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DESIGN IMPROVEMENTS TO
A LOW-COST CARTESIAN ROBOT
FOR INDUSTRIAL APPLICATIONS

A Thesis

Presented for the

Master of Science

Degree

The University of Tennessee, Knoxville

David Paulus

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ABSTRACT

A market survey of 34 East Tennessee companies was conducted as a joint effort between the Mechanical Engineering Department and the Marketing Department at the University of Tennessee in the summer of 1991. The intent of this study was to determine robotics applications criteria for a low cost cartesian robot being developed at the University of Tennessee. The results were used to establish the performance characteristics that this robot should achieve. The study established that approximately 80% of the market can be served by either point-to-point motion or path motion. Payloads of under 10 pounds, reach less than 4 feet and unit price under $25,000 would meet up to 71% of the survey respondents. Furthermore, accuracy requirements up to 0.005 inches and a cycle time of over 2 seconds would meet at least 89% of the market.

The Superior Engineering Design Program (SEDP) robot was compared to the established criteria of the market survey. The SEDP robot has a reach up to 8 feet, payload up to 20 pounds and an accuracy up to 0.005 inches. Maximum velocities up to 48 inches/second can be attained by summing velocities in all 4 degrees of motion. The unit price is projected to be under $15,000. Engineering work packaged the electronics emphasizing space utilization, customer convenience and air flow considerations. Design, selection, fabrication and implementation of necessary safety devices for industrial installation has been completed.

In order to show that the SEDP robot can be a viable candidate to perform the two major types of motion, a feasibility study was conducted. This study included the design,

fabrication and evaluation of a prototype unit to simulate a pick-and-place application for Magic Chef of Cleveland, Tennessee. This application involves moving 6.5 oz. steel gas stove burners from a set point and filling a pallet of 36 openings. Control signal communication between the robot and other auxiliary equipment has been demonstrated. The path motion application required the design of an end effector which contains an air grinder. Geometric patterns were cut in various types of wood to demonstrate this application.

The point-to-point performance was evaluated by comparing attained cycle time and repeatability to Magic Chef criteria. The path motion performance was compared for linearity between input and output paths as well as unacceptable deflections. Recommendations for areas of further work have been made.

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CHAPTER 1

PROJECT BACKGROUND AND INTRODUCTION

1.1 Introduction

The Superior Engineering Design Program (SEDP) of the Mechanical Engineering Department of the University of Tennessee has developed a low cost industrial robot that it plans to market. The second phase SEDP robot was designed by graduate student Mike Kennedy and was fabricated at the University of Tennessee [Kennedy, 1991]. The SEDP robot has been characterized by compliance and statistical testing of the robot hardware and software [Williams, 1992]. Once the capabilities of the SEDP robot were determined, it was necessary to decide what sectors of the industrial market the SEDP robot could serve. A market survey was conducted to determine market information on robotics requirements and potential applications for the SEDP robot [McGuire, 1991].

This thesis addresses a specific industry application for a point-to-point motion application and a proof-of-concept study for path motion applications. Both the point-to-point and path motions were simulated in the laboratory and involved the design, fabrication and testing of the necessary hardware to verify robot performance.

Chapter 1 contains an introduction to some of the terminology used in robotics. Chapter 1 also summarizes the market survey, the robot's motion, robot failures previously noted and improvements required to improve its performance. Results of this investigation are summarized in Chapter 2. Point-to-point and path motions are shown to be attainable for the SEDP robot and are discussed in Chapter 3. Several necessary improvements made to the SEDP robot to make it ready for industrial installation are listed in Chapter 3. Failure modes encountered from endurance testing of the SEDP robot are also listed in Chapter 3. Chapter 4 contains an analysis of the drive system to maximize the robot performance. Chapter 5 contains recommendations for areas for further work.

1.2 Superior Engineering Design Program

The Mechanical Engineering Department of the University of Tennessee, Knoxville has a unique program called the Superior Engineering Design Program (SEDP). The SEDP is not only committed to quality design principles but also to following through the design phase and building the student projects. Through active company participation, the SEDP raises funds that support this unique combination of design and manufacture found only in a few universities. This approach helps both the companies and the students. The company benefits from fresh ideas and strong university support and the student becomes more familiar with realistic design problems.

1.3 Robotics Terminology

There are several terms used regularly in robotics that are addressed here. These terms are included to facilitate the readers understanding in the following sections.

1. <u>End effector</u> or <u>end-of-arm tooling</u> refers to the part of the robot that touches the part or that performs the intended operation. The end effector could be a welder, glue gun, part gripper, water jet cutter or other means to perform the desired operation.

2. Repeatability refers to the dimensional tolerances that the robot can operate within over extended use. Most robots have a repeatability in the range of 0.001-inch. Some precision robots have repeatablities in the range of 0.00001-inch. Repeatability can be enhanced by the use of lead-ins. Lead-ins are chamfers or beveled edges that help align the part for proper orientation. Repeatability can be increased by nearly 25% if the correct lead-in is employed.

3. Compliance allows the end effector to deflect slightly and allow for proper part orientation. Compliance can also increase repeatability. If, for example, a dowel is being placed in a hole, a small amount of compliance would help the dowel align itself more easily. Compliance can be in the system as loose fittings and belts or as a separate unit between the end effector and the robot.

4. Payload or load is the maximum physical weight that the robot can carry while meeting the other stated specifications. The payload must include the weight of the end effector plus the weight of the part being moved.

5. Cycle time refers to the speed at which a robot functions. Cycle time is determined by moving an object from one point to another as quickly as possible. Care should be taken to observe the payload used in cycle time measurements. The inertial forces generated by moving heavier payloads often requires the speed to be reduced in order to maintain the desired level of repeatability.

6. Reach refers to the work envelope or volume within which the end effector can touch all points. Reach specifications indicate maximum planar distances.

1.4 Market Survey

As part of this investigation, a market survey of 118 local companies was conducted to identify desired robotics characteristics. These characteristics were used to direct the SEDP design team in final mechanical and electrical component selection. The information gathered in the survey tabulated reach, payload, accuracy, cycle time and cost for the 34 survey respondents.

The market survey was also used to identify companies that would consider installing the SEDP robot in their facilities. A specific application was identified for the point-to-point motion but no specific application was identified for the path motion.

1.5 Point-to-Point Motion

Point-to-point motion is characterized by the robot moving in a straight line between two points in space. The computer adjusts each axes velocity such that all axes arrive at the destination point simultaneously. Generally, the only significant loads encountered by the robot are inertial loads experienced in acceleration and deceleration.

The Magic Chef application required a simulation in the laboratory. The process included the design, fabrication and testing of a prototype gripper. The SEDP robot was modified for the Magic Chef application and its performance compared to the Magic Chef requirements for cycle time and repeatability. Signal interface function between the SEDP robot and other auxiliary equipment was demonstrated. A summary of this work is included in Section 2.3. The point-to-point application is discussed in detail in Section 3.5.

1.6 Path Motion

Path motion is characterized by the robot moving through a desired path or contour. Path motion velocities are more sensitive than point-to-point motion velocities since the motion between points determines the desired path. Loads on the robot drive system can be large and continuous. In a wood routing operation, the robot must constantly "push" the bit through the wood in all directions.

The market survey also indicated that it would be desirable to have the capability to run the robot in path or contour motions. No specific path motion application was identified from the market survey. The path motion examined was designed to be a generic motion that showed the ability of the SEDP robot to perform path motions. The paths were run and compared for linearity to the input path. Deflections of the SEDP robot were examined only for areas where gross failure looked possible. A summary of this work is included in Section 2.4. The path motion application is discussed in detail in Section 3.6.

1.7 Necessary Improvements

At the initiation of this project, the SEDP robot had some areas identified from earlier studies that needed to be addressed before the robot would be ready for industry installation. These areas are listed below. Results of these improvements are discussed in Section 3.7 and summarized in Chapter 2.

1. The Z shaft "fell" to the furthest extension due to either deliberate or unintentional power interruptions.

2. The electronic components that control the robot were not in a consolidated form.

3. The wires that connect the motors and sensors to the control cabinet were easily obstructed.

4. The Z timing belt was noticed to have tensioning and slippage problems.

1.8 New Failure Modes Observed During Testing

Prior to this study, limited continuous duty tests had been performed. Therefore, endurance tests were developed to force failure of weak components and systems. The endurance tests consisted of a three-dimensional diagonal path with rotation of the end effector system. The tests varied in length of run time and payload. The failures that occurred in the 676 hours of endurance testing are listed in Chapter 2 and suggested solutions are discussed in Section 3.8.

1.9 Motor Optimization

Concurrently with this investigation, an improved stepper motor driver system was designed and built by other engineers working on the project. Several tests were conducted to analyze the performance characteristics of the SEDP robot withthe new system of driver cards. The driver cards are less expensive, have higher operating frequencies and current output than some commercially available drivers. Tests were conducted to determine the best electrical configuration. These tests included torque vs. speed curves and force vs. speed curves for different electrical motor configurations.

Motor performance analysis is summarized in Chapter 2. These curves are explained and the basis of the analysis are detailed in Chapter 4.

CHAPTER 2

RESULTS

2.1 Introduction

This chapter summarizes the results of the tasks performed in Chapter 3. Results of the market survey are summarized. Results of the point-to-point motion are summarized as well as those for path motion. Several necessary improvements made to the SEDP robot to make the robot ready for industry installation are noted. Areas for further development discovered during endurance testing of the robot are noted. Brief comments are made regarding performance analysis of the SEDP robot.

2.2 Market Survey Results

The results of the desired performance characteristics of the 34 survey respondents compared to the capabilities of the SEDP robot are listed in Table 2.1. Cost, which is not a performance characteristic, is included in this summary.

Table 2.1 Survey respondents results of robotics characteristics

ROBOTICS CHARACTERISTICS	% OF CHARACTERISTICS ACHIEVABLE BY SEDP ROBOT
Group point-to-point and path motion	80.6%
Reach less than 4 feet	75.1%
Payload less than 10 pounds	71.4%
Accuracy requirements up to 0.005 inches	92.9%
Cycle time greater than 2 seconds and less than 2 minutes	89.3%
Unit cost less than $25,000	72.7%

2.3 Point-to Point Motion

A suitable end effector was designed and tested on the Magic Chef application which is shown in Figure 2.1. Detailed drawings of the end effector are included in Appendix A. The three jaw, pneumatic end effector performed very well and provided excellent repeatability. The gripper blank design allowed the burner to be placed as much as 1 inch, or 25%, off center and still be grasped.

The gripper blank design also allowed the gripper to grasp circular rods. This additional design task was undertaken to demonstrate robot flexibility and not as a

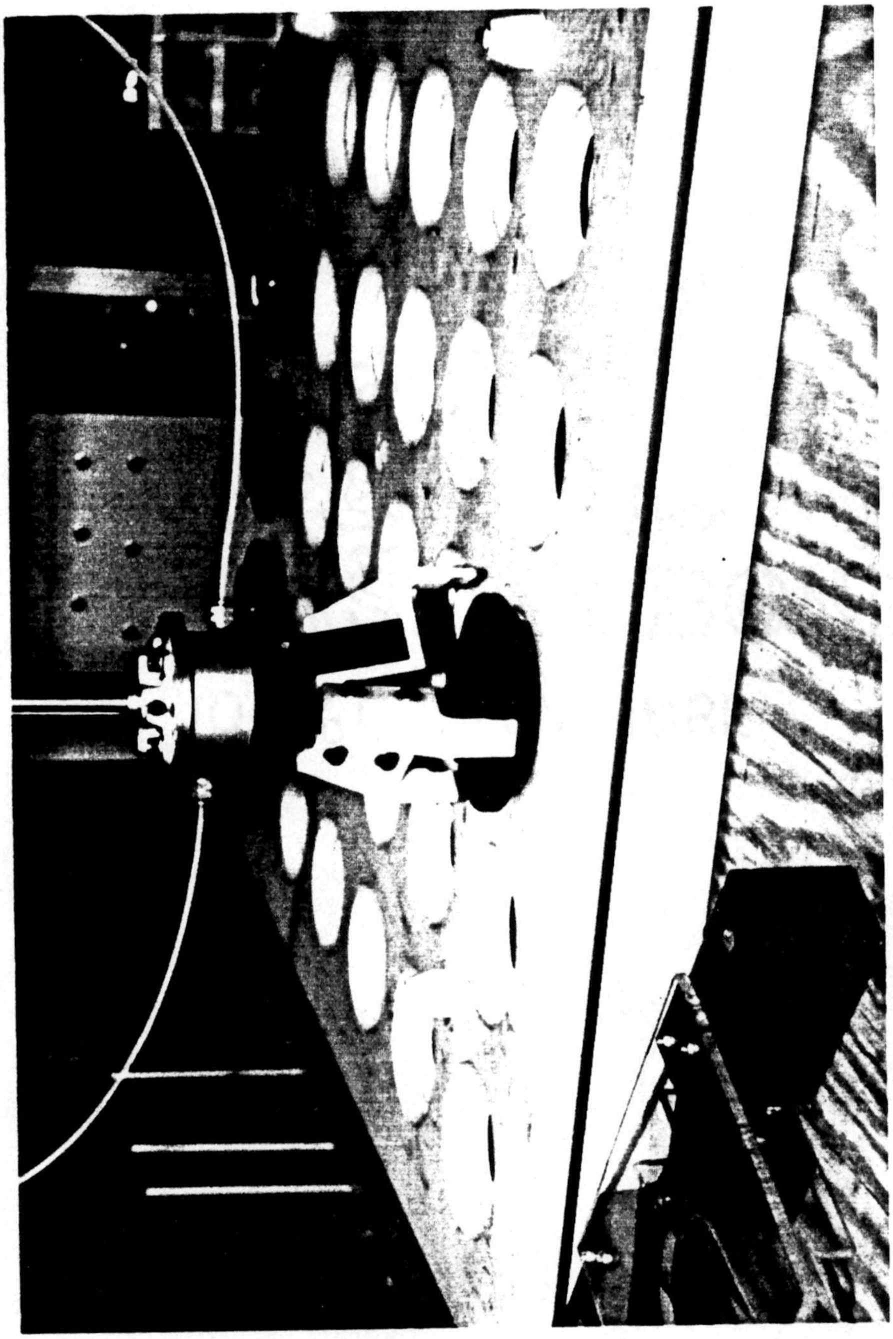


Figure 2.1 Gripper in Magic Chef application

solution to a robotics task identified in the market survey. The gripper blank design allowed the gripper to grasp circular rods from 3/16 inch diameter to 7/16 inch diameter. Line contact between gripper blanks and circular rods is provided only on 1/4 inch diameter rods.

The signal interfaces between the robot and other machinery were shown to be functional. The robot paused or continued its motion depending on the switch input.

The cycle time for the Magic Chef application was met. The robot traversed the furthest path segment and returned to the pick up point in 4.5 seconds. This motion provided a 0.5 second buffer before the next burner would be ready to be moved. The entire pallet was filled in 2 minutes 15 seconds.

2.4 Path Motion

The air grinder attachment to the robot, shown in Figure 2.2, performed the desired task. The linearity of output to input was within the predicted compliance of the robot mechanical drive system. This measurement translates to approximately 0.021 inch with a 3:1 gear reduction as shown in previous studies [Williams, 1992].

The robot structural members were not overloaded by the routing operation. The deflections of the stainless steel shafting were not exaggerated and therefore no failure was predicted.

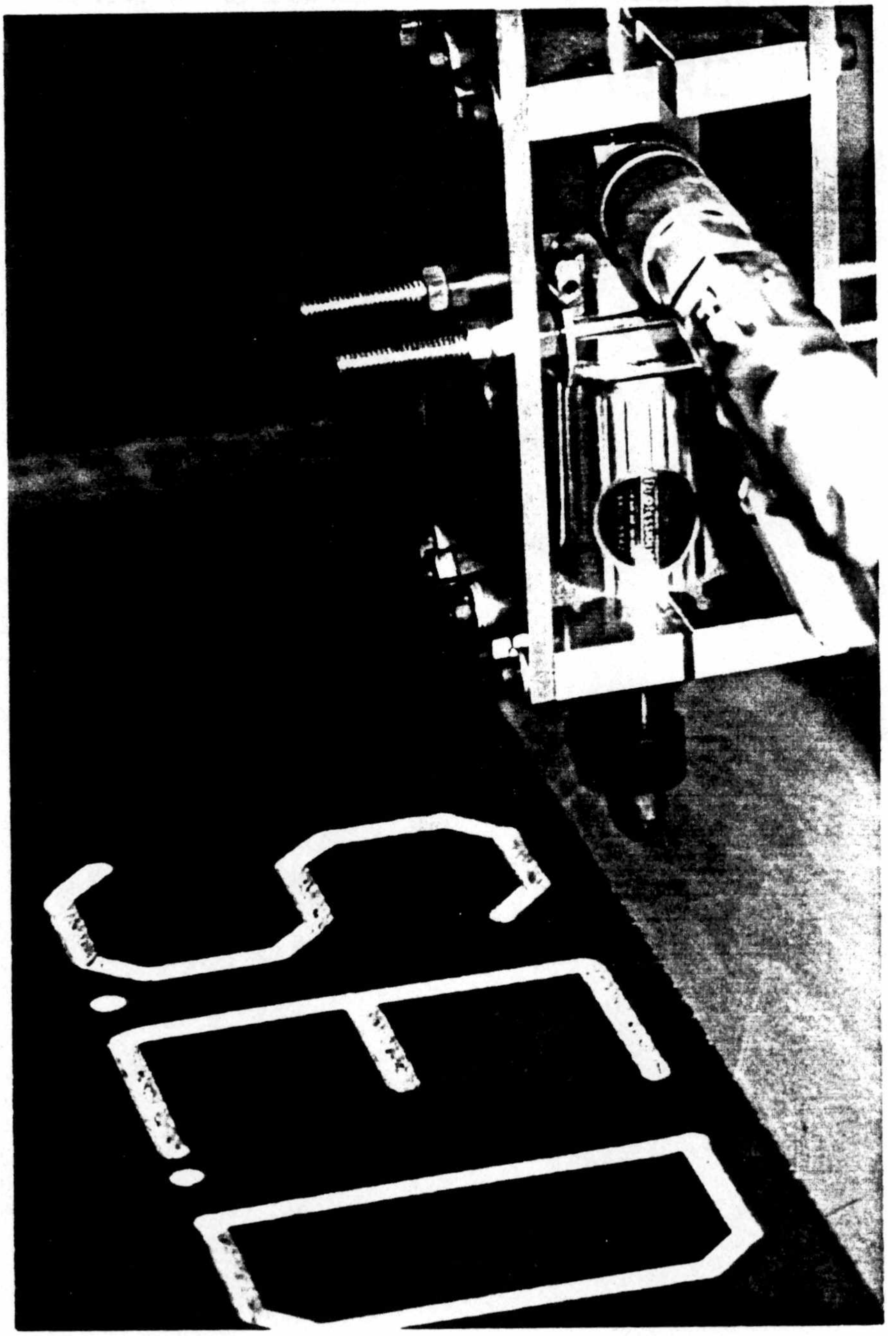


Figure 2.2 Air grinder jig in routing operation

2.5 Necessary Improvements

Several necessary improvements made to the robot to make the robot ready for industrial installation have been installed and evaluated. The results are listed below.

1. An electromagnetic power-off brake was installed to prevent damage to the end effector or objects in the work envelope. The electromechanical power-off brake installed on the back of the Z motor stopped the free fall of the Z shaft within 2 inches of travel with a 32 lb load. This load is over 50% more than the design payload of the SEDP robot.

2. The electronic components were packaged in a single, convenient unit. The electrical components have been placed in a secure, compact cabinet. The cabinet was optimized for heat flow and user interface considerations. Six months of use in both intermittent and continuous operation has shown this solution to be acceptable.

3. The robot was rewired to eliminate obstruction of the control wires. The SEDP robot has been rewired with 16 gauge wire for the motor cables. The rewiring improved the reliability by protecting the wires and improved performance by using heavier gauge wire. The rewiring also improved the appearance of the robot.

4. The tensioning and slippage problems of the Z timing belt have been corrected. The timing belt tensioning problem was solved by machining a slot in the mast that allows 20 degrees of relative motion between the mounting plates and the mast. Endurance testing has shown that the clamping force of the bolts on the top of the mast is sufficient to prevent slippage.

5. The timing belt slippage was solved by replacing the timing belt with a chain ladder type belt. This change provided a doubling of the payload without belt slippage.

2.6 New Failure Modes Observed During Testing

1. During the endurance testing, the optoisolator sensors that are used for the home calibration of the robot were abraded by the slotted sensor disk. This abrasion must be prevented for reliable sensor function.

2. The set screws that attach the pulleys to the drive shafts were noted to loosen during routine operation. This loosening of the set screws allowed unreliable positioning.

3. The air hoses that operate the air gripper were noted to interfere with the optoisolator sensors. This interference caused improper sensor readings or air hose damage.

4. The chain ladder belt that replaced the timing belt on the Z system failed. This failure was caused by improper alignment of the top Z shaft casting and the upper idler gear. This misalignment caused teeth on the belt to be cut off and the robot to lose positional accuracy.

2.7 Performance Analysis

A stepper motor test stand was used to compare motors from different manufacturers and to compare motor torques for different electrical configurations. Figure 2.3 shows a typical force vs. speed curve. This curve was obtained by modifying the stepper motor test stand torque vs. speed curve to correspond to force generated with

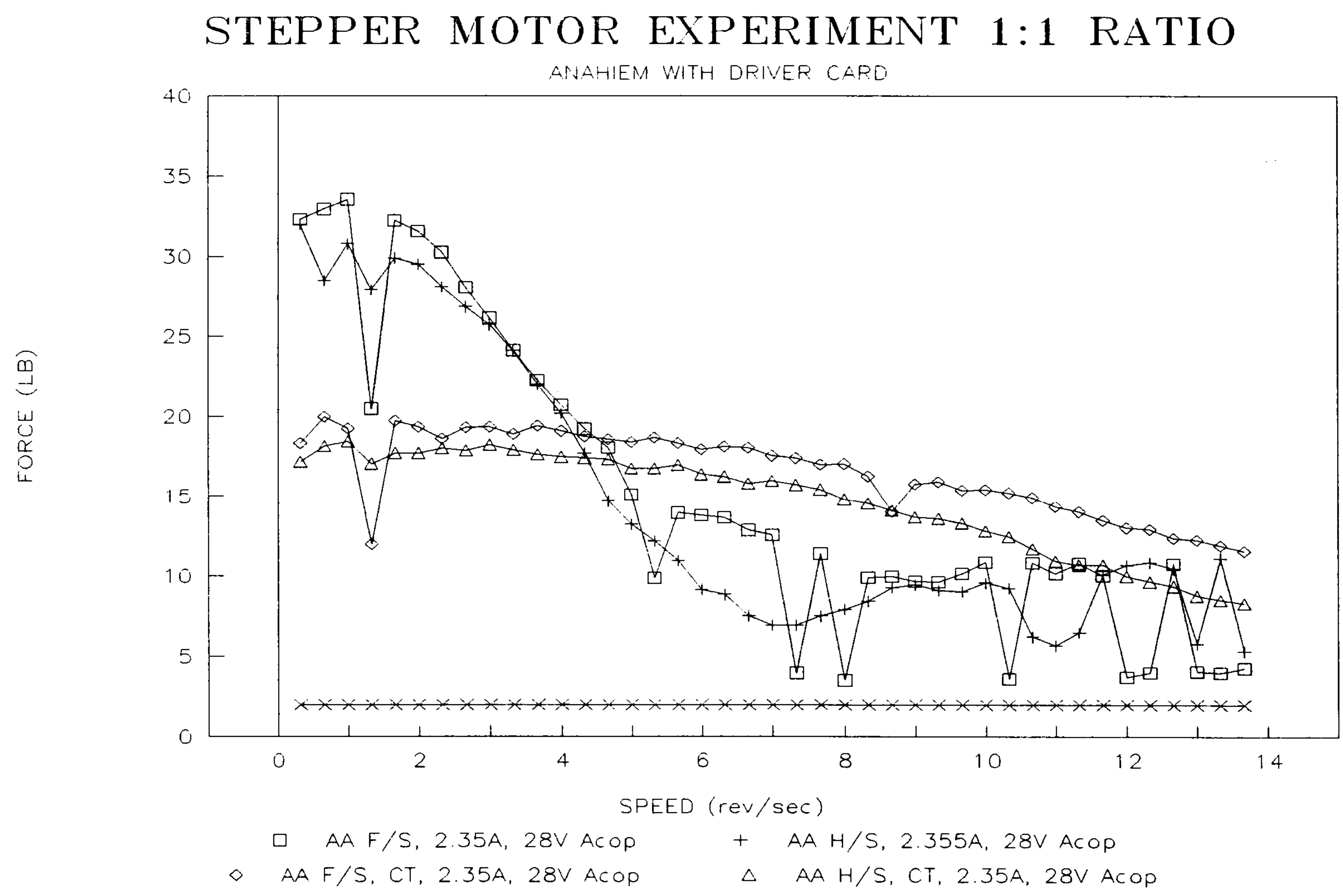


Figure 2.3 Typical force vs. speed curve

a given gear ratio. The curve shows full step (F/S) and half step (H/S) motor operation. The curve also shows full phase and center tap (C/T) operation. A constant 2 pound frictional force is shown on the curve that represents the force needed to move the robot X-Y system. The force is measured with a spring scale attached to the cross block assembly held parallel to the X axis. The calculated force has the 2 pound frictional force subtracted to be consistent with the measured force.

The test stand calculated force results compare with the measured force results as shown in Figure 2.4. There is a large error in the two curves from 0 to 1 rev/sec. The correlation is within 20% over the 1 to 8 rev/sec test range. The measured force was difficult to reproduce with the selected test method and the error in measurements was within the same range as the error in correlation between the two curves. Both curves do show the same trend that force decreases as speed increases.

Figure 2.5 shows a mathematically predicted velocity profile for a 42 inch path segment with maximum velocity of 30 in/sec. The curves represent different values of acceleration. The percentage time spent in the constant velocity portion of the curve is plotted vs. displacement. This curve shows a large effect on the acceleration ramps used in the path motion. This curve shows that to minimize path motion time, one must maximize the constant velocity portion of the path which requires maximization of acceleration.

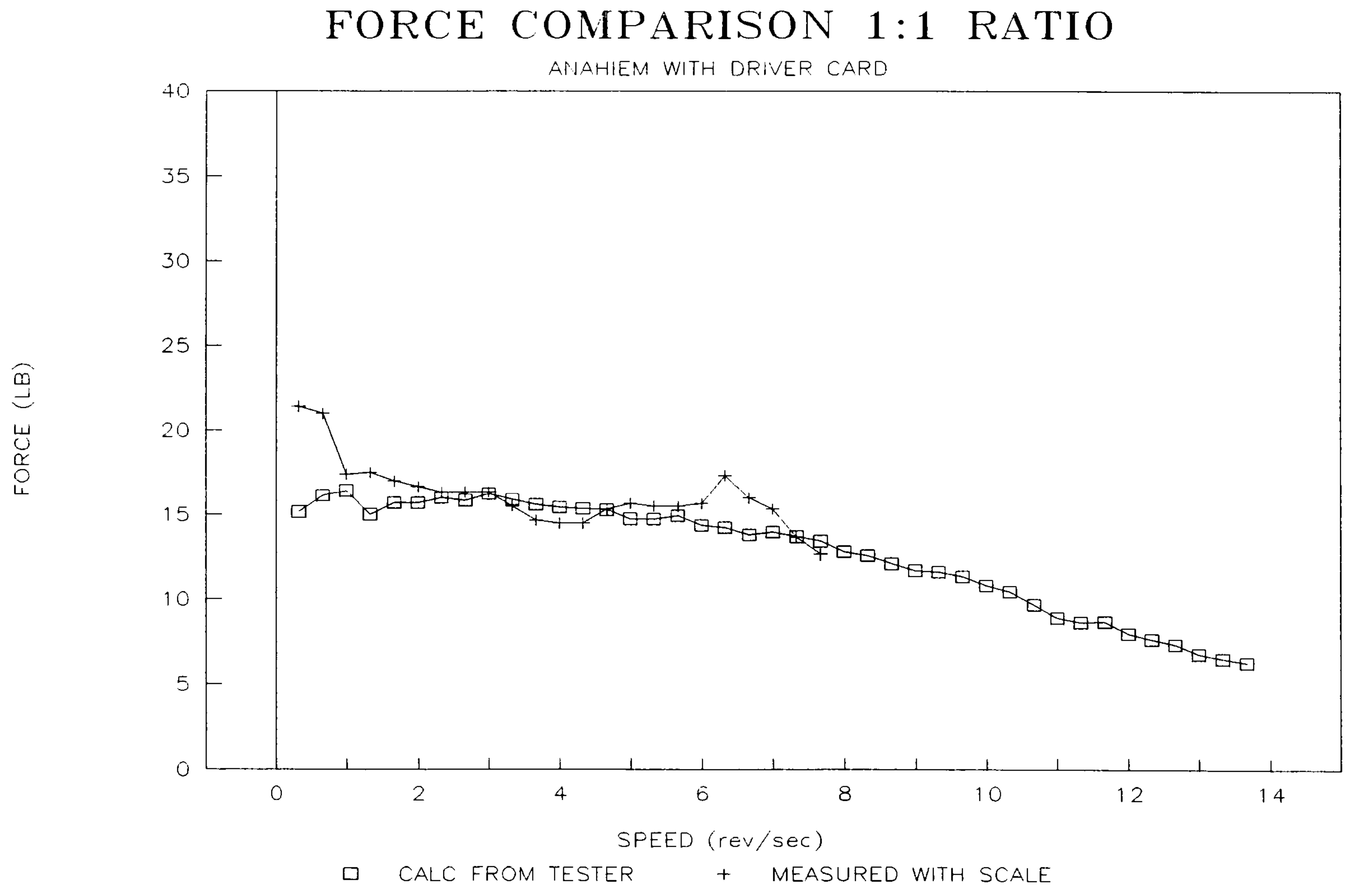


Figure 2.4 Comparison of calculated force and measured force

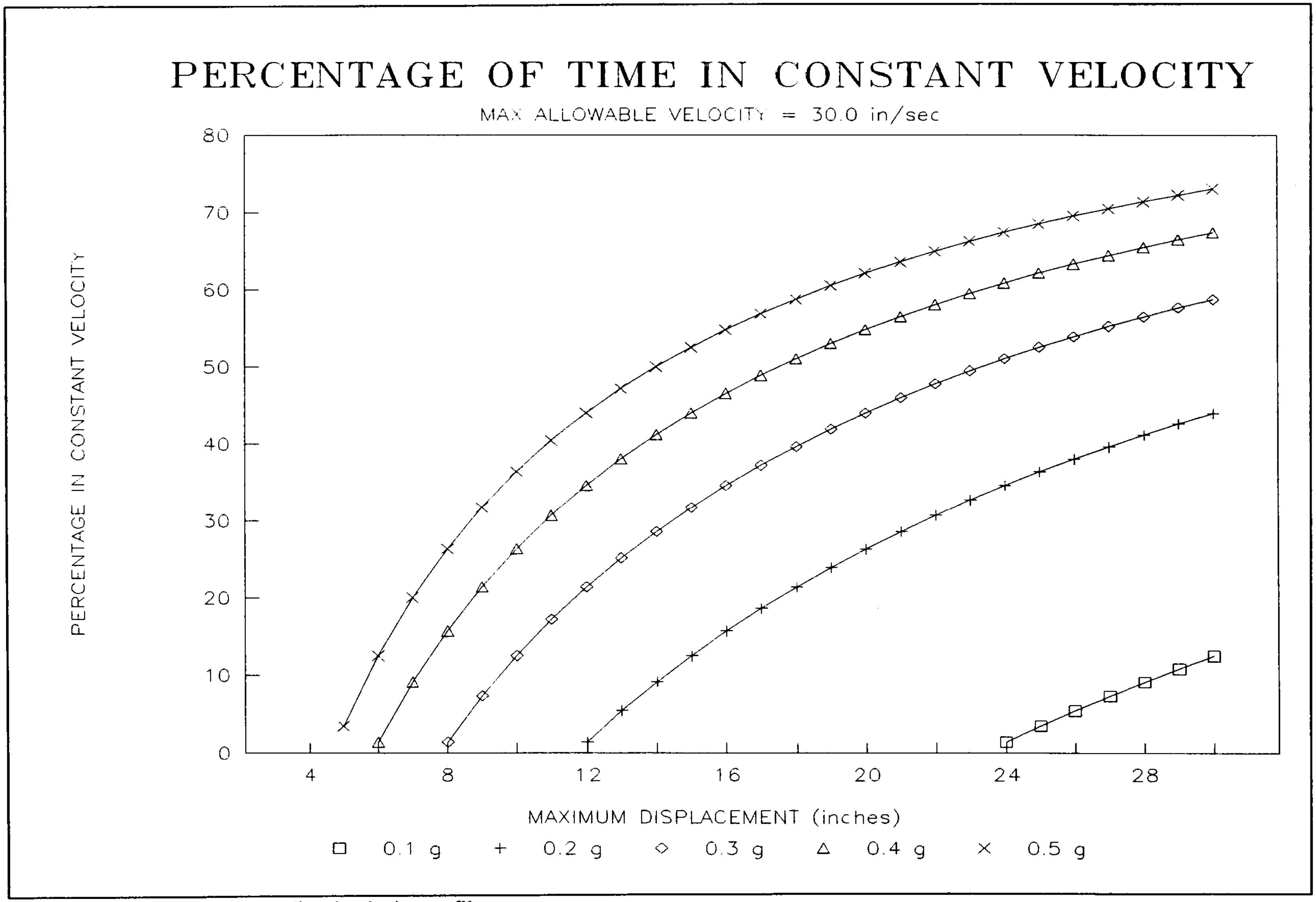


Figure 2.5 Mathematically predicted velocity profile

CHAPTER 3

DISCUSSION

3.1 Introduction

This chapter discusses details of the market survey conducted on robotics characteristics. A short description of the Superior Engineering Design Program (SEDP) robot construction and flexibilities is included in Section 3.4. Point-to-point motion verification of the SEDP robot simulation of the Magic Chef application is discussed in detail in Section 3.5. The proof-of-concept path motion is discussed in Section 3.6. The reader will gain insight into the details of the design and selection process of the necessary improvements to the SEDP robot in Section 3.7. Section 3.8 contains a list of noted failures from endurance tests of the SEDP robot.

3.2 Market Survey

A market survey of robotics applications was conducted in the summer of 1991 as a collaborative effort between the Mechanical Engineering Department and the Marketing Department at the University of Tennessee. Dr. Clement Wilson of the Mechanical Engineering Department and Dr. Pat Postma of the MBA Program initiated the innovative program. The approach involved two individuals, one from engineering and one from business, operating within their respective fields working on a common project.

The Mechanical Engineering Department's Superior Engineering Design Program has developed a cartesian motion robot which it wishes to offer for commercial sale. The MBA internship investigation evaluated cost expenditures and capital investments necessary for appropriate fiscal development. Furthermore, the interaction between the different disciplines was a valuable educational experience for the students involved. The principal student members of the team were Terri McGuire, an MBA intern, and the author.

One purpose of the market study was to examine the desired robotics characteristics which would be useful to local manufacturing companies. The survey, shown in Appendix B, was sent out to 118 manufacturing companies in counties located in and around the University of Tennessee, Knoxville. Thirty-four surveys were returned. These results were tabulated, compared and used to direct the SEDP in it's final design selection of mechanical and electrical components to best meet the desired robotics characteristics determined in the market survey.

The second purpose of the market survey was to identify which companies would consider installing the SEDP robot in their facilities. The best candidate was selected and this robotics task was explored.

3.3 Market Survey Results

The five characteristics of reach, payload, accuracy, cycle time and cost describe a robot. These five characteristics are separated into five categories and graphed. Each of the five characteristics are discussed below.

Figure 3.1 shows reach and payload survey response data. The chart for reach shows that 17.9% of the market could be served by a robot with a reach under 1 foot. A reach of 1 to 2 feet serves an additional 17.9% of the market for a total of 35.8%. A reach of 2 to 4 feet serves an additional 39.3% of the market for a total of 75.1%. A reach of 4 to 8 feet serves an additional 17.9% of the market for a total of 93%. A reach of greater than 8 feet serves the final 7.1% of the market.

The payload chart shows that the largest market of 46.4% requires less than 1 pound of payload. A 1 to 5 pound payload serves an additional 17.9 % of the market for a total of 64.3 %. A 5 to 10 pound payload serves an additional 7.1% of the market for a total of 71.4%. A 10 to 20 pound payload serves an additional 7.1% of the market for a total of 78.5 %. Payloads greater than 20 pounds serve the final 21.4% of the market.

Figure 3.2 shows accuracy and cycle time survey response data. The accuracy range of less than 0.005 inches serves only 7.1% of the market. The region of 0.005 inches to 0.010 inches serves an additional 25.0% of the market for a total of 32.1%. The region of 0.010 inches to 0.050 inches serves an additional 42.9% of the market for a total of 75%. The region of 0.050 inches to 0.250 inches serves an additional 14.3% of the market for a total of 89.3%. The final region of greater than 0.250 inches serves 10.7% of the market.

The cycle time chart shows that the less than 2 second region accounts for 10.7% of the market. The 2 to 10 second region serves an additional 39.3% of the market for a total of 50%. The 10 to 20 second region serves an additional 17.9% of the market for

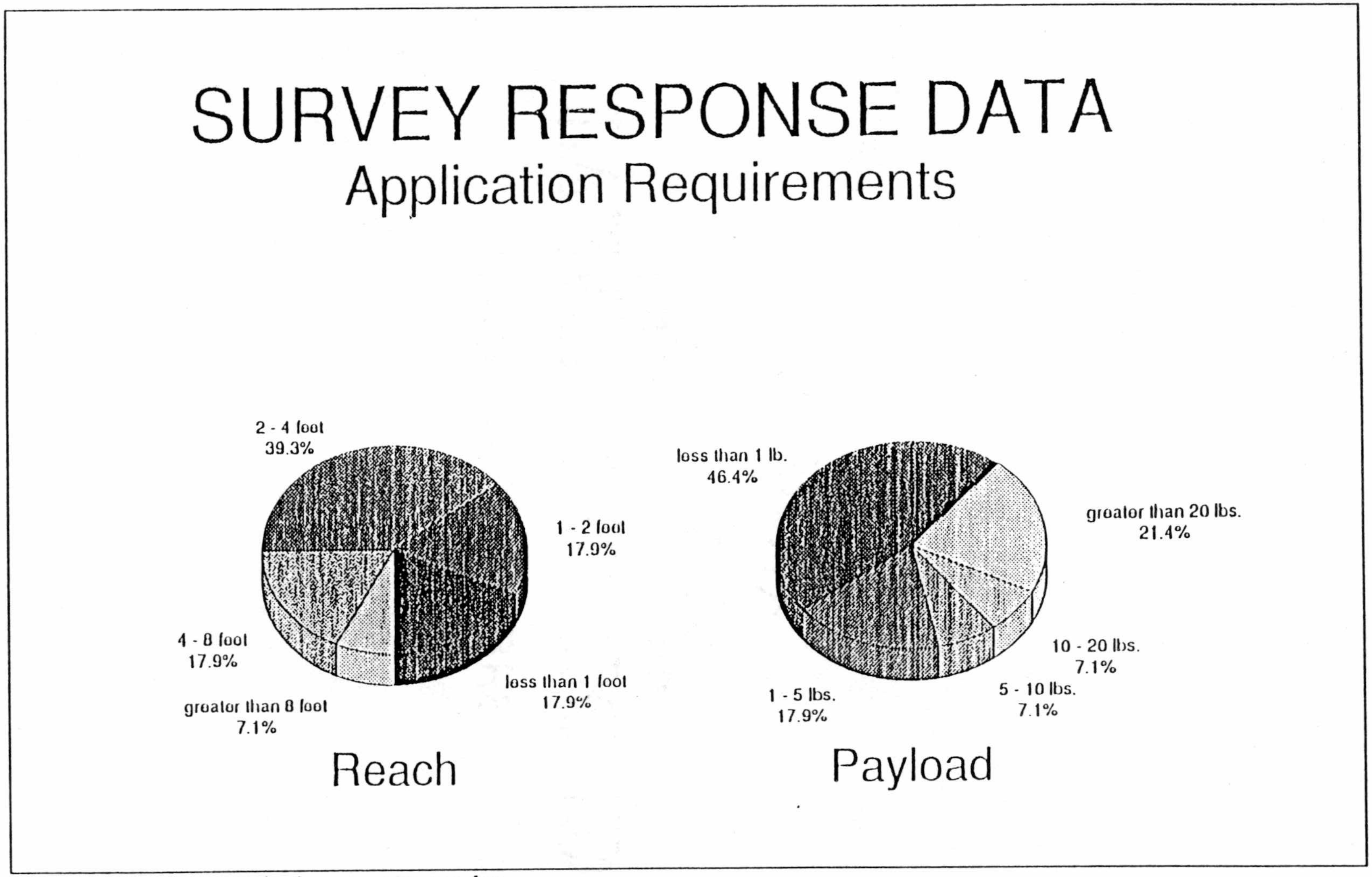


Figure 3.1 Reach and payload survey response data

Source: Terri Nelson McGuire, MARKETING OPPORTUNITY ANALYSIS; The Commercialization of the SEDP Robot, MBA Intern Paper, The University of Tennessee, Knoxville, TN, August 1991, p. II-20.

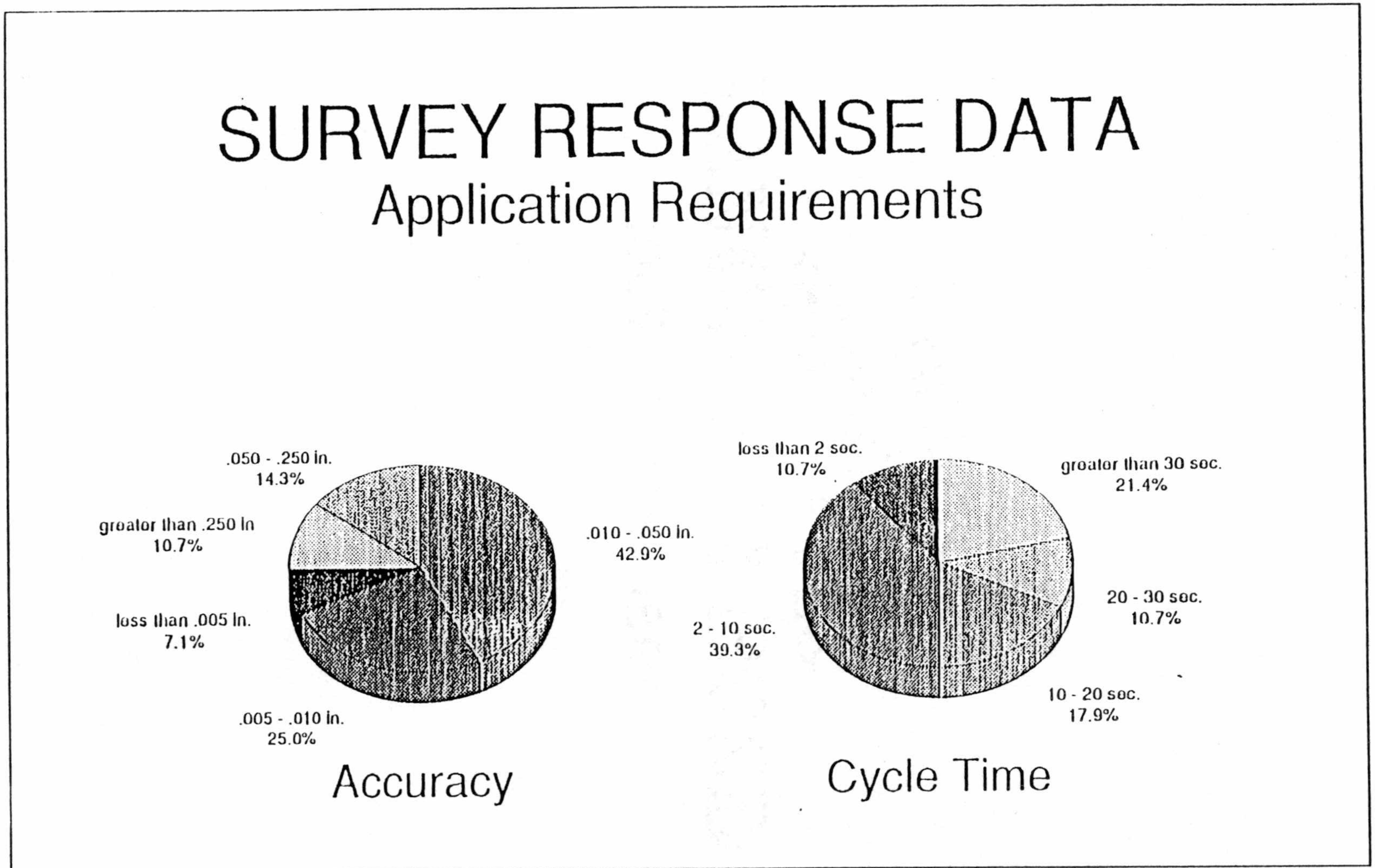


Figure 3.2 Accuracy and cycle time survey response data

Source: Terri Nelson McGuire, MARKETING OPPORTUNITY ANALYSIS; The Commercialization of the SEDP Robot, MBA Intern Paper, The University of Tennessee, Knoxville, TN, August 1991, p. II-21.

a total of 67.9%. The 20 to 30 second region serves an additional 10.7% of the market for a total of 78.6%. The final section of greater than 30 seconds serves the final 21.4% of the market survey data.

Figure 3.3 shows cost justification survey response data. This data was used to determine what a robot containing the necessary capabilities would be worth to the company. The category of less than $5,000 was selected by 22.7% of the respondents. The category of $5,000 to $15,000 serves an additional 22.7% of the market for a total of 45.4%. The category of $15,000 to $25,000 serves an additional 27.3% of the market for a total of 72.7%. The category of $25,000 to $40,000 serves an additional 13.6% of the market respondents for a total of 86.3 %. Greater than $40,000 serves the remaining 13.6% of the respondents.

