A Graduate Level Treatment of the Design of a Machine for the 1999 2.007 Contest

by

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S.B, Mechanical Engineering
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Submitted to the Department of Mechanical Engineering on
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Abstract

This thesis centers on the development of a variety of material for MIT's Introductory Design Engineering course, 2.007 Introduction to Design. The design process emphasized in the teaching of the course is presented, as are course materials such as problem sets and sample solutions. The effects of published examples on student work are briefly introduced, and problem sets for future teachings of the course are developed based on experience and feedback. In addition, a sample machine for the course is designed and constructed using detailed engineering and parametric CAD modeling. This sample machine is intended to serve as a basis for design case studies and examples to be used in future teachings of the course. The sample machine is designed to achieve very high performance while incorporating examples of the application of design methods taught in the course. The mathematical, CAD and FEA modeling methods used in the design of the machine's various modules are documented. The practical use for this design case study will likely be in the form of a web-based tutorial.

Thesis Advisor: Alexander H. Slocum
Title: Professor of Mechanical Engineering

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In addition to the Department, there are many individuals who deserve thanks for their support of this project. Working with Professor Slocum and the 2.007 staff has been a pleasure as well as an education. Teaching and learning from the students in 2.007 has been very rewarding. Leslie Regan, who excels in the handling of administrative issues for the graduate department, has been invaluable. My officemates and Maureen Lynch in the Precision Engineering Research Group were good company, and often helpful. Thanks go to Rebecca for support and motivation. And finally, thanks to my family, who provided encouragment and support as well as good food and careful editing.

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Chapter 1

INTRODUCTION AND MIT 2.007 COURSE DESCRIPTION

1.1 Introduction

This thesis centers on the development of a variety of instructional material for MIT's Introductory Mechanical Engineering design course, course number 2.007: Introduction to Design. The Course materials such as problem sets and sample solutions are presented, as is a case study in the design of a machine for the contest that forms the basis of the course. This Sample Machine is designed and constructed using detailed engineering and parametric CAD modeling. It is intended to serve as a basis for design case studies and examples to be used in future teachings of the course.

1.1.1 The Course and Design Contest

Throughout this text, the MIT course 2.007: Introduction to Design will be referred to as simply 2.007. This course is taken primarily by Mechanical Engineering sophomores and revolves around a design contest which is held at the end of the semester. The course teaches students the principles of engineering design as they each design and construct remotely controlled machines using only the materials and actuators provided in their "kits." At the end of the semester the completed machines compete in a single elimination tournament which is different each year.

The 2.007 Contest for 1999: MechEverest

The name of the contest held during the 1999 teaching of 2.007 is MechEverest[1]. The task presented by the 1999 contest is essentially: score more points than a competing machine by delivering hockey pucks to one of three plus-shaped holes on a metal table of increasing incline. There are limits on time to complete the task, materials, actuators, power and size. Due to the open-ended nature of the task, many possibilities arise for challenging design trade-offs and the payoff for good design is high.

1.1.2 Contents of Chapter 1

The remainder of Chapter 1 describes the course 2.007 and the design process taught. The course is structured around a contest that pits remotely-controlled machines against each other in a single-elimination tournament. Each student chooses a strategy, designs and builds their own machine as an immersive experience to teach the design process they will hopefully employ later in their engi-

1. The MechEverest contest was designed principally by Roger Cortesi and Prof. A. Slocum.

neering careers. The design process emphasized in the teaching of the course is presented in Section 1.5.

Course History and Evolution

2.007, formerly known as 2.70 is MIT's introductory Mechanical engineering design course. It was started in 1972 by Professor Woodie Flowers, who continued to teach the course for many years.

This thesis is written at a time where a minor revolution in the content of the course is drawing to a close. in 1993, the course involved the building of a machine for a contest, but also a more product design-oriented project involving the design of a children's toy for example. In the past 5 years, a slow but clear evolution has been made in the course's focus, leaving it effectively and introduction to machine design, with a heavier emphasis on physics, mathematical modeling, and computer tools.

1.1.3 Contents of Chapter 2

Chapter 2 presents the design and construction of a Sample Machine for the 1999 contest, MechEverest. A photograph of the completed machine in its starting configuration can be seen in Figure 1.1. A complementary view from the CAD model of the machine can be seen in Figure 1.2 on page 18.

The Sample Machine is designed to achieve very high performance and incorporate examples of the design methods taught in the course. It is intended to showcase some of the advanced design, engineering, estimation, and manufacturing methods available to the 2.007 student. An emphasis is placed on how good design decisions can be reached and validated by proper framing of the problem, engineering estimates, simple calculations, finite element analysis and computer-aided solid modeling. The practical use for this design case study will likely be in the form of a web-based tutorial.

The sample machine includes several functional modules, many of which are sufficiently self-contained to serve as independent design case studies. The analytical models developed to design several of the mechanisms match real performance very closely. The completed machine reliably

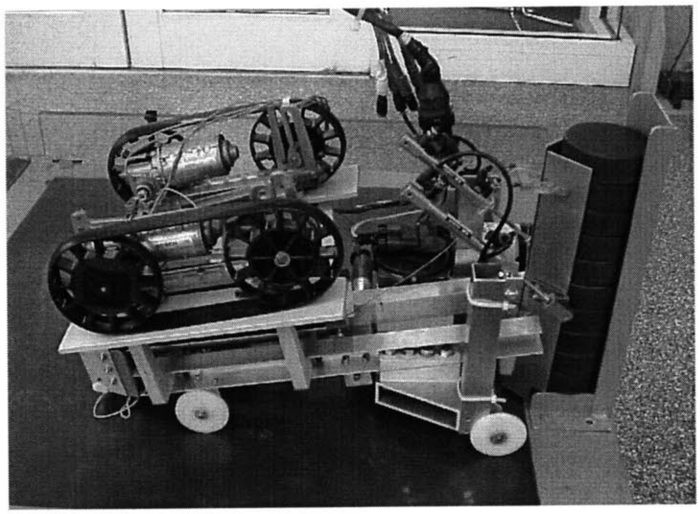

Figure 1.1 Overall view of Sample Machine in Starting Configuration.

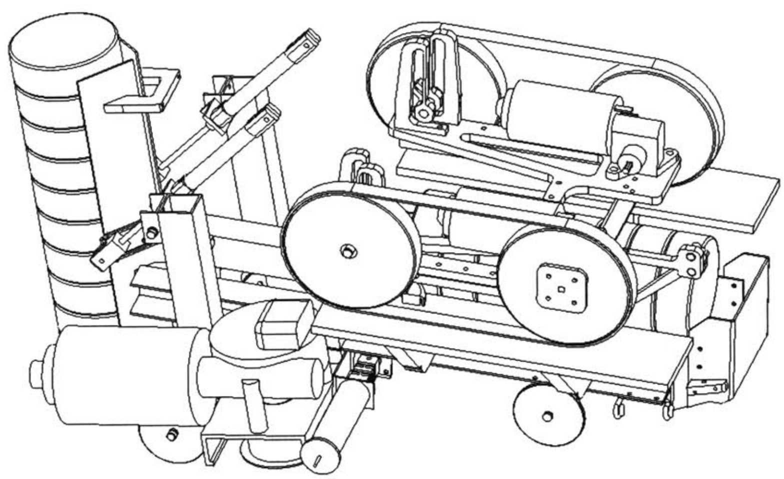

Figure 1.2 View of CAD model of Sample Machine in Starting Configuration.

scores 75 of 100 possible points. The highest score among student-built machines was 58 points.Full manufacturing drawings and process plans for the sample machine are included.

1.1.4 Contents of Appendices

Three appendices are included that contain ancillary material developed during this project.

Appendix A contains properties of the major motors available for use to power machines. The motor properties were measured experimentally, and raw data and torque-speed curves are presented.

