3= ((0.25*m3*r3^2 + 0.0833*m3*L3^2)*cos(ramp + a + b) + (0.5*m3*r3^2)*sin(ram
+ a + b)) + m3*((L2)*cos(ramp + a) + (L3/2)*cos(ramp + a + b)).^2;

I_4=((0.25*m4*r4^2 + 0.0833*m4*L4^2)*cos(ramp + a + b) + (0.5*m4*r4^2)*sin(ramp
+ a + b)) + m4*((L2)*cos(ramp + a) + (L3 + (L4/2))*cos(ramp + a + b)).^2;

Im5=(0.5*m5*r5^2 + m5*(C)^2);

Im6=((0.25*m6*r6^2 + 0.0833*m6*L6^2)*cos(ramp + a) + (0.5*m6*r6^2)*sin(ramp +
)) + m6*(C*cos(ramp + a)).^2;

otal_inertia= I_2 + I_3 + I_4  + Im6 + Im5 + I_1;


set the incline angle of the platform as being 16 degrees
amp = 16*pi/180;



= Total_inertia;
```

OF POOR QUALITY
ORIGINAL PAGE IS

SECOND AND THIRD LINK MOTOR ANALYSIS

* EQUATION DERIVATION

* TABLE OF RESULTS

* GRAPHS
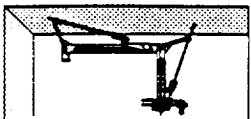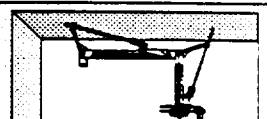
INERTIA CALCULATIONS

SECOND LINK
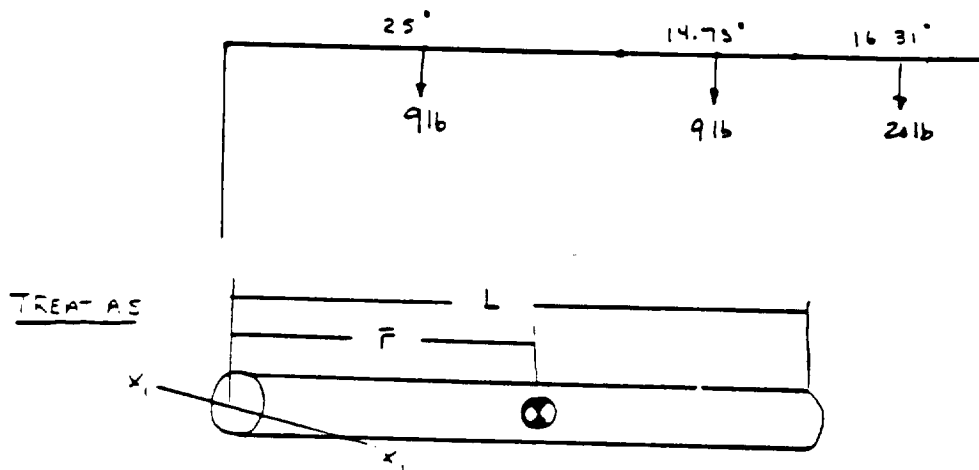
$$\bar{r} = \frac{\Sigma M r}{\Sigma M} = \frac{(9lb)(12.5in) + (9lb)(32.375in) + (20lb)(47.90in)}{(38lb)} = \underline{35.83\ IN}$$

$$L = \underline{50.06\ IN}$$

$$I_{x,x_1} = \frac{1}{4}mr^2 + \frac{1}{3}mL^2 = \frac{1}{4}(38lb)(2in)^2 + \frac{1}{3}(38lb)(50.06in)^2 = \underline{39.845\ E3\ lb\ in^2}$$

$$I_{x,x_1} = \underline{11.64\ kg\ m^2}$$

THIRD LINK

$$\bar{r} = \frac{\Sigma M r}{\Sigma M} = \frac{(9lb)(7.375in) + (20lb)(22.9in)}{(29lb)}$$
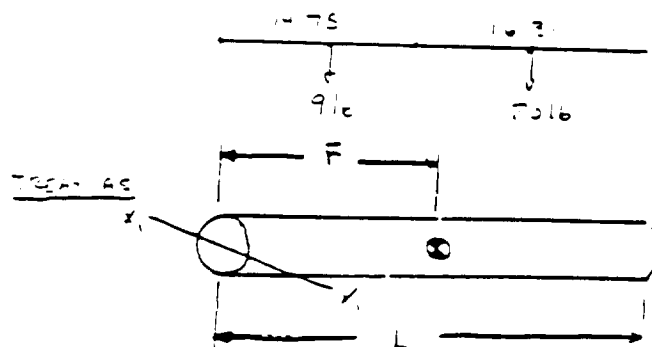
$$\bar{r} = \underline{18.08\ IN}$$

$$L = \underline{31.06\ IN}$$

$$I_{x,x_1} = \frac{1}{4}mr^2 + \frac{1}{3}mL^2 = \frac{1}{4}(29lb)(2in)^2 + \frac{1}{3}(29lb)(31.06in)^2 = \underline{9354.6\ lb\ in^2}$$

$$I_{x,x_1} = \underline{3.65\ kg\ m^2}$$
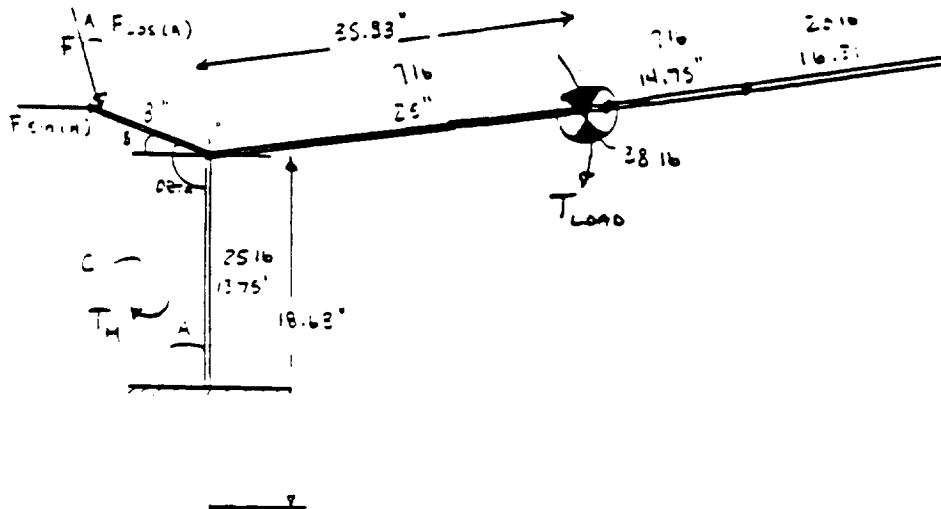
$$c = \sqrt{(8\text{in})^2 + (18.63\text{in})^2 - 2(8\text{in})(18.63\text{in})\cos(\theta\text{ETA})} \quad [\text{IN}]$$

$$\text{LSA} = \cos^{-1}\left[\frac{(18.63\text{in})^2 + c^2 - (8\text{in})^2}{2(18.63\text{in})^2(c)}\right] \quad [\text{Degrees}]$$

$$F = \frac{T_{LOAD}}{\cos(A)(8\text{in})\cos(E) - \sin(A)(8\text{in})\sin(E)} - \frac{(35.83\text{in})\cos 20^\circ - 8)(88\text{lb})}{\cos(A)(8\text{in})\cos(E) - \sin(A)(8\text{in})\sin(E)} \quad [\text{lb}]$$

$$T_M = \frac{F L}{2\pi \varepsilon} = \left[\frac{F(0.2\ \text{in/rev})(16\frac{oz}{lb})}{2(\pi \times 0.95)}\right] \quad [\text{oz-in}]$$

$$C = \sqrt{\,B^2 - (25\,in)^2 - 2(B + X 25\,in)\cos(B)} \qquad [\text{IN}]$$

$$\angle A = \cos^{-1}\left[\frac{(25\,in)^2 - C^2 - (B\,in)^2}{(2)(25\,in)(C)}\right] \qquad [\text{Degrees}]$$

$$F = \frac{T_{LOAD}}{\cos(A)(B\,in)\sin(B) + \sin(A)(B\,in)\cos(B)} = \frac{(29\,lb)\cos(20-B)(18.08\,in)}{\cos(A)(B\,in)\sin(B) + \sin(A)(B\,in)\cos(B)} \qquad [\text{LB}]$$

$$T_M = \frac{F}{2 \pi E} = \frac{F(0.5\text{ }^{in}/\text{rev})}{2(\pi)(0.95)}\left(16\frac{oz}{lb}\right) \qquad [oz \cdot in]$$

Tstatic

torque arm angle w.r.t. horizontal

Tmotor (Shoulder) vs Speed
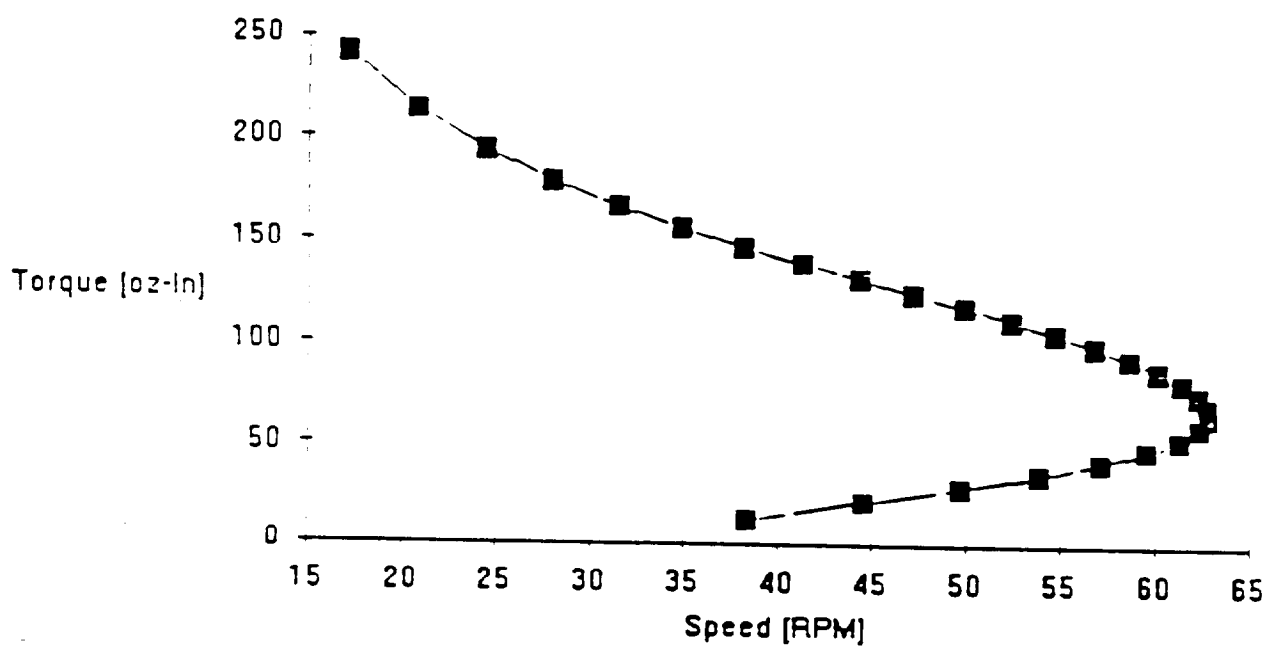
SHOULDER JOINT
Ts·all
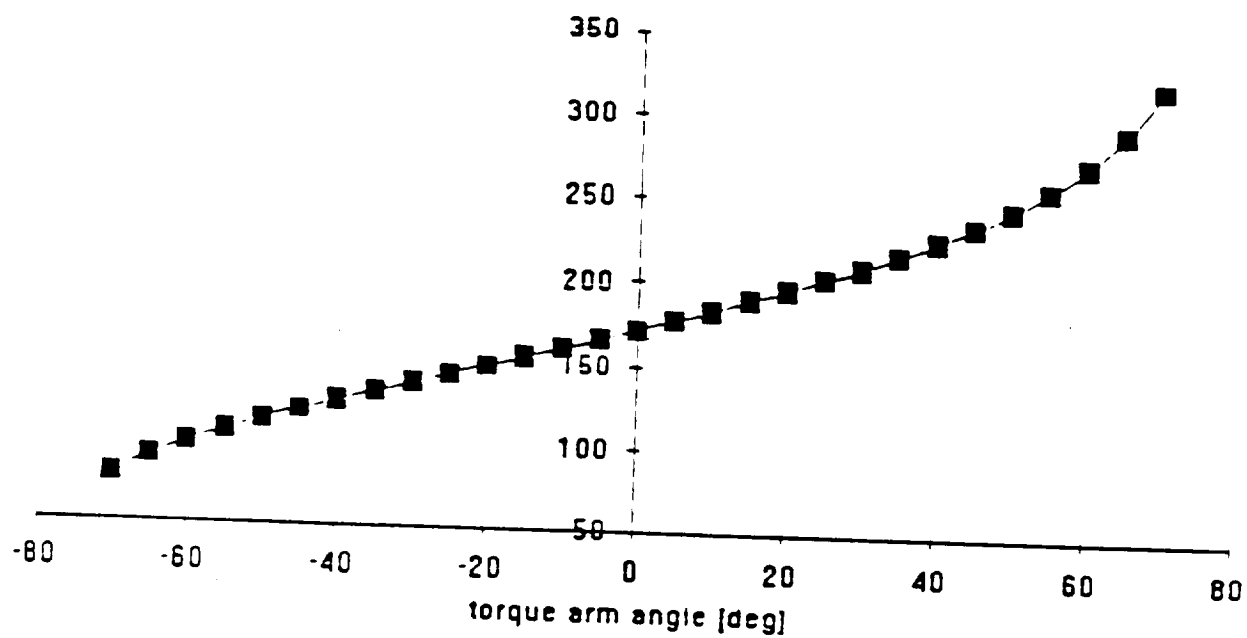
Tmotor [Elbow] vs Speed

speed [rpm]
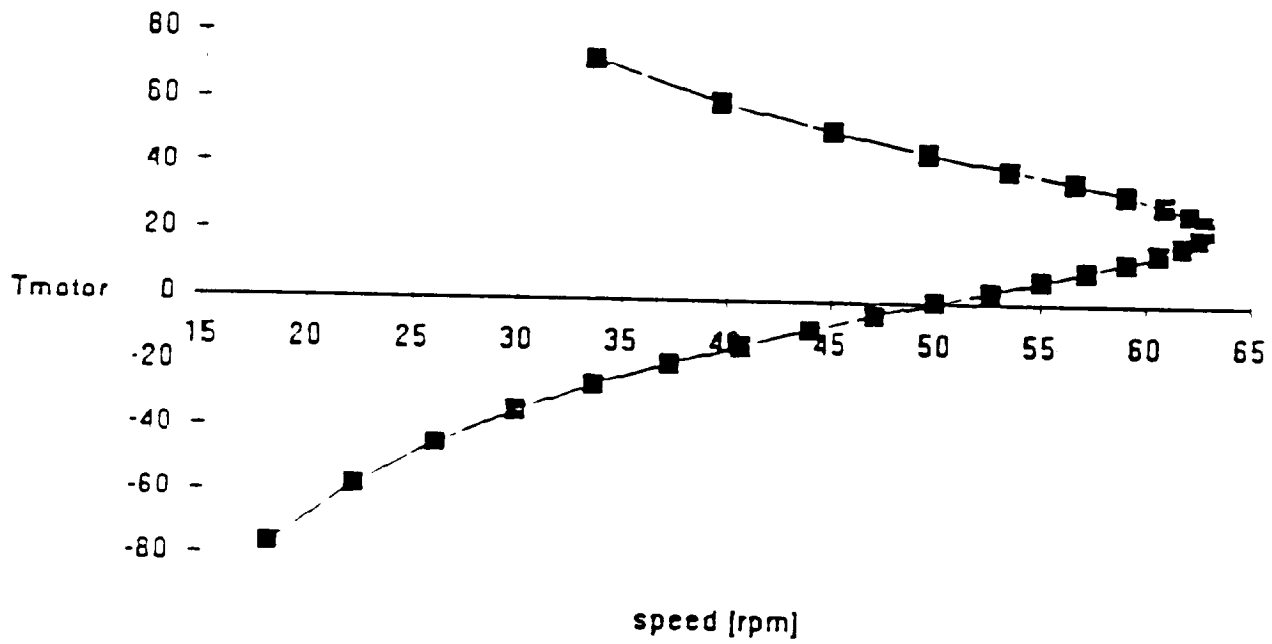
PRODUCT VENDOR

* BALL SCREW

* PRELOADED BALL NUT
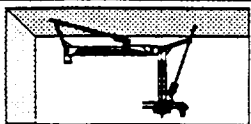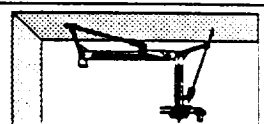
BALL SCREW ASSEMBLIES
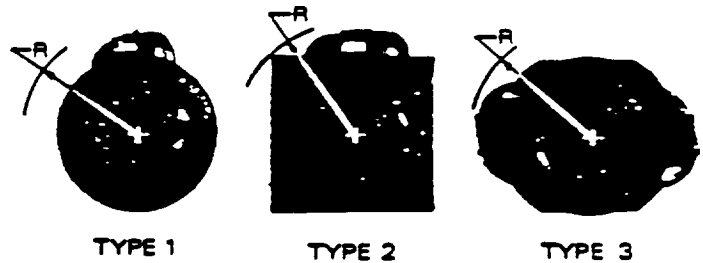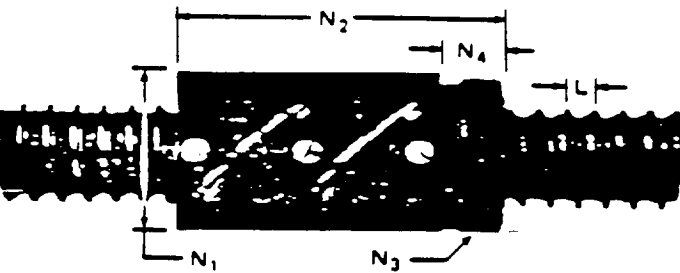
TYPE 1   TYPE 2   TYPE 3

		BALL SCREWS			
Size	Screw Part No.	D Screw, Ball Circle Dia.	L Lead (Inches)	M Minor (Root) Dia.	Right or Left Hand
	R-10-1	.375	.125	.300	R H
⅛	R-11-1	.375	.125	.300	R.H.
	●R-15-1	.375	.125	.300	R H
	●R-16-1	.375	.125	.300	R.H.
	R-20-1	•.500	.500	.390	R H
½	●R-21-1	•.500	.500	.390	R.H.
	●R-22-1	•.500	.500	.390	R H
	R-23-1	•.500	.500	.390	R.H.
	R-30-1	.631	.200	.480	R H
⅝	●SR-30-1	.631	.200	.480	R.H.
	R-31-1	.631	.200	.480	L H
	R-34-1	•.750	.200	.640	R.H.
	R-35-1	•.750	.200	.640	R H
¾	●R-36-1	•.750	.200	.640	R.H.
	R-37-1	•.750	.500	.620	R H
	●R-38-1	•.750	.500	.620	R.H.
	R-40-1	1.000	.250	.820	R H
	●SR-40-1	1.000	.250	.820	R.H.
	R-40-1	1.000	.250	.820	R H
	R-40-1	1.000	.250	.820	R H
	R-41-1	1.000	.250	.820	L H
	R-41-1	1.000	.250	.820	L H.
	R-42-1	•1.000	.250	.870	R H
	R-43-1	•1.000	.500	.870	R.H.
	R-44-1	1.000	1.000	.820	R H
	SR-44-1	1.000	1.000	.820	R.H.
	R-45-1	1.150	.200	1.005	R.H.
	R-50-1	•1.500	.500	1.240	R.H.
	R-53-1	•1.500	.250	1.370	L H
	R-54-1	•1.500	.250	1.370	R.H.
	R-55-1	1.500	1.000	1.140	R.H.
	R-56-1	1.500	1.000	1.140	L H.
	R-58-1	1.500	1.875	1.188	R.H.
	R-60-1	2.250	.500	1.850	R.H.
	R-61-1	•2.000	1.000	2.040	R H
	R-62-1	•2.000	.500	2.040	R.H.
	R-70-1	•2.500	.500	2.190	R H
	R-71-1	•2.500	1.000	2.190	R.H.
	R-74-1	2.500	.250	2.320	R.H.
	R-80-1	3.000	.660	2.480	R.H.

		BALL NUTS						
Nut Part No.	T Type	Operating Load Lbs. for 10⁶ Inches of Travel	Max Static Load Lbs.	N₁ Outside Dia.	R Radius Over Tube	N₂ Overall Length	N₃ Thread Size	N₃ Threads Per Inch	N₄ Thread Length
R-10-2	1	130	1,300	.750	.460	1.00	.664	32	.250
R-11-2	1	280	2,800	.750	.460	1.875	.664	32	.250
●R-15-2	1	25	230	.750	.460	1.00	.664	32	.250
●R-16-2	1	50	460	.750	.460	1.875	.664	32	.250
R-20-2	3	700	3,900	1.062	.680	1.75	.937	16	.375
●R-21-2	3	135	725	1.062	.680	1.75	.937	16	.375
●R-22-2	3	135	725	1.320	.660	1.50	NO	NO	NO
R-23-2	3	700	3,900	1.320	.660	1.50	NO	NO	NO
R-30-2	2	725	5,600	1.0sq.	.797	1.71	.937	16	.500
●SR-30-2	1	123	1,000	1.375	.797	1.71	.937	16	.500
R-31-2	2	725	5,600	1.0sq.	.797	1.71	.937	16	.500
R-34-2	1	1,740	17,800	1.512	.910	2.875	1.250	16	.500
R-35-2	1	870	8,800	1.250	.860	1.875	1.125	18	.500
●R-36-2	1	160	1,350	1.250	.860	1.875	1.125	18	.500
R-37-2	3	3,150	18,500	1.312	1.00	2.937	1.250	16	.500
●R-38-2	3	570	3,950	1.512	1.00	2.937	1.250	16	.500
R-40-2	2	1,600	13,900	1.5sq	1.150	2.347	1.513	18	.600
●SR-40-2	2	285	2,000	1.5sq.	1.190	2.347	1.563	18	.600
R-40A-2	2	3,200	27,800	1.5sq	1.150	3.00	1.563	18	.600
R-40C2-2	1	3,200	27,800	1.825	1.107	3.00	INTEGRAL FLANGE PAGE 18		
R-41-2	2	1,600	13,900	1.5sq	1.150	2.347	1.563	18	.600
R-41C2-2	1	3,200	27,800	1.825	1.107	3.00	INTEGRAL FLANGE PAGE 18		
R-42-2	1	3,400	30,000	1.687	1.150	3.10	1.563	18	.600
R-43-2	1	3,700	30,000	1.687	1.150	3.10	1.563	18	.600
R-44-2	2	2,100	11,900	1.5sq.	1.195	3.00	1.563	18	.600
SR-44-2	2	350	1,900	1.5sq	1.195	3.00	1.563	18	.600
R-45-2	1	2,300	26,000	1.687	1.100	2.50	1.625	20	.485
R-50-2	3	8,050	54,100	2.625	1.812	4.687	2.548	18	.750
R-53-2	1	4,525	44,800	2.093	1.340	3.00	1.967	18	.500
R-54-2	1	4,525	44,800	2.093	1.340	3.00	1.967	18	.500
R-55-2	3	7,500	34,500	2.250	1.718	3.625	2.250	20	1.00
R-56-2	3	7,500	34,500	2.250	1.718	3.625	2.250	20	1.00
R-58-2	3	7,200	29,500	2.25sq.	1.680	5.00	2.250	20	1.00
R-60-2	1	18,800	132,000	3.375	2.275	6.75	3.137	12	1.56
R-61-2	1	23,000	130,000	3.250	2.28	6.375	3.00	12	1.50
R-62-2	1	18,000	130,000	3.250	2.28	6.375	3.00	12	1.50
R-70-2	1	22,500	175,000	4.00	2.75	6.75	3.62	12	1.75
R-71-2	1	26,500	175,000	4.00	2.75	6.75	3.62	12	1.75
R-74-2	1	6,300	81,000	3.375	2.01	3.75	3.34	12	.750
R-80-2	1	44,000	270,000	4.750	3.06	9.312	4.125	12	2.00

SCREWS 1.50" DIAMETER AND LARGER CAN BE ORDERED UP TO 24 FOOT LONG

+ MAJOR DIAMETER (O.D.)
- STAINLESS STEEL

SEE PAGE 18 FOR STANDARD
MOUNTING FLANGES FOR BALL NUTS

PRELOADED BALL NUT ASSEMBLIES

— L_3

C_3

LENGTH AS REQUIRED

C_6

C_2 C_7 C_1 — D_1 — D_2

L_1

C_4

C_5

L_4 L_2
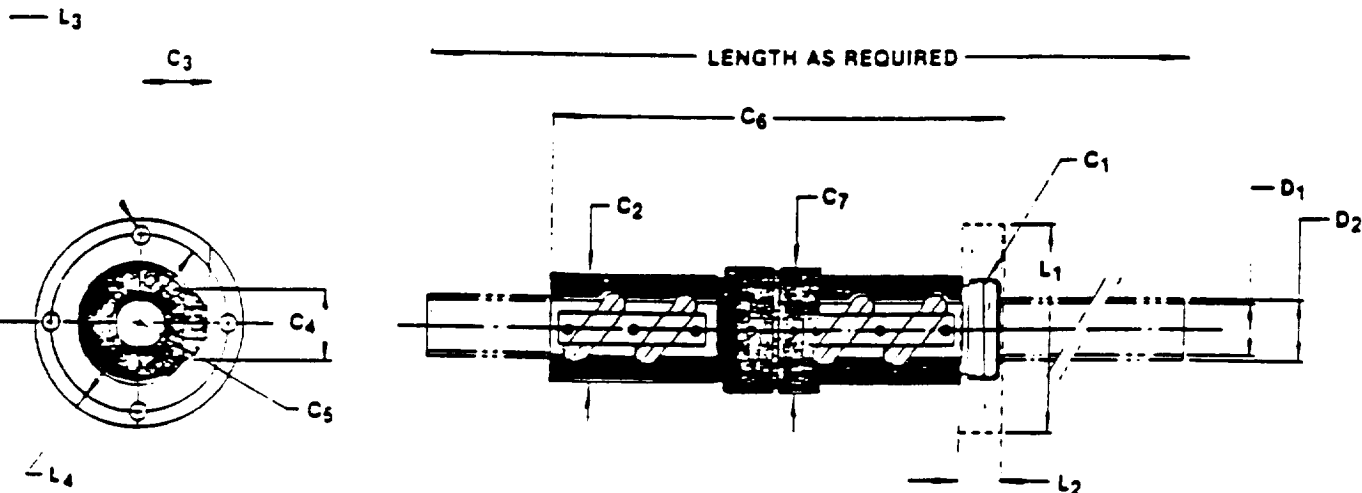
SCREW			BALL NUT							FLANGE (OPTIONAL)			
RBS Model	Minor Dia – D_1	Major Dia – D_2	Thd. Size C_1	C_2	C_3	C_4	C_5	C_6	C_7	Dia. – L_1	Width L_2	L_3 No. of Holes Hole Dia.	B.C.D.
RP 30	.480	.630	.938-16	1.000 sq	.800	.870	.440	3.500	1.150	2.600	.530	4 -.266	2.090
● RP-31	.460	.630	.938-16	1.000 sq	.800	.870	.440	3.500	1.150	2.600	.530	4 -.266	2.090
RP-35	.640	.755	1.125-18	1.250	.910	.930	.440	4.340	1.370	2.600	.530	4 -.266	2.090
RP-37	.630	.755	1.250-16	1.312	1.000	.960	.440	5.500	1.300	2.600	.530	4 -.266	2.090
RP-40	.820	1.000	1.563-18	1.500 sq	1.150	1.100	.440	4.850	1.650	3.250	.630	4 -.266	2.750
● RP-41	.820	1.000	1.563-18	1.500 sq	1.150	1.100	.440	4.850	1.650	3.250	.630	4 -.266	2.750
RP-42	.870	1.010	1.563-18	1.687	1.100	1.100	.440	6.940	1.810	3.250	.630	4 -.266	2.750
RP-43	.870	1.010	1.563-16	1.687	1.100	1.100	.440	6.940	1.810	3.250	.630	4 -.266	2.750
RP-45	1.010	1.135	1.625-20	1.687	1.100	1.270	.560	5.750	1.810	3.200	.500	4 -.266	2.702
RP 50	1.240	1.530	2.548-18	2.625	1.870	1.680	.560	12.130	2.810	4.940	.780	4 -.531	4.062
● RP-53	1.375	1.510	1.967-18	2.093	1.340	1.460	.560	6.500	2.310	4.380	.530	4 -.397	3.440
RP-54	1.375	1.510	1.967-18	2.093	1.340	1.460	.560	6.500	2.310	4.380	.530	4 -.397	3.440
RP-55	1.140	.480	2.250-20	2.625	1.640	1.700	.440	8.190	2.810	4.940	1.020	4 -.531	4.125
● RP-56	1.140	1.480	2.250-20	2.625	1.640	1.700	.440	8.190	2.810	4.940	1.020	4 -.531	4.125
RP-60	1.850	2.200	3.137-12	3.375	2.270	2.560	.125	14.250	4.000	5.380	1.580	6 -.656	4.375
RP-70	2.190	2.540	3.625-12	4.000	2.670	2.480	.880	14.750	4.250	6.000	1.780	8 -.656	5.000
RP-71	2.190	2.540	3.625-12	4.000	2.670	2.480	.880	14.320	4.250	6.000	1.780	8 -.656	5.000
RP-80	2.480	2.935	4.325-12	4.750	3.060	3.350	.125	19.950	5.000	7.380	2.020	8 -.781	6.250

● Left hand assemblies

Wipers
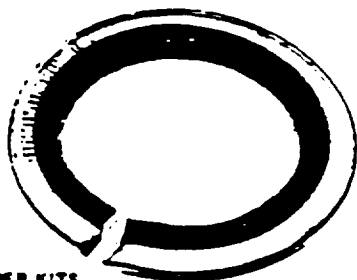
WIPER KITS

These devices serve to prevent most foreign material from entering the ball nut as it translates along the screw. The nylon brush wipers are available on almost all units. However for long term reliability in the presence of dirt, metallic chips etc. metal enclosures bellow type enclosures or extensions should be used in addition to lubrication and wipers.

WIPERS			
MODEL NO.	O.D.	THICKNESS	TYPE
R-10	NOT AVAILABLE		–
R-11	NOT AVAILABLE		–
R-15	NOT AVAILABLE		–
R-16	NOT AVAILABLE		–
R-20	CONSULT FACTORY		–
R-21	CONSULT FACTORY		–
R-22	CONSULT FACTORY		–
R-23	CONSULT FACTORY		–
R-30	.975	.140	A
R-31	.975	.140	A
R-35	1.245	.140	A
R-36	1.245	.140	A
R-37	1.280	.140	C
R-38	1.280	.140	A
R-40	1.500	.140	A
R-40A	1.500	.140	A
R-41	1.500	.140	A
R-42	1.500	.140	A
R-43	1.500	.140	C
R-44	1.500	.140	A
R-45	1.500	.140	A

WIPERS			
MODEL NO.	O.D.	THICKNESS	TYPE
R-50	2.250	.180	C
R-53	1.875	.140	A
R-54	1.875	.140	A
R-55	2.250	.180	A
R-56	2.250	.180	A
R-60	2.375	.180	A
R-61	CONSULT FACTORY		–
R-62	CONSULT FACTORY		–
R-70	3.560	.195	C
R-71	3.560	.195	A
R-80	3.780	.195	B

Add -4 to Model No. to specify Wiper Kit

TYPE A = 2 BRUSH WIPERS, 1 RETAINER
TYPE B = 2 BRUSH WIPERS, 2 SNAP RINGS
TYPE C = 2 BRUSH WIPERS ONLY

APPENDIX C

ENCODER SPEED

ARM WILL MOVE 90°/MIN

Lead screw will Change 11.05"

MOTOR TURNS $\left(11 \text{ IN}\right)\left(\frac{1 \text{ rev}}{0.2 \text{ IN}}\right) = 55.2 \text{ rev}$

MOTOR Speed = 55 RPM

ENCODER = $(3600 \text{ P/Rev})(55 \text{ Rev/min}) = 198,000 \text{ ppmin}$

Freq Response = $100 \times 10^3 / \text{sec}$

theta 1	theta 2	COS(th 1)	COS(th2)	COS(1+2)	SIN(th 1)	SIN(th 2)	SIN(1+2)	Too+Tol	** To **	T11+T12	** T1 **	** T2 **	T12	T19
0.000	0.000	1.000	1.000	1.000	0.000	0.000	0.000	268.000	268.000	-370.000	218.600	-11.900	588.600	0.000
0.000	0.100	1.000	0.995	0.995	0.000	0.100	0.100	273.023	293.347	-369.301	236.993	-22.958	609.075	2.781
0.000	0.200	1.000	0.980	0.980	0.000	0.199	0.199	276.751	316.751	-367.206	255.704	-34.404	628.365	5.452
0.000	0.300	1.000	0.955	0.955	0.000	0.296	0.296	278.986	338.164	-363.747	276.626	-46.042	646.278	7.905
0.000	0.400	1.000	0.921	0.921	0.000	0.389	0.389	279.561	356.420	-358.949	293.642	-57.603	662.634	10.043
0.000	0.500	1.000	0.878	0.878	0.000	0.479	0.479	278.340	371.213	-352.862	312.628	-69.147	677.270	11.781
0.000	0.600	1.000	0.825	0.825	0.000	0.565	0.565	275.233	382.136	-345.547	331.445	-80.268	690.040	13.049
0.000	0.700	1.000	0.765	0.765	0.000	0.644	0.644	270.196	388.891	-337.076	349.943	-90.896	700.817	13.796
0.000	0.800	1.000	0.697	0.697	0.000	0.717	0.717	263.232	391.297	-327.519	367.959	-100.904	709.492	13.994
0.000	0.900	1.000	0.622	0.622	0.000	0.783	0.783	254.402	389.302	-317.025	385.319	-110.184	715.979	13.634
0.000	1.000	1.000	0.540	0.540	0.000	0.841	0.841	243.813	382.980	-305.642	401.840	-118.656	720.213	12.730
0.000	1.100	1.000	0.454	0.454	0.000	0.891	0.891	231.626	372.528	-293.503	417.129	-126.262	722.151	11.319
0.000	1.200	1.000	0.362	0.362	0.000	0.932	0.932	218.048	358.262	-280.730	431.589	-132.967	721.776	9.658
0.000	1.300	1.000	0.267	0.267	0.000	0.964	0.964	203.324	340.602	-267.450	444.422	-138.760	719.089	7.217
0.000	1.400	1.000	0.170	0.170	0.000	0.985	0.985	187.746	320.060	-253.795	455.633	-143.651	714.118	4.690
0.000	1.500	1.000	0.071	0.071	0.000	0.997	0.997	171.591	297.217	-239.903	465.034	-147.665	706.913	1.976
0.000	1.600	1.000	-0.029	-0.029	0.000	1.000	1.000	155.212	272.709	-225.912	472.451	-150.845	697.546	-0.817
0.000	1.700	1.000	-0.129	-0.129	0.000	0.992	0.992	138.930	247.197	-211.963	477.726	-153.241	686.110	-3.578
0.000	1.800	1.000	-0.227	-0.227	0.000	0.974	0.974	123.072	221.347	-198.192	480.723	-154.913	672.719	-6.195
0.000	1.900	1.000	-0.323	-0.323	0.000	0.946	0.946	107.953	195.811	-184.739	481.335	-155.921	657.508	-8.566
0.000	2.000	1.000	-0.416	-0.416	0.000	0.909	0.909	93.866	171.196	-171.719	479.484	-156.327	640.628	-10.595
0.000	2.100	1.000	-0.505	-0.505	0.000	0.863	0.863	81.072	148.051	-159.322	475.129	-156.186	622.249	-12.202
0.000	2.200	1.000	-0.589	-0.589	0.000	0.808	0.808	69.797	126.849	-147.610	468.285	-155.549	602.552	-13.322
0.000	2.300	1.000	-0.666	-0.666	0.000	0.746	0.746	60.219	107.968	-136.721	458.927	-154.455	581.736	-13.912
0.000	2.400	1.000	-0.737	-0.737	0.000	0.675	0.675	52.469	91.684	-126.765	447.190	-152.933	560.009	-13.946
0.000	2.500	1.000	-0.801	-0.801	0.000	0.598	0.598	46.627	78.168	-117.840	433.172	-150.999	537.587	-13.425

Parameter headers: Io = 0, m1 = 60, L1c = 0.5, l1 = 5, m2, L2c = 0.5, l2 = 2, L1 = 1, Th0.. , Th 0. = 2, Th1. = 2, Th2. = 3, Th1.. = -6, Th2... = -6, 9 = 9.81

FIGURE C.1

Motor Operating Curve

FIGURE C.2

width	Length	thickness	Area	perimeter	Gr	Nu	h	m	tanh(mL)	Qout
0.05	0.15	0.004	0.0002	0.108	1.4E+08	54.3594	12.1946	5.68154	0.69223	14.4418
0.1	0.15	0.004	0.0004	0.208	1.4E+08	54.3594	12.1946	5.57533	0.68384	28.0002
0.15	0.15	0.004	0.0006	0.308	1.4E+08	54.3594	12.1946	5.53948	0.68097	41.5548
0.2	0.15	0.004	0.0008	0.408	1.4E+08	54.3594	12.1946	5.52146	0.68097	41.5548
0.25	0.15	0.004	0.001	0.508	1.4E+08	54.3594	12.1946	5.51063	0.67952	55.1085
0.3	0.15	0.004	0.0012	0.608	1.4E+08	54.3594	12.1946	5.51063	0.67864	68.6618
0.35	0.15	0.004	0.0014	0.708	1.4E+08	54.3594	12.1946	5.50339	0.67806	82.2149
0.4	0.15	0.004	0.0016	0.808	1.4E+08	54.3594	12.1946	5.49822	0.67764	95.7679
0.45	0.15	0.004	0.0018	0.908	1.4E+08	54.3594	12.1946	5.49433	0.67732	109.321
0.5	0.15	0.004	0.002	1.008	1.4E+08	54.3594	12.1946	5.49131	0.67708	122.874
0.55	0.15	0.004	0.0022	1.108	1.4E+08	54.3594	12.1946	5.48889	0.67688	136.427
0.6	0.15	0.004	0.0024	1.208	1.4E+88	54.3594	12.1946	5.48691	0.67672	149.979
0.65	0.15	0.004	0.0026	1.308	1.4E+08	54.3594	12.1946	5.48526	0.67658	163.532
0.7	0.15	0.004	0.0028	1.408	1.4E+08	54.3594	12.1946	5.48386	0.67647	177.086
0.75	0.15	0.004	0.003	1.508	1.4E+08	54.3594	12.1946	5.48266	0.67637	190.638
								5.48162	0.67629	204.191

Heat Transfer Calculations for Amplifier Heat Sinks
[length=10cm and thickness=4mm]

Heat Transfer Vs. Width of Aluminum Block
[thickness=2.5cm and Length=15cm]

Heat Transferred

[Watts]

Width of Fin [m]
Heat Sink Requirements
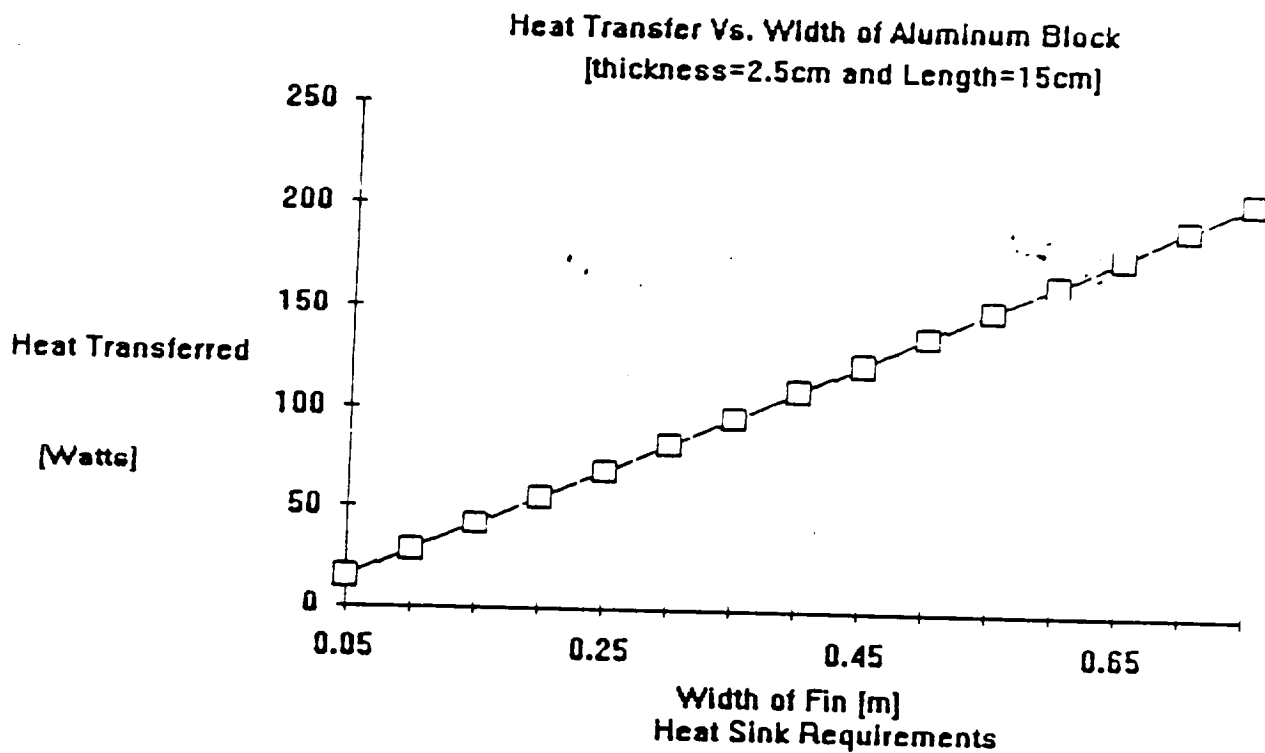
FIGURE C.3

```
set_base 770
clr_act_pos
set_base 769
set_gain 5
set_zero 240
set_pole 0
set_timer 40
clr_act_pos
set_max_vel 5
set_accel 2
sel_mode
repeat 4
set_final_pos 8000
trap_mode
delay 1400
set_final_pos 0
set_accel 2
trap_mode
delay 1400
set_base 770
set_gain 5
set_zero 240
set_pole 0
set_timer 40
set_max_vel 5
set_accel 2
sel_mode
set_final_pos 8000
trap_mode
delay 1400
set_final_pos 0
set_accel 2
trap_mode
delay 1400
next
set_base 770
set_gain 5
set_zero 240
set_pole 0
set_timer 40
set_max_vel 5
set_accel 2
sel_mode
set_final_pos 8000
trap_mode
delay 700
set_base 769
set_gain 5
set_zero 240
set_pole 0
set_timer 40
set_max_vel 5
set_accel 2
sel_mode
set_final_pos 8000
trap_mode
delay 700
set_base 770
set_gain 5
set_zero 240
set_pole 0
set_timer 40
```