The task of robot selection must include a balance of the four important performance parameters of reach, payload, accuracy and cycle time. Cost is not considered a performance characteristic. The cycle time can be met but often at the expense of accuracy by operating the robot too close to the maximum speed and losing positional accuracy. In order to eliminate this problem, a matrix type evaluation process was employed. The survey respondents were each assigned a letter or a number. These characters were placed on a graph of reach vs. payload or accuracy vs. cycle time as shown in Figure 3.4 and Figure 3.5 respectively. The letters were then cross-referenced from one graph to the other to see which letters appeared in obtainable regions. The thinner-lined box shows the capabilities best suited for the SEDP robot. The larger and thicker- lined box shows the regions that the SEDP robot can serve with minimal

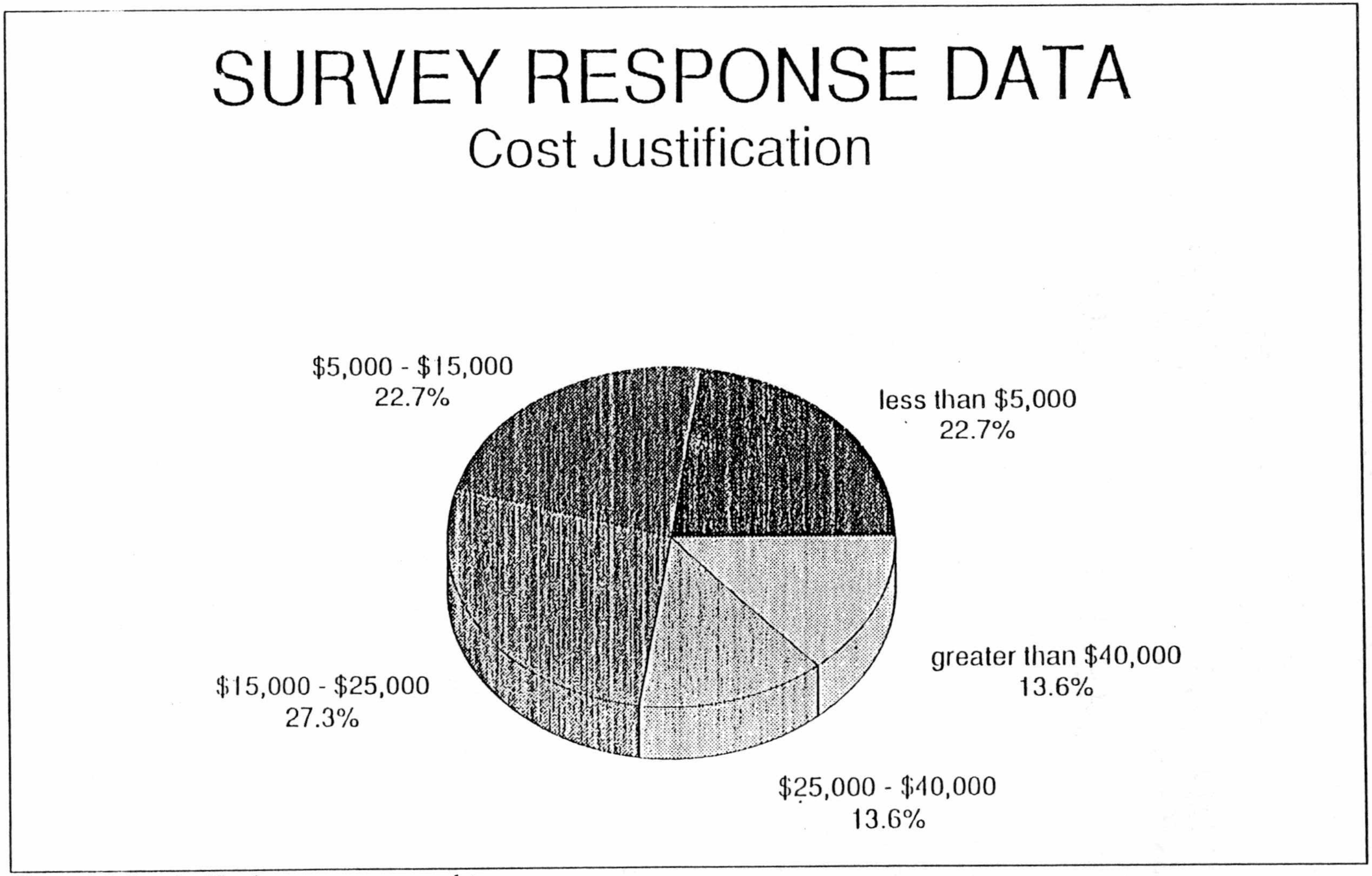
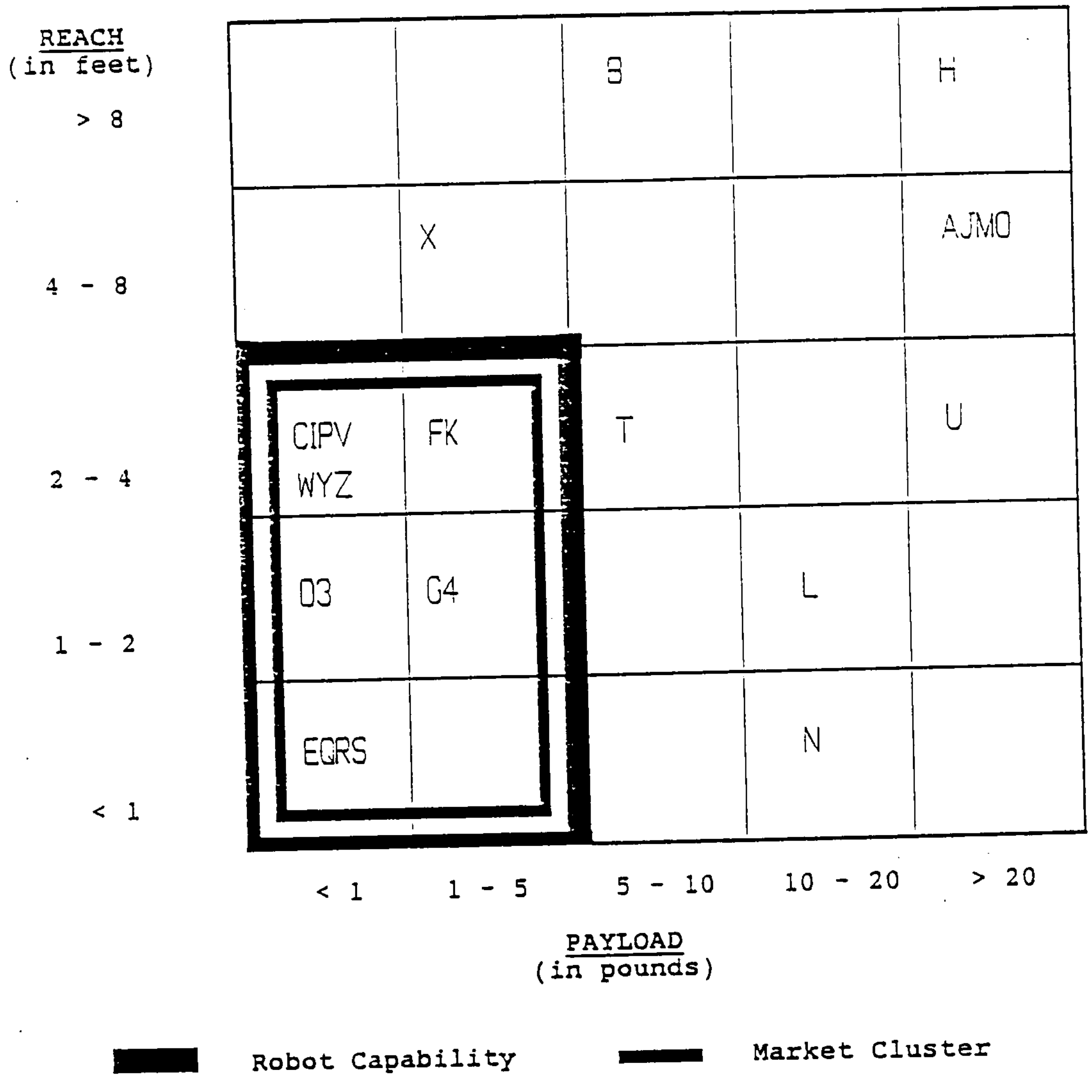


Figure 3.3 Cost justification survey response data

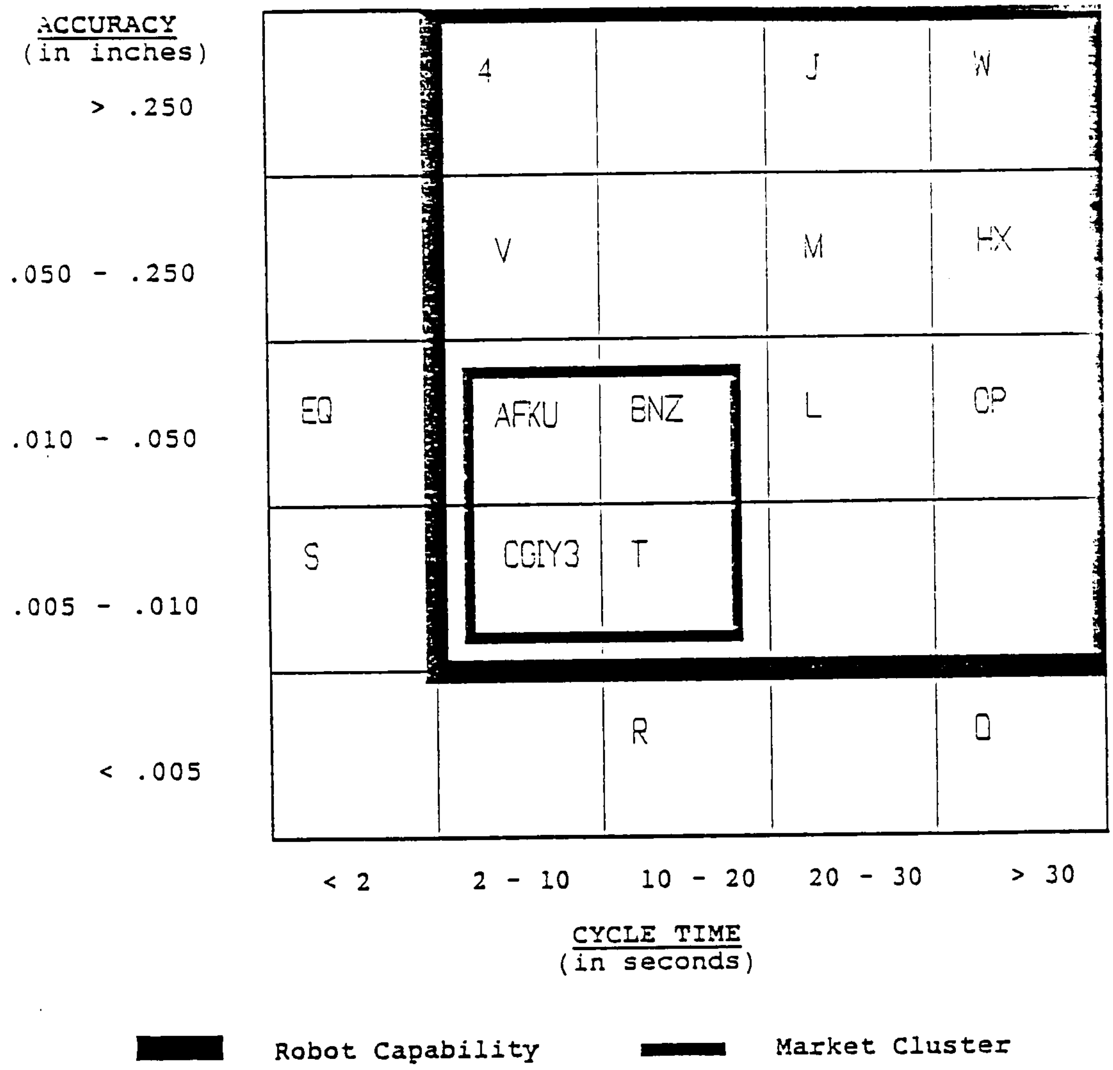
Source: Terri Nelson McGuire, MARKETING OPPORTUNITY ANALYSIS; The Commercialization of the SEDP Robot, MBA Intern Paper, The University of Tennessee, Knoxville, TN, August 1991, p. II-19.



Note: The letters in the table correspond to the companies answering the survey and are identified on the data compilation sheet.

Figure 3.4 Reach and paylod matrix

Source: Terri Nelson McGuire, MARKETING OPPORTUNITY ANALYSIS: The Commercialization of the SEDP Robot, MBA Intern Paper, The University of Tennessee, Knoxville, August 1991, p. II-22.



Note: The letters in the table correspond to the companies answering the survey and are identified on the data compilation sheet.

Figure 3.5 Accuracy and cycle time matrix

Source: Terri Nelson McGuire, MARKETING OPPORTUNITY ANALYSIS: The Commercialization of the SEDP Robot, MBA Intern Paper, The University of Tennessee, Knoxville, August 1991, p. II-23.

modifications. These modifications might include bellow style dust covers for the stainless steel shafting or permanently sealed motors.

The market survey was also used to determine which companies might consider installing the Superior Engineering Design Program's robot in their facilities. Twenty-five of the respondents indicated that they would welcome a follow-up to the survey to find out more on the feasibility of installing the SEDP robot in their facility. After the matrix evaluation was performed, fifteen companies were selected for further evaluation. This number was then narrowed down to eight due to undesirable application specifics such as high dust levels or corrosive environments. Seven more companies were then added because of requirements within the SEDP robot capabilities but outside the best suited region of the matrix or due to expressed interest with working with the SEDP. Due to time constraints, only five of the fifteen selected companies were visited to evaluate application feasibility. Short reports of the five visits are shown in Appendix C.

The market survey indicated that a large majority of applications could be accomplished by either point-to-point or path motion. Laboratory sample handling and tasks requiring extremely high payloads were considered specialty tasks and thus eliminated from the survey summary.

Point to point motion is characterized by moving from one point to the next with no control over the path between the two points. In the case of a cartesian motion robot, the controller moves the X,Y and Z axis such that all axes arrive at the final point at the same time regardless of distances traveled. This type of motion accounted for 57.5% of the applications of the survey. Path motion is one in which the operator programs the path traversed by the robot in moving from one point to another. Path motion accounted for 23.1% of the survey applications.

The difference between the two types of motion can be illustrated with a simple example. Assume there is an application in which the robot is required to move across the diagonal of a square work envelope. In the center of the square is an obstruction. If the motion were point-to-point, the robot would collide with the obstruction. Path motion could be programmed to avoid the obstruction by specifying the path segments. Path motion can also be programmed to follow contours.

A summary of the market survey with respect to the capabilities of the SEDP robot is shown in Table 3.1.

3.4 SEDP Robot Description

The SEDP robot is a cartesian motion robot designed and manufactured to keep cost at a minimum while still maintaining acceptable levels of performance. The construction of the robot is modular to enable the robot to be sized to meet many different requirements while changing only a few components.

The SEDP Robot shown in Figure 3.6 has four degrees of freedom. These degrees of freedom, or directions of motion, allow the SEDP robot to move in four directions either one at a time, all four simultaneously or any desired combination of the four degrees of freedom. The directions of motion are linear in the "X" direction, linear in the "Y" direction, linear in the "Z" direction and rotation (referred to as "theta" in this thesis) about the Z axis.

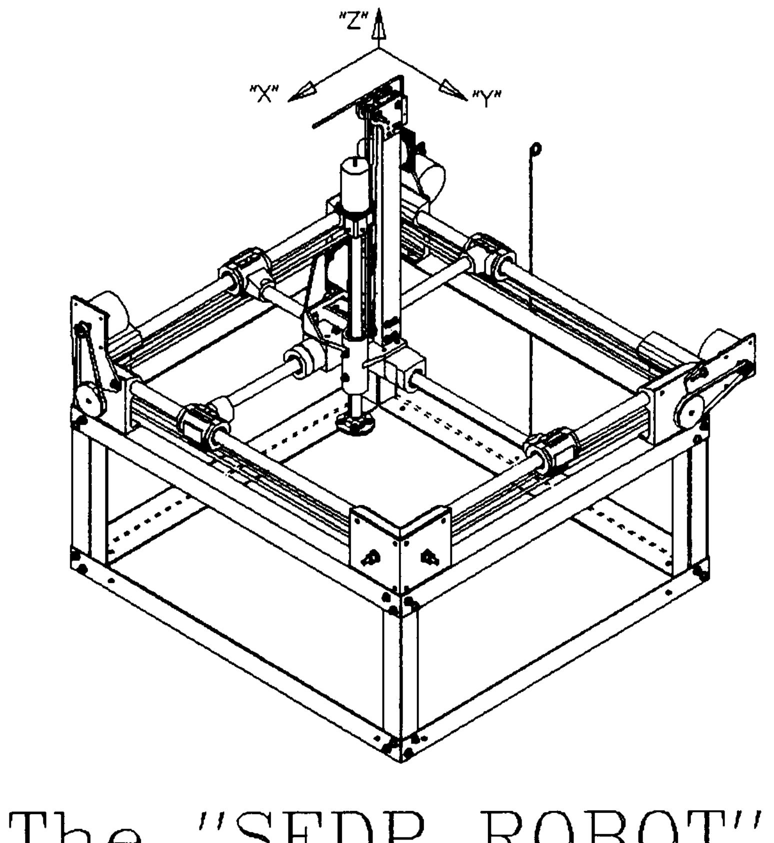


Figure 3.6 The SEDP robot

Source: Michael Earl Kennedy, <u>Low-Volume Production Design and Manufacture of a Low-Cost Industrial Robot</u>, M.S. Thesis in Mechanical Engineering, The University of Tennessee, Knoxville, TN, May 1991, p.49.

Table 3.1 Survey respondents results of robotics characteristics

ROBOTICS CHARACTERISTICS	% OF CHARACTERISTICS ACHIEVABLE BY SEDP ROBOT
Group point-to-point and path motion	80.6%
Reach less than 4 feet	75.1%
Payload less than 10 pounds	71.4%
Accuracy requirements up to 0.005 inches	92.9%
Cycle time greater than 2 seconds and less than 2 minutes	89.3%
Unit cost less than $25,000	72.7%

The frame of the robot consists of vertical and horizontal members as shown in Figure 3.7. The horizontal frame members are 2x2x1/4-inch steel angle and are welded together to provide maximum stiffness. The lower horizontal members rest on four leveling feet to maintain level orientation. The vertical members are 2x2x1/4-inch steel box beam and are bolted to the horizontal members. By selecting the length of these vertical members, the height of the robot can be varied to meet any application. The four corner brackets rest on the top horizontal frame member and are bolted in place as shown in Figure 3.8. Stainless steel shafting connects the four corner brackets and provides

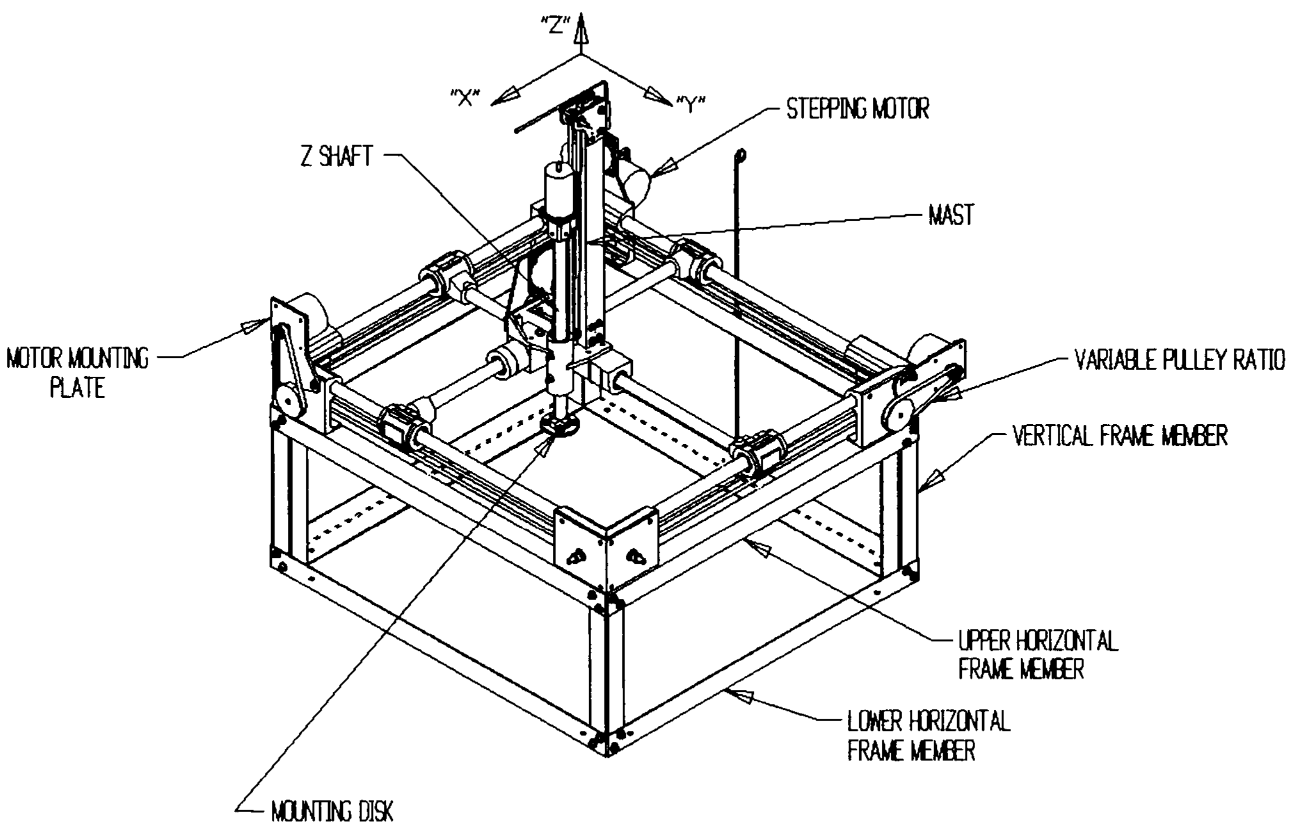


Figure 3.7 Features of the SEDP robot

Source: Michael Earl Kennedy, Low-Volume Production Design and Manufacture of a Low-Cost Industrial Robot, M.S. Thesis in Mechanical Engineering, The University of Tennessee, Knoxville, TN, May 1991, p. 49.

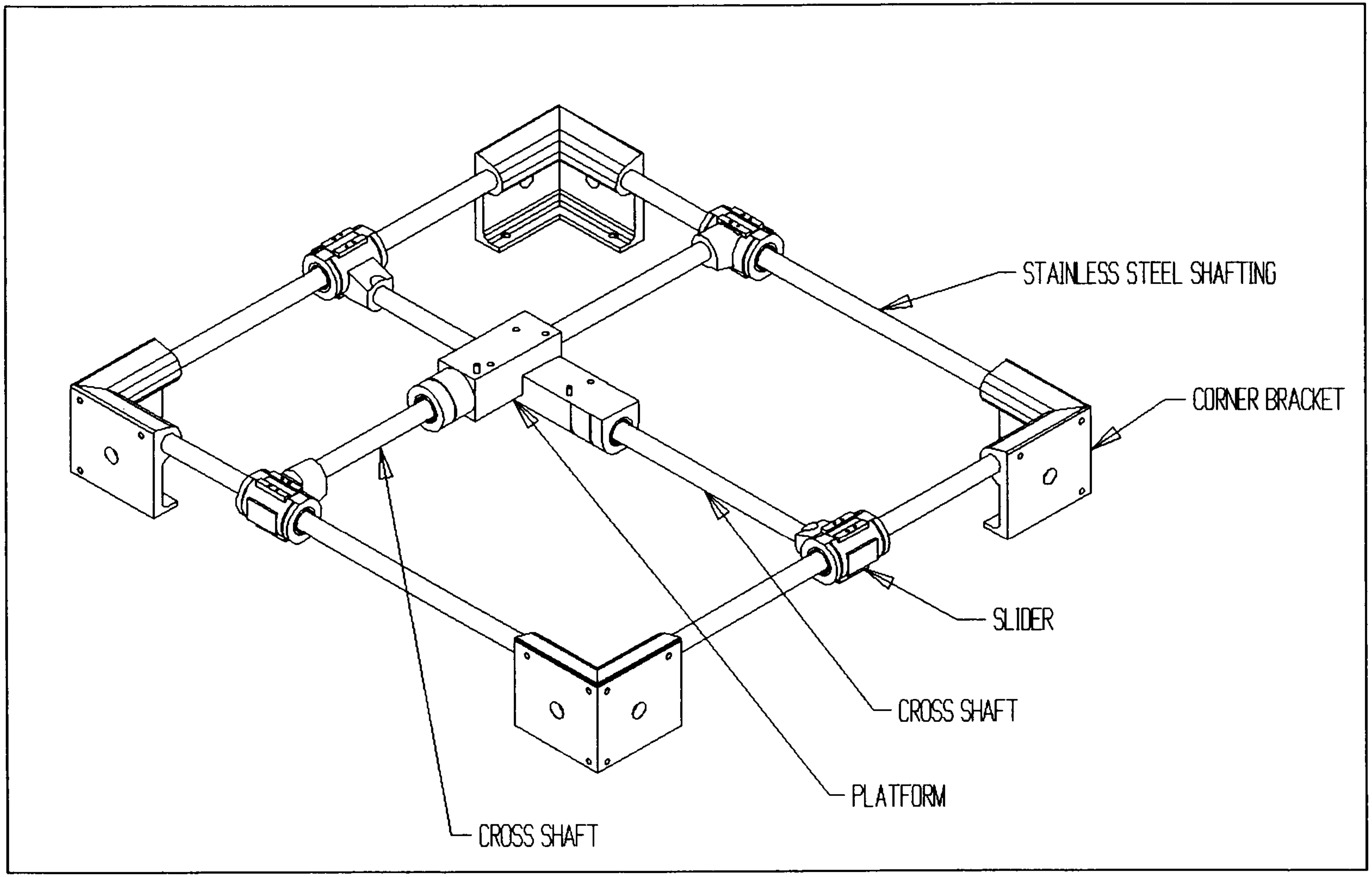


Figure 3.8 Horizontal System

Source: Michael Earl Kennedy, Low-Volume Production Design and Manufacture of a Low-Cost Industrial Robot, M.S. Thesis in Mechanical Engineering, The University of Tennessee, Knoxville, TN, May 1991, p. 70.

smooth, parallel surfaces for the sliders. The cast aluminum sliders contain linear bearings and travel on the shafts and allow for X and Y motion. Two sliders are used for X travel and two sliders are used for Y travel. Cross shafts connect the two X sliders and the two Y sliders. The intersection of these two cross shafts occurs at the platform. The platform forms a base for the mast and the Z shaft as seen in Figure 3.7. The mast provides a second point away from the platform from which the vertical motion, or Z motion, is derived. Rotation about the Z axis is obtained by a stepping motor placed at the top of the Z shaft and connected to the bottom of the Z shaft by an internal connector shaft. This internal connector shaft attaches to the mounting disk to which the end effector is attached.

The X motors are bolted on mounting plates which are connected to two of the corner brackets. A shaft extends through the corner bracket and has a pulley on the inside and on the outside of the corner bracket. The 1.8 degree hybrid stepping motor has a pulley attached to the output shaft and is connected through a timing belt to the outside pulley of the shaft in the corner bracket. The motor mounting plate allows belt tension to be adjusted as well as various pulley reduction ratios to be employed. The inside pulley is connected through a timing belt to the opposite corner bracket. The timing belt passes under the slider and is attached to the slider through a belt tensioning mechanism. The "Y" motion is obtained in the same manner except that the orientation is 90 degrees from the "X" orientation.

The "Z" motion is driven by a similar 1.8 degree hybrid stepping motor as used in the "X" and "Y" motion. The stepping motor is attached to a mounting bracket on the platform which allows for belt tensioning and pulley reduction changes. The stepping motor output shaft has a drive pulley attached which is connected through a timing belt to a pulley on the mounting bracket side of the platform. A shaft through the platform connects the motor driven pulley to the "Z" drive pulley. The "Z" drive pulley is connected through a timing belt to a shaft at the top of the mast. The timing belt is attached to the top of the "Z" shaft. Belt tension is adjusted at the top of the mast.

Stepping motors were selected for this application due to their ability to change direction instantly and for their precise motion control at low cost. The stepping motor has a toothed rotor and stator that provide discrete 1.8 degree steps. The stator magnetic field is oriented such that the rotor moves to an equilibrium position. The rotor will stay in this equilibrium position until the stator field is changed, at which time the rotor moves to a new equilibrium position. Constant rotation is provided by moving the stator field in a continuous cycle and having the rotor "catch up". Direction changes simply involve the reversal of the direction of motion of the stator field which draw the rotor in the opposite direction. While not examined in this thesis, five phase stepping motors are available that provide greater resolution and smoother torque curves.

The modular design was incorporated to maintain a high level of commonality between robots while still allowing diversity in robot operation and size. The size of the robot is changed by using different lengths on the stainless shafting, horizontal frame members and timing belts. The size can be varied from a 2 foot by 2 foot robot to an 8 foot by 8 foot robot in any desired increment. All castings, drive systems and connectors are common regardless of robot size.

Another effort in the design and fabrication of the SEDP robot was to use commercially available parts. The use of readily available parts lowers cost and reduces inventory. By having the majority of the parts available in catalogs or in vendor stores, the robot parts can be quickly and economically purchased and replaced. See Mike Kennedy (1988) for more details on the design of the SEDP robot.

The SEDP Robot is controlled through a personal computer. The minimum requirements of the personal computer are a 286 processor with a clock speed of at least 10 MHz. There should be 1 Megabyte of Random Access Memory (RAM) and 20 Megabytes of hard drive memory for proper program and path storage. While a computer with a high density external drive can store the necessary programs, a hard drive is recommended. A computer with more capability (higher clock speed) will not improve the SEDP robot performance. The computer should have two parallel ports for motor control and signal inputs and outputs. A monochrome monitor is all that is necessary to run the SEDP robot computer program.

The computer program calculates all necessary acceleration ramps and step sequences. The computer is connected to stepping motor drivers that convert the binary computer output to signals for the stepping motors. See Master's Thesis by Steve Johnson for more details on the programming of the SEDP robot [Johnson, 1990].

The SEDP robot performance has been characterized through compliance testing and statistical modeling of performance characteristics. The maximum reach of the SEDP robot is approximately 8 feet. This reach can be extended in extreme cases to almost 12 feet. The maximum payload of the SEDP robot is 20 pounds with a safety factor of 1.5.

The accuracy of the SEDP Robot is variable. With a 3:1 gear ratio on the "X" and "Y" drive systems the positioning accuracy of the robot is 0.005 inches. Changing the drive ratio will adjust the accuracy by the linear ratio of drive ratio to accuracy. If, for example the ratio is changed from 3:1 to 1:1, the positional accuracy will decrease to 0.015 inches. The maximum speed of the SEDP robot is approximately 48 in/sec with all four degrees of motion. This speed is the algebraic sum of 32 in/sec X motion, 32 in/sec Y motion, 12 in/sec Z motion and 8 in/sec theta motion. This speed was obtained with a 1 pound payload. The price of the SEDP robot is approximately $15,000 including the personal computer, computer programs, motor drive circuits and all necessary mechanical and electrical connectors. This price does not include the cost of the end-of-arm tooling which is application specific. See Kennedy for cost details [Kennedy, 1991]. See Williams for compliance testing [Williams, 1992].

3.5 Point-to-Point Application

3.5.1 Introduction

The market survey indicated that point-to-point applications constituted the largest share of the market. A specific application was examined at a Magic Chef division of Maytag in Cleveland, Tennessee. This application involved moving 6.5 oz. steel gas stove burners from a set point and filling a pallet of 36 openings. This task involved the design, fabrication and testing of a prototype unit. Control signal communication between the robot and other equipment was demonstrated.

3.5.2 Robot specifications for application

The SEDP robot needs to be approximately 4 feet by 5 feet with a vertical travel of 1 foot to allow the end effector to touch all points in the work envelope. Theta motion is not necessary since the burners are round and orientation in the pallet is not critical.

The burners are fabricated on a carousel and incremented at 30 degree steps. Burners are unloaded from the carousel by hard automation at a rate of 12 burners per minute. The longest path segment is: grasp burner, 3 inches Z motion, 36 inches X-Y motion, 3 inches Z motion, release burner, 3 inches Z motion, 36 inches X-Y motion, 3 inches Z motion. The robot must therefore travel at an average speed of 20 in/sec to move a burner to the farthest point in the pallet and return before the next burner comes to the end of the unloading chute. This average speed does not include pauses necessary for air manifold pressurization. If pauses are included to allow proper gripper function, the required average speed of the robot would increase to approximately 24 in/sec.

3.5.3 End effector

A 3 jaw pneumatic gripper was selected as the end effector for this application. The selection was based on the inherent self-centering characteristics of the three point design. Pneumatic actuation was selected over hydraulic actuation because of speed and fluid leakage considerations. Magnetic actuation was not selected for unprecise burner manipulation. If the burner is picked up off center, it will remain off center. This solution creates tolerance build-up which is undesirable.

The plastic blanks on the end effector were designed to pick up burners from the outside lip and to allow for maximum burner mislocation while still gripping the burner.

The gripper blanks shown in Figure 3.9 were made from acetal for impact resistance, dimensional stability and good machinability. Furthermore, plastic eliminated damage to the burner from the gripper. Appendix A shows engineering drawings of the gripper blanks. Figure 3.10 shows the plastic gripper blanks attached to the three jaw pneumatic gripper.

The design of the end effector allows for the burner to be placed within 25% of its overall diameter off center with the gripper still able to pick up the burner. This translates to having the 3.88 inch diameter burner 1 inch out of place with the gripper still able to grasp the burner. The gripper blank was designed to allow the robot to pick any burner out of the pallet without interfering with the adjacent burners.

The center flat portions of the gripper blanks are designed to grasp rods. This configuration was designed to allow the robot to perform other point-to-point tasks without purchasing more expensive hardware.. Flexibility is demonstrated by using the same robot to perform various tasks. The gripper blank design provides line contact with 1/4 inch rods. Rods of 3/16 inch diameter through 7/16 inch diameter can be grasped with the gripper.

3.5.4 Signal interfaces

The input signal interfaces used in this application include a micro-switch at the pick-up point that indicates the presence of a burner ready to be picked up. If there is no burner present, the robot will pause until a burner trips the micro-switch and then the motion will be continued. A second switch indicates that the pallet is in place and is ready to be filled. If the switch is open, the robot will pause until the switch is closed

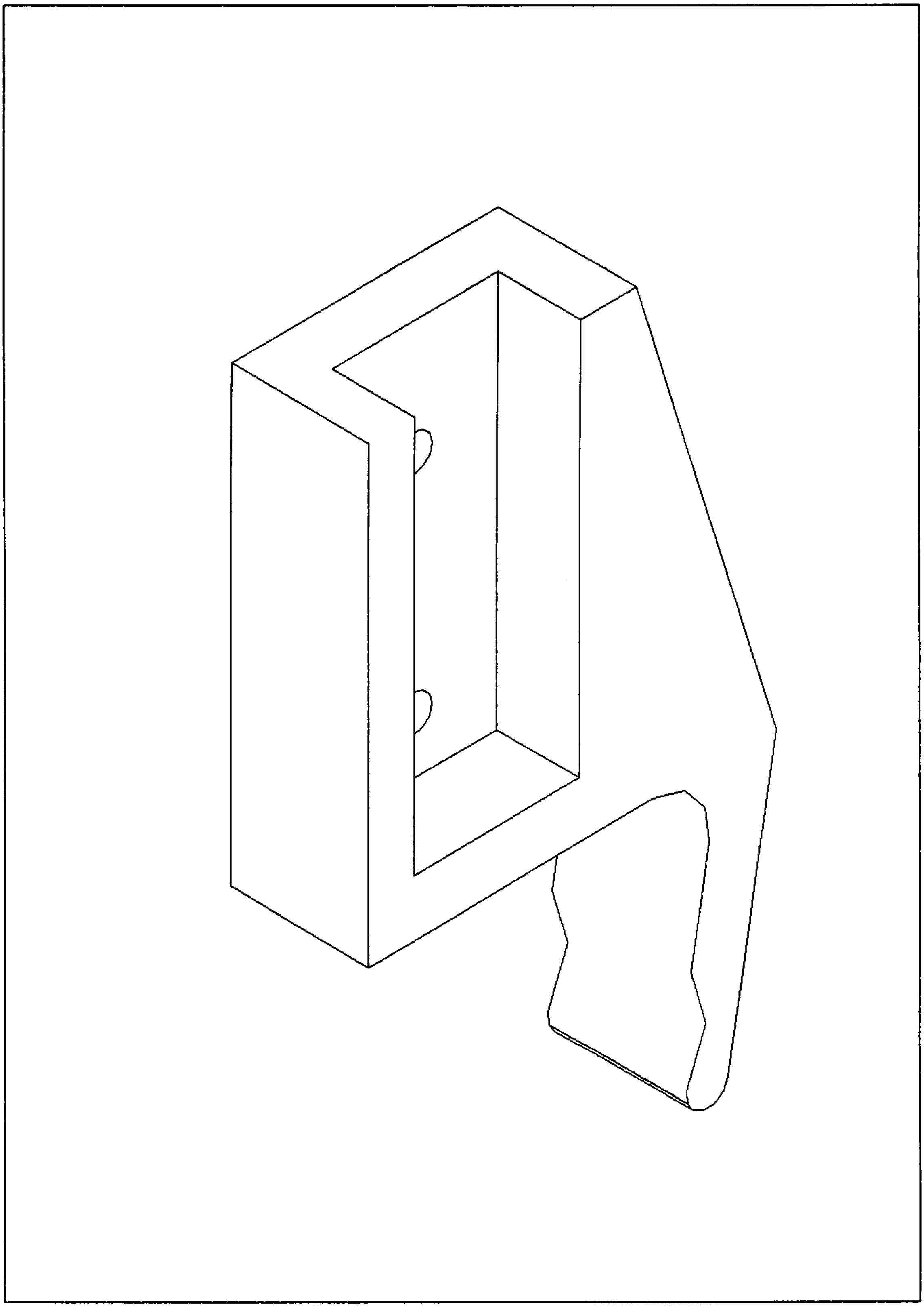


Figure 3.9 Gripper blanks

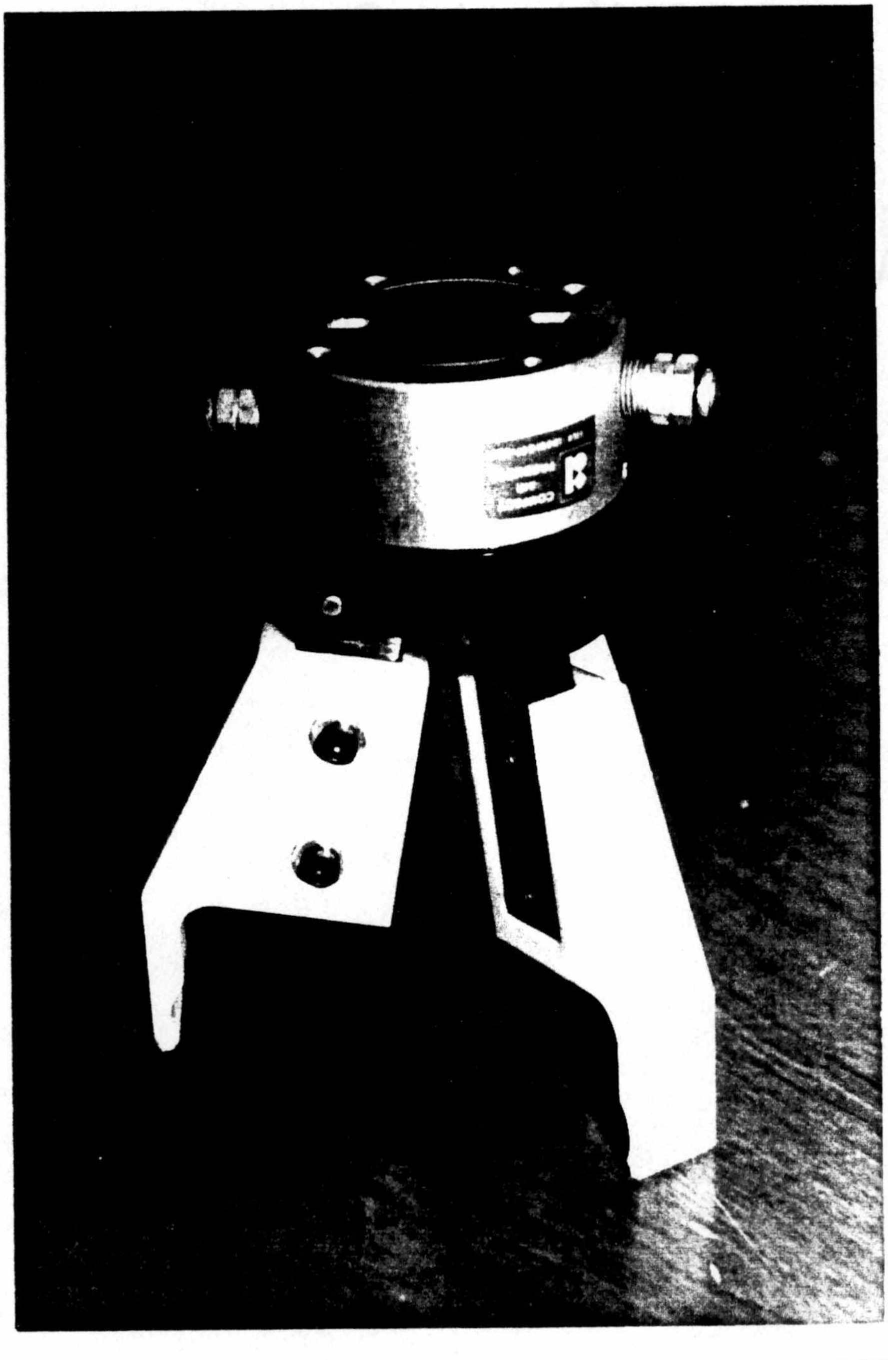


Figure 3.10 Gripper blanks attached to pneumatic gripper

and then initiate the filling of the pallet. This switch mimics the signals that would be present if the pallets were moved in and out by conveyors and demonstrates the signal inputs necessary for this application. Figure 3.11 shows the two input switches and the pallet.

The robot has the ability to handle 2 input signals and 2 output signals. One output signal is used to control the pneumatic solenoid which manipulates the end effector. The second output signal can drive a second gripper or can provide a 24 volt, 1 amp signal for whatever purpose is necessary in a specific application. Both outputs have a second set of contacts so a switch closure can be made from either of the output signals. See Appendix H for circuit diagram.

3.5.5 Results

The end effector functioned as designed. The gripper was able to grasp the burners even when the burners were placed within 1 inch off center. The gripper proved to be functional in moving 1/4 inch rods. The 3-jaw gripper assisted in grasping the rods when they were leaning to one side in the fixture.

The signal interfaces were completely functional. The robot paused or continued according to the input signal.

The cycle time was met for the Magic Chef application. The robot picked up the first burner, placed it in the furthest point in the pallet, returned and pick up the second burner in approximately 4.5 seconds. The robot loaded the entire pallet in 2 minutes and 15 seconds. The robot was operated with a 1:1 gear ratio in the X-Y system and a

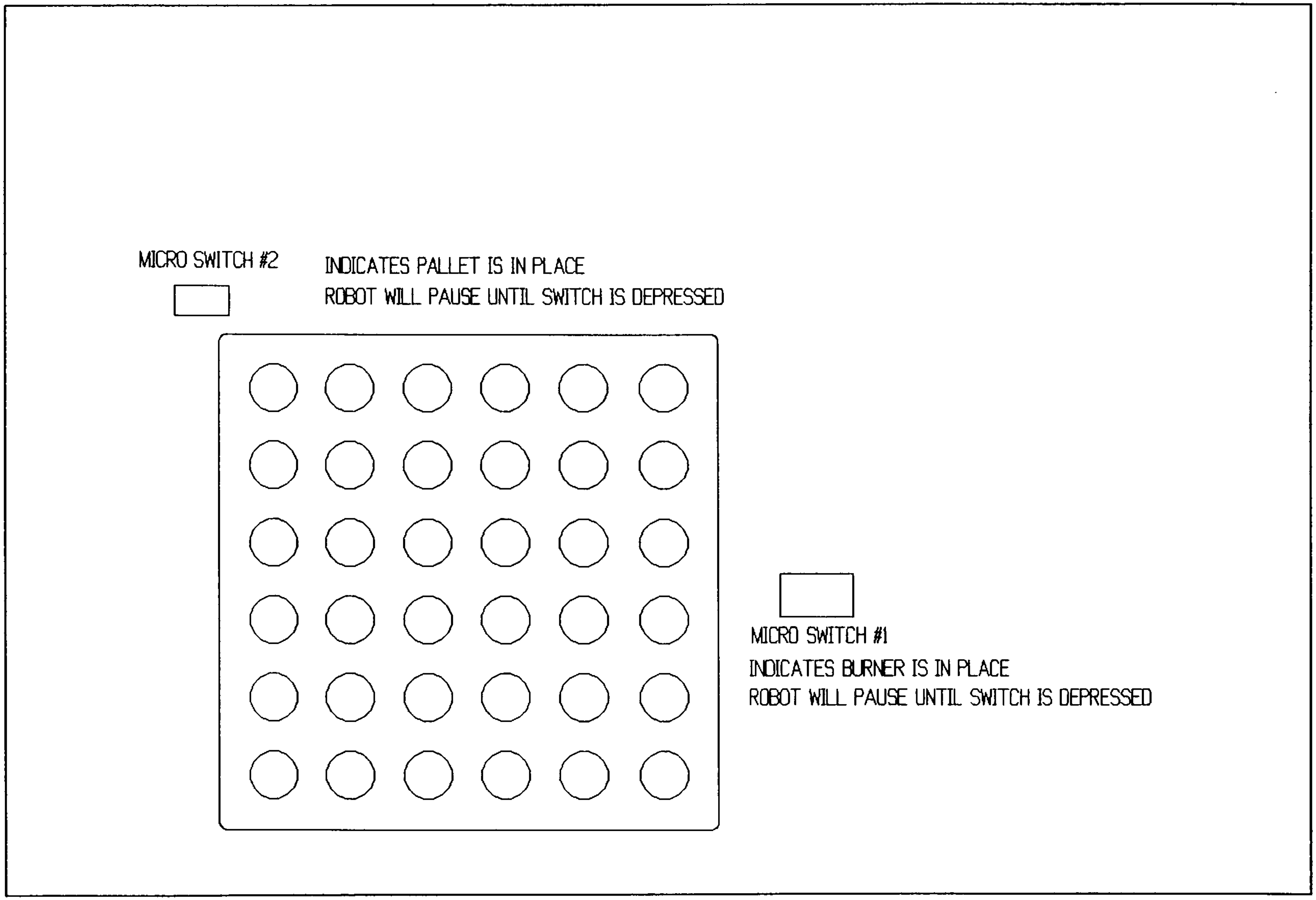


Figure 3.11 Magic Chef input switches and pallet

3:1 ratio in the Z system. The acceleration ramps were set at 0.2g's in X-Y motion and 0.25g's in Z motion.