Appendix B contains problem sets and examples which were revised, updated and augmented for 1999. The 12 weekly problem set assignments relate directly to the design of a machine for the contest. They are arranged to coincide directly with the steps of the design process required to design, build and test a student's machine. The problem sets are the latest revision of an evolving body of material (developed in conjunction with other 2.007 staff). They are included along with examples, and contain changes in emphasis, schedule, and content compared to those from the previous year.

Appendix C contains engineering drawings for all parts of the Sample Machine, as well as process plans for most of them. It also documents some technical details of the structure of the CAD model of the Sample Machine.

1.2 1999 Course Syllabus

The following is a direct inclusion of the published syllabus for the course as prepared by Professor Slocum. It was distributed to all students on the first day of class and should give a good introduction to the course and contest.

2.007 Design & Manufacturing I

Prereq.: 2.670, 2.001
Spring, 1999
3-4-5

Develops students' competence and self-confidence as design engineers. Emphasis on the creative design process bolstered by application of physical laws, and learning to complete projects on schedule. Synthesis, analysis, and design robustness are emphasized. Subject relies on active learning through exercises in lecture and laboratory. A major design-and-build project is featured. Lecture topics include idea generation, estimation, concept selection, machine elements, engineering design calculations, kinematics of mechanisms, design for manufacturing, visual thinking and communication, and designer's professional responsibilities. Students are encouraged to be adept at using spreadsheets and to have some solid modeling experience.

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Webpage and email lists (where all announcements are posted)
http://pergatory.mit.edu/2.007/
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2.007-staff@mit.edu
2.007-sectN@mit.edu (N= 01 to 10)
2.007-supreme@mit.edu
2.007-ua@mit.edu

Lectures
Tuesday and Thursdays in 26-100, 11:00 a.m.– 12:30 p.m.. Open discussion period is 12:30-1:00 p.m. in 26-100. ALL labs are from 1:00-5:00 p.m.. See the attached schedule for lecture topics, problem sets, and lab activities. The course carefully follows the schedule! It is critical that you come to lectures, as there are many in-lecture Funzee quizzes that do not hurt you if you try!

FROM 12:30-1 EVERY LECTURE, unless noted, there will be a "how to solid model" workshop in the lecture hall, where a "consultant" will in real time using a PC projected onto the screen, answer questions.

Labs
The Registrar has scheduled labs, and if you have a serious conflict, see your lab instructor. THE LABS ARE ONLY SCHEDULED IN THE AFTERNOONS, AND THEY ARE NOW 4 HOURS LONG TO GIVE STUDENTS MORE SCHEDULED BUILD TIME.

Course Objective is to enable students through lecture and hands-on experience to:

- Learn the ***process*** of design.
- Combine creative thinking with engineering principles (physics) to turn ideas into robust reality.
- Discover and utilize basic mechanical components.
- Realize the importance of project management.
- Realize the importance of concurrent engineering.
- Complete 2.007 with the skills and confidence to take an unstructured problem and develop it in a systematic manner, a design that exhibits creativity and is well engineered by the use of principles learned in physics and 2.001.

Technical Content

1. Identifying the problem and its functional requirements.
2. Generating potential design parameters to satisfy the functional requirements.
3. Identifying physical principles and their early application to select design parameters.
4. Generating creative concepts on paper and testing simple models.
5. Selecting concepts.
6. Creating a project schedule.
7. Embodiment of the design.
8. Bench-level prototypes of critical elements.
9. Manufacturing and testing the design.
10. Reflecting on the results (closing the design loop).

Text Book

The textbook for the course is Machinery's Handbook, which every designer must have for his or her entire career. It is filled with formulas and useful data, including bolt sizes, tap drill sizes, gear info, etc. We have obtained it for you at a $20 discount! BRING Maureen Lynch in 35-014A a check made payable to MIT for $60! On Tuesday, February 2, 1999, Maureen will be in the Pappalardo Lab from 12:30-2:00 p.m. to collect the textbook fee. She will accept **checks only** made payable to MIT.

Suggested readings for those who are interested in the process of design include:

1. G. Pahl and W. Beitz, Engineering Design, A Systematic Approach, Springer-Verlag, New York, 1988
2. N. P. Suh, The Principles of Design, Oxford University Press, New York, 1990

Incredibly useful handbooks every practicing design engineer should own:

1. R. J. Roark, W. C. Young, Formulas for Stress and Strain, McGraw-Hill Book Company

For students interested in hardware details:

Shigley, J. E., Mitchell, L. D., Mechanical Engineering Design, McGraw-Hill Book Company, New York 1983.

Slocum, A. H., Precision Machine Design, Prentice Hall, Englewood Cliffs N.J., 1992

Overall Goal of 2.007

The overall goal of 2.007 is to help you learn to effectively execute the steps required to practice design in a systematic manner, which is vital if you are to become an effective design engineer. These steps define the process of design:

- **Define problem**
  - Strategy
  - Functional requirements
  - Design Parameters & Physics of the problem
  - Schedule
  - Resources available
- **Develop concepts**
  - Kinematics (motions, forces, and connections)
  - Concept drawings (stick-figure sketches for FBD's, isometric sketches, solid models)
  - Sketch models
  - Preliminary analytical models & identification of critical technologies
  - Bench Level Prototypes (BLPs)
  - Concept selection
  - Preliminary hardware assessment & manufacturing review
  - Update schedule to make sure design can be completed on-time and on-budget
- **Embodiment**
  - Final component selection
  - Detailed layout drawings
  - Set-up analytical optimization spreadsheets
  - Preliminary hardware selection & manufacturing review
- **Details**
  - Final sizing of components and structures
  - Part drawings & manufacturing review
  - Update schedule
- **Prototype and test**
- **Manufacture**

Grading

This is very much an interactive course, and you have a very low chance of passing the course if you do not attend lectures and labs. In lecture and lab, there will be a lot of information presented. You will not succeed if you just try to read the web. Substantial amounts of information will be discussed and illustrated blackboardically that will not be handed out. Your grade is very dependent on the problem sets. Each problem set focuses on helping you create your 2.007 machine. There are no busy-work assignments. Everything is focused on the contest machine from Day 1.

There are a whole series of active learning mini quizzes (Funzees!) in lectures. The lecturer will often stop and ask students to try and solve a problem before solving it on the board. WE really need the students to try and solve the problem, and then at the end of lecture, turn in their solution. You do not have to put your name on the attempt! We want to see how you are doing to see if we are being successful in teaching you what you need to know! Funzees are also an important self-evaluation barometer. If you cannot do them, then you need to study more/tell us what we are not teaching!

You will be responsible for using the Rohrbach method for grading your problem sets. **You will be part of a 3 person grading team that you are responsible for forming in your section!** Each person will review and make comments on each other person's problem sets. Your section instructor will review the teams' comments and will give the team a grade on how effective they are at providing constructive criticism. The instructor will then give each student a grade for their own problem set.

The key to earning an "A" is not putting in long hours, the key to earning an "A" is to relax, follow the schedule, come to class and lab, and to think creatively and deterministically (can you write a spreadsheet to justify and optimize major design decisions, such as the size of a motor?). The student's grade will be largely based by how well the students learn the design process taught in 2.007. This is reflected by how you do on the problem sets (80% of your grade), in addition to having a working machine the week before the final contest.

Real designers in countless companies use this process. Good designers get raises and responsibility and reflect well on themselves and their profession. Bad designers are of no use to anybody.

- A bad designer:
  - Has no respect for project management.
  - Thinks he can just cut-&-fit on the fly.
  - Can see it all in his head and does not need to sketch and test and plan.
  - Works late hours the night before the contest and produces something.
  - Enters the contest and then disappears from the class.
  - Gets at best a "C" in 2.007.