```
set_max_vel 5
set_accel 2
sel_mode
set_final_pos 0
trap_mode
delay 700
set_base 769
set_gain 5
set_zero 240
set_pole 0
set_timer 40
set_max_vel 5
set_accel 2
sel_mode
set_final_pos 0
trap_mode
delay 700
quit
```

FIGURE C.4

this spreadsheet calculates number of turns required for each motor							
to turn the arm through a given angle							
			shoulder					elbow
angle1=		0	-7965.232		angle1=		0	3721.162
angle2=		-20			angle2=		-10	
gamma1=		110			gamma1=		20	
gamma2=		130			gamma2=		30	
lead 1=		18.11923			lead1=		17.69528	
lead 2=		19.86141			lead2=		18.50918	
del lead=		-1.742173			DEL lead		0.813901	

FIGURE C.5
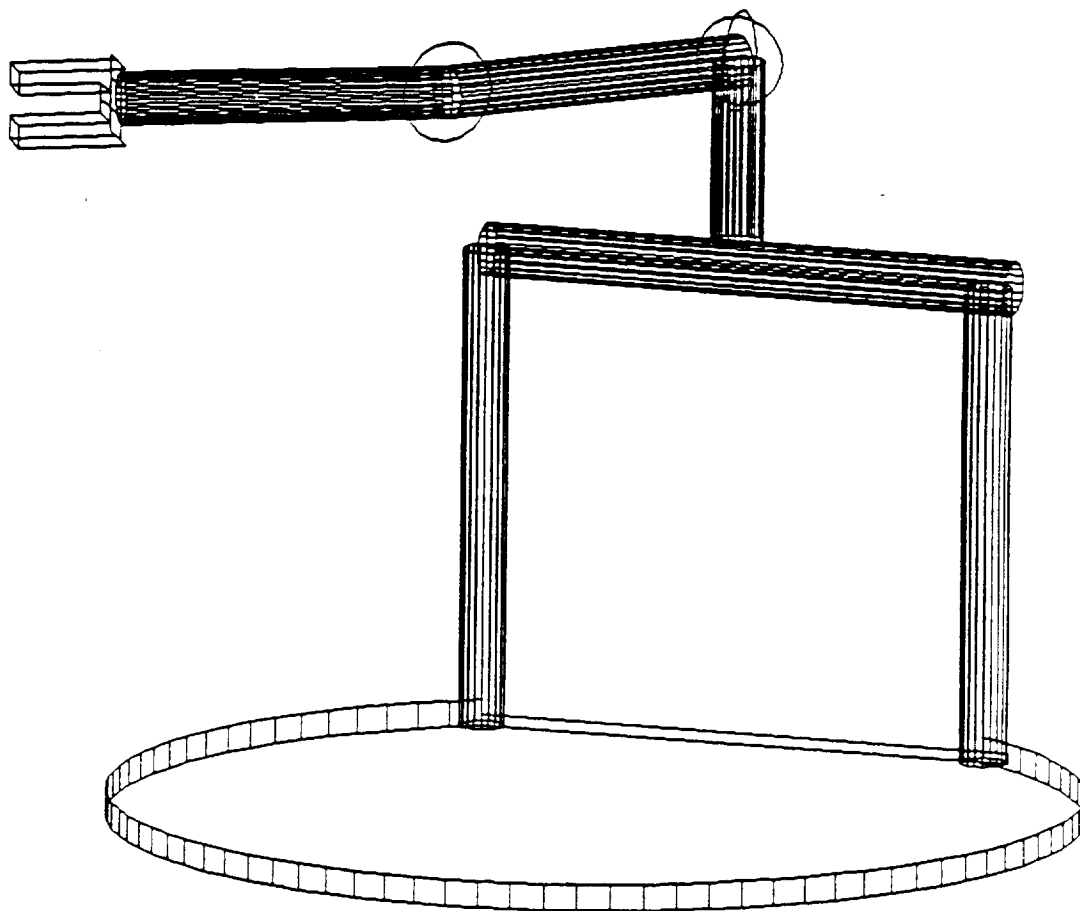
AME 412b   ASPOD ARM

3-D PROGRAMMING MODEL

Fig c.6

APPENDIX D

FRAME STRUCTURE DIAGRAMS
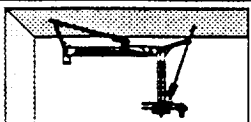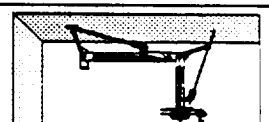
APPENDIX D.1
FRAME ASSEMBLY

TOP VIEW

REAR CROSSMEMBER

FRONT CROSSMEMBER

5.0   6.5   15.0

FRONT VIEW

34.0

36.25

39.0

43.5
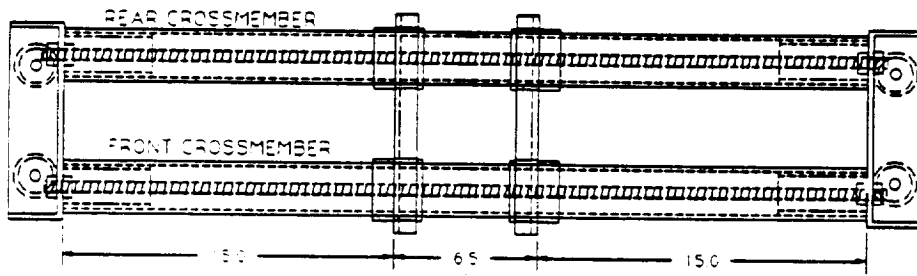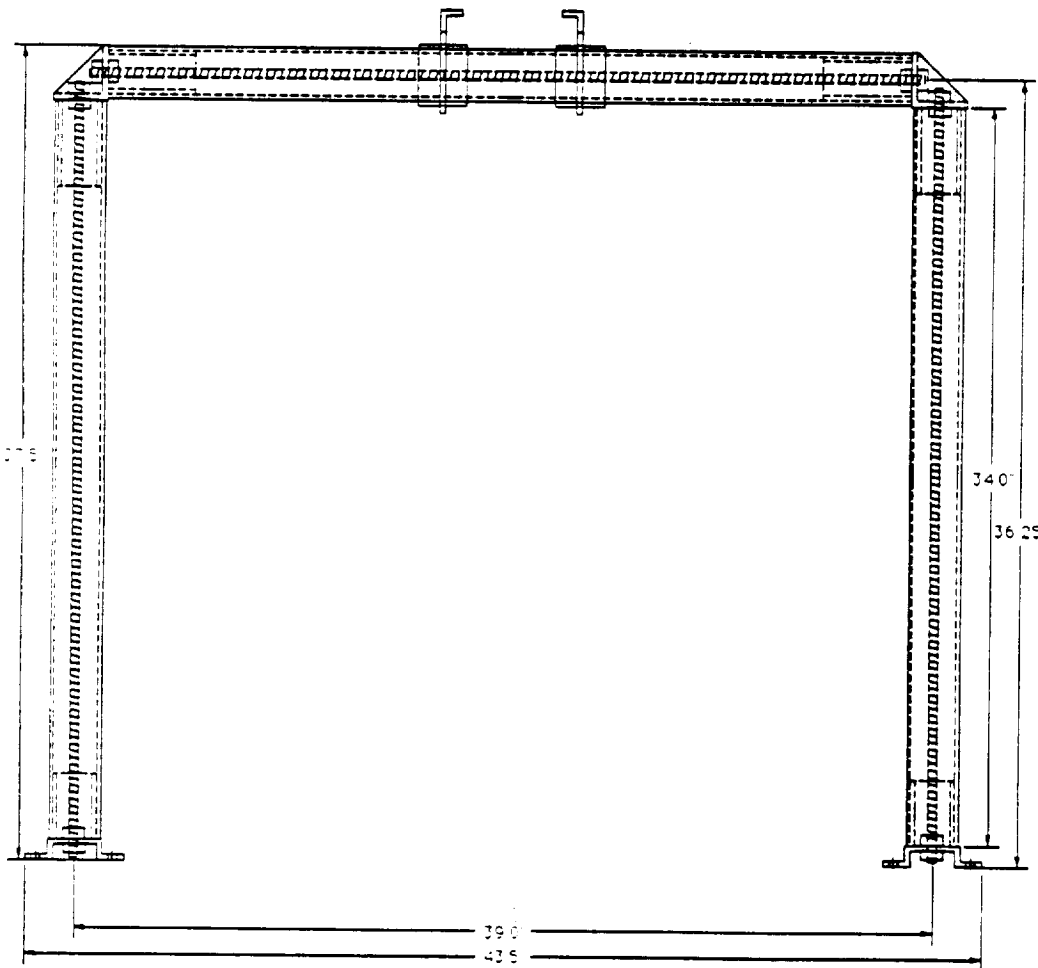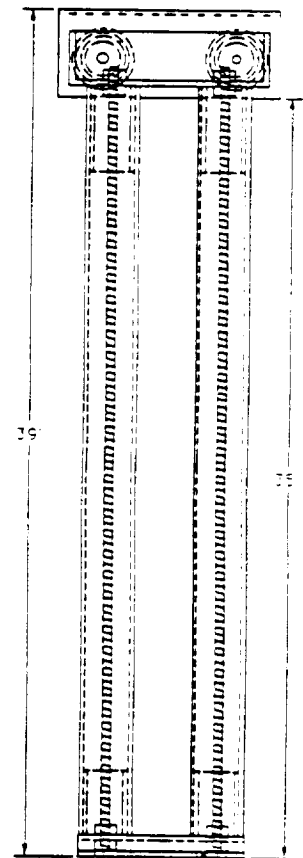
SIDE VIEW

FRAME AND ARM ASSEMBLY
SIDE VIEW
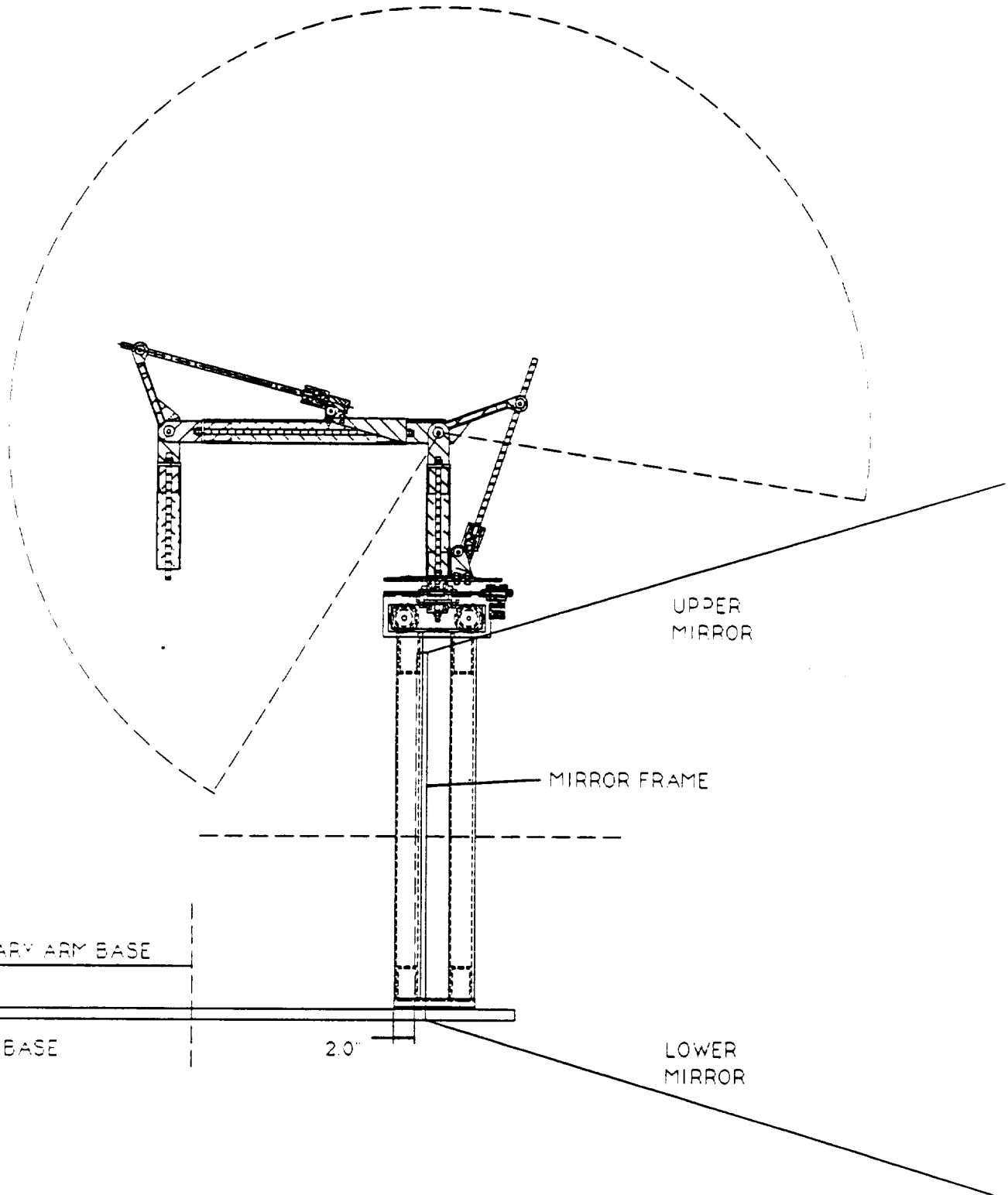
UPPER
MIRROR

MIRROR FRAME

PRIMARY ARM BASE

ASPOD BASE

2.0"

LOWER
MIRROR

FRAME ASSEMBLY
TOP VIEW

LEFT
MIRROR

RIGHT
MIRROR

MIRROR FRAME

SUPPORT TRACK FOR
PRIMARY ARM BASE

ASPOD BASE
BOUNDRY
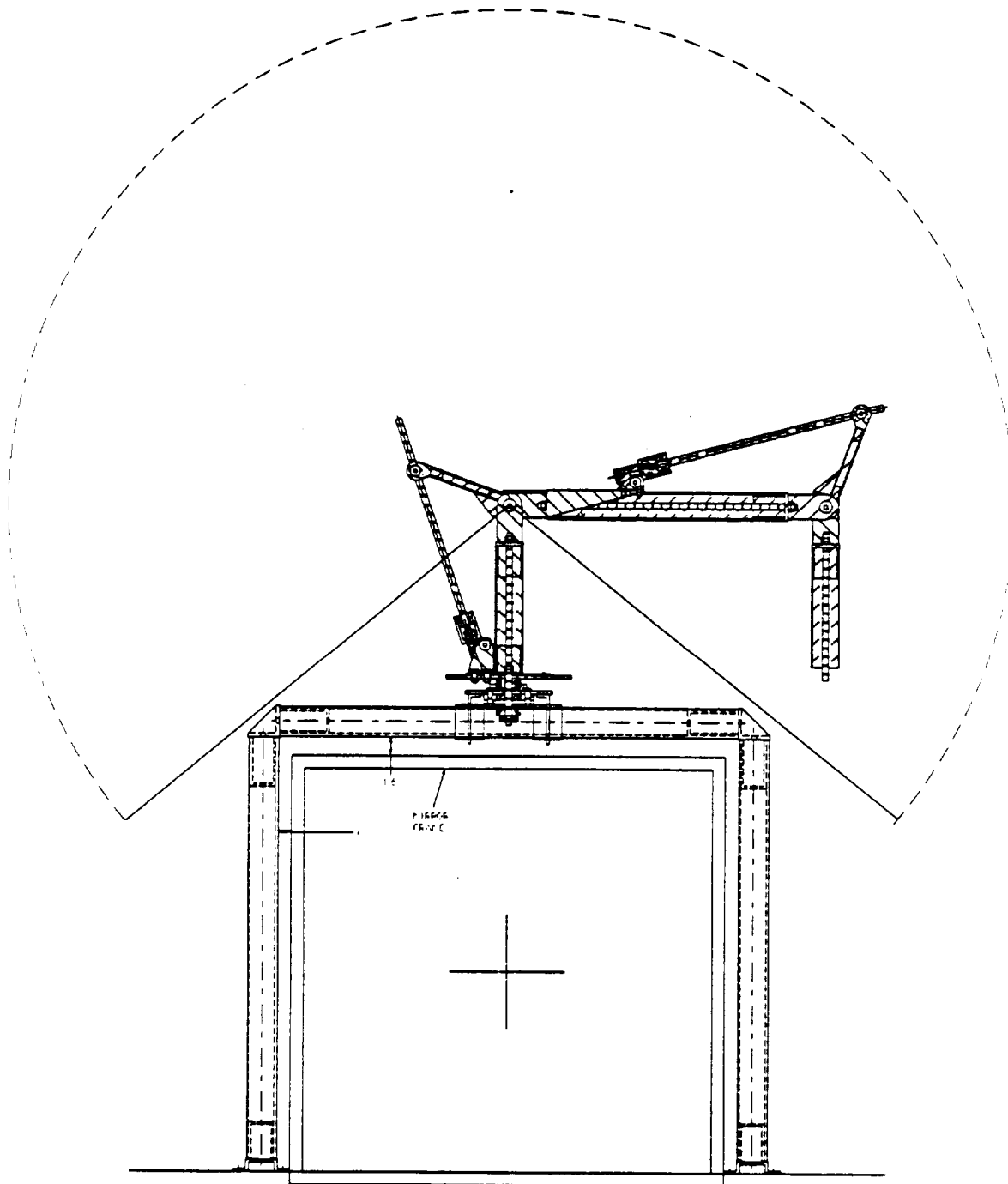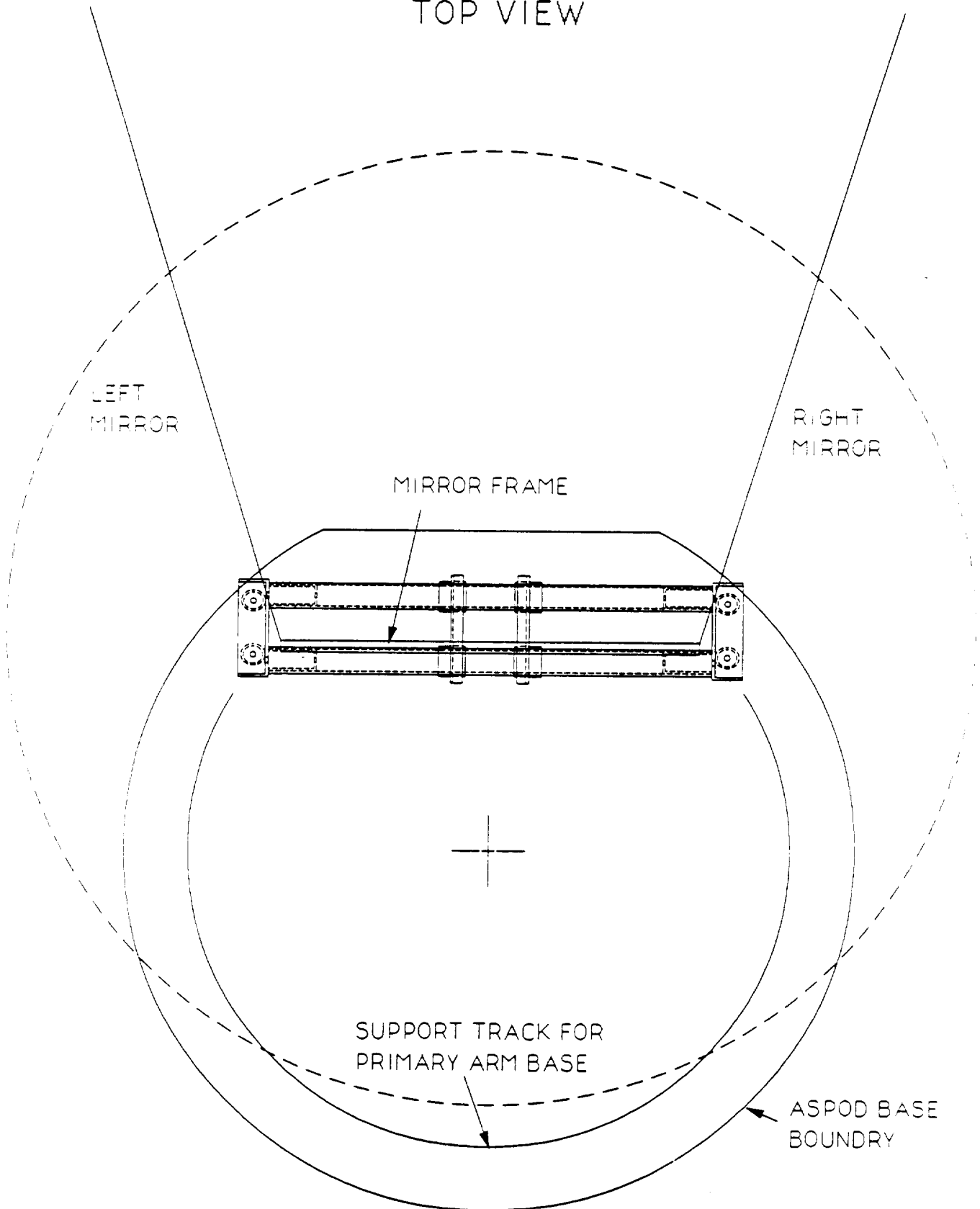
BOTTOM BRACKET
(2 NEEDED)

1.25" 5.0" 1.25"

3.0"

1.0"

4" 5" 4"

.25" THICK

2.25"

2.0"

2.0"

5.5

2.0" O.D, 1.6" I.D

2.5"

1.0" 1.0"

NOTE: 8 - 3/8" BOLTS AND MATCHING NUTS ARE REQUIRED TO ATTACH THESE TWO BRACKETS TO THE SUPPORT STRUCTURE.
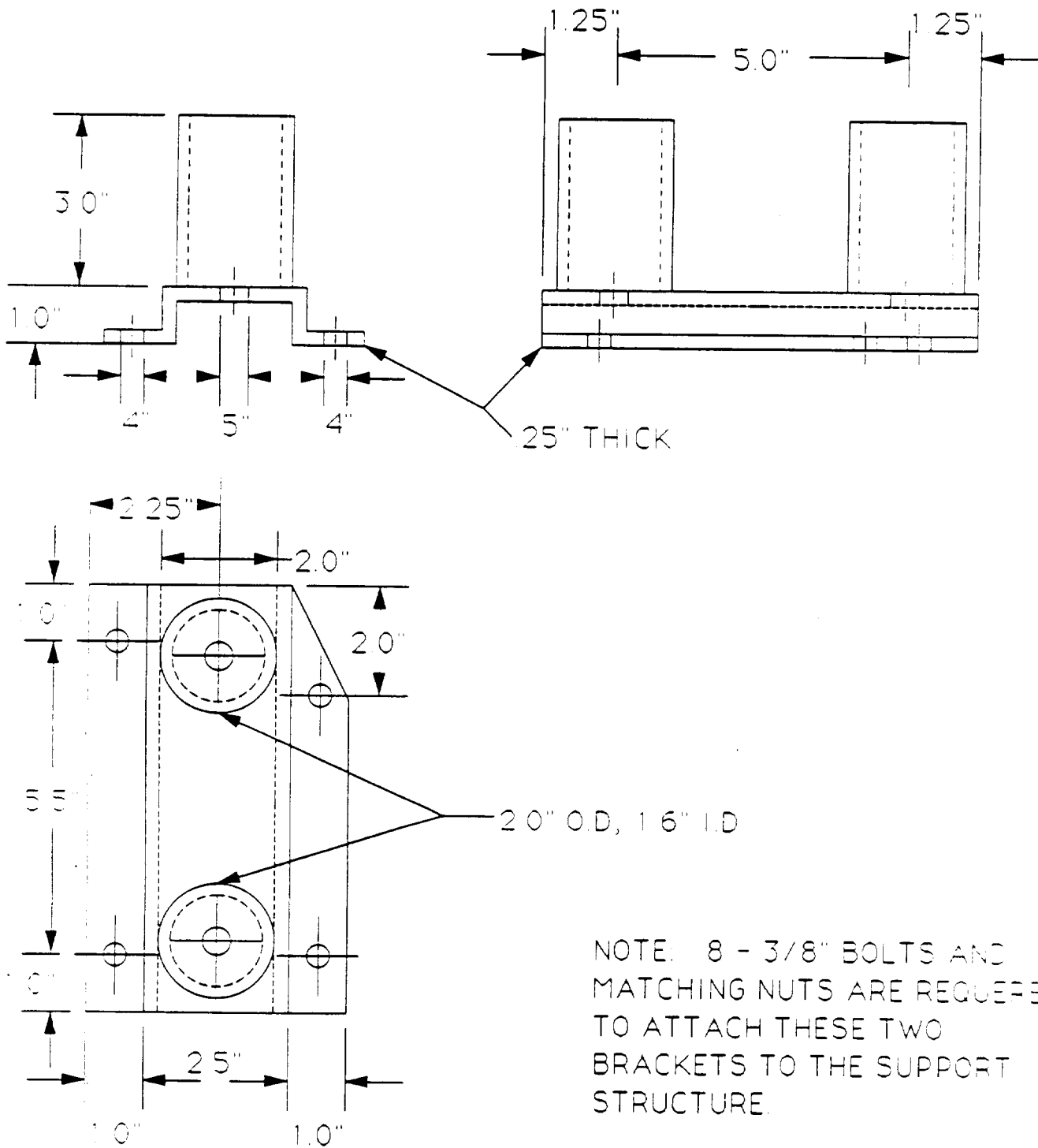
APPENDIX D.6
EDGE BRACKET
(2 NEEDED)

4.0" 1.25"

1.25"

2.0" OD, 1.6" ID.
W/ 0.5" CENTER
HOLE

4.0"

1.5" 6.0" 1.5"

2.5"

.25"

2.5"

2.0"

.25" THICK
ANGLE IRON

5.0"

2.0"
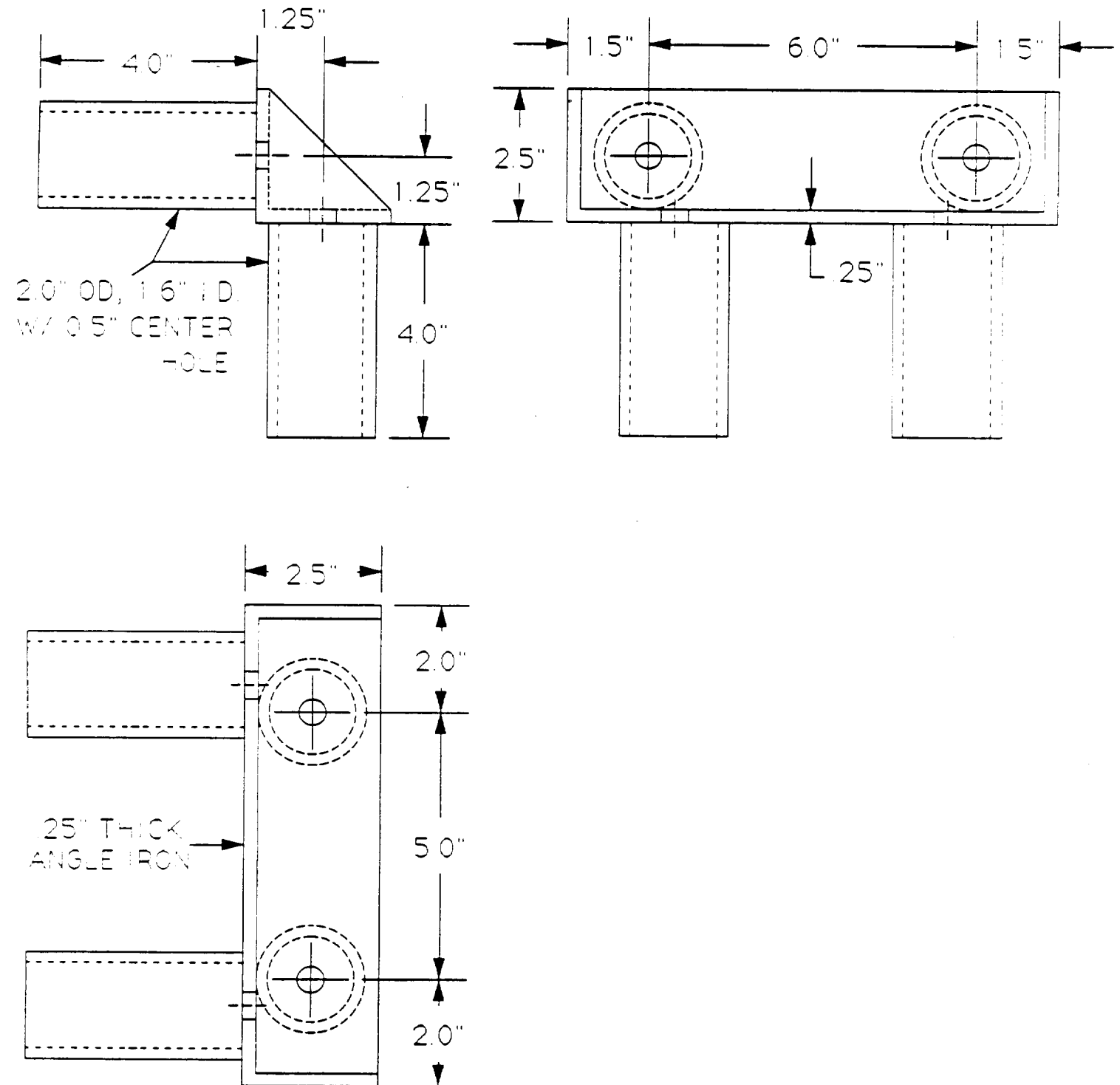
CENTER BRACKET
(2 NEEDED)

1.0"

2.8"   2.4"

1.0"

10.00"

4.00"

.25" THICK ANGLE IRON

2.0"

6.0"

2.0"

2.25"
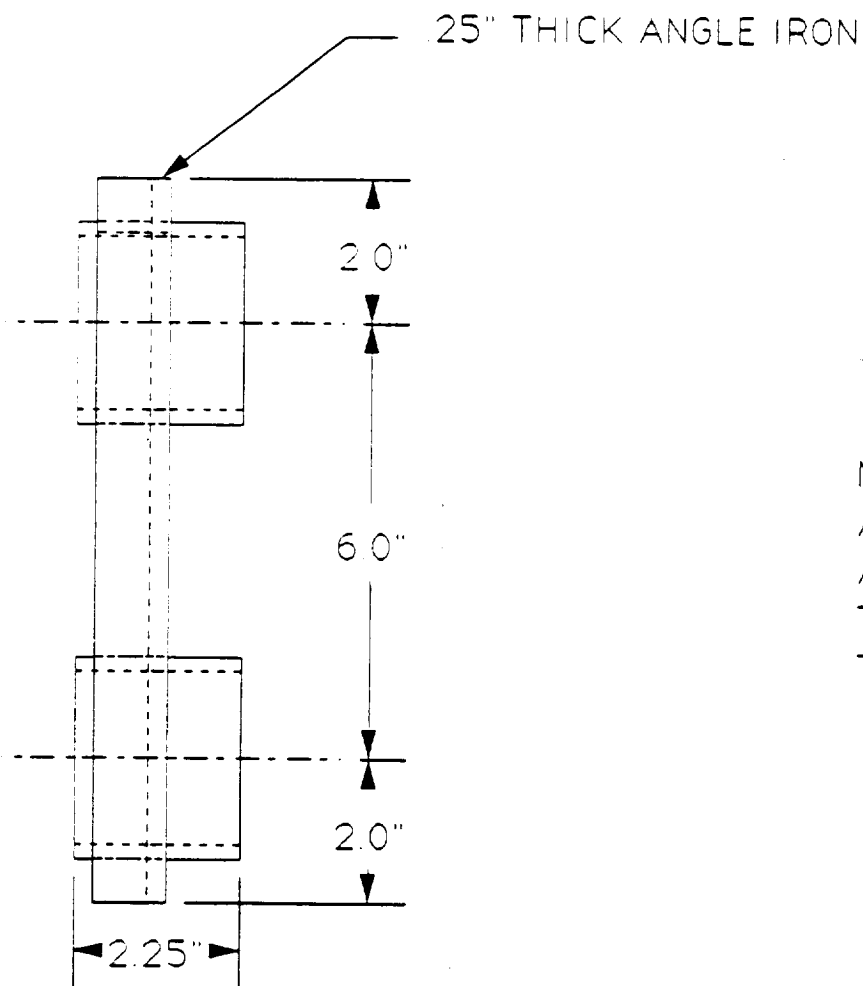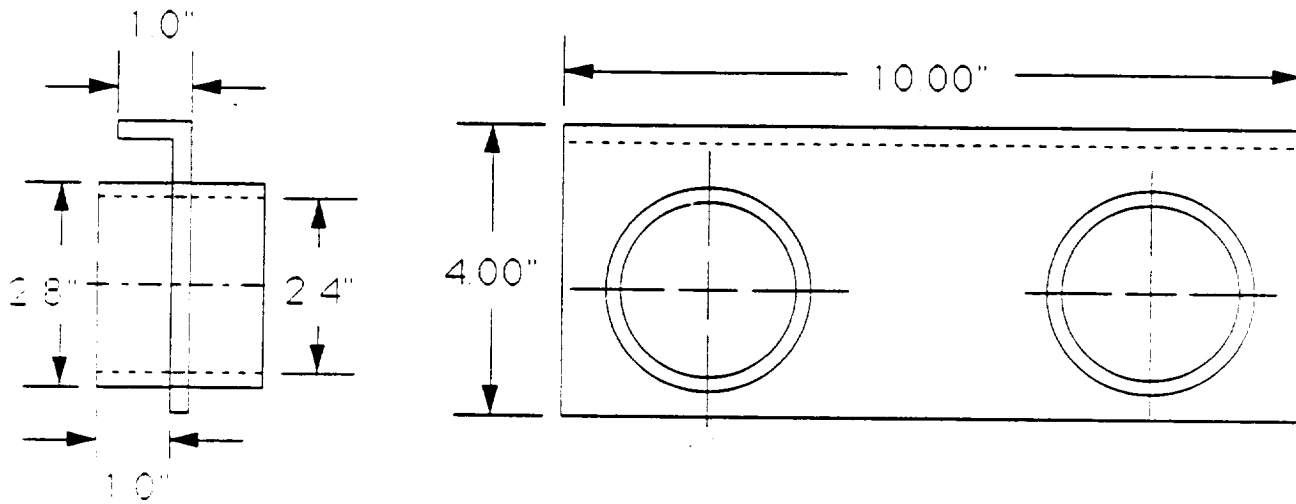
NOTE: 4-3/8 BOLTS
AND MATCHING NUTS
ARE REQUIED TO ATTACH
THE ARM BASE TO THESE
TWO BRACKETS.

SIDE
COMPOSITE
(4 NEEDED)
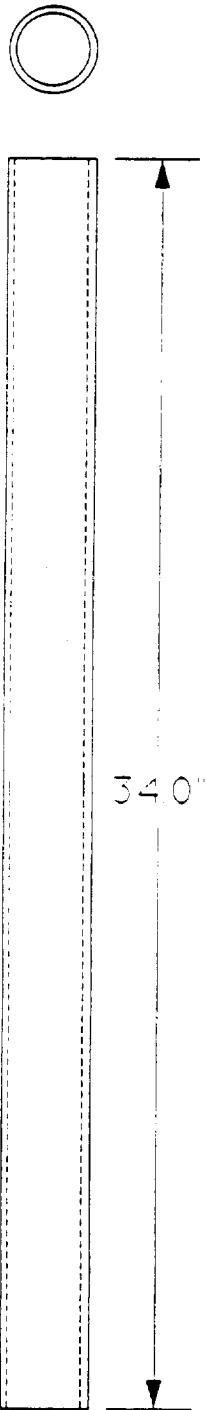
TOP
COMPOSITE
(1 NEEDED)
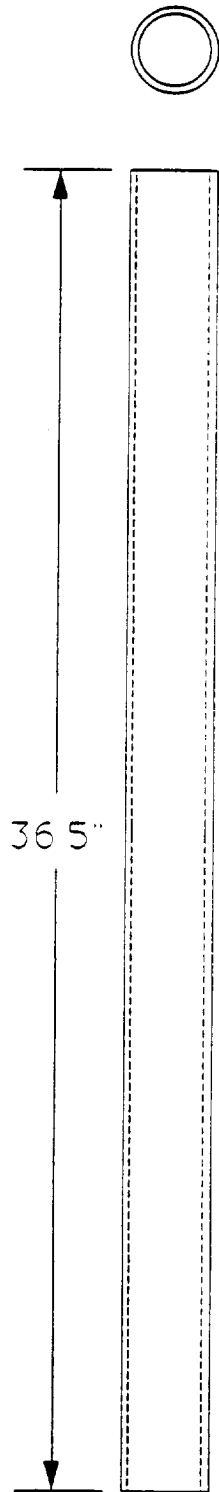
THREAD
RODS
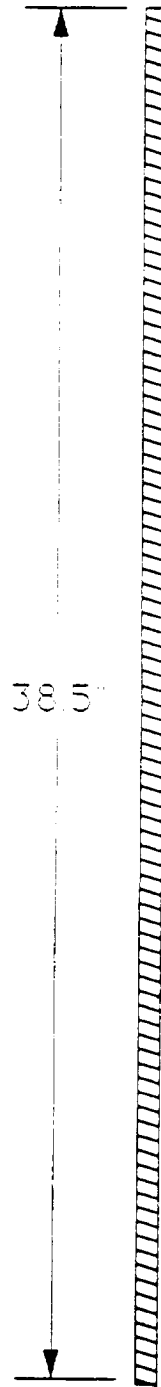
(2 NEEDED)   (4 NEEDED)

34.0"

36.5"

36.0"

38.5"

APPENDIX D.9

.20"
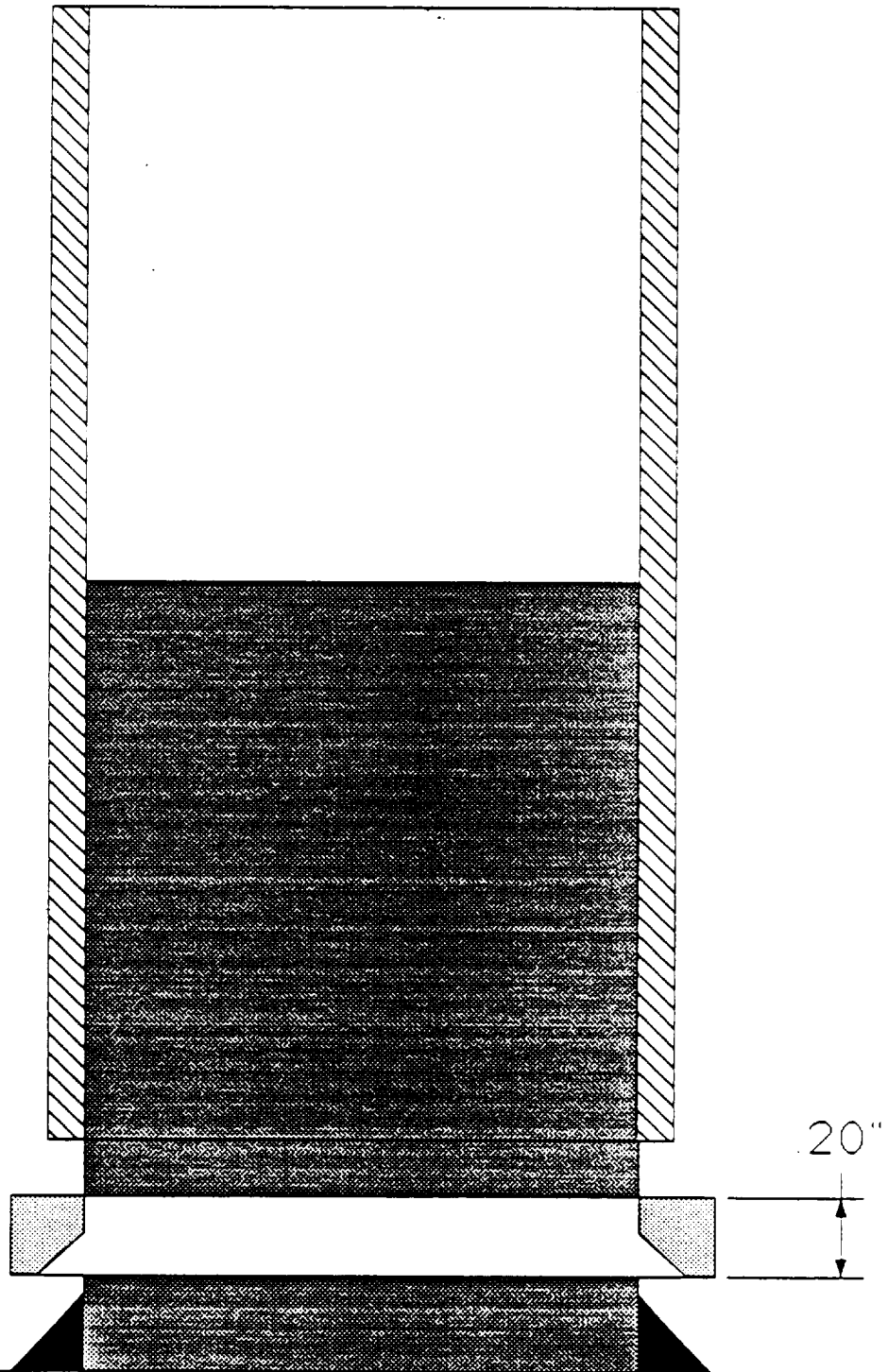
LOAD PLOT
RES
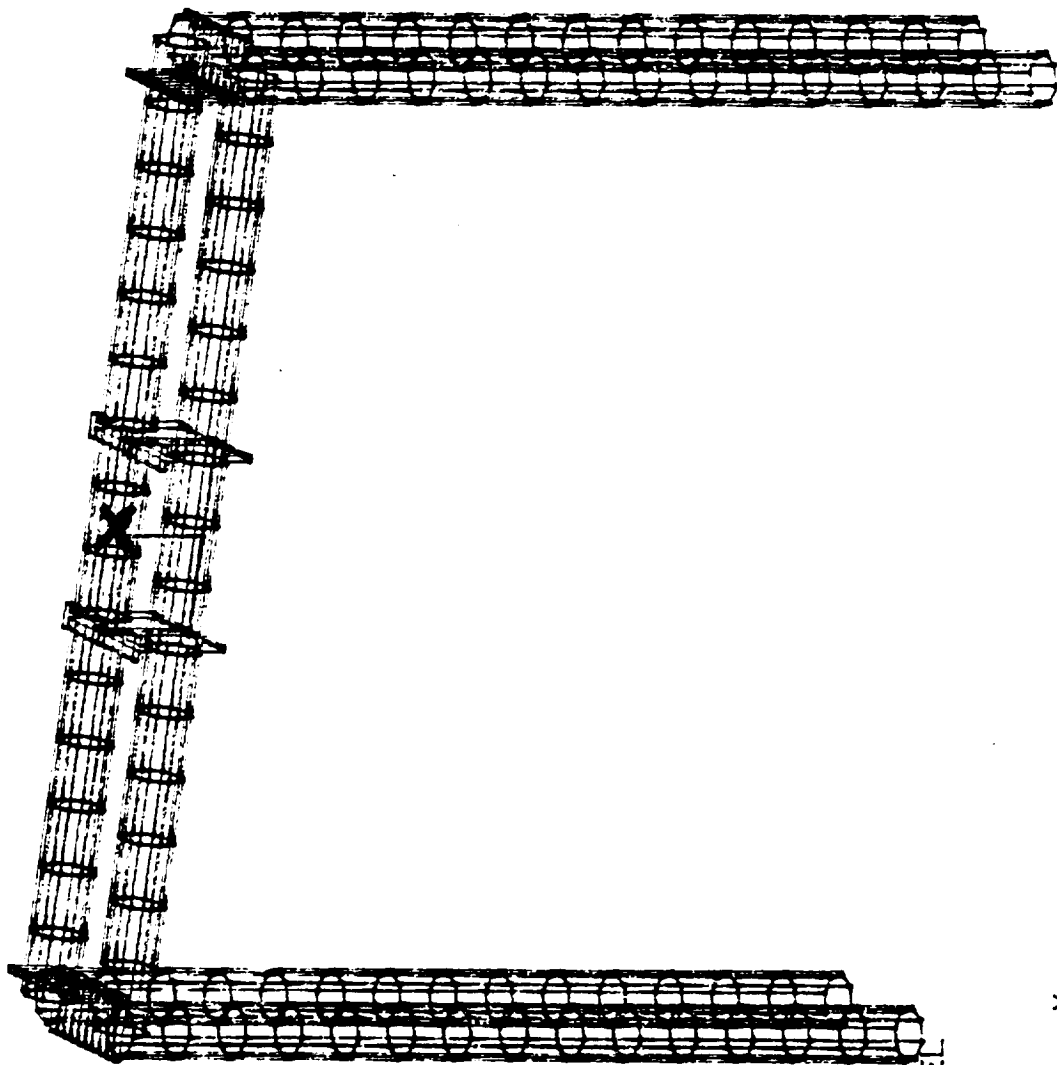
LOADING CASE 1

VIEW DIRECTION
21   52   83
VIEWING DIST.
1.000E+16
PLOT LIMITS
X   0.000E+00
     4.400E+01
Y   0.000E+00
     4.400E+01
Z   -5.501E+00
     0.000E+00
JOB: CURT
25-JAN-87 18:18

LOADS

LOADS

3.000E+02

MODEL
Y

Z   X

4.000E+00

LOADS

LOADS
Y
Z
2.000E+02

LOADING CASE 1

LOADS

2.000E+02

LOADS

MODEL

X
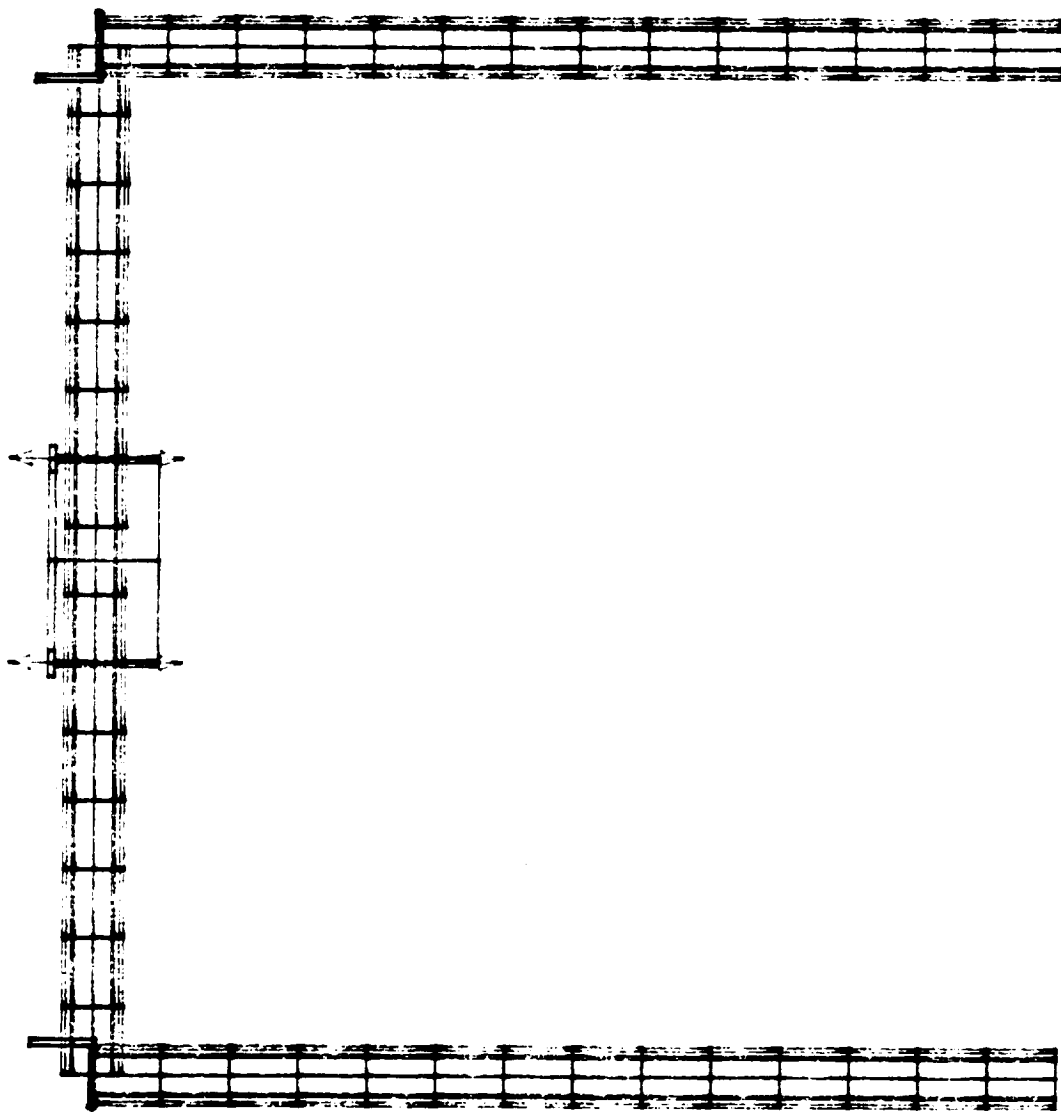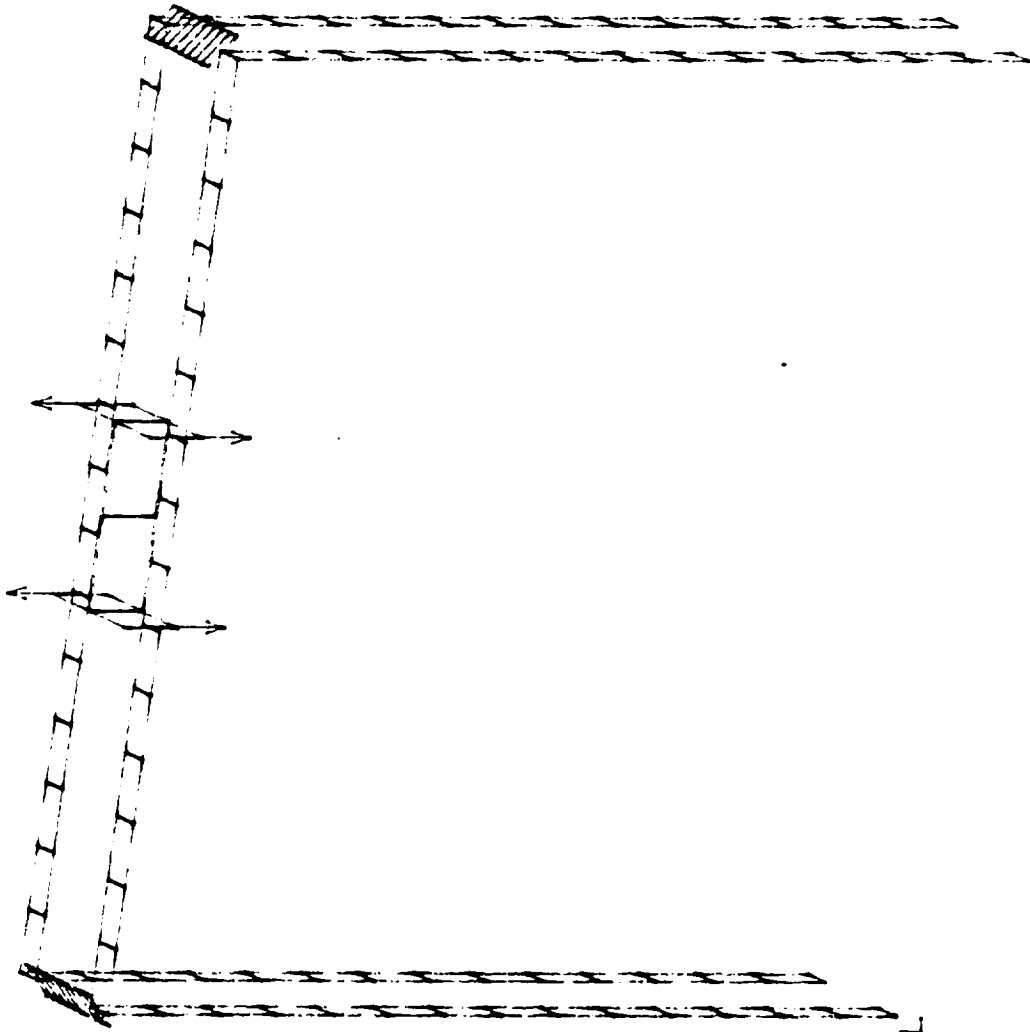
4.000E+00

LOADS

25-JAN-87 18.

APPENDIX D.13

POSITION	THETA	U (in.)	V (in.)	W (in.)	RX (rads)	RY (rads)	RZ (rads)	TOTAL (in.)
STANDARD	270	0	0	1.12E-02	1.46E-03	0	0	0.07154
	315	-6.66E-03	0	-7.55E-03	-9.87E-04	0	-2.83E-04	0.01934
	0	-9.89E-03	0	0	0	0	-4.19E-04	0.020531
OPPOSITE	270	0	-2.66E-04	1.43E-03	1.43E-03	0	0	0.070336
OFFSET	315	-5.81E-03	-1.80E-04	7.50E-03	9.68E-04	0	3.74E-04	0.02097
	0	-8.60E-03	0	0	0	0	-3.73E-04	0.018277
TOP: OFFSET	270	0	0	1.12E-02	1.44E-03	0	0	0.07056
SIDES:	315	-5.80E-03	0	7.53E-03	9.74E-04	0	-2.52E-04	0.04291
STANDARD	0	-8.60E-03	0	0	0	0	-3.74E-04	0.018326
TOP: STAND.	270	0	-2.76E-04	1.11E-02	1.45E-03	0	0	0.071326
SIDES:	315	6.66E-03	-1.86E-04	7.52E-03	9.81E-04	0	2.83E-04	0.024616
OPP. OFFSET	0	-9.67E-03	0	0	0	0	-4.19E-04	0.020531
TOP: STAND.	270	0	0	1.18E-02	1.48E-03	0	0	0.07252
SIDES: OFFSET	315	6.47E-03	0	7.98E-03	1.00E-03	0	2.83E-04	0.025095
TO OUTSIDE	0	-9.58E-03	0	0	0	0	-4.19E-04	0.020531
TOP: STAND.	270	0	0	1.04E-02	1.42E-03	0	0	0.06958
SIDES: OFFSET	315	6.85E-03	0	7.03E-03	9.61E-04	0	2.83E-04	0.02373
TO INSIDE	0	-1.02E-02	0	0	0	0	-4.19E-04	0.020531

Appendix 3

An Autonomous Space Processor for Orbital Debris

End Effector

Submitted to:

Dr. George Botbyl
University of Texas at Austin

In March of
Nineteen Hundred and
Ninety-Two

RC JKM Engineering

David Jacobus
Rogers Hill
Bryan Lee
Mike Cook...

ABSTRACT (McCutchen)

The Autonomous Space Processor for Orbital Debris (ASPOD) project is funded by NASA. Over four million tons of man-made debris is in low earth orbit. This debris is traveling at an average of six miles a second. This project is necessary because the debris is dangerous to spacecraft and satellites. The development of a satellite that removes this debris from its low earth orbit is the major problem. The proposed solution for this problem is the Autonomous Space Processor for Orbital Debris (ASPOD). The overall concept of this project is that a computer controlled television camera will spot the debris, then the satellite will position itself so that the debris can be picked up using a robotic arm in conjunction with the end-effector. Next the object will be split into smaller pieces using concentrated solar power. These pieces will then be moved by the arm and end-effector into a storage bin so that they can be disposed of at a later time. A small part of the overall project is the end-effector that will grip the objects to be disposed of. Successful completion of this project will show that there is a low cost and light weight way to clean up space debris. It will also make space safer for spacecraft and satellites. The end-effector is an integral component of the overall concept .

TABLE OF CONTENTS

I. Introduction

After eight months of design, acquisition, fabrication and assembly, the ASPOD End-effector is completed. A great deal of time has been spent in the machine shop making an end-effector for the salvage vessel of the twenty first century. Cascading piles of aluminum chips have been made as dull, raw stock was transformed into precision pieces of technology. As we ride the crest of the new technology wave, we also complete our budding years of educational edification.

Only a few minor design changes were made since fabrication began four months ago. The final product is a fully operational end-effector with three degrees of freedom. These degrees of freedom include a rotational joint, bending joint, and linear grippers. All motors, encoders, and gear heads are totally enclosed within the end-effector tubing, yielding a clean and uncluttered final product. If cost considerations had not made slip rings unfeasible, all wiring would have also been internal. In the limited time span available an extremely complex robotic system was made operational.

Throughout the following report, each section is accompanied by an individuals name. This may give the appearance that only one person is responsible for each task. But it is important to emphasize that this is a team project and there was a high level of interaction within the group on all topics.

II. Initial Design Specifications

The following specifications will be met by the Autonomous Space Processor for Orbital Debris end-effector system.

GRIPPING ABILITY: The end-effector must be able to grip various sizes and shapes. It is proposed that it picks up an object with a maximum weight of 2 lbs and that the jaws open up 5 inches.

DEGREES OF FREEDOM: The design will have three degrees of freedom. The gripper will open and close. The "wrist" joint will rotate and the "elbow" joint will be a pinned hinge joint.

MASS: A maximum total weight of 10 lbs has been set for the end-effector and its components. This will lower the torques it must overcome while being tested on Earth and decrease the weight that will need to be lifted to orbit.

SPEED: A suitable range for the operation of the hand will be from 1/16 to 3/16 (in/s). The wrist will rotate in the range of 2 to 8 revolutions per minute. The elbow joint will move as slow as necessary to keep acceleration at a minimum.

SENSORS: Encoders in joints will be used to relay rotation positions. Similarly, load cells in the gripping mechanism will report the applied force.

MOTORS: The end-effector and arm will be powered by 12-V DC motors. individual motor sizes will be determined by the torques they are required to produce.

COMPATIBILITY: The end-effector will be mounted on a robotic arm which is being developed by another design group. Cooperation with the robotic arm group will insure that our designs are compatible.

DRIVE SYSTEMS: A system of gears, drive screws and chains will be used to relay torques from motors to joints.

TOLERANCES: Because of the high degree of accuracy required, tolerances of 0.002 inches must be adhered to on all load bearing members.

III. Achieved Design Specifications

The following specifications are the new limitations and constraints for the ASPOD End-effector system.

GRIPPING ABILITY: The end-effector is able to grip various sizes and shapes. It produces a gripping force of approximately 8 pounds. The grippers have a maximum opening range of 4-1/2 inches.

DEGREES OF FREEDOM: The End-effector design incorporates three degrees of freedom. The gripper opens and closes along a linear track. The "wrist" joint rotates more than 360 degrees in either direction. The "elbow" joint is a pinned hinge joint that moves through an angle of 220 degrees.

MASS: The End-effector weighs a total of 9.5 pounds. This meets the 10 pound limit set in the original design specifications.

SPEED: A suitable range for the operation of the hand will be from 1/16 to 3/16 (in/s). The wrist and elbow joints rotate between 6 and 8 revolutions per minute. This minimizes the inertial acceleration.

SENSORS: Magnetic Encoders attached to the end of the motors are used to relay rotation positions.

MOTORS: The end-effector is powered by three motors. A 360 oz-in 12-V DC motor powers the elbow joint. The rotational joint is run by a 670 oz-in 12-V DC motor. And a 200 oz-in 24-V DC motor powers the grippers.

COMPATIBILITY: The end-effector is attachable to a parent robotic arm which has been developed by another design group. Cooperation with the robotic arm group insured that the designs are compatible.

DRIVE SYSTEMS: For all three degrees of freedom, power is transferee from the motor through shaft couplers and drive shafts. For the gripper and bending

joints, a series of gears is used to relay power. But the rotational motor transfers torque by direct drive.

IV. Materials

Proper materials selection is an essential part of the design process. The material selected for each component depends upon the stresses and maximum allowable deflections that each individual part can have. In some cases, the size of the part is limited, thus restricting the selection of possible materials. Some components, gears for example, are only available in certain materials, such as steel. Also the mass of each component should be kept to a minimum to reduce bending moments and forces produced from the weight.

The total weight of the end-effector is an extremely important design consideration. A light final product is desired not only to reduce the forces experienced by the end-effector joints, but also because the composite arm must operate with the end-effector attached. Reducing the mass of the final design can be accomplished by "shaving" nonessential material from individual components. There are numerous parts containing material that could be removed without threatening the integrity of the part. If care is taken to ensure only nonessential parts are shaved, the reduction in mass would be of great benefit.

The total number of components for the entire end-effector is quite large. Fortunately most of these parts are not subjected to large stresses and a careful strength analysis is not necessary. But there are some components that are subjected to large stress values, like shafts, gears and the cylindrical housing. These type of components must be analyzed to ensure that they have the strength needed to avoid failure or unacceptable deflection.

The material selection process can be divided into two categories. The first category contains components that are common throughout the end-effector design, such as the cylindrical housing. The other category contains parts that are unique to individual joints of the end-effector, such as the grippers in the jaw

mechanism. Components from this second category will be discussed in the section dealing with that particular joint.

One component that requires important material selection is the cylindrical housing. Since the housing needs to be 2 inches in diameter an approximately 20 inches in length, a light weight material is needed. But because of the length involved, deflection is a potential problem. Two stiff, light-weight materials that could be used include a graphite composite or a low mass metallic alloy. Since the housing will have numerous openings and drilled holes, a graphite composite may be structurally weakened and is not a good material choice. Although aluminum is heavier than a graphite composite it is easier to machine and keeps its mechanical strength. A hollow aluminum tube with an outside diameter of 2 inches and 0.065 inch wall thickness will provide a stiff, lightweight housing. See Appendix B for weight and deflection calculations.

V. Connection to Arm

The end-effector currently being designed will be mounted on a robotic arm which is being designed by another engineering team. Although the connection between the arm and end-effector is not an actual joint with moving parts, it is an important component. The connection must securely hold the end-effector to the arm while allowing simple attachment and detachment of the end-effector. The shapes and sizes of the tubing to be joined dictates the design of the connection. The composite arm tubing will have an outside diameter of 2.15 inches and a wall thickness of 0.075 inches. A flat aluminum plate will be attached to the end of the composite arm, compliments of the arm design team. The aluminum end-effector tubing will have an outside diameter of 2.00 inches and a wall thickness of 0.065 inches.

These specifications were used to design the end-effector connection. The component that will connect the arm and end-effector was machined from a solid cylindrical block of aluminum. The initial dimensions of the block included a length of 1.75 inches and a diameter of 2.25 inches. The aluminum block was machined to the desired shape for the connection using a lathe and drill press, see Figure 5.1 for connection schematic. The outside diameter sits flush with the 2.00 inch diameter of the end-effector tubing.

Once the initial shape of the connection is set, it must be attached to the tubing on both sides. At the aluminum tubing end of the connection, the diameter was decreased by 0.065 inches to allow the tubing to slide onto the connection. The reduction in diameter must produce a snug fit to properly transmit bending moments without allowing play in the connection. The end-effector tubing was then attached to the connection by six 4-40 countersunk cap screws. The screws sit

flush with the outside diameter of the end-effector tubing and screw into threaded holes in the connection.
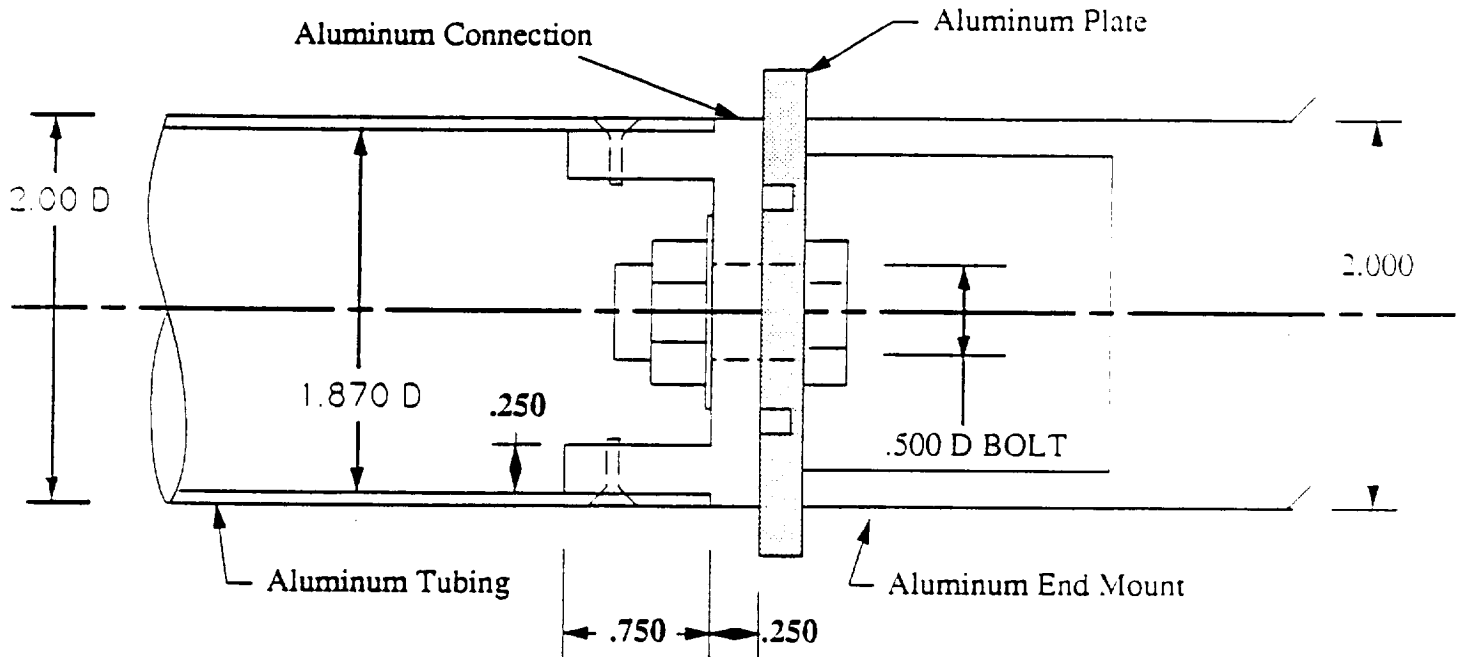
Figure 5.1

A 0.5 inch bolt will hold the connection to the composite arm. A 0.5 inch hole was drilled down the center of the connection. A matching hole was drilled through the flat aluminum plate that is attached to the composite arm. The 0.5 inch bolt will hold the connection to the aluminum plate. A 1.375 inch diameter hole has been machined into the other end of the connection to reduce overall weight and allow room for a nut to be fastened to the bolt. Two 0.125 D inch dowel pins are also permanently embedded in the connection. They slide into mating holes on the flat aluminum plate and provide extra resistance to rotation. See Appendix C for a complete schematic of the connection to the composite arm.

9

VI. Rotational Joint

The design of this joint has involved many steps and modifications. In the design of this joint the amount of rotation has been the main design criteria. There are two ways to approach this problem, one way is to design it for unlimited rotations, and the second is to limit the rotations. For an unlimited rotation the joint would utilize a slip ring, which would allow the wires to be enclosed within the arm. The slip ring was then checked for price and availability and it was found that the slip ring would cost $2316 if purchased from Fabricast Inc. It would not be available for 12-14 weeks. Therefore, the use of a slip ring is not practical, due to the cost and lack of availability. This then lead to a design with a limited rotation. The computer program itself would prevent the wires from twisting and breaking.

Once the basic configuration was determined the design of the joint itself could begin. The final design of this joint is shown in Figure 6.1. The maximum torque for the rotational joint was determined to be 40 in-lbs. A motor capable of producing this torque was then found. The specifications for this motor (part #3) can be found in Appendix C. It was then necessary to support the motor within the tube. This was done by machining a front and back motor support. Part #4 and part #1 respectively. These supports were connected to the motor using the preexisting holes that are designed to help mount the motor. The 4 mounting holes on the front of the motor are 3 millimeters in diameter and the 2 holes on the back of the motor are 2 millimeters in diameter. This should be noted because the rest of the Allen head screws used are in English units. The motor supports prevent the motor from rotating within the tube because the supports are connected to the tube using Allen head screws. There are 4 screws holding each motor support in place.

10

TO ARM
CONNECTION

COUNTERSINK HOLE

REAR MOTOR
SUPPORT (#1)

ENCODER (#3)

4 X 4-40 (#2)

MOTOR
(#3)

AL TUBE (#15)

GEARHEAD
(#3)

FRONT MOTOR
SUPPORT (#4)

4 X 4-40 (#5)

MULTI-JAW
COUPLING (#6)

NUT AND WASHER (#8)

BEARING (#9)

AL RING (#10)

4 X 4-40 (#11)

DRIVE SHAFT (#7)

BEARING (#9)

DRIVE SUPPORT (#12)

4 x M6 (#13)

NUT AND WASHER (#14)

AL TUBE (#16)
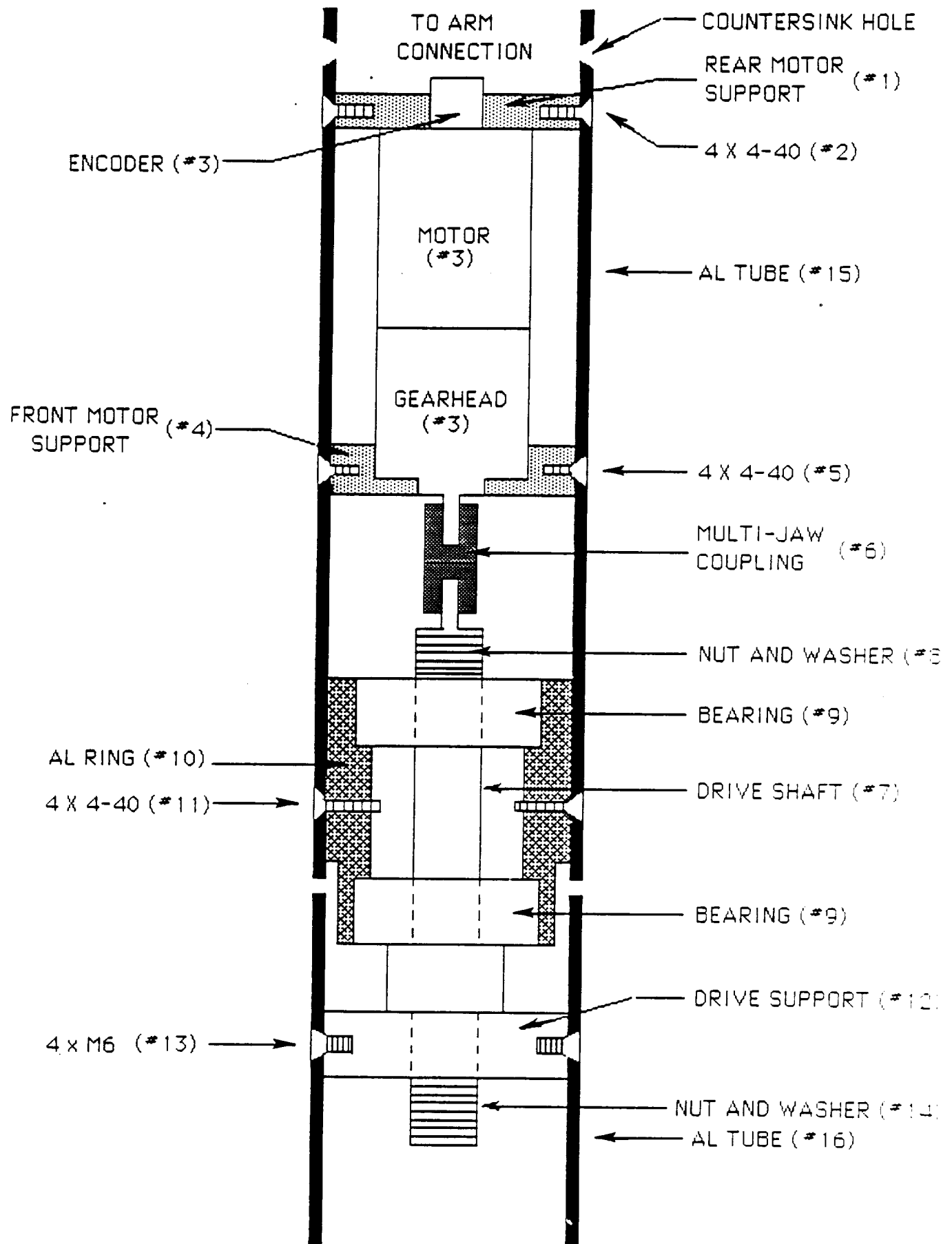
Figure 6.1

1 1

The Allen head screws are parts #2 and #5 and they are 4-40 size Allen head screws. The motor supports also insure that the motor is lined up in the center of the tube. These motor supports can be seen in Appendix C. The next design decision was on how to transmit the torque from the motor to the arm. A drive shaft connected by a multi-jaw coupling to the motor was the solution. This drive shaft turns at a maximum of 18.9 revolutions per minute. The minimum diameter of the drive shaft was also calculated and it was found to be .455 inches in diameter. To permit the drive shaft to rotate in the fixed end of the aluminum tube a set of bearings was used. These bearings were press fit in to the tube and separated by a 0.52 inch thick aluminum ring. These bearings will reduce the load on the motor shaft and by placing the bearings 1 inch apart the deflection will also be reduced. The outside end of the aluminum ring was machined down to allow the aluminum tube to rotate freely. The aluminum ring is held in place by four Allen head screws these Allen head screws kept the ring and the bearings from rotating or moving. The bearings will be held in place by a Nylock nut and washer (part #8). The specifications and designs of the shaft coupling (part #6), the drive shaft (part #7), the aluminum ring (part #10), and the bearings (part #9) is in Appendix C.

Once the drive shaft is past the bearings it will be connected to the rotational part of the end-effector. The end of the drive shaft will be threaded in order to connect it to the rotational end of the end-effector. The threads are 1/2-13 threads. On the end of the drive shaft will be the drive support. The drive support is how the torque of the motor is translated to the end-effector. A 0.5 inch hole will be drilled in the drive support and be threaded this will allow the drive support to be screwed on to the drive shaft. The drive shaft and the threads must be perfectly flat and straight so that the arm rotates straight. The drive support is held in place by four Allen head screws. These screws are 6 millimeters in size. A self-locking nut and washer will be placed on the drive shaft after the drive support to insure that it

12

does not back off or loosen. See Appendix C for the specifications and drawings of the drive shaft, nut and washer (part #14), and drive support (part #12). The screws that will be used to hold all pieces will be Allen head countersink screws because of their high strength.

The design of the joint has been extensive and has lead to this final product. The production phase of the project went well with very few problems or changes. The only real change occurs in the design of the aluminum ring. The outside diameter of one end was machined down to allow the tube to rotate freely. This was the only production change.

The finished product is of high quality it works very well and meets all specifications. The overall cost of the rotational joint was $537.85. The motor for the rotational joint cost $435.65, and the labor was free. The rotational joint has exceeded expectations.

A. Materials

A critical component that must be carefully designed is the shaft that connects the two separate sides of the rotational joint. This shaft will experience alternating bending moments, shear forces, and torques as it rotates. The shaft also experiences stress concentrations were the diameter changes. It is critical that the shaft be adequately designed to prevent fatigue failure. The deflection of the shaft must also be kept to a minimum. Any deflection in the shaft would be amplified along the remaining length of the end-effector, creating a much larger deflection at the gripping surface.

There are two major variables that can be adjusted in the shaft design, the material selected and the minimum shaft diameter. Although steel is much heavier than aluminum, it is also considerably stronger. Do to the high strength

13

required and space considerations, steel was the material selected. For the analysis of the shaft, 1030 steel was used. Fatigue analysis was preformed to find an appropriate minimum shaft diameter. Then the minimum shaft diameter was checked for a possible unacceptable deflection. See Appendix C for calculations. Based on a factor of safety of 2.5, the minimum shaft diameter was found to be 0.45 inches.

B. Motor

The motor selected for the rotational joint is a 12 volt 2842s Micro Mo. motor with a 30/1 gear head and a 415:1 reduction ratio. The maximum stall torque for this motor gear head combination is 772.7 Oz-in. The torque required to rotate the wrist with the elbow bent through the horizontal plane is 672 Oz-in. See Appendix C for calculations. The maximum output power of the motor is 9.4 Watts The maximum RPM this rotational joint can experience is 18.9 RPM.

VII. Elbow Joint

The next joint on the ASPOD End-Effector is the elbow joint. Below is a two view sketch of the design prototype.

Elbow Connection

Inner Knuckle

Spriral Bevel Gears

Axial Bearing Cap

Cap Screws

Axial Shaft

Set Screws

Taper Bearings

Pinion Bracket

Shaft Coupler

Pinion Shaft

Outer Knuckle
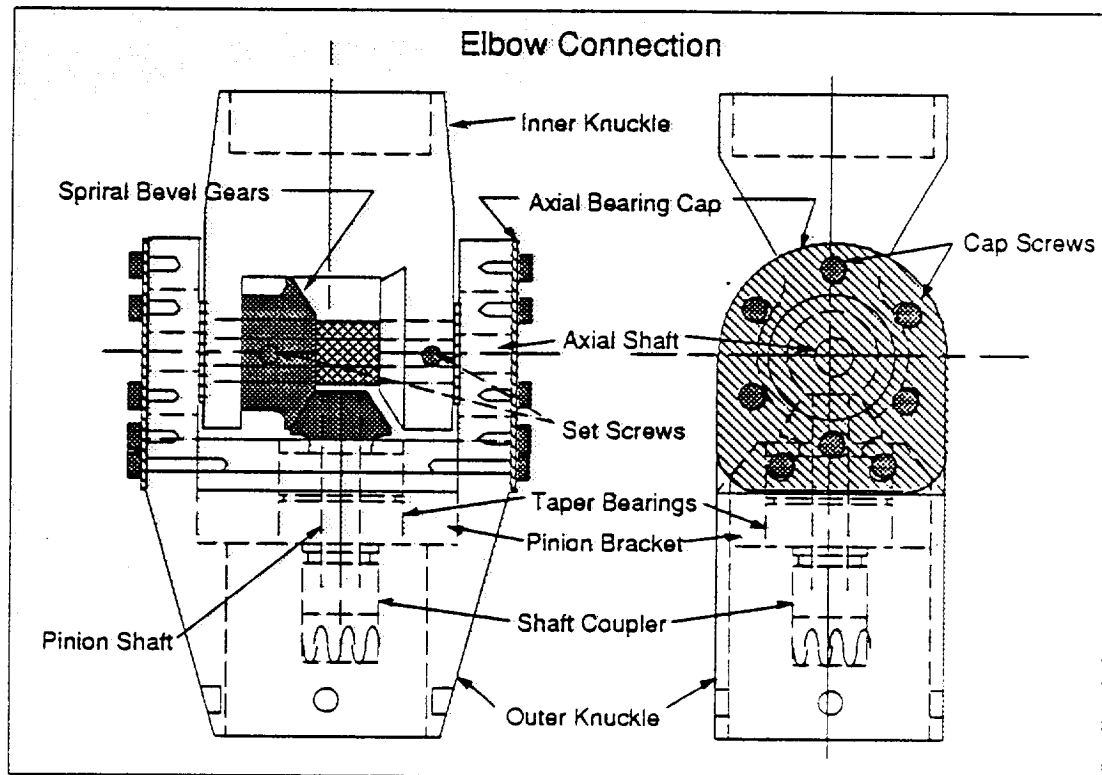
Figure 7.1

The elbow prototype consists of two major design constraints. Design reliability and design aesthetics. As Design engineers we strive to design a perfect product. Unfortunately, due to physical laws of nature such as friction, wear, and corrosion we are seldom successful. The best a designer can hope for is to design a product that is resistant to friction, wear and corrosion. As Designers we can also design in qualities to help enhance the product's reliability, such as ease of assembly, maintenance and adjustability. The ASPOD elbow is such a product that was designed with reliability and aesthetic considerations in mind.

15

A.   Drive Gears

The ASPOD elbow is driven by a set of spiral bevel gears. Spiral bevel gears have overlapping tooth action which results in a smoother gear action, lower noise, and higher load capacity than a straight bevel of equal size. The duty load of the bevel gears is, at most four hours per week and their rotation will never exceed 25 revolutions per minute. Therefore, little or no lubrication is required for these gears. However, a light Teflon coating on each gear is recommended to prevent any wear that might occur during operation. The bevel gears are made of hardened steel to help prevent against chipping of the teeth during operation. One of the design considerations was to find gears which could handle the stress on the gear teeth under normal and extreme operating conditions. The gears for this joint must be made of hardened steel or they may chip or fatigue. See Appendix E for stress on gear teeth calculations.

B.   Axial Bearings

Another design problem that must not be over looked is movement of the inner knuckle along the axis of rotation. If this happens then the bevel gears will not mesh properly resulting in unnecessary play and extensive wear on the teeth. To prevent this axial movement from occuring, taper bearings are preloaded in the outer knuckle in an opposing manner. Taper bearings from Timkin corporation are able to operate under radial and axial force. A series of cap screws on each side of the outer knuckle hold the axial cap to the bearings and regulates the preload force. The preload force on the axial caps was determined experimentally during the testing phase of the project. Nine to twelve foot-pounds of torque is required

on the axial cap screws to lock the position of the large bevel gear and to provide enough resisting force to the gripper moment, arm which helps to stabilize the gripper in a horizon plane without a voltage input to the motor.

C   Pinion Bracket

The pinion Bracket is designed as a single unit. Its unique shape will mate snugly inside cut out of the outer knuckle. Four bolts, two below each axial bearing help to hold the assembly in place. This single unit design feature helps to aid the operator in the assembly process. The nut at the base of the pinion shaft would be nearly impossible to access inside of the Outer Knuckle if the Pinion Bracket were connected to the Outer Knuckle. See Figure 7.1. Therefore the Bracket was designed to be removed from the top end of the Outer Knuckle to allow access to the nut, washer, and shaft coupler. Another benefit of the removable Pinion Bracket is that it allows for future modifications. If upon final assembly a flaw in the gear alignment is found due to the positioning of the pinion gear. The flaw can be repaired by reconstructing the Pinion Bracket rather than reconstructing the entire Outer Knuckle. Therefore, since the Pinion Bracket allows for ease of accessibility and freedom for future modifications it will serve as an effective component in the overall bending joint design.

D.   Pinion Shaft

The pinion shaft is a 0.3750 in diameter steel shaft turned down to 0.3175 in on one end and 0.3125 in on the other end. A set screw will be tapped in the pinion gear and tightened against a ground flat surface on the pinion shaft. This allows adjustability of the pinion with respect to the gear. The pinion shaft is supported in

a similar manner to the axial shaft by two opposing taper bearings, loaded into the pinion bracket and held firm by a 3/8 - 16 washer and nut. The nut preloads the bearings to prevent lateral movement in the pinion gear. The preload torque was experimentally determined in the testing stage. Twelve to Fourteen foot-pounds of torque is required on the nut in order to provide enough resistive force to help stabilize the gripper moment arm in the horizontal plane under gravity. Finally a shaft coupler will be added to the base of the pinion shaft. It's purpose is to create a dividing point between the motor and the pinion shaft. The Pinion Bracket will be accessed from the top of the Outer Knuckle and the motor will be accessed from below. With the motor and the Pinion shaft in place no tools can be used to assemble or disassemble the Pinion shaft and Motor shaft connection therefore a multi-jaw coupler is used.