3.6 Path Motion Application

3.6.1 Introduction

The market survey indicated that the second largest market of robotics applications were those involving path motions. No specific path motion application was identified in the market survey.

Without a specific application, a generic path motion application was designed. This application was to attach an air grinder to the SEDP robot and rout wood. This application was considered to be one of the most stringent requirements that the SEDP robot would likely encounter. With a proof-of-concept verified, any task of less stringent requirements would also be achievable.

3.6.2 Robot specifications for application

The SEDP robot requires some components to be redesigned for an application such as wood routing. The size of the robot is determined by the application so no specifics can be stated regarding size. The stainless steel shafting must have dust covers to eliminate dust and debris from entering the slider bearings. The stepping motors need to be completely sealed to keep out foreign materials. The home calibration sensors must be shielded from dust to avoid false readings. The control cabinet needs a better filter installed to keep dust out of the electronics. The computer must be encased in an industrial cabinet or placed outside the dusty environment.

3.6.3 End effector

An air grinder was selected for the routing operation due its small size and high power output. The air grinder selected operates at 4 CFM at 90 psi. The shop air supply was 100 psi which dropped to 76 psi with the air grinder operating due to the large losses encountered in long air lines. While the pressure was below the design operating limits, there was sufficient power for this operation. More air pressure would allow the SEDP robot to move at faster speeds while maintaining clean cuts.

The air grinder was attached in-line with the Z shaft as shown in Figure 3.12 for the in-line attachment. A second method of attaching the air grinder to the Z shaft that was considered was the offset attachment. As shown in Figure 3.12, the in-line attachment caused a longer moment arm, a, as compared to the offset attachment moment arm b. However, the larger forces created by the larger moment arm were considered easier to overcome compared to the complexities of programming paths with an offset, c, in one axis and not the other axis. The two attachment points on the Z shaft were selected for lighter weight and higher stiffness considerations than a single, wider attachment point. The lower air grinder attachment point holds the tool rigidly. The upper attachment point allows for alignment of the air grinder within the jig with the two opposite facing U-bolts. A photograph of the grinder jig attached to the robot is shown in Figure 3.13.

3.6.4 Results

The air grinder attached to the SEDP robot performed the desired task. The router bit used was a 45 degree 1/2 inch beveled carbide bit. The robot paths were run on

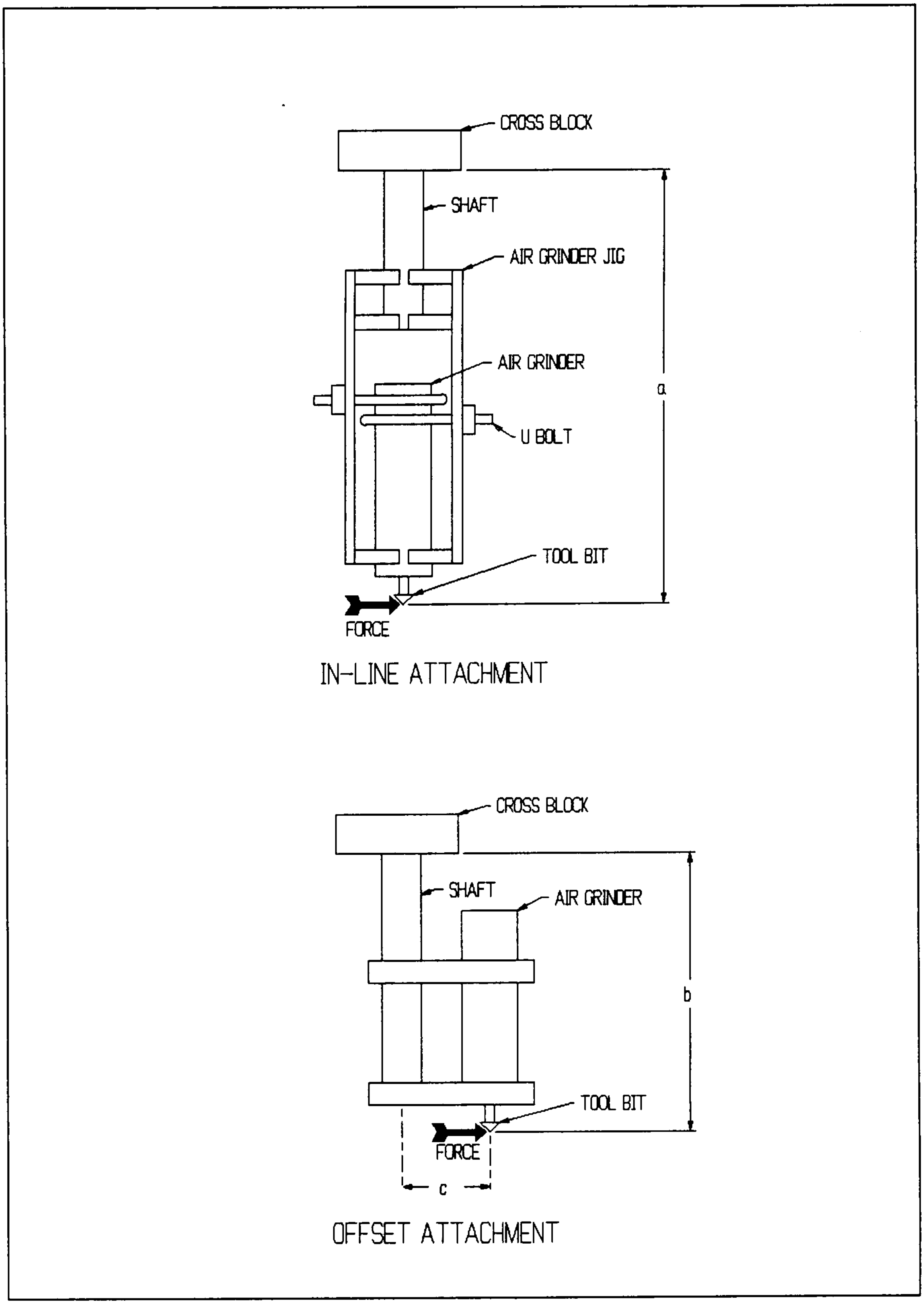


Figure 3.12 Air grinder attachment schemes

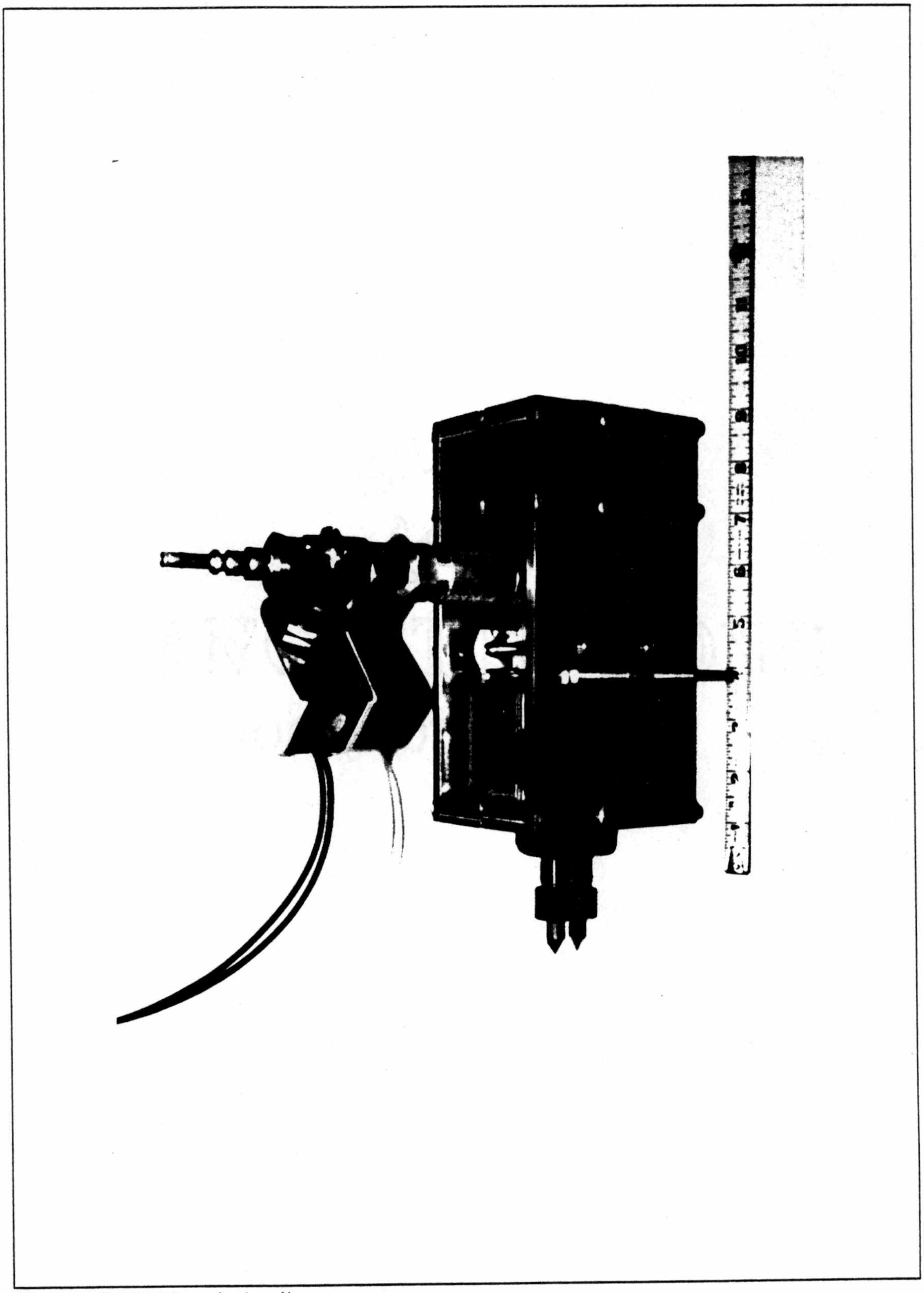


Figure 3.13 Air grinder jig

several types of wood. The path spelling "S.E.D.P. ROBOT" was cut in particle board, Douglas Fir and medium density fiberboard. Portions of letters were cut in red oak, melamine and plywood.

Since different types of wood require different feed rates and depths of cuts, characterizing the router operation would be beyond the proof-of-concept attempted in this thesis. A slow deep cut followed by a second, faster shallow cut was found to produce better results. For example, in cutting the medium density fiberboard, the first cut was at 1 in/sec and a depth of 1/4 inch. The second cut was the same depth and speed. In actuality, the second pass had some depth since the loading on the Z belt was reduced and thus had less compliance. The second cut allowed the air grinder to smooth out the bevels while operating at a much higher speed than in the first cut. When the red oak was cut, the speed was increased to 3 in/sec and the depth reduced to approximately 1/8 inch. Higher speeds were necessary to avoid burning the wood. The smaller depth of cut was needed to avoid "wavy" motion in the oak grain structure. A summary of the tests run is included in Table 3.1.

The robot was operated with a 1:1 gear ratio for the X-Y system and a 3:1 gear ratio was used for the Z system. A 1:1 gear ratio was selected as a worst case. According to Williams the compliance of the X-Y system is approximately 0.020 inches for a 3:1 gear reduction [Williams, 1992]. Theoretical results predict 0.005 inch accuracy based on motor resolution capabilities. Therefore, a 0.016 inch belt "stretch" is encountered in the robot mechanical drive system. This "stretch" would remain constant

Table 3.1 Summary of routing operations

TYPE OF WOOD	DEPTH OF CUT	ROBOT SPEED	# OF PASSES	COMMENTS
DOUGLAS FIR	1/8	0.5	2	SMOOTH
	1/8	1.0	2	SOME TEARING
MDFB	1/8	1	1	SMOOTH
	1/8	2	1	SOME WAVE
	1/4	1	2	SMOOTH
	1/4	2	2	SMOOTH
MELAMINE	1/8	1	2	SMOOTH
	1/4	1	2	SMOOTH
PARTICLE BOARD	1/16	0.125	2	SMOOTH
	1/8	0.125	2	SMOOTH
	1/4	0.125	2	SMOOTH
	3/8	0.125	2	SOME WAVE
	1/2	0.125	2	WAVE
	1/4	1	1	SOME WAVE
	1/4	1	2	SMOOTH
	1/4	1 THEN 2	2	SMOOTH
PLYWOOD	1/4	0.5	1	SOME WAVE
RED OAK	1/8	0.5	1	BURNED
	1/8	1	1	SOME BURNING
	1/8	2	1	SMOOTH
	1/8	3	1	SOME TEARING

The principle parameters of this routing study are listed in the headings of Table 3.1. A successful operating space can be defined by varying the principle parameters as shown in Table 3.1.

and be added to the theoretical 0.015 inch 1:1 ratio. The overall compliance would then be approximately 0.030 inches in the X-Y system. While a 1:1 gear ratio performed well, a 3:1 gear ratio is recommended for better accuracy. The acceleration ramps were set at 0.2g's for X-Y motion and 0.25g's for Z motion. Visual deflections of the robot were not noted to be excessive and the robot did not lose phase even after loading the air grinder heavily.

3.7 Necessary Improvements

This section addresses several problems in the SEDP robot that needed to be resolved before the robot is ready for industrial applications. These problems are stated and their suggested solutions described. A brief summary of component costs is included in Appendix D.

3.7.1 Power-off brake

Problem

There existed a situation in which the Z shaft "fell" to the farthest extension due to either deliberate or unintentional power interruptions. This situation was deemed unacceptable due to high impact forces generated from carrying large loads. There was also potential for damage to expensive end effectors or damage to objects in the work envelope.

Solution

The solution to the power-off problem was determined from a weighted average analysis. Four possible solutions were considered from a preliminary engineering analysis for further study. The four possible solutions were an electromagnetic power-off brake, a ratchet and solenoid pawl system at the top of the mast, a rack machined in the Z shaft with a solenoid driven pawl or a frictional wedge between the Z shaft and the cross block assembly. These four solutions were compared based on cost, reliability, safety and ease of installation. Numerical values were assigned to the four comparative factors. The weighted average results, shown in Table 3.2, indicate that the best overall solution was the electromagnetic power-off brake, which is shown in Figure 3.14 attached to the Z motor. While this solution had the second highest cost, the proven reliability in similar applications and ease of installation were seen as assets which offset the higher cost. Modifications made to the system included spacer blocks to provide clearance between the brake and the top Z casting. Spacer blocks also required the use of longer bolts and a longer shaft through the cross block. There was no extra safety requirement to consider for the electromagnetic brake. The static torque of the selected brake was 240 oz-in or approximately 40% more static torque than the stepper motor can produce.

The ratchet and pawl at the top of the mast was eliminated due to the added weight at the top of the mast and the impact loads from sudden stops. Cost was the second lowest for the ratchet and pawl, but the extra machining time required for attachment to the mast while maintaining proper positioning was comparable to the electromagnetic brake. The ratchet and pawl system would require extra safety covers to enclose the gear teeth and other possible pinch points.

The rack system was eliminated due to the prohibitive cost of machining the case hardened stainless steel Z shaft. The rack system eliminated approximately 3 inches of Z travel and would require extra safety covers.

Table 3.2 Robot brake weighted average

	WEDGE	ELECTROMAGNETIC POWER-OFF BRAKE	RATCHET AND PAWL	RACK
RELIABILITY 4	4 (16)	1 (4)	2 (8)	3 (12)
SAFETY 3	4 (12)	1 (3)	3 (9)	2 (6)
COST 2	1 (2)	3 (6)	2 (4)	4 (8)
TIME 1	3 (3)	1 (1)	2 (2)	4 (4)
TOTAL	33	14	23	30

Numbers associated with factors on right indicate weight assigned to each of the factors. High numbers are more important than low numbers. Numbers in parenthesis indicate product of factor and weighted average numbers. Low point score denotes best overall solution.

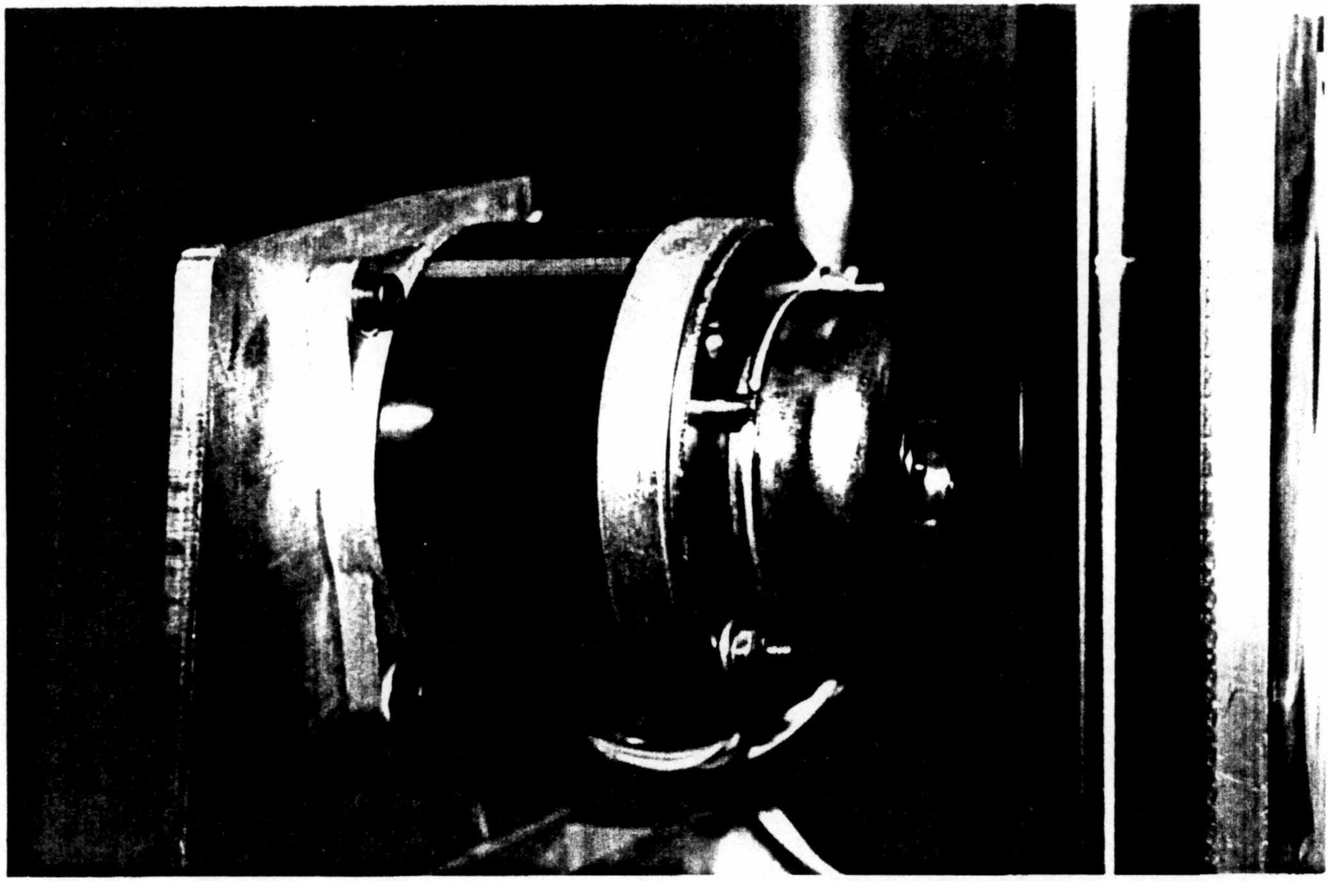


Figure 3.14 Electromagnetic power-off brake attached to Z motor

The frictional wedge was the lowest cost solution, but was eliminated because of an approximate 3 inch reduction in the Z travel. The frictional forces were determined to be quite variable depending on the lubrication used on the Z shaft. There was a concern of wedging the unit such that the motor could not overcome the frictional force and would require operator intervention to reset the robot. Operator intervention was considered an undesirable condition to be avoided.

Results

The stepper motor had a four bolt pattern holding the motor together. Two bolts were replaced with longer bolts and used to hold the brake in place. The other two bolts were left undisturbed to maintain stepper motor integrity. The electromagnetic brake was installed on the back of the double shafted Z motor and bolted in place. The brake was burnished for 3 minutes at 320 rpm as recommended by the brake manufacturer. The brake was tested and found to stop the Z shaft at power off within 5/16 inch with no load. The robot was next loaded with 32 pounds. Power was shut off and the brake stopped the load within 2 inches of travel. These results were determined to be satisfactory for precluding damage to the end effector or to objects within the work envelope at power off conditions.

3.7.2 Packaged electrical components

Problem

Previous to this thesis, all the controlling electrical components were not in a convenient arrangement. As part of this project, the components were gathered and placed in a single, consolidated unit. The components required to be more user-friendly and those most susceptible to improper electrical connections were given special attention.

Solution

The items packaged into a single unit were the power supply, the motor driver cards, the sensor card and the air gripper control mechanisms. A cabinet 16"x20"x8" was selected to hold these components. Each of the three driver cards shown in Figure 3.15 occupies a volume of 5"x7"x2" and is mounted vertically in the cabinet to allow maximum airflow over the heat sinks. A circuit diagram of the driver card is shown in Appendix H. The driver cards are plugged into the mother board and supported by nylon supports on both the top and bottom at the connection point in the back of the box as shown in Figure 3.16. The cards are supported in the rear by a 1/8"x3/8" angle attached to a 1"x3/8" aluminum cross member. A cooling fan is mounted in the bottom of the cabinet and blows upward across the heat sinks. Two vents are provided at either top side for exhaust air. See Figure 3.17 for heat flow path. The motor and sensor connections are all gathered on the same side of the box. Motor and sensor connectors are locking, circular connectors with alignment pins which eliminate improper connections to the control cabinet. The motor connectors are arranged at the bottom of the cabinet and separated from the sensor connectors by a strip terminal block used for sensor input and output. This separation helps eliminate improper connection of sensors to motor drivers. See Figure 3.18 for a photograph of the control cabinet.

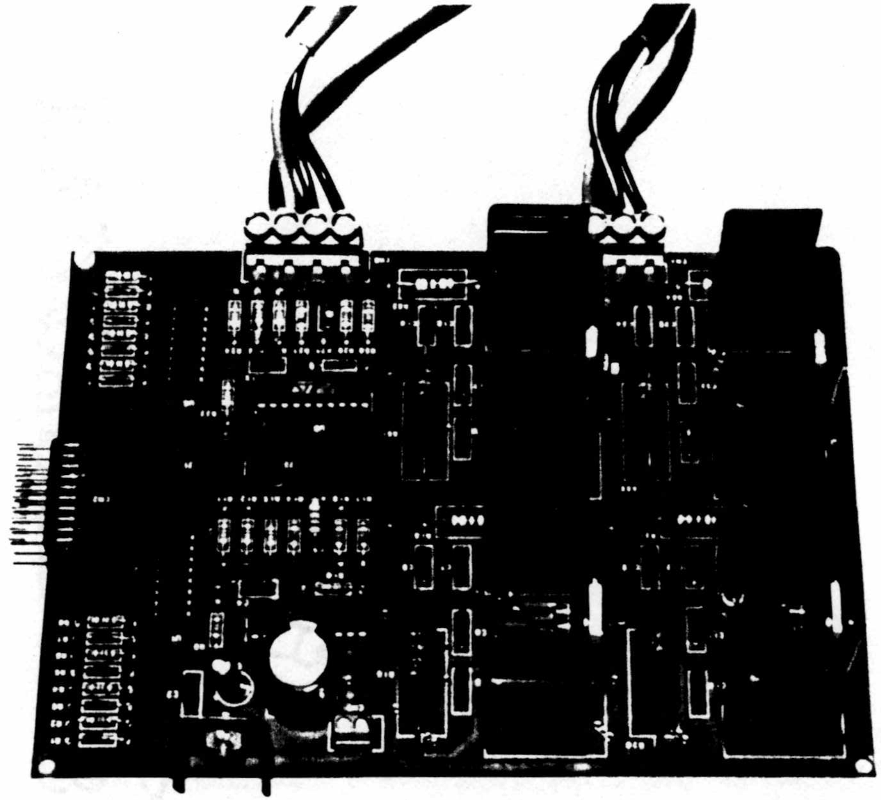


Figure 3.15 SEDP robot driver card

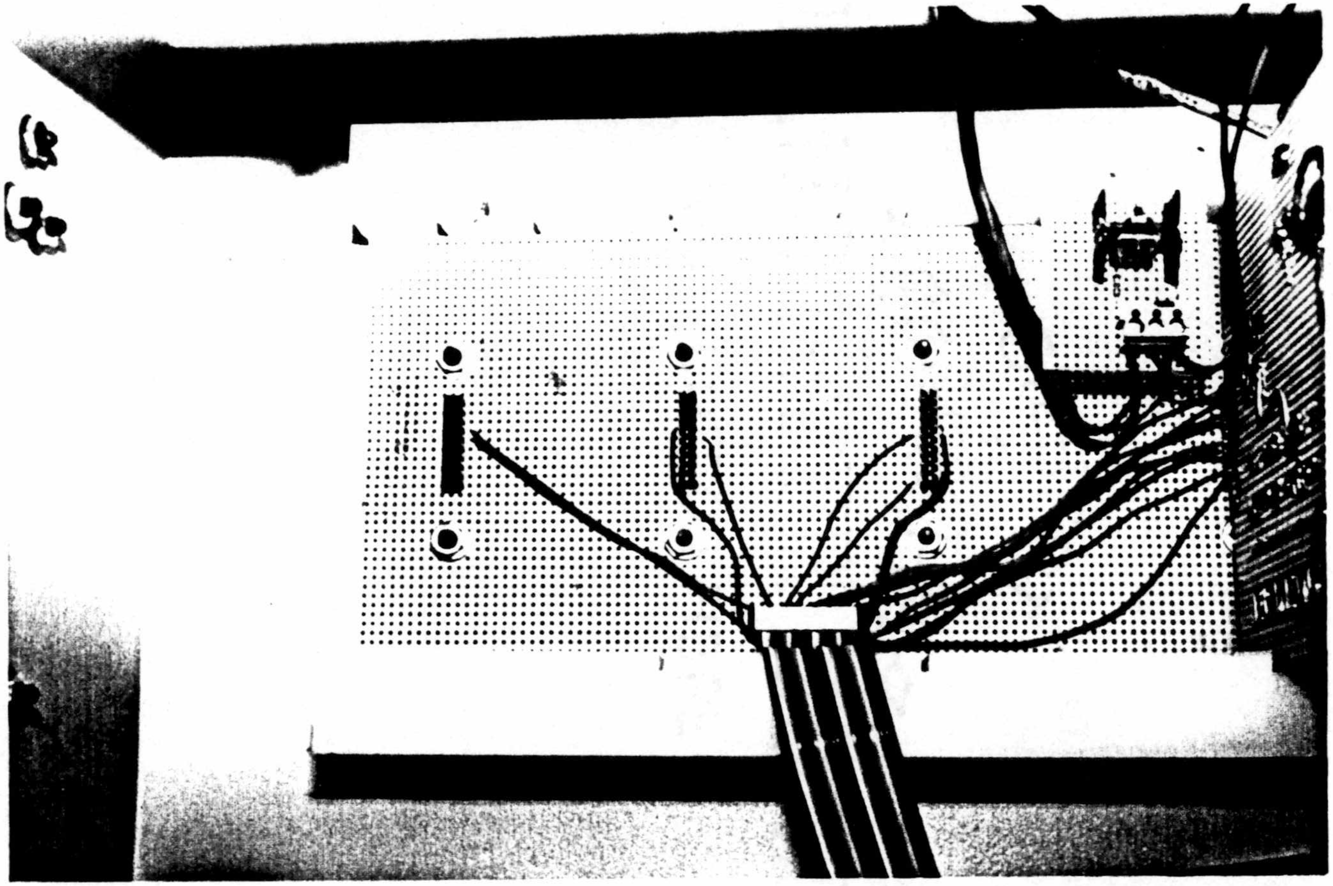


Figure 3.16 Mother board and driver card supports

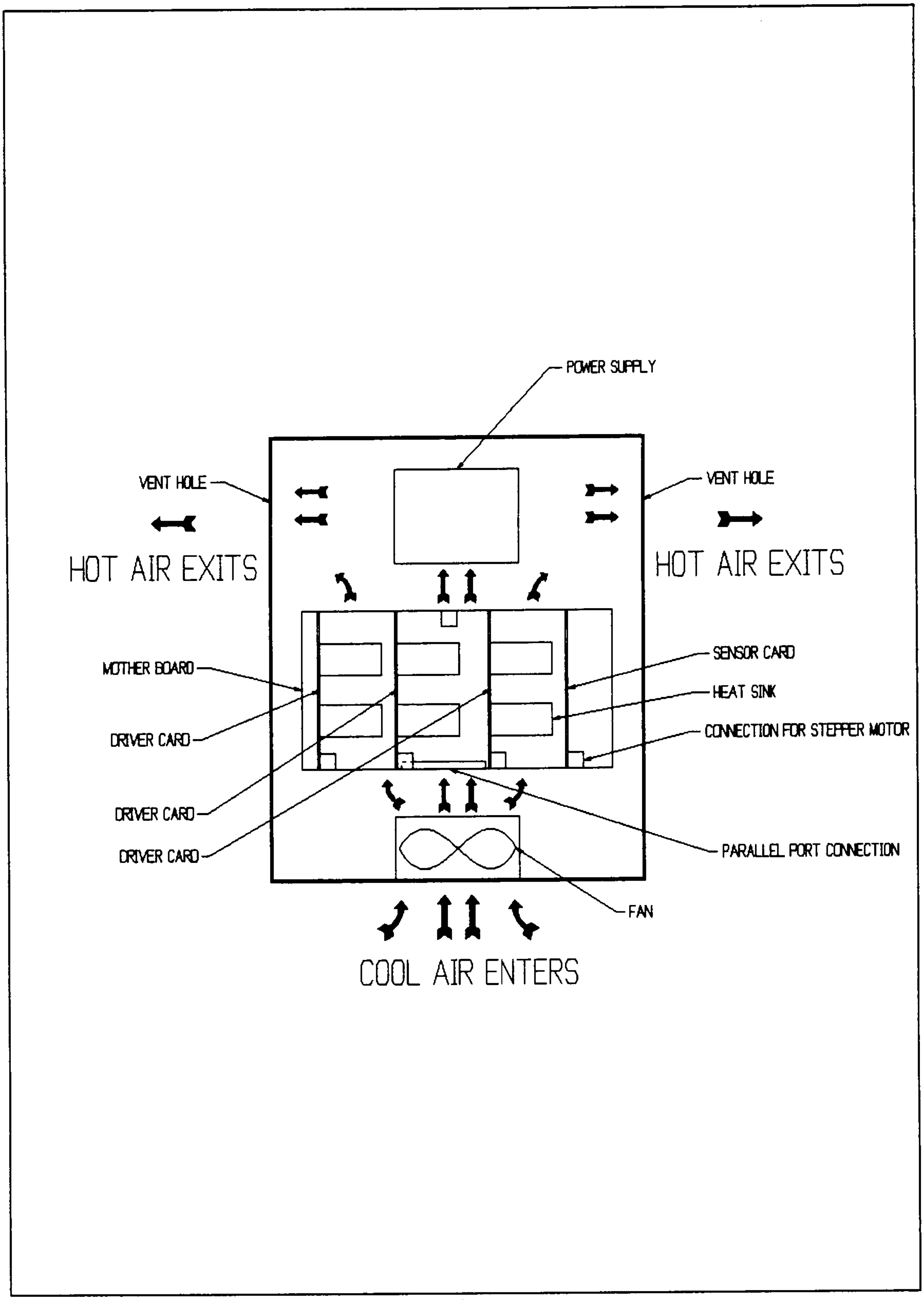


Figure 3.17 Control cabinet heat flow path

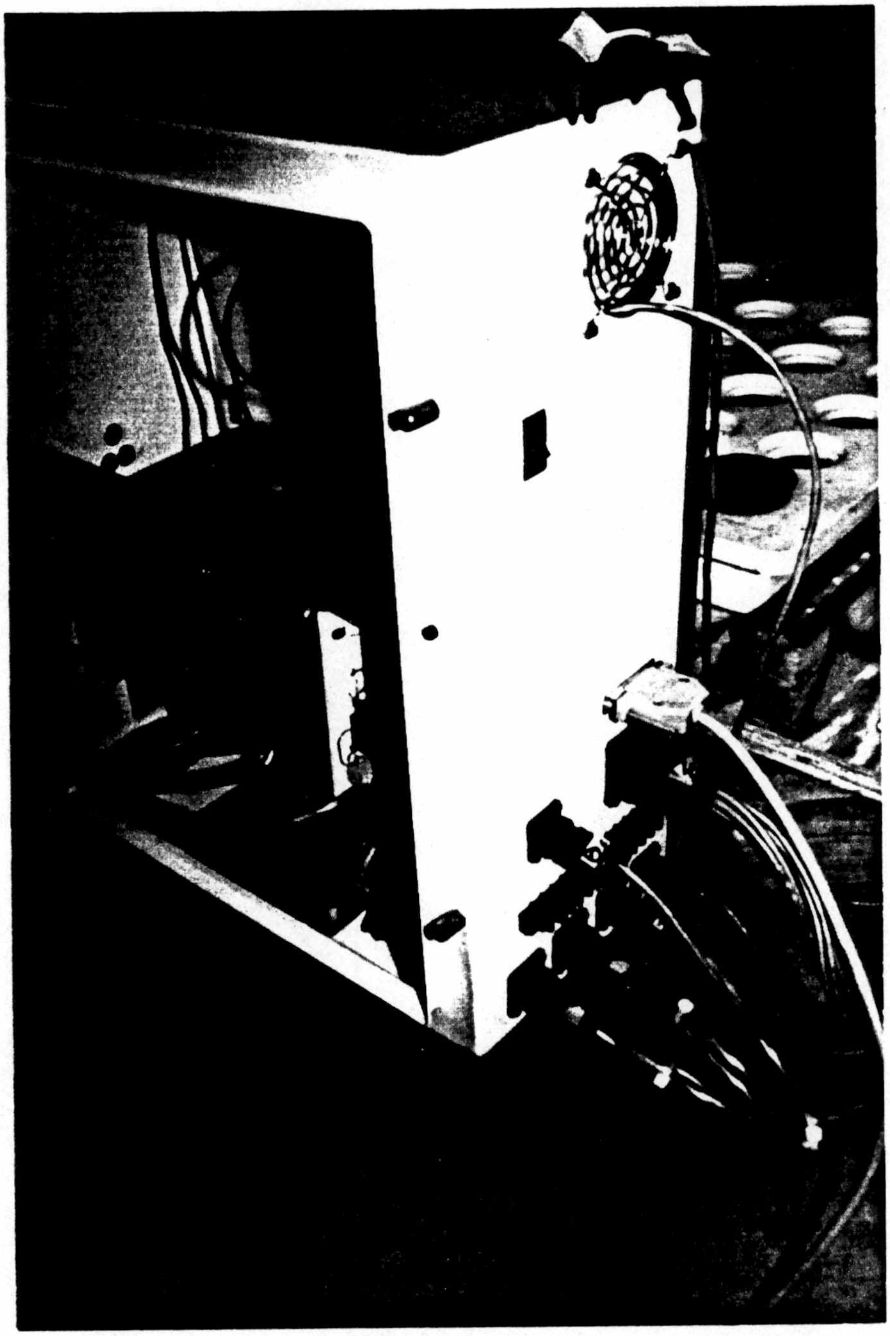


Figure 3.18 SEDP robot control cabinet

3.7.3 Rewire robot

Problem

The wires that connected the control box to the motors and sensors were loosely attached to the frame and were easily obstructed.

Solution

The wires were replaced and anchored to the frame behind the top horizontal frame members. The wires were tie wrapped together to form a bundle on the home corner vertical support. Heavier gauge wires (16 gauge vs. 20 gauge) were installed to help reduce resistance and improve signal transmission to the motors. This solution shown in Figure 3.19 has proved to be quite effective.

3.7.4 Tensioning of the Z belt

Problem

The tensioning of the Z belt was a task that required two people to provide sufficient tension on the Z belt such that the belt functioned properly. The complication from the original design was due to the installation of a shear pin between the two mounting plates and the mast as shown in Figure 3.20. One person had to tension the belt while the second attempted to install the shear pin.

Solution

The mast was machined with a slot that allowed up to 20 degrees of relative rotation between the mounting plates and the mast. This solution made it easier for one person to tension the belt properly. The shear pin was eliminated thereby relying only

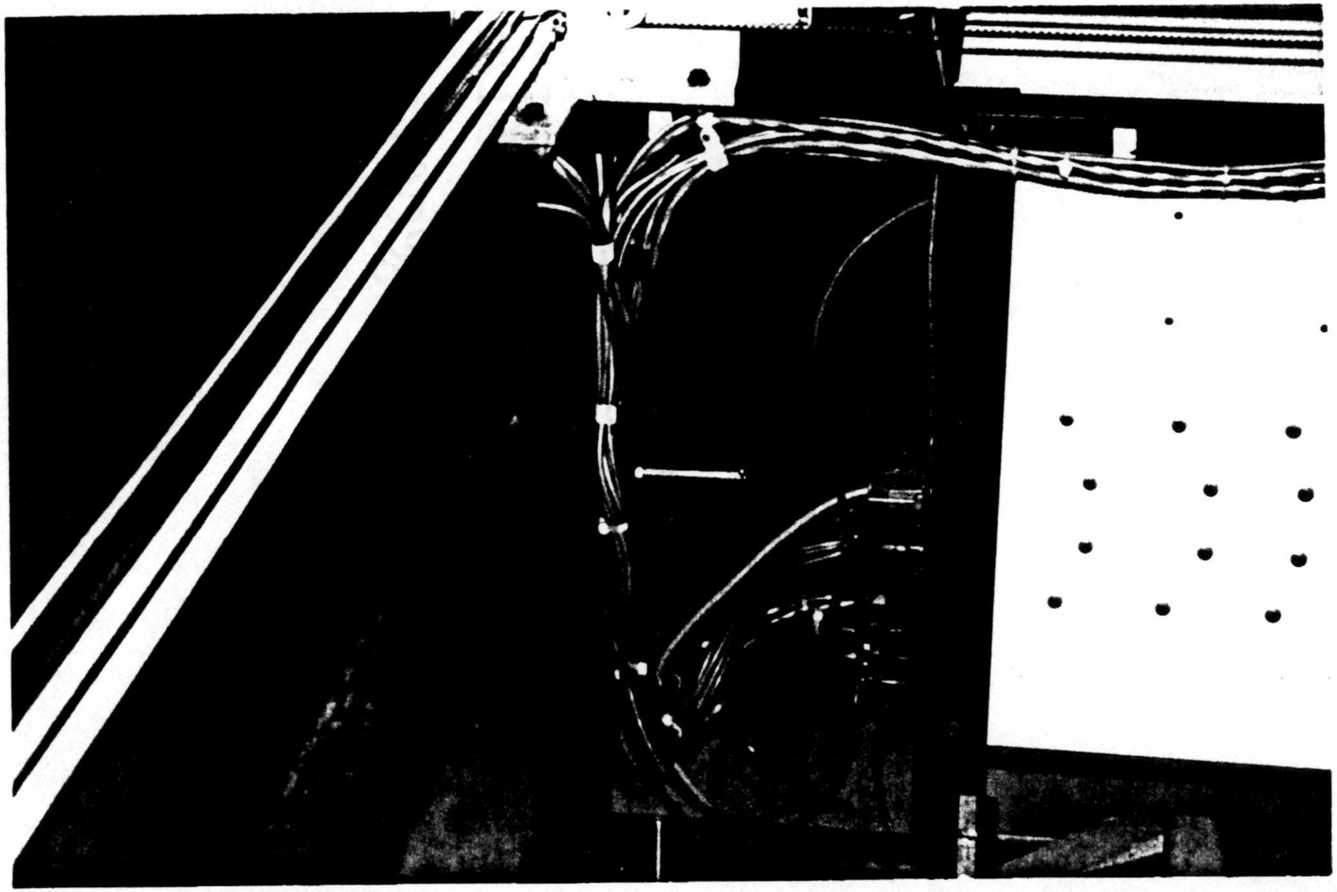


Figure 3.19 View of rewiring of robot

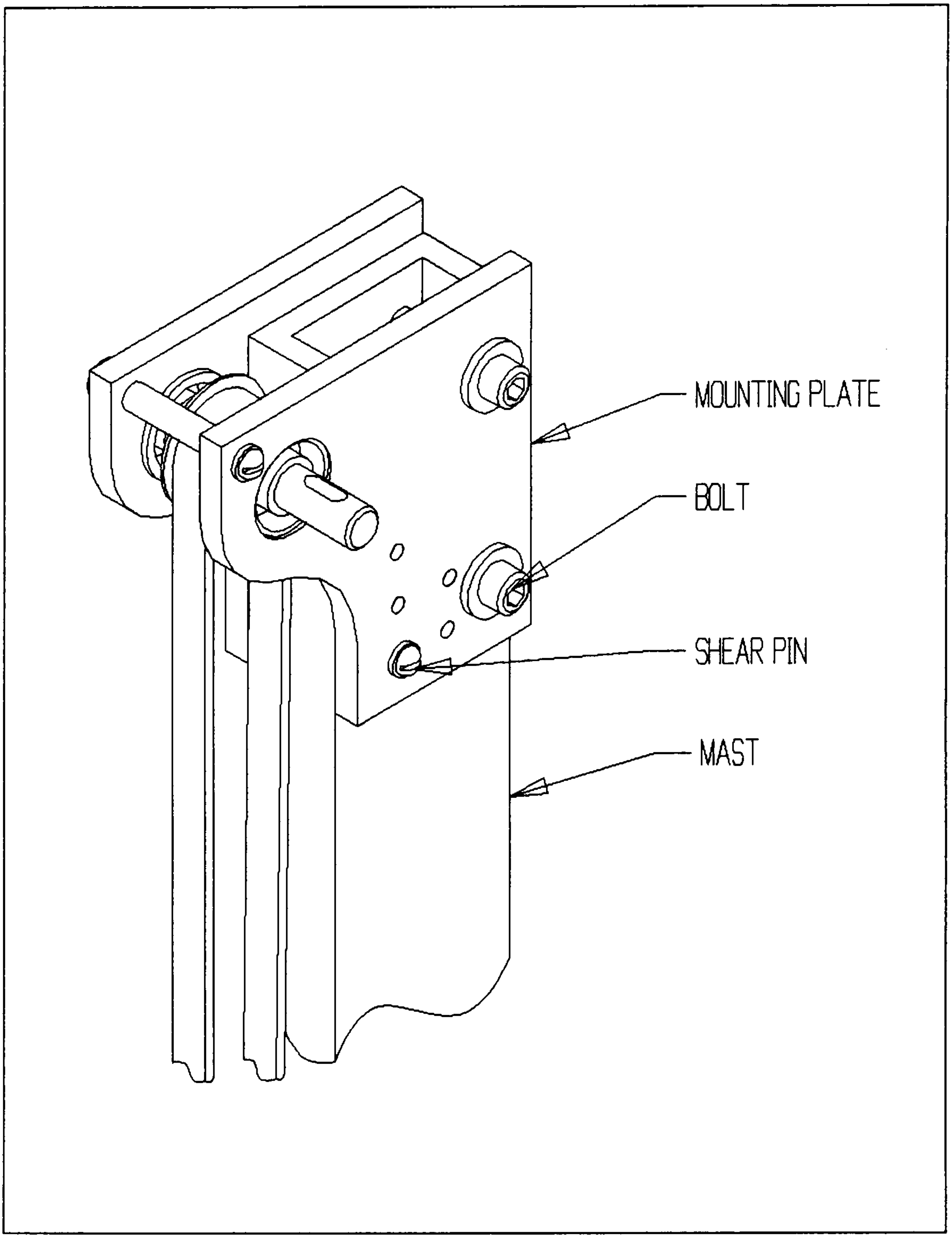


Figure 3.20 View of top of mast

Source: Michael Earl Kennedy, Low-Volume Production Design and Manufacture of a Low-Cost Industrial Robot, M.S. Thesis in Mechanical Engineering, The University of Tennessee, Knoxville, TN, May 1991, p.115.

on frictional forces to hold the belt tension. Subsequent intermittent and continuous endurance testing has shown this solution to be reliable.

3.7.5 Belt slippage

Problem

The Z belt was noticed to "cog" or jump teeth on the Z driver pulley if the belt was not tensioned extremely taut when the robot was operating with a load exceeding 15 pounds. The driver pulley diameter could not be increased due to space constraints.

Solution

The timing belt was replaced with a chain ladder type belt. The chain ladder belt would not "cog" even when the robot operated with loads up to 40 pounds, or twice the design payload. This belt and pulley substitution also caused the tensioning of the Z belt to be a much less critical parameter in payload considerations.

While the timing belt replacement did increase the payload of the robot, endurance testing caused the belt to fail. This failure is noted in Section 3.8.

3.8 New Failure Modes Observed During Testing

There have been a few failures noted in the 676 hours of endurance tests that are listed with possible solutions that can be implemented in the next design phase. The failures and suggested solutions are as follows.