2.007 is far more about learning the process of design, by designing and building your machine, than just building a machine to compete in the contest. Without knowing the process of design, you will not be able to compete on real design projects in the real world.

Notebooks

Normally, a designer keeps a detailed bound notebook for invention date establishment. You can do this for 2.007, and then photocopy sketches, calculations, etc. you may want to use for your problem set. However, we recognize that this can be difficult in a course, so loose-leaf paper in a 3 ring binder will be acceptable. You should have a 3-ring binder for handouts, notes, and returned problem sets.

Lab Assignments

The Registrar assured me that for those who properly registered for the course, and innumerable e-mails were sent out, that there will be no conflicts. If you made changes to your schedule, to move courses around, then you need to get together with friends and swap sections, or change other courses.

MechEverest! Contest kits and lab fee

There are a lot of materials required for 2.007, and although many companies have made donations, we still usually collect a lab fee, BUT this year because of a grant from General Motors, there is no lab fee! You must bring your 2.670 toolkit to lab, as you will need it. Your kit will be in your locker. Be careful with your kits, as the motors and pistons must be returned at the end of the semester or you will have to replace them. **Keep critical components locked up**.

The actuators are generally irreplaceable! They must all be turned in. You do not have the option of "buying your actuators". So if you think you want to keep you machine, design the machine so the actuators are easily removable (good design practice) and the staff will assist you with finding catalog replacement actuators. Sorry, but for the course we must have identical sets.

There is a VERY good chance we will get each student 5 Black & Decker electric screwdrivers as the motors for the course, and you could keep them (and hence your machines intact)! We will find out the first week! You would have to buy the pneumatics at a cost of $30/machine if you wanted to keep them.

Course Schedule

COME TO LECTURES AND LABS AND DO THE WEEKLY ASSIGNMENTS. Tape together the project plan for the course and hang it on your wall. Add other course milestones, and use it to carefully plan your semester. Use the plan as a reminder to not fall behind! If you are falling behind, you need to ask for help, and also ask yourself if you are doing TOO much!

If you follow the schedule and work smart on the problem sets, you can earn an "A" all without ever having to spend an evening or a weekend in the shop. THE DESIGN PROCESS WORKS! 2.007 is a 12-unit course that is created to enable you to complete it on time and on budget!

Some very important scheduling issues:

- The "ship date" of your machine (the day it is impounded and you can no longer work on it) is **Friday April 30**. The "customer" (you!) takes it out of the box Tuesday May 5 at 4 PM, and then takes it to the Johnson Athletics Center (W34) (ice rink!) for the contest. Welcome to the real world!

- There will be no weekend hours for the shop!

- The shop opens at 7:30 AM and closes at 5:00 PM, so create a normal working person's schedule! However, you may not use the morning hours of 9-1 if you are scheduled for the following courses, 2.001, 2.002, 2.003, 2.004J, 2.005, 2.010 and 2.671. Do not skip your "Core" subjects to work on your machine. Use the early mornings when things are calm! Pace yourself! If you do the classic "wait until the last minute", you will fail not only in 2.007, but also in the real world!

- DO THE PROBLEM SETS-they are planned around the design process, and they will help to

1.3 The 1999 Contest, MechEverest

One of the two identical Contest Tables on which machines competed is shown in Figure 1.3. Figure 1.4 contains a sketch of the table that was published with the Contest Rules, showing starting and scoring locations. A side view with dimensions is seen in Figure 1.5 on page 25.

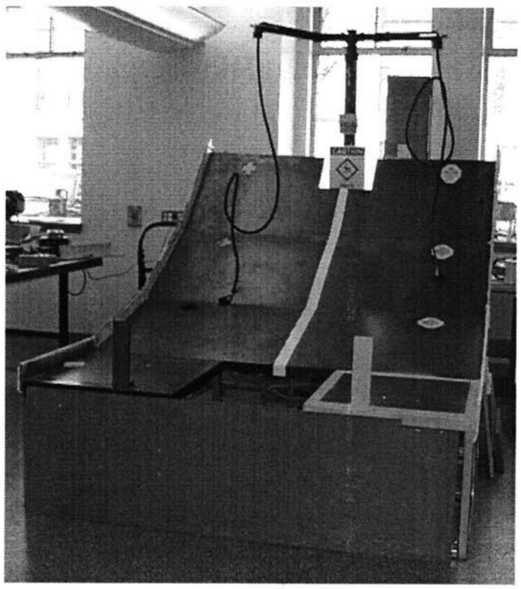


Figure 1.3 Photograph of actual Contest Table.

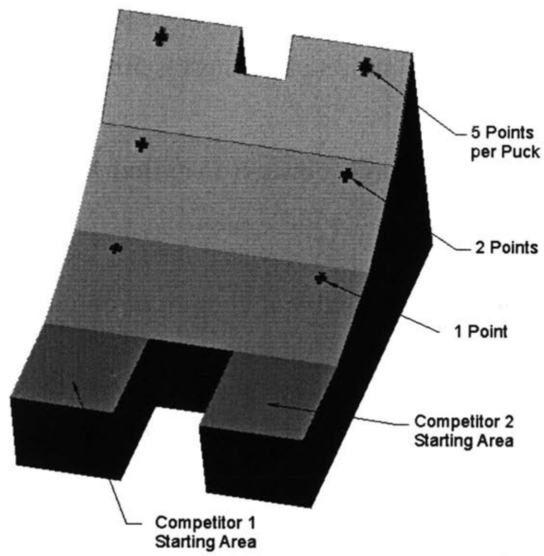


Figure 1.4 MechEverest Contest Table as depicted in the Contest Rules.

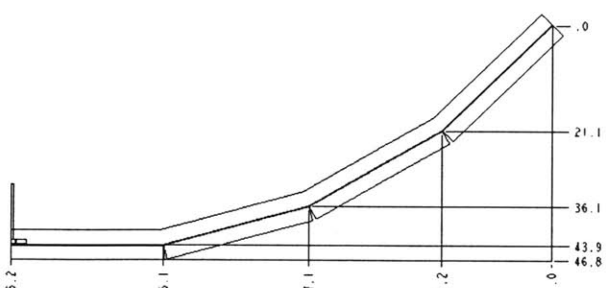


Figure 1.5 Dimensioned side view of 1999 Contest Table.

The following documents regarding the Contest Rules are excerpted from the 1999 2.007 web page *[2.007 web page]*

The Contest

The contest gives you a real design goal on which to focus.

- Learning is enhanced with a real-world focused problem.
- The contest is also a means to compare your design to other designs.
- In the real world, you will be judged and compared every day.
- History shows the contest is 50% designing and building, and 50% driving.

This year's contest is called MechEverest!

- Design and build a remotely controlled machine that achieves the highest score at the end of a 45 second contest.
- The contest table is comprised of four sections, each at increasing angles of inclination.
- The contest table is made of sheet steel. It will be painted.
- Each competitor may begin with UP TO ten hockey pucks loaded into their machine.
- The object is to drop the pucks into the cross-shaped holes as high as possible on the table.
- The competitor's score increases exponentially with the height up the ramp. The lowest holes are worth 1 point per puck, the middle: 2, the top: 5!
- The starting zone comprises all the surface area which is horizontal (0 degree section on the contest tables), including the colored frame. The starting zone also extends beyond the horizontal surface by 1" in all directions. On the walled side, this 1" is measured form the outside of the wall.
- A machine's starting configuration must be able to fit unconstrained into the green shipping box, with the lid on the correct way.
- No machine may touch the side walls of the table before the contest begins.
- The maximum current that may be drawn from the umbilical is 7A.

Read the contest description and rules very carefully! Check the web for updates.