E. Axial Shaft

The axial shaft is a is a 0.6250 in diameter steel shaft turned down to 0.3750 in on both sides with a standard 1/8 " X 1/16 " key way rooted through the length of the large diameter. See Figure E.1. The Outer knuckle will be connected to the Inner Knuckle with the Axial shaft. Washers will be placed on each end of the axial shaft to maintain the 1/16 in clearance between the outer Knuckle and the Inner Knuckle. Since the gear rests against the Inner Knuckle and the pinion is connected to the Outer Knuckle the washers also serve to maintain 0.004 in clearance between the gears. This is another example of adjustability. The washers can be machined and replaced to maintain proper gear clearance more easily than machining new Outer and Inner Knuckles.

F.   Motor Mount

The motor will be mounted to the outer knuckle with the motor mount bracket in Figure E.2. Four, three millimeter cap screws will hold the motor to the mounting bracket. A single machine screw will support the mounting bracket to the sleeve. This screw will keep the connecting holes on the mounting bracket lined up with the connecting holes on the sleeve while an assembler aligns the connecting holes with the corresponding connecting holes on the outer knuckle. With everything assembled correctly the shaft couplers will be in perfect alignment with each other.

G.   Materials

Now that all of the major failure points have been carefully considered the design aesthetics can be improved on. The Outer knuckle, Inner knuckle, and pinion shaft bracket are machined out of stock Aluminum. The bevel gears are hardened steel and black in color. The Axial bearing cover on both sides of the outer knuckle are made from polished brass to complement the machine finished aluminum that it rests against. To offset the brass color, all cap screws in the axial bearing cover are black Allen head in shape and symmetric about the center line axis. One subtle aspect that the drawings do not show is the fact that all sharp edges rounded in the final product. Smooth transitions from the round two inch diameter sleeves to the rectangular mid section are also incorporated in the final product. With contrasting metals, colors, symmetry and smooth transitions the End effector elbow should give the appeal of a solid state product.

H.   Adjustability

When machining a complex component such as the End-effector bending joint, a machinist can spend days even weeks setting up a job, checking the precisions and machining the part. The last thing the machinist wants to do is to re-machine a part because of a subtle design flaw. This is why it is important to have adjustability designed into the part. For example the a pinion's ability to slide vertically along the pinion shaft to help make up the vertical clearance between the gears. The pinion bracket, unattached to the Outer Knuckle, gave the flexibility to replace the pinion bracket if upon completion of the elbow the pinion shaft was is not parallel to the center-line of the arm; the bracket can be re-machined more easily than the Outer knuckle. These adjustability considerations help aid to the products reliability. If the product fails there is room to improve.

I.   Motor Selection

The motor chosen for the elbow is a 12 volt Micro Mo 2842s with a 30/1 gear head of 134:1 reduction ratio. This motor and gear head combination offers 603 Oz-in of stall torque. Calculations for torque on the elbow show that only 340 Oz-in are required to operate the elbow and forearm at a horizontal position. This will allow for a large margin of safety. The recommended max continuous RPM is 22.4 in the motor and the forearm will rotate at 10 RPM due to the 2:1 reduction of the bevel gears. The power required by the motor assuming that the forearm rotates at 10 RPM is approx 5 watts, and the motor efficiency is 72%. For motor mounting considerations ,it is not that important to be concerned about heat dissipation from the motor since the 5 watts of power output from the motor will be converted into useable energy. However some thermal dissipation will occur. The motor chart in

20

Appendix E shows that 16 degrees per watt will dissipate from the case to the surroundings, assuming that the motor is suspended in mid air. Since the motor will be attached to a gear head the gear head will act like a heat sink and draw the heat away from the motor.

J.   Improvements

Upon testing the elbow connection intolerable amounts of play began to propagate in each axial connection of the elbow due to the slipping of shaft couplers on the rotational shafts. The sources of play were: motor shaft/shaft coupler connection, pinion shaft/shaft coupler connection, pinion shaft/pinion gear connection and the axial shaft key way. The play in the key way was removed by milling a flat surface on the axial shaft and inserting a set screw through the inner knuckle and perpendicular to the flat surface. The play on the shaft couplers and their mating shafts was removed by drilling a shallow hole in the shaft for the set screw to sit into and securing the set screws with lock tight. Other modifications include removing excess material from the Inner Knuckle and the Pinion Bracket. All modifications are noted in their respective drawings. See Inner knuckle drawing, Main axial drawing, and Pinion bracket drawing.

VIII.   Gripper

A.   Constraints:

1.   The gripper is to be able to hold an object of one pound, and up 5 inches in diameter with a factor of safety of two while subject to accelerations and conditions it will incur during normal working conditions in land based service.

2.   The gripper (not the entire arm) will maintain accurate jaw placement to a 1/32" error during normal working conditions in land based service.

3.   The gripper will be controllable by a computer program based instruction set, as opposed to manual control by a human operator.

4.   The gripper shall be no larger than 10 inches by 5 inches by 5 inches.

5.   The gripper will be maintainable (Disassembly will be possible, and will not require any structural modifications to the individual parts.)

6.   The gripper will interface with the rest of the effector and in turn the rest of the arm.

B. Design
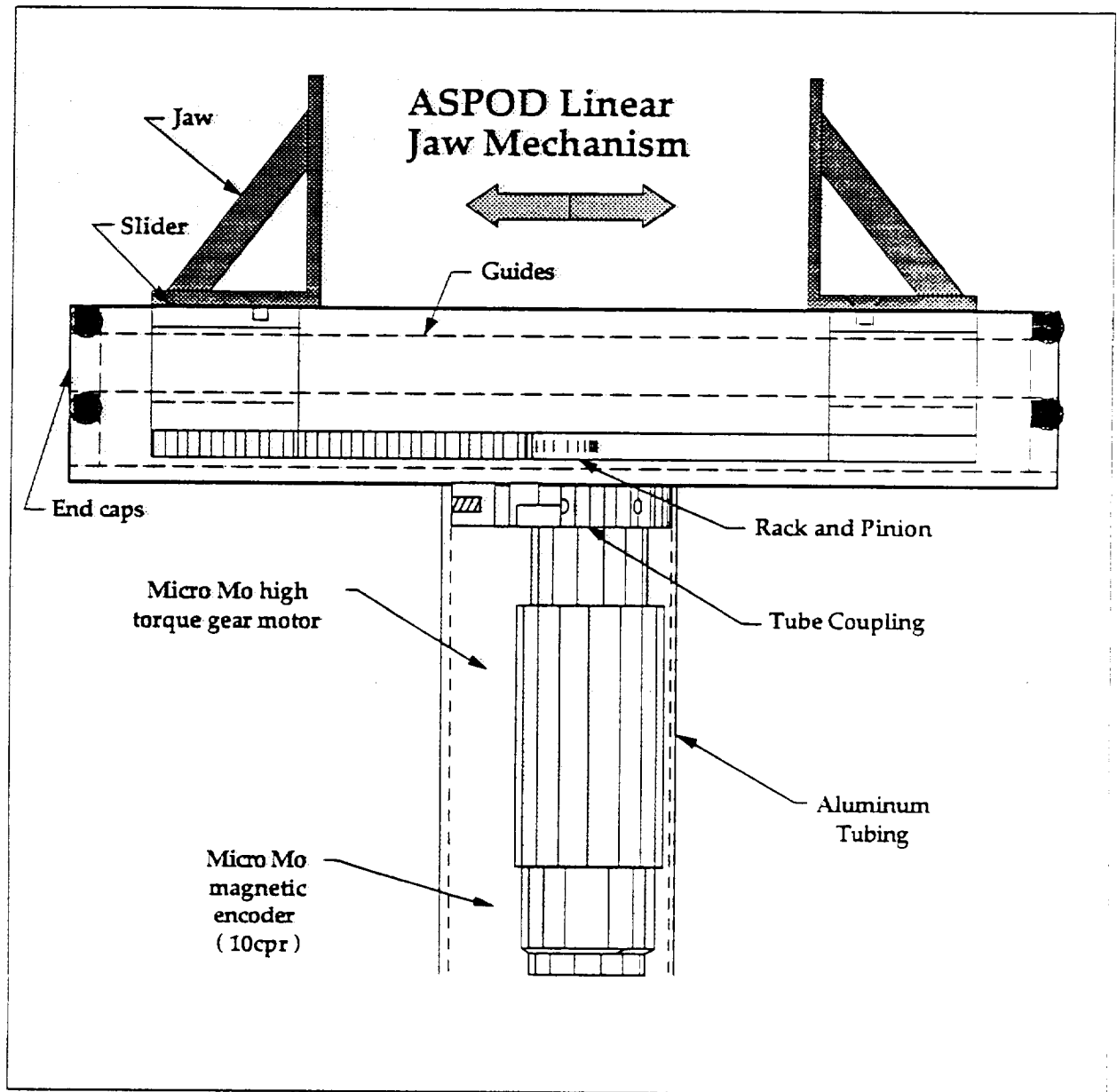
Figure 8.1

In the design of the gripper mechanism, there are many considerations. Since the design will be used for demonstration purposes, it will have to survive transport procedures, and be able to perform in a gravity environment. Also, being an experimental prototype, the mechanisms should have the ability to be easily

modified. To meet the operating requirements the design shown in Figure 8.1 above, will be used. Removeable jaws attach to two sliders. The sliders are supported by two aluminum guide shafts connected to two end plates. The jaws will be forced by a high torque Micro Mo gear motor through a rack and pinion mechanism. The end caps, motor, and tube coupling will all be mounted rigidly to an aluminum housing. All the parts are designed to be simple to make, and replace.

Removable Jaws

Removable Jaw

Dowel Pin

Slider
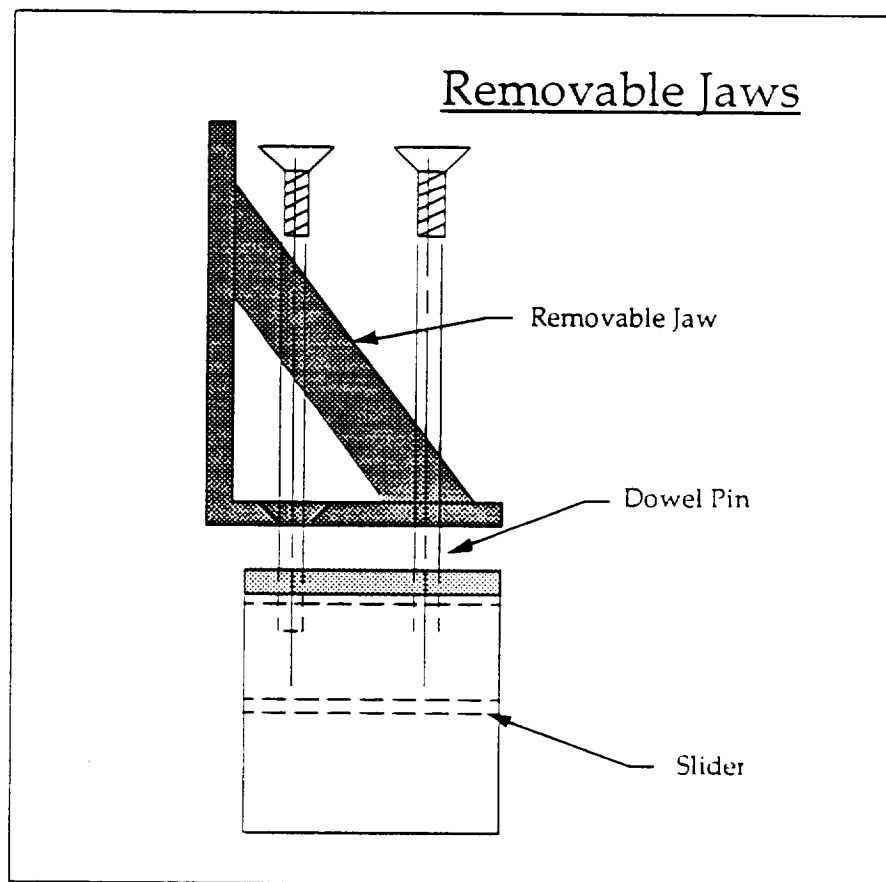
Figure 8.2

Two of the simplest parts are the removable jaws. Jaws that can be removed and replaced, allow for easy modifications in case of design requirement changes.

24

For the initial design each jaw will be machined out of a single piece of Plexiglass. The connection to the slider will consist of two screws to secure the jaw to the slider (see Figure 8.2 above). To hold the an object at maximum specifications, the jaws must supply 7.5 lbs of force. At these parameters, the screws must support fatigue loading with a maximum normal load of 11.25 lb, and a maximum shear load of 7.5 lbs. A 10-32 screw with a 0.02 in^2 stress area requires a preload of 8.245 lb. The Hencky-Mises equation was used along with an approximation of the Goodman criteria to find that a minimum of 0.02623 screws would be needed to hold the jaw securely in place. Complete calculations are contained in appendix E.

The jaws above will be mounted to two aluminum sliders located inside the housing. The sliders are supported by two aluminum guide rods, and driven by a steel rack. At the 7.5 lb holding force the slider transmits a moment of 24.375 in-lbs to the aluminum guide rods. During a maximum holding condition the guide rods will deflect a maximum of 4.22e-5 inches over its length. The guide rods are supported by two end caps.To check for safety, it was assumed that all the force was transferred to one end cap. 0.22265 6-32 screws are required to support this loading. At 4 screws per support, the screws will not fail due to fatigue.
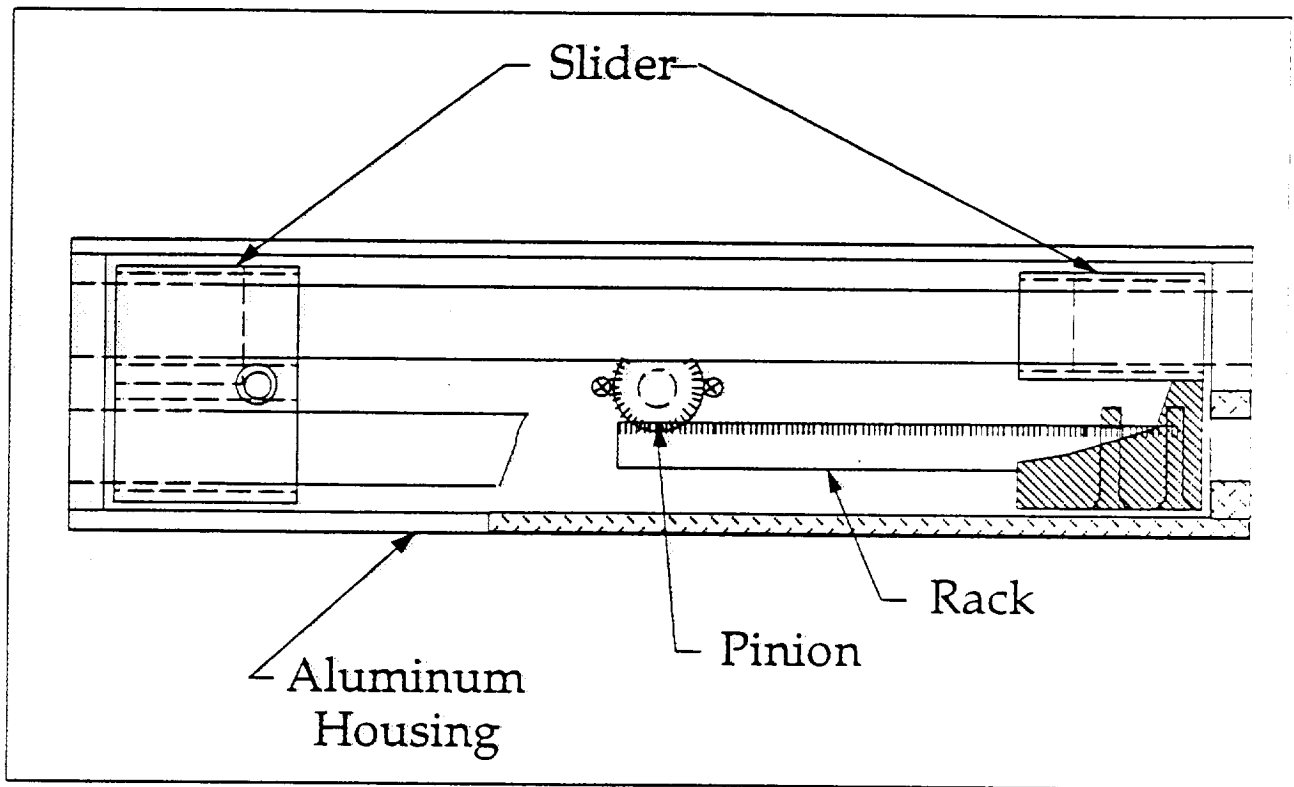
Figure 8.3

Each slider is also connected to a rack. The rack and pinion system is driven by a Micro Mo high torque motor mounted to the back of the housing (see figure 8.1). Since each jaw must supply 7.5 lbs of force to the object, the pinion must supply 7.5 lbs to each rack. Therefore the motor must supply 10.005 in-lbs (160 oz-in) of torque through the 0.667" diameter pinion. The Micro Mo motor being used supplies 200 oz-in of torque resulting in a factor of safety of 2.5. Originally, the racks were to be held to the pinion by the center support, however, preliminary testing indicated that the center support was not necessary (Calculations in appendix E).

The end caps, sliders, guides, rack, and pinion are all contained inside of a U-shaped aluminum housing. The housing is extremely rigid to prevent unnecessary movement and deflection. The rest of the robot arm interfaces the housing

through a tube coupling. The tube coupling is basically a large aluminum washer sandwiched between the front of the motor and the front of the housing (See figure 8.1). Six screws secure the support tube to the coupling. Accounting for the weight of the gripper and the maximum load, the tube coupling requires 0.027584 screws (Appendix E).

Six Allen head cap screws secure the aluminum tubing to the tube coupling. This aluminum tubing provides a supporting structure from the elbow to the gripper. The original design called for an aluminum heat sink to be mounted around the motor. Preliminary testing determined that a heat sink was not necessary. However, if during more rigorous testing the motor is in danger of overheating, a heat sink can easily be added. If the motor is still in danger of over heating, other corrective measures will be considered.

C   Motor

The motor must supply 160 oz-in of torque to meet with a factor of safety of two holding requirement. The motor being used for this is a Micro Mo 2233-C024s high torque gear motor. This motor operates through a 750:1 gear reduction to supply 200 oz-in of torque. The Micro Mo motor was chosen for its high torque, small size, and low cost (Micro Mo supplied a free product sample.). Originally a Pittman high torque motor was specified, but when Pittman announced shipping delays, Micro Mo was recontacted. After some discussion it was determined that a product sample could be obtained.

Although the sample Micro Mo gear motor has a gear head with an offset output shaft, very little adjustment was needed. With the motor skewed to one side inside the connecting tube, the pinion remained centered between the two

sliders. Since the twisting axis rotates at a relatively low speed, the any imbalance caused by the skewed mounting is negligible.

The gripper design is currently being machined and built. In the evaluation of the design, great care was taken to find a simple but durable design. On of the tools used was the Hencky-Mises equation with the Goodman criteria. These techniques were used to construct a spreadsheet for evaluating the fatigue life of the many small screws in the gripper structure. Preventive measures like this will make redesign more rare and easier.

D. Materials

The material used to make the actual grippers must be carefully selected. Since the end-effector is a linear jaw design, the slightest deflection of the gripper will significantly reduce the gripping force. Also the gripping surface must have a high coefficient of friction to reduce the possibility of the object slipping between the grippers.

Three materials considered for the grippers include: steel, aluminum, and plastic. After analysis to find the size and weight of each material to insure a minimum deflection, plastic was chosen as the optimum material. Also, instead of square sided grippers, a triangular design was chosen. The triangular grippers will provide better support while keeping the total size to a minimum. See Appendix F for calculations. The calculated minimum width of the gripper base is 0.23 inches.

To reduce the possibility of the object slipping between the grippers, the inside of the plastic grippers may be covered with a material having a high friction coefficient such as rubber. The current grippers are coated with a 0.125 in. thick sheet of foam rubber. This surface seems to be a good overall choice, but different materials could be used depending upon specific applications.

As the grippers open and close, they are supported by two linear guides. These linear guides could be subjected to a large bending stress as the grippers apply a force on an object. For this reason, stress and deflection analysis are done to find the best material selection for the guide shafts. See Appendix F for calculations. Although steel guides would have a smaller minimum diameter, they would be heavier than aluminum guides of comparable strength. Therefore aluminum guides with a 0.5 inch diameter were chosen.

IX. Control System

ASPOD Control System
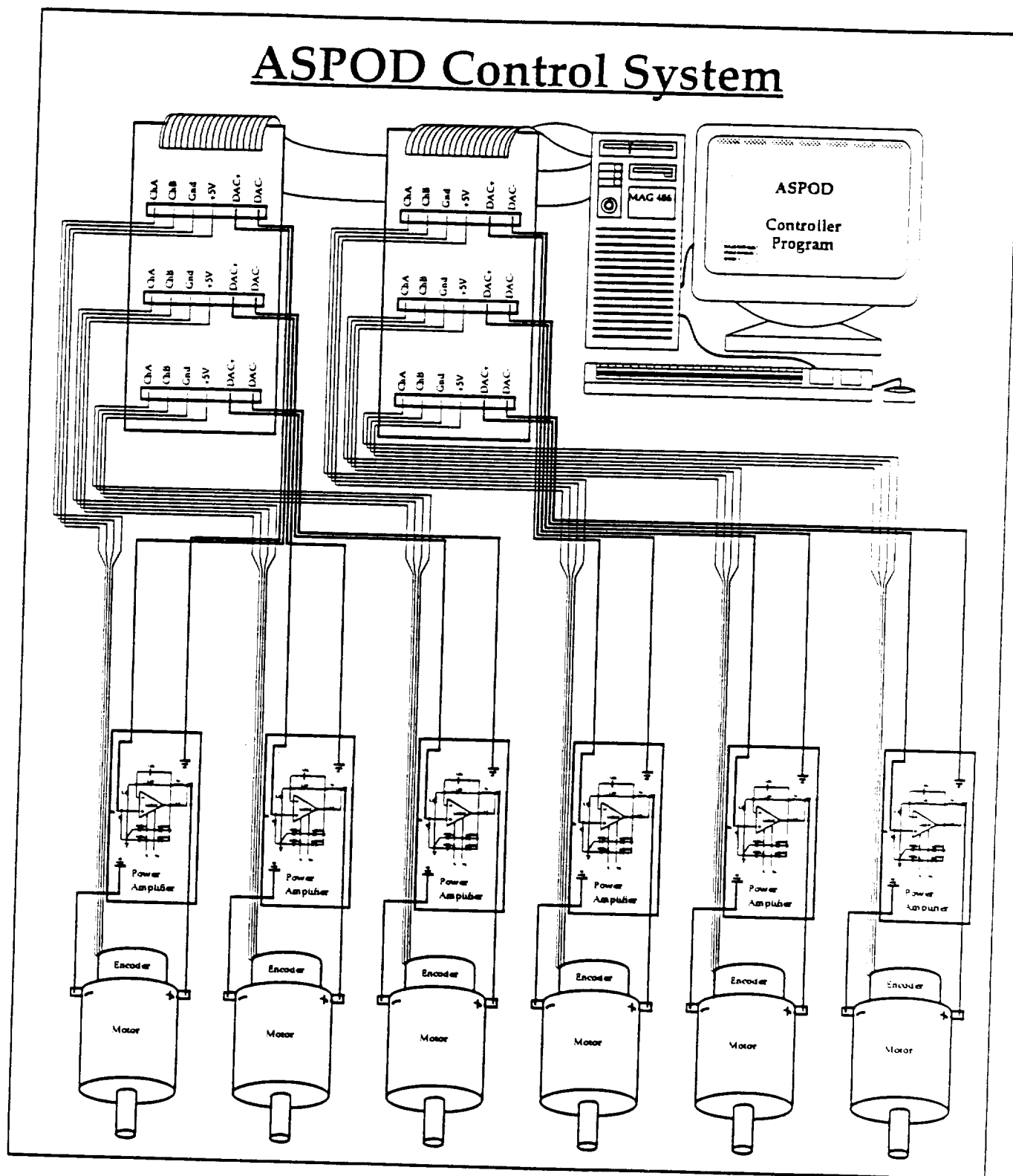
Figure 9.1

In the current design, one of the major upgrades from last years arm is the control system. The control system (A general block diagram is shown above in figure 9.1.) allows the operator to program a desired output into the terminal. The computer based control system then calculates the specific system requirements, provides the system commands, and moves the system to the desired state while checking for errors. This process starts at the computer terminal. The user specifies a move using one of the programming methods available. The controller card inside the computer converts the logical command to a voltage command and sends the command to the appropriate axis via the connection card (Shown in Figure 9.1). The power amplifier converts the output signal to an appropriate motor input command signal. While the motor is in a control mode the controller card reads the encoder output, comparing the output to the desired position. The controller card will move the motor to the deserted position and keep it there until another command is given. The major components used in the control system are the actuators, the feedback sensors, the interface hardware, the controller card, and the computer based instructions.

A.   Actuators

The actuators used for the end effector are all Micro Mo high torque gear motors with integrally mounted magnetic encoders. The motors used for the bending and the twisting joint require a twelve volt power output, while the gripper motor requires twenty four volts. The controller card offers a convenient method for adjusting the output signal. Gain and offset potentiometers are supplied for each axis and can be adjusted for a desired output. The details concerning each motor are contained in the section associated with each joint.

C-3

B.   Encoders

In the ASPOD end effector design, the actuators are all DC motors requiring an analog output from the controller card. Attached to the back of the motors are the feedback sensors. In the case of the three Micro Mo motors the feedback sensors are magnetic encoders. Magnetic encoders were chosen because they were cheaper and more readily available as an integral package from the manufacturer. Although, the output is similar to that of an optical encoder, the interface hardware is having trouble interpreting the feedback signal. Testing is currently being conducted using an oscilloscope to determine possible sources of error.

Gripper Encoder

A Micro Mo motor drives the rack and pinion mechanism on the gripper. The racks each travel 2.095 inches for one revolution of the pinion. However, the optical encoder on the back of the motor travels 750 revolutions for each pinion revolution. At

10 counts per revolution, the encoder has reads 0.000069833 inches per count with quadrature decoding. This is well under the 1/32 inch resolution specified in the gripper constraints (see encoder calculations in appendix F).

Elbow Encoder

The motor for the elbow joint is to be controlled to within 1/32" at the tip of the jaws (neglecting backlash). The length of the end effector from the bending (elbow) joint to the tip of the jaws is about 10 inches. At this length, the elbow goes

through an angular displacement of 0.179014° / count. The encoder resolution available from Micro Mo is type HE with a resolution of 15 counts per revolution. With a quadrature decoding and a gear reduction of 268:1 this encoder is accurate to 0.02238806° / count. Therefore the 03b was selected (Appendix F).

Wrist Encoder

The motor for the wrist joint is to be controlled to within 1/32" at the tip of the jaws (neglecting backlash). The length of the end effector from the bending (elbow) joint to the tip of the jaws is about 10 inches. At this length, the elbow goes through an angular displacement of 0.179014° / count. The lowest encoder resolution available from Micro Mo is type HE with a resolution of 15 counts per revolution. With a quadrature decoding and a gear reduction of 159:1 this encoder is accurate to 0.03773585° / count. Therefore the 03b was selected (Appendix F).

C   Interface Hardware

In the control system the controller card does not interface directly to the encoders and the motors. First the controller connects to a wiring interface card which in turn connects to the power amplifiers and the encoders (See Figure 9.1). The interface card was supplied by Servo Systems with the controller card. The power amplifier circuits were constructed by Peter Wagner of the arm design team.

Power Amplifiers

The power amplifier circuits were designed around a National Semiconductor LM12C operational amplifier. The circuit involves two power

supplies powering a common bus. Each power amplifier circuit draws power off the bus to distribute to the appropriate motor. Problems were experienced with the circuit construction. Circuit construction utilized breadboard wiring system. Numerous problems were experienced with wires coming loose or shorting. Two diodes were destroyed in this manner. Therefore summer work will include constructing a better circuit configuration to interface with the motors and the controller card.
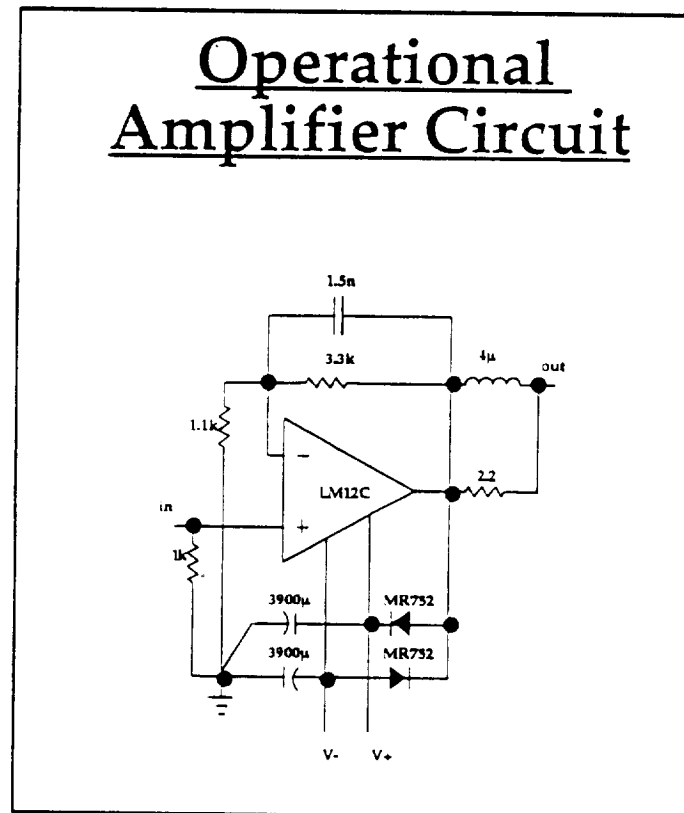
Figure 9.2

D.   Controller Card

The controller card is the main processor of the control system. The Omnitech Robotics MC-3000 card is a 3 axis controller card designed around three Hewlett Packard HCTL-1000 motion controller IC chips. One MC-3000's is sufficient for the three axis of control required for the end effector. Although several control modes are available, the trapezoidal profile mode is being used. Trapezoidal mode is ideal for robotic applications because it offers reasonable velocity and acceleration control with positioning control. An acceleration/deceleration and a maximum velocity are specified by the user. When the card receives a position command, it accelerates the motor until maximum velocity is reached or until motor is halfway to the desired position. Then the motor is decelerated at the programmed deceleration. After the motor is decelerated, the card checks for position, and adjust to the programmed value.

E.   Total Control Programming

Although a decoding program was provided by Servo Systems, a better user interface was desired. A personal goal was to have a program that fulfilled three goals. The program should be easy to use, powerful, and of course the program should be able to run the robot arm through fixed routines. Originally the "C++" programming language was chosen for the program. However, it was later decided to use "Turbo Pascal 6.0". Turbo Pascal is easier to learn and compiles quicker, significantly lessening development time. Turbo Pascal also came equiped with extra libraries for windows and mouse interface programming. These libraries were not included with C++.

35

The libraries for the mouse and for windows were necessary to construct a menu and mouse driven program. The ease of use associated with a menu driven program puts the commands in "pull down" menus allowing a new user to learn commands quicker. The windows display the output in a more ascetically pleasing manner. This type of graphical user interface did pose some problems to the programmer. A new programming method was needed. The program is based on events and objects. Every procedure, variable or other object is controlled or utilized by events. Every action taken by the program or the user is an event requiring an event handler to identify actions with reactions. In this manner the supporting procedures or objects in the program occupy nearly sixteen hundred lines of code while the actual program only requires six. The menu diagram shown below gives a general idea of the layout of the command structure.

Menu Layout

| File | Edit | Search | Windows | Base | Should | Elbow | Twist | Bend | Grip | Command |

Search (under Search):
- Search
- Find ...
- Replace ...
- Search Again

Edit (under Edit):
- Edit
- Undo
- Cut
- Copy
- Paste
- Show Clipboard
- Clear

File (under File):
- Open
- New
- Save
- Save as ...
- Change Dir .
- DOS Shell
- Reset
- Default
- Decode
- NTest
- Exit

Windows:
- Size/Move
- Zoom
- Tile
- Cascade
- Next
- Previous
- Close

- Calculator

Base / Should menus:
- Gain Set
- Zero Set
- Pole Set
- Timer Set
- Velocity Set
- Acceleration Set
- Position
- Clear Position
- Move Setting
- Current Values
- Execute
- Test

(repeated blocks for Base, Should, Elbow, Twist, Bend, Grip)

Command:

Reset	Home
Base Left	Alt-F5
Base Right	Alt-F6
Shoulder Up	Alt-F7
Shoulder Down	Alt-F8
Elbow Up	Alt-F9
Elbow Down	Alt-F10
Twist Left	F5
Twist Right	F6
Bend Up	F7
Bend Down	F8
Gripper Close	F9
Gripper Open	F10

ASPOD Controller Program: Menu Diagram.

Figure 9.3

In the menu diagram shown above the layout is constructed in an intuitive manner. The first three submenus, File, Edit , and Search deal with the full featured file editor and the command file execution. The Windows submenu controls the arrangement and placement of the text, file and other windows on the screen. The Windows menu can also provide an easy to use calculator. The next set of windows Base, Should, Elbow, Twist, Bend, and Grip contain commands for setting the various parameters associated with trapezoidal mode operation. Trapezoidal mode will accelerate at a set rate to maximum velocity, move at this velocity and decelerate at the set rate. At the end of the trapezoidal profile the chip switches to position control mode to keep the axis at the desired setting. The final heading in the main menu is the Command menu. These commands send each axis a command voltage to move the axis in the specified direction until another voltage command or a reset command is sent to that axis. The key codes at the right of each command allow the operator to move the arm using keyboard commands. Listed below is the full set of menu commands and a brief description of each.

Menu Command List:

File:

       Open: Opens an existing file for editing.

       New: Creates a new file for editing.

       Save: Saves current file in the active window.

       Save as. . . : Saves current file under a new name.

       Change Dir: Changes the current working file directory.

       DOS Shell: Exits to a dos shell were it is possible to execute limited DOS commands.

       Reset: Sends a hard reset to all six axis (Clearing all previous settings).

       Default: Sets all trapezoidal values to a default assigned inside the program.

Decode: Executes a routine program, decoding commands and values.

NTest: Used to test a decoding procedure inside the program (For debugging).

Exit: Exits the ASPOD Controller program.

Edit:

Undo: Cancels the last change made in the file editor.

Cut: Removes a block of selected text from the current window and saves it to the clipboard.

Copy: Copies a block of selected text from the current window to the clipboard.

Paste: Pastes a block of text to the current file window at the current cursor position.

Show Clipboard: Shows the contents of the clipboard.

Clear: Removes a block of text from the current window.

Search:

Find . . .: Searches the current window for a defined string of text.

Replace . . .: Replaces the defined string of text with another string of text in the current window.

Search Again: Re-executes the last search command.

Windows:

Size/Move: Resizes or moves the current window.

Zoom: Makes the the current window the size of the entire screen.

Tile: Tiles visible windows on the screen.

Cascade: Layers the visible windows on the screen with the current window on top.

Next: Moves the next window to the current status:

Previous: Moves the previous window to the current position.

Close: Closes the current window.

Calculator: Opens a calculator on the screen.

Base, Should, Elbow, Twist, Bend, and Grip:

Gain Set: Used to set the gain of axis.

Zero Set: Used to set the zero of the axis.

Pole Set: Used to set the pole of the axis.

Timer Set: Used to set the Timer Value of the axis.

Velocity Set: Used to set the Maximum Velocity of the axis.

Acceleration Set: Used to set the Acceleration of the axis.

Position: Returns the current position of the current axis.

Clear Position: Sets the actual position registers to zero.

Move Setting: Sets the final position register to a user defined value.

Current Values: Gives an output window with the current axis' Gain, Zero, Pole, Velocity, and Acceleration values.

Execute: Executes a trapezoidal-mode for the axis.

Test: Executes a routine to test encoder output.

Command:

Reset: Resets the last axis to receive a move command.

Base Left: Sends a voltage command moving the base left.

Base Right: Sends a voltage command moving the base right.

Shoulder Up: Sends a voltage command moving the first bending axis up.

Shoulder Down: Sends a voltage command moving the first bending axis down.

Elbow Up: Sends a voltage command moving the second bending joint up.

Elbow Down: Sends a voltage command moving the second bending joint down.

Twist Left: Sends a voltage command moving the twisting joint left.

Twist Right: Sends a voltage command moving the twisting joint right.

Bend Up: Sends a voltage command moving the third bending joint up.

Bend Down: Sends a voltage command moving the third bending joint down.

Gripper Close: Sends a voltage command moving the gripper jaws inward.

Gripper Open: Sends a voltage command moving the gripper jaws outward.

Notice that for both the main menu headings and the menu commands in most cases one letter is both bold and underlined. In the case of the menu commands, pressing the "Alt" key and the highlighted letter will open that submenu. Once the submenu is open, a command in that submenu may be executed by pressing the key corresponding to the highlighted letter. An alternate, easier method for choosing commands is by using the mouse. With this method, the mouse is used to move the cursor to the desired submenu, the right mouse button is "clicked" (depressed and released) opening the submenu, then the right mouse button is clicked while the cursor is over the desired menu item. This procedure will execute the desired menu command. Some commands offer yet an additional method use them. When the each submenu is open, some of the commands have key sequences adjacent to them against the right hand side of the box. These key sequences are known as "Hot-Keys". By executing the Hot-Key sequence on the keyboard, the desired command can be effected without having to use the menus. For example an elbow move can be executed by using the mouse or the keyboard to go through the menu system, or by pressing the "Alt" key with the "O" (Example screen in figure 9.4 below).

Example Screens From Program