3.8.1 Sensor abrasion

Failure

The optoisolator sensors used for the home calibration of the robot became worn by the rotating disks if the disks were not properly centered in the sensor slot as shown in Figure 3.21. The sensor plastic case was shaved off by the slot in the disk and the particulate matter fell into the slot of the sensor and prohibited light transmission between emitter and detector. This condition was observed in all the degrees of freedom of the robot.

Suggested Solution

The disks need to be aligned properly in the sensor slot so the disk cannot touch the sides of the slot. An optoisolator sensor with a wider gap would help eliminate the abrasion problem. The sensor system needs to be designed for assembly. The mounting brackets should have no alignment capabilities. The sensor disks should be located in the shafts with roll pins to avoid slippage that might occur with the set screws. With all components fixed in the assembly process, there is no room for the misalignment that caused the sensor abrasion problem.

3.8.2 Set screws back driven

Failure

Some set screws were noted to back-out or loosen in routine operation of the robot due to load reversals on the screw tips. These set screws were located on the drive pulleys and in the casting at the top of the Z shaft. The set screws that had backed out

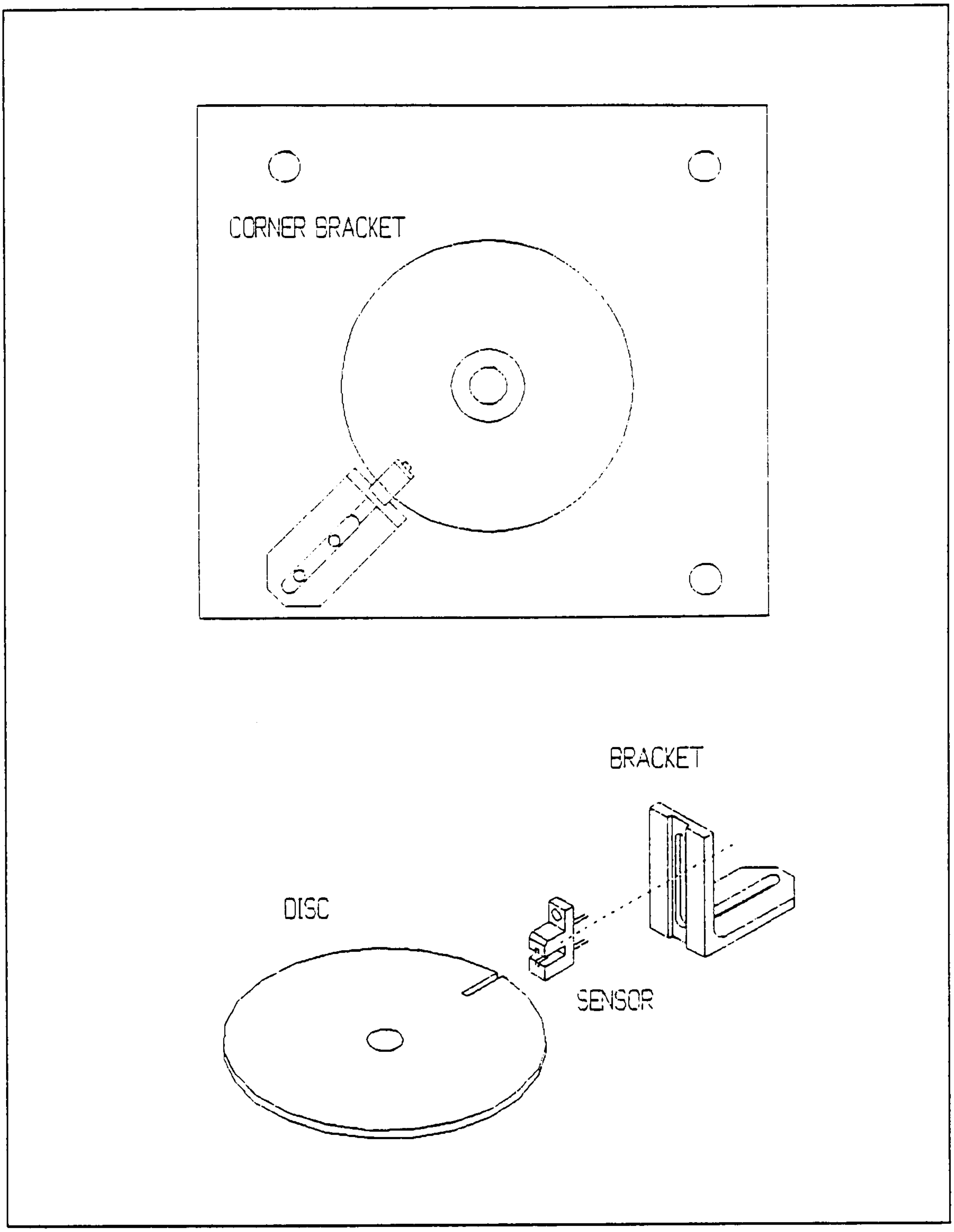


Figure 3.21 Sensor and sensor disk

Source: Anthony Paul Williams, Evaluation of a Low-Cost Industrial Robot, M.S. Thesis in Mechanical Engineering, The University of Tennessee, Knoxville, TN, May 1992, p.79.

were set screws that had no adhesive. Some set screws had adhesive (specific) applied and these set screws were not noted to back out.

Suggested Solution

Adhesive bonding can be used on the set screws threads to prevent the screws from backing out. The set screws can be replaced with roll pins when the design is fixed.

3.8.3 Air hose interference

Failure

The air hoses that supply air to the gripper have been observed to interfere with the Z absolute sensor. The air hoses worked their way into the sensor slot and gave false home calibration readings. In some cases the hoses were also stretched and damaged.

Suggested Solution

The air hoses must be attached to the Z shaft in such a way as to eliminate damage to the air hoses and damage to the Z sensor. Possibly a coiled air line attached to the bottom of the mast to the gripper would eliminate damage to the Z sensor or the air lines.

3.8.4 Chain ladder missing teeth

Failure

The chain ladder that replaced the timing belt on the Z system was noted to have several teeth missing. The missing teeth were believed to have occurred from the over-tightening of the Z chain ladder. This was accentuated by the fact that the casting at the top of the shaft had rotated (counterclockwise looking down on the shaft). The Z system is shown in Figure 3.22. This caused a misalignment of the chain ladder on the top idler

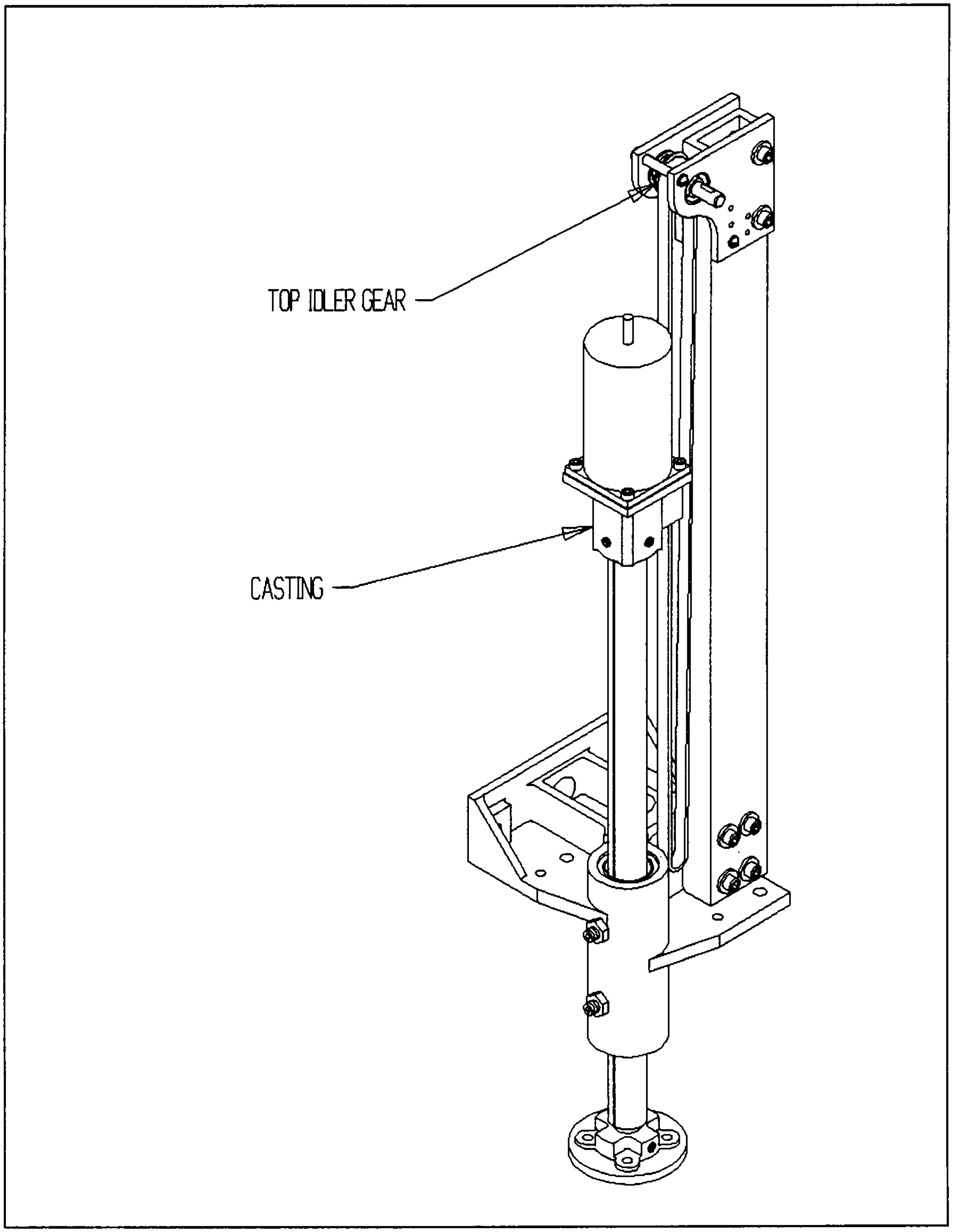


Figure 3.22 Robot vertical system

Source: Michael Earl Kennedy, Low-Volume Production Design and Manufacture of a Low-Cost Industrial Robot, M.S. Thesis in Mechanical Engineering, The University of Tennessee, Knoxville, TN, May 1991, p.101.

gear. The gear wore the coating off one side of the chain ladder and then climbed onto the chain. The gear teeth then cut the plastic rungs off the ladder. These missing teeth caused the robot to lose position in vertical motion.

Suggested Solution

A chain ladder is constructed by placing 2 cables parallel to each other and coating the cables with a resilient plastic coating. The ladder has solid plastic cross members or "rungs" between the coated cables similar to an extension ladder. The advantage of the chain ladder over the timing belt is the amount of positive engagement of the driver pulley [Berg, 1988, p.71].

The chain ladder belt adjustment specification should be changed such that there is approximately 1/2 inch play in the belt at mid span with a 20 pound payload. The casting at the top of the Z shaft must be properly aligned such that the flat belt attachment section is parallel to the mast side. The alignment of the upper and lower gears should be determined and appropriate spacers installed to maintain alignment. The chain ladder doubled the payload of the robot by eliminating the belt "cogging" of the timing belt. The chain ladder belt is noted to be more sensitive to misalignment of the pulleys than the timing belt. Further testing is necessary to determine if this belt substitution is a reliable solution.

CHAPTER 4

DRIVE SYSTEM ANALYSIS

4.1 Introduction

The stepper motors used in the SEDP robot are 1.8 degree hybrid stepping motors. These motors allow for many different electrical connections which can alter the motor performance characteristics. The motors can be run in half-step or full-step mode. The motors can be connected in full-phase or center tap. Torque vs. speed and force vs. speed graphs will be shown for the different connections.

4.2 Torque vs. Speed Analysis

4.2.1 Introduction

Torque vs. speed data was obtained from running a series of tests on the stepper motor test stand. The theory is that the stepper motor is driven to a specified speed by a dc motor and then the dc motor begins to oppose the stepper motor rotation after the desired test speed is obtained. Then the dc motor is operated as a generator and the current generated is proportional to the torque being applied to the motor. The dc motor opposes rotation until the stepper motor breaks phase. The principles of operation of this apparatus are described in detail in previous studies [Moscone 1991].

4.2.2 Tests

The stepper motors were tested on the stepper motor tester and the results graphed. Figure 4.1 shows the graph of torque vs. speed for the Anaheim brand motors used for the X-Y motion. The full phase connection provides a high initial torque that drops off significantly at high speeds and becomes unstable at very high speeds. The center tap connection does not provide a strong initial torque but the curve is desirably flat over a very wide speed range. Figure 4.2 shows a similar test for the Vexta brand motor used in the Z system. It is noted that the Vexta motor of Figure 4.2 does not exhibit the same high speed instabilities of the Anaheim motor in Figure 4.1.

The above results were qualitatively correct, but quantitatively questionable since the stepper motor driver system used an expensive commercial driver. The tests were rerun using the driver cards designed and fabricated at the University of Tennessee, thus simulating the actual conditions the motors would experience. The motors were connected to a 28-volt unregulated Accopian brand power supply with all connections made to the robot to simulate voltage spikes and transients.

As seen in these second tests shown for the Anaheim brand motor, Figure 4.3, and for the Vexta brand motor, Figure 4.4, the motor torques average 20 oz-in less (average approximately 12%) than the earlier tests. The full-phase graphs show instability occurs at lower speeds. Other torque vs. speed curves for different tests are shown in Appendix E.

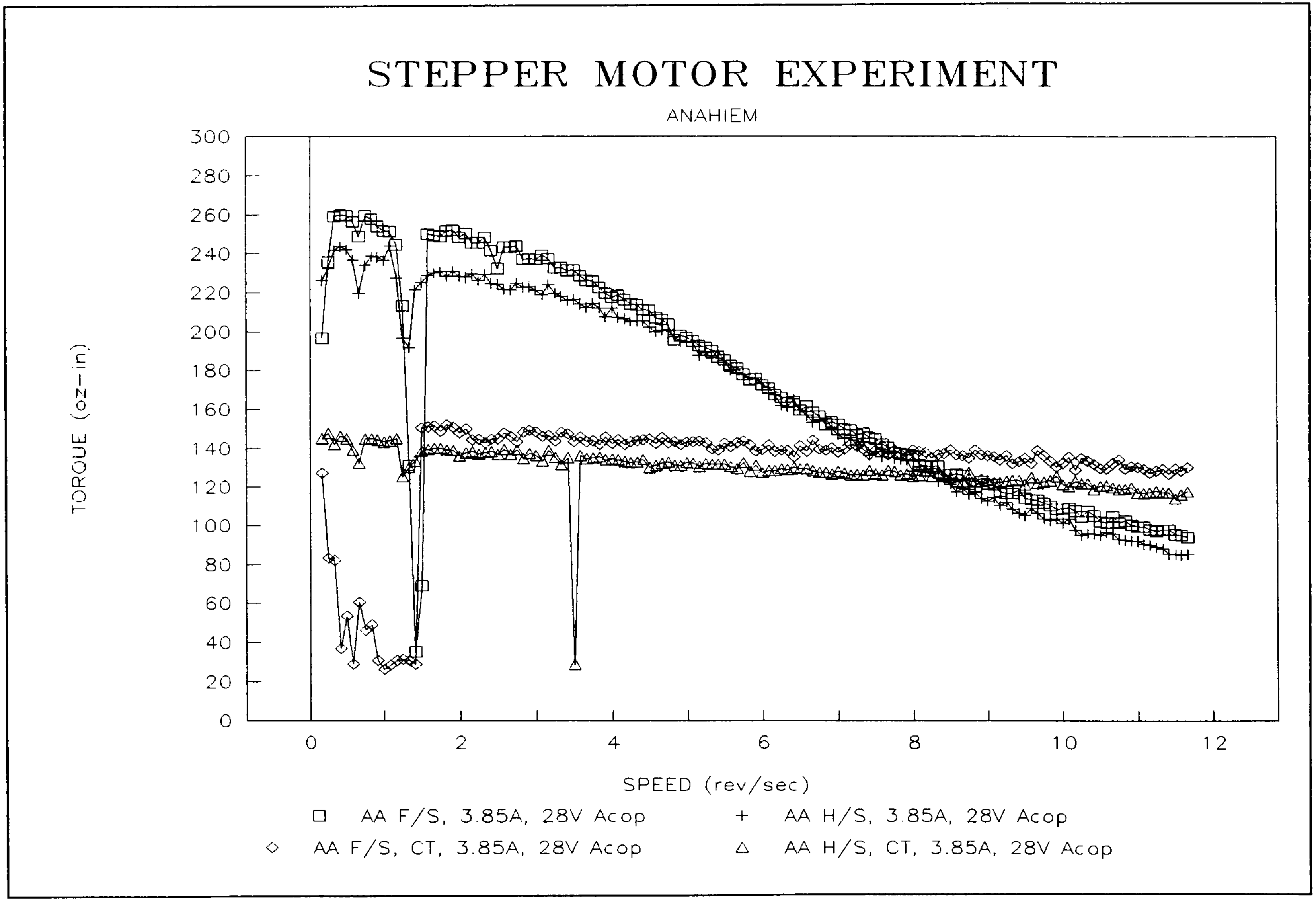


Figure 4.1 Anaheim motor torque vs. speed curve

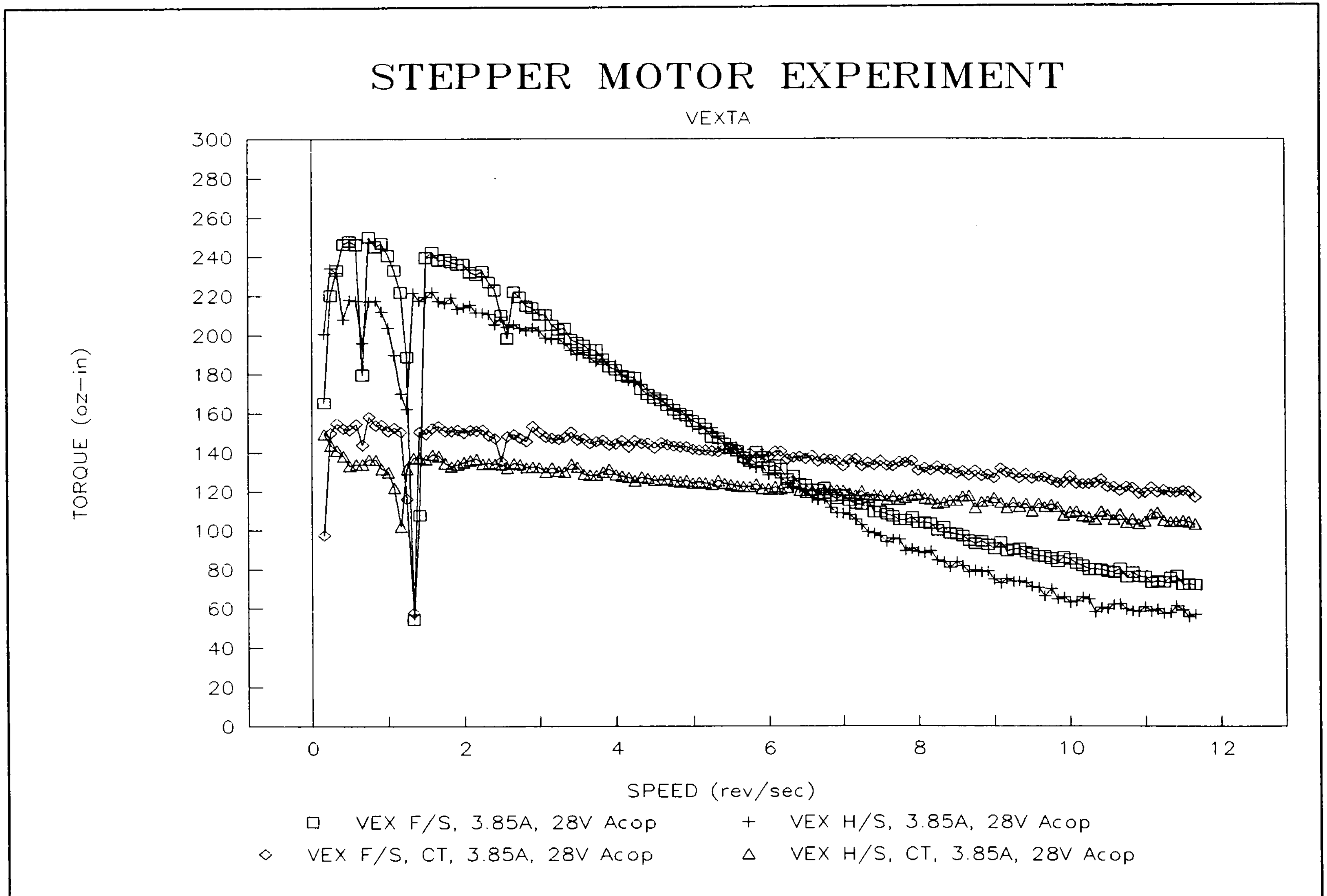


Figure 4.2 Vexta motor torque vs. speed curve

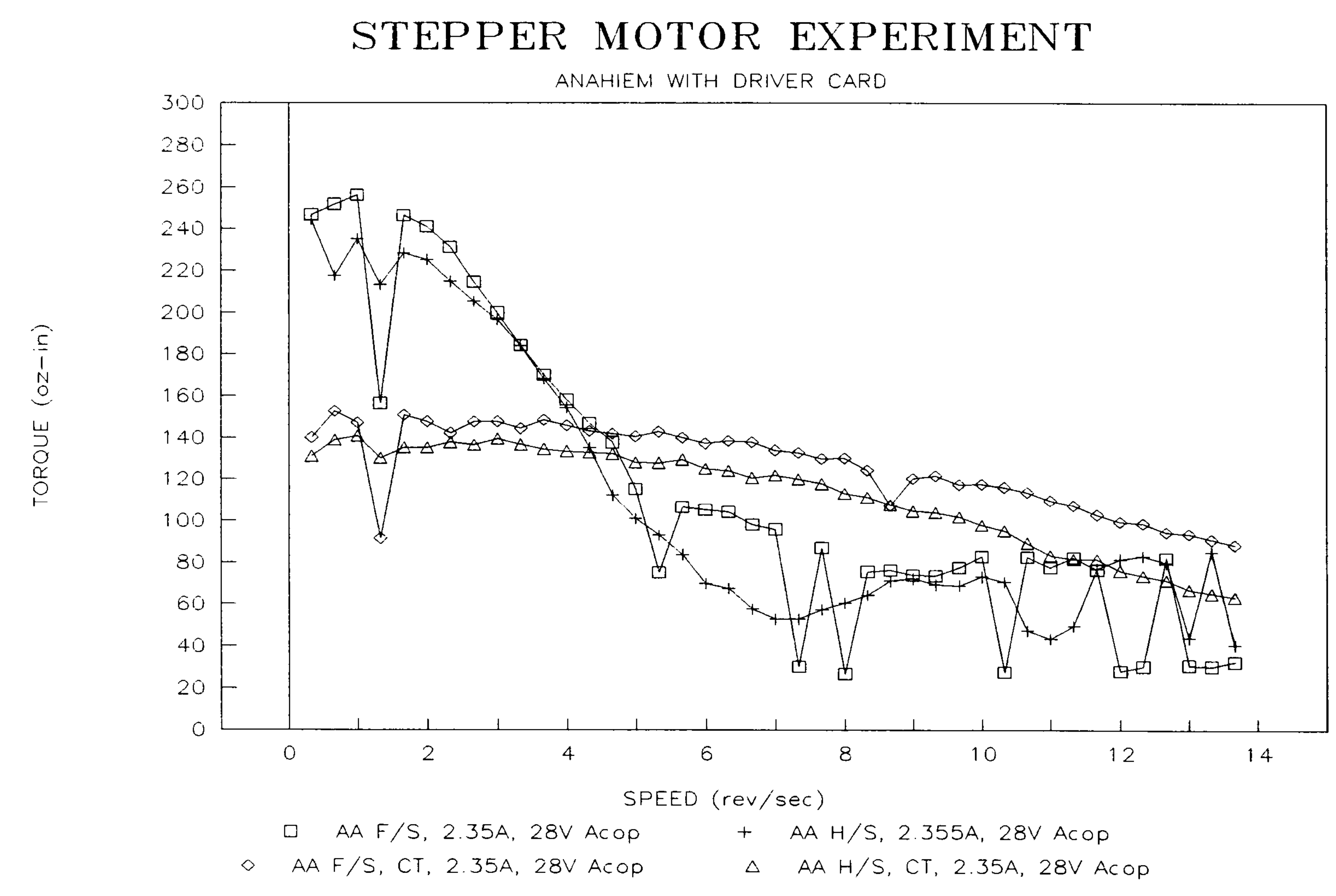


Figure 4.3 Anaheim motor torque vs. speed curve with SEDP driver

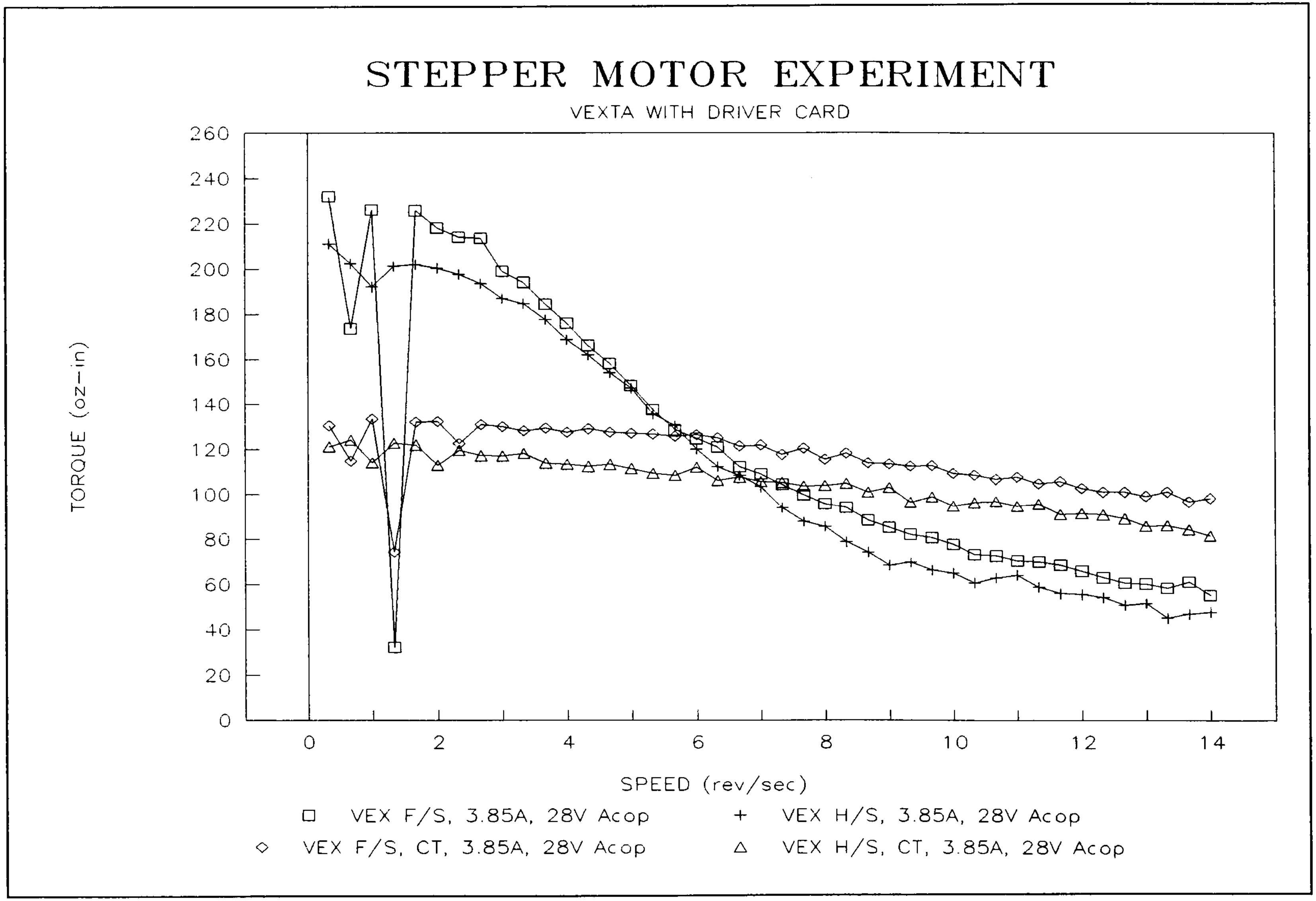


Figure 4.4 Vexta motor torque vs. speed curve with SEDP driver

4.2.3 Results

The stepper motor test stand testing provided useful information on relative torques for different electrical connections. Relative torque curves obtained for stepper motors from different manufacturers were also important information. It was decided that the motors should be run in center tap, half-step mode for the best robot performance over the largest speed range. In this configuration the torque is almost constant which simplifies the computer algorithms used in acceleration ramp calculations.

4.3 Force vs. Speed Analysis

4.3.1 Introduction

The torque vs. speed curves of section 4.2 were useful in selecting the best electrical connection configuration and stepper motor manufacturer. However, it was considered more useful to know the force that the stepper motors could apply to the drive system than to know the torque generated. Therefore, the torque vs. speed curves were modified to show the force available to drive the system for a given gear ratio.

4.3.2 Tests

Figure 4.5 shows the force vs. speed curve for a 1:1 gear ratio using the Anaheim brand motor. The force needed to overcome the system friction is also shown as a constant value of 2 pounds. The friction force was obtained by disconnecting the motors from the drive system and pulling the cross block assembly with a spring scale. It can be seen from this figure that the motor provides a force of almost five times the friction force even at speeds of 10 rps or 600 rpm.

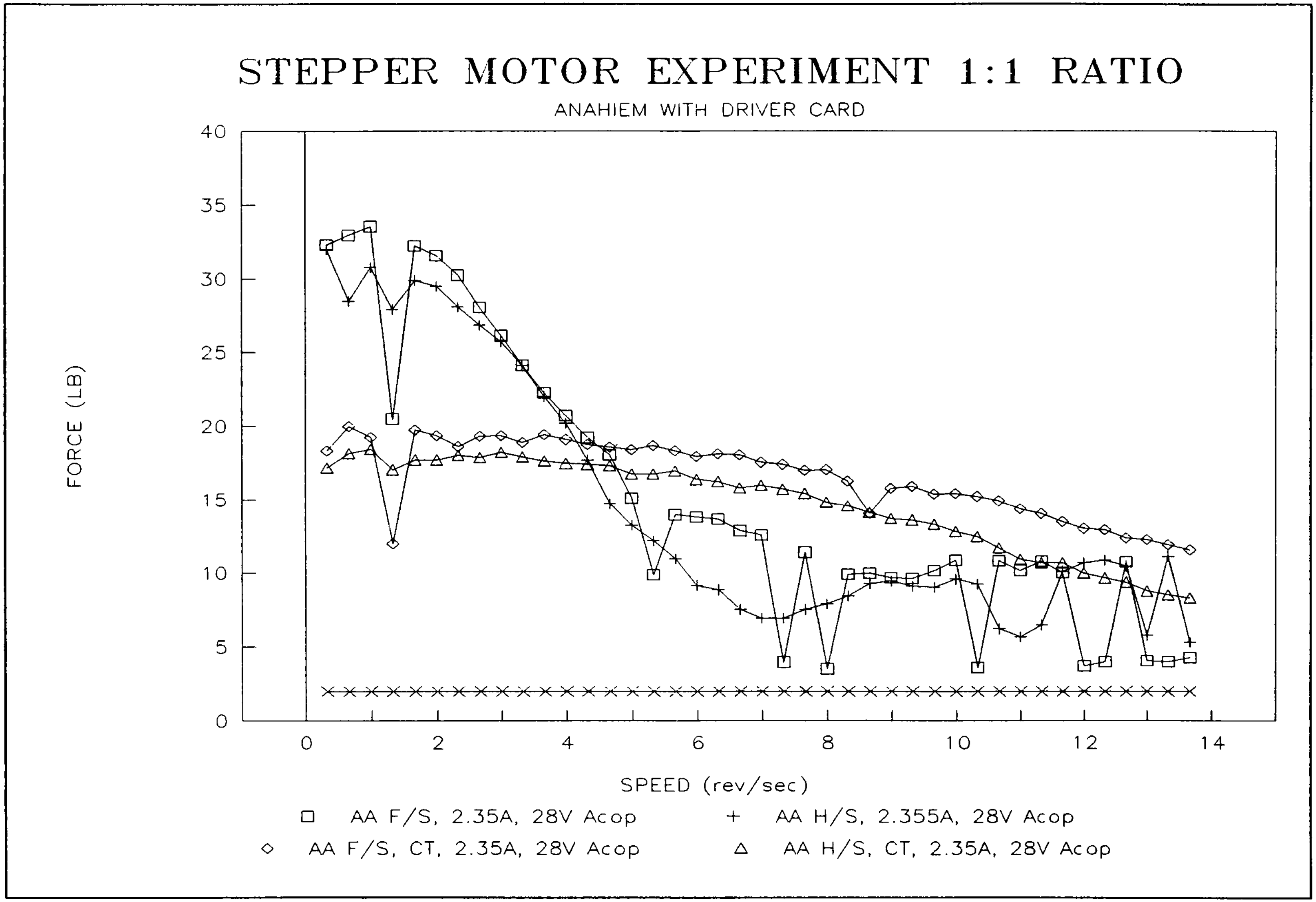


Figure 4.5 Anaheim motor force vs. speed curve with 1:1 gear ratio

Figure 4.6 shows the force vs. speed curve for a 1:1 gear ratio using the Vexta brand motor. It can be seen from this figure that the motor provides a force of almost seven times the friction force at speeds up to 600 rpm. The 2 pound frictional force is also shown.

Figure 4.7 shows the force vs. speed curve for a 3:1 gear ratio using the Anaheim brand motor. Here, the motor generates almost twenty times the force required to overcome the frictional force at the same 10 rps or 600 rpm.

Figure 4.8 shows the force vs. speed curve for a 3:1 gear ratio using the Vexta motor. Here, the motor generates almost twenty times the force required to overcome the frictional force at the same 10 rps or 600 rpm.

4.3.3 Results

The validity of these force vs. speed curves was checked by testing the available force on the slider with a spring scale at various speeds. The scale was attached to the cross block assembly approximately 2.75 inches above the Y cross shaft and held parallel to the Y cross shaft. The paths run consisted of only X motion with the Y slider remaining in the home position. Figure 4.9 shows the measured force vs. speed curve for a 1:1 gear ratio using the Anaheim brand motor with the UT driver cards.

The theoretical force generated from the stepper motor test stand is compared to the actual force measured from the spring scale in Figure 4.10. The frictional force has been subtracted from the test stand calculated force to be more consistent with the