1.3.1 Addendum to Rules for MechEverest

2.007 1999 Contest Rules

Answers to Frequently Asked Questions

- After 45 seconds, the power to your machine will stop. The official score will be counted after all motion stops (when steady state is achieved).
- The table's side walls are being developed—suggestions are welcome. (E-mail roger, rcortesi@mit)
- There are currently no walls planned for the area between starting zones, or along the top edge of the table.
- The details of features below the scoring holes (chutes, etc.) are being designed.
- Electronic score counting is for real-time audience feedback only—the official score is derived from the number of pucks in the baskets under each hole. "Fooling" the sensor does not get you more points.
- There will be magnets available in the kit. Each student will have at least 1 permanent magnet capable of a max. force of 25 lb. (no gap). Real force at 2mm spacing will be much lower—ballpark guess is 2.5lb. The magnets are rings with: OD= 2", ID=.188", height=.313"
- Projectiles must be safe enough that you would be willing to have them shot at you.
- The size constraint in more detail: The judges must be convinced that your starting configuration is able to fit entirely inside their reference green bin, with the lid on. Any constraint of the machine by the walls or lid of the bin means the machine doesn't fit.
- The starting area extends beyond the walls of the table by 1". Your starting configuration may not touch the walls.
- Regarding attacking opponent: A contestant will be disqualified if any part of their machine crosses the midplane of the table before scoring a point. The intent here is to eliminate the possibility (intentional or no) that a machine is eliminated by any means other than being outscored.
- There will be judges at the contest— you can expect to be held to the spirit of the rules, not just the letter.
- The ice hockey pucks weigh 165 grams each, are 3" diameter, and 1" thick.
- The details of how the 2 sets of 10 extra pucks will be positioned are also currently being designed. The intent will be to accommodate simple methods for collecting the entire (stack?) of 10 pucks, and they will be near the starting area.
- An addition has been made to the kit: you will have one 12x12x1/4" sheet of polycarbonate (Lexan)

Please send questions, suggestions or concerns to 2.007-supreme@mit.edu or 2.007-staff.

[2.007 web page, Schmidt-Lange]

1.3.2 Control System

One important additional constraint which was not explicitly published in the contest rules involves the method by which a machine is controlled during the contest. The table has a control system which transmits power to machine through an overhead cord referred to as the "umbilical." This cord supplies power to four electric motor circuits and two pneumatic circuits. These circuits are controlled by handheld control boxes, depicted in Figure 1.6. The lower box in Figure 1.6 includes two proportional control levers, while the upper box contains two forward and reverse rocker switches and two pneumatic pressure toggle switches. The actual controllers used in the contest also featured two toggle switches in the lower controller that switched the pairs of electric circuits between 5- and 12-Volt ranges. The quick connectors that supply electric and pneumatic power to the machines are shown in Figure 1.7.

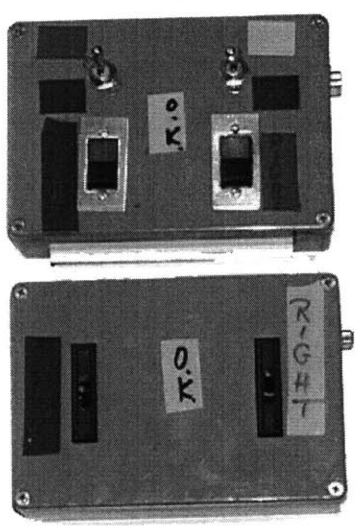


Figure 1.6 Handheld Control boxes for 2.007 contest.

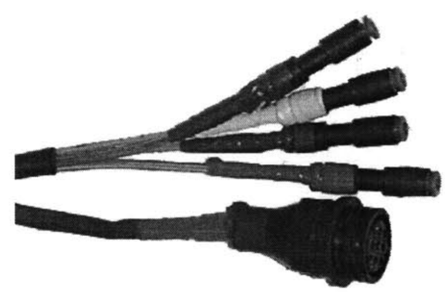


Figure 1.7 Connectors at end of power supply cord.

1.4 Kit Contents

Each student receives a storage locker and a large plastic bin full of materials from which the machine may be made. In general, the kit, as it is called, contains several actuators, which are reused form year to year, structural materials like wood, metal and plastic, small mechanical components like gears and springs, etc. The kit contents for the 1999 contest are listed in Table 1.1 on page 30.

TABLE 1.1 1999 2.007 Kit Contents

Qty.	Description:
	Electrically Powered Actuators and Accessories
2	Windshield wiper motors
2	Windshield wiper electrical connectors
2	Al flanges for windshield wiper motors
2	Bosch wormgear motors
4	1/4" electrical spade connectors (for Bosch motors)
1	Green DC gearmotor
1	Mid-size DC motor
1	Mabuchi motor
1	Mabuchi motor with transmission
1	1 1/8" dia DC solenoid
up to 3	Black and Decker cordless screwdrivers
	Pneumatic Actuators and Accessories
2	Double-acting air cylinder
2	Clevis (fits on end of cylinder)
4	Air flow controls
2	Y-connector
1	1.5 m x 4mm OD polyurethane tubing
	Wood
1	3" x 1/4" x 24" basswood slat
1	4" x 1/2" x 24" basswood slat
	Aluminum
1	1/4" x 2" x 12" bar, 6061
1	18" x 18" x 1/16" sheet, 5052
2	3/8" dia x 12" rod, 6061
1	1" x 3" x 12" box extrusion, 6061
2	1/4" x 24" rod, 6061
1	1" x 1" x 24" box extrusion
2	1" x 1" x 1/16" x 24" U-channel, 6061
	Steel
4'	1" x .048" mild steel strip
1	12" x 12" x 18 ga. mild steel sheet
1	1/2" DIA x 12" mild steel rod
1	1/4" DIA x 12" mild steel HEX rod
1	4mm x 4mm x 13" square rod
1	1/4" dia x 24" steel rod
30	1/8" dia x 36" welding rod
1	12" long piano hinge

TABLE 1.1 1999 2.007 Kit Contents

	Plastic
4	5.5" x 1" molded plastic wheels
1	4.4 oz. can of low temp. thermoplastic pellets
1	1" dia x 6" Delrin rod
1	2" dia x 6" Delrin rod
1	1/2" square x 6" UHMW rod
2	Small graduated cup
1	12" x 3/8" ID Tygon tubing
1	12" x 1/4" ID Tygon tubing
1	12" x 1/8" ID Tygon tubing
	Rubber and Foam
	we need wheels for the toothbelts
3	Rubber toothed belts (do not fit anything)
3	White rubber belt
1	Buna-N cord stock 1/8" dia x 4'
1	Buna-N 1/16" sheet stock, 24" x 6"
1	Blue Foam Square 6"x6"x1/2" with hole
2	Rubber stoppers
2	Rubber gloves
2	Small rubber bands
2	Medium rubber bands
2	Large rubber bands
	Miscellaneous
2	flat ceramic disk magnets
2	Plastic square shaft flanges (press fits on 4mm shaft)
6	Duplo blocks (red, green & blue)
1	36" x 12" cheesecloth
1	25' of your choice of string from 2.70 rolls only
1	up to 20' of 18 AWG hook-up wire (for electrical connections only)
1	11.5 oz of 26 AWG bondable magnet wire (for winding coils only)
1	6" Plastic Ruler
	Springs
2	Compression springs
2	Extension springs
2	Torsion springs
4	Constant force springs

TABLE 1.1 1999 2.007 Kit Contents

	Gears
2	Black plastic gears, 24 Pitch, 48T
2	Black plastic gears, 24 Pitch, 24T
2	Nylon Gear, 24 Pitch, 42T
2	Nylon Gear, 24 Pitch, 25T
2	Nylon Gear, 24 Pitch, 12T
	Bearings
10	Flanged Nyliner bearings, 1/4" bore
20	Nylon washers 1/4" I.D.
20	Nylon washers #10 I.D.
20	Nylon washers #6 I.D.
	Misc. Electrical
1	Roll of electrical tape
1	Circular Plastic Connector (and 8 connector wires) (quick-disconnect)
	Fasteners and Adhesives
	Bolts, nuts, washers
	An Assortment of Adhesives
	3M Two Part Epoxy

1.5 Design Process

The course 2.007 aims to teach students real-world design techniques by encouraging their use in the design of a machine for the contest. Problem Sets are used to create weekly milestones and ensure the completion of all steps in the process in a timely manner. This section discusses the general design philosophy that is conveyed and the Problem Sets, which provide a framework for the application of the process.