```
┌─[■]══════════════════════════ Output 0 ══════════════════════════[↑]─┐
│                                                                       │
│       Autonomous Space Processer of Orbital Debris                    │
│                                                                       │
│          Robotic Arm Controller Program                               │
│                                                                       │
│                                                                       │
│          Written By: Bjoern J. Kutz                                   │
│                                                                       │
│                                                                       │
│            Adv: Dr. Kumar Ramohalli                                   │
│                 Copyright 1992                                        │
│                                                                       │
│                                                                       │
│                                                                       │
└───────────────────────────────────────────────────────────────────────┘
```

F2 Save   F3 Open   Alt-F3 Close   F5 Zoom   F6 Next   Ctrl-F1 Menu

File   Edit   Search   Windows   Base   Should >Elbow< Twist   Bend   Grip   Command

```
                                              ┌──────────────────────────┐
                                              │ Gain Set                 │
                                              │ Zero Set                 │
                                              │ Pole Set                 │
                                              │ Timer Set                │
                                              │ Velocity Set             │
                                              │ Acceleration Set         │
                                              │ Position                 │
                                              │ Clear position           │
                                              │ Move Setting             │
                                              │ Current Values  Ctrl-F9  │
                                              │ Execute         >Alt-o<  │
                                              │ Test                     │
                                              └──────────────────────────┘
```

F2 Save   F3 Open   Alt-F3 Close   F5 Zoom   F6 Next   Ctrl-F1 Menu

Figure 9.4

42

The method described above involves executing a trapezoidal command move using the menu system. The menu trapezoidal command method is only one of three available for moving the arm. Along with the menu executed trapezoidal command A series of commands may be listed in a command file along with necessary values making a routine, or a command voltage may be sent to specific axis.

The menu executed trapezoidal command is advantageous when testing moves in order to build a routine. To see what will happen when a command is executed enter the test values and execute. If the affect is not desired return the arm to the original position and try again. By testing commands like this the user can come up with a programmed routine.

Once the user compiles enough commands, the full featured file editor can be used to construct a command file. A command file is constructed be placing the necessary commands (One per line.) in a list with any needed values on the line following. A List of trapezoidal commands is given below along with the needed value if any.

set_base   Sets the current base used. If base equals

        768   Base axis selected.

        769   First bending axis selected.

        770   Second bending axis selected.

        776   Effector twisting axis selected.

        777   Effector bending axis selected.

        778   Gripper selected.

Once the base is set all commands that follow affect that axis until the base is set to another axis.

43

set_gain	Used to set the gain. (0 - 255 integer)
set_zero	Used to set the zero. (0 - 255 integer)
set_timer	Sets the sampling rate. (0 - 255 integer)
set_pole	Sets the pole. (0-255 integer)
set_max_vel	Sets the maximum velocity in encoder counts per timer step. (0 - 127 integer)
set_accel	Sets the acceleration and deceleration in encoder count increase per sample step. (0 - 65535 integer)
clr_act_pos	Sets the actual position to zero. (No Value)
set_final_pos	Sets the final position in encoder counts. (-8388608 - 8388607 integer)
get_act_pos	Displays actual position. (No Value)
trap_mode	Executes trapezoidal move. (No Value)
delay	Delays program execution. (0 - 10000 integer)
reset	Halts all commands for the current axis; clears all settings. (No Value)
dac	Sends a specified voltage to axis. (0 = full negative, 127 = zero voltage, and 255 = full positive.)
quit	Terminates program execution. (No Value)

To show how these commands might be used an example routine is shown below.