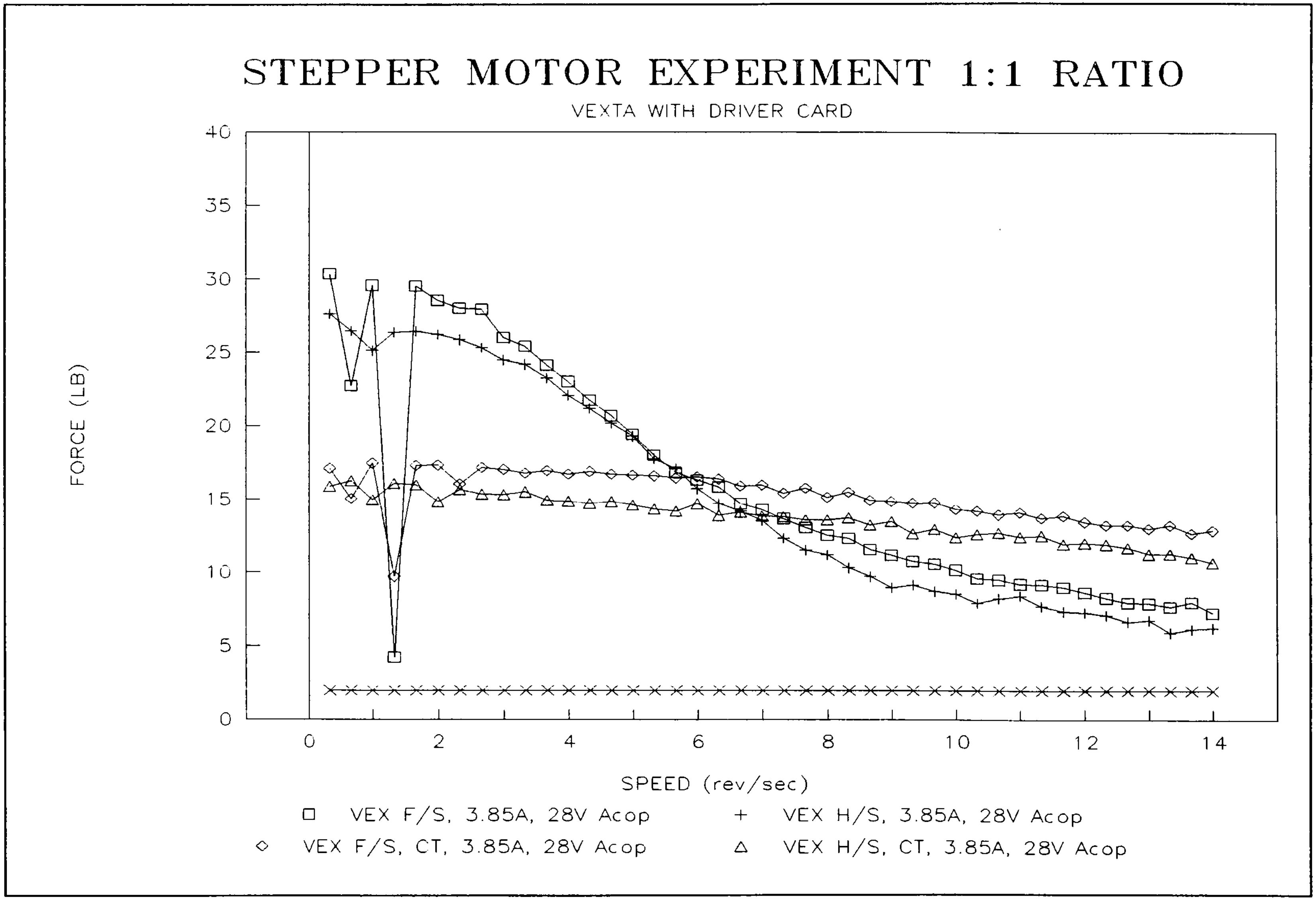


Figure 4.6 Vexta motor force vs. speed curve with 1:1 gear ratio

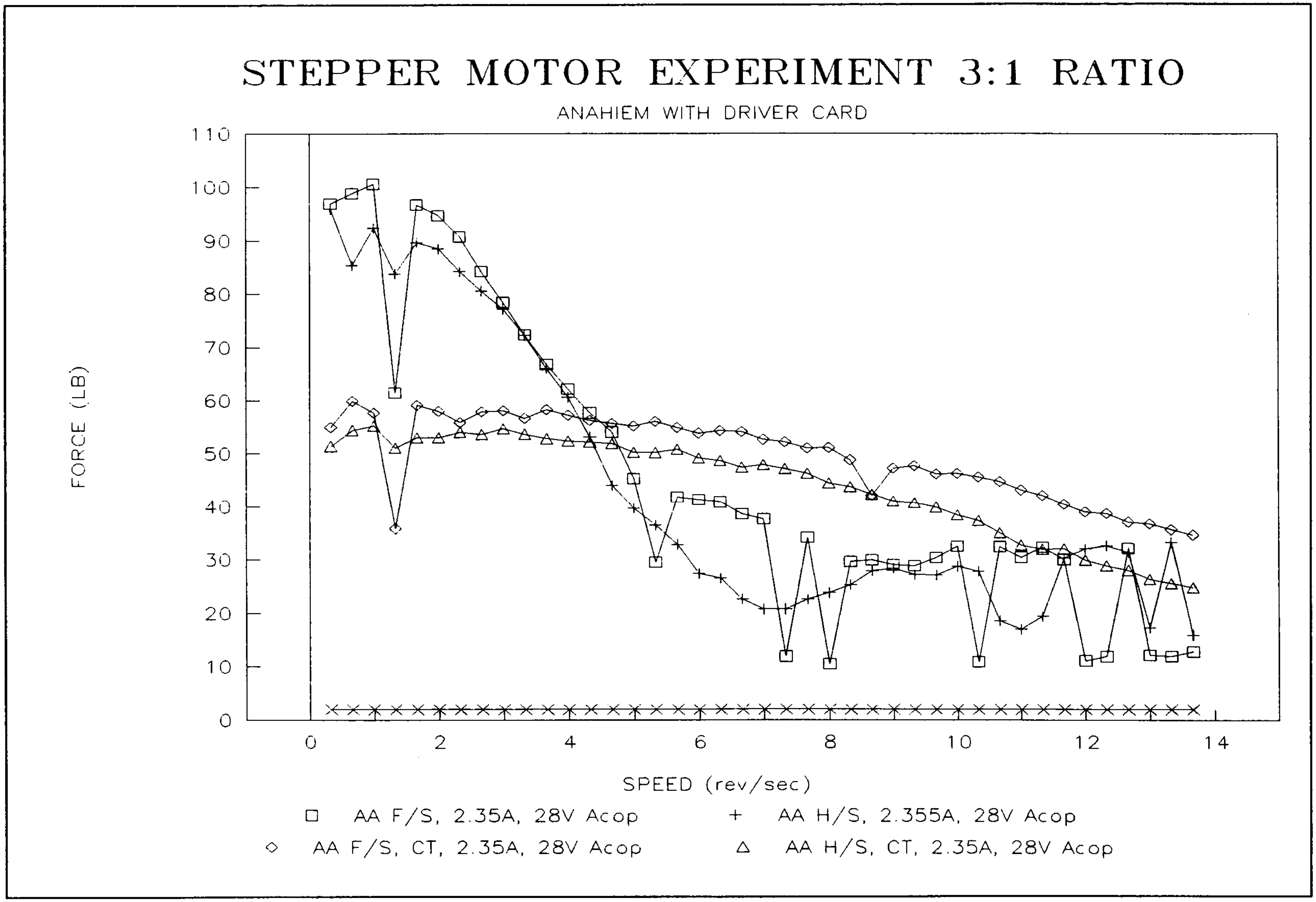


Figure 4.7 Anaheim motor force vs. speed curve with 3:1 gear ratio

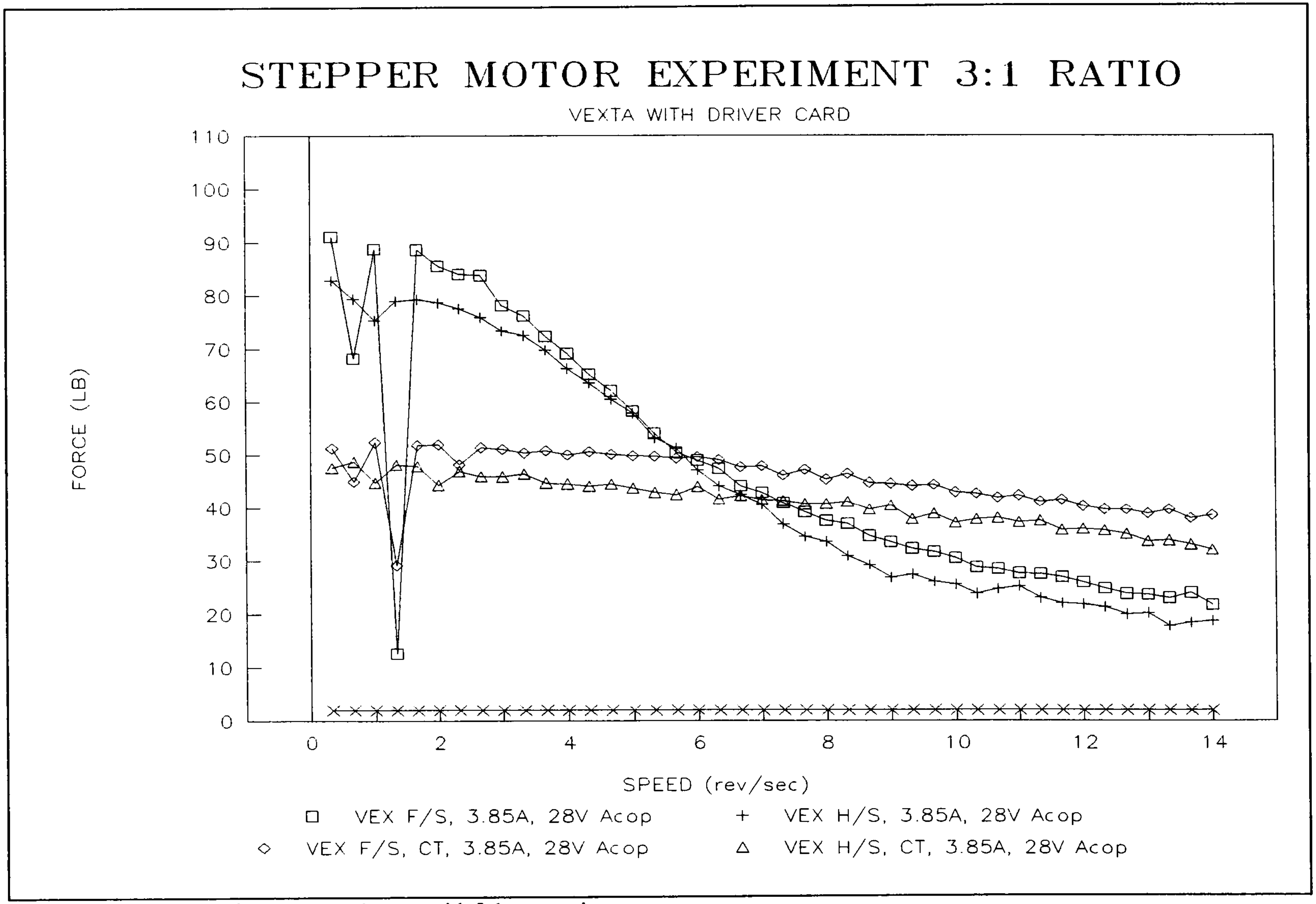


Figure 4.8 Vexta motor force vs. speed curve with 3:1 gear ratio

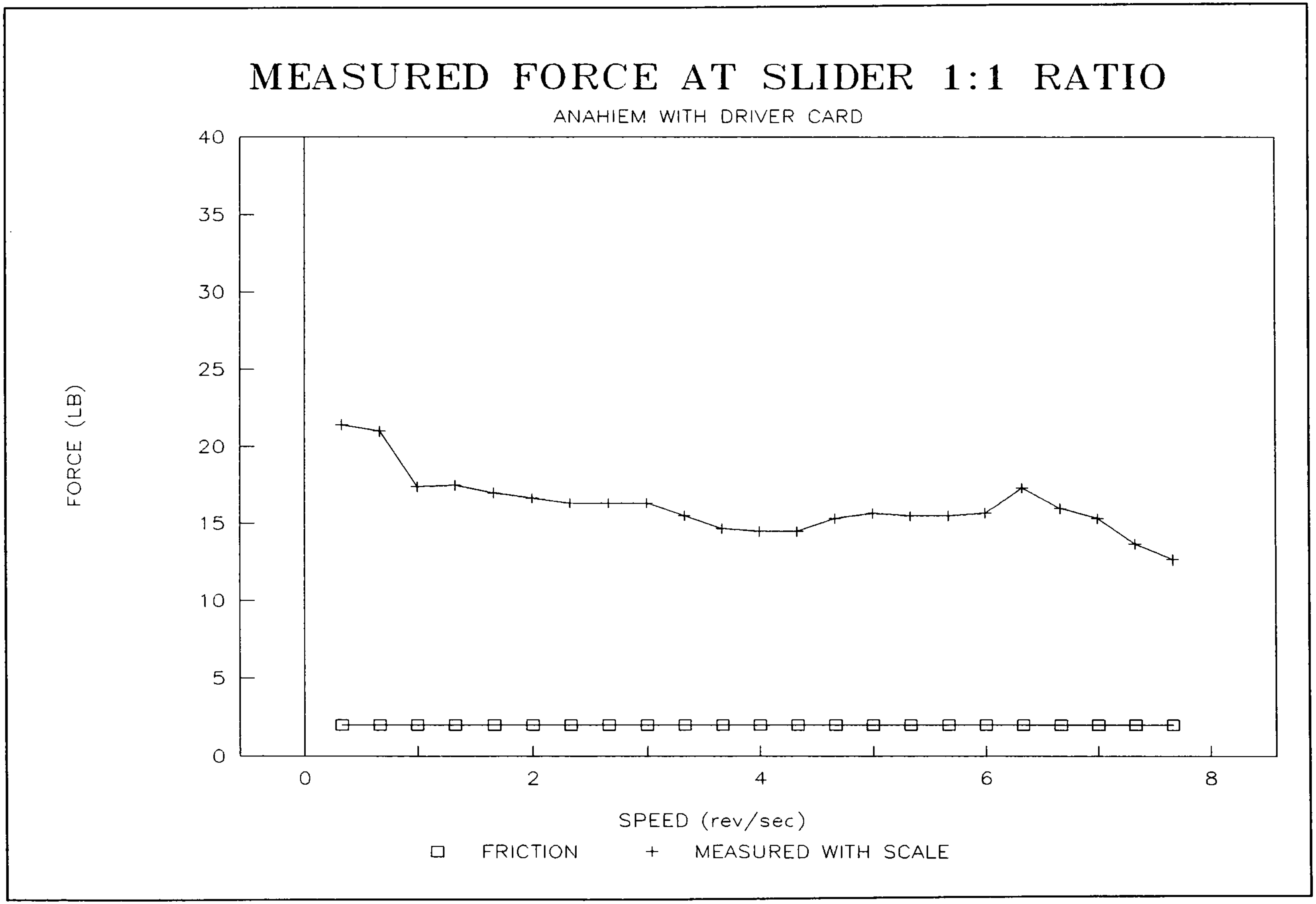


Figure 4.9 Anaheim motor measured force with 1:1 gear ratio

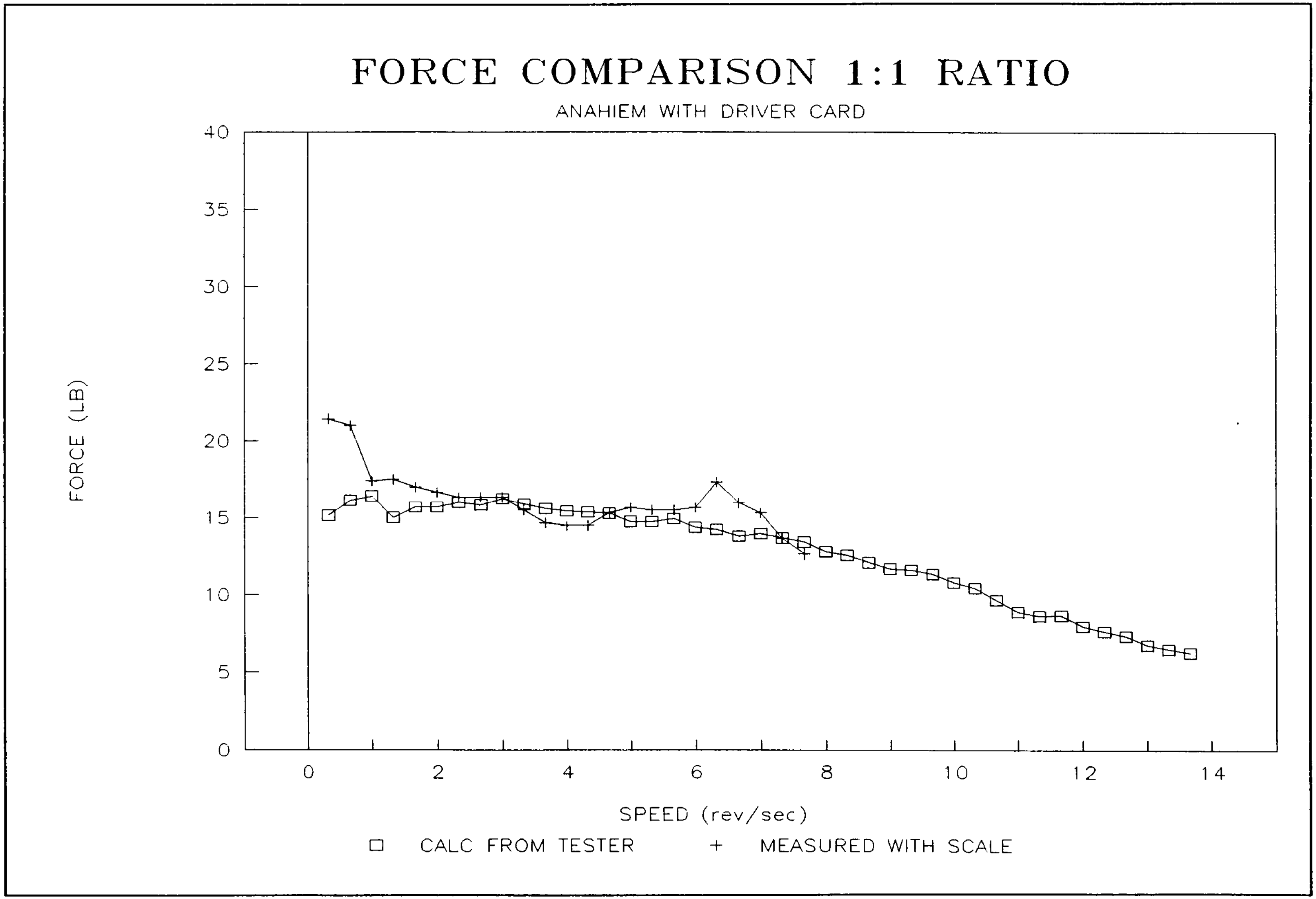


Figure 4.10 Comparison of calculated force and measured force

measured force. This figure indicates that the correlation is acceptable. Both curves show the same general trend that the force decreases as the speed increases. The initial measured force is larger than the test stand calculated force. After approximately 1 rev/sec the measured force falls to within 12% of the test stand value. The measured force varies about the calculated force until 6.5 rev/sec where a spike is encountered. After the spike the measure force falls to the calculated test stand force at 7.2 rev/sec.

One reason for the difference in the measured force and the test stand calculated force is that the measured force was difficult to reproduce. The force varied greatly at the same speed. An average of 3 data points was taken for each speed to compensate for the varied measurements. Another reason for the differences between the measured force and the test stand generated force is from the way the test rig obtains the torque. The stepper motor is driven to the desired speed by the dc motor. This allows the stepper motor to pass by resonance points that it would otherwise not be able to go beyond. Testing has shown that the robot will not function after 7.5 rev/sec regardless of the gear ratio selection.

4.4 Computer Output

The personal computer that drives the SEDP robot has limitations. The computer algorithms used to calculate acceleration ramps and velocities is computationally intensive. The computer output is plotted vs. computer input in Figure 4.11. This figure shows that the computer output varies within 17% about the input up to 13 in/sec. After 13 in/sec the output of the computer is constant regardless of the input using a 3:1 gear

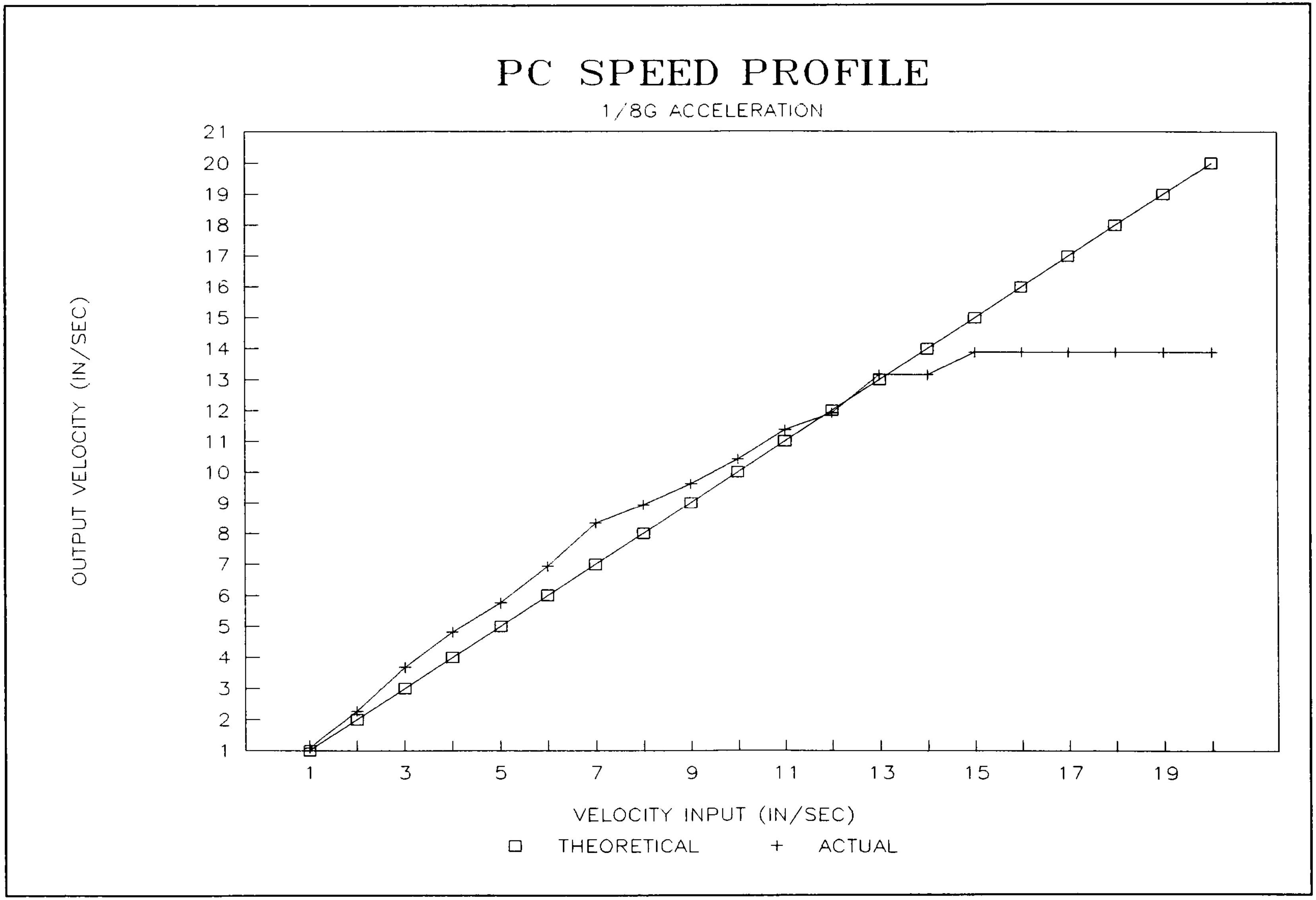


Figure 4.11 Computer output vs. computer input

ratio in the calculations. This saturation is due to the time required to perform internal calculations. If the computer capabilities are increased, the frequency of the chopper driver circuit is exceeded and the robot will lose phase. Therefore, as stated in Section 3.4, the computer capabilities can be increased but no further improvements in the robot performance can be expected.

4.5 Velocity Analysis

The SEDP robot operates using constant acceleration and constant deceleration ramps. A phase plot was constructed to show the relationship between velocity and displacement. Figure 4.12 shows a phase plot of velocity vs. displacement for a 42 inch path with maximum velocity of 30 in/sec and acceleration of 0.2g. This figure shows that a significant portion (approximately 30%) of the path is in the acceleration and deceleration ramps. The percentage of time spent in the constant velocity portion of the path segment increases as the acceleration ramp increases. Figure 4.13 shows a phase plot with 42 inch travel, 0.5g acceleration and 30 in/sec maximum velocity. Figure 4.14 shows a phase plot with 42 inch travel, 1g acceleration and 30 in/sec maximum velocity.

The phase plots were limited in the amount of information that they delivered without excessive effort to obtain. It was decided to create a velocity profile that plotted percent time in constant velocity portion vs. displacement as shown in Figure 4.15. This plot shows that as the displacement increases, the percent time in the constant velocity portion drops off. This is expected since some time is required to reach the maximum velocity. It is seen that a dramatic increase from 30% to 85% occurs when the

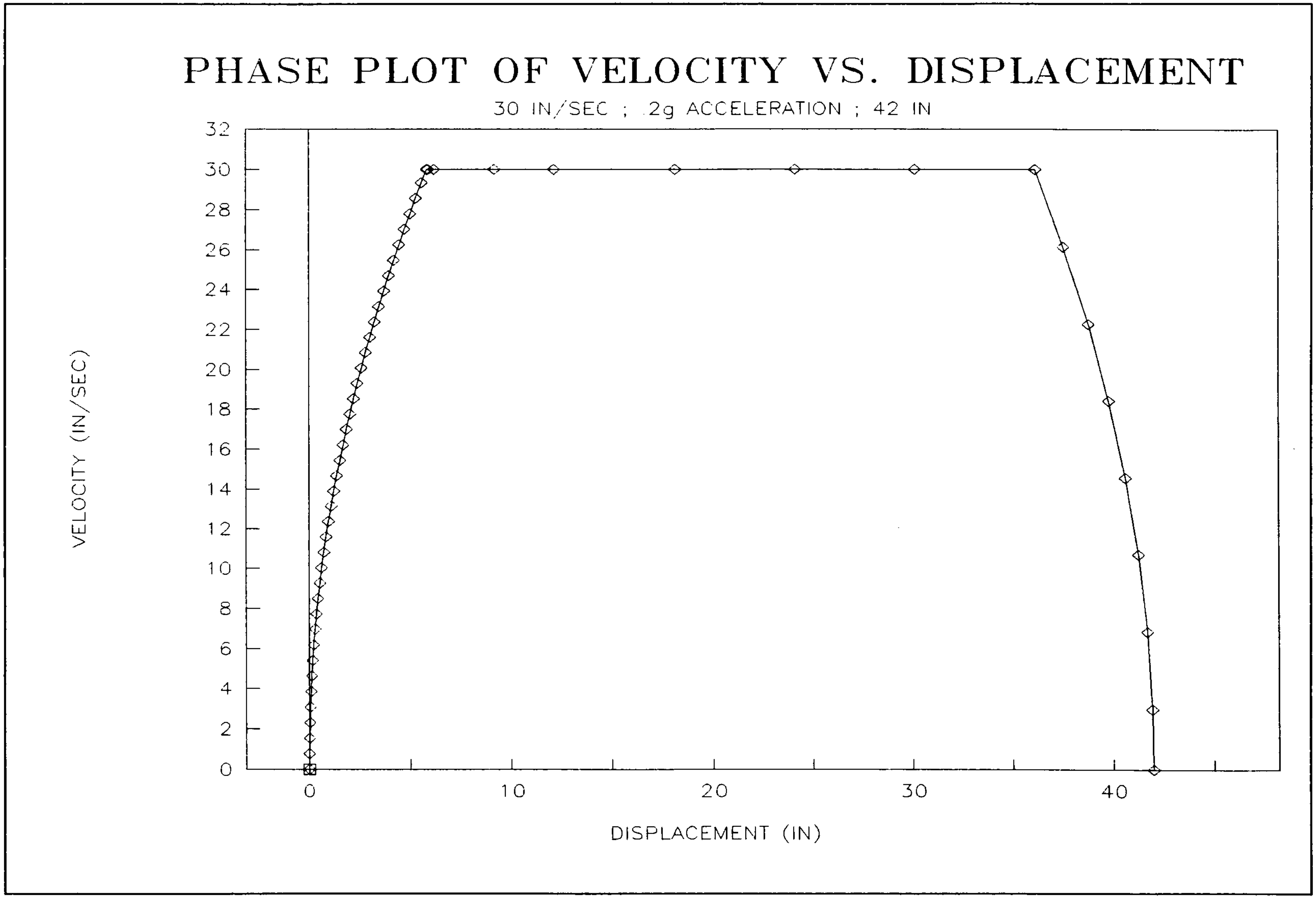


Figure 4.12 Phase plot with 0.2g acceleration

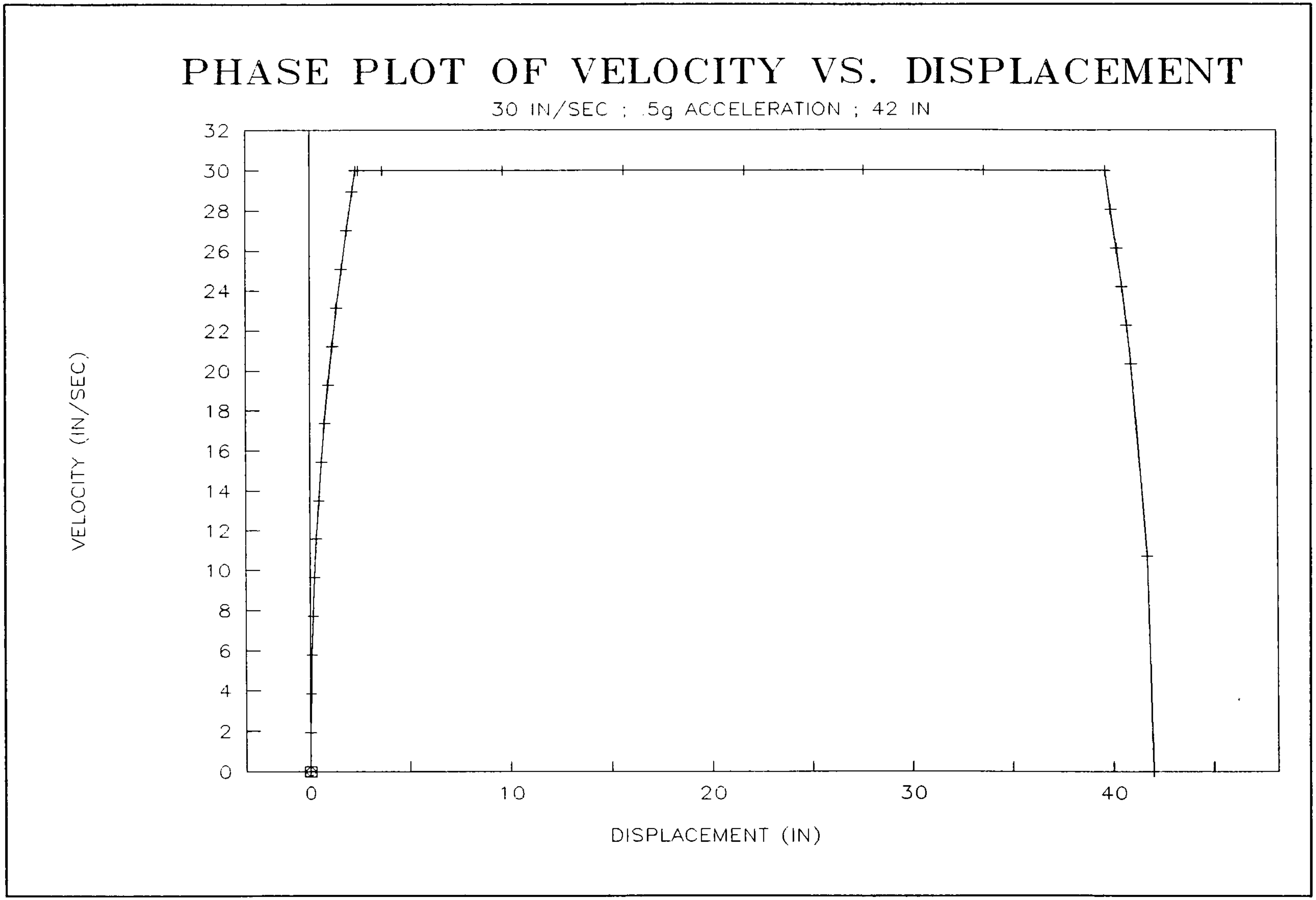


Figure 4.13 Phase plot with 0.5g acceleration

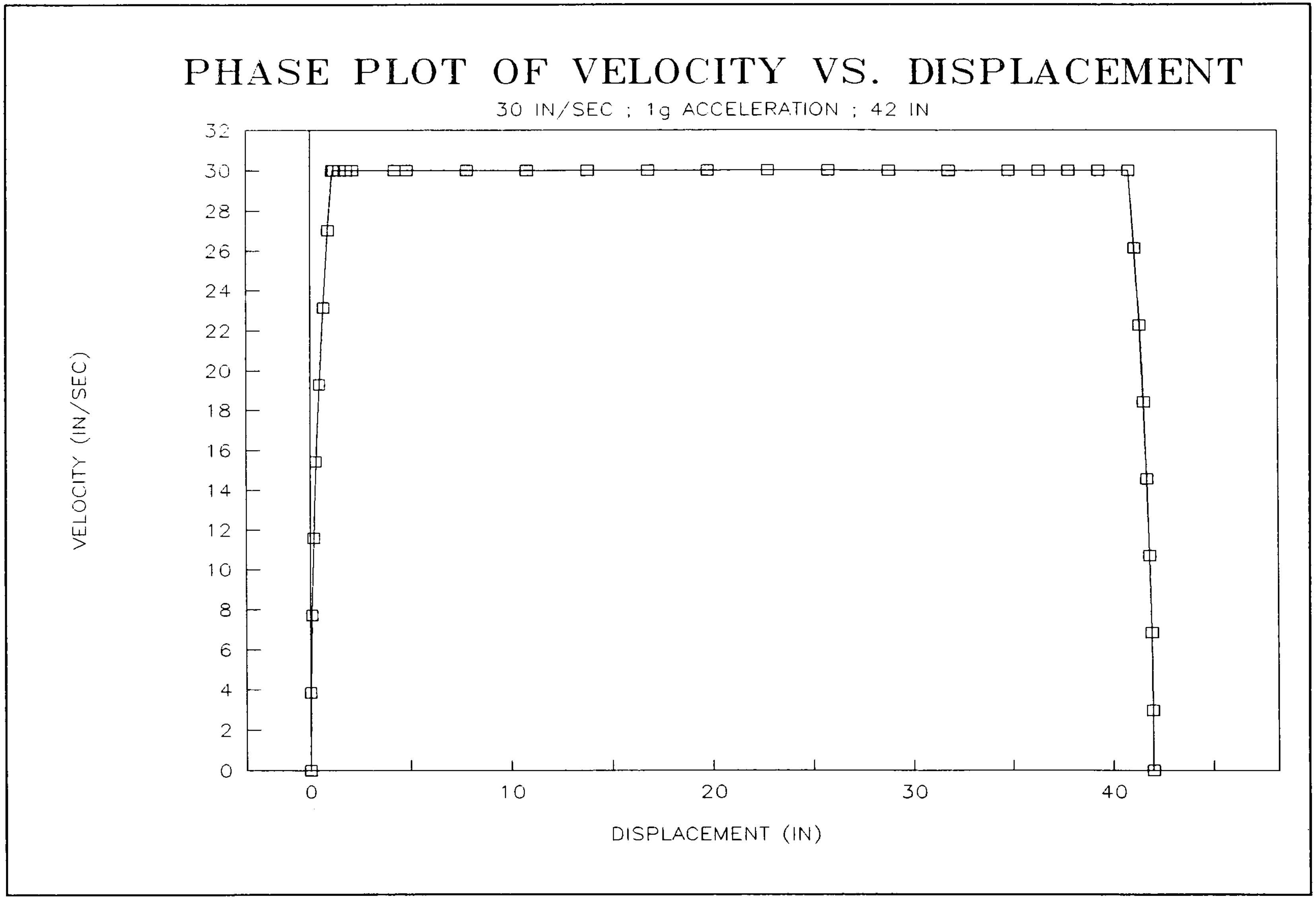


Figure 4.14 Phase plot with 1g acceleration

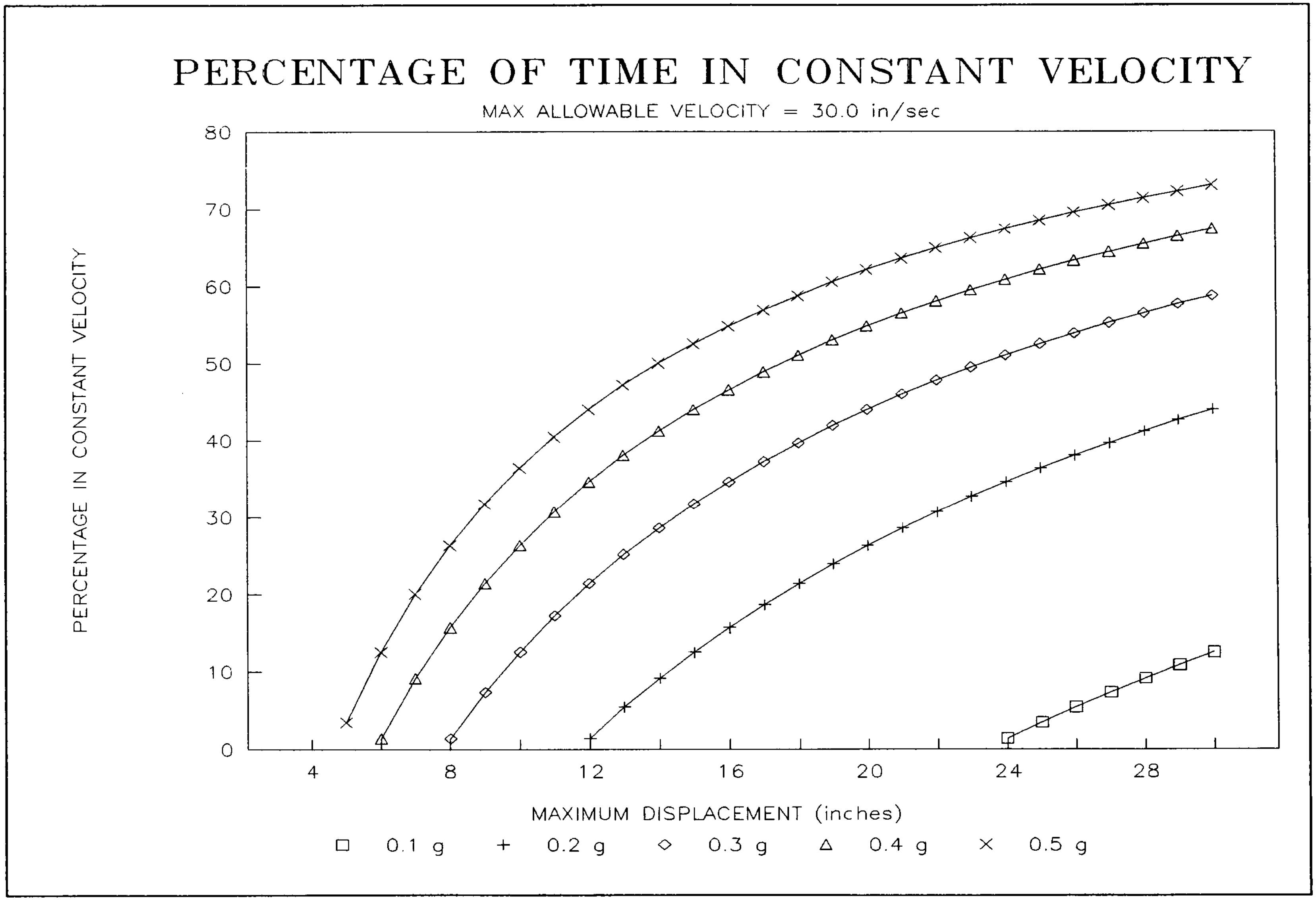


Figure 4.15 Velocity profile for 0.1g to 0.5g acceleration

acceleration is increased from 0.1g to 0.5g with a maximum velocity of 30 in/sec. It can be seen from this graph that with a 0.1g acceleration, a constant velocity section of the curve will not be reached unless the path is at least 24 inches long. Likewise, with a 0.2g acceleration, the path must be at least 12 inches before a constant velocity section will be reached. If the path is less than 12 inches, then the robot will be in the acceleration and deceleration ramps for the entire path. Figure 4.16 shows the remaining curves for acceleration ramps from 0.6g to 1g. The equations used in the velocity analysis are include in Appendix F.

From the curves of this section it has been shown that it is most desirable to operate the robot with the highest possible acceleration ramp. This will allow the robot to operate in the constant velocity portion of the curve for the longest portion of time and therefore decrease the overall cycle time.

When setting up the SEDP robot for an application, select the smallest gear ratio that will satisfy the force and positioning accuracy requirements. The cycle time can be then be minimized by selecting the highest acceleration ramp that will function without breaking phase of the stepper motors. This determination is best done by simulation and not by theoretical means. Certain applications, such as moving liquids, might require small acceleration ramps.

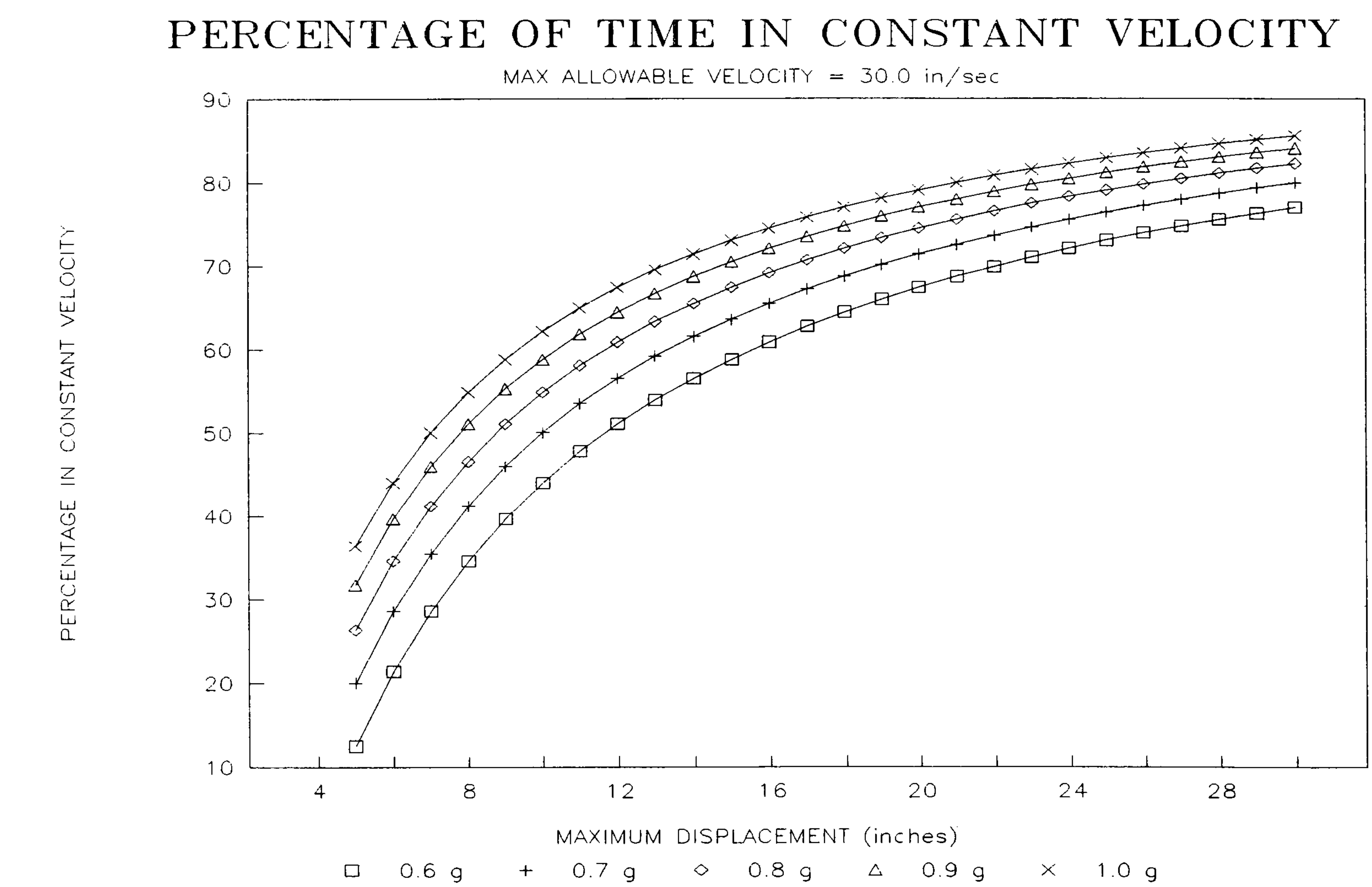


Figure 4.16 Velocity profile for 0.6g to 1g acceleration

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 Introduction

The market survey has established the criteria that the SEDP robot should meet. Suitable end effectors were designed and fabricated which demonstrate both point-to-point and path motion applications. Several improvements were made to the design and function of the SEDP robot.

While the robot has made significant advancement towards being an industrially viable candidate, there are a few areas that need further development. These areas will be discussed in the following sections.

5.2 Point-to-Point Motion

The point-to-point motion demonstrated in this thesis was a specific application identified in the market survey. The robot performed the Magic Chef application by meeting the cycle time and accuracy requirements. The gripper blank design allowed for precise movement of the burners.

Robot velocity was determined to be a significant factor in the point-to-point applications. The robot was operated near its maximum velocity in order to obtain the required average velocity for the Magic Chef application. In order to obtain even higher velocities and steeper acceleration ramps, the weight of the cross-block assembly can be minimized. The weight can be decreased by using hollow cross shafts and placing some "lightening holes" in the cross-block and platform castings. The weight will be further reduced by decreasing the Z mast and shaft lengths to coincide with application requirements. The theta motor can be removed if theta motion is not required. The above modifications will reduce the weight by approximately 12 pounds (25%). This change will allow higher maximum velocities if the payload remains the same; or allow 12 pounds more payload if the maximum velocities remain the same; or increase the margin of safety if the payload and maximum velocities remain the same.

Other types of robot drive systems should be considered. The robot can be run with a variety of drive systems. A dc servo driven system will provide feedback information as well as improve high speed operation. There are also 5 phase stepper motors that provide higher motor resolution and smoother high speed operation.

5.3 Path Motion

The path motion pointed out the undesirable compliance in the timing belts. This compliance allowed the air grinder to "walk" around the wood.

There are many types of timing belts available on the market today. The belts currently used on the SEDP robot are 3/8 inch wide XLT timing belts. A wider belt will provide less compliance in belt stretch. Changing the belt width will require analysis of the sliders and pulleys to determine what modifications would be required. Different tooth profiles are claimed to improve belt performance.

The routing operation was intended to show a proof-of-concept for a path motion application. An improved fixture for holding the work piece should be devised. The work piece was held at both ends with no attachment in the center section. The center portion of the work piece was noticed to deflect or "bow" when the air grinder was lowered to cut. The center deflection caused noticeable cutting changes in the wood.

The jig that attached the air grinder to the robot can be redesigned to minimize the weight of the end effector. The weight optimization will require sizing the components to accommodate the stresses encountered by the tool.

5.4 Endurance Testing

The endurance testing of the SEDP robot was an invaluable experience. The robot failed in several areas as discussed in Section 3.8. While most of these failures were not considered major, they are areas that need to be addressed in order to have an adequately reliable industrial robot. The noted failures in the endurance testing were; sensor abrasion, set screws backing out, air hose interference and chain ladder missing teeth.

5.5 Other Considerations

While not related to the endurance testing, the robot requires safety covers on the exposed pulley reductions. If a safety curtain or proximity sensors are used, the belt covers may not be necessary. The safety issue is one that is dependant on the application and the safety requirements of the facility.

The computer programs that operate the robot need some modifications. Most of the program problems have been identified and some have been solved at the time of this writing. All of the identified problems need to be addressed to have a commercially suitable robot.

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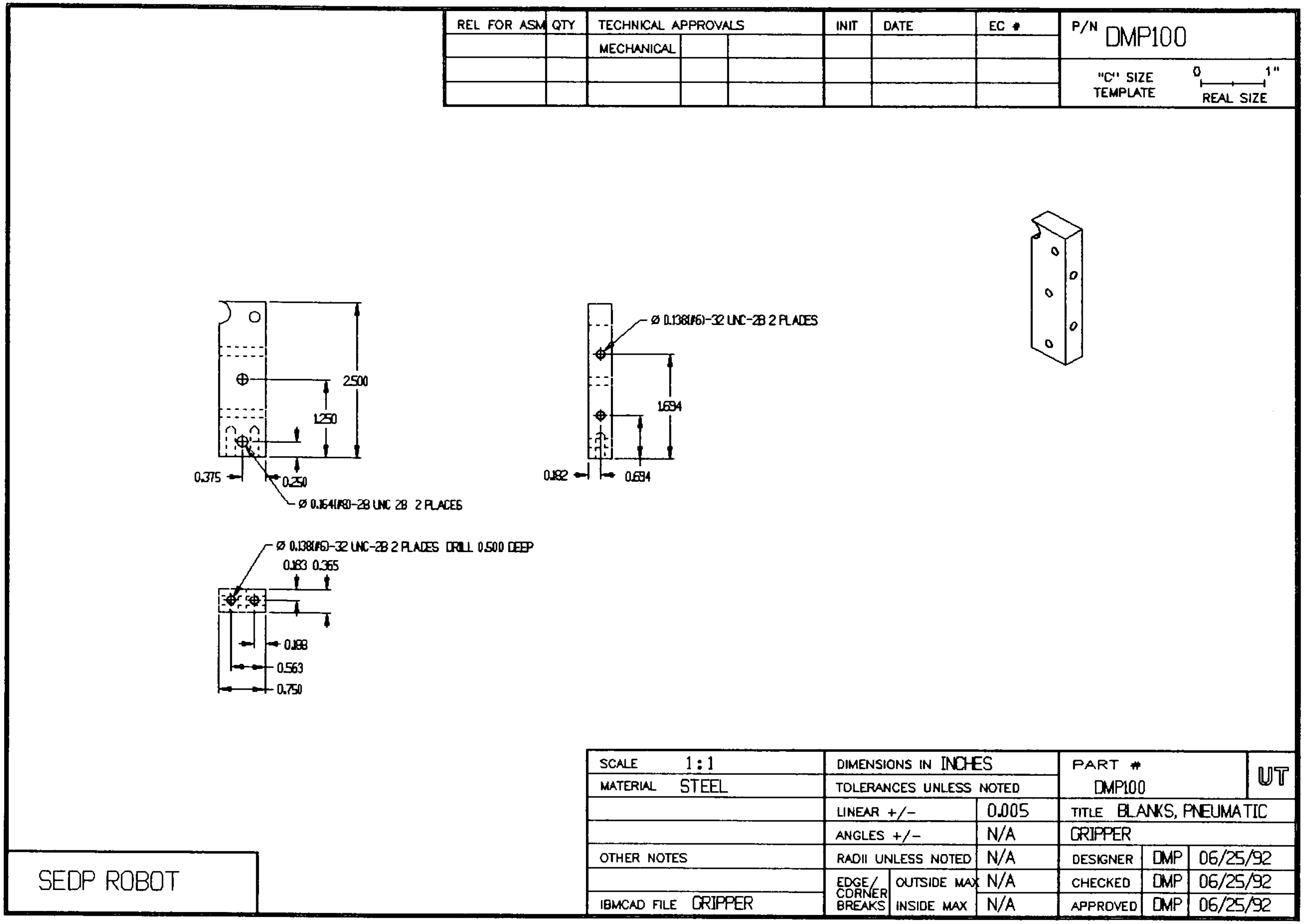
APPENDICES

APPENDIX A

Detailed Drawings


REL FOR ASM
QTY
TECHNICAL APPROVALS
MECHANICAL
INIT
DATE
EC #
P/N DMP100
"C" SIZE TEMPLATE
0 1"
REAL SIZE
2.500
1.250
0.375
0.250
Ø 0.164(#8)-28 UNC 2B 2 PLACES
Ø 0.138(#6)-32 UNC-2B 2 PLACES
1.694
0.694
0.182
Ø 0.138(#6)-32 UNC-2B 2 PLACES DRILL 0.500 DEEP
0.183 0.365
0.188
0.563
0.750
SEDP ROBOT
SCALE 1:1
MATERIAL STEEL
OTHER NOTES
IBMCAD FILE GRIPPER
DIMENSIONS IN INCHES
TOLERANCES UNLESS NOTED
LINEAR +/- 0.005
ANGLES +/- N/A
RADII UNLESS NOTED N/A
EDGE/ CORNER BREAKS OUTSIDE MAX N/A
INSIDE MAX N/A
PART # DMP100
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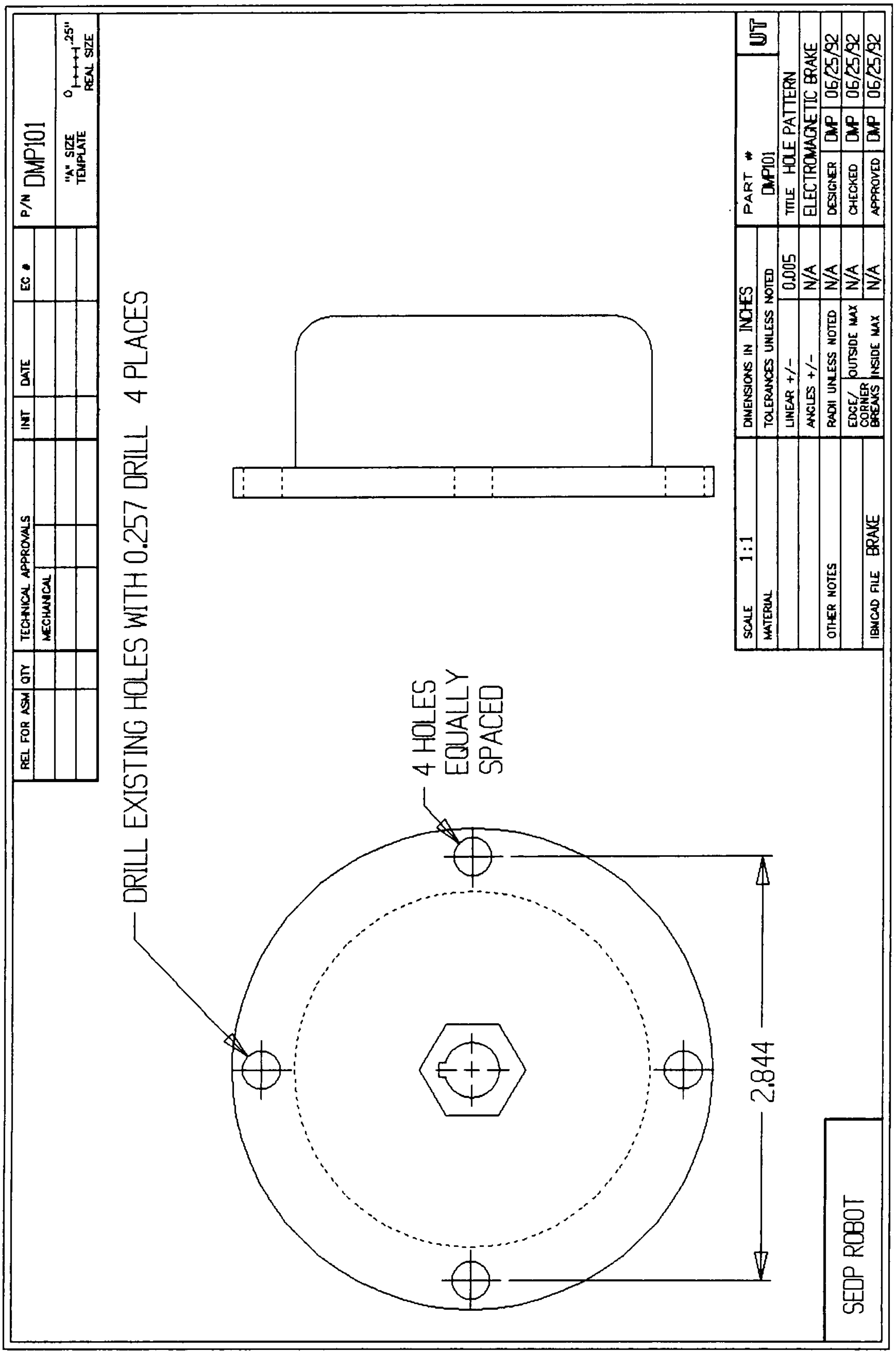
TITLE BLANKS, PNEUMATIC GRIPPER
DESIGNER DMP 06/25/92
CHECKED DMP 06/25/92
APPROVED DMP 06/25/92