1.5.1 The Role of Problem Sets

Problem Sets, weekly homework assignment to be turned in for evaluation, were a rarity for this course until relatively recently. The problem sets have evolved over the past 5 years to become what is hopefully a cohesive set of tasks that tracks the design process taught in class. The desired effect is the completion of a well-engineered machine with minimal irrelevant work.

Part of the author's role as a Teaching Assistant for 2.007 in the Spring of 1999 involved updating, revising and publishing problem sets. Copies of the Problem Sets as they were distributed for 1999 and comments are included in Appendix B.

Design Process Flow as Covered in the Problem Sets. Problem Sets 1 through 6 are described in detail by their associated tasks in Figure 1.8 on page 34. Problem Sets 7, 8 and 9 are manufacturing Problem Sets and identical to PS 6. Problem Sets 10 and 11 shift from completion of manufacturing to testing and final preparation. Problem Set 12 is the creation of a Design Portfolio.

1.5.2 Design Process Flow

1. Identify the Task
2. Extract Functional Requirements, possible Design Parameters and Relevant Physics.
3. Generate Concepts
4. Develop concept selection criteria
5. Proof of concept physics/modeling
6. Select design from concepts
7. Design details and integrate modules

Figure 1.8 Flow chart of Design Steps as they correlate to Problem Sets for 1999 course.[a]

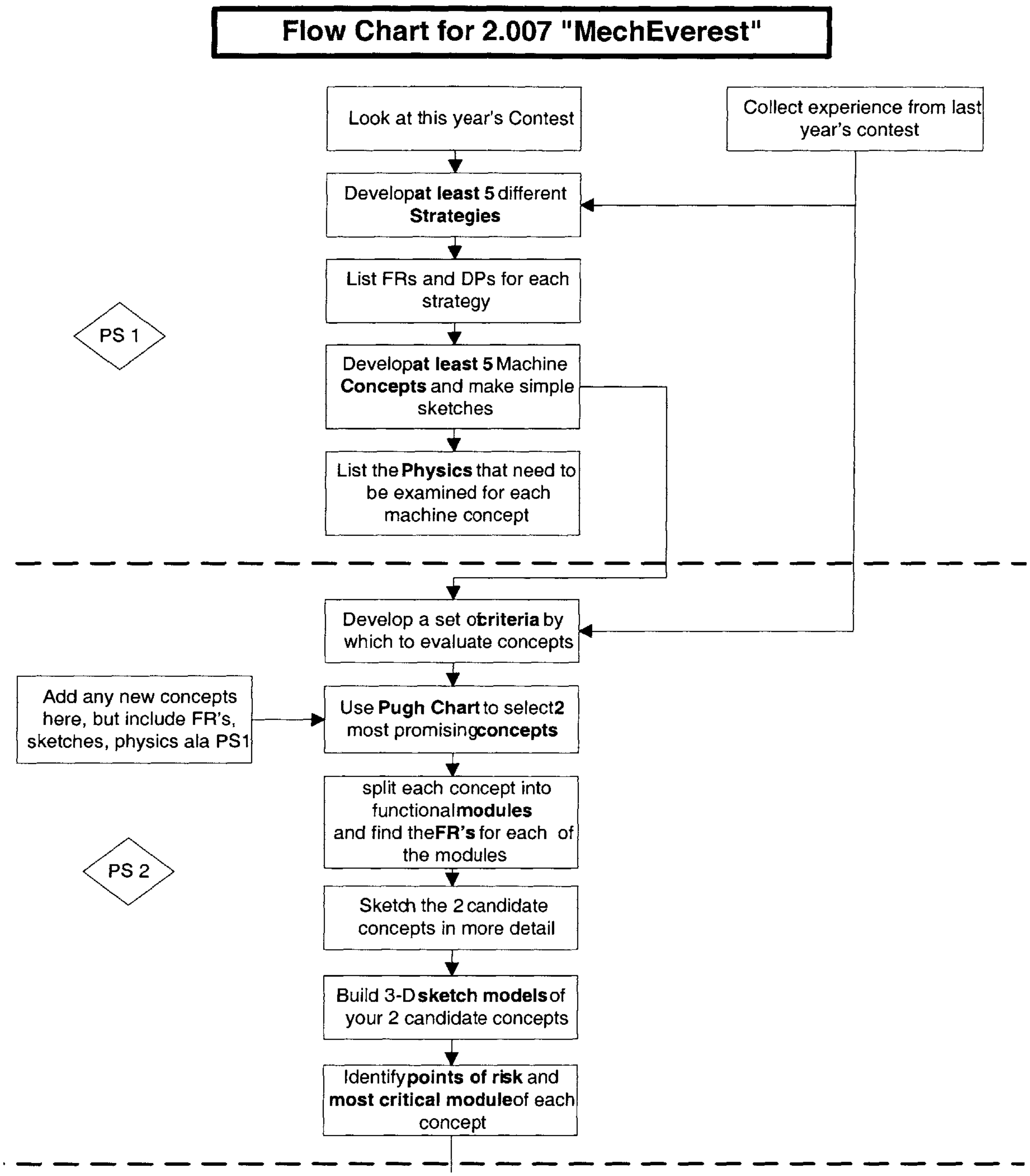


Figure 1.8a Portion of Design Task Flow Chart for Problem Sets 1 and 2.