```
set_base
776
reset
clr_act_pos
set_gain
```

```
10
set_zero
240
set_pole
40
set_timer
40
set_max_vel
127
set_accel
70
set_final_pos
10000
trap_mode
delay
2000
set_base
778
dac
255
delay
2000
dac
127
reset
set_base
776
reset
quit
```

The routine shown above operates the twisting joint of the end effector and the gripper. After setting the zero, pole, gain and other parameters, the twisting joint will turn 10,000 encoder counts at max velocity while the program delays for 2000 units (about 400 units per second). Then the gripper will close at full voltage for another 2000 units of delay. Finally the gripper voltage will be set back to zero, and both axis will receive a hard reset. Routines like this are easy to design and test using the file editor inside the controller program.

A final alternate to trapezoidal commands and command routines are the straight keyboard commands. Occasionally, the trapezoidal command mode is not

the most convenient method for moving the arm. For this reason a set of "Hot-Keys" have been assigned to positive, negative and zero voltage out commands for each axis. A list of these commands is located under the Commands menu. To move an axis the user hits the "escape" key until the "All axis have been reset." message is displayed. Then the Hot-Key sequence corresponding to the desired motion is hit. The joint should move. Once the axis has moved to the desired point, the user hits the home key to stop the motion. The home key will only stop the last axis to be activated by a voltage out command.

Although the current program is easy to use and powerful, several improvements are still possible. To make programming even easier the trapezoidal menu commands and the Hot-Key output commands could be tied to a file writing utility. In this scheme, commands could be tested using the menu or the Hot-Key commands. Then if desired the commands could be written to an routine file. This type of routine will make programming easier and faster.

X. Cost Analysis

A. GRIPPER

Description	From	Quantity	Cost
2233-U024s 750:1 Motor*	Micro Mo	1	No Charge
Bearings	Granberry Bearing	4	$89.52
Rack gear	Boston Gear	2.0 ft	$26.26
Pinion gear	Boston Gear	1	$8.03
Misc. Metal**	Gould & Simpson	3 lbs	$26.00
		Sub Total	$149.81

B. BENDING JOINT

2338s 592:1 Motor*	Micro Mo. Electronics Inc.	1	$374.15
Cone Bearings	Granberry Bearing	4	$89.52
Shaft Coupler	Boston Gear	1	$24.45
Bevel Gears	Boston Gear	2	$67.30
Aluminum Stock**	Gould & Simpson	5 lbs	$38.00
		Sub Total	$593.42

C. ROTATIONAL JOINT

2842s 415:1 Motor*	Micro Mo. Electronics Inc.	1	$435.65
Bearings	Granberry Bearing	2	$47.49
Shaft Coupler	Boston Gear	1	$18.40
Aluminum Stock**	Gould & Simpson	1 lb	$4.91
Screws	Hardware Metal Specialists	--	$15.00
Washer -Nuts	Hardware Metal Specialists	4	$5.35
		Sub Total	$527.80

D. UNIVERSAL JOINT

Aluminum Tubing**	Gould & Simpson	36.0 in	$20.10

Aluminum Stock**	Gould & Simpson	2 lbs	$26.00
		Sub Total	$46.10

E. MISCELLANEOUS

Fasteners			$20.00
Wiring			$20.00
		Sub Total	$40.00
		Total	**$1,357.13**

* Motor price includes gear head and optical encoder.
** Prices include service cost of cutting stock

ASPOD End Effector: Milestone Chart (Spring 92)

Week of	January 20	27	February 3	10	17	24	March 2	9	16	23	30	April 6	13	20	27	May
Order Parts	▲	△					▲									
Receive Parts	▲				△					▲						
Fabricate Parts	▲				△								▲			
Assemble and Test		▲					△							▲		
Redesign		▲					▲									
Progress Report and Demo							3/3									
Reconstruct Final Arm							△		△			▲			▲	
Test and Adjust							△				△	▲				▲
Preliminary Demo												,4/7				
Refinement											△			▲		▲
Final Demo to Instructors														,4/23		
Final Oral and Demo																.5/1
Final Project Reports																.5/5

Figure 11.1

49
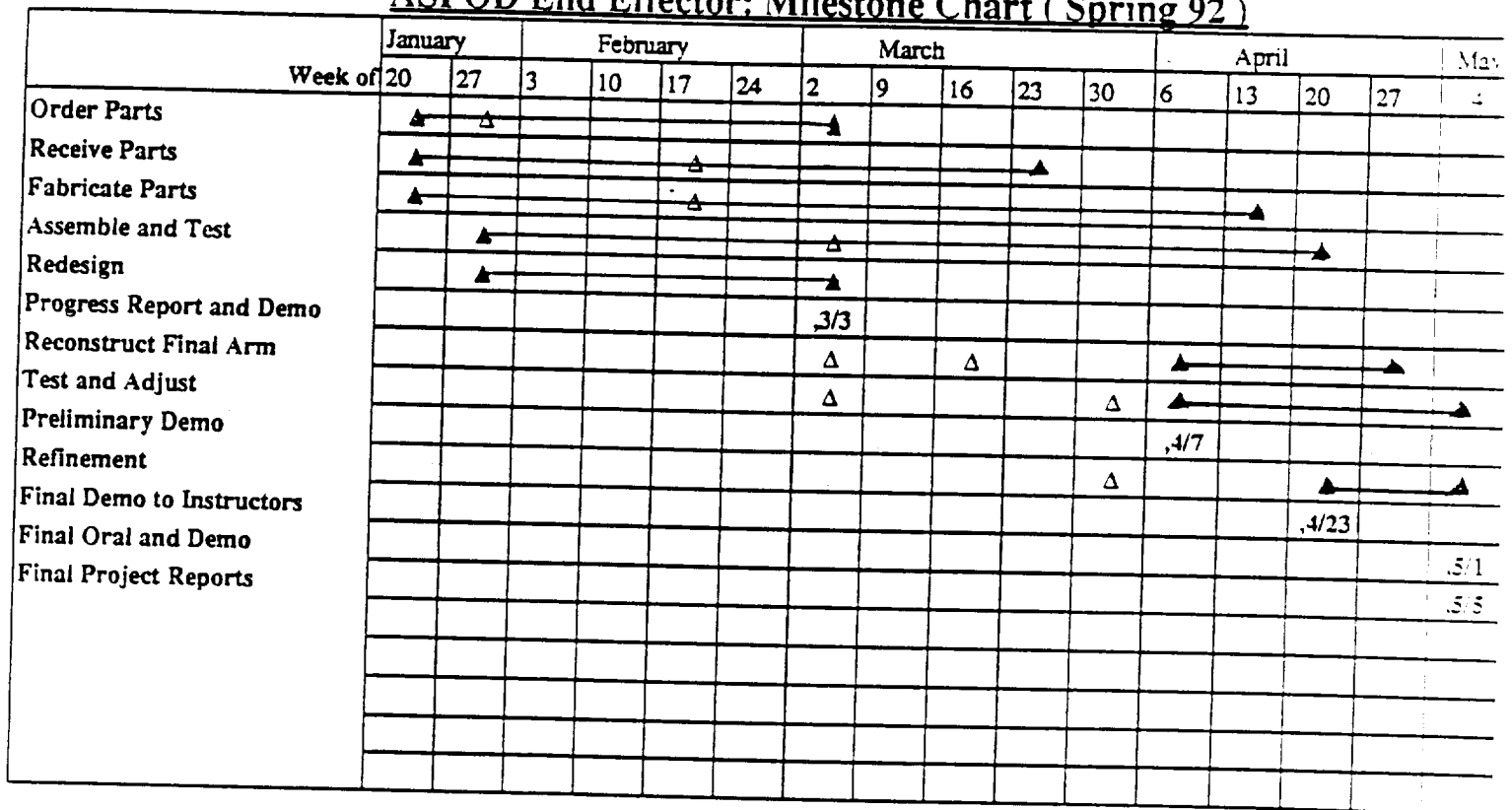
XII. CONCLUSION

The final design of the ASPOD End-effector has come a long way since the project began. Drawings along with a detailed analysis of each part were first completed. The process of drawing the individual parts uncovered design flaws that were not otherwise easily detected. This early modification of the design has resulted in very few changes to the design during machining.

The design process was originally divided up into technical subproblems such as materials, motors and controls. But as the design progressed, it became apparent that the tasks should be divided by end-effector section. The design sections were the gripper, rotational joint, bending joint, and the universal connection.

This change in task assignment made the design process smother and more efficient.

It is difficult at best to relate the amount of time and effort required to produce a quality product like the end-effector. Half of the entire project time was spent designing, modifying, and redesigning the end-effector subsystems. Then countless hours were spent in the machine shop and at the computer terminal producing the hardware and the software needed to make the end-effector a reality. The excessive amount of time and effort that went into this project is evident in the quality of the final product.

APPENDIX A
MATERIALS

Weight Calculations for Housings

I^{st} housing

assuming $t = \frac{1}{8}''$

$l = w = 3''$

$A = l^2 - (l - 2t)^2$

$A = 4 - (2 - \frac{1}{4})^2$

$A = 0.9375 \ in^2$

$V = 7.5 \ in^3$

assuming Aluminum

$Wt = 0.735 \ lb$
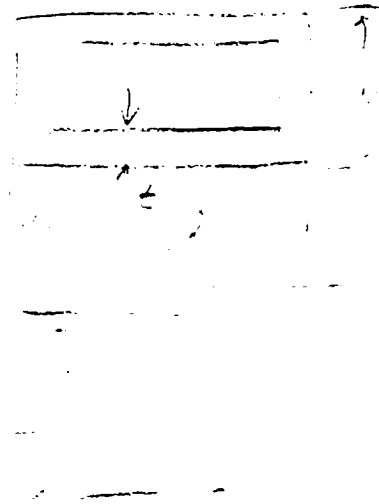
Calculated Wt's for 2nd and 3rd housings for a different
sized wall thickness.

$D_o = 2.00''$ $D_i = 1.75 \ or \ 1.875$

$t = \frac{1}{8} \ or \ t = \frac{1}{16}''$

$A = \frac{\pi D_o^2}{4} - \frac{\pi D_i^2}{4}$

$A = \frac{\pi}{4} (D_o^2 - D_i^2)$

$A = \frac{\pi}{4} (2.00^2 - 1.75^2)$

$A = 0.7363 \ in^2 \ or \ A = 0.3744$

$V = 0.7363 \ L$

or $V = 0.3804 \ L$
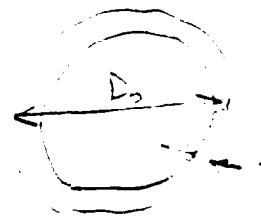
$Wt_2 = .7363$

$Wt_2 = 0.361$

$Wt_2 = 0.186$

$V_3 = .7363 L$

$Wt_3 = (3.313)(...)$

$Wt_3 = 0.325 \ lb$ for $\frac{1}{8}''$ thick

$Wt_3 = 0.168 \ lb$ for $\frac{1}{16}''$ thick

Minimum thickness calculations of cylindrical housing continued.

Assume aluminum.
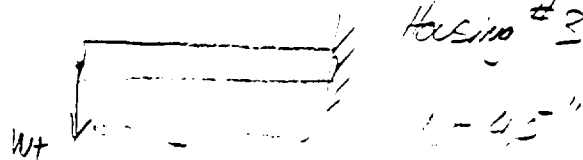
Housing #3

$L = 4.5''$

$$\theta = \frac{PL^2}{2EI}$$

$$I = \frac{\pi d^3 t}{8}$$

$$\theta = \frac{Wt \, L^2 \, 8}{2 E \, \pi d^3 t}$$

$$t = \frac{4 \, Wt \, L^2}{\pi d^3 \theta E}$$

$$t = \frac{4(4.735)(4.5)^2}{\pi (.75)^3 (.0175) E}$$

$$t = \frac{1.???}{E} \qquad \frac{???}{\,in^2}$$

$$t = 0.001 \ in$$

$D_o = 1.75''$

Find t.

Assumed much greater than ???
when calculating the ??? to ???
So assumption is O.K.

Minimum thickness calculations for housing
subjected to largest stress (housing #3).

$D_0 = 2.00$ Find minimum t.
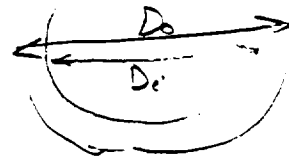
Approximate weight housing must
support (weight of gripper and object)

Same thickness can be
used for the inner
circular housing since
this housing is required
to _____ _____

$rack \ wt = (3in)(.25in)(.25in)(.29\#)$

$rack \ wt = 0.05\#$

$\underline{2 \ rack \ wt = 0.10\#}$

$gear \ wt = \dfrac{(.667 in)^2 (.25)}{4} \pi (.29\#)$

$gear \ wt = 0.025\#$

$gripper \ wt = ____$

$2 \times gripper \ wt = ____$

$housing \ wt_1 = 0.735\#$

$wt_2 = 0.372\#$

$wt_3 = ____$

$motor_1 \ wt = 0.392\#$

$motor_2 \ wt = 0.604\#$

$motor_3 \ wt = 0.604\#$

$Miscellaneous \ wt = \underline{1}$
includes wires, _____ _____

$total \ wt = 4.435\#$

Assume total wt supported at end of housing?

housing 3

wt
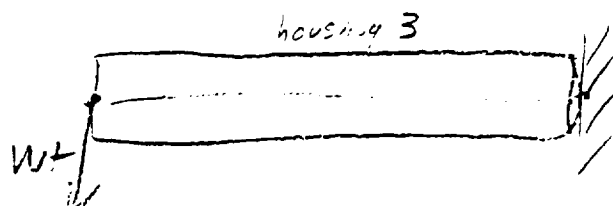
APPENDIX B
CONNECTION TO ARM

Aluminum Connection

Aluminum Plate

2.00 D

1.870 D

.250

2.000

.500 D BOLT

Aluminum Tubing

.750

.250

Aluminum End Mount
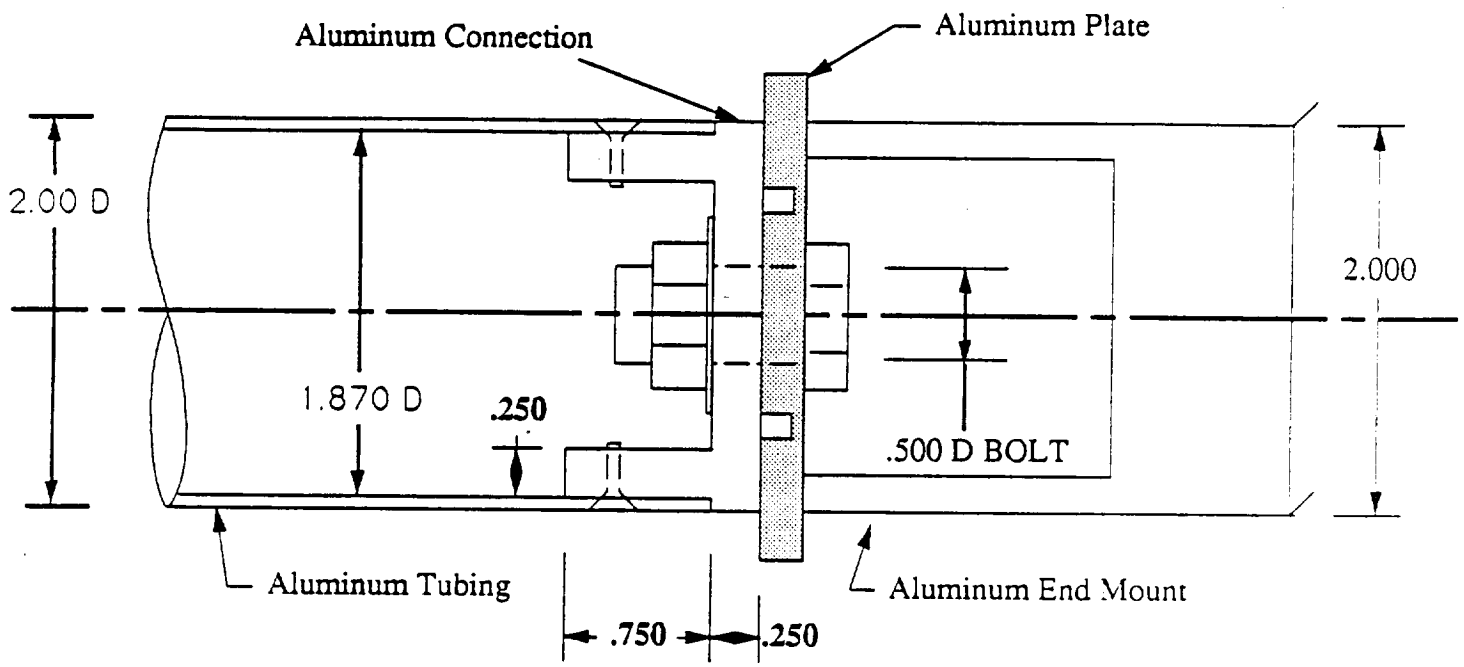
Side View of Entire Connection

.500 D

2.000

1.870

0.125 D Dowel Pins
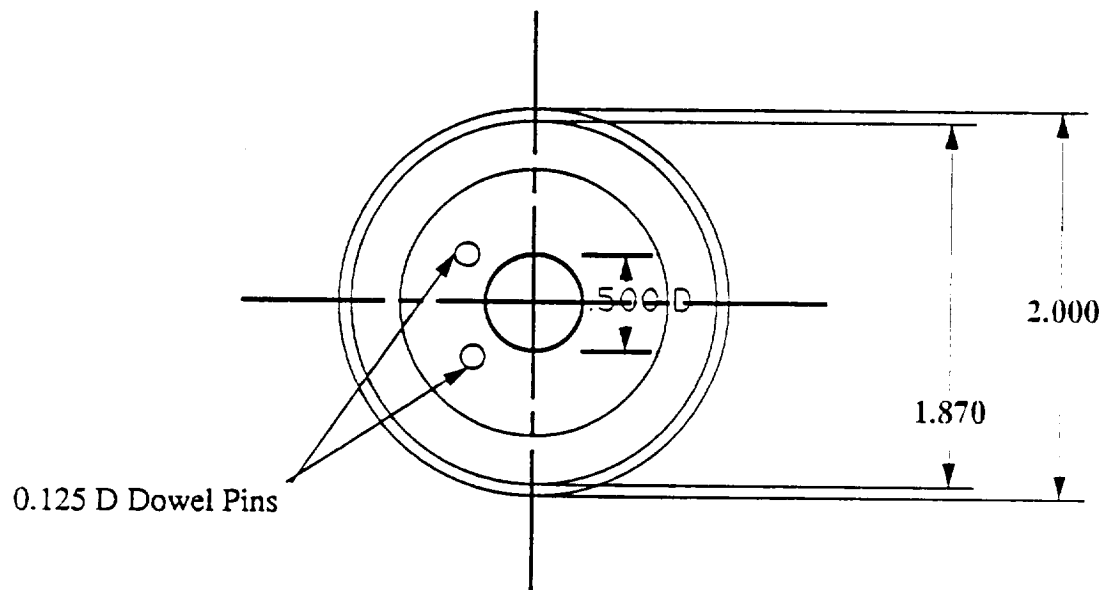
Front View of Aluminum Component

ASPOD End Effector Design Team	Todd Jacobson
Effector Connection	**Material: Aluminum**
Scale: 1 inch = 1 inch	

APPENDIX C
ROTATIONAL JOINT

PARTS LIST

1. Rear Motor Support
2. Allen Screws (4)
3. Motor, Gearhead, and Encoder
4. Front Motor Support
5. Allen Screws (4)
6. Multi-jaw Shaft Coupling
7. Drive Shaft
8. Nut and Washer
9. Bearings (2)
10. Aluminum Ring
11. Allen Screws (4)
12. Drive Support
13. Allen Screws (4)
14. Nut and Washer
15. Aluminum Tube
16. Aluminum Tube

Ø=.25"

.3"

Ø=1.86"

Ø=0.67"

1.86"

M2

4 x 4-40

BACK VIEW

SIDE VIEW

FRONT VIEW
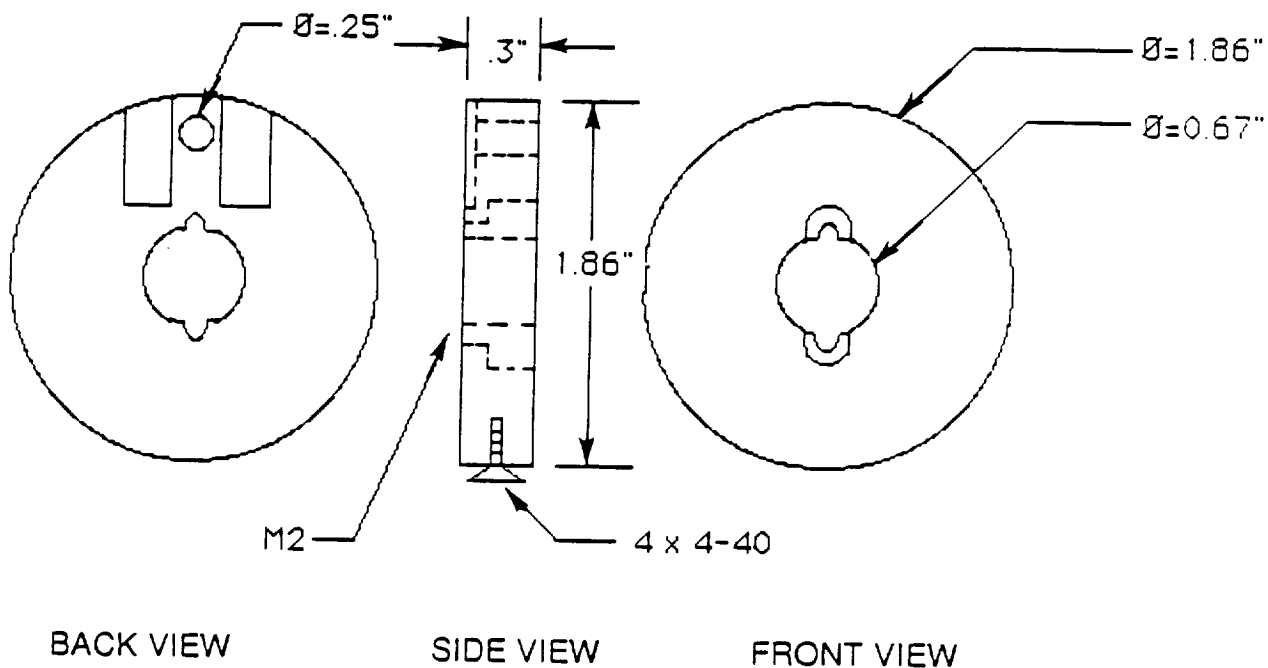
ASPOD End Effector	Matt McCutchen
Rear Motor Support	PART #1
Scale: 1 inch = 1 inch	Material: Aluminum

SPECIFICATIONS

PART #2

Allen Screws

Head: Countersink
Size: 4 - 4 0
Quantity: 4

MicroMo MOTORS

DC MicroMotors Series 2842

- Standard Motor Contains Two Ball Bearings
- Fits Our Screw-On Planetary Gearhead Series 23/1, 32/1, 31 DC and 38/1 (Metal Case)
- Available with Integral Optical Encoders (15, 100, 180, 500 or 1000 Pulses Per Revolution) and DC Tachometers
- Available in 6, 12, 24, 28 and 48 Volt Types
- High Temperature Version (125° C) Standard

Continuous Duty Ratings:
    Speed up to 5,000 RPM
    Torque up to 3 oz-in
    Power Output up to 6 Watts

Electrical Specifications:

For Motor Type 2842S					
Supply Voltage nom. (Volts)	6	12	24	28	48
Armature Resistance (Ohm) ±12%	1.6	5.3	21.0		
Max. Power Output (Watts)	6.0	6.8	6.0		
Max. Efficiency (%)	70	72	72		
No Load Speed (RPM) ±12%	4,000	4,890	1,800		
No Load Current (mA) ±50%	100	50	25		
Friction Torque (oz-in)					
Stall Torque (oz-in)					
Velocity Constant (RPM/Volt)	804	404			
Back EMF Constant (mV/RPM)			1.3		
Torque Constant (oz-in/Amp)					
Armature Inductance (mH)					

Mechanical Specifications:

Mechanical Time Constant (ms)				
Rotor Inertia (x10⁻⁴ oz-in sec²)				
Radial Acceleration (x10³ Rad/S²)				

Pre Load Ball Bearings Standard

Thermal Resistance (°C/W)	
Rotor to Case	7 All Types
Case to Ambient	16 All Types
Max. Shaft Loading (oz)	
Radial (@ 3,000 RPM) (3mm from bearing)	32 All Types
Axial (Standing Still)	32 All Types
Weight (oz)	4.7 All Types
Rotor Temperature Range	-30 to +125° C

Direction of Rotation is Reversible, Clockwise as Seen from Shaft End if Red Positive Pole Connected to Positive Side of Voltage Supply

DC MicroMotors Series 2842

Dimensional Outlines:

2842 S . . .

Dimensions are in mm (in.)

Dimensions with no tolerance indicated
are as follows

For Dimensions	Tolerance
Less than or equal to 6 mm	± 1 mm (0.039)
Less than or equal to 30 mm	± 2 mm (0.079)
Less than or equal to 120 mm	± 3 mm (0.118)

Ordering Information:

Example: To Order a 6 Volt 2842 Motor intended to Fit Our 34 PG Gearhead

Motor   28 42 S 006 C ... + 34PG ...

Motor Diameter

Motor Length

Output Shaft Configuration

S – 30 mm Diam x 10.6 mm Shaft End

Commutator

C – Copper

Nominal Voltage

MMF 05905K

MicroMo® GEARHEADS

Gearhead Series 30/1

- Fits Motor Series 2338, 2444, 2842, 3540, and 3557.
- Planetary Gearing with Metal Case (Steel, Nickel Plated).
- 2 Sealed Ball Bearings Standard.
- Quiet, Precise Operation.

Actual Size

Maximum Ratings:

Temperature Range: -30°C to 100°C (-22°F to 212°F)
Load on Output Shaft:
    RADIAL: (15mm from bearing) 150 N (540 oz.)
    AXIAL: 150 N (540 oz.)
Maximum press fit force: 200 N (720 oz.)
Bearing Play:
    RADIAL: 0.015mm (.0006 in.)
    AXIAL: 0.15mm (.0060 in.)
Recommended Input Speed for Continuous Operation: 3000 RPM
Backlash, Unloaded ≤1°
Note: Direction of rotation is identical to direction of motor rotation. All gearheads are reversible.
Maximum Continuous Output Torque: 640 oz-in.
                                           4.5 Nm
Maximum Intermittent Output Torque: 850 oz-in.
                                           6.0 Nm

1	2		3		4		5		6	
Reduction Ratio[1]	Weight Without Motor		Length Without Motor		Length With Motor 2338S		Length With Motor 2444S		Length With Motor 2842S	
			L2		L1		L1		L1	
	g	oz	mm	in	mm	in	mm	in	mm	in
3.71:1	107	3.77	10.2	.402	64.6	2.543	71.0	2.795	69.0	2.716
14:1	139	4.90	10.2	.716	72.6	2.859	79.0	3.110	77.0	3.031
43:1	171	6.03	26.2	1.031	80.6	3.173	87.0	3.425	85.0	3.346
66:1	171	6.03	26.2	1.031	80.6	3.173	87.0	3.425	85.0	3.346
134:1	203	7.16	34.2	1.346	88.6	3.488	95.0	3.740	93.0	3.661
159:1	203	7.16	34.2	1.346	88.6	3.488	95.0	3.740	93.0	3.661
246:1	203	7.16	34.2	1.346	88.6	3.488	95.0	3.740	93.0	3.661
415:1	235	8.29	42.2	1.661	96.6	3.803	103.0	4.055	101.0	3.976
592:1	235	8.29	42.2	1.661	96.6	3.803	103.0	4.055	101.0	3.976
989:1	235	8.29	42.2	1.661	96.6	3.803	103.0	4.055	101.0	3.976
1526:1	235	8.29	42.2	1.661	96.6	3.803	103.0	4.055	101.0	3.976

7		8		9		10	11
Length[2] With Motor 3540K		Maximum Torque Output				Rotation Direction	Efficiency
		Continuous Operation		Intermittent Operation			
L1							
mm	in	Nm	oz in	Nm	oz in		%
68.4	2.693	1.5	212	3.0	425	All ratios	88
76.4	3.008	0.35	50	0.5	71	rotate	80
84.4	3.323	1.2	170	1.6	227	clockwise	70
84.4	3.323	1.8	255	2.4	340	as viewed	70
92.4	3.638	3.5	496	4.5	638	from	60
92.4	3.638	4.5	638	6.0	850	Shaft End	60
92.4	3.638	4.5	638	6.0	850	with	60
100.4	3.953	4.5	638	6.0	850	Driving	55
100.4	3.953	4.5	638	6.0	850	Motor	55
100.4	3.953	4.5	638	6.0	850	turning	55
100.4	3.953	4.5	638	6.0	850	clockwise	55

[1] To fit with Motor 3557 add 17mm (.669 in.) to column 7
[2] Ratio 3.71:1 has all steel gears.
Ratios 14:1 and higher have plastic gears in the input stage. (Available with all steel gears, consult MicroMo.)

-- Specifications Subject to Change --

Gearhead Series 30/1

Dimensional Outlines:

Front View   30/1 with Motor 2338, 2444 or 2842   30/1 with Motor 3540 or 3557

Dimensions are in mm (in.).

Dimensions with no tolerance indicated are as follows:

For Dimensions	Tolerance
Less than or equal to 6mm	± 1mm (.0039")
Less than or equal to 30mm	± 2mm (.0079)
Less than or equal to 120mm	± 3mm (.0118")

HMF029015K

4 x 4-40

4 x M3

1.867"

1.179"

4 x M3

1.179"

0.71"

1.867"

0.710"

t=0.0625"

0.5"

SIDE VIEW

FRONT VIEW

ASPOD End Effector	Matt McCutchen
Front Motor Support	PART #4
Scale: 1 inch = 1 inch	Material: Aluminum

SPECIFICATIONS

PART #5

Allen Screws

Head: Countersink
Size: 4 - 4 0
Quantity: 4

SHAFT COUPLINGS

MULTI-JAW TYPE

UNTREATED STEEL COUPLINGS for use in light duty applications, require no lubrication.

BORE SIZES FROM 3/16" to 1/2"

COMPLETE WITH STANDARD SETSCREWS

STANDARD TOLERANCES

DIMENSION		TOLERANCE
BORE	All	± 0005

REFERENCE PAGES

Alignment—163
Keyways and Setscrews—164

ALL DIMENSIONS IN INCHES
ORDER BY CATALOG NUMBER OR ITEM CODE

Coupling Size	Bore	O.D.	Length†	Bore Length++	Assembly Clearance ‡	Hub Dia.	Hub Proj.	Teeth	Steel Catalog Number	Item Code
FA5	3/16 1/4	1/2	1-1/8	1/2	1-9/32	7/16	7/16	10	FA5 3/16-3/16 FA5 1/4-1/4	07900 07904
FA75	5/16 3/8	3/4	1-1/2	5/8	1-3/4	11/16	33/64	10	FA75 5/16-5/16 FA75 3/8-3/8	07910 07912
FA10	7/16 1/2	1	2	7/8	2-9/32	15/16	3/4	12	FA10 7/16-7/16 FA10 1/2-1/2	07908 07906

†Total length of coupling with jaws engaged full depth.
++Length of hole in each half.
‡Approximate total length of coupling with jaws completely disengaged.

RIGID (ONE PIECE) TYPE

BORE SIZES FROM 1/4" to 1-1/4"
COMPLETE WITH STANDARD SETSCREWS

ALL DIMENSIONS IN INCHES
ORDER BY CATALOG NUMBER OR ITEM CODE

Bore	O.D.	Overall Length	A	Catalog Number	Item Code
1/4	1/2	3/4	3/16	CR4	34200
5/16	5/8	1	1/4	CR5	34202
3/8	3/4	1	1/4	CR6	34204
1/2	1	1-1/2	3/8	CR8	34206
5/8	1-1/4	2	1/2	CR10	34208
3/4	1-1/2	2	1/2	CR12	34210
7/8	1-3/4	2	1/2	CR14	34212
1	2	3	3/4	CR16	34214
1-1/4	2-1/4	4	1	CR20	34216

REFERENCE PAGES

Keyways and Setscrews—164

STANDARD TOLERANCES

DIMENSION		TOLERANCE
BORE	All	+ .001 - 000

BOSTON GEAR

Ø=1/2"-13

Ø=0.5"

Ø=0.8"

Ø=1/2"-13

Ø=.3125

0.5"

0.75" 0.69" 2.07" 0.79" 1.25"

5.55"

ASPOD End Effector	Matt McCutchen
Drive Shaft	PART #7
Scale: 1 inch = 1 inch	Material: Aluminum

SPECIFICATIONS

PART #8

Nut and Washer

Size: 0.5" Nylock Nut
0.5" Standard Flat Washer

SPECIFICATIONS

PART #9

Bearings

Bore d:	0.5000"
Outside D:	1.5000"
Width T:	0.5408"
Cone:	00050
Cup:	00152

Ø=1.87"

Ø=1.50"

Ø=1.25"

Ø=1.87"

0.534"

Ø=1.5"

1.00"

4 x 4-40

Ø=1.25"

0.69"

0.534"

0.0625"
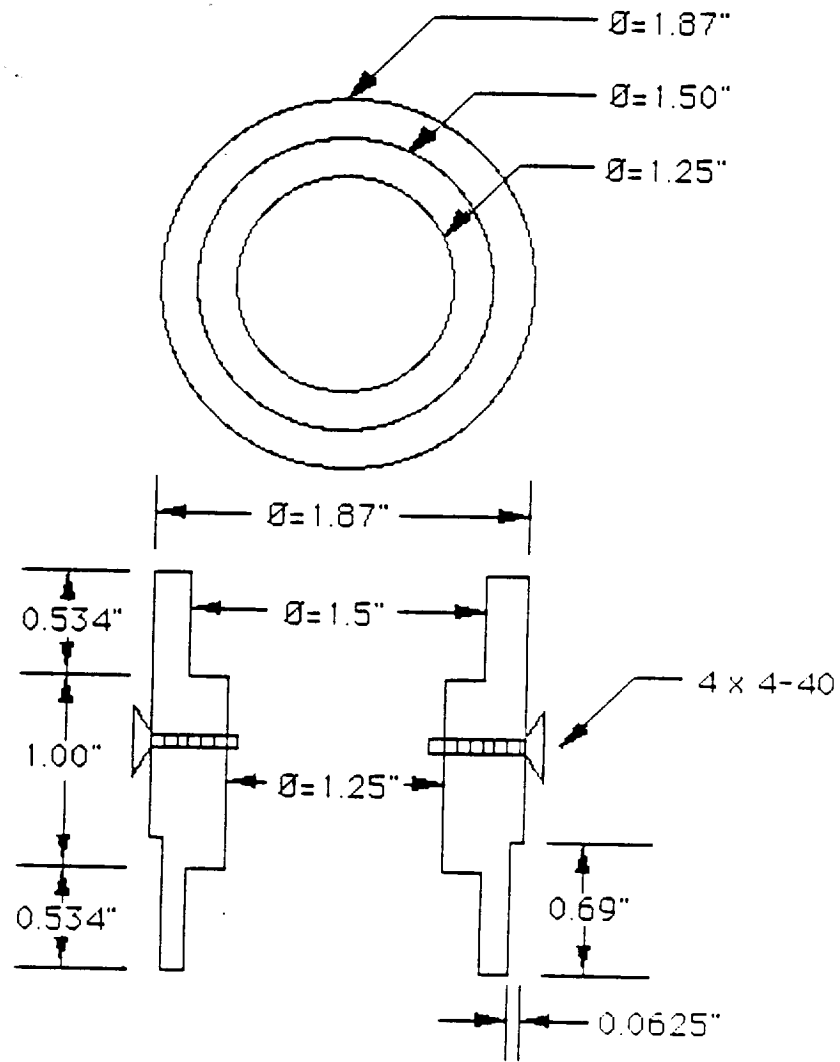
ASPOD End Effector	Matt McCutchen
Aluminum Ring	**PART #10**
Scale: 1 inch = 1 inch	Material: Aluminum

SPECIFICATIONS

PART #11

Allen Screws

Head: Countersink
Size: 4 - 4 0
Quantity: 4

4 x M6

Ø=1.86"

Ø=0.5"

1.86"

0.5"
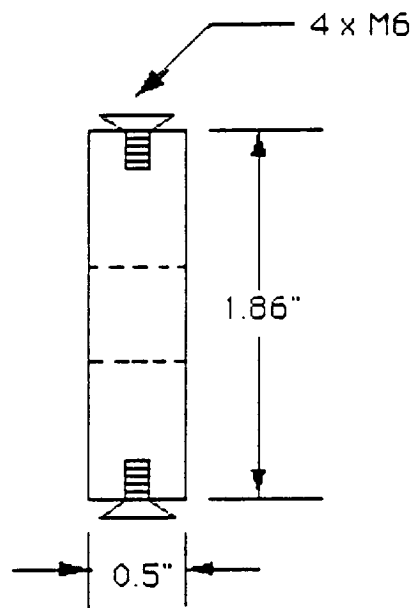
SIDE VIEW   FRONT VIEW
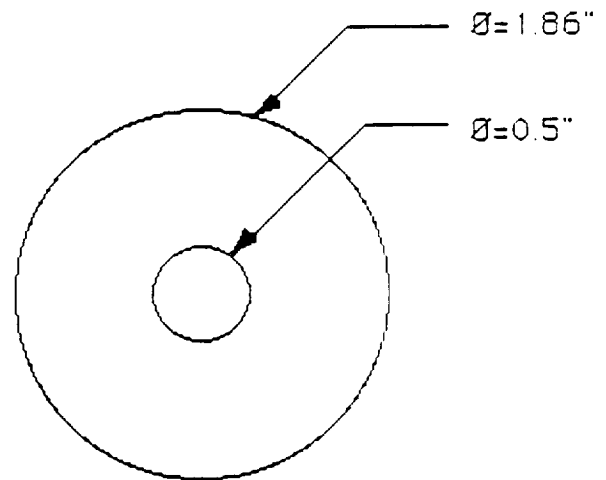
ASPOD End Effector	Matt McCutchen
Drive Support	PART #12
Scale: 1 inch = 1 inch	Material: Aluminum

SPECIFICATIONS

PART #13

Allen Screws

Head: Countersink
Size: M6
Quantity: 4

SPECIFICATIONS

PART #14

Nut and Washer

Size: 0.5" Nylock Nut
             0.5" Standard Flat Washer

0.56"

3.69"

3.94"

1.84"

0.37"

10.4"
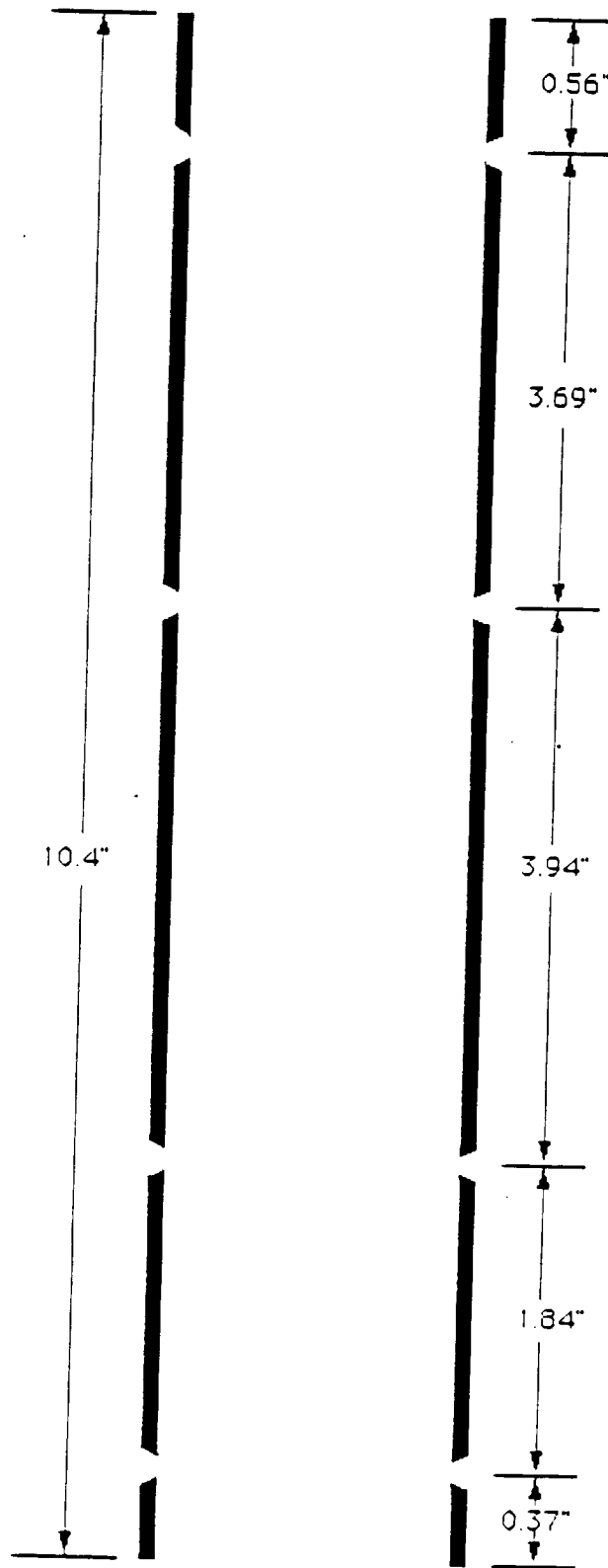
ASPOD End Effector	Matt McCutchen
Aluminum Tube	PART #15
Scale: 1 inch = 1 inch	Material: Aluminum

9.5"

7.83"

1.67"
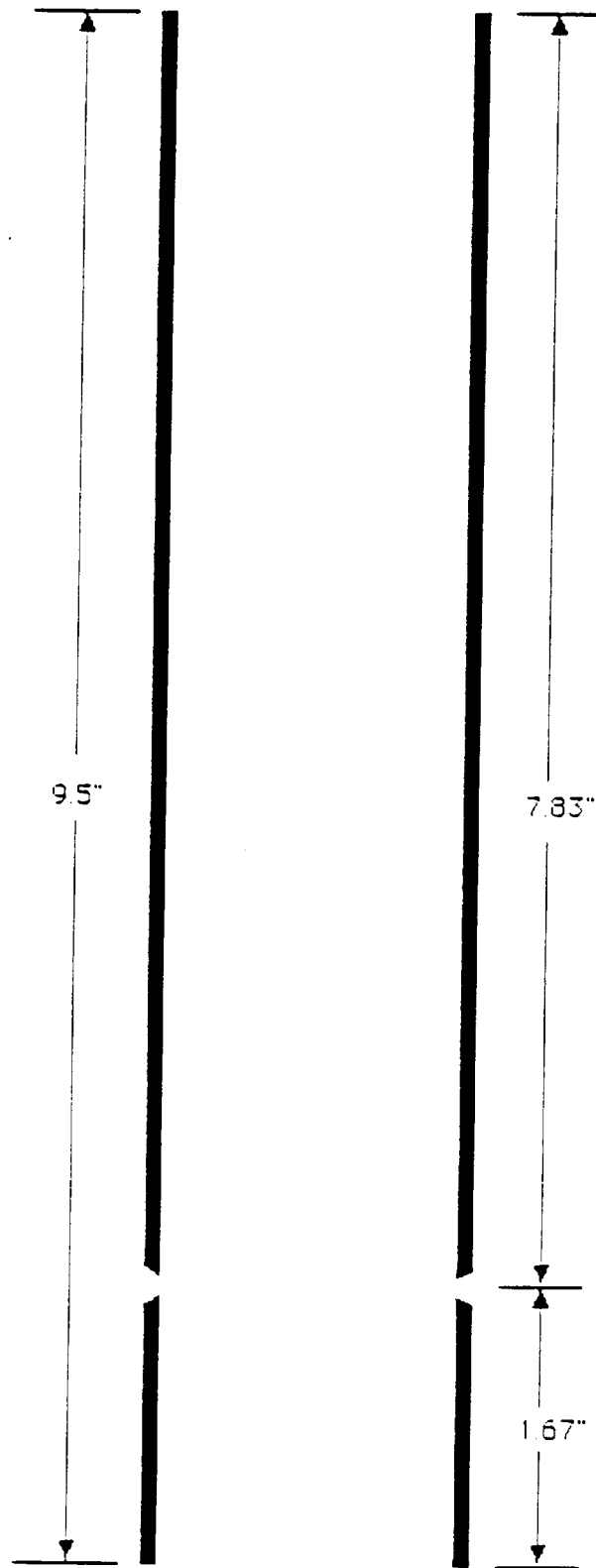
ASPOD End Effector	Matt McCutchen
Aluminum Tube	PART #16
Scale: 1 inch = 1 inch	Material: Aluminum

COST ANALYSIS

			COST
1.	Motor-gearhead-encoder		$435.65
2.	Bearings:	Cup	$26.67
		Cone	$20.82
3.	Multi-jaw Shaft Coupling		$18.40
4.	Screws		$15.00
5.	Aluminum Tubing		$10.05
6.	Washer and Nuts		$5.35
7.	Aluminum Stock:	Aluminum Ring Motor Support Drive Support	$4.91

---

8. TOTAL **$537.85**

Rotational Shaft Stress Analysis

For minimum diameter.

Torque (From Motor)

$$T_m = 1400 \text{ oz-in}$$
$$T_m = 77.5 \text{ lb-in}$$

$$\sigma_A' = \frac{32 M_a}{\pi d^3} = \frac{1085}{d^3}$$

$$\tau_m' = \frac{16 T_m}{\pi d^3} = \frac{445.6}{d^3}$$

Alternating Shear Stress (From shear)

$$\tau_A' = \frac{F}{A} = \frac{9 lb}{\frac{\pi d^2}{4}}$$

$$\tau_A' = \frac{11.46}{d^2}$$

Stress Concentration Factor

$$K_t = 1.4 \text{ for bending}$$

$$K_t = 1.2 \text{ for torsion}$$

$$\sigma_A = \left(\frac{1085}{d^3}\right)(1.4)$$

$$\sigma_A = \frac{1519}{d^3} \qquad \tau_M = \frac{535}{d^3} \qquad \tau_a = \frac{13.75}{d^2}$$

From Westinghouse code formula:

$$n \sqrt{\left(\frac{2 \tau_a}{S_e} + \frac{2 \tau_m}{S_y}\right)^2 + \left(\frac{\sigma_a}{S_e} + \frac{\sigma_m}{S_y}\right)^2} = 1$$

$$2.5 \sqrt{\left(\frac{2}{44,200}\frac{13.75}{d^2} + \frac{2}{94,200}\frac{535}{d^3}\right)^2 + \left(\frac{1519}{d^3}\frac{1}{44,200}\right)^2} = 1$$

$$2.5 \left[\left(\frac{0.0006222}{d^2} + \frac{0.011359}{d^3}\right)^2 + \left(\frac{0.034367}{d^3}\right)^2\right]^{1/2} = 1$$

$$2.5 \left[\frac{3.87 \times 10^{-7}}{d^4} + \frac{1.42 \times 10^{-5}}{d^5} + \frac{1.296 \times 10^{-4}}{d^6} + \frac{1.19 \times 10^{-3}}{d^6}\right]^{1/2} = 1$$

Hard to solve for d. Instead try various sized diameters until the factor of safety calculated is 2.5.

Continued Stress Analysis for rotational
Shaft. (including Stress concentration)

$$\left[\frac{3.87 \times 10^{-7}}{d^4} + \frac{1.42 \times 10^{-5}}{d^5} + \frac{.31 \times 10^{-3}}{d^6} \right]^{1/2} = \frac{1}{N}$$

For $d = .500$ $N = 3.45$

$$\boxed{\text{For } d = .450 \qquad N = 2.51}$$

This diameter was calculated using 1030 Steel
with:

$$S_{y} = 94 \text{ kpsi}$$
$$S_{ut} = 123 \text{ kpsi}$$

$S_e' = (.504) S_{ut}$

$S_e' = 62 \text{ kpsi}$

$S_e = S_e' \text{(correction factors)}$

$S_e = (62)(.75)(.95)(1)$

$S_e = 44.2 \text{ kpsi}$

deflection of shaft:
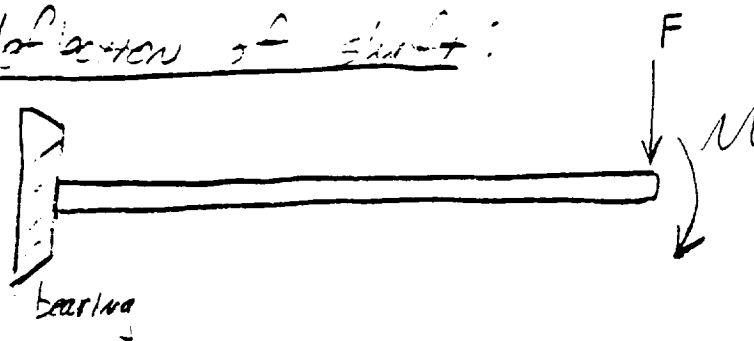
$L = 2$ in

$M = 106.5$ lb·in

$d = .475$ in

deflection angle θ:

$$\theta = \frac{ML}{EI} = \frac{(106.5 \text{ lb·in})(2 \text{ in})}{(30 \times 10^6 \text{ lb/in}^2)} \frac{64}{\pi(.45 \text{ in})^4}$$

$$\theta = (0.00353 \text{ rad})\left(\frac{180°}{\pi \text{ rad}}\right)$$

$$\theta = 0.202°$$

$$\theta = \frac{PL^2}{2EI} = \frac{}{2(30\times10^6 \text{ lb/in})}$$

$$\theta = 0.171°$$
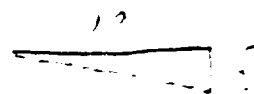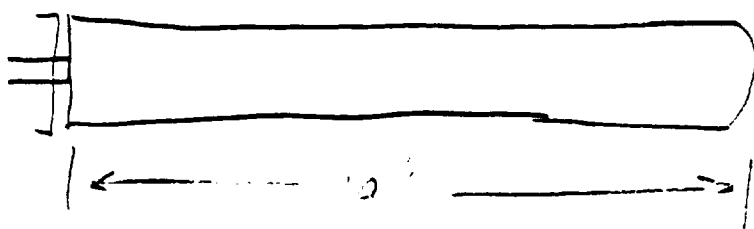
total deflection of gripper and object gripped (maximum)

$$\sin \theta = \frac{c}{19}$$

$$c = \sin(0.2191) \cdot 19''$$

$$\underline{c = 0.073''} \quad \text{at end of gripper arm.}$$

APPENDIX C
Wrist Motor Calculations
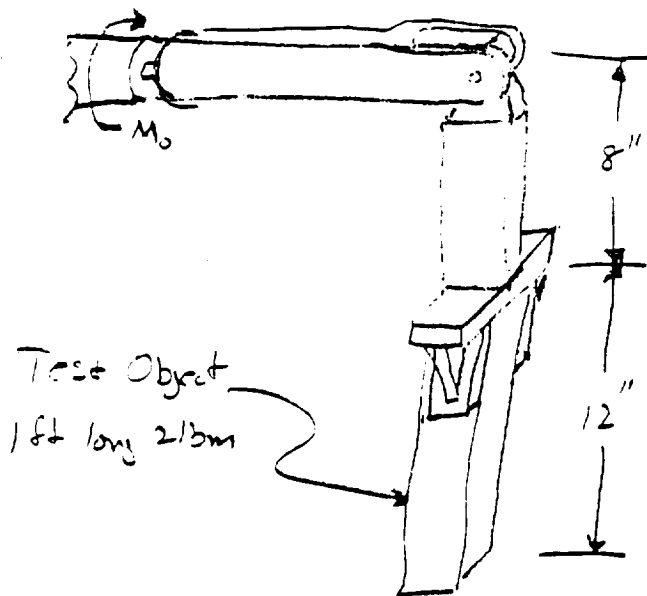
Approx Weight of
Gripper and forearm
= 3.5 lbm

$M_o = (3.5)(4) + (2)(14) = 42$ lbm

$= 672$ oz-in

Test Object
1 ft long 2 lbm

Motor & Gearhead Selection

1.378" D

1.5" D

0.3150" D

Motor
3540

Gearhead
38/2

3.77
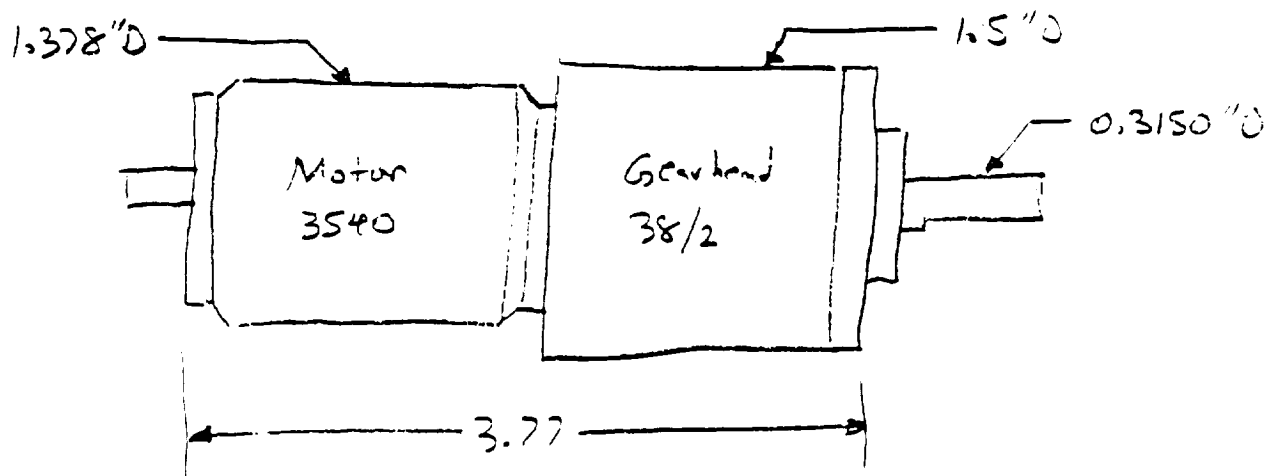
Micro Mo Electronics Inc

Motor 3540 K   12 V

Gearhead 38/2   159:1

Max Power Output
$P = (672 \text{ oz-in})(18.9 \text{ RPM})(.00074)$
$P = 9.39$ watts

Max Stall Torque
$T = (8.1)(159)(60\% \text{ Efficiency})$
$T = 772.7$ oz-in

Max Continous RPM
$n = \dfrac{3000}{159} = 18.9$ RPM

APPENDIX D
ELBOW JOINT

APPENDIX D

Calculations for Bevel Gears

Lewis Formula $\quad \sigma = \dfrac{WP}{FY(.75)}\left(\dfrac{600+V}{600}\right)$

$M_o = \dfrac{W \cdot D}{2} \rightarrow W = \dfrac{2M_o}{D}$, $P = \dfrac{N}{D}$

σ = Safe Material Stress
W = Tooth Load
P = Diametral Pitch
F = Face Width
Y = Tooth form factor
V = Pitch line Velocity
D = Pitch diameter
M_o = Moment about elbow axis
N = Number of Teeth

Substitute the above equations into the Lewis formula

$$\sigma = \dfrac{2M_o N}{D^2 FY(.75)}\left(\dfrac{600+V}{600}\right)$$

Pinion

$V_p = .262 \times (\text{Pitch Diameter}) \times (\text{RPM}) = \text{Ft/min}$

$V_p = (.262)(.68)(22.4) = 4 \text{ ft/min}$

$\sigma = \dfrac{2\left(\frac{42}{2}\right)(13)}{.68^2 (.25)(.3+5)(.75)}\left(\dfrac{600+4}{600}\right) = 16.4 \text{ KSI} \quad < \quad$ Case-hardened Steel = 25.0 KSI

Gear

$V_G = (.262)(1.37)(11.2) = 4 \text{ ft/min}$

$\sigma = \dfrac{2(42)(26)}{(1.37)^2 (.25)(.283)(.75)}\left(\dfrac{600+4}{600}\right) = 22.1 \text{ KSI} < $ Case-hardened Steel = 25.0 KSI

APPENDIX D
Bevel Gears Selected
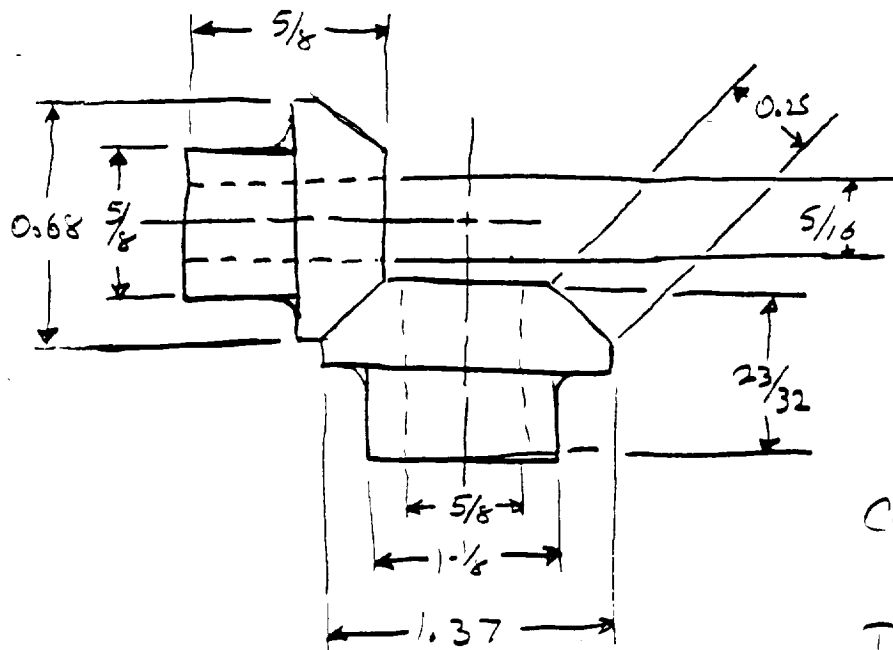
Boston Gear
Spiral Bevel Gear
Hardened Steel

Catalog Number SH192-G
SH192-P

Item Code 11910
11912

(dimensions shown: 5/8, 0.68, 5/8, 0.25, 5/16, 23/32, 5/8, 1-1/8, 1.37)

APPENDIX D

Elbow Motor Calculations

Test Object
1 ft long, 2 lbm
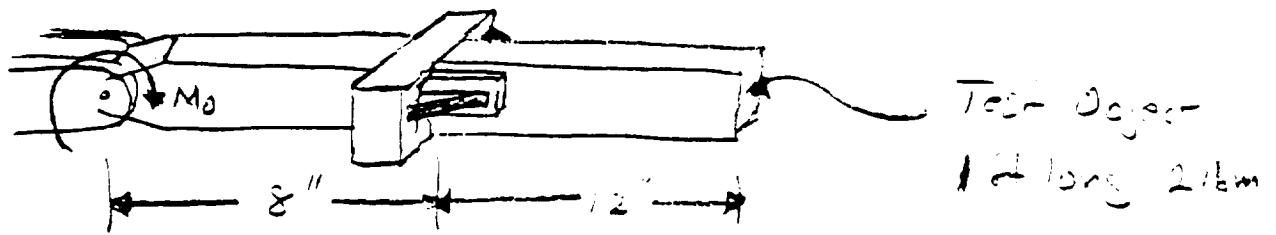
Approx Weight of gripper & forearm = 3.5 lbm

$M_0 = (4)(3.5) + (14)(2) = 42$ lbm·in
$= 672$ oz·in

with 2:1 Bevel Gears
Required Torque
$= 336$ oz·in

Motor & Gearhead Selection

1.1024"D
1.1811"D
2.3150"D
Motor 2842S
Gearhead 30/1
3.661'
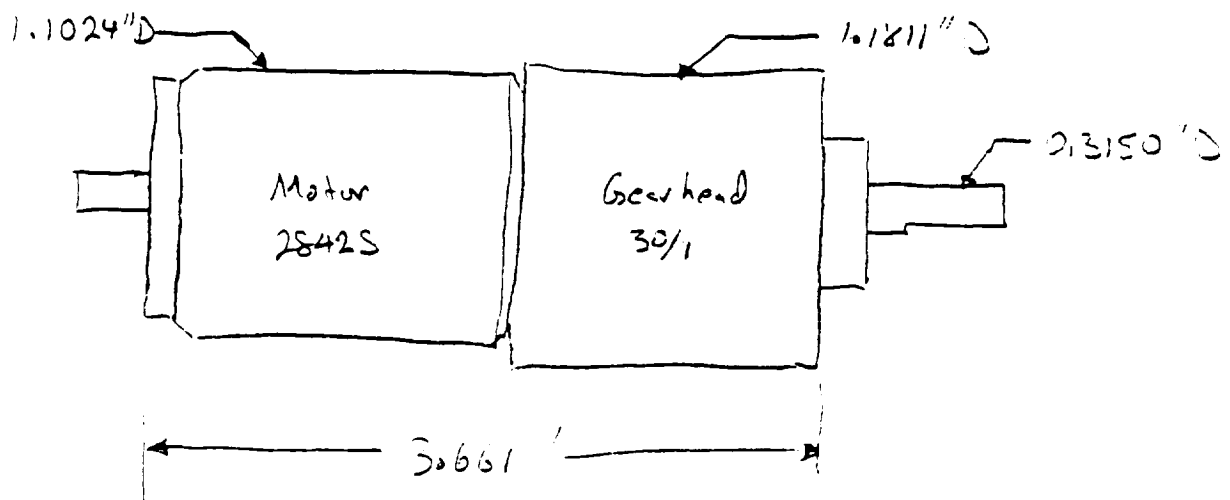
Micro Mo Electronics Inc
Motor 2842S   12V
Gearhead 30/1   134:1

Max Output Power
$P = (20 \text{ RPM})(336 \text{ oz-in})(.00074)$
$P = 4.97$ Watts

Max Stall Torque
$T = (7.5)(134)(60\% \text{ Efficiency})$
$T = 603$ oz-in

Max Continuous RPM
$N = \dfrac{3000}{134} = 22.4$

Note: This is max RPM
of Pinion Gear. Map
rotation speed is 11.2 RPM

Elbow Connection

Cap Screws

Inner Knuckle

Axial Bearing Cap

Axial Shaft

Set Screws

Taper Bearings

Pinion Bracket

Shaft Coupler

Outer Knuckle

Spriral Bevel Gears

Pinion Shaft

Ø1.250

Ø.125

30.0°

2.000

2.250

2.500

2.625

3.616

1.938
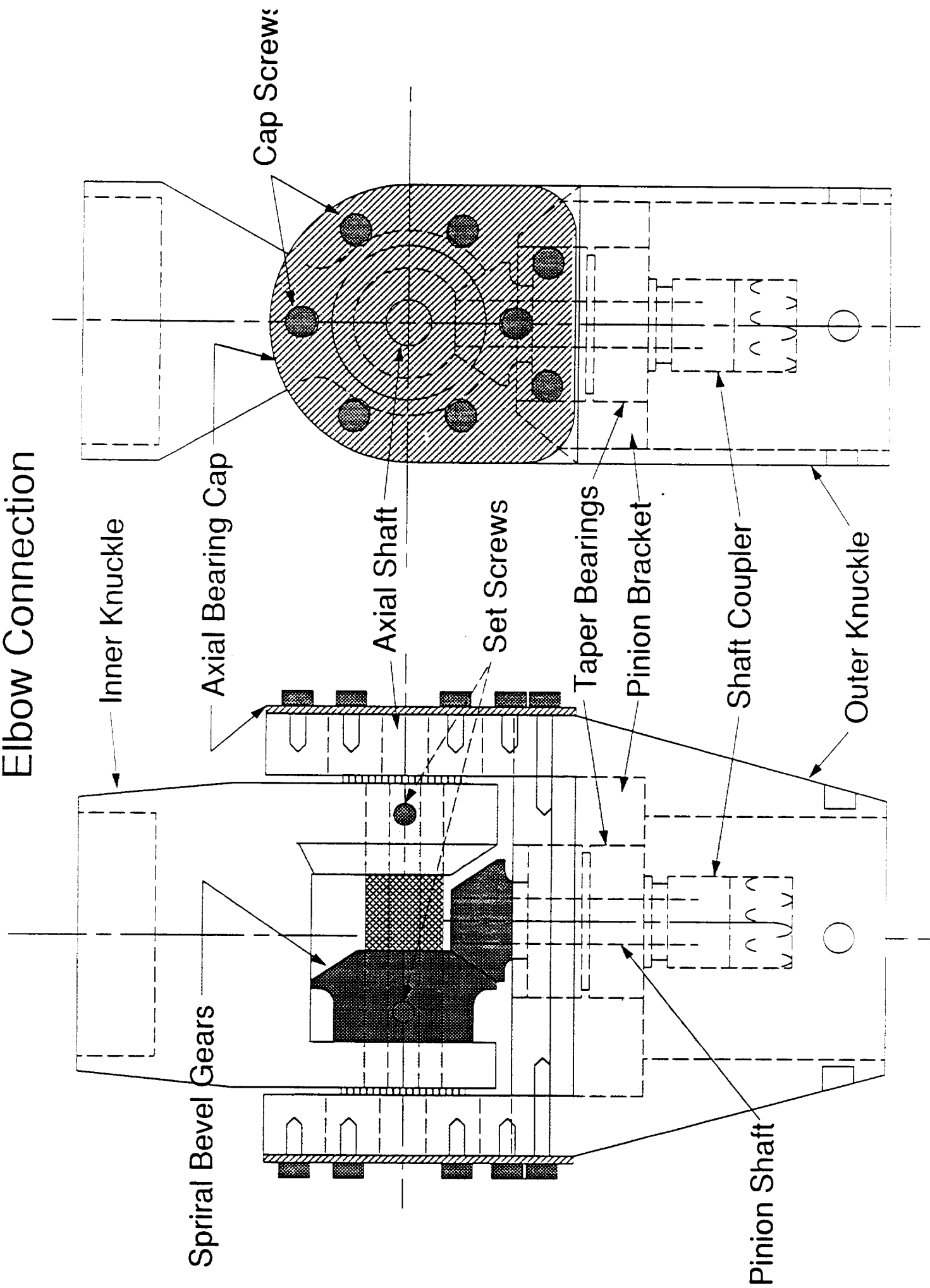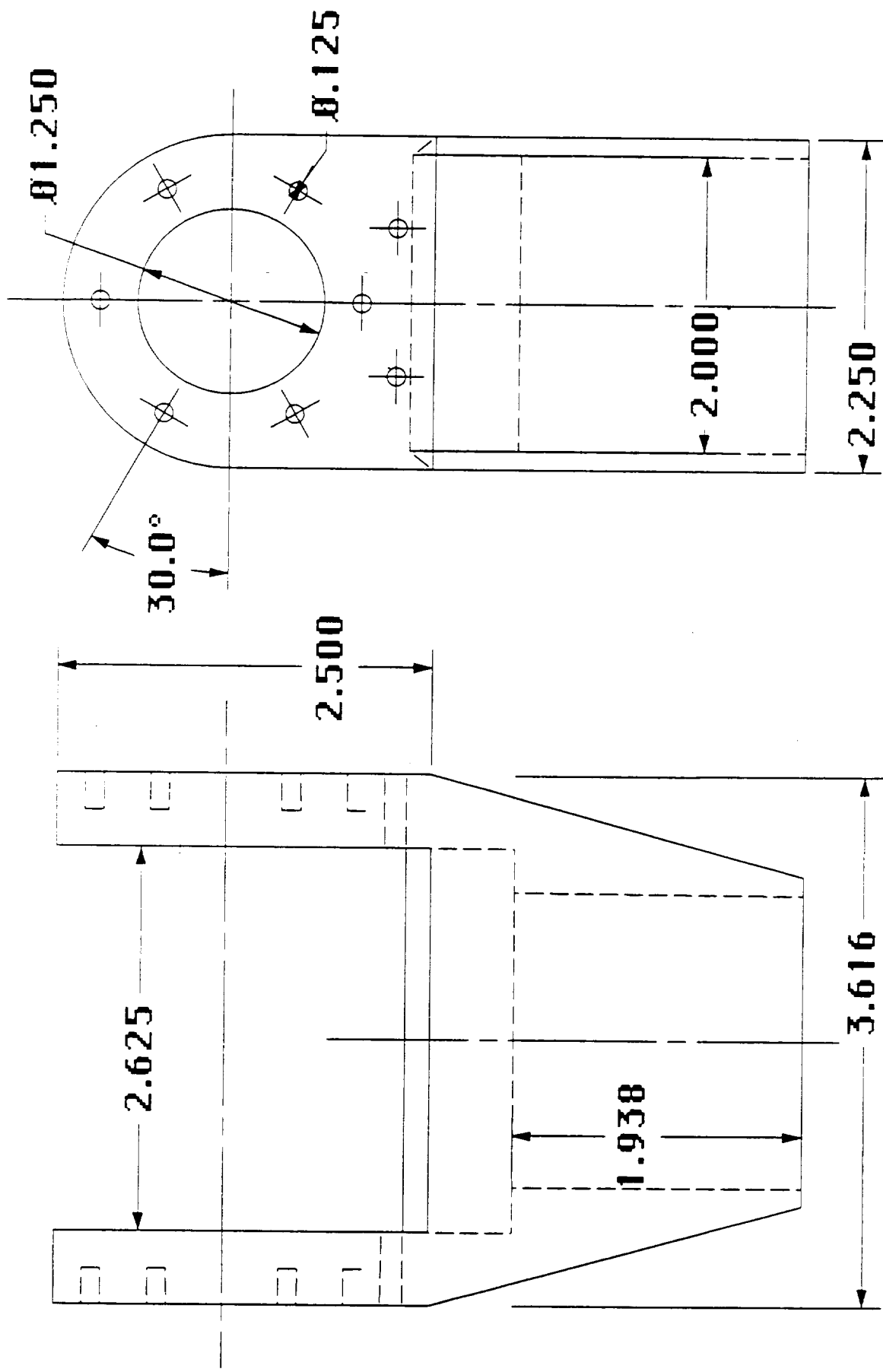
| ASPOD End-Effector | Outer Knuckle | Scale 1"=1" | William D. Lyle |

Ø0.625

Ø1.500

Standard 3/16 in Key Way

2.250

10-32 set screw

New material Removed

3.375

.500

1.375

.625

.375

| ASPOD End Effector | Inner Knuckle | Scale 1"=1" | William D. Lyle |

.378
.313
.313
.502
1.331
.500
2.375

| Pinion Axial | Scale 1"=1" |

Standard
3/16 in
Key way

.375
.375
.563
2.500
Ø.625
.563
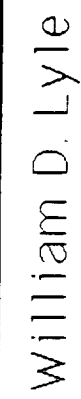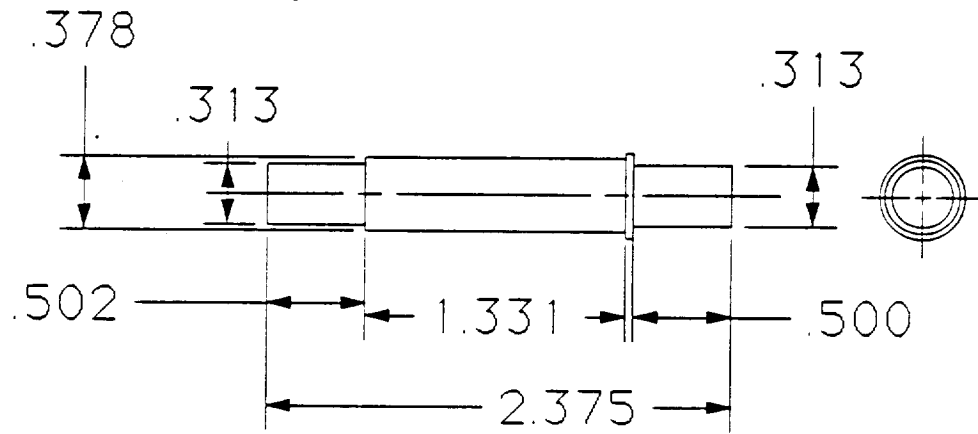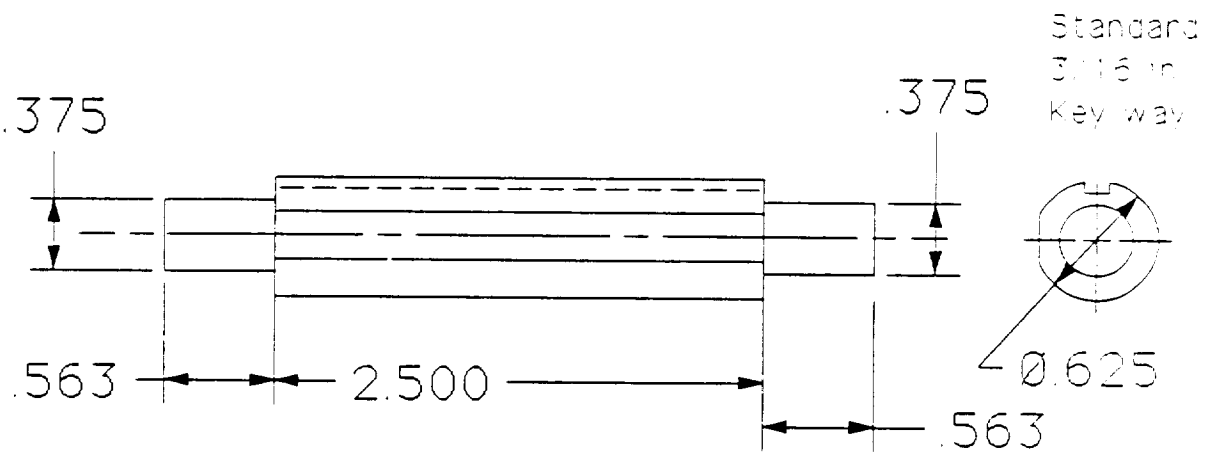
| Main Axial | Scale 1"=1" |
| ASPOD End-Effector | William D. Lyle |

Scale 1"=1"

Ø1.250

2.000

2.625

1.392

.681

1.062

1.125

Excess Material Removed
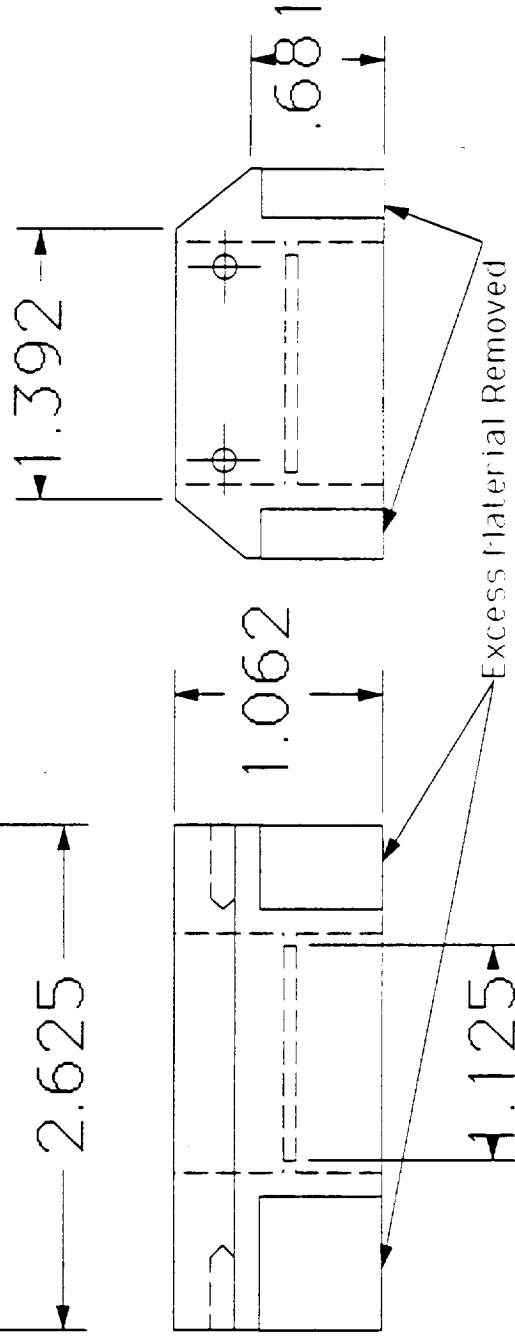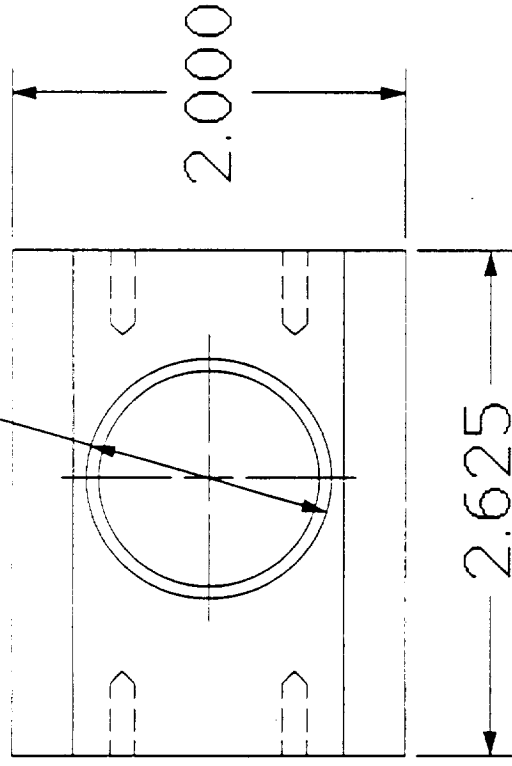
| ASPOD End Effector | Pinion Bracket | William D. Lyle |

1.500

1.875

Top View

Motor mount to
2 in OD sleve

.188

.625

.750

1.000

.250

Front View

1.250
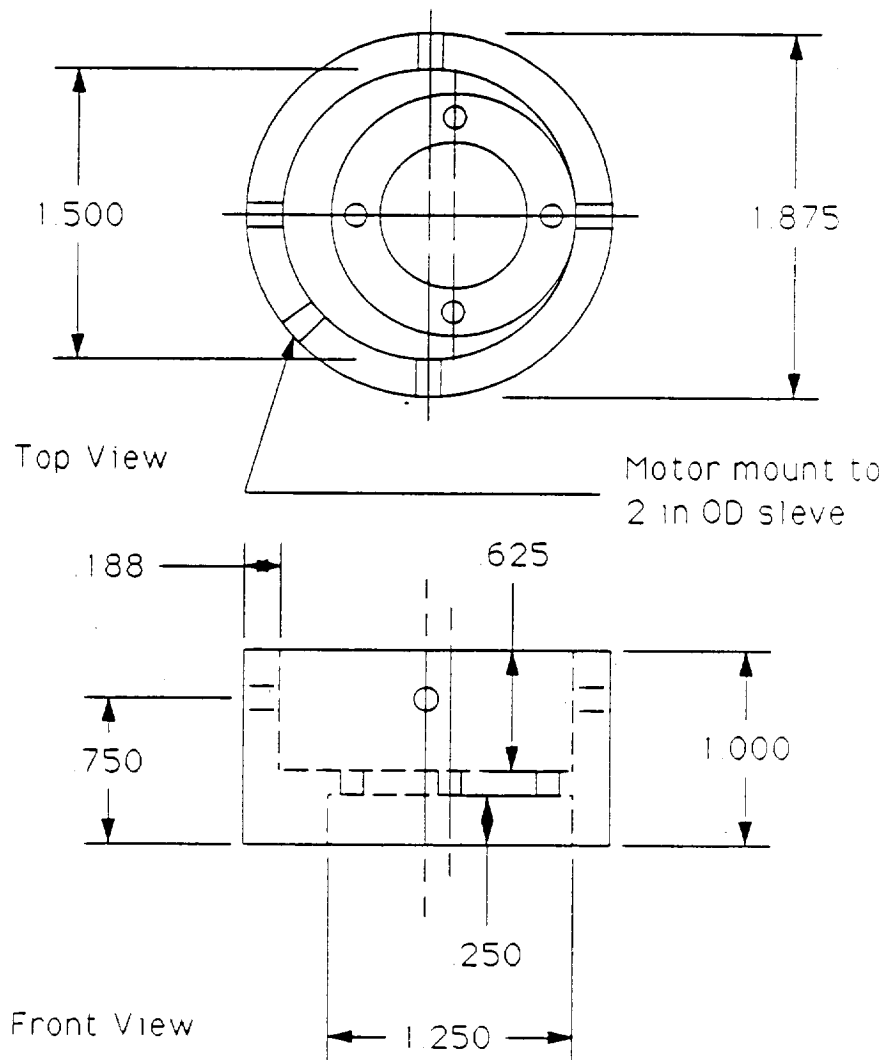
Mounting Bracket	Scale 1"=1"
ASPOD End-Effector	William D. Lyle

Ø.125   Ø.750

2.500

60.0°

2.250

Front Veiw

.063
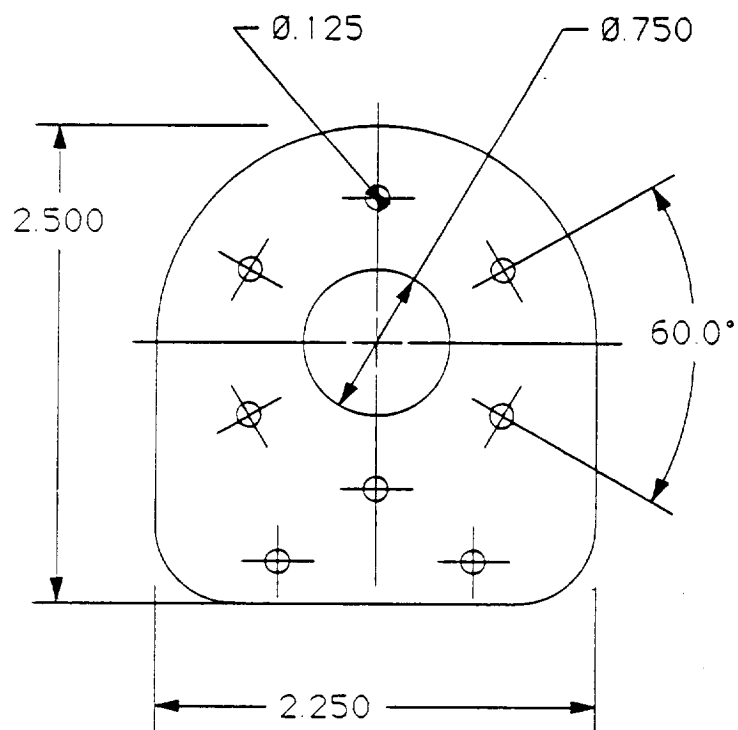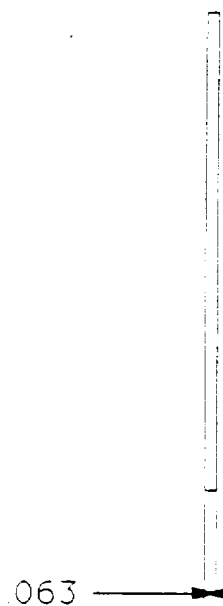
Side veiw

Axial Cap	Scale 1" = 1"
ASDPOD End-effector	Todd Jacobson

MicroMo® MOTORS

DC MicroMotors Series 2842

- Standard Motor Contains Two Ball Bearings.
- Fits Our Screw-On Planetary Gearhead Series 23/1, 32PG, 34 PG and 38/1 (Metal Case, 12:1 to 54,880:1)
- Available with Integral Optical Encoders (15, 100, 180, 500, or 1000 Pulses Per Revolution) and DC Tachometers.
- Available in 6, 12, 24, 28 and 36 Volt Types.
- High Temperature Version (125°C) Standard.

Continuous Duty Ratings: [1]

Speeds up to 5,000 RPM

Torque up to 3 oz-in

Power Output up to 6 Watts

Electrical Specifications:

@ 72°F (22°C)

For Motor Type 2842S	006C	012C	024C	028C	036C
Supply Voltage nom. (Volts)	6	12	24	28	36
Armature Resistance (Ohm) $\pm$12%	1.6	5.3	21.0	28.5	46.0
Max. Power Output (Watts)[2]	6.0	6.8	6.9	6.9	7.0
Max. Efficiency (%)[2]	70	72	72	72	72
No Load Speed (RPM) $\pm$12[2]	4,900	4,800	4,800	4,800	5,200
No Load Current (mA) $\pm$50%[3]	100	50	25	22	17
Friction Torque (@ No Load Speed)(oz-in)	.17	.17	17	.17	.17
Stall Torque (oz-in)[2]	5.9	7.5	7.5	7.6	7.0
Velocity Constant (RPM/Volt)	839	404	202	173	148
Back EMF Constant (mV/RPM)	1.19	2.47	4.94	5.77	6.77
Torque Constant (oz-in/Amp)	1.61	3.34	6.68	7.80	9.16
Armature Inductance (mH)	.145	580	2.50	3.20	5.00

Mechanical Specifications:

Mechanical Time Constant (mS)[2]	.13	15	15	15	15
Rotor Inertia (x10^{-4} oz-in-Sec^2)	2.22	2.22	2.22	2.22	2.22
Radial Acceleration (x10^3 Rad/Sec^2)[2]	34	33	33	33	36

Pre-Load Ball Bearings Standard

Thermal Resistances (°C/W)
 Rotor to Case   2 All Types
 Case to Ambient   16 All Types

Max. Shaft Loading (oz)
 Radial (@ 3,000 RPM) (3mm from bearing)   72 All Types
 Axial (Standing Still)   72 All Types
Weight (oz)   4.7 All Types
Rotor Temperature Range   —22°F to +257°F / —30°C to +125°C

Direction of Rotation is Reversible and Clockwise as Seen From Shaft End if Red Lead or Solder Tab Marked + is Connected to Positive Side of Voltage Supply.

(1) Life Expectancy Greater Than 1,000 Hrs. if These Ratings are Observed. Ratings are Presented Independent of Each Other.
(2) Specified at Nominal Supply Voltage. (Radial Accel. @ Twice Supply Volt.)
(3) Specified with Shaft Diameter - 3 mm. At No-Load Speed.
(4) Bearing Life Expectancy Greater Than 1,000 Hrs. if Loading Data are Observed.

—Specifications Subject to Change—

MOTORS

DC MicroMotors Series 2842

Dimensional Outlines:

2842 S . . .

Dimensions are in mm (in)

Dimensions with no tolerance indicated
are as follows:

For Dimensions:	Tolerance
Less than or equal to 6 mm	+ 1 mm (0039")
Less than or equal to 30 mm	+ 2 mm (0079")
Less than or equal to 120 mm	+ 3 mm (0118")

Ordering Information:

Example: To Order a 6 Volt, 2842 Motor intended to Fit Our 34 PG Gearheads, Specify:

Motor 28 42 S 006 C ... + 34PG , 480:1

Motor Diameter
Motor Length
Output Shaft Configuration
  S = 3.0 mm. Diam. x 10.6 mm. Shaft End
Nominal Voltage
Commutator Plating Material:
  C = Copper
Special Order Numbers (where applicable)
Gearhead Type
Desired Gear Ratio

ORIGINAL PAGE IS
OF POOR QUALITY

Micro Mo ELECTRONICS INC.

742 Second Avenue S. / St. Petersburg, Florida 33701 / Phone: 813/822-2529 / Telex: 807-982

MME-05905K

LITHO U.S.A.

MicroMo® GEARHEADS

Gearhead Series 30/1

- Fits Motor Series 2338, 2444, 2842, 3540, and 3557.
- Planetary Gearing with Metal Case (Steel, Nickel-Plated).
- 2 Sealed Ball Bearings Standard.
- Quiet, Precise Operation.

Maximum Ratings:

Temperature Range: -30°C to 100°C (-22°F to 212°F)
Load on Output Shaft:
   RADIAL: (15mm from bearing) 150 N (540 oz.)
   AXIAL: 150 N (540 oz.)
Maximum press fit force: 200 N (720 oz.)
Bearing Play:
   RADIAL: 0.015mm (.0006 in.)
   AXIAL: 0.15mm (.0060 in.)
Recommended Input Speed for Continuous Operation: 3000 RPM
Backlash, Unloaded ≤1°
Note: Direction of rotation is identical to direction of motor rotation. All gearheads are reversible.
Maximum Continuous Output Torque: 640 oz-in.
                                              4.5 Nm
Maximum Intermittent Output Torque: 850 oz-in.
                                              6.0 Nm

Actual Size

1 Reduction Ratio [1]	2 Weight Without Motor		3 Length Without Motor L2		4 Length With Motor 2338S L1		5 Length With Motor 2444S L1		6 Length With Motor 2842S L1	
	g	oz	mm	in	mm	in	mm	in	mm	in
3.71:1	107	3.77	10.2	.402	64.6	2.543	71.0	2.795	69.0	2.716
14:1	139	4.90	18.2	.716	72.6	2.858	79.0	3.110	77.0	3.031
43:1	171	6.03	26.2	1.031	80.6	3.173	87.0	3.425	85.0	3.346
66:1	171	6.03	26.2	1.031	80.6	3.173	87.0	3.425	85.0	3.346
134:1	203	7.16	34.2	1.346	88.6	3.488	95.0	3.740	93.0	3.661
159:1	203	7.16	34.2	1.346	88.6	3.488	95.0	3.740	93.0	3.661
246:1	203	7.16	34.2	1.346	88.6	3.488	95.0	3.740	93.0	3.661
415:1	235	8.29	42.2	1.661	96.6	3.803	103.0	4.055	101.0	3.976
592:1	235	8.29	42.2	1.661	96.6	3.803	103.0	4.055	101.0	3.976
989:1	235	8.29	42.2	1.661	96.6	3.803	103.0	4.055	101.0	3.976
1526:1	235	8.29	42.2	1.661	96.6	3.803	103.0	4.055	101.0	3.976

7 Length [2] With Motor 3540K L1		8	9		10 Rotation Direction	11 Effi- ciency
		Maximum Torque Output				
		Continuous Operation	Intermittent Operation			
mm	in	Nm	oz-in	Nm	oz-in		%

mm	in	Nm	oz-in	Nm	oz-in	Rotation Direction	%
68.4	2.693	1.5	212	3.0	425	All ratios	88
76.4	3.008	0.35	50	0.5	71	rotate	80
84.4	3.323	1.2	170	1.6	227	clockwise	70
84.4	3.323	1.8	255	2.4	340	as viewed	70
92.4	3.638	3.5	496	4.5	638	from	60
92.4	3.638	4.5	638	6.0	850	Shaft End	60
92.4	3.638	4.5	638	6.0	850	with	60
100.4	3.953	4.5	638	6.0	850	Driving	55
100.4	3.953	4.5	638	6.0	850	Motor	55
100.4	3.953	4.5	638	6.0	850	turning	55
100.4	3.953	4.5	638	6.0	850	clockwise	55

(1) To find length with Motor 3557, add 17mm (.669 in.) to column 7.
(2) Ratio 3.71:1 has all steel gears.
    Ratios 14:1 and higher have plastic gears in the input stage. (Available with all steel gears - consult Micro Mo.)

GEARHEADS
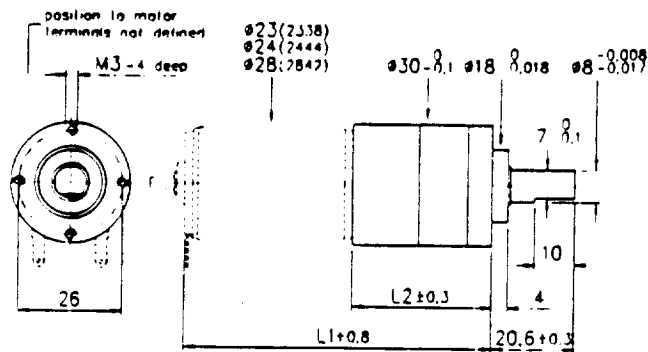
-- Specifications Subject To Change --

Dimensional Outlines:

position to motor terminals not defined

M3 - 4 deep

ø23(2338)
ø24(2444)
ø28(2842)

ø30 $-^{0}_{0.1}$ ø18 $-^{0}_{0.018}$ ø8 $-^{-0.008}_{-0.017}$

7 $-^{0}_{0.1}$

10

26

L2 ±0.3

L1±0.8

20.6 +0.3

4

Front View   **30/1 with Motor 2338, 2444 or 2842**

ø35 $\begin{smallmatrix}(3557)\\(3540)\end{smallmatrix}$ ø30 $-^{0}_{0.1}$ ø18 $-^{0}_{0.018}$ ø8 $-^{-0.008}_{-0.017}$

7 $-^{0}_{0.1}$

10

L2 ±0.3 (+1,4)

L1±0.8

20.5 ±0.3

4

30/1 with Motor 3540 or 3557

Dimensions are in mm (in.).

Dimensions with no tolerance indicated are as follows:

For Dimensions:	Tolerance
Less than or equal to 6mm	±1mm (.0039")
Less than or equal to 30mm	±2mm (.0079")
Less than or equal to 120mm	±3mm (.0118")

MME099015K

Litho U.S.A.

SPUR GEARS

LEWIS FORMULA (Barth Revision)

Gear failure can occur due to tooth breakage (tooth stress) or surface failure (surface durability) as a result of fatigue and wear. Strength is determined in terms of tooth-beam stresses for static and dynamic conditions, following well established formula and procedures. Satisfactory results may be obtained by the use of Barth's Revision to the Lewis Formula, which considers beam strength but not wear. The formula is satisfactory for commercial gears at Pitch Circle velocities of up to 1500 FPM. It is this formula that is the basis for all Boston Spur Gear ratings.

METALLIC SPUR GEARS

$$W = \frac{SFY}{P}\left(\frac{600}{600 + V}\right)$$

W = Tooth Load, Lbs. (along the Pitch Line)
S = Safe Material Stress (static) Lbs. per Sq. In. (Table II)
F = Face Width, In.
Y = Tooth Form Factor (Table I)
P = Diametral Pitch
D = Pitch Diameter
V = Pitch Line Velocity, Ft. per Min. = .262 × PD × RPM

For NON-METALLIC GEARS, the modified Lewis Formula shown below may be used with (S) values of 6000 PSI for Phenolic Laminated material.

$$W = \frac{SFY}{P}\left(\frac{150}{200 + V} + .25\right)$$

TABLE II—VALUES OF SAFE STATIC STRESS (s)

Material	(s) Lb. per Sq. In.
Plastic	5000
Bronze	10000
Cast Iron	12000
Steel .20 Carbon (Untreated)	20000
.20 Carbon (Case-hardened)	25000
.40 Carbon (Untreated)	25000
.40 Carbon (Heat-treated)	30000
.40 C. Alloy (Heat-treated)	40000