DRILL EXISTING HOLES WITH 0.257 DRILL 4 PLACES
4 HOLES EQUALLY SPACED
2.844
SEDP ROBOT
REL FOR ASM
QTY
TECHNICAL APPROVALS
MECHANICAL
INT
DATE
EC #
P/N DMP101
"A" SIZE TEMPLATE
0 .25"
REAL SIZE
SCALE 1:1
MATERIAL
OTHER NOTES
IBMCAD FILE BRAKE
DIMENSIONS IN INCHES
TOLERANCES UNLESS NOTED
LINEAR +/- 0.005
ANGLES +/- N/A
RADII UNLESS NOTED N/A
EDGE/ CORNER BREAKS OUTSIDE MAX N/A
INSIDE MAX N/A
PART # DMP101
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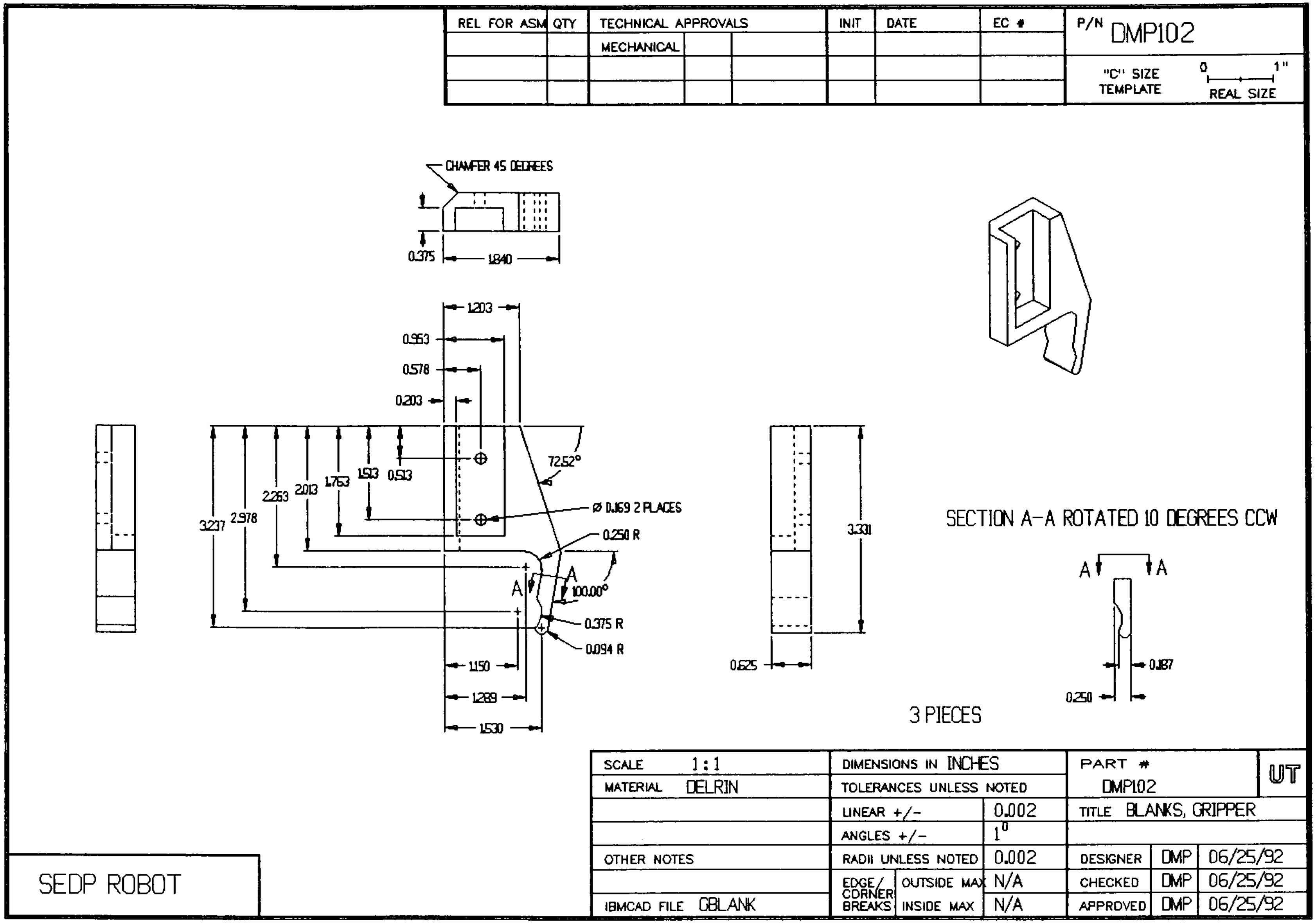
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QTY
TECHNICAL APPROVALS
MECHANICAL
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DATE
EC #
P/N DMP102
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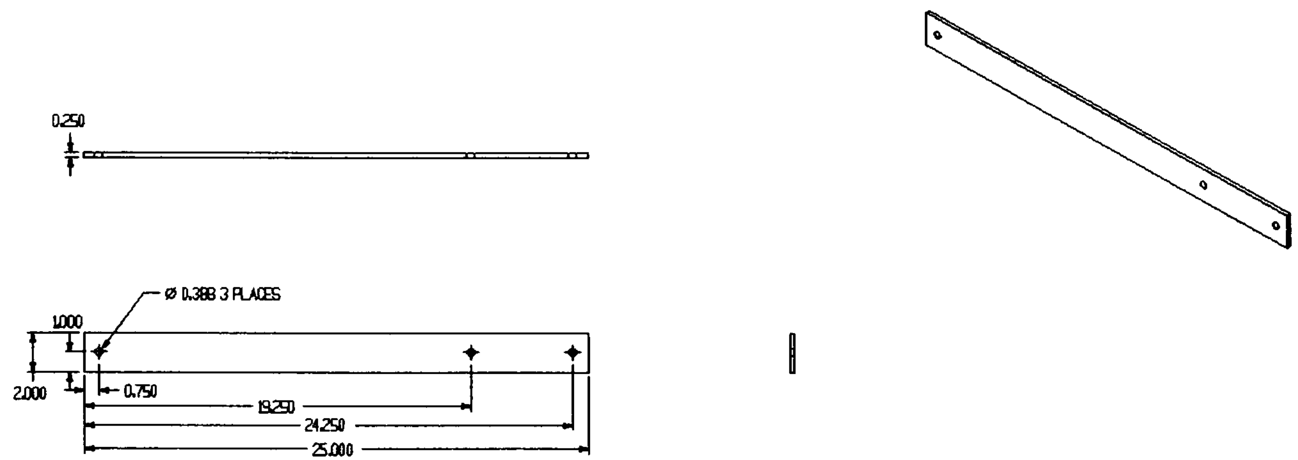
REAL SIZE
CHAMFER 45 DEGREES
0.375
1.840
1.203
0.953
0.578
0.203
3.237
2.978
2.263
2.013
1.763
1.513
0.513
72.52°
Ø 0.169 2 PLACES
0.250 R
A
A
100.00°
0.375 R
0.094 R
1.150
1.289
1.530
3.331
0.625
SECTION A-A ROTATED 10 DEGREES CCW
A
A
0.187
0.250
3 PIECES
SEDP ROBOT
SCALE 1:1
MATERIAL DELRIN
OTHER NOTES
IBMCAD FILE GBLANK
DIMENSIONS IN INCHES
TOLERANCES UNLESS NOTED
LINEAR +/- 0.002
ANGLES +/- 1°
RADII UNLESS NOTED 0.002
EDGE/CORNER BREAKS OUTSIDE MAX N/A
INSIDE MAX N/A
PART # DMP102
UT
TITLE BLANKS, GRIPPER
DESIGNER DMP 06/25/92
CHECKED DMP 06/25/92
APPROVED DMP 06/25/92

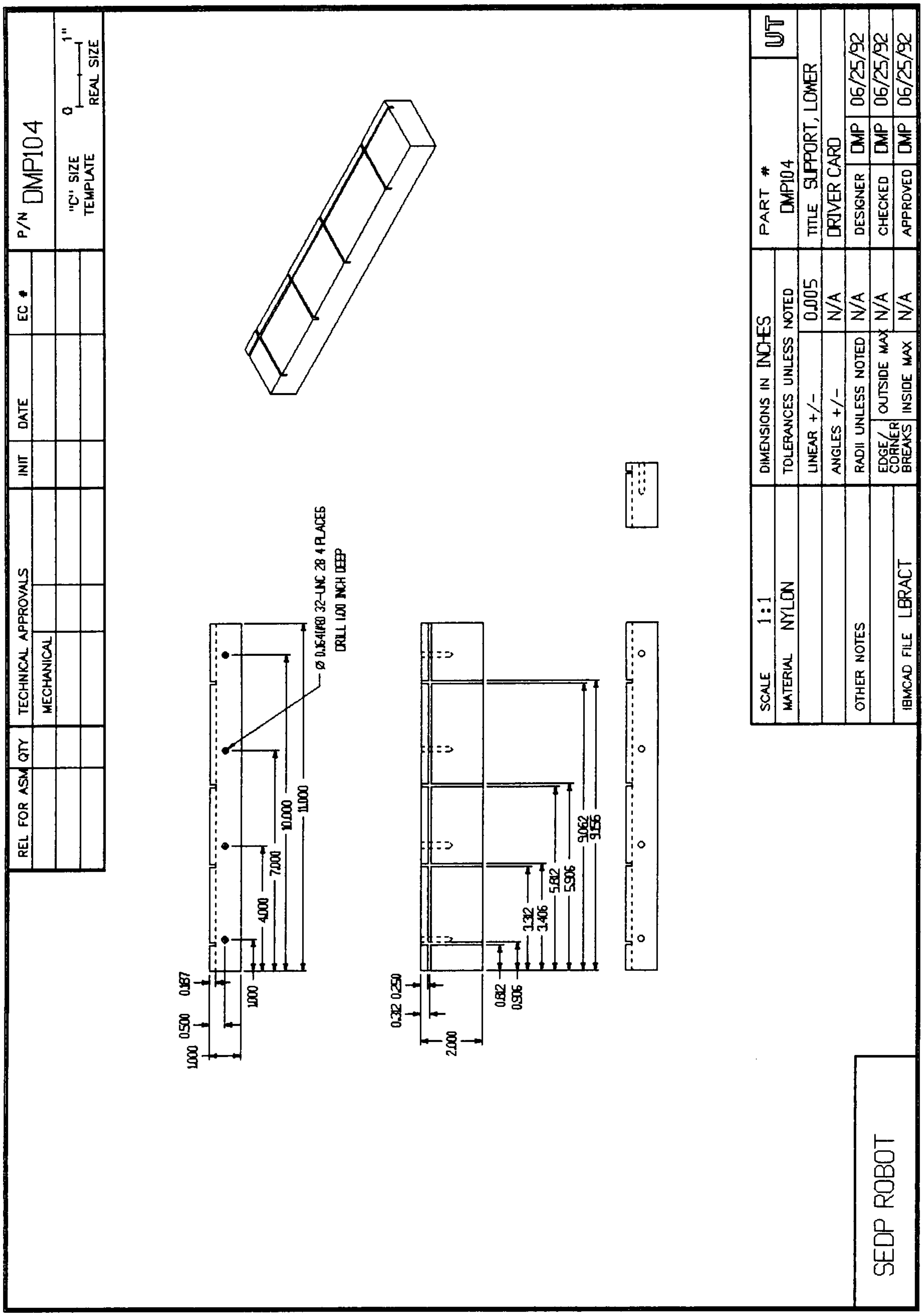
REL FOR ASM	QTY	TECHNICAL APPROVALS			INIT	DATE	EC #	P/N DMP103
		MECHANICAL						"C" SIZE TEMPLATE — 0 to 1" REAL SIZE



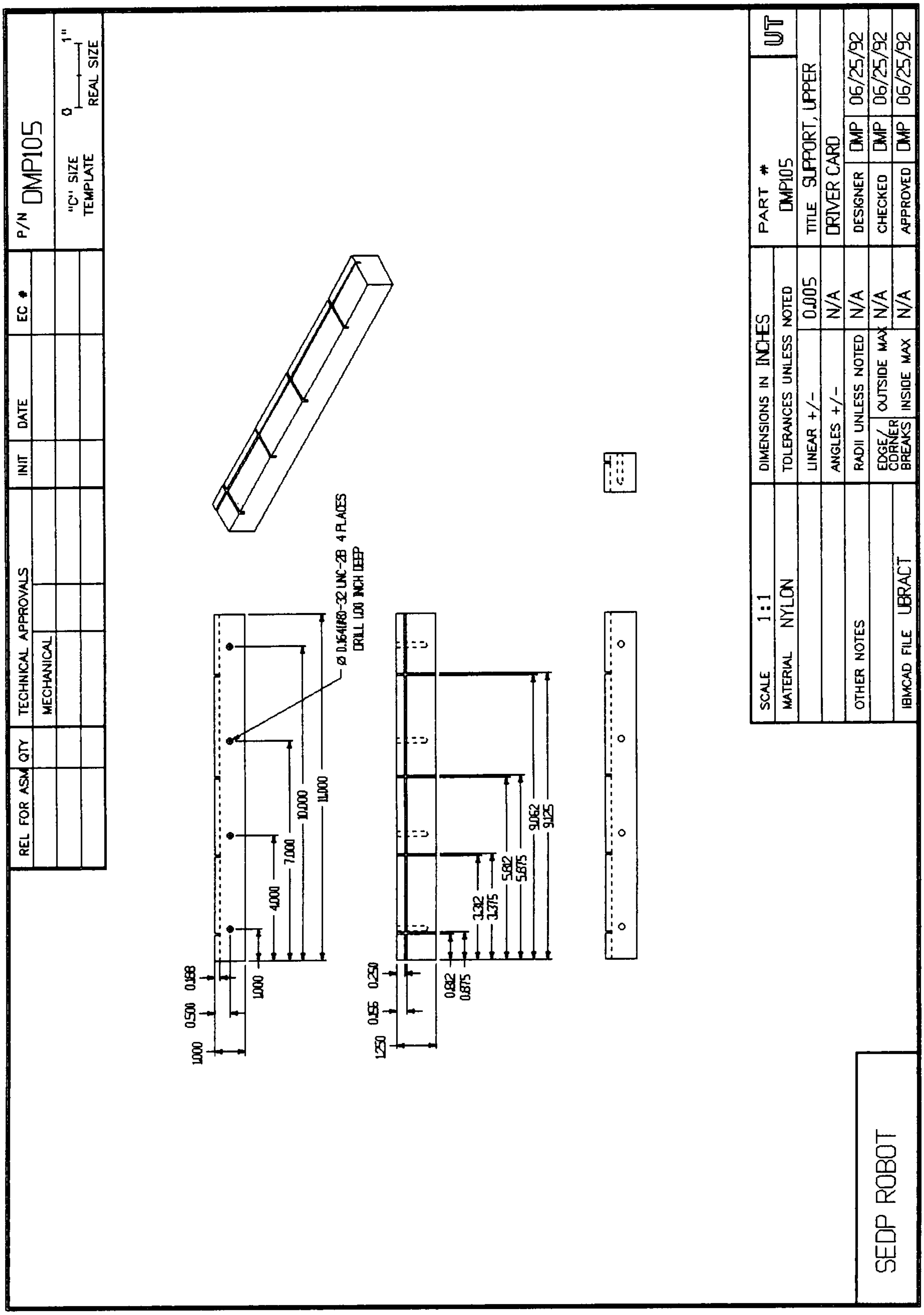
2 PIECES

SEDP ROBOT

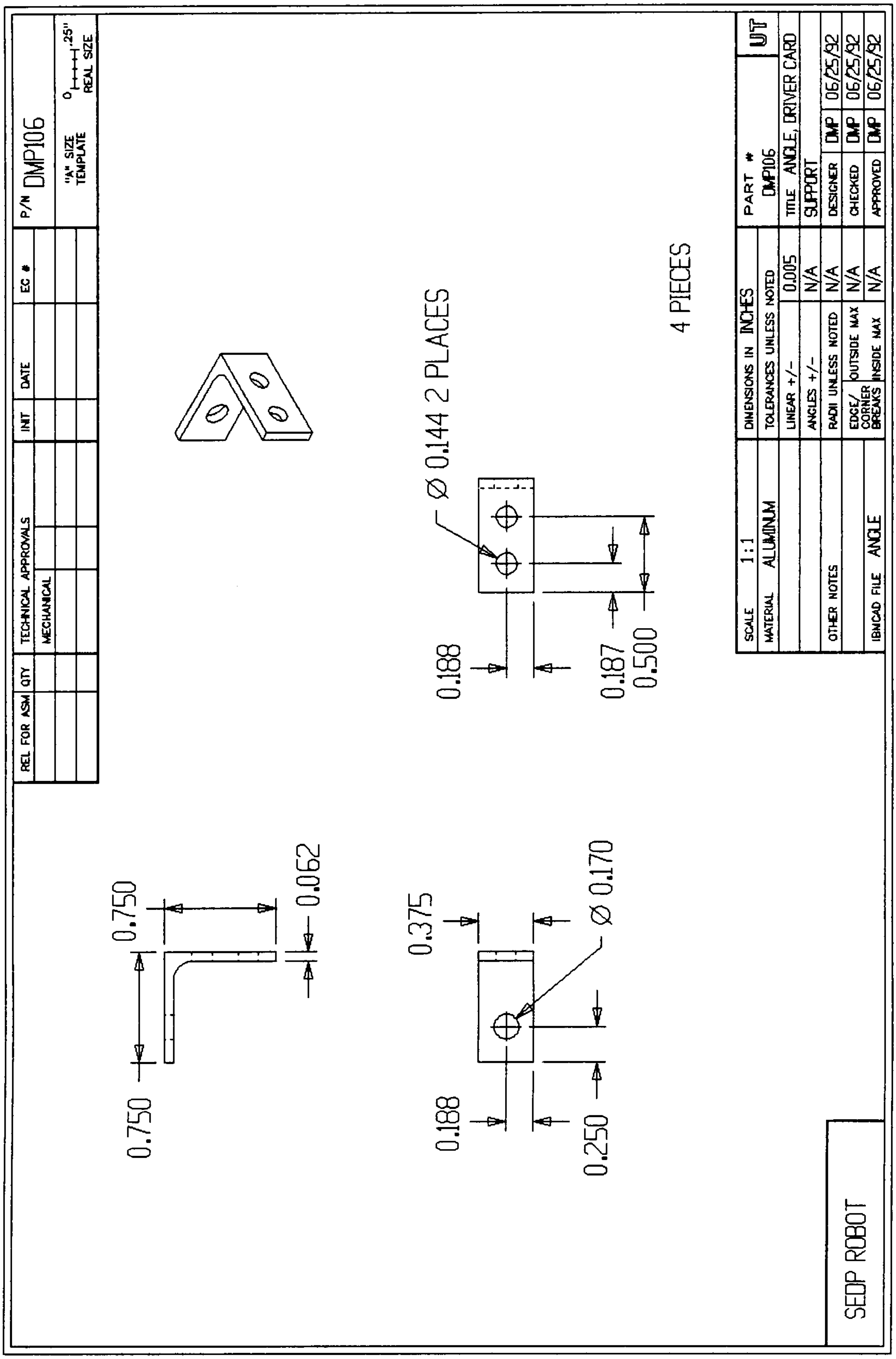
SCALE 1:1	DIMENSIONS IN INCHES		PART # DMP103		UT
MATERIAL STEEL	TOLERANCES UNLESS NOTED				
	LINEAR +/-	0.005	TITLE SUPPORT, ELECTRICAL		
	ANGLES +/-	N/A	CABINET		
OTHER NOTES	RADII UNLESS NOTED	N/A	DESIGNER	DMP	06/25/92
	EDGE/CORNER BREAKS OUTSIDE MAX	N/A	CHECKED	DMP	06/25/92
IBMCAD FILE BRACKET	EDGE/CORNER BREAKS INSIDE MAX	N/A	APPROVED	DMP	06/25/92

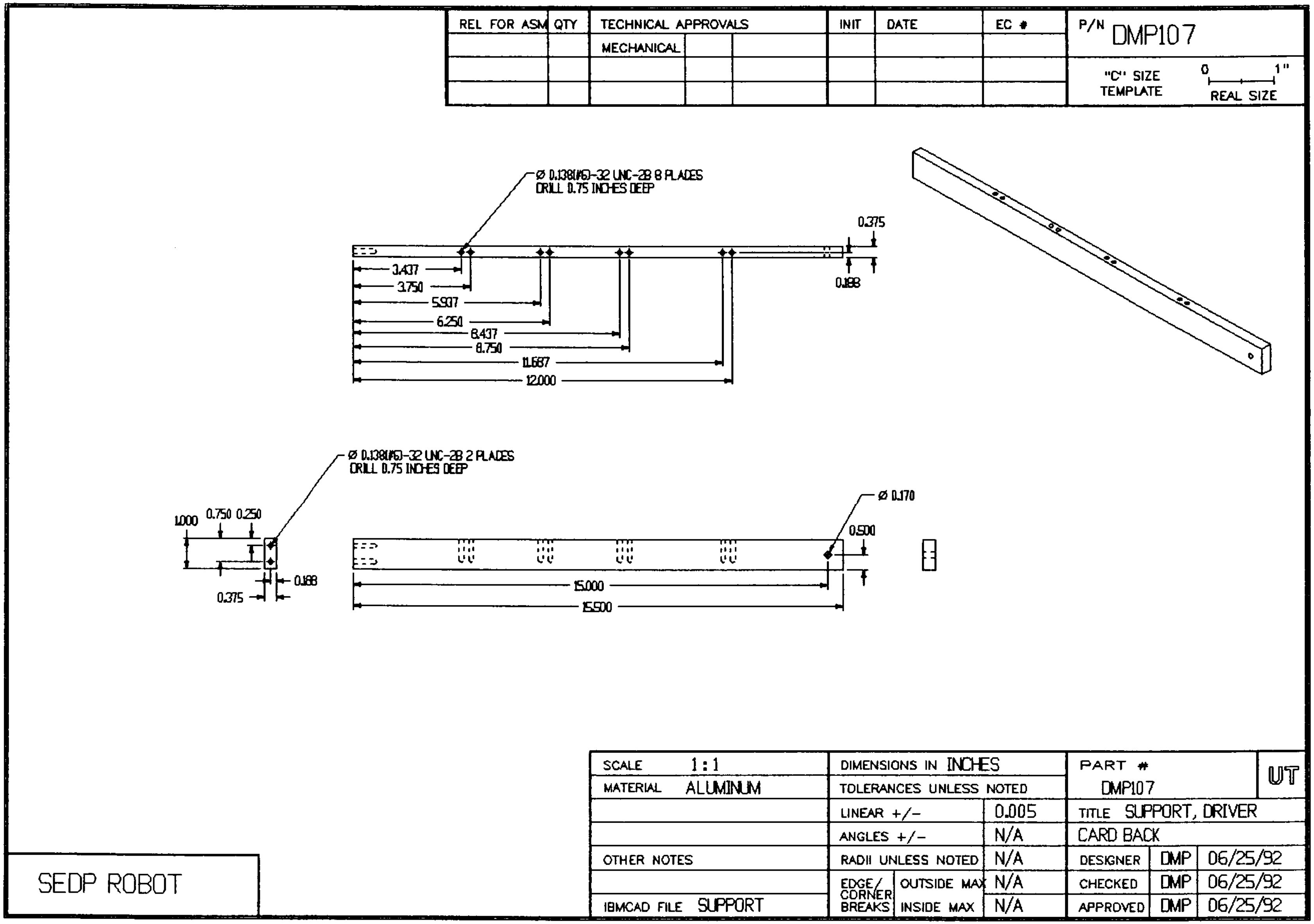


P/N DMP104
"C" SIZE TEMPLATE
REAL SIZE
REL FOR ASM
QTY
TECHNICAL APPROVALS
MECHANICAL
INIT
DATE
EC #
Ø 0.1640(#8) 32-UNC 2B 4 PLACES
DRILL 1.00 INCH DEEP
SCALE 1:1
MATERIAL NYLON
OTHER NOTES
IBMCAD FILE LBRACT
DIMENSIONS IN INCHES
TOLERANCES UNLESS NOTED
LINEAR +/- 0.005
ANGLES +/- N/A
RADII UNLESS NOTED N/A
EDGE/ CORNER BREAKS OUTSIDE MAX N/A
INSIDE MAX N/A
PART #
DMP104
UT
TITLE SUPPORT, LOWER
DRIVER CARD
DESIGNER DMP 06/25/92
CHECKED DMP 06/25/92
APPROVED DMP 06/25/92
SEDP ROBOT

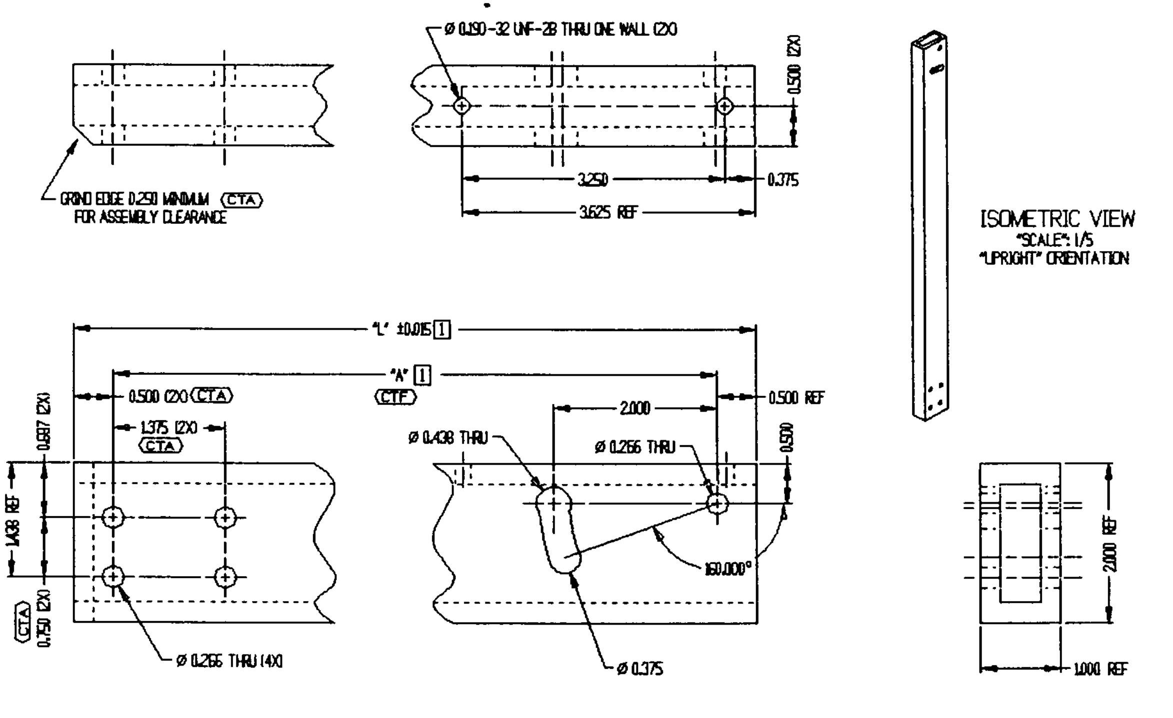


REL FOR ASM
QTY
TECHNICAL APPROVALS
MECHANICAL
INIT
DATE
EC #
P/N DMP105
"C" SIZE TEMPLATE
0 1"
REAL SIZE
Ø 0.164(#8)-32 UNC-2B 4 PLACES
DRILL 1.00 INCH DEEP
SCALE 1:1
MATERIAL NYLON
OTHER NOTES
IBMCAD FILE LIBRACT
DIMENSIONS IN INCHES
TOLERANCES UNLESS NOTED
LINEAR +/- 0.005
ANGLES +/- N/A
RADII UNLESS NOTED N/A
EDGE/CORNER BREAKS OUTSIDE MAX N/A
INSIDE MAX N/A
PART # DMP105
UT
TITLE SUPPORT, UPPER
DRIVER CARD
DESIGNER DMP 06/25/92
CHECKED DMP 06/25/92
APPROVED DMP 06/25/92
SEDP ROBOT


P/N DMP106
"A" SIZE TEMPLATE
0 .25" REAL SIZE
REL FOR ASM
QTY
TECHNICAL APPROVALS
MECHANICAL
INIT
DATE
EC #
0.750
0.750
0.062
0.375
Ø 0.170
0.188
0.250
Ø 0.144 2 PLACES
0.188
0.187
0.500
4 PIECES
SCALE 1:1
MATERIAL ALUMINUM
OTHER NOTES
IBMCAD FILE ANGLE
DIMENSIONS IN INCHES
TOLERANCES UNLESS NOTED
LINEAR +/- 0.005
ANGLES +/- N/A
RADII UNLESS NOTED N/A
EDGE/CORNER BREAKS OUTSIDE MAX N/A
INSIDE MAX N/A
PART # DMP106
UT
TITLE ANGLE, DRIVER CARD SUPPORT
DESIGNER DMP 06/25/92
CHECKED DMP 06/25/92
APPROVED DMP 06/25/92
SEDP ROBOT


REL FOR ASM
QTY
TECHNICAL APPROVALS
MECHANICAL
INIT
DATE
EC #
P/N DMP107
"C" SIZE TEMPLATE
0
1"
REAL SIZE
Ø 0.138(#6)-32 UNC-2B 8 PLACES DRILL 0.75 INCHES DEEP
0.375
0.188
3.437
3.750
5.937
6.250
8.437
8.750
11.687
12.000
Ø 0.138(#6)-32 UNC-2B 2 PLACES DRILL 0.75 INCHES DEEP
1.000
0.750
0.250
0.188
0.375
Ø 0.170
0.500
15.000
15.500
SEDP ROBOT
SCALE 1:1
MATERIAL ALUMINUM
OTHER NOTES
IBMCAD FILE SUPPORT
DIMENSIONS IN INCHES
TOLERANCES UNLESS NOTED
LINEAR +/- 0.005
ANGLES +/- N/A
RADII UNLESS NOTED N/A
EDGE/ CORNER BREAKS OUTSIDE MAX N/A
INSIDE MAX N/A
PART # DMP107
UT
TITLE SUPPORT, DRIVER
CARD BACK
DESIGNER DMP 06/25/92
CHECKED DMP 06/25/92
APPROVED DMP 06/25/92

REL FOR ASM	QTY	TECHNICAL APPROVALS			INIT	DATE	EC #	P/N DMP108
ASY591-ZZZ	1	MECHANICAL	DMP	06/25/92				"C" SIZE TEMPLATE; 0 – 1" REAL SIZE



NOTES :

1. TUBE NOMINAL LENGTH IS DESIGNATED BY THE PART SUFFIX, AND INDICATES THE SPECIFIED "Z" TRAVEL FOR THE ROBOT ASSEMBLY. ACTUAL PART LENGTHS ARE DETERMINED FROM THE NOMINAL LENGTH. SEE P/N SUFFIX CHART.

2. TUBE IS T6061 ALUMINUM, 1.000"x2.000" RECTANGULAR TUBE, 0.250 WALL.
   SUGGESTED VENDOR:
   LOFTIS
   CHATTANOOGA, TN
   ALTERNATE MATERIAL AND VENDOR MAY BE PERMITTED, BUT SPECIFIC ENGINEERING APPROVAL IS REQUIRED.

P/N SUFFIX CHART: 1

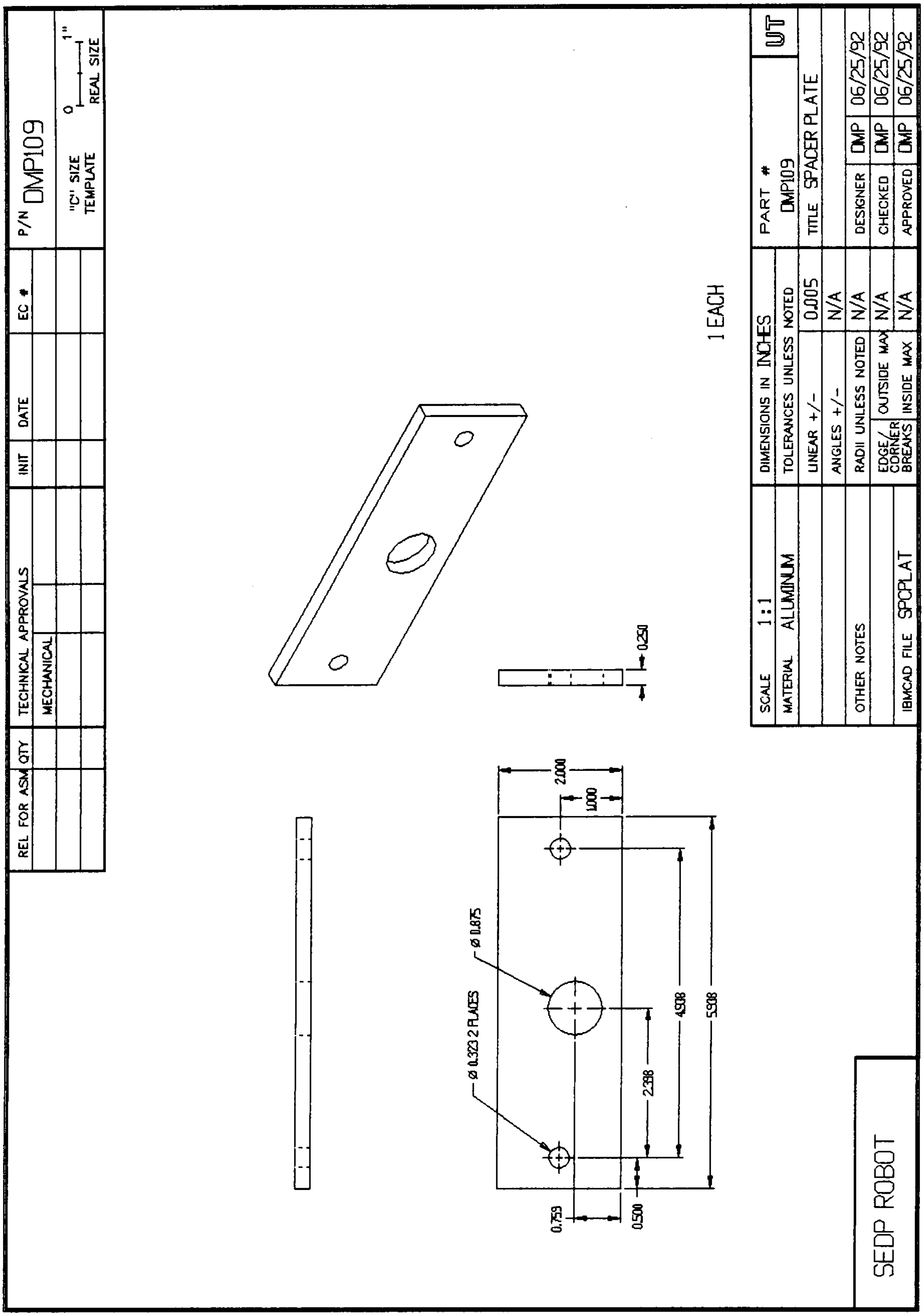
P/N SUFFIX	"NOMINAL" LENGTH	LENGTH "L"	LENGTH "A"
-120	12.00	22.906	21.906
-150	15.00	25.906	24.906
-175	17.50	28.406	27.406
-200	20.00	31.625	30.625
-240	24.00	35.500	34.500

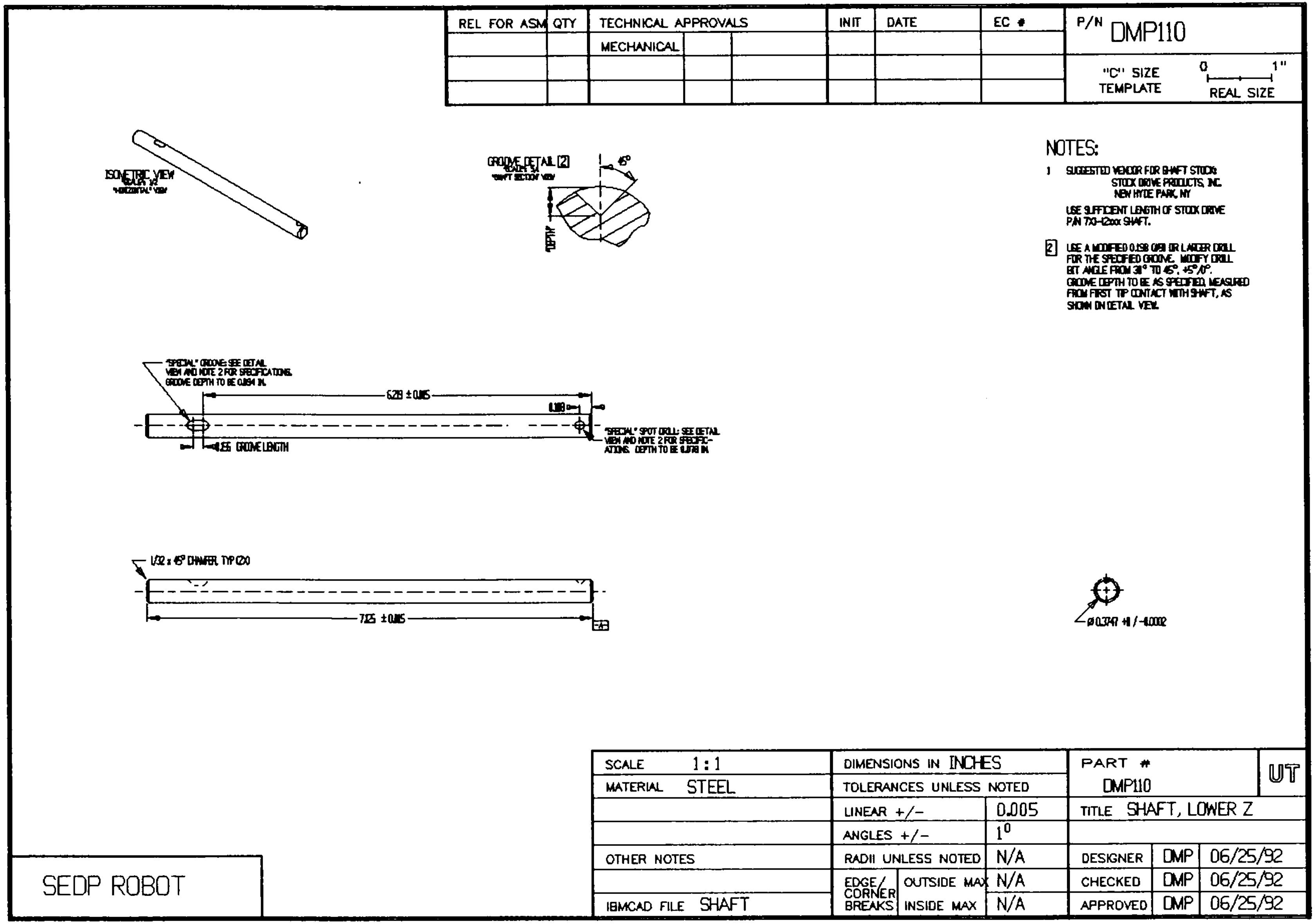
DIMENSIONAL 'KEY' CODES:

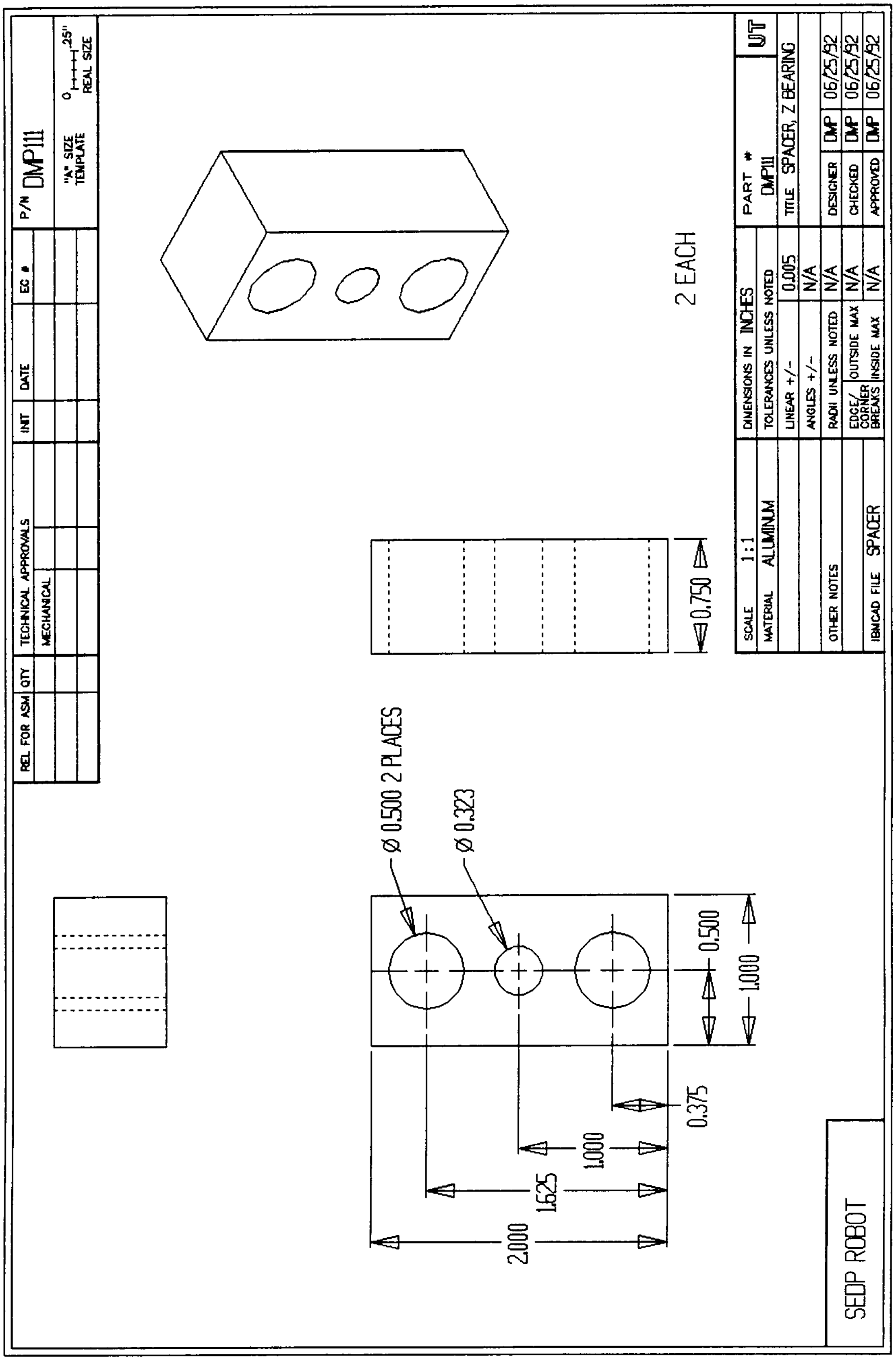
SYM	SYMBOL DESCRIPTION
(CTA)	"CRITICAL TO ASSEMBLY" DIMENSION
(CTF)	"CRITICAL TO FUNCTION" DIMENSION
(CTM)	"CRITICAL TO MANUFACTURE" DIMENSION

SEDP ROBOT

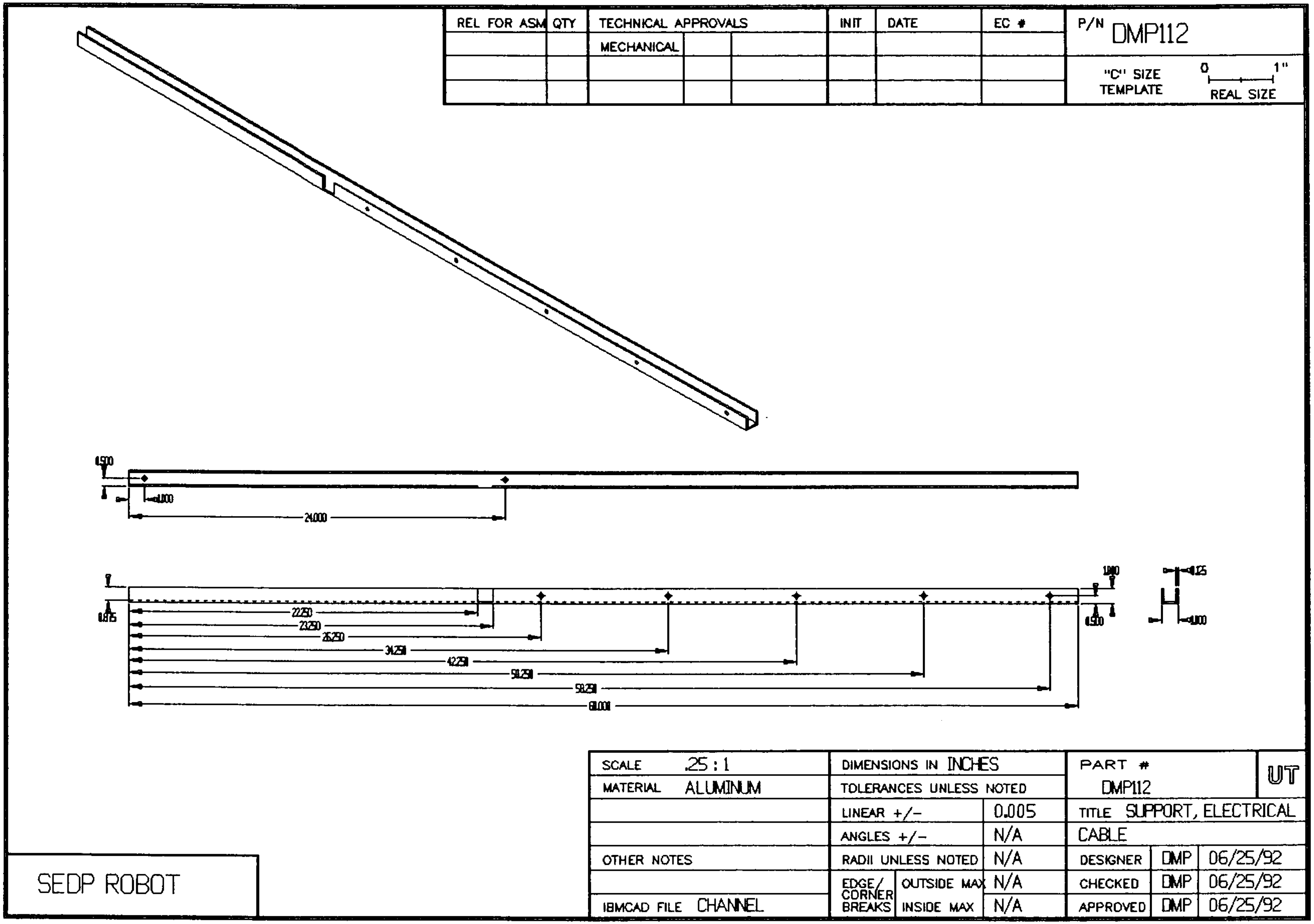
SCALE 1:1	DIMENSIONS IN INCHES			PART # DMP108	UT
MATERIAL SEE NOTE 2	TOLERANCES UNLESS NOTED				
	LINEAR +/-		0.002	TITLE MAST, Z AXIS	
	ANGLES +/-		1°		
OTHER NOTES	RADII UNLESS NOTED		0.020	DESIGNER DMP	06/25/92
	EDGE/CORNER BREAKS	OUTSIDE MAX	0.020	CHECKED DMP	06/25/92
IBMCAD FILE ZMAST		INSIDE MAX	0.020	APPROVED DMP	06/25/92