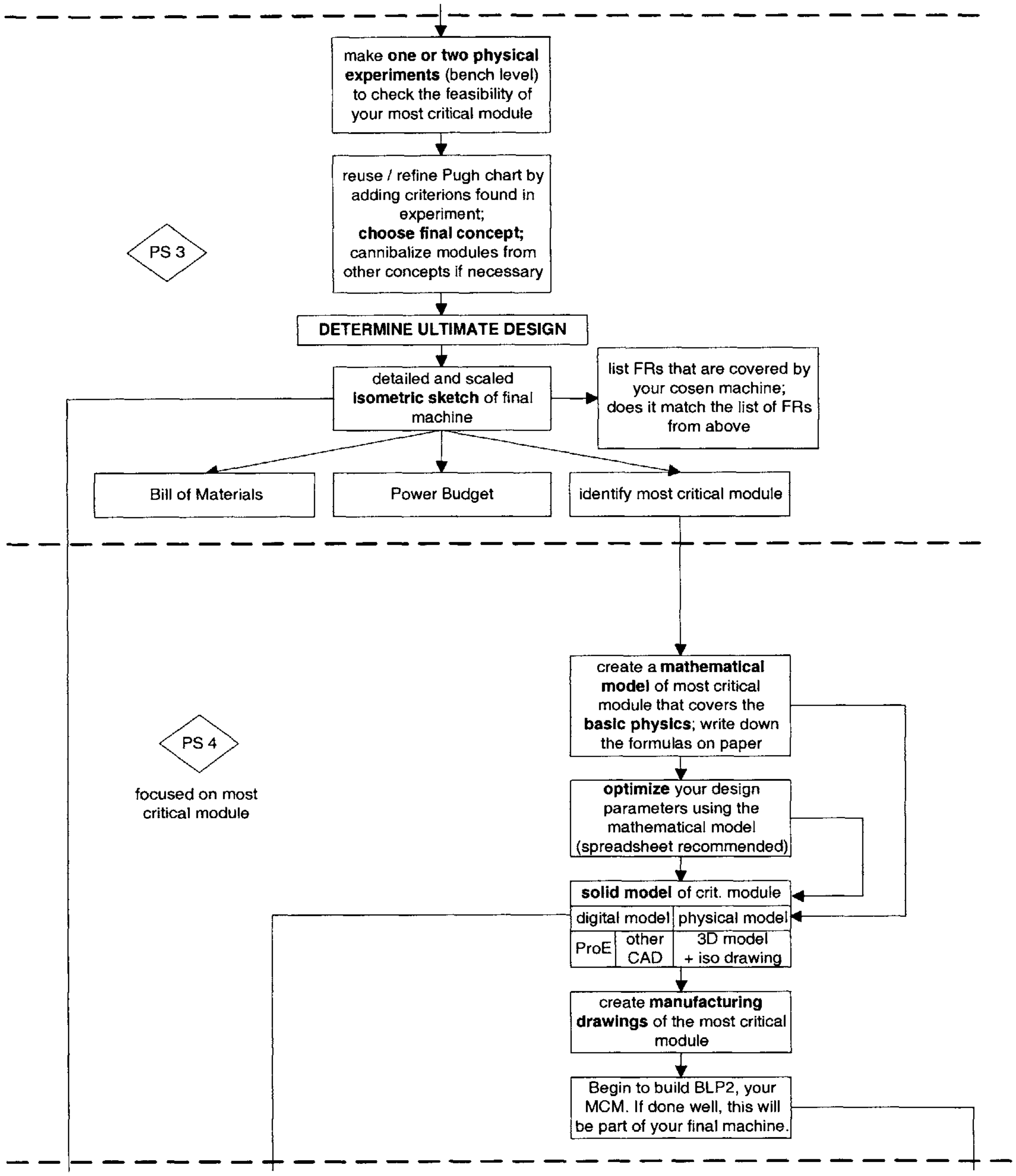


Figure 1.8b Portion of Design Task Flow Chart for Problem Sets 3 and 4.

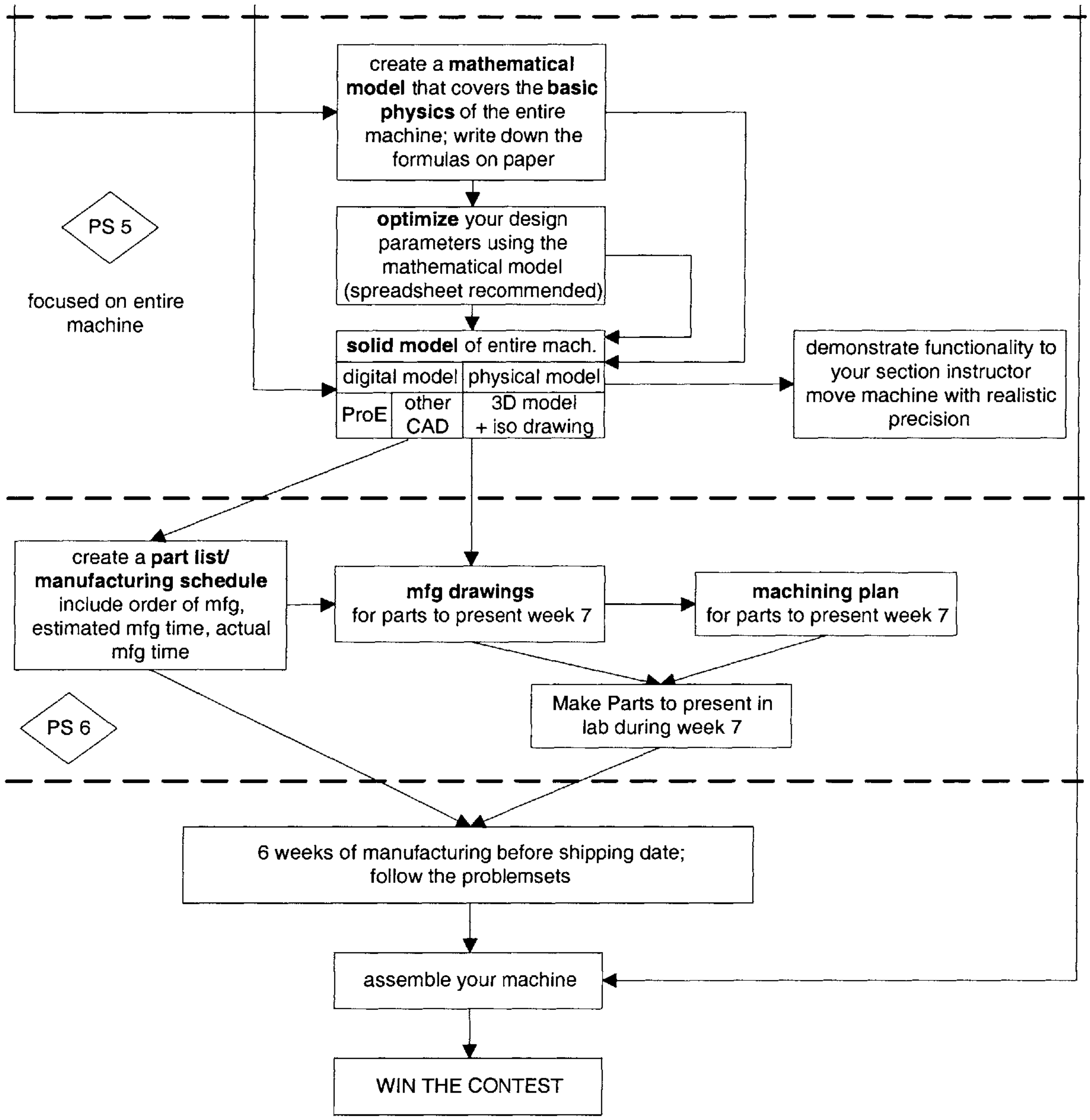


Figure 1.8c Portion of Design Task Flow Chart for Problem Sets 5 and 6.

a. This chart was developed with Joachim Sihler.

8. Reevaluate

Identify the Task. The first step in approaching a design problem is to define the task as clearly as possible.

Functional Requirements, Design Parameters and basic Physics.

This course uses concepts and terminology from the field of axiomatic design. More detailed discussions of these concepts and other tools for design can be found in *Principles of Design* by Suh *[Suh, 1990]*.

Functional Requirements. The Task leads to certain fundamental Functional Requirements (FRs). For example, in this contest, one of the Functional Requirements that is most easily extracted from the task is that the machine must accomplish its goal with 45 seconds of power. For those who enjoy splitting hairs, this is different from "the machine must achieve the task in 45 seconds" since the rules allow events that continue after the power stops to count towards a machine's score. In most cases, the difference between these types of FR are not significant, but they are a good mental exercise to really bare the fundamentals of the problem, and can sometimes lead to the discovery of very successful strategies.

Possible Design Parameters. For each Functional Requirement, it is desirable to generate a list of possible Design Parameters (DPs). The terminology here is sometimes a bit confusing. In the context of science and engineering, the term *parameter* often refers to a variable that is semi-constant. In formal design theory, Design Parameters are often considered to be variables like beam thickness or cross-section, wheel diameter, or gear ratio. This type of parameter with a direct physical value easily fits into a strategy where a single DP is sought to correspond to FR. With one DP for each FR the satisfaction of all FRs is independent, and everyone can be pleased. In reality there is usually some unavoidable coupling between FRs leading to the need to make design trade-offs. An example of where decoupling of FRs is possible and yields a better design can be found in the discussion of the Rover wheels in Section 2.3.3 on page 63.

In this course, and in *Precision Machine Design [Slocum, 1992]*, the concept of a Design Parameter is sometimes generalized for application at a higher level in the design process. Design Parameters of this type can border on possible design concepts. Design Parameters of this type corresponding to the FR "deposit hockey pucks in a hole" might include a crane, a catapult or a bulldozer.