Max. allowable torque (T) that should be imposed on a gear will be the safe tooth load (W) multiplied by $\frac{D}{2}$ or $T = \frac{W \times D}{2}$

The safe horsepower capacity of the gear (at a given RPM) can be calculated from $HP = \frac{T \times RPM}{63,025}$ or directly from (W) and (V),

$$HP = \frac{WV}{33,000}$$

For a known HP, $T = \frac{63025 \times HP}{RPM}$

TABLE I   Y FACTORS

Number of Teeth	14½° Full Depth Involute	20° Full Depth Involute
10	0.176	0.201
11	0.192	0.226
12	0.210	0.245
13	0.223	0.264
14	0.236	0.276
15	0.245	0.289
16	0.255	0.295
17	0.264	0.302
18	0.270	0.308
19	0.277	0.314
20	0.283	0.320
22	0.292	0.330
24	0.302	0.337
26	0.308	0.344
28	0.314	0.352
30	0.318	0.358
32	0.322	0.364
34	0.325	0.370
36	0.329	0.377
38	0.332	0.383
40	0.336	0.389
45	0.340	0.399
50	0.346	0.408
55	0.352	0.415
60	0.355	0.421
65	0.358	0.425
70	0.360	0.429
75	0.361	0.433
80	0.363	0.436
90	0.366	0.442
100	0.368	0.446
150	0.375	0.458
200	0.378	0.463
300	0.382	0.471
Rack	0.390	0.484

BOSTON GEAR

MITER AND BEVEL GEARS
TOOTH STRENGTH (Straight Tooth)

The beam strength of Miter and Bevel gears (straight tooth) may be calculated using the Lewis Formula revised to compensate for the differences between Spur and Bevel gears. Several factors are often combined to make allowance for the tooth taper and the normal overhung mounting of Bevel gears.

$$W = \frac{SFY}{P}\left(\frac{600}{600 + V}\right).75$$

W = Tooth Load, Lbs. (Along the Pitch Line)
S = Safe Material Stress (Static), Lbs. per Sq. In. (Table 1)
F = Face Width, In.
Y = Tooth Form Factor (Table II)
P = Diametral Pitch
D = Pitch Diameter
V = Pitch Line Velocity, Ft. per Min. = .262 × P.D. × RPM

TABLE I—VALUES OF SAFE STATIC STRESS (s)

Material	(s) Lb. per Sq. In.
Cast Iron	10000
Steel .20 Carbon (Untreated)	12000
Steel .20 Carbon (Case-hardened)	25000
Steel .40 Carbon (Untreated)	25000
Steel .40 Carbon (Heat-treated)	30000
Steel .40 C. Alloy (Heat-treated)	40000

TABLE II TOOTH FORM FACTOR (Y)
20°P.A. — Long Addendum Pinions
Short Addendum Gears

No. Teeth Pinion	RATIO 1 Pin.	1 Gear	1.5 Pin.	1.5 Gear	2 Pin.	2 Gear	3 Pin.	3 Gear	4 Pin.	4 Gear	6 Pin.	6 Gear
12	–	–	–	–	345	283	355	302	358	305	361	324
14	–	–	349	292	367	301	377	317	380	323	405	352
16	333		367	311	386	320	396	333	402	339	443	377
18	342		383	328	402	336	415	346	427	364	474	399
20	352		402	339	418	349	427	355	456	386	500	421
24	371		424	364	443	368	471	377	506	405	–	–
28	386		446	383	462	386	509	396	543	421	–	–
32	399		462	396	487	402	540	412	–	–	–	–
36	408		477	408	518	415	569	424	–	–	–	–
40	418		–	–	543	424	594	434	–	–	–	–

HORSEPOWER AND TORQUE

Max. allowable torque (T) that should be imposed on a gear will be the safe tooth load (W) multiplied by $\frac{D}{2}$ or $T = \frac{W \times D}{2}$

The safe horsepower capacity of the gear (at a given RPM) can be calculated from $HP = \frac{T \times RPM}{63,025}$ or directly from (W) and (V):

$$HP = \frac{WV}{33,000}$$

For a known HP, $T = \frac{63025 \times HP}{RPM}$

THRUST

The axial thrust loads developed by straight tooth miter and bevel gears always tend to separate the gears.
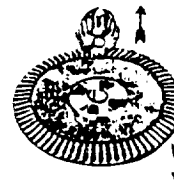
For Spiral Bevel and Miter Gears, the direction of axial thrust loads developed by the driver and driven gears will depend upon the hand and direction of rotation. Stock Spiral Bevel pinions cut Left Hand only, Gears Right Hand only.
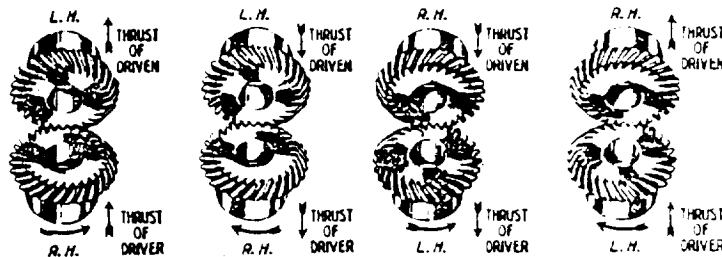
The magnitude of the thrust may be calculated from the formulae below, based on calculated HP, and an appropriate Thrust Bearing selected.

STRAIGHT BEVELS and MITERS

$$\text{Gear Thrust} = \frac{126,050 \times HP}{RPM \times \text{Pitch Diameter}} \times \tan\alpha \cos\beta$$

$$\text{Pinion Thrust} = \frac{126,050 \times HP}{RPM \times \text{Pitch Diameter}} \times \tan\alpha \sin\beta$$

SPIRAL BEVEL and MITERS

Thrust values for Pinions and Gears are given for four possible combinations

R H SPIRAL CLOCKWISE	$T_J = \frac{126,050 \times HP}{RPM \times D}\left(\frac{\tan\alpha \sin\beta}{\cos\gamma} - \tan\gamma \cos\beta\right)$
L H SPIRAL C CLOCKWISE	$T_G = \frac{126,050 \times HP}{RPM \times D}\left(\frac{\tan\alpha \cos\beta}{\cos\gamma} + \tan\gamma \sin\beta\right)$
L H SPIRAL CLOCKWISE	$T_\mu = \frac{126,050 \times HP}{RPM \times D}\left(\frac{\tan\alpha \sin\beta}{\cos\gamma} + \tan\gamma \cos\beta\right)$
R H SPIRAL C CLOCKWISE	$T_G = \frac{126,050 \times HP}{RPM \times D}\left(\frac{\tan\alpha \cos\beta}{\cos\gamma} + \tan\gamma \sin\beta\right)$

α = Tooth Pressure Angle
β = 1/2 Pitch Angle
Pitch Angle = $\tan^{-1}\left(\frac{N_p}{N_G}\right)$
γ = Spiral Angle = 35°

BOSTON GEAR

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GENERAL

MATERIALS

Boston Gear stock steel gears are made from a .20 carbon steel. Case-hardening produces a wear resistant, durable surface and a higher strength core. Carburizing and hardening is the most common process used. Several proprietary nitriding processes are available for producing an essentially distortion-free part with a relatively shallow but wear-resistant case. Boston stock worms are made of either a .20 or .45 carbon steel. Selection of material is based on size and whether furnished as hardened or untreated.

Stock cast iron gears are manufactured from ASTM — Class 30 cast iron to Boston Gear specification. This provides a fine-grained material with good wear-resistant properties.

Bronze worm and helical gears are produced from several alloys selected for bearing and strength properties. Phosphor bronze is used for helicals and some worm gears (12P and coarser). Finer pitch worm gears are made from several different grades of bronze, dependent on size.

Non-metallic spur Gears listed in this Catalog are made from cotton reinforced phenolic normally referred to as Grade "C."

Plastic Gears listed are molded from either Delrin®, Acetal or Minlon®.

STYLES

Boston Spur, Helical, and Worm Gears are carried in Plain, Web, or Spoke styles, as illustrated
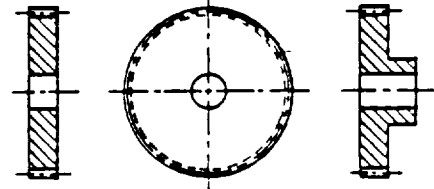
PLAIN — A
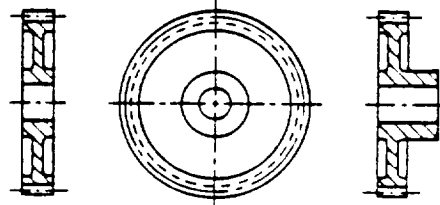
WEB — B
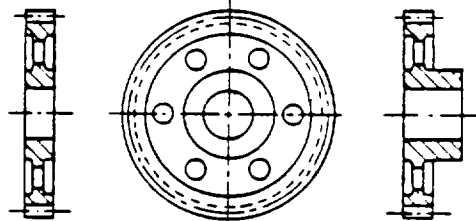
WEB WITH
LIGHTNING HOLES — C
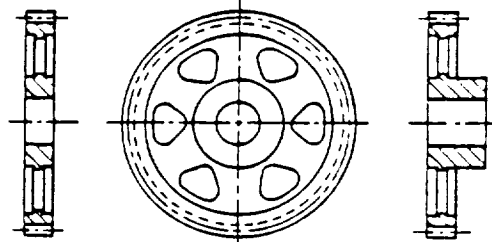
SPOKE — D

STANDARD KEYWAYS and SETSCREWS

Diam. of Hole	St'd Keyway		Recommended Setscrew
	W	d	
5/16 to 7/16"	3/32"	3/64"	10 — 32
1/2 to 9/16	1/8	1/16	1/4 — 20
5/8 to 7/8	3/16	3/32	5/16 — 18
15/16 to 1-1/4	1/4	1/8	3/8 — 16
1- 5/16 to 1-3/8	5/16	5/32	7/16 — 14
1- 7/16 to 1-3/4	3/8	3/16	1/2 — 13
1-13/16 to 2-1/4	1/2	1/4	9/16 — 12
2- 5/16 to 2-3/4	5/8	5/16	5/8 — 11
2-13/16 to 3-1/4	3/4	3/8	3/4 — 10
3- 5/16 to 3-3/4	7/8	7/16	7/8 — 9
3-13/16 to 4-1/2	1	1/2	1 — 8
4- 9/16 to 5-1/2	1-1/4	7/16	1-1/8 — 7
5- 9/16 to 6-1/2	1-1/2	1/2	1-1/4 — 6
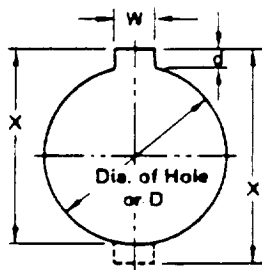
FORMULA:

$$X = \sqrt{(D/2)^2 - (W/2)^2} + d + D/2$$
$$X' = 2X - D$$

EXAMPLE:

Hole 1"; Keyway 1/4" wide by 1/8" deep.

$$X = \sqrt{(1/2)^2 - (1/8)^2} + 1/8 + 1/2 = 1.109"$$
$$X' = 2.218 - 1.000 = 1.218"$$

BOSTON GEAR

BEARING DIMENSIONS BY CONE BORE

This listing, by cone bore, contains most of The Timken Company TS type bearings. For additional types and other cups or cones in a ~~particular series refer to sections 1-2~~

bore d	outside diameter D	width T	cone	cup	bore d	outside diameter D	width T	cone	cup
7.938 0.3125	31.991 1.2595	10.008 0.3940	A2031	A2126	17.462 0.6875	44.450 1.7500	12.700 0.5000	4C	6
9.525 0.3750	31.991 1.2595	10.008 0.3940	A2037	A2127	17.462 0.6875	46.990 1.8500	15.250 0.6004	05068	05186
11.112 0.4375	34.988 1.3775	10.998 0.4330	A4044	A4138	17.653 0.6950	49.225 1.9380	19.846 0.7813	09070	09195
11.112 0.4375	35.918 1.4140	17.635 0.6943	00068X	00153X	18.000 0.7087	47.000 1.8504	14.381 0.5662	05070X	05185
12.000 0.4724	31.991 1.2595	10.008 0.3940	A2047	A2126	19.000 0.7480	49.225 1.9380	23.812 0.9375	09075	09196
12.680 0.4992	34.988 1.3775	10.998 0.4330	A4049	A4138	19.000 0.7480	49.225 1.9380	23.812 0.9375	09078	09194
12.692 0.4997	36.512 1.4375	17.635 0.7067	00079X	00152X	19.004 0.7482	53.975 2.1250	19.367 0.7625	1774	1730
12.692	38.100								

TS

SHAFT COUPLINGS

MULTI-JAW TYPE

UNTREATED STEEL COUPLINGS for use in light duty applications, require no lubrication.

BORE SIZES FROM 3/16" to 1/2"

COMPLETE WITH STANDARD SETSCREWS

STANDARD TOLERANCES

DIMENSION		TOLERANCE
BORE	All	± 0005

REFERENCE PAGES

Alignment—163
Keyways and Setscrews—164

ALL DIMENSIONS IN INCHES
ORDER BY CATALOG NUMBER OR ITEM CODE

Coupling Size	Bore	O.D.	Length†	Bore Length++	Assembly Clearance ‡	Hub Dia.	Hub Proj.	Teeth	Steel Catalog Number	Item Code
FA5	3/16	1/2	1-1/8	1/2	1-9/32	7/16	7/16	10	FA5 3/16-3/16	07900
	1/4								FA5 1/4-1/4	07904
FA75	5/16	3/4	1-1/2	5/8	1-3/4	11/16	33/64	10	FA75 5/16-5/16	07910
	3/8								FA75 3/8-3/8	07912
FA10	7/16	1	2	7/8	2-9/32	15/16	3/4	12	FA10 7/16-7/16	07908
	1/2								FA10 1/2-1/2	07906

†Total length of coupling with jaws engaged full depth.
++Length of hole in each half.
‡Approximate total length of coupling with jaws completely disengaged.

RIGID (ONE PIECE) TYPE

BORE SIZES FROM 1/4" to 1-1/4"
COMPLETE WITH STANDARD SETSCREWS

ALL DIMENSIONS IN INCHES
ORDER BY CATALOG NUMBER OR ITEM CODE

Bore	O.D.	Overall Length	A	Catalog Number	Item Code
1/4	1/2	3/4	3/16	CR4	34200
5/16	5/8	1	1/4	CR5	34202
3/8	3/4	1	1/4	CR6	34204
1/2	1	1-1/2	3/8	CR8	34206
5/8	1-1/4	2	1/2	CR10	34208
3/4	1-1/2	2	1/2	CR12	34210
7/8	1-3/4	2	1/2	CR14	34212
1	2	3	3/4	CR16	34214
1-1/4	2-1/4	4	1	CR20	34216

REFERENCE PAGES

Keyways and Setscrews—164

STANDARD TOLERANCES

DIMENSION		TOLERANCE
BORE	All	+ 001 - 000

BOSTON GEAR

APPENDIX E
GRIPPER

1/4

4 3/16

.5415"

.3335"

Solid aluminum guide rod

Part #1003

8 3/8

"Boston Gear" steel spur gear. 16 Teeth; .667 " Pitch Dia; .75" Outside Dia; 5/16" Bore Dia; 24 Diametral pitch. 14 1/2 ° Pressure angle. Cat # S2416, Item code 09634.

Part # 1004

Part # 1005

"Boston Gear" Steel Rack. Pitch line to back .208", over all thickness 1/4", 24 diametral pitch, 14 1/2° Pressure angle, face width 1/4". Cat # L505-2, Item Code 12732.

.208

1/4

1/4
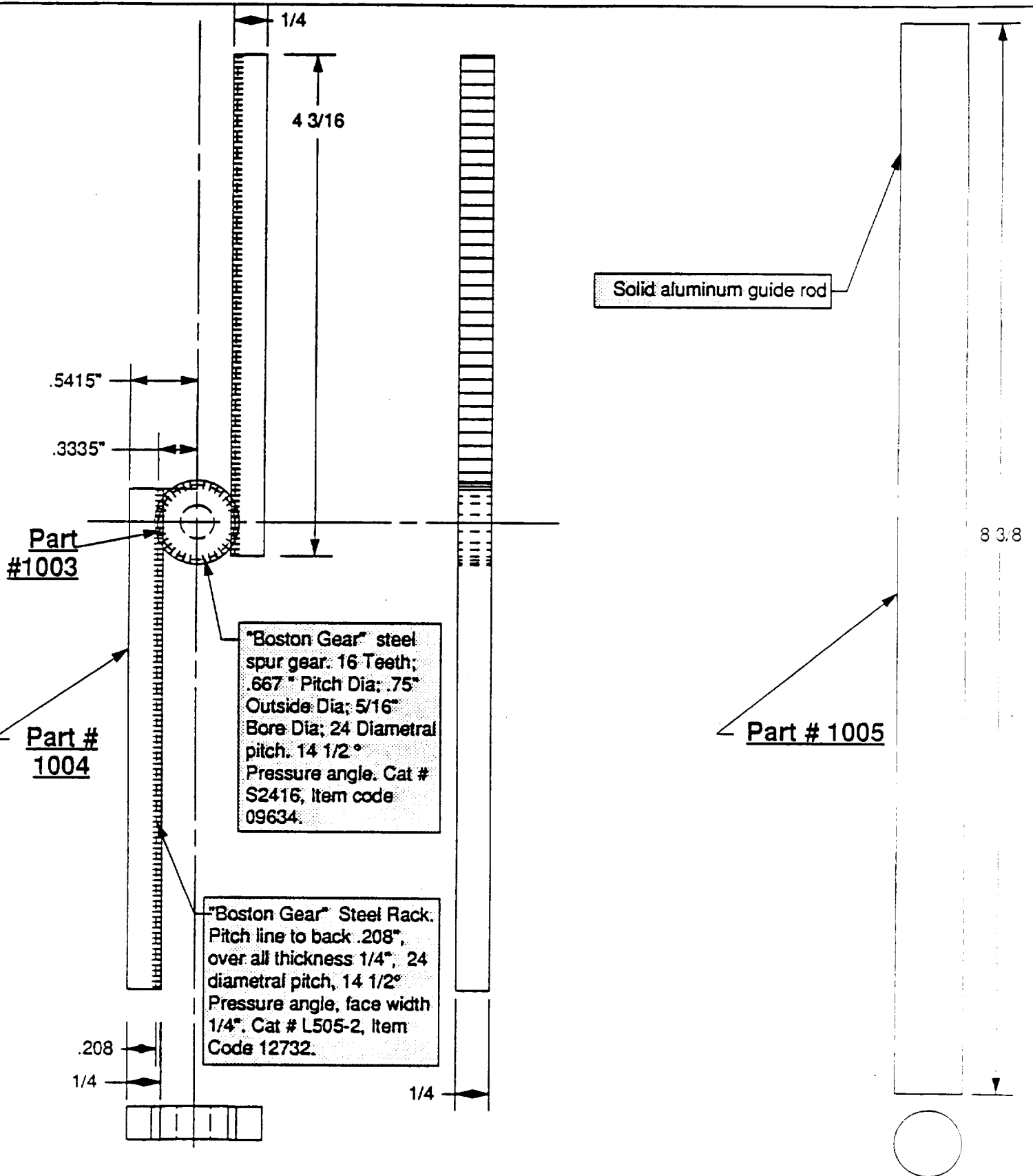
ASPOD End Effector Design Team	Bjorn Kutz
Rack and Pinion Mechanism; and Guide Rod	
Scale: 1 inch = 1 inch	Part #s 1003, 1004, 1005

Typ. 1/8"Ø
1/8" Thru ,
Counter sink ,
1/8" Deep

1/8

15°

8 3/8

0.262

3 x #4-40 UNC-2B,
3-Holes EQ. SP., 1.062 Ø
B.C.

4 3/16

0.50" Ø Thru.

1/8

2

1 7/8

/8

1 3/8

1 1/2

5/8

1/8

1
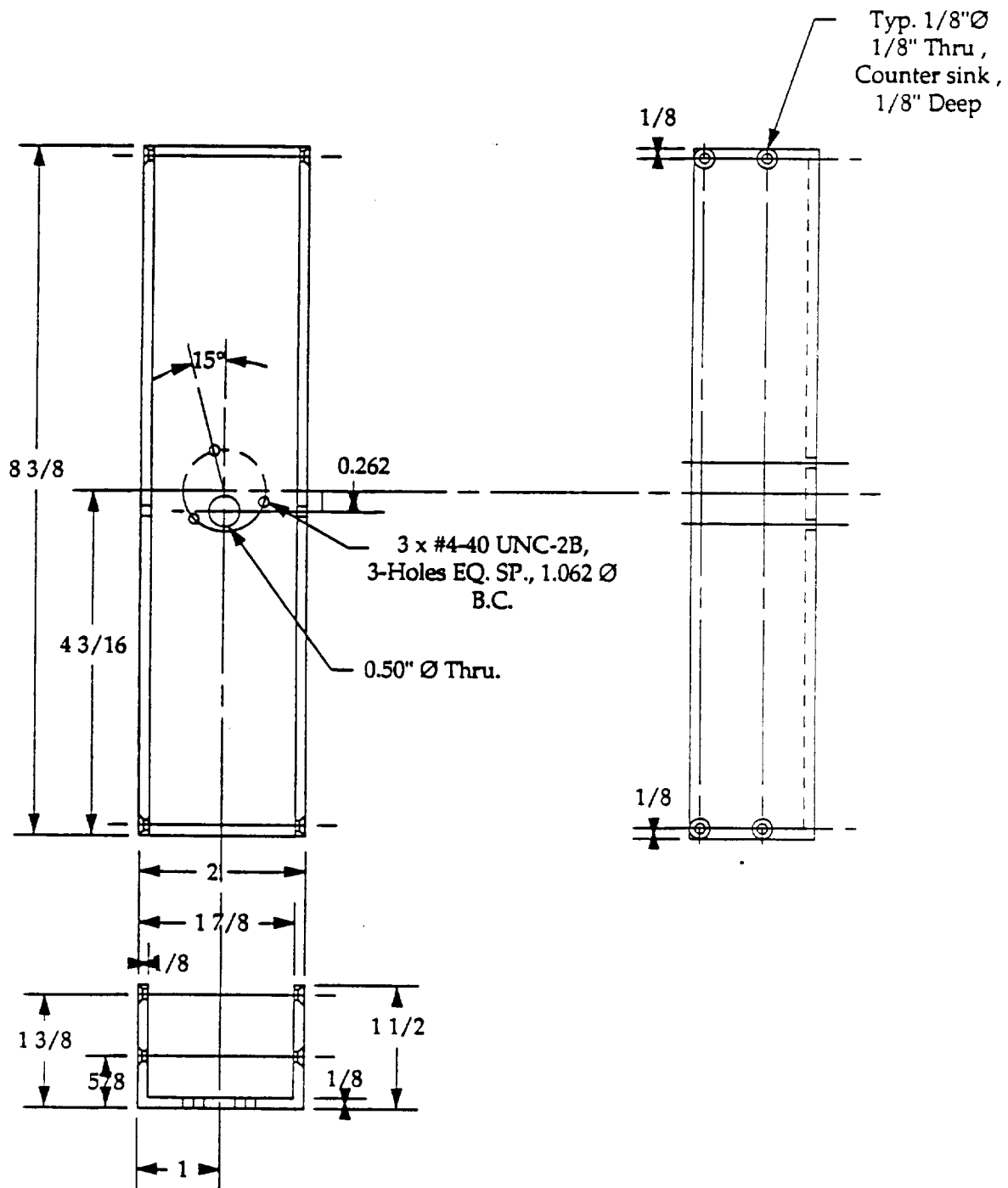
ASPOD End Effector Design Team	Bjorn Kutz
Effector Housing	Material: Aluminum
Scale: 1 inch = 2 inches	Part # 1001

1 5/8

1 1/4

3/8

1 1/4

15/16

5/16

Part # 1009

Boston Gear "Bost n Bronze" sleeve bearing Item Code 34732

5/8

Ø1/2

1 1/4

Ø5/8

1/8

1/8

1/4" Deep, 1/8" Ø, 2 places.

1 5/16

1/4

1/4

9/16

13/16

Part # 1008

13/16

1 1/4
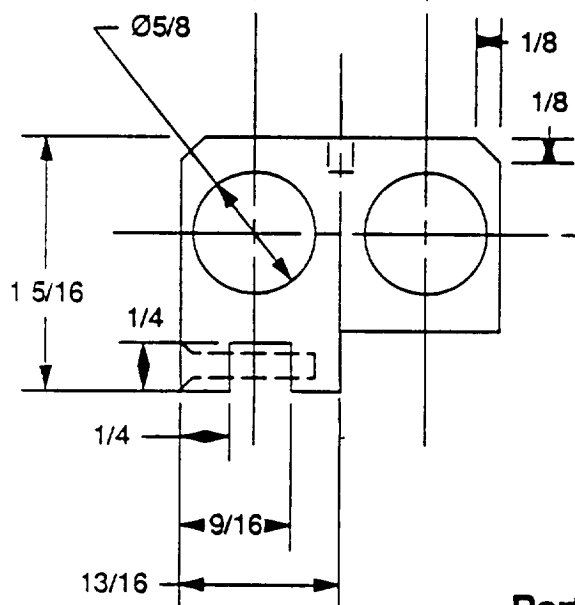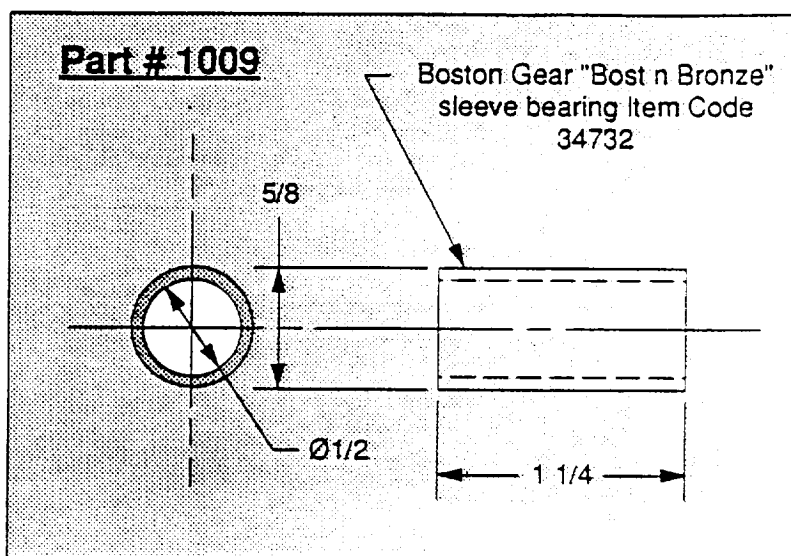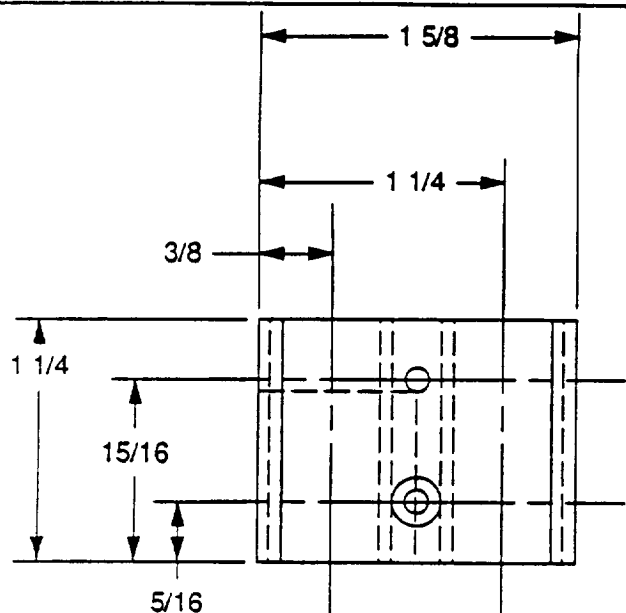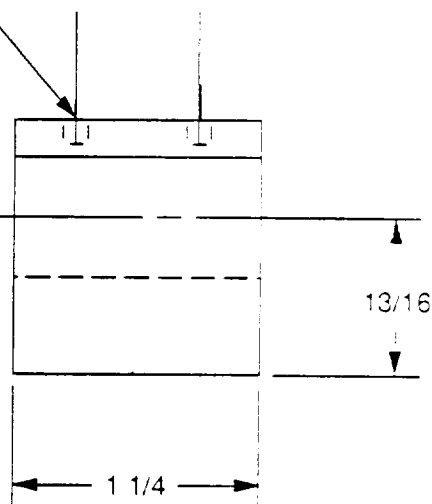
ASPOD End Effector Design Team	Bjorn Kutz
Slider Mechanism	**Material: Aluminum**
Scale: 1 inch = 1 inch	Part #s 1008, 1009

15°

Ø 1 7/8"

3 x #4-40 UNC-2B,
3-Holes EQ. SP.,
1.062 Ø B.C.

0.262

6x 10-32, 3/16"
deep, 60° apart

0.500" Thru

3/16"

3/8"
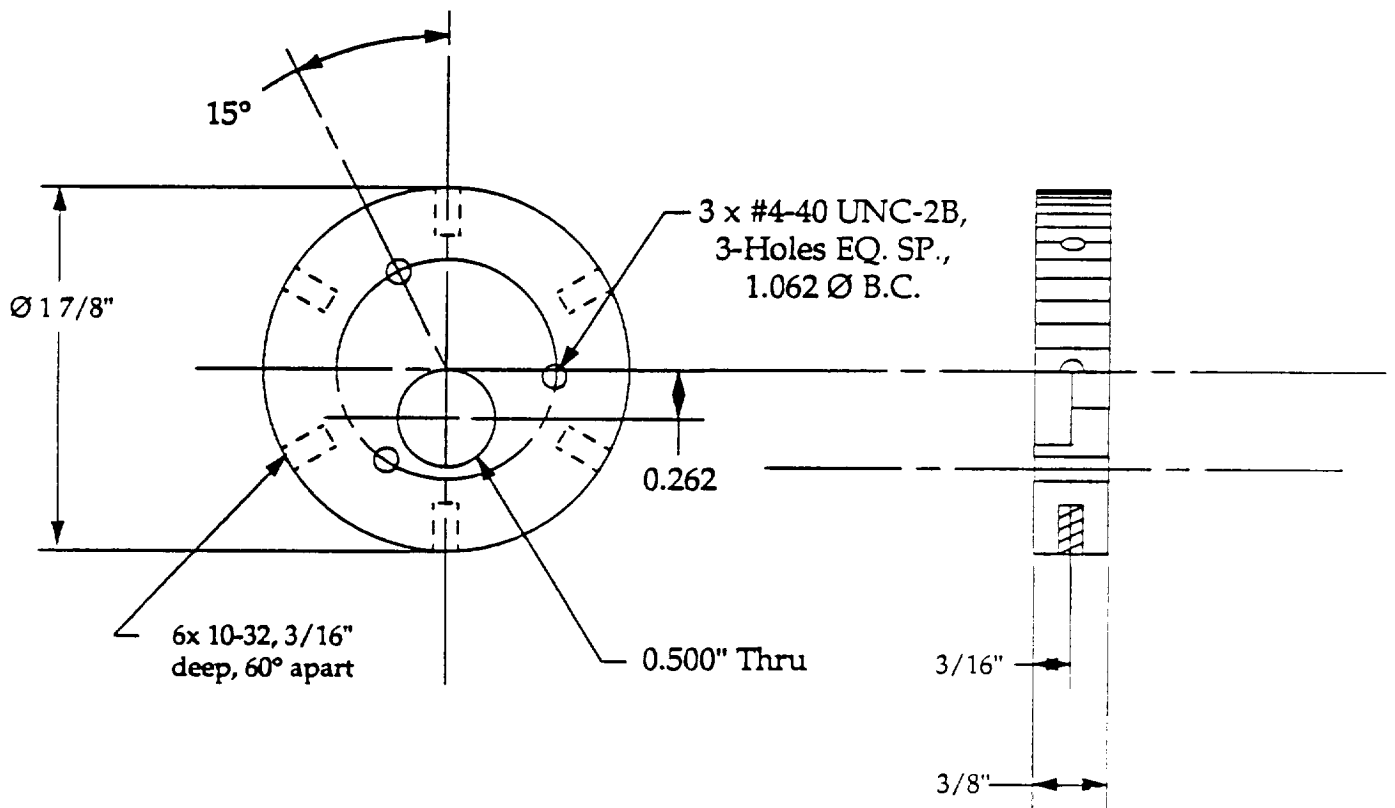
All surfaces finish
machined.

All dimensions in inches
unless otherwise noted

ASPOD End Effector Design Team	Bjorn Kutz
Tubing Connector	Material: Aluminum
Scale: 1 inch = 1 inch	Part # 1010

Ø.500

1/4

1/8

1 1/4

7/8

1 3/8

1/2

3/8

7/8   7/8

4 x 6-32, 1/4"deep

E: 2 Gripper Calculations
2-4-92

➤ - Gripper Calculations

$\mu = .40$ $P = 2^{lb}$

k   5"   ⊗

10"

1"
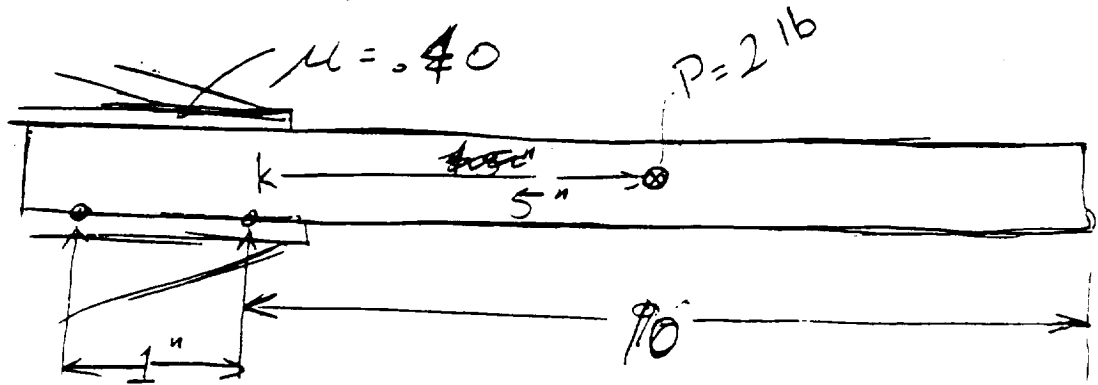
10 in lbs   torque applied by ⅔
if assuming 1 — g max acceleration

20 in lbs $\frac{20}{.2}$ = 100 lbs on side

200 lbs applied · .667

⇒ 133.4 in lbs   (Too Large)

Try Something different

2 lb load at 3" distance

6 in lbs ÷ 1.0 in = 6 lbs

$\frac{6}{.4}$ = 15 lbs × 2 for both sides

30 .667 = 20.01 in lbs

Still too Large

2 - 4 - 92

Gripper Constraints (Load)

2 lb Load @ 3" => 6 in lbs

$$\frac{6}{8} = 7.5 \text{ lbs per side} \times 2$$

.667 · 15 lbs = 10.005 in lbs = 160.08 in lbs

Screw calculations for removable jaw

2-27-92

Jaws

7.5 lb →

torque on → 7.5 lb · 1.5" = 11.25 in lbs
jaw by object held

$P_m = 5.625$
$P_a = 5.625$

1.5"

Screw

1/3"

$= 3.75$
$= 3.75$

4"

From Shigley
1983

torque ~~etc~~ max Load on
screw = 11.25 in lbs / 1"
$S_L = 11.25$ lb $P_m = 5.625$
$P_a = 5.625$

10·32 Screws

For Screw: $S_y = 120,000$ lb yield strength
$S_u = 150,000$ lb   ultimate strength

$E_{A l} = 10,298,000$
$E_{St} = 30,023,000$

Screw dia = .19" = ϕ_s

Surface Factor = $k_a = .675$
Size factor = $k_b = 1$
Temperature fact = $k_d = 1$
Reliability fact = $k_c = .753$
Thread Coeff = 3
Stress conc fact = $1/\text{Thread coeff} = .333$

Aluminum thickness = $1/8$" = t

Bolt Spring Const = $K_b = \dfrac{\pi \phi_s^2 E_s}{4 \cdot t} = 6,509,907$

Plate Spring Const = $K_m = \dfrac{\pi \phi_s^2 E_{Al} \cdot 2}{t} = 18,086,595$

Spring term = $\dfrac{K_b}{K_b + K_m} = .267$

2-27-92

~~Fatigue Strength = Se~~

$$Se' = Su \cdot \frac{1}{2} = 75,000$$

Fatigue Strength = ~~ka~~ $Se = Se' \cdot ka \cdot kb \cdot kd \cdot kc \cdot ke = 12,706.875$

Preload $= Km (Pm + Pa)/(Km + Kb) = 8.245$ lb $= F_i$

- Alternating Stress $= \sigma_a = \dfrac{Kb}{Kb + Km} \cdot \dfrac{P}{2 A_t}$

$$P = P_{max} = P_m + P_a = 1125 \qquad A_t = \text{Stress } A_t$$

$$\sigma_a = 75.120 \ lb/in^2$$

- Mean Stress $= \dfrac{Kb}{Kb + Km} \cdot \dfrac{P}{2 A_t} + \dfrac{F_i}{A_t} = \sigma_m$

$$\sigma_m = 487.38 \ lb/in^2$$

- Mean shear stress $= \sigma_{ms} = \dfrac{P_{ms}}{A_t} = 187.5$

- Alternating shear Stress $= \sigma_{as} \dfrac{P_{as}}{A_t} = 187.5$

Using Henchy Van Mises: While approximating Goodman
Criteria

Max static stress:

$$\sigma_s^* = \sqrt{(\sigma_a + \sigma_m)^2 + 3(\sigma_{as} - \sigma_{ms})^2}$$

$$\sigma_s^* = 859.23 \text{ psi}$$

Factor of safety static = $\dfrac{S_y}{\sigma_s^*} = 139.66$

\# of screws needed = $\dfrac{1}{FS_s} = .00716$

Max mean stress: $\sigma_m^* = \sqrt{\sigma_m^2 + 3 \cdot \sigma_{ms}^2} = 585.67 \text{ psi}$

$$FS_{mean} = \dfrac{S_y}{\sigma_m^*} = 204.89$$

\# of Screws = $\dfrac{1}{FS_m} = .00488$

Max Alt Stress: $\sigma_a^* = \sqrt{(\sigma_a^2 + 3\,\sigma_{as}^2)} = 333.33 \text{ psi}$

$$FS_a = \dfrac{S_e}{\sigma_a^*} = 38.12$$

\# of Screws = .02623

- All this construted on a spread sheet
  attahed

Deflection of Guide Rod 2-27-92
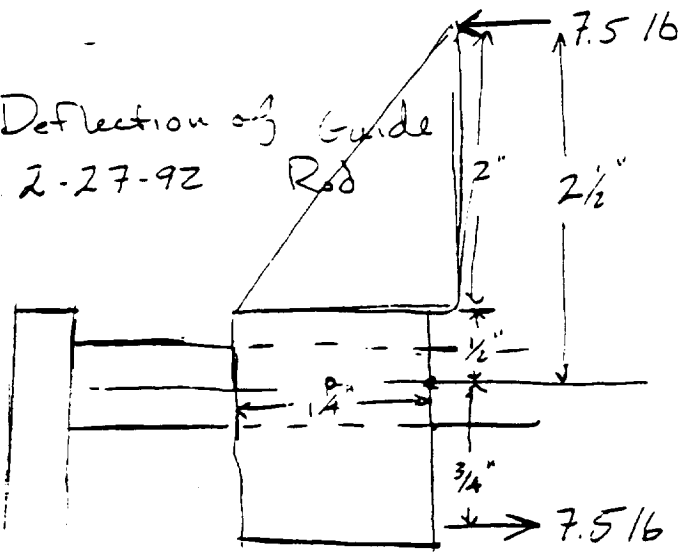
$7.5 \cdot 2.5 + 7.5 \cdot .75 = ? \cdot 1.25$

$? = \dfrac{7.5 \cdot 2.5 + 7.5 \cdot .75}{1.25}$

moment $= 7.5 \cdot 2.5 + 7.5 \cdot .75$

moment $= 24.375$ in lb

$? = 19.5$ lb
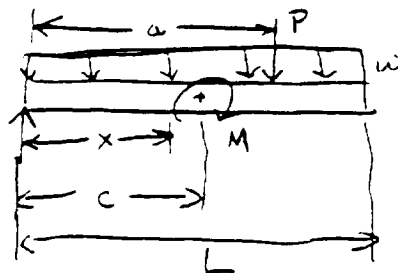
$I = \dfrac{\pi r^4}{4}$

equation from HDtbk eq cond.

$$y = \frac{P(L-a)\,x}{6LEI} \cdot \left(x^2 + (L-a)^2 - L^2\right) - \frac{Mx}{EI}\left(\frac{x^2}{6L} - \frac{L}{3} - \frac{c^2}{2L}\right)$$

$$- \frac{\omega x}{24 EI} \cdot \left(L^3 + x^2(x-2L)\right)$$

$$I = \frac{\pi (.25)^4}{4} = 3.068 \cdot 10^{-3}$$

$a = 2 \qquad P = 2\,lb \qquad x = 2 \qquad c = 2 \quad L = 4 \qquad M = 24.375$

$$y = \frac{2(4-2)\,2}{6 \cdot 4 \cdot (10.3 \cdot 10^6)(3.068 \cdot 10^{-3})}(4 + 4 - 16) - \frac{24.375 \cdot 2}{(10.3 \cdot 10^6)(3.068 \cdot 10^{-3})}\left(\frac{4}{6 \cdot 4}\right) \cdot$$

$$\left(2 - \frac{4}{6 \cdot 4} - \frac{4}{3} - \frac{4}{24}\right) =$$

$y = -8.4387 \cdot 10^5 \, z$ inches   deflection for 1 roe

$$y = -\frac{8.4378 \cdot 10^5}{2} z$$

Screws for End caps
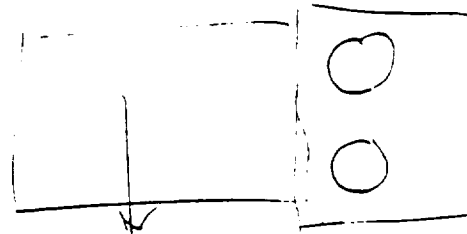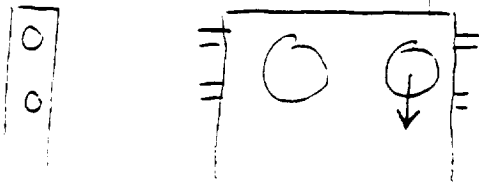
24.375 lbs in lb   moment @ 1"

⇒ 24.375 lb + 2 lb weight = 26.375 lb
                                                    max

$\cancel{\text{FS}}$ for afatigue

6-32 screws

$P_{ase} = 13.875 = P_{as}$
$13.875 = P_{ms}$
$1 = P_a$
$1 = P_m$

→ Spread sheet

for 6-32 screws → use 36 drill → .1065" ∅
                                  37   "   → .1040 ∅
take nomenal d to be .1040"

$$A_t = \frac{\pi \cdot .1040^2}{4} = .008495"$$

Screws needed = .027 , .22265

Calculations for minimum thickness
and weight of gripper components.

--- parameters:

Gripping Force = 20 lbf $\theta = 0.001745$ rad

Maximum angle of deflection $\theta = 0.1°$

(for a 2 in length, $\delta = 0.0035$ in)

Gripper

$F = 20$ lbf

$q = 10$ lbf/in

cross section
width (h)
inches
(b)
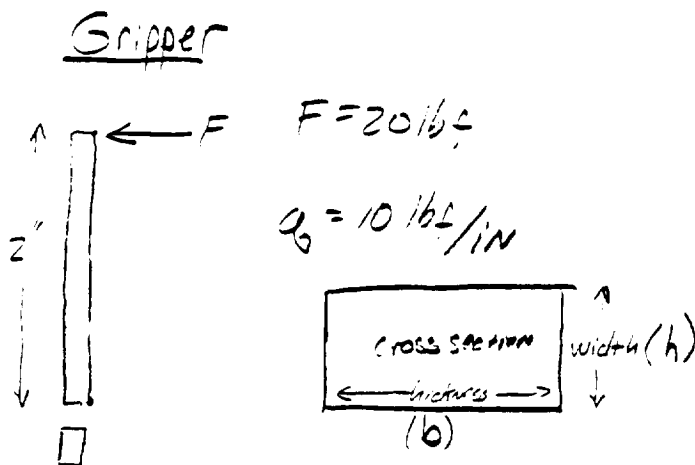
$$\delta = \frac{FL^2}{2EI} = \frac{(20\ lbf/in)(2\ in)^2}{2EI}$$

$$\theta = \frac{10\ lbf/in\ (2\ in)^2/2}{2(E)\ b^3\ (1.1\ in)}$$

$$\boxed{b = \sqrt[3]{\frac{125033}{E}}}$$

Aluminum

$b_{Alum} = 0.230$ in

$\forall = 0.506$ in³

Weight = 0.0496 lb each gripper

$E_{steel} = 30 \times 10^6$ psi

$E_{Alum} = 10.3 \times 10^6$ psi

Unit weights

$W_{steel} = 0.282\ lb/in^3$

$W_{Alum} = 0.073\ lb/in^3$

For a 1.1 inch width
(allowing for 2 racks & pinion)

$$I = \frac{b^3 h}{12} = \frac{b^3 (1.1)}{12}$$

Steel

$b_{steel} = 0.161$ in

$\forall = (2\ in)(0.161\ in)(1.1)$

$\forall = 0.3542$ in³

Weight $W = 0.0999$ lb for each gripper

Linear Guide Shaft Material Analysis

Assume circular cross section
Find Diameter
So that $\theta = 0.1°$

$$\theta = \frac{ML}{24EI}$$

$$I = \frac{ML}{24E\theta}$$

$$\frac{\pi D^4}{64} = \frac{(80)(8)}{24(0.001745)E}$$

$$D = \sqrt[4]{\frac{(80)(8)(64)}{24(.001745)\pi E}}$$

$$\boxed{D = \sqrt[4]{\frac{311317.4}{E}}}$$

$M_{max} = 80 \, lb (2in)(2)$
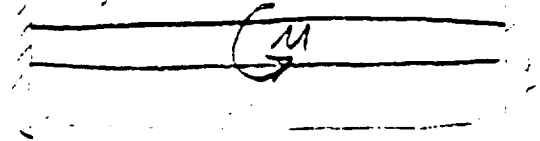
$M_{max} = 80 \, lb \cdot in$

$$I = \frac{\pi D^4}{64}$$

$E_{steel} = 30 \times 10^6$

$E_{Aluminum} = 10.3 \times 10^6$

$W_{steel} = 0.282 \, lb/in^3$

$W_{Al} = 0.098 \, lb/in^3$

Aluminum

$D = 0.417 \, in$

$\forall = \frac{\pi (0.417)^2}{4}(8")$

$\forall = 1.093 \, in^3$

$W_t = 0.107 \, lb$

Steel

$D = 0.319 \, in$

$\forall = \frac{\pi (.319)^2}{4}(8")$

$\forall = 0.640 \, in^3$

$W_t = 0.180 \, lb$

APPENDIX E

Calculations For Rack and Pinion Gears
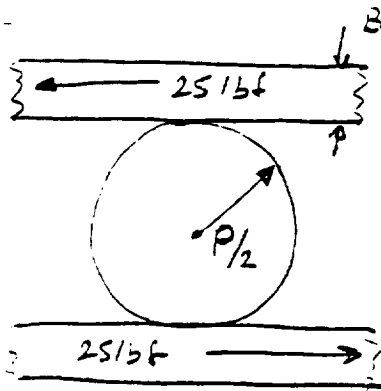
Rack & Pinion Gear Set.

Assumptions:

The rack and Pinion will not experience any gripping force until the instant that the jaws encounter an object. From the instant the jaws encounter the object to the instant 25 lbf gripping force is applied is a very short time $dt \approx 0$ so

$$\bar{V} = a \, dt^{\,0}$$

$$\bar{V} \approx 0$$

Gripper force = 25 lbf

To calculate the stress on one tooth of the rack and pinion. Use the *Lewis* Formula.

Lewis Formula
$$\sigma = \frac{WP}{FY}\left(\frac{600+V}{600}\right)$$

σ = Safe Material Stress

W = Tooth Load

F = Face width

Y = Tooth form factor

V = Pitch line Velocity

P = Diametral Pitch

N = # of Teeth

P = Pitch Diameter

B = Thickness

Pinion Calculations

$P = 24$ $F = \frac{1}{4}''$ $N = 12$ $P = 0.5''$ $v = 25$

$$\sigma = \frac{(25)(24)}{(\frac{1}{4})(0.210)} = \underline{11.4\ ksi}$$

Stress for Steel = 20.0 ksi

Rack Calculation

$P = 24$ $F = \frac{1}{4}$ $B = .208$ $W = 25\,lbf$

$$\sigma = \frac{(25)(24)}{(\frac{1}{4})(.390)} = \underline{6.15\ ksi}$$

Stress for Brass = 10.0 ksi

APPENDIX E

Rack and Pinion Solenoid
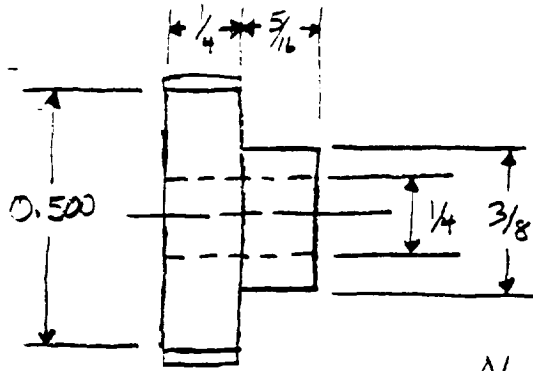
Boston Gear
Catalog Number H2412
Item Code   09596

Number of Teeth = 12
Standard Keyway
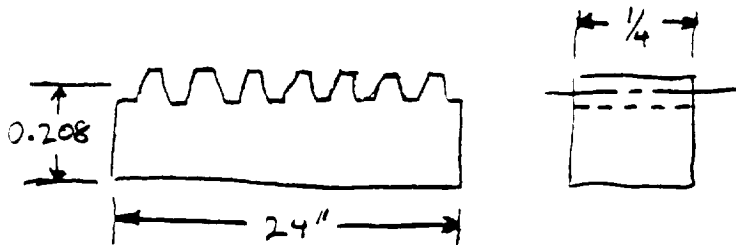
Boston Gear
Catalog Number G579-2
Item Code   12716

RACK

48 THROUGH 3 DIAMETRAL PITCH
NYLON, BRASS AND STEEL

14½° PRESSURE ANGLE
(Will not operate with 20° spurs)

ALL DIMENSIONS IN INCHES
ORDER BY CATALOG NUMBER OR ITEM CODE

Overall Thickness	Pitch Line to Back (B)	Nominal Length (Feet)	Mating Spur Gear Page No.	NYLON Catalog Number	NYLON Item Code	BRASS Catalog Number	BRASS Item Code	STEEL Catalog Number	STEEL Item Code
48	**DIAMETRAL PITCH**							**FACE WIDTH=1/8"**	
1/8	.104	1 / 2	6	GP586-1 / —	53899 / —	— / G586-2	— / 12724	— / L501-2	— / 12726
32	**DIAMETRAL PITCH**							**FACE WIDTH=3/16"**	
3/16	156	1 / 2 / 4	6,7	GP583-1 / — / —	53900 / — / —	— / G583-2 / G583-4	— / 12720 / 12722	— / L503-2 / L503-4	— / 12728 / 12730
24	**DIAMETRAL PITCH**							**FACE WIDTH=1/4"**	
1/4	208	1 / 2 / 4	7,8	GP579-1 / — / —	53901 / — / —	— / G579-2 / G579-4	— / 12716 / 12718	— / L505-2 / L505-4	— / 12732 / 12734
20	**DIAMETRAL PITCH**							**FACE WIDTH=3/8"**	
3/8	.325	2 / 4 / 6	8,9	— / — / —	— / — / —	— / — / —	— / — / —	L509-2 / L509-4 / L509-6	12736 / 12738 / 12740
16	**DIAMETRAL PITCH**							**FACE WIDTH=5/16" ***	
5/16	250	2 / 4	9,10	— / —	— / —	G576-2 / G576-4	12712 / 12714	L510-2 / L510-4	12742 / 12744
1/2	.438	4 / 6		— / —	— / —	— / —	— / —	L512-4 / L512-6	12746 / 12748
12	**DIAMETRAL PITCH**							**FACE WIDTH=3/4"**	
1/2	.417	4 / 6	10,11	— / —	— / —	— / —	— / —	L514-4 / L514-6	12750 / 12752
3/4	667	4 / 6		— / —	— / —	— / —	— / —	L515-4 / L515-6	12754 / 12756
10	**DIAMETRAL PITCH**							**FACE WIDTH=1"**	
5/8	525	4 / 6	11,12	— / —	— / —	— / —	— / —	L516-4 / L516-6	37324 / 37326
1	900	4 / 6		— / —	— / —	— / —	— / —	L517-4 / L517-6	37328 / 37330
8	**DIAMETRAL PITCH**							**FACE WIDTH=1-1/4"**	
3/4	625	4 / 6	12,13	— / —	— / —	— / —	— / —	L518-4 / L518-6	37332 / 37334
1-1/4	1 125	4 / 6		— / —	— / —	— / —	— / —	L519-4 / L519-6	37336 / 37338
6	**DIAMETRAL PITCH**							**FACE WIDTH=1-1/2"**	
1	833	4 / 6	13,14	— / —	— / —	— / —	— / —	L520-4 / L520-6	37340 / 37342
1-1/2	1.333	4 / 6		— / —	— / —	— / —	— / —	L521-4 / L521-6	37344 / 37346
5	**DIAMETRAL PITCH**							**FACE WIDTH=1-3/4"**	
1-1/4	1.050	4 / 6	14	— / —	— / —	— / —	— / —	L522-4 / L522-6	37348 / 37350
4	**DIAMETRAL PITCH**							**FACE WIDTH=2"**	
1-1/2	1 250	4 / 6	15	— / —	— / —	— / —	— / —	L523-4 / L523-6	37352 / 37354
3	**DIAMETRAL PITCH**							**FACE WIDTH=3"**	
1-1/2	1.167	4 / 6	15	— / —	— / —	— / —	— / —	L524-4 / L524-6	37356 / 37358

* Face Width of L512-4 and L512-6 = 1/2"

PITCH LINE TO BACK (B)

WIDTH

LENGTH

OVERALL THICKNESS

STANDARD TOLERANCES‡

DIMENSION		TOLERANCE
LENGTH,+	All	+ 1.000 - .000
FACE WIDTH	1/8 - 3/4	+ .000 - .002
	7/8 - 1-1/2	+ .000 - .003
	1-3/4 - 2	+ .000 - .004
	3	+ .000 - .006

†Ends not machined. Tolerance allows for cutting and matching. Nylon Rack is molded in proper lengths to permit end to end butting without interruption of tooth spacing.

‡Brass and steel only.

REFERENCE PAGES

BOSTON GEAR

SPUR GEARS

ALL DIMENSIONS IN INCHES
ORDER BY CATALOG NUMBER OR ITEM CODE

No. of Teeth	Pitch Dia.	Bore	Hub Dia.	Hub Proj.	Style See Page 150	Without Hub Catalog Number	Without Hub Item Code	With Hub & Setscrew† Catalog Number	With Hub & Setscrew† Item Code

24 DIAMETRAL PITCH

FACE = 1/4"
OUTSIDE DIA. = PITCH DIA. + .083"
OVERALL LENGTH = 1/4" + HUB PROJ.

STEEL

No. of Teeth	Pitch Dia.	Bore	Hub Dia.	Hub Proj.	Style	Without Hub Cat. No.	Item Code	With Hub Cat. No.	Item Code
12	.500	1/4	–	–		S2412	09630		
15	.625	1/4	–	–		S2415	09632		
16	.667	5/16	–	–		S2416	09634		
18	.750	5/16	–	–		S2418	09636		
21	.875	3/8	–	–		S2421	09638		
24	1.000		–	–		S2424	09640		
30	1.250		–	–		S2430	09642		
36	1.500		–	–		S2436	09644		
42	1.750	1/2	–	–		S2442	09646		
48	2.000		–	–		S2448	09648		
60	2.500		–	–		S2460	09650		
72	3.000		–	–		S2472	09652		
12	.500	1/4	3/8	5/16	A	–	–	H2412	09596
14	.583	1/4	15/32	5/16		–	–	H2414	09598
15	.625	1/4	1/2			–	–	H2415	09600
16	.667	5/16	35/64	5/16		–	–	H2416	09602
18	.750	5/16	5/8	5/16		–	–	H2418	09604
20	.833	5/16	23/32			–	–	H2420	09606
21	.875		3/4	5/16		–	–	H2421	09608
24	1.000		7/8			–	–	H2424	09610
30	1.250		1			–	–	H2430	09612
36	1.500	3/8	1-1/8	3/8		–	–	H2436	09614
42	1.750		1-1/8			–	–	H2442	09616
48	2.000		1-1/4			–	–	H2448	09618
60	2.500		1-1/4			–	–	H2460	09620
72	3.000		1-3/8			–	–	H2472	09622
96	4.000	1/2	2	1/2		–	–	H2496	09624
120	5.000		2-1/4			–	–	H24120	09626
144	6.000		2-1/4			–	–	H24144	09628

20 DIAMETRAL PITCH

FACE = 3/8"
OUTSIDE DIA. = PITCH DIA. + .100"
OVERALL LENGTH = 3/8" + HUB PROJ.

STEEL

No. of Teeth	Pitch Dia.	Bore	Hub Proj.	Style	Without Hub Cat. No.	Item Code	With Hub Cat. No.	Item Code
12	600*	5/16	29/64	3/8	NA11B	09662	NA11B-5/16	46000
12	600	5/16	29/64	3/8	NA12B	09664	NA12B-5/16	46001
13	650	5/16	1/2	3/8	NA13B	09666	NA13B-5/16	46002
14	700	5/16	35/64	3/8	NA14B	09668	NA14B-5/16	46003
15	750	3/8	19/32	3/8	NA15B	09670	NA15B-3/8	46004
16	800	3/8	41/64	3/8	NA16B	09672	NA16B-3/8	46005
18	900	3/8	47/64	3/8	NA18B	09674	NA18B-3/8	46006
20	1 000	3/8, 1/2	27/32	3/8	NA20B	09676	NA20B-3/8	46007
20	1 000				–	–	NA20B-1/2	46008
22	1 100	3/8, 1/2	53/64	3/8	NA22B	09678	NA22B-3/8	46009
22	1 100				–	–	NA22B-1/2	46010
24	1 200	3/8, 1/2	59/64	3/8	NA24	09680	NA24-3/8	46011
24	1 200				–	–	NA24-1/2	46012
25	1 250	3/8, 1/2	31/32	3/8	NA25B	09682	NA25B-3/8	46013
25	1 250				–	–	NA25B-1/2	46014
28	1 400	3/8, 1/2	1-7/64	3/8	NA28B	09684	NA28B-3/8	46015
28	1 400				–	–	NA28B-1/2	46016
30	1 500	3/8, 1/2	1-7/32	3/8	NA30B	09686	NA30B-3/8	46017
30	1 500				–	–	NA30B-1/2	46018
32	1 600	3/8, 1/2	1-5/16	1/2	NA32	09688	NA32-3/8	46019
32	1 600				–	–	NA32-1/2	46020
35	1 750	3/8, 1/2	1-29/64	1/2	NA35	09690	NA35-3/8	46021
35	1 750				–	–	NA35-1/2	46022
36	1 800	3/8, 1/2	1-33/64	1/2	NA36	09692	NA36-3/8	46023
36	1 800				–	–	NA36-1/2	46024
40	2 000	3/8, 1/2, 5/8, 3/4	1-23/32	1/2	NA40	09694	NA40-3/8	46025
40	2 000				–	–	NA40-1/2	46026
40	2 000				–	–	NA40-5/8	46027
40	2 000				–	–	NA40-3/4	46028
48	2 400	3/8	1-21/64	1/2	NA48A	10208		
50	2 500	3/8	1-27/64	1/2	NA50A	10210		
60	3 000	3/8	1-59/64	1/2	NA60A	10212		
64	3 200	3/8	2-1/8	1/2	NA64A	10214		

Continued

FACE ▭ HUB PROJ.
KEYWAY
PITCH DIA.
BORE / HUB DIA.
OVERALL LENGTH

STANDARD TOLERANCES

DIMENSION		TOLERANCE
BORE	All	± .0005
HUB DIA.	All	± 1/32

REFERENCE PAGES

Alterations — 149
Horsepower Ratings — 38, 39
Lubrication — 149
Materials — 150
Selection Procedure — 37

*Special Pitch Diameter, used for calculating Center Distance only, not Ratio.

†H2412 & H2414 have #35 (.110) drilled hole through one wall.
No keyway.
H2415 has one setscrew, no keyway.

NA-5/16" bore has #35 (.110) drilled hole through one wall.

NA-3/8" and 1/2" bores have one setscrew. No keyway.

NA-5/8" & 3/4" bores have standard keyway at 90° to setscrew. See Page 150.

Screw Stress Spreadsheet Data

Using 10-32 Screws   Jaw Mount

Nominal Diameter	Total Plate Thick	Mean Shear Stress	
0.19	0.125	187.5	
Tensile Stress A	Cap Height	Alt Shear Stress	
0.02	0.19	187.5	
Mean load	Cap Diameter		
5.625	0.305		
Alternating Load	Mean Shear Load	Max Static Stress	Desired FS=1.0
5.625	3.75	859.2329428	
Yield Strength	Alt Shear Load	FS Static	Screws Needed
120000	3.75	139.6594498	0.007160275
Ultimate Strength	Spring Bolt Kb	Max Mean Stress	
150000	6809906.616	585.6691945	
Modulus Aluminum	Spring Plate Km	FS Mean	Screws Needed
10298000	18686585.17	204.8938225	0.004880577
Modulus Steel	Spring Term	Max Alt Stress	
30023000	0.267091907	333.3342229	
Surface Factor ka	Se'	FS Alternating	Screws Needed
0.675	75000	38.12052327	0.026232588
Size Factor kb	Se		
1	12706.875		
Temp Factor kd			
1			
Reliability kc	Preload Fi		
0.753	8.245216045		
Thread Coeff	Alternating Stress		
3	75.11959887		
Stress Conc Ke	Mean Stress		
0.333333333	487.3804011		

Using 10-32 Screws

Nominal Diameter	Total Plate Thick	Mean Shear Stress	
0.19	0.125	200	
Tensile Stress A	Cap Height	Alt Shear Stress	
0.02	0.19	200	
Mean load	Cap Diameter		
4	0.305		
Alternating Load	Mean Shear Load	Max Static Stress	Desired FS=1.0
4	4	800	
Yield Strength	Alt Shear Load	FS Static	Screws Needed
120000	4	150	0.006666667
Ultimate Strength	Spring Bolt Kb	Max Mean Stress	
150000	6809906.616	490.019202	
Modulus Aluminum	Spring Plate Km	FS Mean	Screws Needed
10298000	18686585.17	244.8883626	0.004083493
Modulus Steel	Spring Term	Max Alt Stress	
30023000	0.267091907	350.5046697	
Surface Factor ka	Se'	FS Alternating	Screws Needed
0.675	75000	36.25308334	0.027583861
Size Factor kb	Se		
1	12706.875		
Temp Factor kd			
1			
Reliability kc	Preload Fi		
0.753	5.863264743		
Thread Coeff	Alternating Stress		
3	53.41838142		
Stress Conc Ke	Mean Stress		
0.333333333	346.5816186		

Using 6-32 Screws

End Cap Screws

Nominal Diameter	Total Plate Thick	Mean Shear Stress	
0.104	0.125	1633.313714	
Tensile Stress A	Cap Height	Alt Shear Stress	
0.008495		1633.313714	
Mean load	Cap Diameter		
1			
Alternating Load	Mean Shear Load	Max Static Stress	Desired FS=1.0
1	13.875	5662.860829	
Yield Strength	Alt Shear Load	FS Static	Screws Needed
120000	13.875	21.19070265	0.047190507
Ultimate Strength	Spring Bolt Kb	Max Mean Stress	
150000	2040331.024	2836.327487	
Modulus Aluminum	Spring Plate Km	FS Mean	Screws Needed
10298000	5598728.677	42.30823153	0.023636062
Modulus Steel	Spring Term	Max Alt Stress	
30023000	0.267091907	2829.157049	
Surface Factor ka	Se'	FS Alternating	Screws Needed
0.675	75000	4.491399658	0.222647744
Size Factor kb	Se		
1	12706.875		
Temp Factor kd			
1			
Reliability kc	Preload Fi		
0.753	1.465816186		
Thread Coeff	Alternating Stress		
3	31.44107205		
Stress Conc Ke	Mean Stress		
0.333333333	203.9915354		

	A	B	C	D
1		Using 6-32 Screws		End Cap Screws
2				
3	Nominal Diameter	Total Plate Thick	Mean Shear Stress	
4	0.104	0.125	=B10/A6	
5	Tensile Stress A	Cap Height	Alt Shear Stress	
6	0.008495		=B12/A6	
7	Mean load	Cap Diameter		
8	1			
9	Alternating Load	Mean Shear Load	Max Static Stress	Desired FS=1.0
10	1	13.875	=(B28+B30)^2+3*(C4+C6)^2)^0.5	
11	Yield Strength	Alt Shear Load	FS Static	Screws Needed
12	120000	13.875	=A12/C10	=1/C12
13	Ultimate Strength	Spring Bolt Kb	Max Mean Stress	
14	150000	=P10*(A4^2)*A18/(4*(B4))	=(B30^2+3*C4^2)^0.5	
15	Modulus Aluminum	Spring Plate Km	FS Mean	Screws Needed
16	10298000	=P10^2*(A4^2)*A16/(B4)	=A12/C14	=1/C16
17	Modulus Steel	Spring Term	Max Alt Stress	
18	30023000	=B14/(B14+B16)	=(B28^2+3*C6^2)^0.5	
19	Surface Factor ka	Se'	FS Alternating	Screws Needed
20	0.675	=A14^0.5	=B22/C18	=1/C20
21	Size Factor kb	Se		
22	1	=B20*A20*A22*A24*A26*A30		
23	Temp Factor kd			
24	1			
25	Reliability kc	Preload Fi		
26	0.753	=B16*(A8+A10)/(B14+B16)		
27	Thread Coeff	Alternating Stress		
28	3	=B18*(A8+A10)/(2*A6)		
29	Stress Conc Ke	Mean Stress		
30	=1/A28	=B18*(A8+A10)/(2*A6)+B26/A6		

APPENDIX F
ENCODERS

F1 Gripper Calculations (encoder)

— For the gripper
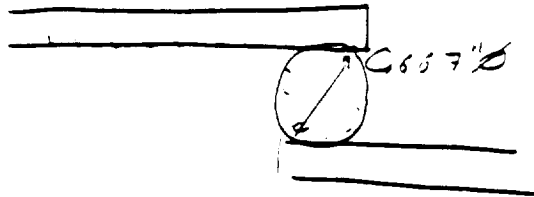
Perimeter of pinion = 0.657 · ~ = 2.095"/rev

motor makes 750 rev per pinion rev

encoder specs 10 cpr × 4 (quad) = 40 cpr

Resolution = 0.000 069833 "/count

Encoder Calculations

2. Elbow Joint: Micro Mo" 036
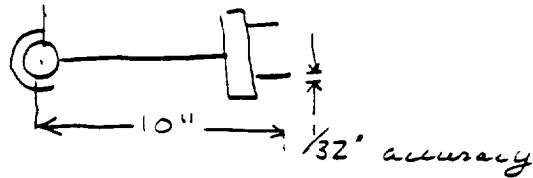
$$\tan \theta = \frac{.03125}{10} \qquad \theta = \tan^{-1} \frac{.03125}{10}$$

$$\theta = .179049° = \text{max °/count}$$

$$360°/\text{rev} \cdot \frac{1 \text{ rev}}{258 \text{ rev motor}} = 1.3432836°/\text{rev motor}$$

Using Again A "Micro Mo" 036

• 15 ^{c}/rev · 4 = 60

○ $\frac{1.3432836°}{60} = .02238806°/\text{count}$

=D 036 is Ok (From Micro Mo)

3. Wrist Joint: "Micro-Mo" 10b
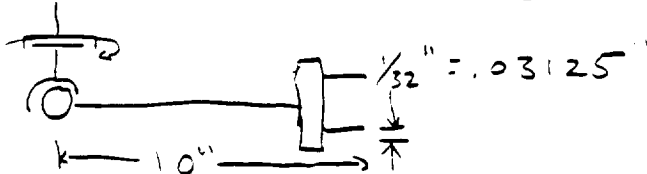
$$\Rightarrow \text{Max °/count} = .179049 \quad \text{(From elbow calculations)}$$

$$360°/\text{rev} \cdot \frac{1 \text{ rev}}{159 \text{ rev motor}} = 2.264151°/\text{rev motor}$$

Using "MicroMo" 036 =D

15 counts/rev · 4 = 60
(quad)

$$\frac{2.264151°}{60} = .03773585 °/\text{count}$$

Therefore a "Micro Mo" 036 is specified for all three motors

C-4

MicroMo® MAGNETIC ENCODERS

Magnetic Encoder Series HE

- Square Wave Output.
- TTL/CMOS Compatible.
- 10, 12, 15, or 16 PPR Standard (other Resolutions Available on Request).
- Available as an Integral Package with 13, 15, 16, 22, 23, 28, and 35mm Motor Series.
- 2 Channels, 90° Phase Shift.
- Also Available as a Free-Standing Unit with Precision Metal Housing.
- Weighs Less Than 1 oz.

General Specifications:

Nominal Power Requirement:	5mA Nominal @5VDC @22°C
Maximum Operating Voltage:	15.0 VDC
Signal Phase Shift and Tolerance:	90° ± 45° (2 Phase Signal)
Maximum Signal Frequency:	7.2K Hz
Operating Temperature Range:	-20°C to 85°C
Storage Temperature Range:	-40°C to 110°C
Connection:	Standard 6 Conductor 28 ga. Ribbon Cable With 10 Pin Ribbon Cable Connector
Maximum Asymmetry:	10%
Signal Rise Time:	Less than 5µS
Phase Relationship:	Channel A leads Channel B when using 15PPR Wheel (odd number). Channel B leads Channel A when using 10, 12, and 16PPR Wheel (even number).
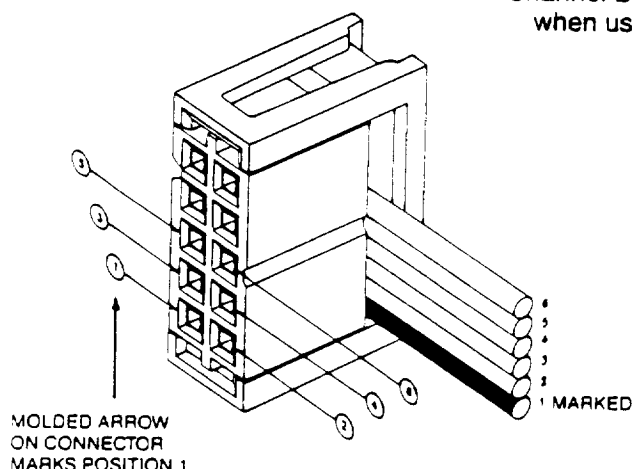
HEM STANDARD CONNECTION 6 (SIX) CIRCUITS

1	MARKED MOTOR +
2	+VDC 15.0 MAXIMUM (5mA @5VDC)
3	CHANNEL A OUTPUT
4	CHANNEL B OUTPUT
5	-VDC GROUND
6	MOTOR -

MOLDED ARROW
ON CONNECTOR
MARKS POSITION 1

Ordering Information:

```
        HE   M   1516        15
```

Configuration
  M = Integral With Motor
  F = Free Standing
Motor Designation
(Omit for F Configuration)
Pinion or Shaft
on Motor Designation

Additional Cable Length
Options (in.) Available
Upon Request

Resolution
  10 = 10PPR
  12 = 12PPR
  15 = 15PPR
  16 = 16PPR
Other Resolutions Available
On Request
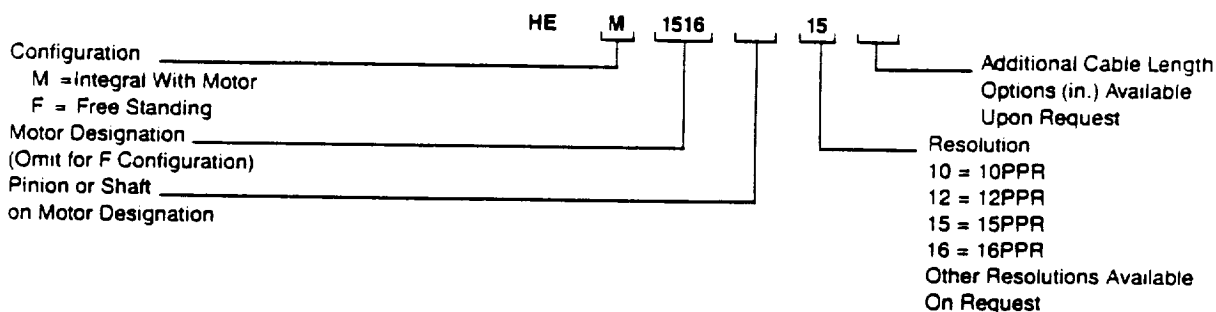
MAGNETIC ENCODERS

MicroMo® MAGNETIC ENCODERS

Magnetic Micro Encoder Series HE

- Square Wave Output
- Logic Compatible
- 10 Pulse Per Revolution Standard
- Available as an Integral Package with 10 and 12 mm Motor Series
- 2 Channels, 90° Phase Shift

HEM 10 . . . Actual Size
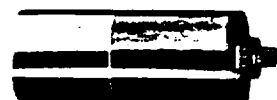
HEM 12 . . . Actual Size

General Specifications:

Nominal Power Requirement	5mA Nominal @ 5 VDC @ 22°C
Maximum Operating Voltage	15.0 VDC
Signal Phase Shift and Tolerance	90° ± 45° (2 phase signal)
Maximum Signal Frequency	7.2 K Hz
Operating Temperature Range	−20° C to 85° C
Storage Temperature Range	−40° C to 110° C
Connection	Standard 6 conductor 28 ga. ribbon cable with 10 pin ribbon cable connector
Maximum Asymmetry	10%
Signal Rise Time	Less than 5μS

PHASE RELATIONSHIP

Channel A leads Channel B when motor rotation is clockwise as seen from shaft end.

HEM STANDARD CONNECTION 6 (SIX) CIRCUITS

1 MARKED MOTOR +
2 + VDC 15.0 MAXIMUM (5mA @ 5 VDC)
3 CHANNEL A OUTPUT
4 CHANNEL B OUTPUT
5 −VDC GROUND
6 MOTOR −

MOLDED ARROW ON CONNECTOR MARKS POSITION 1

Ordering Information

HE M 1212 ___ 10 ___

Configuration
 M = Integral With Motor
Motor Designation
Pinion or Shaft
on Motor Designation

Additional Cable Length Options (in.) Available Upon Request

Resolution
10 = 10 PPR
Other Resolutions Available On Request

MAGNETIC ENCODERS

— Specifications Subject to Change —
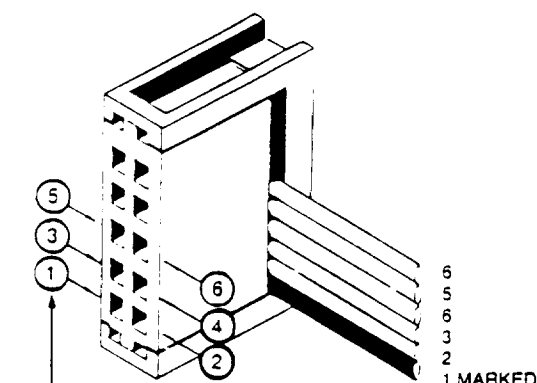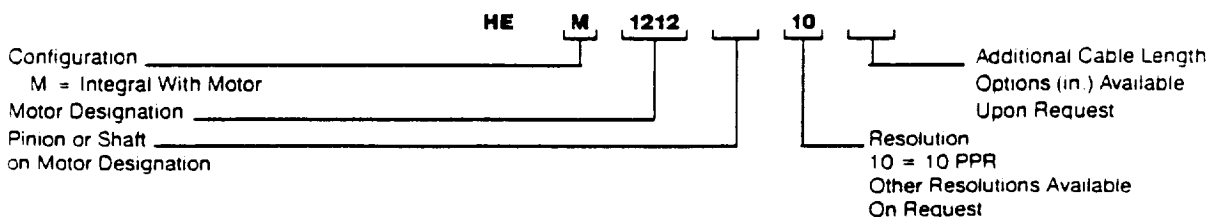
1.2 Features

- FULL SIZED EXPANSION CARD FOR PC/XT/AT AND COMPATIBLES
- CLOSED LOOP HIGH PERFORMANCE POSITION AND VELOCITY CONTROL OF DC BRUSH, DC BRUSH-LESS, AND STEP MOTORS
- PROGRAMMABLE DIGITAL COMPENSATION FILTER AND SAMPLE TIMER
- PROGRAMMABLE POSITION AND VELOCITY PROFILE CONTROL WITH VELOCITY AND ACCELERATION LIMITS
- 24 BIT POSITION COUNTER
- ENCODER FEEDBACK SELECTABLE FOR SINGLE OR DIFFERENTIAL INPUTS
- 20 KHz PWM OUTPUT, PULSE AND SIGN
- MOTOR COMMUTATOR FOR DC BRUSHLESS OR STEP MOTORS, WITH PROGRAMMABLE PHASE OVER-LAP AND PHASE ADVANCE
- 4 DIGITAL OUTPUT BITS
- 4 DIGITAL INPUT BITS
- HIGH SPEED INTERFACE TO PC USES ONLY 3 REGISTERS IN PC I/O SPACE
- REGISTER WRITE TIME 1 MICROSECOND
- REGISTER READ TIME 2.1 MICROSECOND
- DEMONSTRATION SOFTWARE PROVIDED IN C, BASIC, AND TURBO PASCAL LANGUAGES

1.3 Specifications

1.3.1 Performance Specifications

Position Range

24 bits (16,777,216 [quadrature counts])

Velocity Range

$31 - 32*10^6$ [quadrature counts/sec]

Acceleration Range

$2 - 2000$ [quadrature counts/sec^2]

Loop Sample Time

64 - 2048 [microseconds]

Maximum Encoder Frequency

312.5 [kHz]

PWM Modulation Frequency

20 kHZ

1.3.2 Electrical Specifications

ELECTRICAL SPECIFICATIONS

PARAMETER	SYM	MIN	TYP	MAX	UNIT	COMMENT
POWER SUPPLY REQ.						
+5 V Current	Icc		1.2	3	A	
+12 V Current	Icc		100	250	mA	
-12 v Current	Icc		100	250	mA	
DAC MOTOR CMD OUTPUT						
source Current	Ioh		10	20	mA	
sink Current	Iol		5	8	mA	
max Voltage (FFH)				+10	V	User Adjustable
min Voltage (00H)		-10			V	User Adjustable
COMMUTATOR OUTPUTS PHA,PHB,PHC,PHD AND PWM OUTPUTS PULSE, SIGN AND TTL LEVEL DIGITAL OUTPUTS						
output V high	Voh	2.4	3.4		V	at Ioh = -3mA
output V low	Vol		.25	.4	V	at Iol = 12mA
output I high	Ioh			-15	mA	
output I low	Iol			24	mA	
PWM modulation freq.			20		kHz	
DIGITAL OUTPUTS, OPTO-COUPLED						
collector current Icc				30	mA	
breakdown V	BVceo	30	85		V	at Ic = 1.0mA
breakdown V	BVeco	6	13		V	at Ie = 100 micro A
DIGITAL INPUTS TTL LEVEL						
high input V	Vih	2			V	
low Input V	Vil			+0.8	V	
High Input I	Iih			20	micro A	
low Input I	Iil			-0.2	mA	
DIGITAL INPUTS OPTO-COUPLED						
diode fwd I	If		20	60	mA	270 ohm on board
diode rev V	Vr			3	V	
diode fwd V	Vf		1.25	1.50	V	at If = 20 mA
ENCODER INPUTS SINGLE ENDED INPUT MODE						
input low V	Vil			+0.8	V	
input high V	Vih	2.4			V	
ENCODER INPUTS DIFFERENTIAL INPUT MODE					RS-422/3	
input cmn mode V			+-7	+-25	V	
input diff mode V			+-6	+-25	V	

APPENDIX G
PROGRAM

```pascal
{**********************************************}
{                                }
{     Controller program for          }
{                                }
{     Autonomous Space Processor For Orbital    }
{     Debris ( ASPOD ) End Effector          }
{                                }
{**********************************************}

program Effector;

{$M 8192,8192,655360}
{$X+,S-}

uses Dos, Objects, Drivers, Memory, Views, Menus, Dialogs,
  StdDlg, MsgBox, App, Calc, Buffers, Editors;

const
  HeapSize = 32 * (1024 div 16);

const
  MaxLines        = 100;
  WinCount: Integer =   0;
  BaBase:integer   = 768;              { Base Addresses for the six axis }
  ShBase: integer  = 769;
  ElBase: integer  = 770;
  TBase:integer    = 776;
  BBase: integer   = 777;
  GBase: integer   = 778;
  cmOpen          = 100;
  cmNew           = 101;
  cmChangeDir      = 102;
  cmDosShell       = 103;
  cmCalculator     = 104;
  cmShowClip       = 105;
  cmFileOpen       = 200;  { Begin Command List}
  cmNewWin          = 201;   { New Window }
  cmGrip          = 202;   { Yet unassigned for dialog box }
  cmCurGrip        = 203;   { Current Position - Gripper }
  cmDeltGrip       = 204;   { Final Position Setting - Gripper }
  cmGoGrip         = 205;   { Execute Trapazoidal Profile Move }
  cmWhatGrip        = 106;   { Get Final Position Setting for gripper }
  cmGripBox        = 107;   { Create Dialog Box - Dummie }
  cmDefaultset     = 108;   { Reset all values to Default }
  cmWhatTwist       = 109;   { SAA For twisting Joint }
  cmCurTwist        = 110;
```

```
cmDeltTwist      = 111;
cmGoTwist        = 112;
cmCurBend        = 113;    { SAA For Bending joint }
cmDeltBend       = 114;
cmGoBend         = 115;
cmWhatBend       = 116;
cmCurBase        = 117;    { SAA For Base }
cmDeltBase       = 118;
cmGoBase         = 119;
cmCurShould      = 120;    { SAA For Shoulder }
cmDeltShould     = 121;
cmGoShould       = 122;
cmCurElbow       = 123;    { SAA For Elbow }
cmDeltElbow      = 124;
cmGoElbow        = 125;
cmBaGainSet      = 128;    { Gain set for all six joints - Ba = Base }
cmShGainSet      = 129;    { Sh = Shoulder }
cmElGainset      = 130;    { El = Elbow }
cmTGainSet       = 131;    { T = Twist }
cmBGainSet       = 132;    { B = Bend }
cmGGainSet       = 133;    { G = Grip }
cmBaZeroSet      = 134;    { Zero set for all six joints }
cmShZeroSet      = 135;
cmElZeroSet      = 136;
cmBZeroSet       = 137;
cmTZeroSet       = 138;
cmGZeroSet       = 139;
cmBaPoleset      = 140;    { Pole set for all six joints }
cmShPoleset      = 141;
cmElPoleset      = 142;
cmTPoleset       = 143;
cmBPoleset       = 144;
cmGPoleset       = 145;
cmBaTimerSet     = 146;    { Timer set for all six joints }
cmShTimerSet     = 147;
cmElTimerSet     = 148;
cmTTimerSet      = 149;
cmBTimerSet      = 150;
cmGTimerSet      = 151;
cmBaVelSet       = 152;    { Maximum velocity set for all six joints }
cmElVelSet       = 153;
cmShVelSet       = 154;
cmTVelSet        = 155;
cmBVelSet        = 156;
cmGVelSet        = 157;
cmBaAccSet       = 158;    { Acceleration set for all six joints }
```