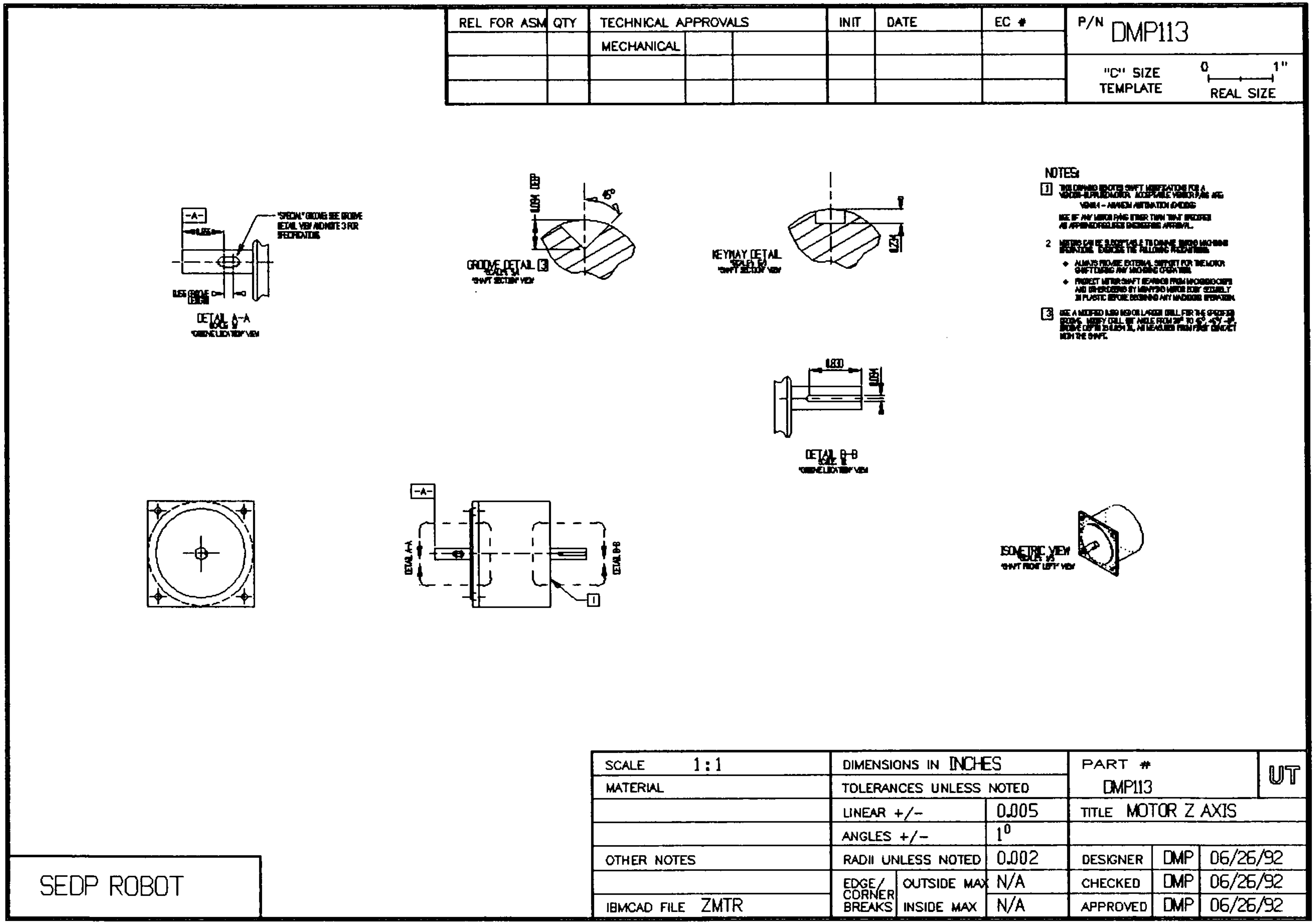

P/N DMP109
"C" SIZE TEMPLATE
0 1"
REAL SIZE
REL FOR ASM
QTY
TECHNICAL APPROVALS
MECHANICAL
INIT
DATE
EC #
1 EACH
0.250
2.000
1.000
Ø 0.875
Ø 0.323 2 PLACES
2.398
4.938
5.938
0.759
0.500
SCALE 1:1
MATERIAL ALUMINUM
OTHER NOTES
IBMCAD FILE SPCPLAT
DIMENSIONS IN INCHES
TOLERANCES UNLESS NOTED
LINEAR +/- 0.005
ANGLES +/- N/A
RADII UNLESS NOTED N/A
EDGE/CORNER BREAKS OUTSIDE MAX N/A
INSIDE MAX N/A
PART # DMP109
TITLE SPACER PLATE
UT
DESIGNER DMP 06/25/92
CHECKED DMP 06/25/92
APPROVED DMP 06/25/92
SEDP ROBOT


REL FOR ASM
QTY
TECHNICAL APPROVALS
MECHANICAL
INIT
DATE
EC #
P/N DMP110
"C" SIZE TEMPLATE
0
1"
REAL SIZE
NOTES:
1 SUGGESTED VENDOR FOR SHAFT STOCK: STOCK DRIVE PRODUCTS, INC. NEW HYDE PARK, NY
USE SUFFICIENT LENGTH OF STOCK DRIVE P/N 7X3-12xxx SHAFT.
2 USE A MODIFIED 0.198 OR LARGER DRILL FOR THE SPECIFIED GROOVE. MODIFY DRILL BIT ANGLE FROM 31° TO 45°, +5°/0°. GROOVE DEPTH TO BE AS SPECIFIED, MEASURED FROM FIRST TIP CONTACT WITH SHAFT, AS SHOWN ON DETAIL VIEW.
ISOMETRIC VIEW
GROOVE DETAIL 2
45°
DEPTH
"SPECIAL" GROOVE: SEE DETAIL VIEW AND NOTE 2 FOR SPECIFICATIONS. GROOVE DEPTH TO BE 0.094 IN.
GROOVE LENGTH
"SPECIAL" SPOT DRILL: SEE DETAIL VIEW AND NOTE 2 FOR SPECIFICATIONS. DEPTH TO BE 0.078 IN.
1/32 x 45° CHAMFER, TYP (2X)
SCALE 1:1
MATERIAL STEEL
OTHER NOTES
IBMCAD FILE SHAFT
DIMENSIONS IN INCHES
TOLERANCES UNLESS NOTED
LINEAR +/- 0.005
ANGLES +/- 1°
RADII UNLESS NOTED N/A
EDGE/CORNER BREAKS OUTSIDE MAX N/A
INSIDE MAX N/A
PART # DMP110
UT
TITLE SHAFT, LOWER Z
DESIGNER DMP 06/25/92
CHECKED DMP 06/25/92
APPROVED DMP 06/25/92
SEDP ROBOT

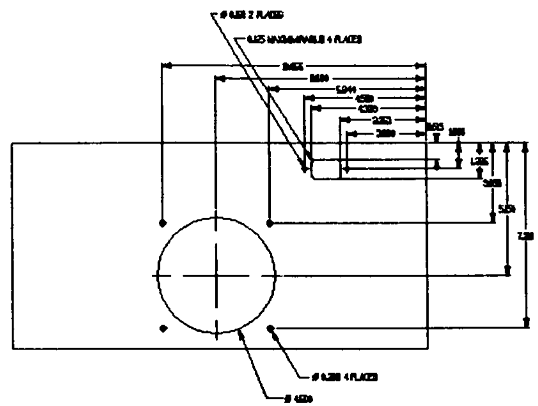


P/N DMP111
"A" SIZE TEMPLATE
0 .25" REAL SIZE
REL FOR ASM
QTY
TECHNICAL APPROVALS
MECHANICAL
INT
DATE
EC #
Ø 0.500 2 PLACES
Ø 0.323
0.750
2 EACH
0.500
1.000
0.375
1.000
1.625
2.000
SEDP ROBOT
SCALE 1:1
MATERIAL ALUMINUM
OTHER NOTES
IBMCAD FILE SPACER
DIMENSIONS IN INCHES
TOLERANCES UNLESS NOTED
LINEAR +/- 0.005
ANGLES +/- N/A
RADII UNLESS NOTED N/A
EDGE/ CORNER BREAKS OUTSIDE MAX N/A
INSIDE MAX N/A
PART # DMP111
UT
TITLE SPACER, Z BEARING
DESIGNER DMP 06/25/92
CHECKED DMP 06/25/92
APPROVED DMP 06/25/92


REL FOR ASM
QTY
TECHNICAL APPROVALS
MECHANICAL
INIT
DATE
EC #
P/N DMP112
"C" SIZE TEMPLATE
0 1"
REAL SIZE
SEDP ROBOT
SCALE .25 : 1
MATERIAL ALUMINUM
OTHER NOTES
IBMCAD FILE CHANNEL
DIMENSIONS IN INCHES
TOLERANCES UNLESS NOTED
LINEAR +/- 0.005
ANGLES +/- N/A
RADII UNLESS NOTED N/A
EDGE/ CORNER BREAKS OUTSIDE MAX N/A
INSIDE MAX N/A
PART #
DMP112
UT
TITLE SUPPORT, ELECTRICAL CABLE
DESIGNER DMP 06/25/92
CHECKED DMP 06/25/92
APPROVED DMP 06/25/92


REL FOR ASM
QTY
TECHNICAL APPROVALS
MECHANICAL
INIT
DATE
EC #
P/N DMP113
"C" SIZE TEMPLATE
0 1"
REAL SIZE
-A-
DETAIL A-A
GROOVE DETAIL 3
KEYWAY DETAIL
NOTES:
DETAIL B-B
DETAIL A-A
DETAIL B-B
1
ISOMETRIC VIEW
SCALE 1:1
MATERIAL
OTHER NOTES
IBMCAD FILE ZMTR
DIMENSIONS IN INCHES
TOLERANCES UNLESS NOTED
LINEAR +/- 0.005
ANGLES +/- 1°
RADII UNLESS NOTED 0.002
EDGE/CORNER BREAKS OUTSIDE MAX N/A
INSIDE MAX N/A
PART # DMP113
UT
TITLE MOTOR Z AXIS
DESIGNER DMP 06/26/92
CHECKED DMP 06/26/92
APPROVED DMP 06/26/92
SEDP ROBOT

REL FOR ASM	QTY	TECHNICAL APPROVALS			INIT	DATE	EC #	P/N DMP114-A
		MECHANICAL						"D" SIZE TEMPLATE 0 — 1" REAL SIZE



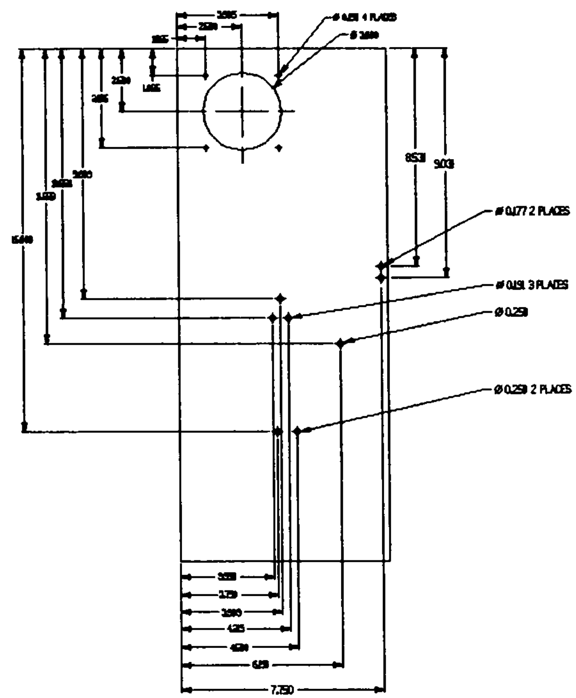
SEDP ROBOT

SCALE 1:2	DIMENSIONS IN INCHES		PART # DMP114-A	UT
MATERIAL SHEET METAL	TOLERANCES UNLESS NOTED			
	LINEAR +/-	0.005	TITLE CABINET, ELECTRONICS	
	ANGLES +/-	1°		
OTHER NOTES BOTTOM VIEW	RADII UNLESS NOTED	0.005	DESIGNER DMP	06/26/92
	EDGE/ CORNER BREAKS OUTSIDE MAX	N/A	CHECKED DMP	06/26/92
IBMCAD FILE CABINET	INSIDE MAX	N/A	APPROVED DMP	06/26/92

REL FOR ASM	QTY	TECHNICAL APPROVALS	INT	DATE	EC #
		MECHANICAL			

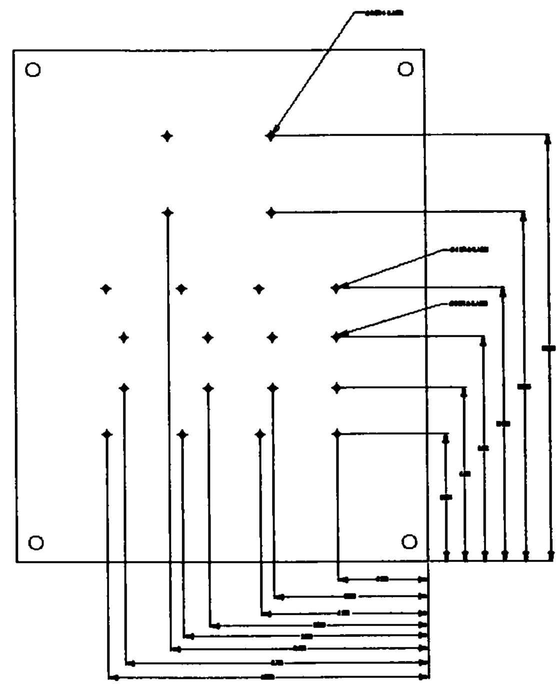
P/N DMP114-B

"D" SIZE TEMPLATE — 0 1" REAL SIZE



SEDP ROBOT

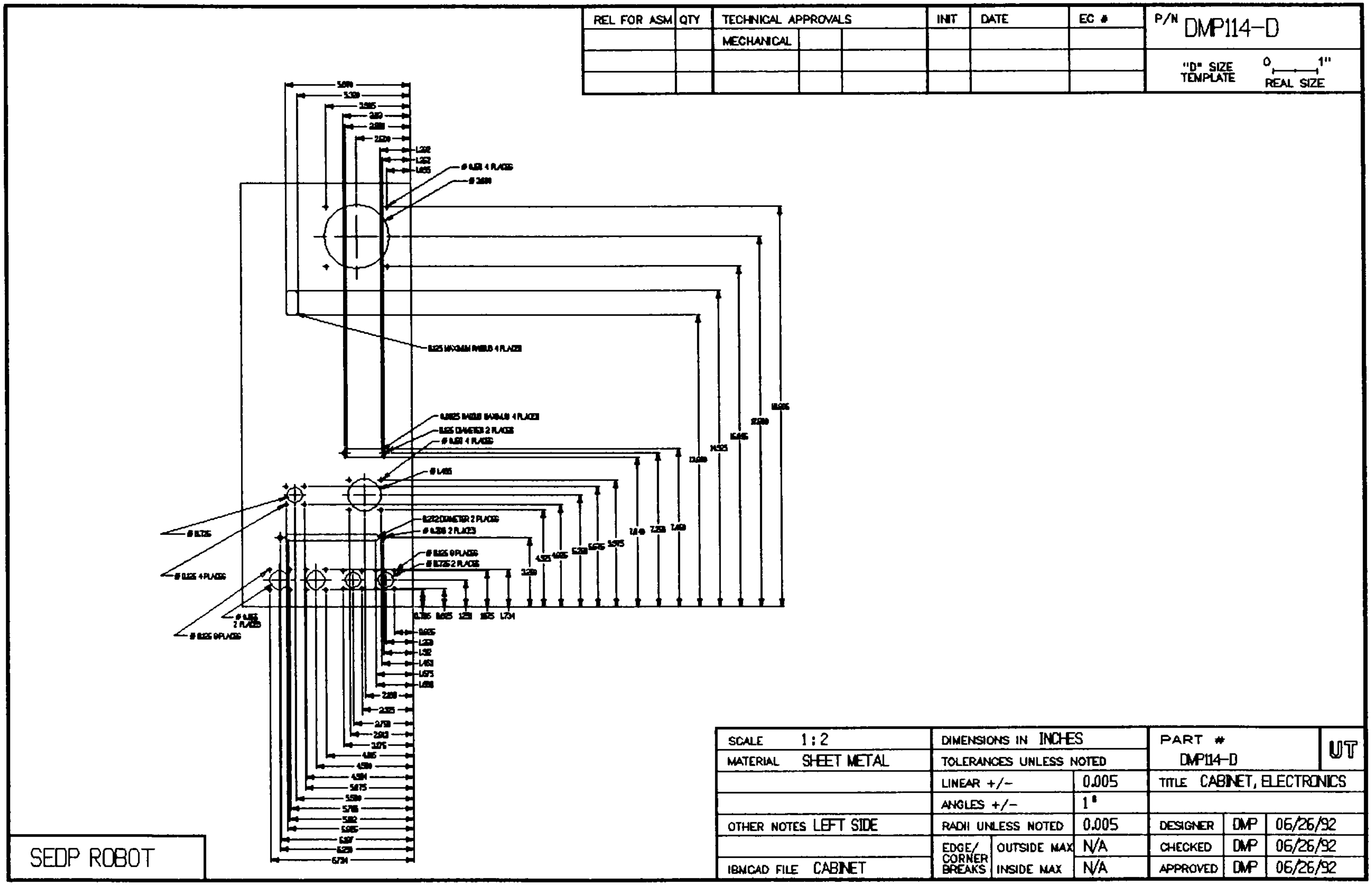
SCALE 1:2	DIMENSIONS IN INCHES		PART # DMP114-B		UT
MATERIAL SHEET METAL	TOLERANCES UNLESS NOTED		TITLE CABINET, ELECTRONICS		
	LINEAR +/-	0.005			
	ANGLES +/-	1°			
OTHER NOTES RIGHT SIDE	RADII UNLESS NOTED	0.005	DESIGNER	DMP	06/26/92
	EDGE/CORNER BREAKS OUTSIDE MAX	N/A	CHECKED	DMP	06/26/92
IBMCAD FILE CABINET	EDGE/CORNER BREAKS INSIDE MAX	N/A	APPROVED	DMP	06/26/92



REL FOR ASM	QTY	TECHNICAL APPROVALS	INIT	DATE	EC #	P/N DMP114-C
		MECHANICAL				"D" SIZE TEMPLATE 0 1" REAL SIZE

SCALE 1:2	DIMENSIONS IN INCHES		PART # DMP114-C		UT
MATERIAL SHEET METAL	TOLERANCES UNLESS NOTED		TITLE CABINET, ELECTRONICS		
	LINEAR +/-	0.005			
	ANGLES +/-	1°			
OTHER NOTES BACK VIEW	RADII UNLESS NOTED	0.005	DESIGNER	DMP	06/26/92
	EDGE/ CORNER BREAKS OUTSIDE MAX	N/A	CHECKED	DMP	06/26/92
IBMCAD FILE CABINET	INSIDE MAX	N/A	APPROVED	DMP	06/26/92

SEDP ROBOT


REL FOR ASM
QTY
TECHNICAL APPROVALS
MECHANICAL
INIT
DATE
EC #
P/N DMP114-D
"D" SIZE TEMPLATE
0 1"
REAL SIZE
SCALE 1:2
MATERIAL SHEET METAL
OTHER NOTES LEFT SIDE
IBMCAD FILE CABINET
DIMENSIONS IN INCHES
TOLERANCES UNLESS NOTED
LINEAR +/- 0.005
ANGLES +/- 1°
RADII UNLESS NOTED 0.005
EDGE/ CORNER BREAKS OUTSIDE MAX N/A
INSIDE MAX N/A
PART #
DMP114-D
UT
TITLE CABINET, ELECTRONICS
DESIGNER DMP 06/26/92
CHECKED DMP 06/26/92
APPROVED DMP 06/26/92
SEDP ROBOT

APPENDIX B

Market Survey

EXHIBIT 1
SURVEY OF ROBOT APPLICATIONS
(Individual responses will be kept confidential.)

Section I:

1. Please check which of the following operations are routinely performed at your facility:

____ material handling ____ programmed path cutting
____ grinding/sanding ____ welding
____ drilling ____ metal stamping
____ die casting ____ packaging
____ part assembly ____ precision assembly
____ laboratory testing ____ spray painting
____ other please explain) ______________________________
____
____
____

2. Do you currently use robots in any of your business operations?
____ yes ____ no

If so: Describe the specific applications for which you currently use robots in your facilities? ______________________________
____
____
____
____
____

3. A graduate student engineering design team at The University of Tennessee has developed a low-cost, easy-to-use PC controlled robot which performs repetitive series of tasks with a repeatability range of .005 - .010 inches. Please describe any applications in your facility which you think might be a viable candidate for such a robot. ______________________________
____
____
____
____
____
____

4. What is the most a robot could cost to justify its use in your most important potential application?

____ less than \$5,000 ____ \$5,000 - \$15,000
____ \$15,000 - \$25,000 ____ \$25,000 - \$40,000
____ more than \$40,000

Section II:

Consider an important, routinely performed activity at your facility involving repetitive tasks. Then please complete the following section for that task. An extra page is provided if you can identify additional applications.

Identify the application you will be describing: ________________
____
____

5. How far is the object typically moved?
   ____ less than 1 foot   ____ 1 - 2 feet
   ____ 2 - 4 feet   ____ 4 - 8 feet
   ____ greater than 8 feet

6. What is the weight of the object to be moved?
   ____ less than 1 lb.   ____ 1 - 5 lbs.
   ____ 5 - 10 lbs.   ____ 10 - 20 lbs.
   ____ greater than 20 lbs.

7. What is the typical positioning accuracy required?
   ____ less than .005 in.   ____ .005 - .010 in.
   ____ .010 - .050 in.   ____ .050 - .250 in.
   ____ greater than .250 in.

8. What is the typical cycle time of the task?
   ____ less than 2 seconds   ____ 2 - 10 seconds
   ____ 10 - 20 seconds   ____ 20 - 30 seconds
   ____ greater than 30 seconds

Section III:

Work environment:

9. Is your working environment damaging or corrosive to machines?
   ____ yes ____ no

   If so, what is the type of damage or corrosive? (for example: acid or dust) ________________
   ____
   ____

10. Is your working environment hazardous to humans?
   ____ yes ____ no
   If so, what is the type of hazard? ________________
   ____
   ____

Section IV:

Other:

11. If a probable application for the UT designed robot is identified for operations of your type, would you be interested in discussing a prototype development project with the engineering school?
____ yes ____ no

We would like to follow-up a few of our mail survey responses with telephone conversations. Please provide us with your name and correct address and telephone number by filling out the information below or by attaching a business card.

Name: ____________________

Business: ____________________

Address: ____________________

____

Telephone: ____________________

We are very excited about this project and feel any information you can provide will be extremely helpful. We sincerely appreciate your time and cooperation.

Thank you.

Additional Application Specifications: This page is a continuation of Section II. Please identify any additional applications in your facility.

Identify the application you will be describing: ______________

____

____

1. How far is the object typically moved?
   - ____ less than 1 foot
   - ____ 1 - 2 feet
   - ____ 2 - 4 feet
   - ____ 4 - 8 feet
   - ____ greater than 8 feet

2. What is the weight of the object to be moved?
   - ____ less than 1 lb.
   - ____ 1 - 5 lbs.
   - ____ 5 - 10 lbs.
   - ____ 10 - 20 lbs.
   - ____ greater than 20 lbs.

3. What is the typical positioning accuracy required?
   - ____ less than .005 in.
   - ____ .005 - .010 in.
   - ____ .010 - .050 in.
   - ____ .050 - .250 in.
   - ____ greater than .250 in.

4. What is the typical cycle time of the task?
   - ____ less than 2 seconds
   - ____ 2 - 10 seconds
   - ____ 10 - 20 seconds
   - ____ 20 - 30 seconds
   - ____ greater than 30 seconds

Identify the application you will be describing: ______________

____

____

1. How far is the object typically moved?
   - ____ less than 1 foot
   - ____ 1 - 2 feet
   - ____ 2 - 4 feet
   - ____ 4 - 8 feet
   - ____ greater than 8 feet

2. What is the weight of the object to be moved?
   - ____ less than 1 lb.
   - ____ 1 - 5 lbs.
   - ____ 5 - 10 lbs.
   - ____ 10 - 20 lbs.
   - ____ greater than 20 lbs.

3. What is the typical positioning accuracy required?
   - ____ less than .005 in.
   - ____ .005 - .010 in.
   - ____ .010 - .050 in.
   - ____ .050 - .250 in.
   - ____ greater than .250 in.

4. What is the typical cycle time of the task?
   - ____ less than 2 seconds
   - ____ 2 - 10 seconds
   - ____ 10 - 20 seconds
   - ____ 20 - 30 seconds
   - ____ greater than 30 seconds

APPENDIX C

Plant Trip Summary

PLANT TRIP SUMMARIES

Gemtron - 9:00 a.m., Thursday, July 18, 1991

Gemtron Corporation is a glass fabricator, primarily for the appliance industry, and is located in Sweetwater, approximately a 45 minute drive from campus. We talked with Mr. Tony Brimer, Chief Engineer, and Mr. Gene Farmer, North Plant Production Manager. After touring the plant, it was agreed that the most probable application for the robot was unloading glass from shipping crates onto a conveyor feeding a cutting machine. Currently, Gemtron operates 4 of these cutting stations manually. Although this seems to be a possible application, some of our major concerns are the weight of the glass (up to 20 pounds), the necessary rotation of the glass for proper placement on the conveyor, and the positioning of the robot frame in relation to the crate cart. Although very anxious to work with the University, they stressed the importance of continuity of production with minimum down time.

Magic Chef - 9:00 a.m., Tuesday, July 23, 1991

Magic Chef is an appliance manufacturer located in Cleveland, approximately a 1 1/4 hour drive from campus. Mr. Ed Sendler, Director of Industrial Engineering, talked with us and gave us an extensive tour of their large facilities. As Magic Chef is currently installing a series of non-synchronous conveyors and is heavily involved in upgrading many of their lines and assembly processes, the opportunities for robot applications here are numerous. Two immediate applications were observed. The first application is the feeding and unloading of small metal plates into a punch press. The second operation involves palletizing small gas burners directly from a carousel assembly press or from a 2-foot slide chute. Mr. Sendler also expressed future interest in sub-assembly operations as Magic Chef continues to develop their new lines.

MidLab, Inc. - 1:30 p.m., Tuesday, July 23, 1991

MidLab is a cleaning and detergent product manufacturer located in Sweetwater, again about a 45 minute drive from campus. We talked with Mr. Matt Schenk, who is apparently a recently hired engineer. He seemed very focused on redesigning the lines, but because of the high levels of acids and bases used in the products manufactured, contamination of the robot structure and components, as well as non-explosive motors, would have to be taken into consideration. Regardless of these concerns, the only workable application at this time is the capping of plastic bottles, for which the cycle time might prove to be a significant obstacle in competing with the manual operation now in place.

Rexnord, Inc. - 9:00 a.m., Wednesday, July 24, 1991

Rexnord, a division of Link Belt, is a bearing manufacturer in Clinton and is a co-op sponsor of the engineering program. Mr. Kirk Ingall, Chief Engineer, gave us a tour of the plant and talked about possible applications for the robot. Each of the two applications Mr. Ingall proposed was not suitable for the robot as it was designed. One of these applications involved lifting very heavy parts (approximately 50 pounds), and the other involved exposure to extreme temperatures. Given that the plant is already utilizing high-volume fixed automation equipment, no potential applications within the capabilities of the robot were observed.

ALCOA - 10:00 a.m., Thursday, July 25, 1991

ALCOA (Aluminum Company of America) is a contributor to the Superior Engineering Design Program and an Engineering co-op sponsor. Mr. Terry Elmy, Senior Staff Mechanical Engineer, gave Dave a tour of the North Plant, as I was not informed prior to the visit that pants were required for plant tours. The aluminum coil bagging application Mr. Elmy suggested would require a very large work envelope and a complicated end-effector. The removal of spacers from between heated aluminum ingots was also examined, but the random orientation and extreme temperature of the spacers made this an unlikely application as well. In general, the scale of operations at ALCOA is much larger than the capabilities of the robot.

APPENDIX D

Component Cost

REQ'D QTY	P/N	PART NAME, DESCRIPTION	VENDOR	VENDOR P/N	AS'SY P/N	AS'SY LEVEL	COST/FT ($)
STEPPER MOTOR CHOPPER DRIVER CARD							
2		Transistor Optoisolator	Digi-Key	PS2501-4NEC			$2.20
2		Stepper Motor Controller	Marshal	L297			$5.39
4		DMOS Full Bridge Driver	Marshal	L6203			$6.90
1		+5 Volt Voltage Regulator	Digi-Key	LM340T-5			$0.60
1		4.5 Watt Heat Sink	Digi-Key	HS115			$0.18
4		Large Heat Sink	Marshal	70238			$1.81
5		#6-32 1/2 inch screw	McMasters	91251A148			$0.07
5		#6-32 nut	McMasters	91841A007			$0.00
0.01		Heat Sink Grease 1oz tube	Newark	00Z1049			$10.32
2		16 Pin IC Socket	Digi-Key	A9316			$0.33
2		20 Pin IC Socket	Digi-Key	A9320			$0.41
1		2 Pin Terminal Block	Bluff City	17-27-01-0			$0.49
2		4 Pin Terminal Block	Bluff City	17-14-95-5			$0.56
1		90 Deg Dual Row Connectors	Digi-Key	929740-05-36-ND			$4.75
1		Dual Row Connectors	Digi-Key	929836-10-36-ND			$2.27
		Jumper Block (1 to 8 needed)	Digi-Key	929950-00-ND			$0.11
8		1N4148 diodes	Digi-Key	1N4148			$0.06
9		270 ohm 1/4 Watt 5%	Digi-Key	270Q			$0.05
8		4.7K ohm 1/4 Watt 5%	Digi-Key	4.7KQ			$0.05
1		15K ohm 1/4 Watt 5%	Digi-Key	15KQ			$0.05
4		22K ohm 1/4 Watt 5%	Digi-Key	22KQ			$0.05
2		1.00K ohm 1/4 Watt 1%	Digi-Key	1.00KX			$0.10
2		RS (19K --> 4K ohm) 1/4 Watt 1%	Digi-Key	??.??KX			$0.10
4		10 ohm 1 Watt 5%	Digi-Key	P10W-1			$0.19
4		0.25 ohm 5 Watt 1%	Digi-Key	SC5E0.25-ND			$1.85
1		0.0033uF 50V Polyester Cap	Digi-Key	P4557			$0.12
16		0.01uF 50V Metal Film Cap	Digi-Key	P4513			$0.12
8		0.22uF 50V Metal Film Cap	Digi-Key	P4529			$0.24
1		10uF 50V Electrolytic Cap	Digi-Key	P5272			$0.16
1		1000uF 50V Electrolytic Cap	Digi-Key	P5280			$1.50
1		Printed Circuit - Driver Card					$40.00
I/O and Sensor Card							
0.147		5" x 7" perfboard 0.100" spacing	Digi-Key	V1013-ND			$17.81
2		14 Pin IC Socket	Digi-Key	A9314			$0.29
4		16 Pin IC Socket	Digi-Key	A9316			$0.33
10		2 Contact Terminal Block	Digi-Key	ED1610			$0.66
1		90 Deg Dual Row Connectors	Digi-Key	929740-05-36-ND			$4.75
1		Transistor Optoisolator	Digi-Key	PS2501-4NEC			$2.20
2		2N2222 NPN Transistor 50V 500mA	Digi-Key	2N2222			$0.65
1		High Power +24 Volt Regulator	UT ASS'Y				$2.52
1		+5 Volt Voltage Regulator	Digi-Key	LM340T-5			$0.60
1		#6-32 1/2 inch screw	McMasters	91251A148			$0.07
1		#6-32 nut	McMasters	91841A007			$0.00
0.01		Heat Sink Grease 1oz tube	Newark	00Z1049			$10.32
1		10 Watt Heat Sink	Digi-Key	HS104-2			$0.52
8		1N4148 diodes	Digi-Key	1N4148			$0.06
11		270 ohm 1/4 Watt 5%	Digi-Key	270Q			$0.05
12		4.7K ohm 1/4 Watt 5%	Digi-Key	4.7KQ			$0.05

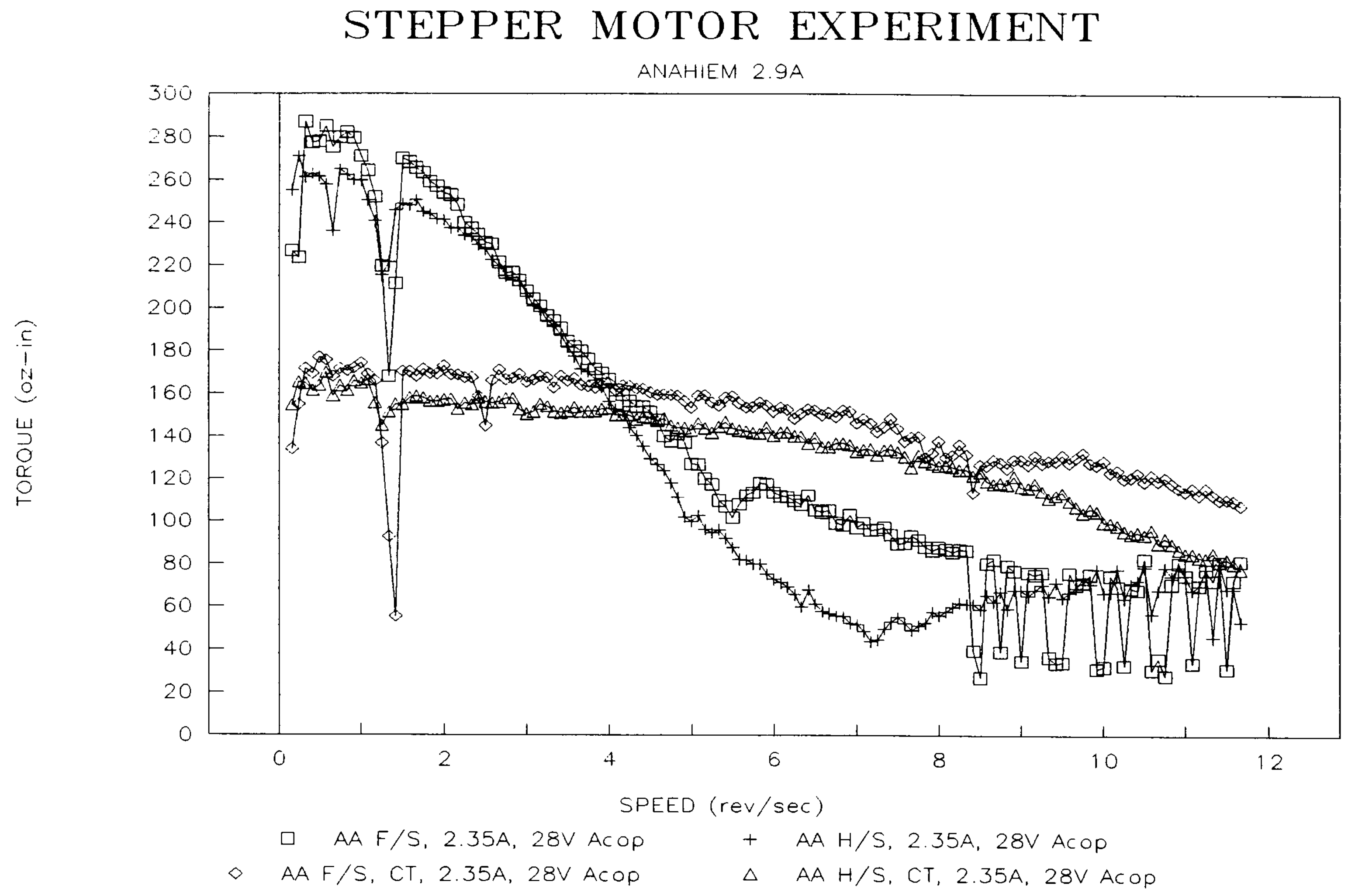
REQ'D QTY	P/N	PART NAME, DESCRIPTION	VENDOR	VENDOR P/N	ASS'Y P/N	ASS'Y LEVEL	COST/PT ($)
2		10uF 50V Electrolytic Cap	Digi-Key	P5272			$0.15
1		1000uF 50V Electrolytic Cap	Digi-Key	P5330			$1.50
1		LED	Digi-Key	P300			$0.18
2		DPDT Relay	Digi-Key	Z770-ND			$3.21
MOTHER BOARD							
0.294		3" x 10" perfboard 0.100" spacing	Digi-Key	V1013-ND			$17.31
2		Straight Dual-Row Female	Digi-Key	929740-05-36-ND			$4.75
1		Dual Row Connectors	Digi-Key	929836-10-36-ND			$2.27
High Power +24 Volt Regulator							
0.029		1" x 3" perfboard 0.100" spacing	Digi-Key	V1013-ND			$17.31
1		3 Contact Terminal Block	Digi-Key	ED1610			$0.66
1		2.4K ohm 1/4 Watt 5%	Digi-Key	2.4KQ			$0.05
1		1N4749A 24V 1W Zener Diode	Digi-Key	1N4749A			$0.25
1		1N4003 1A 200PIV Diode	Digi-Key	1N4003			$0.07
1		NPN Darlington Transistor 2A 60V	Digi-Key	TIP110PH-ND			$0.45
1		#6-32 1/2 inch screw	McMasters	91251A148			$0.07
1		#6-32 nut	McMasters	91841A007			$0.00
0.01		Heat Sink Grease 1oz tube	Newark	00Z1049			$10.32
2		4.5 Watt Heat Sink	Digi-Key	HS115			$0.18
		Total					
DRIVER BOX							
3		Stepper Motor Driver Cards	UT ASS'Y				$118.37
1		I/O and Sensor Card	UT ASS'Y				$33.25
1		High Power +24 Volt Regulator	UT ASS'Y				$2.52
1		D-L20H1608LPB Enclosure	Newark	39F5354			$100.93
1		Fan	Newark	31F8106			$35.55
1		Fan Cord	Newark	81F8125			$1.70
1		Filter and Fan Guard	Newark	81F2837			$2.55
2		Fan Guard	Newark	81F8127			$2.45
1		Recessed Power Receptacle	Newark	81F6090			$1.07
1		Power Cord	Newark	81N6701			$4.00
1		12 Terminal Barrier Block	Newark	14F2027			$3.06
3		4 Pin Square Flange Receptacle	Newark	44F8387			$1.52
3		4 Pin Protective Cap	Newark	87F4118			$1.97
2		9 Pin Square Flange Receptacle	Newark	44F8399			$1.63
2		9 Pin Protective Cap	Newark	87F4120			$2.20
1		24 Pin Square Flange Receptacle	Newark	46F322			$2.16
1		24 Pin Protective Cap	Newark	87F4109			$2.54
1		16 Amp Rocker Switch	Digi-Key	SW315-ND			$1.06
1		25 Pin PC connector	Digi-Key	225M-ND			$0.90
1		D-sub panel mounting kit	Digi-Key	A9007			$1.22
1		20 Pin Termination Jumper	Digi-Key	CIAX6-2036M-ND			$4.00
1		High Power +24 Volt Regulator	UT ASS'Y				$2.52
24		#4-40 3/8" screw	McMaster	91251A108			$0.07
4		#4-40 washer	McMaster	93019A109			$0.01

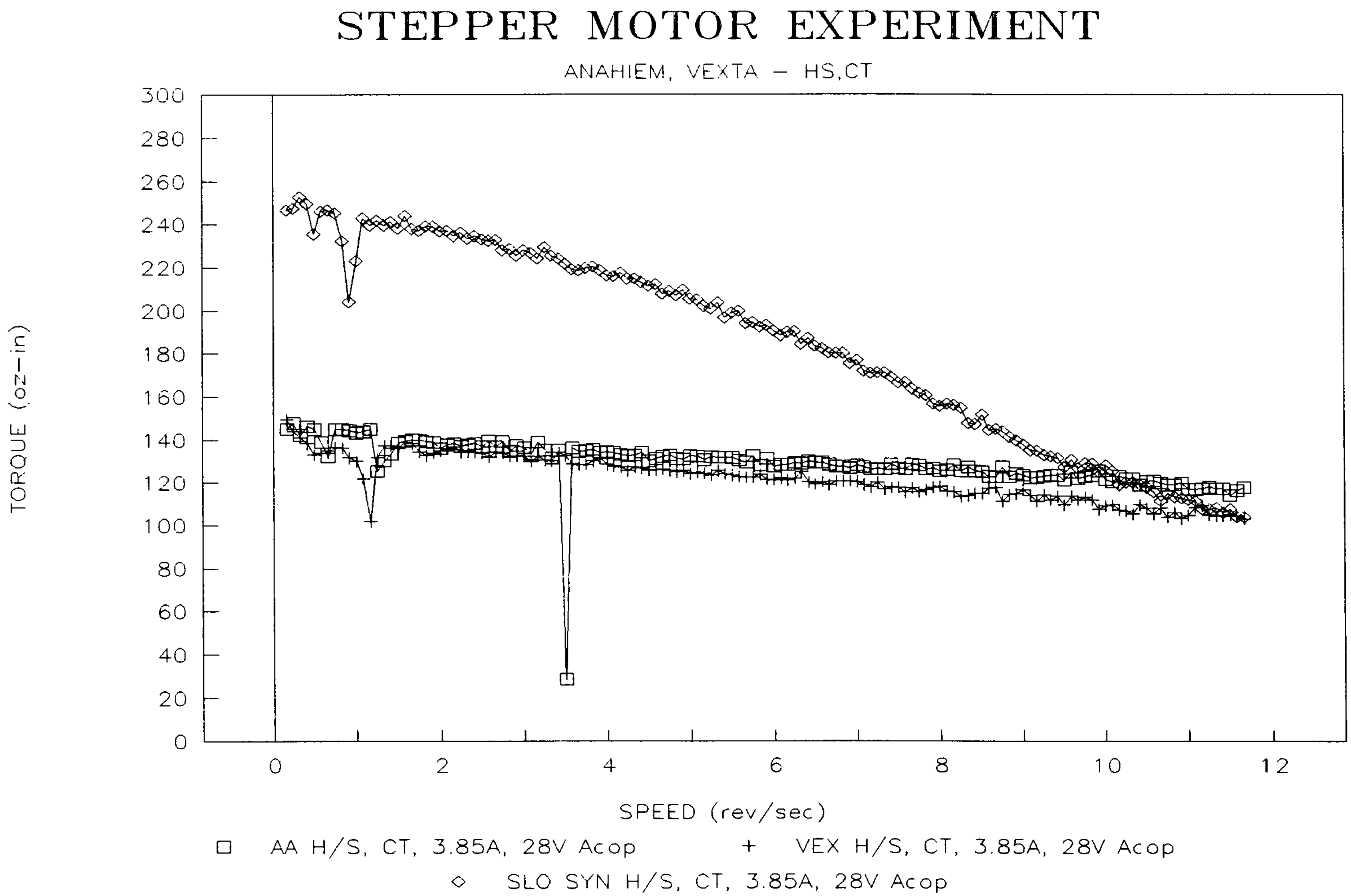
REQ'D QTY	P/N	PART NAME, DESCRIPTION	VENDOR	VENDOR P/N	AS'SY P/N	AS'SY LEVEL	COST/PT ($)
24		#4-40 locking washer	McMaster	91102A005			$0.00
24		#4-40 nut	McMaster	91841A005			$0.02
8		#6-32 1/2" screw	McMaster	91251A148			$0.07
16		#6-32 3/4" screw	McMaster	91251A151			$0.03
8		#6-32 washer	McMaster	98019A114			$0.01
16		#6-32 locking washer	McMaster	91102A007			$0.00
16		#6-32 nut	McMaster	91841A007			$0.00
16		#8-32 3/4" screw	McMaster	91251A197			$0.08
24		#8-32 washer	McMaster	98019A125			$0.01
8		#8-32 nut	McMaster	91841A009			$0.02
2		#10-24 1/2" screw	McMaster	91251A242			$0.07
3		#10-24 1 1/4" screw	McMaster	91251A249			$0.11
10		#10-24 washer	McMaster	98019A130			$0.13
5		#10-24 nut	McMaster	91841A011			$0.02
8		Rubber Gromit	McMaster	9600K16			$0.06
ELECTROMAGNETIC POWER-OFF BRAKE							
1		Electromagnetic power-off brake	Inertia Dynamics	FSBR-015-3-0-3-0-1			$75.00