Basic Physics. Though sometimes shied away from, this is a good time to generate at least a list of the relevant engineering physics that will need to be applied in the design. Especially for teaching purposes, the general identification of what needs to be investigated is at least as important as the precise formulas and equations involved. For example, indicating that reaction torque generated in accelerating a machine while driving up an incline may tip the machine over is almost as good as writing the moment equations about the center of mass that are involved. It is very beneficial to identify certain general cases of physics (i.e magnetic traction enhancement) that will be applicable to several designs and make explicit general physical/mathematical models that can give real answers about the relative (and absolute) worth of concepts. Often the exercise of using an instinctively generated concept to generate a general math/physics model can reveal faulty assumptions, or catalyze new variations that are superior to the preconceived notion of what the form the embodiment of the concept will take.

Concepts. Concepts should be generated from the beginning of the project. Concepts are best recorded and communicated with a simple sketch and short description. Sketches are especially important in helping novice designers to develop spatial skills.

Criteria . To evaluate the concepts by organized methods, it is useful to have a well-defined set of criteria. In most cases, many of the criteria are closely linked to the FR's, and this dependence can be direct or indirect. Often, the *initial* concept selection process requires that estimates be made of how different concepts rate with respect to the criteria. For example, the FR of scoring points relates closely to the criterion "ability to score points" used to evaluate concepts. A less direct relationship is illustrated by the time limit. The FR in this case is "complete task with 45 seconds of power", and the criterion influenced may be "robustness of strategy."

There are also **Functional Requirement-Independent Criteria** that can be very important, like "likelihood of being completed in designer's schedule" and "manufacturability." One could argue that realistic constraints such as available development time and manufacturability are implicit FRs. These requirements can also be considered project management FRs as opposed to Design FRs. It is found to be most natural to begin the use of FR's at the technical level, then use the requirements on time management, manufacturing, etc. in addition to FR-derived criteria to evaluate and choose among the concepts. Perhaps the top-level FRs can be included before the technical design step in a top level project management FR-DP table. A personal favorite FR-independent criterion is the "coolness factor." Often when designing a machine for this course, it is hard to know for certain the relative worth of different strategies, and a large part of many students' concept selection process involves a subjective affinity for a certain concept. Many students do not have victory in the contest as a personal goal. The pursuit of a design concept for subjective reasons should not be regarded as illegitimate in technical design (it enters in the real world as "marketing/marketability") as long as it is explicitly acknowledged. The temptation to "fudge" the numbers to yield a result favoring the predetermined favorite design is common, and destroys the benefits of the explicit valuing of different designs with respect to a single complete set of selection criteria.

Physics and modeling. When three or so best concepts have been identified as well as possible without detailed analysis (i.e. by estimating of relative values with respect to criteria) it becomes time to introduce some "real numbers." The main goal is to achieve greater certainty, so several methods may be appropriate:

- Computer Aided Design / Digital Solid Modeling
- First-Pass or Proof-of-Concept Mathematical Modeling
- Physical Solid Modeling
- Finite Element Analysis
- Bench Level Prototype

Concept Selection. Using the information gained and the selection criteria (and any new criteria that have been discovered during the process) the best design should be selected. There are a number of tools and methods for this, from the product-design Pugh Chart, a weighted Pugh Chart, up to very scalable methods like AHP matrices *[Slocum, 1992]*. A demonstration of the use of a Pugh Chart for concept selection can be seen in examples published with Problem set 2 in Appendix B.

Detailed Design and Packaging. one of the most challenging aspects of the design of a complex machine is the integration of different modules. It is often hard to account for the coupling between modules. CAD tools can be very helpful here by allowing easy prototyping and revealing problems while corrections can still easily be made.

Reevaluation. It is always acceptable to realize things have changed and a former solution is no longer the best approach. Having well-constructed general mathematical and solid models in place often pays dividends when updating or rearrangement is required.

Mathematical Models. The development of good mathematical models to predict the performance of machine modules and design the details of mechanisms is a very important part of learning the design process. Mathematical models are covered and demonstrated extensively in chapter 2.

A Word About the Use of Spreadsheets

The use of spreadsheets as a useful tool for mathematical/physics modeling in Design is presented in the course. Based on experience there are a few philosophical points that should be kept in mind. Spreadsheets allow the easy computation of iterative models (rather than requiring optimization analysis). This is important because it is often easiest for students new to design modeling to attack problems a small piece at a time. Fully symbolic analysis, with a single symbolic result is an ideal- but in cases where errors are likely (sign, trigonometry, etc.) they are risky, as they can mask "bugs." The presence of intermediate steps in the solutions allows easier "reality checks." Some negative points concerning the use of spreadsheet models is that they can easily be built in a manner that disguises the intended design flow. A collection of formulae that automatically recalculates may make it too easy to just record dependencies than to create a clear problem with a clear result.

1.5.3 Using Computer Solid Modeling to Teach Design

It can be beneficial to encourage novice designers to use computer solid modeling tools. The exercise of explicitly defining part geometry and placement can reveal design oversights. The potential for learning by doing- and needing to redo- is greater and less painful when the doing involves placing parts in a computer model as opposed to cutting metal, wood and plastic.

Linking Spreadsheets to Solid Models

The Puck Truck assembly's relations file (see Appendix C) contains the "behind-the-scenes" formulas linking various parameters and dimension values in the model. In the case of this model, the most common use for relations is to force several dimensions to always have the same value without changing them all at the same time manually. The other, more interesting set of relations ensures that the Pro/Engineer model of the puck collection mechanism corresponds exactly in geometry with the mathematical (spreadsheet) model which is used to predict whether or not the mechanism will function correctly.

Further details regarding the design process taught can be found in the Problem Sets in Appendix B.

Chapter 2

DESIGN AND CONSTRUCTION OF A SAMPLE MACHINE

2.1 Motivation

This chapter covers of the conception, design, building and testing of a Sample Machine (Figure 2.1) for the 1999 contest. The machine is intended to provide a set of real design case studies for use as teaching aids in the future. The degree of engineering involved in the design of the sample machine is slightly more complex than that undertaken by the average student, but this is because it is intended to show possibilities and the application of methods taught in class, rather than show what is required to receive a certain grade, etc.

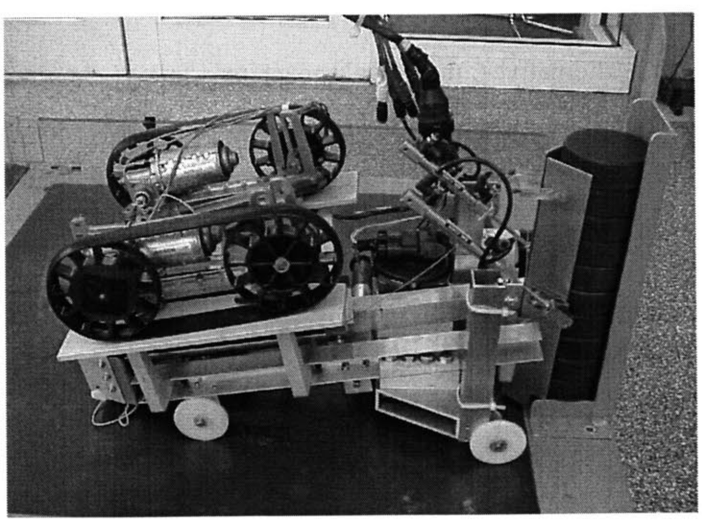


Figure 2.1 Starting Configuration of Sample Machine.