```
cmShAccSet      = 159;
cmElAccSet      = 160;
cmTAccSet       = 161;
cmBAccSet       = 162;
cmGAccSet       = 163;
cmBaGetValues   = 164;    { Get current values for Gain, zero, pole, velocity and
acceleration. }
cmshGetValues   = 165;
cmElGetValues   = 166;
cmTGetValues    = 167;
cmBGetValues    = 168;
cmGGetValues    = 169;
cmResetCom      = 170;
cmBaPos         = 171;
cmShPos         = 172;
cmElPos         = 173;
cmTPos          = 174;
cmBPos          = 175;
cmGPos          = 176;
cmBaNeg         = 177;
cmShNeg         = 178;
cmElNeg         = 179;
cmTNeg          = 180;
cmBNeg          = 190;
cmGNeg          = 191;
cmWFile         = 192;
cmBaClPos       = 193;
cmShClPOs       = 194;
cmElClPos       = 195;
cmTClPos        = 196;
cmBClPos        = 197;
cmGClPos        = 198;
cmZeroCom       = 199;
cmBaTest        = 90;
cmShTest        = 91;
cmElTest        = 92;
cmTTest         = 93;
cmBTest         = 94;
cmGTest         = 95;
cmDecod         = 96;
cmNumTest       = 97;


var
  WinNum: integer;              { To pass a number to each window }
  Base: integer;                { Holds the base address of the current axis }
```

```pascal
  Values: array[0..10] of string[50];        { For the Current Values listing window }
  Com: array[0..9] of string[20];            { Array for command sets }
  Arg: array[0..9] of integer;               { Array for corresponding arguments }
  J10: integer;                              { Ten line counter }
  ClipWindow: PEditWindow;


type
  PASPOD = ^ASPOD;
  ASPOD = object(TApplication)               { Lists objects used in ASPOD-Application }
    constructor Init;
    destructor Done; virtual;
    procedure OutOfMemory; virtual;
    procedure HandleEvent(var Event: TEvent); virtual; { Defines Command actions }
    procedure InitMenuBar; virtual;          { Defines MenuBar and menu items }
    procedure InitStatusLine; virtual;       { Def Status Line }
    procedure ANewWindow(Num2: integer);     { Current Value O/P Win }
    procedure Go(basetmp: integer);          { Execute Trap move }
    procedure Default;                       { Sets all values to default-msg }
    procedure Res;                           { Performs a reset on all axis-msg }
    procedure zero;                          { o/p zero command }
    procedure PosMove(BaseTmp, pow: integer);   { o/p full positive command to Basetmp}
    procedure NegMove(BaseTmp, pow: integer);   { Full Neg Cm to Basetmp }
    procedure TCurrent(BaseTmp: integer);    { Displays current position of BaseTmp }
    procedure final(BaseTmp: integer);       { Sets Final position Of BaseTmp-msg }
    procedure whatfinal(BaseTmp: integer);   { Dispays Final position of BaseTmp }
    procedure SetGain(BaseTmpG: integer);    { Sets Gain }
    procedure SetZero(BaseTmpZ: integer);    { You get the picture }
    procedure SetPole(BaseTmpP: integer);
    procedure SetTimer(BaseTmpT: integer);
    procedure SetVel(BaseTmpV: integer);
    procedure SetAcc(BaseTmpA: integer);
    procedure ClearPos(BaseTmp: integer);
    procedure GetVal(BaseTmpVal: integer);   { Displays current values }
    procedure Test(BaseTmp: integer);        { Tests BaseTmp }
    procedure Decode;
    procedure NTest;
  end;



  SWindow = ^AWindow;                        { Defines Current value window stuff }
  AWindow = object(TWindow)
    constructor Init(Bound: TRect; WinTit: String; WindowN: Word);
  end;


  SInterior = ^AInterior;                    { Interior Def for Cur Value Window }
```

```pascal
AInterior = object(TView)
  constructor Init(var Bound: TRect);
  procedure Draw; virtual;
end;


{ AInterior }
constructor AInterior.Init(var Bound: TRect);    { Current Value O/P Window Stuff }
begin
  TView.Init(Bound);
  GrowMode := gfGrowHiX + gfGrowHiY;
  Options := Options or ofFramed;
end;

procedure AInterior.Draw;
var i: integer;
const
  Greeting: string = 'Hello, World!';
begin
  TView.Draw;
  for i := 0 to 10 do
  WriteStr(4, 2+i, Values[i],$01);
end;

{ AWindow }
constructor AWindow.Init(Bound: TRect; WinTit: String; WindowN: Word);
var
  S: string[3];
  Interior: sInterior;
begin
  Str(WindowN, S);
  TWindow.Init(Bound, WinTit + ' ' + S, wnNoNumber);
  GetClipRect(Bound);
  Bound.Grow(-1,-1);
  Interior := New(SInterior, Init(Bound));
  Insert(Interior);
end;


function IToS (I:Longint): String;   { Convert any integer type into a string }
var
  S: String[11];
Begin
  Str(I,S);
  IToS := S;
end;
```

```
function ExecDialog(P: PDialog; Data: Pointer): Word;
var
  Result: Word;
begin
  Result : = cmCancel;  .
  P := PDialog(Application^.ValidView(P));
  if P < > nil then
  begin
    if Data < > nil then P^.SetData(Data^);
    Result := DeskTop^.ExecView(P);
    if (Result < > cmCancel) and (Data < > nil) then P^.GetData(Data^);
    Dispose(P, Done);
  end;
  ExecDialog := Result;
end;


function CreateFindDialog: PDialog;
var
  D: PDialog;
  Control: PView;
  R: TRect;
begin
  R.Assign(0, 0, 38, 12);
  D := New(PDialog, Init(R, 'Find'));
  with D^ do
  begin
    Options := Options or ofCentered;

    R.Assign(3, 3, 32, 4);
    Control := New(PInputLine, Init(R, 80));
    Insert(Control);
    R.Assign(2, 2, 15, 3);
    Insert(New(PLabel, Init(R, '~T~ext to find', Control)));
    R.Assign(32, 3, 35, 4);
    Insert(New(PHistory, Init(R, PInputLine(Control), 10)));

    R.Assign(3, 5, 35, 7);
    Insert(New(PCheckBoxes, Init(R,
      NewSItem('~C~ase sensitive',
      NewSItem('~W~hole words only', nil)))));

    R.Assign(14, 9, 24, 11);
    Insert(New(PButton, Init(R, 'O~K~', cmOk, bfDefault)));
    Inc(R.A.X, 12); Inc(R.B.X, 12);
    Insert(New(PButton, Init(R, 'Cancel', cmCancel, bfNormal)));
```

```
      SelectNext(False);
    end;
  CreateFindDialog : = D;
end;


function CreateReplaceDialog: PDialog;
var
  D: PDialog;
  Control: PView;
  R: TRect;
begin
  R.Assign(0, 0, 40, 16);
  D : = New(PDialog, Init(R, 'Replace'));
  with D^ do
  begin
    Options : = Options or ofCentered;

    R.Assign(3, 3, 34, 4);
    Control : = New(PInputLine, Init(R, 80));
    Insert(Control);
    R.Assign(2, 2, 15, 3);
    Insert(New(PLabel, Init(R, ' ~ T ~ ext to find', Control)));
    R.Assign(34, 3, 37, 4);
    Insert(New(PHistory, Init(R, PInputLine(Control), 10)));

    R.Assign(3, 6, 34, 7);
    Control : = New(PInputLine, Init(R, 80));
    Insert(Control);
    R.Assign(2, 5, 12, 6);
    Insert(New(PLabel, Init(R, ' ~ N ~ ew text', Control)));
    R.Assign(34, 6, 37, 7);
    Insert(New(PHistory, Init(R, PInputLine(Control), 11)));

    R.Assign(3, 8, 37, 12);
    Insert(New(PCheckBoxes, Init(R,
      NewSItem(' ~ C ~ ase sensitive',
      NewSItem(' ~ W ~ hole words only',
      NewSItem(' ~ P ~ rompt on replace',
      NewSItem(' ~ R ~ eplace all', nil)))))));

    R.Assign(17, 13, 27, 15);
    Insert(New(PButton, Init(R, 'O ~ K ~ ', cmOk, bfDefault)));
    R.Assign(28, 13, 38, 15);
    Insert(New(PButton, Init(R, 'Cancel', cmCancel, bfNormal)));

    SelectNext(False);
```

```
  end;
  CreateReplaceDialog := D;
end;


function DoEditDialog(Dialog: Integer; Info: Pointer): Word; far;
var
  R: TRect;
  T: TPoint;
begin
  case Dialog of
    edOutOfMemory:
      DoEditDialog := MessageBox('Not enough memory for this operation.',
        nil, mfError + mfOkButton);
    edReadError:
      DoEditDialog := MessageBox('Error reading file %s.',
        @Info, mfError + mfOkButton);
    edWriteError:
      DoEditDialog := MessageBox('Error writing file %s.',
        @Info, mfError + mfOkButton);
    edCreateError:
      DoEditDialog := MessageBox('Error creating file %s.',
        @Info, mfError + mfOkButton);
    edSaveModify:
      DoEditDialog := MessageBox('%s has been modified. Save?',
        @Info, mfInformation + mfYesNoCancel);
    edSaveUntitled:
      DoEditDialog := MessageBox('Save untitled file?',
        nil, mfInformation + mfYesNoCancel);
    edSaveAs:
      DoEditDialog := ExecDialog(New(PFileDialog, Init('*.*',
        'Save file as', '~N~ame', fdOkButton, 101)), Info);
    edFind:
      DoEditDialog := ExecDialog(CreateFindDialog, Info);
    edSearchFailed:
      DoEditDialog := MessageBox('Search string not found.',
        nil, mfError + mfOkButton);
    edReplace:
      DoEditDialog := ExecDialog(CreateReplaceDialog, Info);
    edReplacePrompt:
      begin
        { Avoid placing the dialog on the same line as the cursor }
        R.Assign(0, 1, 40, 8);
        R.Move((Desktop^.Size.X - R.B.X) div 2, 0);
        Desktop^.MakeGlobal(R.B, T);
        Inc(T.Y);
        if TPoint(Info).Y <= T.Y then
```

```
        R.Move(0, Desktop^.Size.Y - R.B.Y - 2);
        DoEditDialog := MessageBoxRect(R, 'Replace this occurence?',
          nil, mfYesNoCancel + mfInformation);
      end;
  end;
end;

function OpenEditor(FileName: FNameStr; Visible: Boolean): PEditWindow;
var
  P: PView;
  R: TRect;
begin
  DeskTop^.GetExtent(R);
  P := Application^.ValidView(New(PEditWindow,
    Init(R, FileName, wnNoNumber)));
  if not Visible then P^.Hide;
  DeskTop^.Insert(P);
  OpenEditor := PEditWindow(P);
end;



{*******************************************************}
{                                        }
{   List of procedures from MC 3000        }          }
{                                        }
{*******************************************************}

    procedure set_Base(Num: integer);
    Begin
      Base := Num;
    end;


    procedure regout(reg,val,Basetmp :integer);
    begin
    port[BaseTmp+reg*1024]:=val;
    end;


    function regin(reg,BaseTmp :integer) : integer;
    begin
    regin:=port[BaseTmp+reg*1024];
    end;


    procedure resetP;
    begin
```

```pascal
      regout(5,0,768);
      regout(5,0,769);
      regout(5,0,770);
      regout(5,0,776);
      regout(5,0,777);
      regout(5,0,778);
      end;


      procedure initialize;
      begin
      regout(5,1,Base);
      end;

procedure sel_mode;
begin
  regout (5,3,base);
end;

procedure align;
begin
regout(5,2,Base);
end;

      procedure delay_sec(sec :Shortint);
      var c,c2 :integer;
      begin
      for c: =0 to sec do
         begin
            For c2: =1 to 1000 do
            inc (c2);
         end;
      end;

      procedure trap_mode;
      begin
      regout(0,8,Base);
      end;

procedure pv_mode;
begin
regout(0,0,Base);
regout(0,11,Base);
regout(5,3,Base);
end;

procedure int_mode;
```

```
begin
regout(0,0,Base);
regout(0,3,Base);
regout(0,13,Base);
regout(5,3,Base);
.end;

procedure set_cmd_pos(pos: Longint);
var
low,med,high: Shortint;
begin
low: =lo(round(pos));
med: =hi(round(pos));
high: = hi(round(pos/256));
regout(14,low,Base);
regout(13,med,Base);
regout(12,high,Base);
end;

    procedure clr_act_pos;
    begin
    regout(19,0,Base);
    end;

    procedure set_final_pos(pos: longint);
    var
    low,med,high: Shortint;
    begin
      low: =pos and $000000FF;
      med: =pos shr 8 and $000000FF;
      high: = pos shr 16 and $000000FF;
      regout(41,low,Base);
      regout(42,med,Base);
      regout(43,high,Base);
    end;

function get_cmd_pos:real;
begin
get_cmd_pos: =0;
end;

    function get_act_pos:longint;
    var
      low,med,high: Shortint; retval: longint;
    begin
      high: =regin(20,Base);
```

```pascal
    med: =regin(19,Base);
    low: =regin(18,Base);
    retval: =high*65536+med*256+low;
    if ( retval > 8388607 ) then retval := retval - 16777215;
    get_act_pos := retval;
  end;



function get_final_pos:Longint;
var high, low, med: Shortint; retval: Longint;
begin
  high := regin(43,Base);
  med := regin(42,Base);
  Low := regin(41,Base);
  retval := High*65536+med*256+low;
  get_Final_Pos := retval;
end;

procedure set_gain(gain: Shortint);
begin
  regout(34,gain,Base);
end;

function get_gain: Shortint;
begin
  get_gain: =regin(34,Base);
end;

procedure set_pole(pole: Shortint);
begin
  regout(33,pole,Base);
end;

function get_pole: Shortint;
begin
  get_pole: =regin(33,Base);
end;

procedure set_zero(zero: integer);
begin
  regout(32,zero,Base);
end;

function get_zero: integer;
begin
```

```
      get_zero: =regin(32,Base);
   end;


   procedure set_accel(accel: integer);
   begin
     regout(38,lo(accel),Base);
     regout(39,hi(accel),Base);
   end;


   function get_accel: integer;
   begin
     get_accel: =regin(38,Base) + regin(39,Base)*256;
   end;


   procedure set_timer(timer: Shortint);
   begin
     regout(15,timer,Base);
   end;


   procedure set_max_vel(vel: Shortint);
   begin
     regout(40,vel,Base);
   end;


   function get_max_vel: Shortint;
   begin
     get_max_vel: =regin(40,Base);
   end;

procedure set_prop_vel(vel: integer);
begin
regout(35,lo(vel),Base);
regout(36,hi(vel),Base);
end;

function get_prop_vel: integer;
begin
get_prop_vel: =regin(35,Base) + regin(36,Base)*256;
end;

procedure set_int_vel(vel: integer);
begin
regout(60,vel,Base);
end;

function get_int_vel: integer;
```

```
begin
get_int_vel: =regin(60,Base);
end;

function get_act_vel: integer;
begin
get_act_vel: =regin(52,Base) + regin(53,Base)*256;
end;

procedure go_cntrl_mode;
begin
regout(5,3,Base);
end;

    procedure quit;
    begin
      exit;
    end;

procedure set_status(status: integer);
begin
regout(7,status,Base);
end;

function get_status: integer;
begin
get_status: =regin(7,Base);
end;

procedure set_bipolar;
begin
regout(0,2,Base);
end;

procedure set_unipolar;
begin
regout(0,10,Base);
end;

procedure open_loop_comm;
begin
regout(0,12,Base);
end;

procedure closed_loop_comm;
begin
```

```
      regout(0,12,Base);
   end;

      procedure set_do(val: integer);
      begin
        port[776+1]:=val;
      end;

      function get_di: integer;
      begin
        get_di:=port[776+2];
      end;

procedure set_ring(ring: integer);
begin
regout(24,ring,Base);
end;

function get_ring: integer;
begin
get_ring:=regin(24,Base);
end;

procedure set_x_reg(x: integer);
begin
regout(26,x,Base);
end;

function get_x_reg: integer;
begin
get_x_reg:=regin(26,Base);
end;

procedure set_y_reg(y: integer);
begin
regout(27,y,Base);
end;

function get_y_reg: integer;
begin
get_y_reg:=regin(27,Base);
end;

procedure set_offset(offset: integer);
begin
regout(28,offset,Base);
```

```
end;

function get_offset: integer;
begin
get_offset: =regin(28,Base);
end;

procedure set_max_adv(adv: integer);
begin
regout(31,adv,Base);
end;

function get_max_adv: integer;
begin
get_max_adv: =regin(31,Base);
end;

procedure set_vel_timer(timer: integer);
begin
regout(25,timer,Base);
end;

    procedure set_dac(dac: Shortint);
    begin
        regout(8,dac,Base);
    end;

    function get_dac: Shortint;
    begin
      get_dac: =regin(8,Base);
    end;

procedure set_pwm(pwm: integer);
begin
regout(9,pwm,Base);
end;

function get_pwm: integer;
begin
get_pwm: =regin(9,Base);
end;

procedure clr_emerg_flags;
var
tmp: integer;
begin
```

```
tmp: =regin(7,Base);
regout(7,tmp,Base);
end;

    procedure home;
    begin
      regout(5,0,Base);
      regout(36,0,Base);
      regout(35,-10,Base);
      regout(0,11,Base);
      regout(5,3,Base);
    while (get_di = 0)  do ;
      regout(5,0,Base);
    end;

procedure set_flag(flag: Shortint);
begin
regout(0,flag+8,Base);
end;

procedure clr_flag(flag :Shortint);
begin
regout(0,flag,Base);
end;

    procedure set_default;
    var i: integer;
    Begin
      For i : = 768 to 770 do
        begin
            set_base(i);
            set_gain(5);
            set_zero(240);
            set_pole(0);
            set_timer(40);
            set_max_vel(10);
            set_accel(10);
        end;
      For i : = 776 to 778 do
      begin
            set_base(i);
            set_gain(10);
            set_zero(240);
            set_pole(0);
            set_timer(40);
            set_max_vel(10);
```

```
            set_accel(10);
        end;
    END;




{***********************************************************}
{                                        }
{       End of MC-3000 Procedures              }
{                                        }
{***********************************************************}

constructor ASPOD.Init;
var
  H: Word;
  R: TRect;
begin
  H := PtrRec(HeapEnd).Seg - PtrRec(HeapPtr).Seg;
  if H > HeapSize then BufHeapSize := H - HeapSize else BufHeapSize := 0;
  InitBuffers;
  TApplication.Init;
  DisableCommands([cmSave, cmSaveAs, cmCut, cmCopy, cmPaste, cmClear,
    cmUndo, cmFind, cmReplace, cmSearchAgain]);
  EditorDialog := DoEditDialog;
  ClipWindow := OpenEditor('', False);
  if ClipWindow < > nil then
  begin
    Clipboard := ClipWindow^.Editor;
    Clipboard^.CanUndo := False;
  end;
  Values[0] := '    Autonomous Space Processer of Orbital Debris';
  Values[1] := ' ';
  Values[2] := '        Robotic Arm Controller Program';
  Values[3] := ' ';
  Values[4] := ' ';
  Values[5] := ' ';
  Values[6] := '       Written By: Bjoern J. Kutz';
  Values[7] := ' ';
  Values[8] := ' ';
  Values[9] := '      Adv: Dr. Kumar Ramohalli';
  Values[10]:= '        Copyright 1992';
  ANewWindow(0);
end;

destructor ASPOD.Done;
begin
  TApplication.Done;
```

```pascal
    DoneBuffers;
  end;

  procedure ASPOD.HandleEvent(var Event: TEvent);

  procedure FileOpen;
  var
    FileName: FNameStr;
  begin
    FileName := '*.*';
    if ExecDialog(New(PFileDialog, Init('*.*', 'Open file',
      '~N~ame', fdOpenButton, 100)), @FileName) < > cmCancel then
      OpenEditor(FileName, True);
  end;

  procedure FileNew;
  begin
    OpenEditor('', True);
  end;

  procedure ChangeDir;
  begin
    ExecDialog(New(PChDirDialog, Init(cdNormal, 0)), nil);
  end;

  procedure DosShell;
  begin
    DoneSysError;
    DoneEvents;
    DoneVideo;
    DoneMemory;
    SetMemTop(Ptr(BufHeapPtr, 0));
    PrintStr('Type EXIT to return to TVEDIT...');
    SwapVectors;
    Exec(GetEnv('COMSPEC'), '');
    SwapVectors;
    SetMemTop(Ptr(BufHeapEnd, 0));
    InitMemory;
    InitVideo;
    InitEvents;
    InitSysError;
    Redraw;
  end;

  procedure ShowClip;
  begin
```

```pascal
  ClipWindow^.Select;
  ClipWindow^.Show;
end;


procedure Tile;
var
  R: TRect;
begin
  Desktop^.GetExtent(R);
  Desktop^.Tile(R);
end;


procedure Cascade;
var
  R: TRect;
begin
  Desktop^.GetExtent(R);
  Desktop^.Cascade(R);
end;


procedure Calculator;
begin
  DeskTop^.Insert(ValidView(New(PCalculator, Init)));
end;




{ ASPOD }
begin
  TApplication.HandleEvent(Event);
  case Event.What of
    evCommand:
      case Event.Command of
        cmOpen: FileOpen;
      cmNew: FileNew;
      cmChangeDir: ChangeDir;
      cmDosShell: DosShell;
      cmCalculator: Calculator;
      cmShowClip: ShowClip;
      cmTile: Tile;
      cmCascade: Cascade;
      cmCurBase: TCurrent(BaBase);
      cmDeltBase: final(BaBase);
      cmGoBase: go(BaBase);
      cmCurShould: TCurrent(ShBase);
```

```
cmDeltShould: final(ShBase);
cmGoShould: go(ShBase);
cmCurElbow: TCurrent(ElBase);
cmDeltElbow: final(ElBase);
cmGoElbow: go(ElBase);
cmCurTwist: TCurrent(TBase);
cmDeltTwist: final(TBase);
cmGoTwist: go(TBase);
cmCurBend: TCurrent(BBase);
cmDeltBend: final(BBase);
cmGoBend: go(BBase);
cmCurGrip: TCurrent(GBase);
cmDeltGrip: final(GBase);
cmGoGrip: go(GBase);
cmDefaultSet: Default;
cmBaGainSet: SetGain(BaBase);
cmShGainSet: SetGain(ShBase);
cmElGainset: SetGain(ElBase);
cmTGainSet: SetGain(TBase);
cmBGainSet: SetGain(BBase);
cmGGainSet: SetGain(GBase);
cmBaZeroSet: SetZero(BaBase);
cmShZeroSet: SetZero(ShBase);
cmElZeroSet: SetZero(ElBase);
cmTZeroSet: SetZero(TBase);
cmBZeroSet: SetZero(BBase);
cmGZeroSet: SetZero(GBase);
cmBaPoleset: SetPole(BaBase);
cmShPoleset: SetPole(ShBase);
cmElPoleset: SetPole(ElBase);
cmTPoleset: SetPole(TBase);
cmBPoleset: SetPole(BBase);
cmGPoleset: SetPole(GBase);
cmBaTimerSet: SetTimer(BaBase);
cmShTimerSet: SetTimer(ShBase);
cmElTimerSet: SetTimer(ElBase);
cmTTimerSet: SetTimer(TBase);
cmBTimerSet: SetTimer(BBase);
cmGTimerSet: SetTimer(GBase);
cmBaVelSet: SetVel(BaBase);
cmShVelSet: SetVel(ShBase);
cmElVelSet: SetVel(ElBase);
cmTVelSet: SetVel(TBase);
cmBVelSet: SetVel(BBase);
cmGVelSet: SetVel(GBase);
cmBaAccSet: SetAcc(BaBase);
```

```
        cmShAccSet: SetAcc(ShBase);
        cmElAccSet: SetAcc(ElBase);
        cmTAccSet: SetAcc(TBase);
        cmBAccSet: SetAcc(BBase);
        cmGAccSet: SetAcc(GBase);
        cmBaGetValues: getVal(BaBase);
        cmshGetValues: getVal(ShBase);
        cmElGetValues: getVal(ElBase);
        cmTGetValues: getVal(TBase);
        cmBGetValues: getVal(BBase);
        cmGGetValues: getVal(GBase);
        cmResetCom: Res;
        cmZeroCom: Zero;
        cmBaPos: PosMove(BaBase,197);
        cmShPos: PosMove(ShBase,197);
        cmElPos: PosMove(ElBase,197);
        cmTPos: PosMove(TBase,255);
        cmBPos: PosMove(BBase,255);
        cmGPos: PosMove(GBase,255);
        cmBaNeg: NegMove(BaBase,57);
        cmShNeg: NegMove(ShBase,57);
        cmElNeg: NegMove(ElBase,57);
        cmTNeg: NegMove(TBase,0);
        cmBNeg: NegMove(BBase,0);
        cmGNeg: NegMove(GBase,0);
        cmBaClPos: ClearPos(BaBase);
        cmShClPOs: ClearPos(ShBase);
        cmElClPos: ClearPos(ElBase);
        cmTClPos: ClearPos(TBase);
        cmBClPos: ClearPos(BBase);
        cmGClPos: ClearPos(GBase);
      cmBaTest: Test(BaBase);
      cmShTest: Test(ShBase);
      cmElTest: Test(ElBase);
      cmTTest: Test(TBase);
      cmBTest: Test(BBase);
      cmGTest: Test(GBase);
      cmDecod: Decode;
      cmNumTest: NTest;
       else
         Exit;
       end;
  else
    Exit;
  end;
ClearEvent(Event);
```

```
end;

procedure ASPOD.InitMenuBar;
var R: TRect;
begin
  GetExtent(R);
  R.B.Y := R.A.Y + 1;
  MenuBar := New(PMenuBar, Init(R, NewMenu(
    NewSubMenu('~F~ile', hcNoContext, NewMenu(
      NewItem('~O~pen...', 'F3', kbF3, cmOpen, hcNoContext,
      NewItem('~N~ew', '', kbNoKey, cmNew, hcNoContext,
      NewItem('~S~ave', 'F2', kbF2, cmSave, hcNoContext,
      NewItem('S~a~ve as...', '', kbNoKey, cmSaveAs, hcNoContext,
      NewLine(
      NewItem('~C~hange dir...', '', kbNoKey, cmChangeDir, hcNoContext,
      NewItem('~D~OS shell', '', kbNoKey, cmDosShell, hcNoContext,
      NewItem('~R~eset','Esc', kbEsc, cmResetCom, hcNoContext,
      NewItem('De~f~ault','Ctrl-F10', kbCTRLF10, cmDefaultset, hcNoContext,
      NewItem('D~e~code',' ', kbNoKey, cmDecod, hcNoContext,
      NewItem('N~T~est',' ', kbNoKey, cmNumTest, hcNOContext,
      NewItem('E~x~it', 'Alt-X', kbAltX, cmQuit, hcNoContext,
      nil))))))))))))),
    NewSubMenu('~E~dit', hcNoContext, NewMenu(
      NewItem('~U~ndo', '', kbNoKey, cmUndo, hcNoContext,
      NewLine(
      NewItem('Cu~t~', 'Shift-Del', kbShiftDel, cmCut, hcNoContext,
      NewItem('~C~opy', 'Ctrl-Ins', kbCtrlIns, cmCopy, hcNoContext,
      NewItem('~P~aste', 'Shift-Ins', kbShiftIns, cmPaste, hcNoContext,
      NewItem('~S~how clipboard', '', kbNoKey, cmShowClip, hcNoContext,
      NewLine(
      NewItem('~C~lear', 'Ctrl-Del', kbCtrlDel, cmClear, hcNoContext,
      nil)))))))))),
    NewSubMenu('~S~earch', hcNoContext, NewMenu(
      NewItem('~F~ind...', '', kbNoKey, cmFind, hcNoContext,
      NewItem('~R~eplace...', '', kbNoKey, cmReplace, hcNoContext,
      NewItem('~S~earch again', '', kbNoKey, cmSearchAgain, hcNoContext,
      nil)))),
    NewSubMenu('~W~indows', hcNoContext, NewMenu(
      NewItem('~S~ize/move','Ctrl-F2', kbCtrlF2, cmResize, hcNoContext,
      NewItem('~Z~oom', '', kbNoKey, cmZoom, hcNoContext,
      NewItem('~T~ile', '', kbNoKey, cmTile, hcNoContext,
      NewItem('C~a~scade', '', kbNoKey, cmCascade, hcNoContext,
      NewItem('~N~ext', 'F1', kbF1, cmNext, hcNoContext,
      NewItem('~P~revious', 'Shift-F1', kbShiftF1, cmPrev, hcNoContext,
      NewItem('~C~lose', 'Alt-F3', kbAltF3, cmClose, hcNoContext,
      NewLine(
```

```
   NewItem('Ca~1~culator', '', kbNoKey, cmCalculator, hcNoContext,
   nil)))))))))),
NewSubMenu('~B~ase', hcNoContext, NewMenu(
   NewItem('~G~ain Set','', kbNoKey, cmBaGainSet, hcNoContext,
   NewItem('~Z~ero Set','', kbNoKey, cmBaZeroSet, hcNoContext,
   NewItem('~P~ole Set','', kbNokey, cmBaPoleSet, hcNoContext,
   NewItem('~T~imer Set','', kbNoKey, cmBaTimerSet, hcNoContext,
   NewItem('~V~elocity Set','', kbNoKey, cmBaVelSet, hcNoContext,
   NewItem('~A~cceleration Set','', kbNoKey, cmBaAccSet, hcNoContext,
   NewItem('P~o~sition','', kbNoKey, cmCurBase, hcNoContext,
   NewItem('C~1~ear position','', kbNoKey, cmBaClPos, hcNoContext,
   NewItem('~M~ove Setting','', kbNoKey, cmDeltBase, hcNoContext,
   NewItem('~C~urrent Values','Ctrl-F7', kbCTRLF7, cmBaGetValues, hcNoContext,
   NewItem('~E~xecute','Alt-V', kbALTV, cmGoBase, hcNoContext,
   NewItem('~T~est',' ', kbNoKey, cmBaTest, hcNoContext,
   nil)))))))))))))),
 NewSubMenu('Shoul~d~ ', hcNoContext, NewMenu(
   NewItem('~G~ain Set','', kbNoKey, cmShGainSet, hcNoContext,
   NewItem('~Z~ero Set','', kbNoKey, cmShZeroSet, hcNoContext,
   NewItem('~P~ole Set','', kbNokey, cmShPoleSet, hcNoContext,
   NewItem('~T~imer Set','', kbNoKey, cmShTimerSet, hcNoContext,
   NewItem('~V~elocity Set','', kbNoKey, cmShVelSet, hcNoContext,
   NewItem('~A~cceleration Set','', kbNoKey, cmShAccSet, hcNoContext,
   NewItem('P~o~sition','', kbNoKey, cmCurShould, hcNoContext,
   NewItem('C~1~ear position','', kbNoKey, cmShClPos, hcNoContext,
   NewItem('~M~ove Setting','', kbNoKey, cmDeltShould, hcNoContext,
   NewItem('~C~urrent Values','Ctrl-F8', kbCtrlF8, cmShGetValues, hcNoContext,
   NewItem('~E~xecute','Alt-M', kbALTM, cmGoShould, hcNoContext,
   NewItem('~T~est',' ', kbNoKey, cmShTest, hcNoContext,
   nil)))))))))))))),
NewSubMenu('E~1~bow', hcNoContext, NewMenu(
   NewItem('~G~ain Set','', kbNoKey, cmElGainSet, hcNoContext,
   NewItem('~Z~ero Set','', kbNoKey, cmElZeroSet, hcNoContext,
   NewItem('~P~ole Set','', kbNokey, cmELPoleSet, hcNoContext,
   NewItem('~T~imer Set','', kbNoKey, cmElTimerSet, hcNoContext,
   NewItem('~V~elocity Set','', kbNoKey, cmElVelSet, hcNoContext,
   NewItem('~A~cceleration Set','', kbNoKey, cmElAccSet, hcNoContext,
   NewItem('P~o~sition','', kbNoKey, cmCurElbow, hcNoContext,
   NewItem('C~1~ear position','', kbNoKey, cmELClPos, hcNoContext,
   NewItem('~M~ove Setting','', kbNoKey, cmDeltElbow, hcNoContext,
   NewItem('~C~urrent Values','Ctrl-F9', kbCTRLF9, cmElGetValues, hcNoContext,
   NewItem('~E~xecute','Alt-O', kbALTO, cmGoElbow, hcNoContext,
   NewItem('~T~est',' ', kbNoKey, cmElTest, hcNoContext,
   nil)))))))))))))),
NewSubMenu('~T~wist', hcNoContext, NewMenu(
   NewItem('~G~ain Set','', kbNoKey, cmTGainSet, hcNoContext,
```

```
   NewItem(' ~ Z ~ ero Set','', kbNoKey, cmTZeroSet, hcNoContext,
   NewItem(' ~ P ~ ole Set','', kbNokey, cmTPoleSet, hcNoContext,
   NewItem(' ~ T ~ imer Set','', kbNoKey, cmTTimerSet, hcNoContext,
   NewItem(' ~ V ~ elocity Set','', kbNoKey, cmTVelSet, hcNoContext,
   NewItem(' ~ A ~ cceleration Set','', kbNoKey, cmTAccSet, hcNoContext,
   NewItem('P ~ o ~ sition','', kbNoKey, cmCurTwist, hcNoContext,
   NewItem('C ~ l ~ ear position','', kbNoKey, cmTClPos, hcNoContext,
   NewItem(' ~ M ~ ove Setting','', kbNoKey, cmDeltTwist, hcNoContext,
   NewItem(' ~ C ~ urrent Values','Ctrl-F10', kbCTRLF10, cmTGetValues, hcNoContext,
   NewItem(' ~ E ~ xecute','Alt-Z', kbALTZ, cmGoTwist, hcNoContext,
   NewItem(' ~ T ~ est',' ', kbNoKey, cmTTest, hcNoContext,
   nil)))))))))))),
  NewSubMenu('Be ~ n ~ d', hcNoContext, NewMenu(
   NewItem(' ~ G ~ ain Set','', kbNoKey, cmBGainSet, hcNoContext,
   NewItem(' ~ Z ~ ero Set','', kbNoKey, cmBZeroSet, hcNoContext,
   NewItem(' ~ P ~ ole Set','', kbNokey, cmBPoleSet, hcNoContext,
   NewItem(' ~ T ~ imer Set','', kbNoKey, cmBTimerSet, hcNoContext,
   NewItem(' ~ V ~ elocity Set','', kbNoKey, cmBVelSet, hcNoContext,
   NewItem(' ~ A ~ cceleration Set','', kbNoKey, cmBAccSet, hcNoContext,
   NewItem('P ~ o ~ sition','', kbNoKey, cmCurBend, hcNoContext,
   NewItem('C ~ l ~ ear position','', kbNoKey, cmBClPos, hcNoContext,
   NewItem(' ~ M ~ ove Setting','', kbNoKey, cmDeltBend, hcNoContext,
   NewItem(' ~ C ~ urrent Values','Ctrl-F5', kbCtrlF5, cmBGetValues, hcNoContext,
   NewItem(' ~ E ~ xecute','Alt-Q', kbALTq, cmGoBend, hcNoContext,
   NewItem(' ~ T ~ est',' ', kbNoKey, cmBTest, hcNoContext,
   nil)))))))))))),
 NewSubMenu(' ~ G ~ rip', hcNoContext, NewMenu(
   NewItem(' ~ G ~ ain Set','', kbNoKey, cmGGainSet, hcNoContext,
   NewItem(' ~ Z ~ ero Set','', kbNoKey, cmGZeroSet, hcNoContext,
   NewItem(' ~ P ~ ole Set','', kbNokey, cmGPoleSet, hcNoContext,
   NewItem(' ~ T ~ imer Set','', kbNoKey, cmGTimerSet, hcNoContext,
   NewItem(' ~ V ~ elocity Set','', kbNoKey, cmGVelSet, hcNoContext,
   NewItem(' ~ A ~ cceleration Set','', kbNoKey, cmGAccSet, hcNoContext,
   NewItem('P ~ o ~ sition','', kbNoKey, cmCurGrip, hcNoContext,
   NewItem('C ~ l ~ ear position','', kbNoKey, cmGClPos, hcNoContext,
   NewItem(' ~ M ~ ove Setting','', kbNoKey, cmDeltGrip, hcNoContext,
   NewItem(' ~ C ~ urrent Values','Ctrl-F6', kbCtrlF6, cmGGetValues, hcNoContext,
   NewItem(' ~ E ~ xecute','Alt-U', kbALTu, cmGoGrip, hcNoContext,
   NewItem(' ~ T ~ est',' ', kbNoKey, cmGTest, hcNoContext,
   nil)))))))))))),
 NewSubMenu(' ~ C ~ ommand',hcNoContext, NewMenu(
   NewItem(' ~ R ~ eset','Home', kbHOME, cmZeroCom, hcNOContext,
   NewItem('Base L ~ e ~ ft','Alt-F5', kbALTF5, cmBaPos, hcNoContext,
   NewItem('Base R ~ i ~ ght','Alt-F6', kbALTF6, cmBaNeg, hcNoContext,
   NewItem('Shoulder ~ U ~ p','Alt-F7', kbAltF7, cmShPos, hcNoContext,
   NewItem('Shoulder ~ D ~ own','Alt-F8', kbALtF8, cmShNeg, hcNoContext,
```

```pascal
        NewItem('Elbow ~U~p','Alt-F9', kbALTF9, cmElPos, hcNoContext,
        NewItem('Elbow ~D~own','Alt-F10', kbALTF10, cmElNeg, hcNoContext,
        NewItem('Twist ~L~eft','F5', kbF5, cmTPos, hcNoContext,
        NewItem('Twist ~R~ight','F6', kbF6, cmTNeg, hcNoContext,
        NewItem('Bend ~U~p','F7', kbF7, cmBPos, hcNoContext,
        NewItem('Bend ~D~own','F8', kbF8, cmBNeg, hcNoContext,
        NewItem('Gripper ~C~lose','F9', kbF9, cmGNeg, hcNoContext,
        NewItem('Gripper ~O~pen','F10', kbF10, cmGPos, hcNoContext,
      nil)))))))))))),
        nil))))
      )))))))));
end;


procedure ASPOD.InitStatusLine;
var
  R: TRect;
begin
  GetExtent(R);
  R.A.Y := R.B.Y - 1;
  New(StatusLine, Init(R,
    NewStatusDef(0, $FFFF,
      NewStatusKey(' ~F2~ Save', kbF2, cmSave,
      NewStatusKey(' ~F3~ Open', kbF3, cmOpen,
      NewStatusKey(' ~Alt-F3~ Close', kbAltF3, cmClose,
      NewStatusKey(' ~F5~ Zoom', kbF5, cmZoom,
      NewStatusKey(' ~F6~ Next', kbF6, cmNext,
      NewStatusKey(' ~Ctrl-F1~ Menu', kbCTRLF1, cmMenu,
      NewStatusKey('', kbCtrlF5, cmResize,
      nil))))))),
    nil)));
end;


procedure ASPOD.NTest;
var
  Low, High: integer;
  TestVal: Longint;
  NTestVal: Longint;
Begin
  TestVal := 267242409;
  low := Lo(TestVal);
  High := Hi(TestVal);
  writeln ( 'the Values Are: ', TestVal,' ', Low ,' ', High);
  NTestVal := TestVal shr 16;
  low := Lo(NTestVal);
  High := Hi(NTestVal);
  writeln ( 'the Values Are: ', NTestVal,' ', Low ,' ', High);
```

```pascal
end;

procedure ASPOD.zero;                        { o/p zero command }
Begin
  regout(8,127,base);
end;


procedure ASPOD.PosMove(BaseTmp, pow: integer);    { o/p full positive command to
Basetmp}
Begin
  Set_Base(BaseTmp);
  regout(8,pow,BaseTmp);
end;

procedure ASPOD.NegMove(BaseTmp, pow: integer);   { Full Neg Cm to Basetmp }
Begin
  Set_Base(BaseTmp);
  regout(8,pow,BaseTmp);
end;

procedure ASPOD.Res;
var i: integer;  { function DoEditDialog(Dialog: Integer; Info: Pointer): Word; far;
var
  R: TRect;  }
  T: TPoint;
  Info: Pointer;
  com: Tbufstream;
Begin;
  resetP;
 { com }
  For i := 0 to 10 do
  Values[i] := 'All Axis have been RESET';
  ANewWindow(000);
end;

procedure ASPOD.Default;
var  i: integer;
begin
  set_default;
  Values[0] := 'All Effector values have been set to default.';
  For i := 1 to 10 do
  Values[i] := ' ';
  ANewWindow(0);
end;
```

```pascal
procedure ASPOD.TCurrent(BaseTmp: integer);
  var position: Longint;
begin;
  set_Base (BaseTmp);
  position := get_act_pos;
  writeln ('The Current Position is for ',BaseTmp,' is ',position);
  end;


Procedure ASPOD.final(BaseTmp: integer);
var FinalPosition: Longint;
begin
  writestr (4,4,'BaseTmp',4);
  base := BaseTmp;
  writeln ('What is your desired final position?');
  readln (finalposition);
  set_final_pos(FinalPosition);
  writeln ('Position set.')
end;


Procedure ASPOD.WhatFinal(BaseTmp: integer);
var
  FinalPosition: Longint;
  i: integer;
Begin
  writeln (BaseTmp);
  Set_Base(BaseTmp);
  finalposition := get_final_pos;
  writeln(' The current final position is ',finalposition);
end;


procedure ASPOD.SetGain(BaseTmpG: integer);
var G: integer;
Begin
  writeln ('Num = ',BaseTmpg);
  set_Base(BaseTmpg);
  writeln ('What is the new Gain?');
  readln (G);
  Set_Gain(G);
  writeln ('The new Gain for joint # ',BaseTmpg,' is ', get_gain);
end;


procedure ASPOD.SetZero(BaseTmpz: integer);
var Z: integer;
Begin
  writeln ('Num = ',BaseTmpz);
  set_Base(BaseTmpz);
```

```pascal
    writeln ('What is the new Zero?');
    readln (Z);
    Set_Zero(Z);
    writeln ('The new Zero for joint # ',BaseTmpz,' is ', get_Zero);
  end;


procedure ASPOD.SetPole(BaseTmpp: integer);
var G: integer;
Begin
  writeln ('Num = ',BaseTmpp);
  set_Base(BaseTmpp);
  writeln ('What is the new Pole?');
  readln (G);
  Set_Pole(G);
  writeln ('The new Pole for joint # ',BaseTmpp,' is ', get_Pole);
end;


procedure ASPOD.SetTimer(BaseTmpt: integer);
var G: integer;
Begin
  writeln ('Num = ',BaseTmpt);
  set_Base(BaseTmpt);
  writeln ('What is the new Timer Value?');
  readln (G);
  Set_timer(G);
end;


procedure ASPOD.SetVel(BaseTmpv: integer);
var G: integer;
Begin
  writeln ('Num = ',BaseTmpv);
  set_Base(BaseTmpv);
  writeln ('What is the new Velocity?');
  readln (G);
  Set_max_vel(G);
  writeln ('The new Velocity for joint # ',BaseTmpv,' is ', get_max_vel);
end;


procedure ASPOD.SetAcc(BaseTmpa: integer);
var G: integer;
Begin
  set_Base(BaseTmpa);
  Writeln ('What is the new Acceleration?');
  readln (G);
  Set_accel(G);
  Writeln ('The new Acceleration for joint # ',BaseTmpa,' is ',get_accel);
```

```
{  Lout[2] := ' ';
   Lout[3] := ' ';
   BNewWindow(BaseTmpa); }
end;

procedure ASPOD.ClearPos(BaseTmp: integer);
Begin
Set_Base(BaseTmp);
clr_act_pos;
end;

procedure ASPOD.GetVal(BaseTmpval: integer);
var
   Nstr: string[4];
   i, tmp: integer;
begin
   set_Base(BaseTmpval);
   tmp := BaseTmpVal;
   Nstr := IToS(BaseTmpval);
   Values[0] := 'The Current GAIN for joint # ' + Nstr + ' is ' + IToS(get_gain);
   Values[1] := 'The Current ZERO for joint # ' + Nstr + ' is ' + IToS(get_zero);
   Values[2] := 'The Current POLE for joint # ' + Nstr + ' is ' + IToS(get_pole);
   Values[3] := 'The Current VELOCITY for joint # ' + Nstr + ' is ' + IToS(get_max_vel);
   Values[4] := 'The Current ACCELERATION for joint # ' + Nstr + ' is ' + IToS(get_accel);
   For i := 5 to 10 do
      Values[i] := ' ';
   ANewWindow(tmp);
end;


procedure ASPOD.Go(Basetmp: integer);
Begin
   set_Base(Basetmp);
   trap_mode;
end;

procedure ASPOD.Test(BaseTmp: integer);
var
   i: integer;
Begin
   set_Base(Basetmp);
   writeln ('Actual position:', get_act_pos);
   clr_act_pos;
   writeln ('Actual position:', get_act_pos);
   for i := 1 to 5 do
   Begin
```

```pascal
      PosMove(BaseTmp,197);
      delay_sec(100);
      Zero;
      writeln ('Actual position:' , get_act_pos);
   end;
end;

procedure ASPOD.Decode;
var
   i,j,k, Low, Med, high: integer;
   Fil, Comm: String[13];
   SIArg: ShortInt;
   IArg, pow: integer;
   LIArg: LongInt;
   FileName: Text;
Begin
   Values[0] := 'What is the File Name you would like to run ?';
   for i := 1 to 10 do Values[i] :=  ' ';
   ANewWindow(0);
   setCursor(10,12);
   readln(Fil);
   Assign(FileName, Fil);
   { $I- }
   reset(FileName);
   { $I+ }
   if IOResult < > 0 then
      writeln ('Can not open File');
   Comm := 'Go';
   While not Eof(FileName) and (Comm < > 'quit ') and (Comm < > '') do
   Begin
      readln (fileName, Comm);

      if comm = 'set_base ' then
      Begin
        readln (filename, Iarg);
        Base := Iarg;
        writeln ('Command is ', Comm,' ',IArg);
      end;


      if comm = 'set_gain ' then
      Begin
        readln (filename, Iarg);
        regout(34, Iarg, Base);
        writeln ('Command is ', Comm,' ',IArg);
      end;
```

```pascal
if comm = 'set_zero ' then
Begin
  readln (filename, Iarg);
  regout(32, Iarg, Base);
  writeln ('Command is ', Comm,' ',IArg);
end;

if comm = 'set_pole ' then
Begin
  readln (filename, Iarg);
  regout(33, Iarg, Base);
  writeln ('Command is ', Comm,' ',IArg);
end;

if comm = 'set_timer ' then
Begin
  readln (filename, Iarg);
  regout(15, Iarg, Base);
  writeln ('Command is ', Comm,' ',IArg);
end;

if comm = 'set_max_vel ' then
Begin
  readln (filename, Iarg);
  regout(40, Iarg, Base);
  writeln ('Command is ', Comm,' ',IArg);
end;

if comm = 'set_accel ' then
Begin
  readln (filename, Iarg);
  regout(38, lo(Iarg), Base);
  regout(39, hi(Iarg), Base);
  writeln ('Command is ', Comm,' ',IArg);
end;

if comm = 'set_final_pos' then
Begin
  readln (filename, LIArg);
  low:=LIArg and $000000FF;
  med:=LIArg Shr 8 and $000000FF;
  high:=LIArg shr 16 and $000000FF;
  regout(41, Low, Base);
  regout(42, med, Base);
  regout(43, high, Base);
  writeln ('Command is ', Comm,' ',LIArg);
```

```
      writeln ('Low is ',Low,' Med is ',Med,' High is ',High);
   end;

   if comm = 'delay ' then
   Begin
     readln (filename, Iarg);
     for j := 1 to 1000*Iarg do
     for k := 1 to 1000 do;
     inc(k);
     writeln ('Command is ', Comm,' ',IArg);
   end;

   if comm = 'clr_act_pos ' then
   Begin
     regout(19, 0, Base);
     writeln ('Command is ', Comm);
   end;

   if comm = 'com_out ' then
   Begin
     readln(filename, Iarg);
     pow := Iarg;
     port[base+8*1024]:=pow;
     writeln ('Command is ',comm,' ',Iarg);
   end;


   if comm = 'sel_mode ' then
   Begin
     regout(5, 3, Base);
     writeln ('Command is ', Comm);
   end;

   if comm = 'repeat ' then
   Begin
     readln (filename, Iarg);
     writeln ('Command is ', Comm);
   end;

   if comm = 'trap_mode ' then
   Begin
     regout(0, 8, Base);
     writeln ('Command is ', Comm);
   end;

   if comm = 'next ' then i:=0;
```

```
    End;
    Close(FileName);
  End;



procedure ASPOD.ANewWindow(Num2: integer);
var
  Window: SWindow;
  R: TRect;
  WinTit: String;
begin
  WinNum := Num2;
  if (Num2 = BaBase) then Wintit := 'Base';
  if (Num2 = ShBase) then Wintit := 'Shoulder';
  if (Num2 = ElBase) then Wintit := 'Elbow';
  if (Num2 = TBase) then Wintit := 'Twist';
  if (Num2 = BBase) then Wintit := 'Bend';
  if (Num2 = GBase) then Wintit := 'Grip';
  if (Num2 = 0) then Wintit := 'Output';
  R.Assign(1, 1, 75, 20);
  Window := New(SWindow, Init(R, WinTit , WinNum));
  DeskTop^. Insert(Window);
end;



procedure ASPOD.OutOfMemory;
begin
  MessageBox('Not enough memory for this operation.',
    nil, mfError + mfOkButton);
end;



var
  MyApp: ASPOD;

begin
  MyApp.Init;
  MyApp.Run;
  MyApp.Done;
end.
```