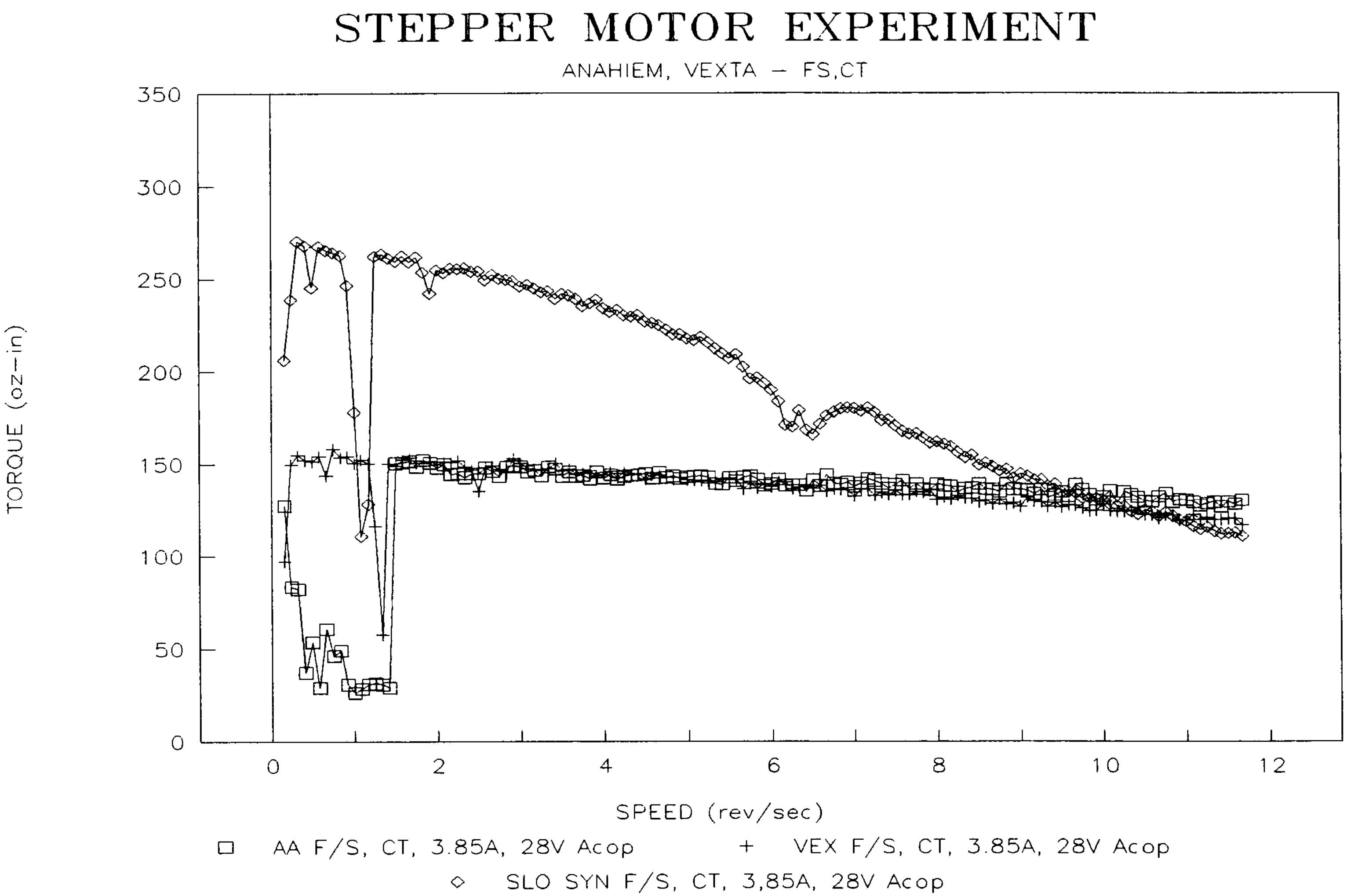
COMPONENT TOTAL $595.48

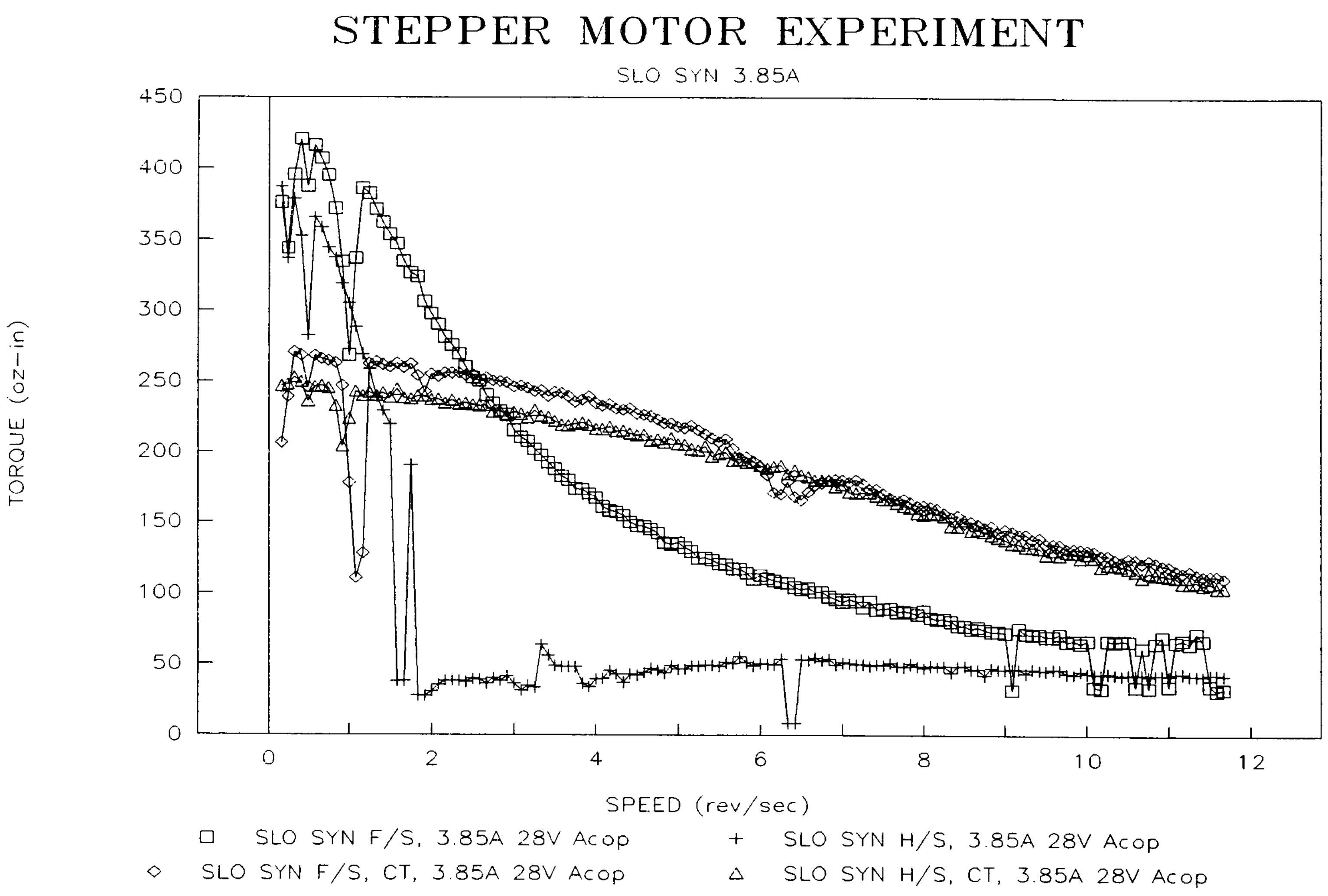
APPENDIX E

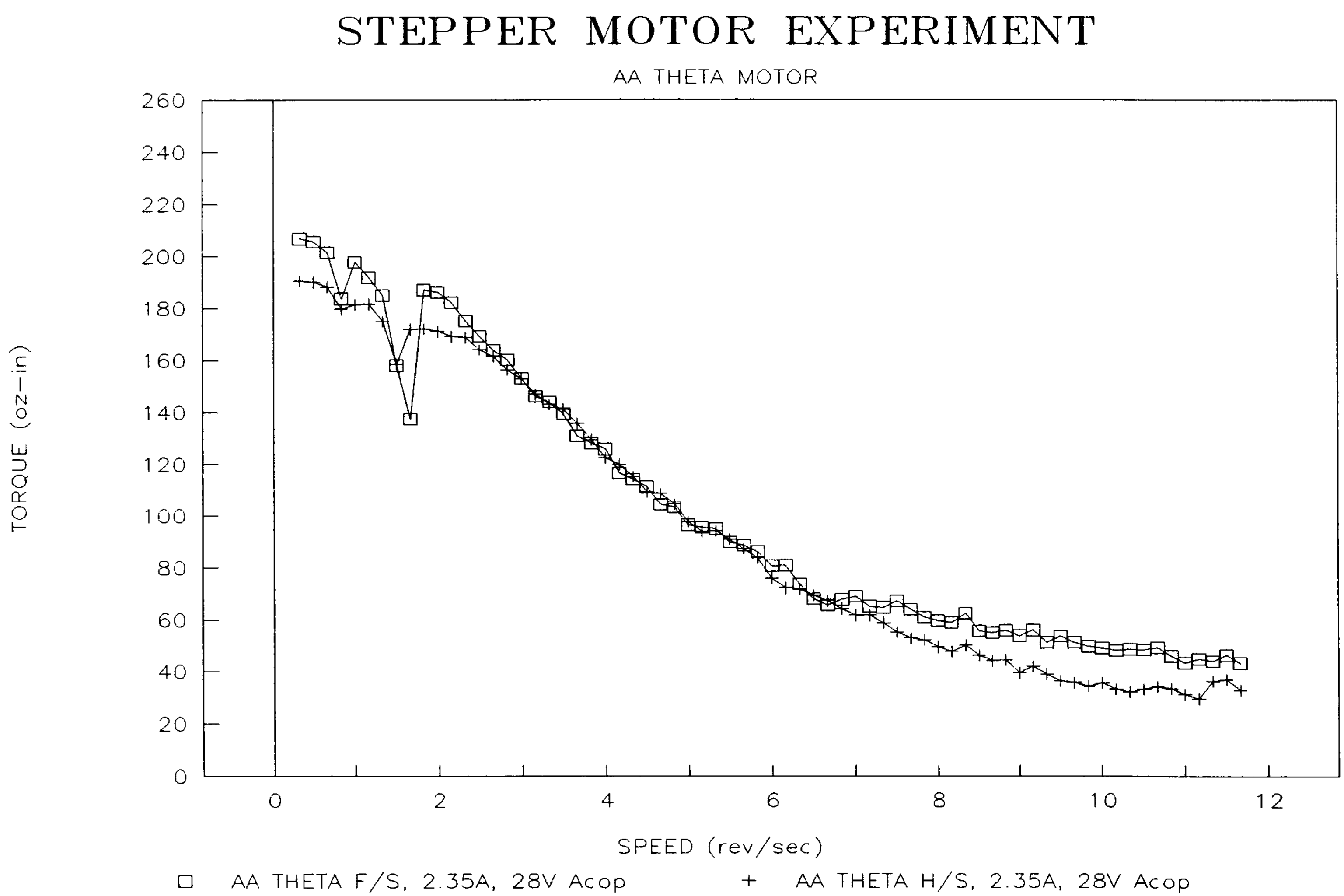
Torque vs. Speed Curves

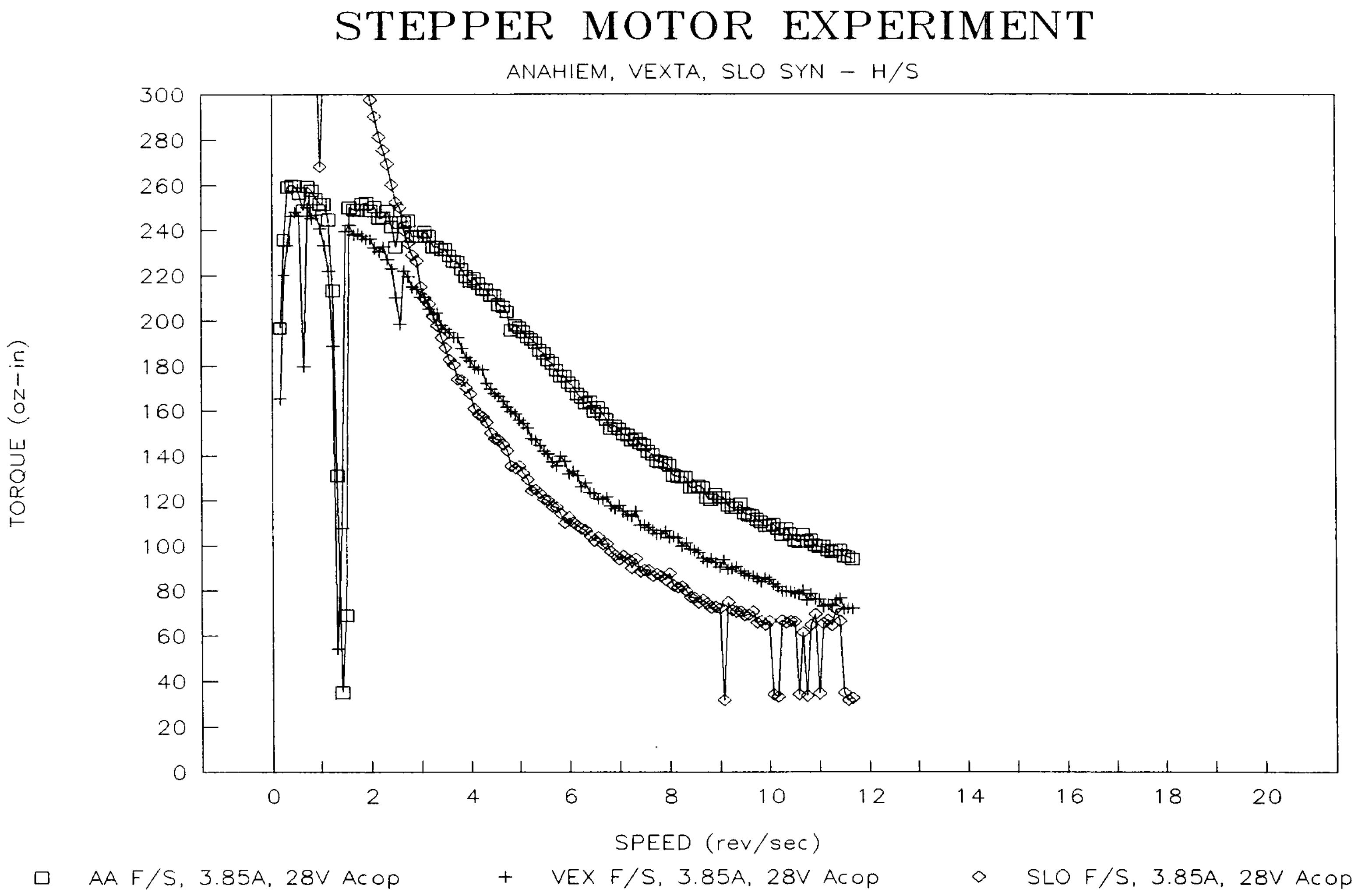

STEPPER MOTOR EXPERIMENT
ANAHIEM 2.9A
TORQUE (oz-in)
0
20
40
60
80
100
120
140
160
180
200
220
240
260
280
300
0
2
4
6
8
10
12
SPEED (rev/sec)
AA F/S, 2.35A, 28V Acop
AA H/S, 2.35A, 28V Acop
AA F/S, CT, 2.35A, 28V Acop
AA H/S, CT, 2.35A, 28V Acop

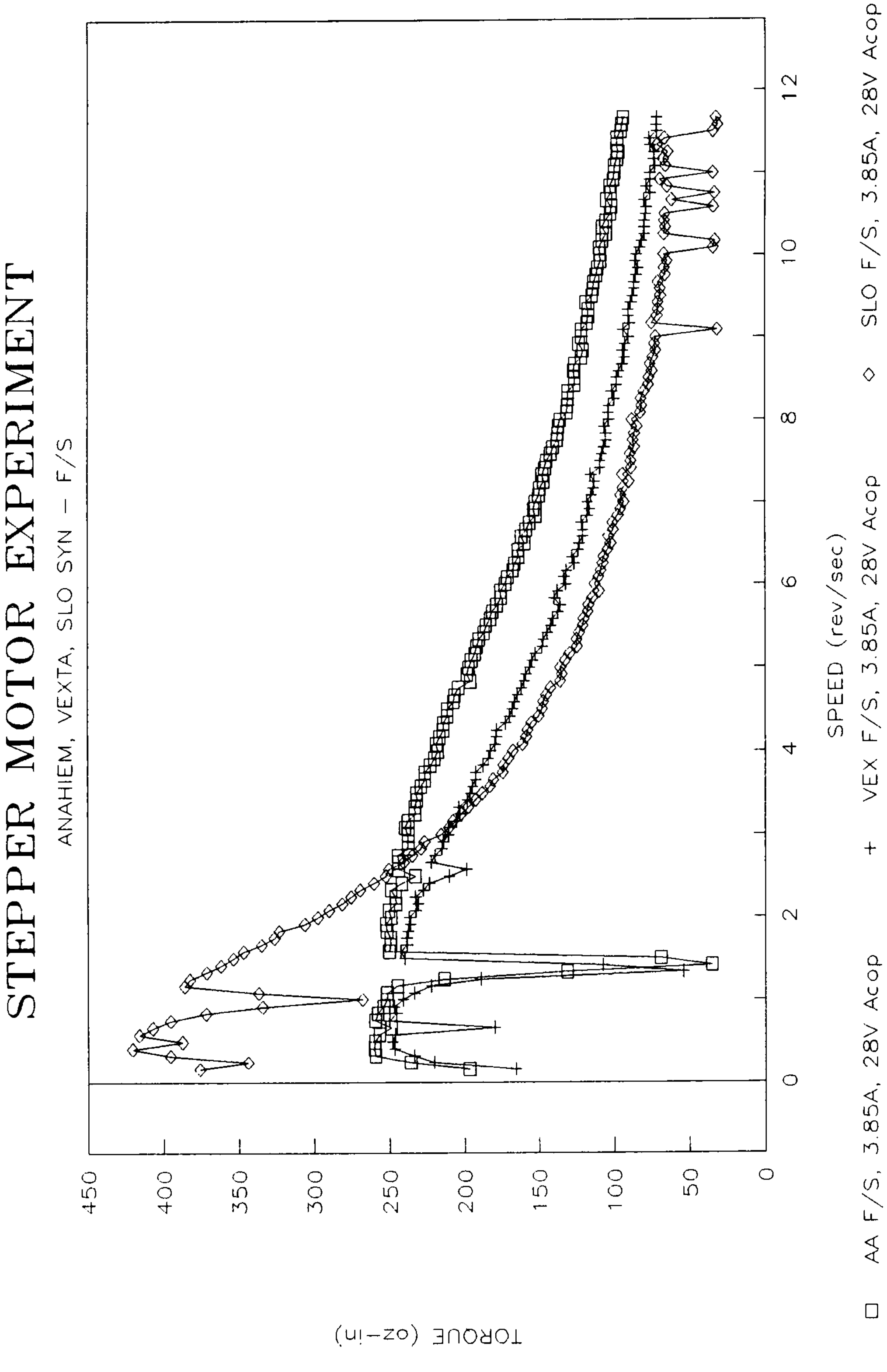

STEPPER MOTOR EXPERIMENT
ANAHIEM, VEXTA – HS,CT
TORQUE (oz–in)
300
280
260
240
220
200
180
160
140
120
100
80
60
40
20
0
2
4
6
8
10
12
SPEED (rev/sec)
AA H/S, CT, 3.85A, 28V Acop
VEX H/S, CT, 3.85A, 28V Acop
SLO SYN H/S, CT, 3.85A, 28V Acop

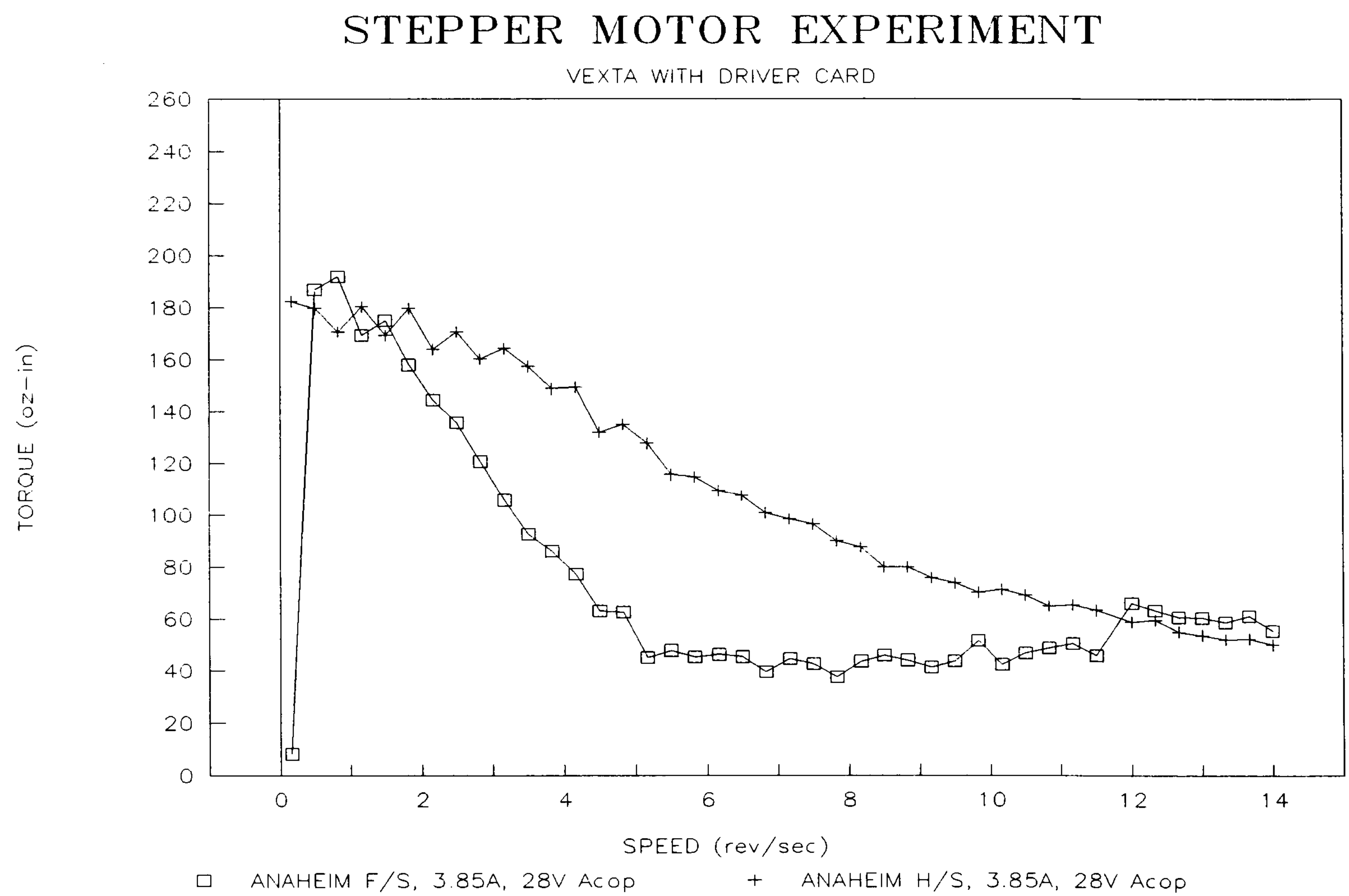

STEPPER MOTOR EXPERIMENT
ANAHIEM, VEXTA – FS,CT
TORQUE (oz-in)
0
50
100
150
200
250
300
350
SPEED (rev/sec)
0
2
4
6
8
10
12
□ AA F/S, CT, 3.85A, 28V Acop
+ VEX F/S, CT, 3.85A, 28V Acop
◇ SLO SYN F/S, CT, 3,85A, 28V Acop


STEPPER MOTOR EXPERIMENT
SLO SYN 3.85A
TORQUE (oz-in)
450
400
350
300
250
200
150
100
50
0
0
2
4
6
8
10
12
SPEED (rev/sec)
□ SLO SYN F/S, 3.85A 28V Acop
+ SLO SYN H/S, 3.85A 28V Acop
◇ SLO SYN F/S, CT, 3.85A 28V Acop
△ SLO SYN H/S, CT, 3.85A 28V Acop


STEPPER MOTOR EXPERIMENT
AA THETA MOTOR
TORQUE (oz-in)
260
240
220
200
180
160
140
120
100
80
60
40
20
0
0
2
4
6
8
10
12
SPEED (rev/sec)
□ AA THETA F/S, 2.35A, 28V Acop
+ AA THETA H/S, 2.35A, 28V Acop

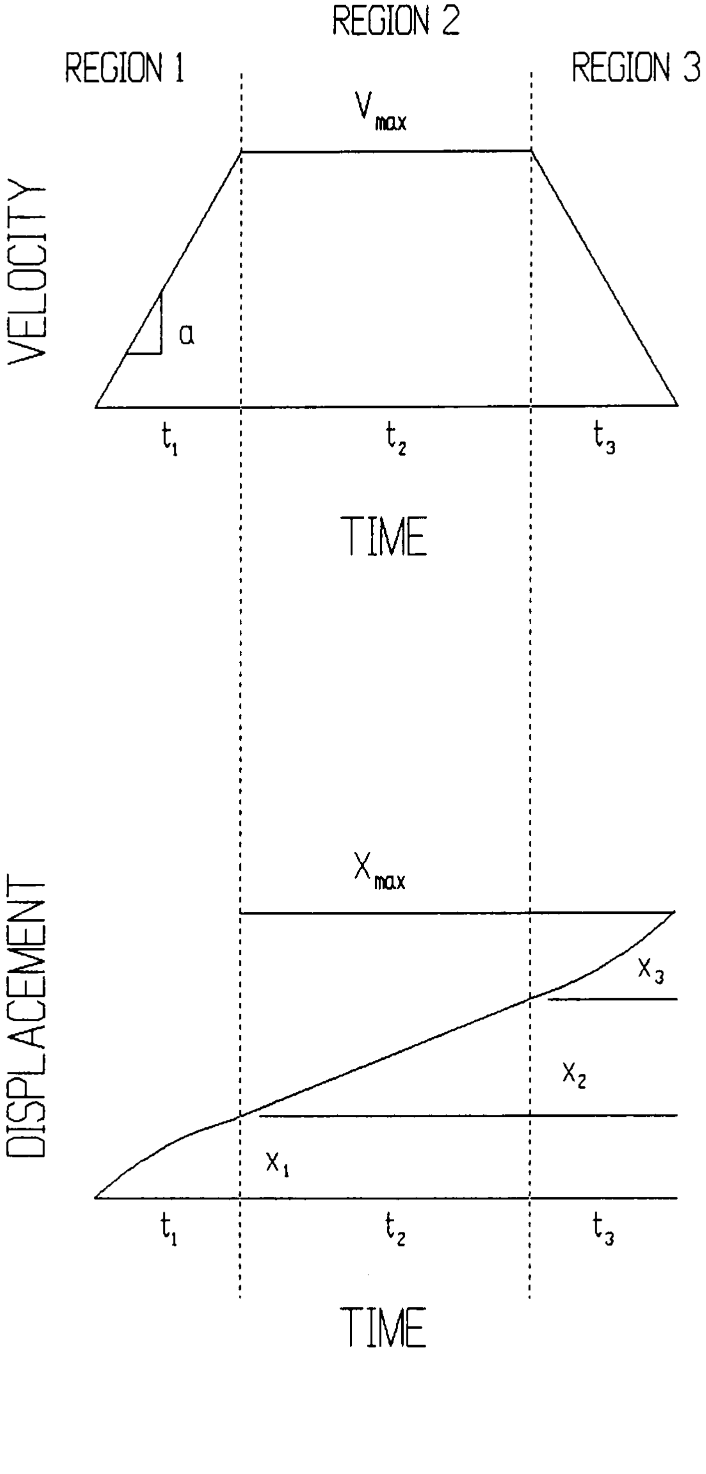

STEPPER MOTOR EXPERIMENT
ANAHIEM, VEXTA, SLO SYN - H/S
TORQUE (oz-in)
300
280
260
240
220
200
180
160
140
120
100
80
60
40
20
0
0
2
4
6
8
10
12
14
16
18
20
SPEED (rev/sec)
□ AA F/S, 3.85A, 28V Acop
+ VEX F/S, 3.85A, 28V Acop
◇ SLO F/S, 3.85A, 28V Acop


STEPPER MOTOR EXPERIMENT
ANAHIEM, VEXTA, SLO SYN - F/S
TORQUE (oz-in)
450
400
350
300
250
200
150
100
50
0
SPEED (rev/sec)
0
2
4
6
8
10
12
□ AA F/S, 3.85A, 28V Acop
+ VEX F/S, 3.85A, 28V Acop
◇ SLO F/S, 3.85A, 28V Acop


STEPPER MOTOR EXPERIMENT
VEXTA WITH DRIVER CARD
TORQUE (oz-in)
0
20
40
60
80
100
120
140
160
180
200
220
240
260
SPEED (rev/sec)
0
2
4
6
8
10
12
14
ANAHEIM F/S, 3.85A, 28V Acop
+ ANAHEIM H/S, 3.85A, 28V Acop

APPENDIX F

Velocity Analysis Calculations


REGION 2
REGION 1
REGION 3
V max
VELOCITY
a
t1
t2
t3
TIME
X max
DISPLACEMENT
X3
X2
X1
t1
t2
t3
TIME

In general, the equation for constant motion acceleration is;

$$x(t) = x_0 + v_o t + \frac{1}{2}(at^2)$$

Solving for each term;

$$x_1 = 0 + 0 + \frac{1}{2}at_1^2 \quad ; \quad x_1' = at_1 = v_{max}$$

$$x_2 = 0 + v_{max}t_2 + 0 \quad ; \quad x_2' = v_{max}$$

$$x_3 = 0 + v_{max}t_3 - \frac{1}{2}t_3^2$$

Summing;

$$x_{max} = x_1 + x_2 + x_3 = \frac{1}{2}at_1^2 + v_{max}t_2 + v_{max}t_3 - \frac{1}{2}at_3^2$$

Solving for maximum displacement;

$$t_1 = \frac{v_{max}}{a} = t_3$$

$$x_{max} = v_{max}t_2 + \frac{v_{max}^2}{a}$$

Solving for time spent in constant velocity portion;

$$t_2 = \frac{x_{max} - \frac{v_{max}^2}{a}}{v_{max}} = \frac{x_{max}}{v_{max}} - \frac{v_{max}}{a}$$

Assume values given for x_{max}, v_{max}, and a then t_2 becomes

$$t_2 = \frac{\frac{x_{max}}{v_{max}} - \frac{v_{max}}{a}}{2\frac{v_{max}}{a} + \frac{x_{max}}{v_{max}} - \frac{v_{max}}{a}} = \frac{x_{max}a - v_{max}^2}{x_{max}a + v_{max}^2}$$

Limiting value of maximum velocity for a given g value and a given maximum displacement can be found by:

Let

$$t_2 = x_2 = 0$$

Then

$$x_1 = \frac{1}{2} a t_1^2 \quad ; \quad x_1' = a t_1 = v_{max}$$

$$x_3 = v_{max} t_3 - \frac{1}{2} t_3^2$$

$$t_1 = t_3 = \frac{v_{max}}{a}$$

$$x_{max} = x_1 + x_3 = \frac{1}{2} a t_1^2 + v_{max} t_3 - \frac{1}{2} a t_3^2$$

$$x_{max} = v_{max} t_3 = \frac{v_{max}^2}{a}$$

Therefore;

$$v_{max} = \sqrt{a x_{max}}$$

Confirm by setting t_2 to zero on previous page

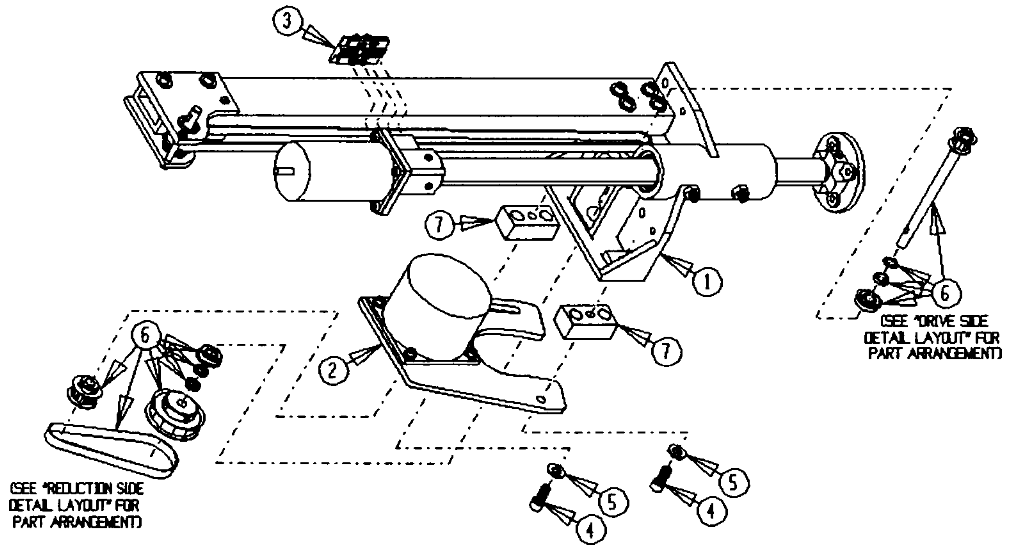
$$t_2 = 0 = \frac{x_{max}}{v_{max}} - \frac{v_{max}}{a} = a x_{max} - v_{max}^2$$

Note: The above equations were used in determining the phase plots and velocity profile curves.

APPENDIX G

Assembly Drawing

REL FOR ASM	QTY	TECHNICAL APPROVALS			INIT	DATE	EC #	P/N ASY582
ASY506-RRR	1	MECHANICAL	MEK	24 MAR 91				"A" SIZE TEMPLATE 0 .25" REAL SIZE



ASSEMBLY PARTS LIST

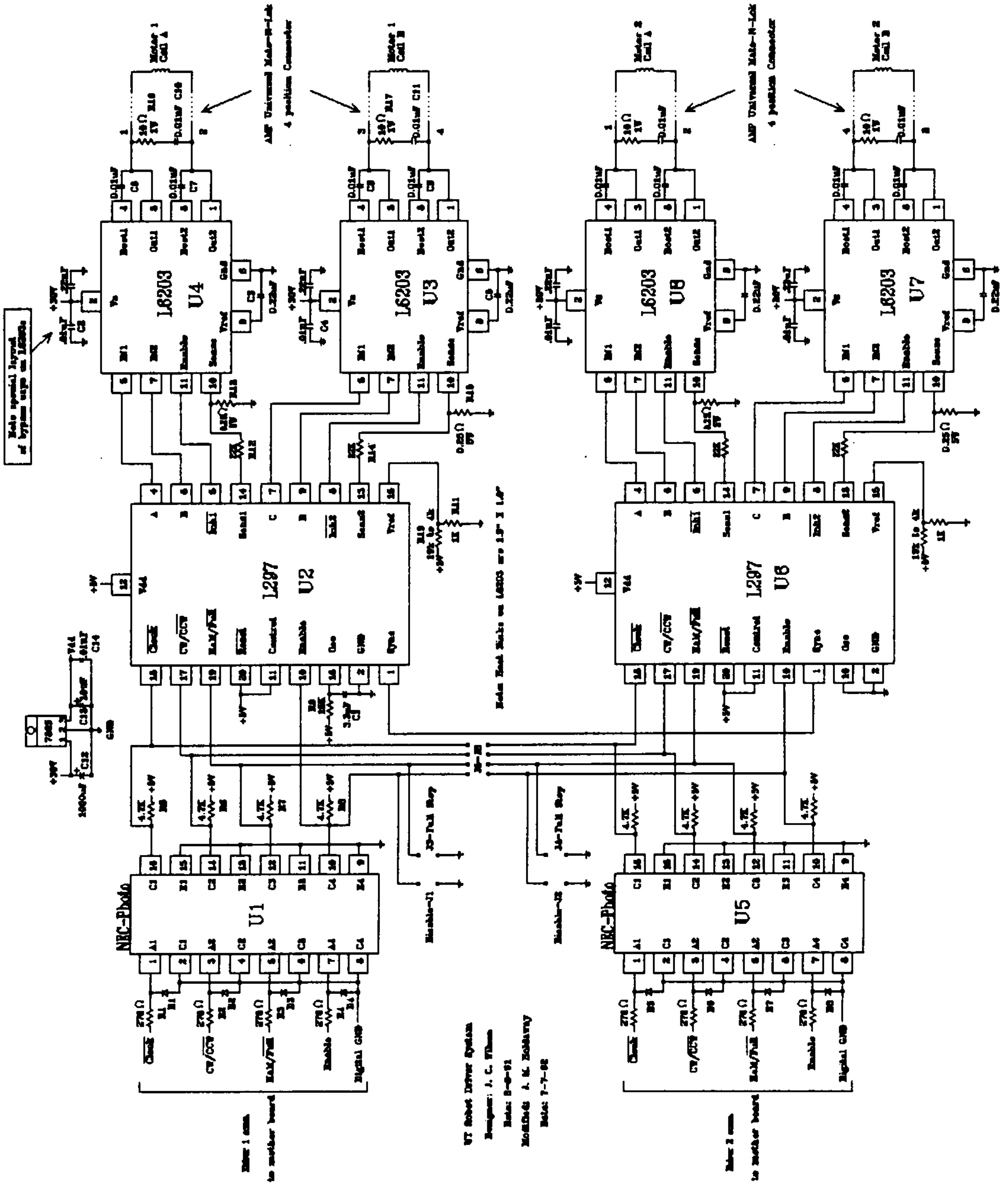
ITEM	QTY	P/N	PART DESCRIPTION
1	1	ASY561-ZZZ	ASSEMBLY, Z MOTION
2	1	ASY536	ASSEMBLY, Z MOTOR
3	1	ASY540	ASSEMBLY, BELT ATTACHMENT
4	2	VEN451-075	SHCS, 0.312 UNF, 150 LONG
5	2	VEN487	WASHER, FOR Ø0.312 SCREW
6	1	KIT621	KIT, Z REDUCTION DRIVE
7	2	0290	SPACER, Z MOTOR PLATE

ASY582

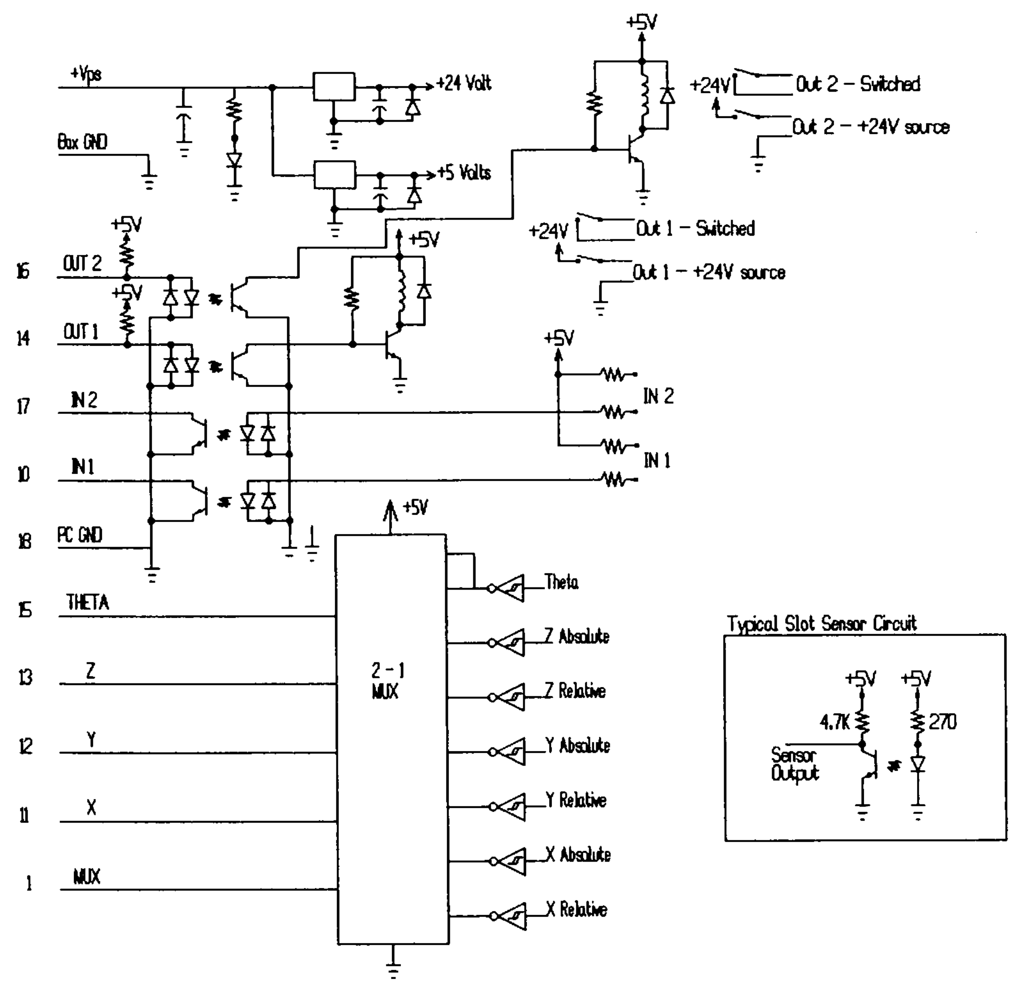
SCALE 1/8	DIMENSIONS IN INCHES		PART # ASY581-RRR UT
MATERIAL N/A	TOLERANCES UNLESS NOTED		
	LINEAR +/-	N/A	TITLE ASSEMBLY, Z-THETA DRIVE
	ANGLES +/-	N/A	
OTHER NOTES	RADII UNLESS NOTED	N/A	DESIGNER MEK 24 MAR 91
	EDGE/CORNER BREAKS OUTSIDE MAX	N/A	CHECKED MEK 24 MAR 91
IBMCAD FILE DAVE	INSIDE MAX	N/A	APPROVED MEK 24 MAR 91

APPENDIX H

Circuit Diagrams


L6203
U4
U3
U6
U7
L297
U2
U8
NRC-Photo
U1
U5

TERMINAL BLOCK CIRCUIT



X, Y and Z sensors:

1:	Xa - +V	13:	not used
2:	Xa - Signal	14:	not used
3:	Xa - GND	15:	Zr - +V
4:	not used	16:	Xr - +V
5:	Ya - +V	17:	Xr - Signal
6:	Ya - Signal	18:	Xr - GND
7:	Ya - GND	19:	not used
8:	not used	20:	Zr - Signal
9:	not used	21:	Yr - +V
10:	Za - +V	22:	Yr - Signal
11:	Za - Signal	23:	Yr - GND
12:	Za - GND	24:	Zr - GND

Terminal Block:

2IN2	2IN2	1IN1	1IN1	O2	O2	O2	O2	O1	O1	O1	O1
-	+	-	+	+	-	sw	sw	+	-	sw	sw

X & Y Motor Connectors:

1:	L - Xa+	6:	R - Xb-
2:	L - Xa-	7:	R - Xa+
3:	R - Xb+	8:	R - Xa-
4:	L - Xb+	9:	not used
5:	L - Xb-		

Z Motor Connectors:

1:	A+	3:	B+
2:	A-	4:	B-

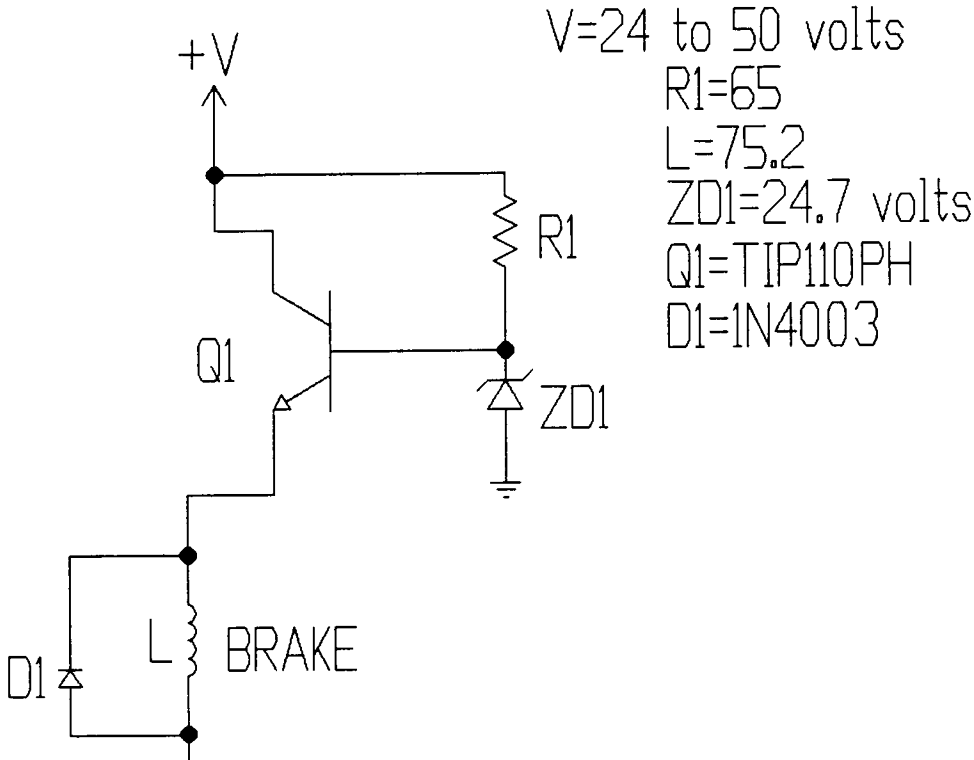
Theta Motor Connectors:

1:	A+	3:	B+
2:	A-	4:	B-

Theta Sensor:

1:	Signal	3:	GND
2:	+V	4:	not used

BRAKE CIRCUIT



VITA

The author, David M. Paulus, was born on October 26, 1963. He was the fourth of five sons of James and Suzanne Paulus; all which became engineers. He attended public schools in Hamilton, Ohio. After high school graduation, he attended the University of Dayton in Dayton, Ohio. Mr. Paulus worked as an overhead crane operator at a local paper company during his summer breaks. This summer experience helped reenforce the drive to obtain his degree in engineering. He received his Bachelor's Degree in Mechanical Engineering in April, 1986.

Mr. Paulus accepted a position with Pratt & Whitney Aircraft in June 1986. He worked as an analytical engineer for three years estimating weights, CG's and moments of inertia for advanced military jet engine components. After the third year he then transferred to a design group for new experiences in designing jet nozzle components.

He left Pratt & Whitney in July 1990 to pursue a Master's Degree in Mechanical Engineering and gain knowledge into manufacturing techniques.