The practical embodiment of the Sample Machine as a set of design case studies will likely be in the form of a tutorial section on the 2.007 world wide web page. The examples from the design of the Sample Machine may also be useful in teaching recitation sections, since the details can be covered in depth and questions can be answered in person. The design case studies for individual modules can be used independently, perhaps to demonstrate specific methods and tools. However, there is already too much material to be covered in lecture and lab meetings, so making the material available on the web page would likely give the best access to those students who feel they would benefit from it. In further support of the publishing of these examples on the 2.007 web page, the course evaluation forms distributed at the end of the semester showed that student reactions to the 1999 web page were positive. They also support the addition of more technical content to the web page. Of course, with only 5 comments from 130 students, there is significant room for error.

Comments About the Course Web Page from Course Evaluation Questionnaires

- Make the web page and the pro/engineer information more accessible
- Have more web stuff - especially on topics like linkages, gears, etc.
- The home page is useful
- Have more web stuff
- Website was helpful

2.2 Concept Selection for the Sample Machine

After considering several alternatives, the sample machine's task is chosen as the 1999 contest, MechEverest, following normal rules. Since the machine will be used as the basis for case studies in design methods used in this course, some additional requirements are used in choosing a design concept.

Functional Requirements for Sample Machine

- Can be completed in time available
- Will not significantly influence students' designs
- Provides opportunities for powerful use of CAD tools
- Functions reliably
- Allows challenging design and engineering
- Makes good teaching example

- Performs impressively
- Challenges designer's skills
- Is a friendly competitor
- Adhere to all contest rules

Early concepts:

- Grappling-hook launcher and winch
- Wall-crawler
- Mountain climber placebo[1]
- Airplane Launcher placebo
- Low point scorer with opponent-blocker
- Collect extra pucks, but don't score any points
- Magnetic vehicle to travel on underside of table.
- Rover to drive over top of table and winch back up
- Rover with magnets places hook for rest of machine to winch up, deposit 20 pucks in top hole (max. score)

Weighing the concepts with respect to selection criteria corresponding to the above Functional Requirements the strategy chosen was last in the list of concepts. The placebos were discarded as too cute and not close enough to a real machine to function as a serious design example. It was also quite difficult to come up with a challenging task that was different from the contest, but used the same parts and table, so the path chosen was to design and build an ambitious machine for the contest. The problem of "polluting" the design environment for students was addressed by using generic examples until after students had selected their concepts.

Because the total cargo of 18 pucks and associated deposition mechanism weighs approximately 12 pounds, it was found impractical to transport the pucks to the topmost scoring hole in traditional vehicle.

2.2.1 Sample Machine Overview

The selected strategy concept consists of two vehicles: the Rover and the Puck Truck. The strategy includes several major functions, each of which is associated with a different functional module:

1. The term placebo is used in the 2.007 contest to refer to entertaining non-competitive machines that are used occasionally to fill empty spots in contest rounds.

- Anchoring cord to top of table above scoring hole. (Rover)
- Collecting the stack of 10 additional pucks (Puck Truck— Puck Collecting Module)
- Ascending the table with load of pucks and depositing mechanism. (Puck Truck— Ascending Winch Module)
- Depositing pucks. (Puck Truck— Puck Depositing Module)

Figures

An alternate view of the starting configuration of the finished machine is shown in Figure 2.2. A

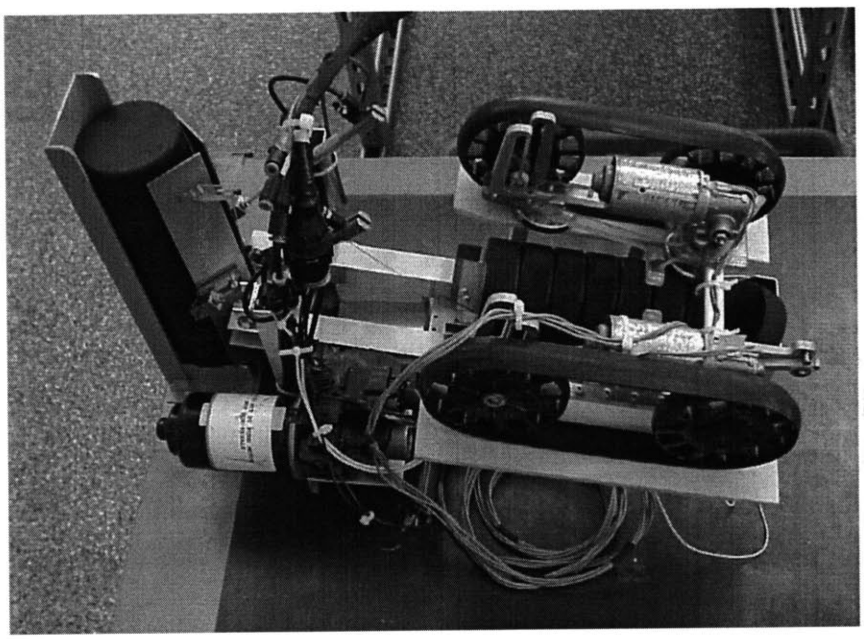


Figure 2.2 Top/Side view of Starting Configuration.

view of the CAD model of the machine is shown in Figure 2.3 on page 47. A succession of still images of the collecting of pucks and the departure of the Rover is shown in Figure 2.4 on page 48. Figure 2.5 on page 50 shows the Rover anchoring to the top, the Puck Truck ascending and pucks being deposited.

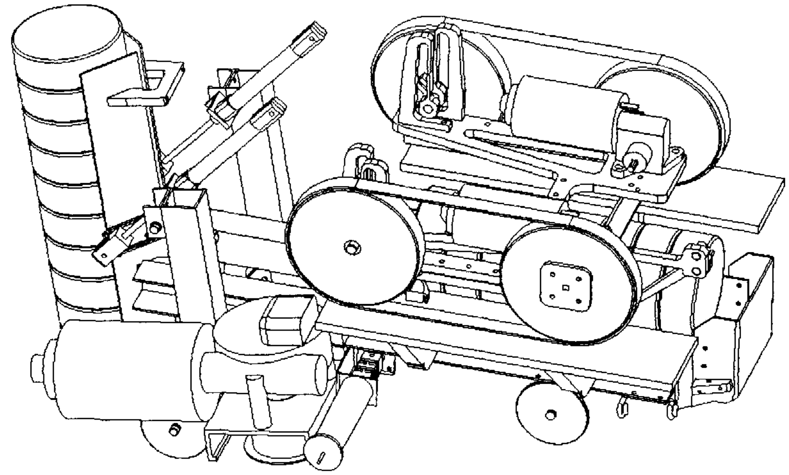


Figure 2.3 View of CAD model of Sample Machine.

Figure 2.4 Photo Sequence of Puck Collecting and Rover Departure

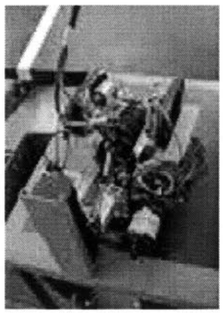


Figure 2.4a Starting Configuration.

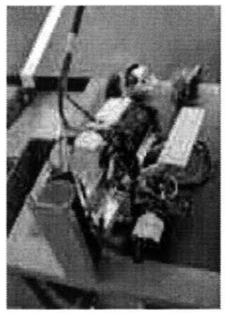


Figure 2.4b Rover departure.

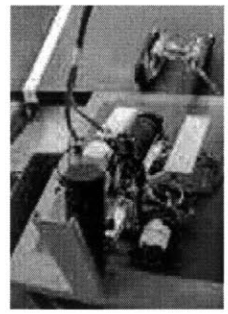


Figure 2.4c Puck collecting.

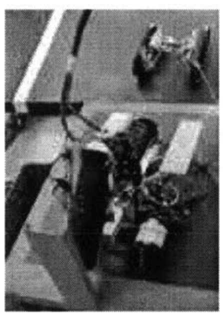


Figure 2.4d Puck collecting.

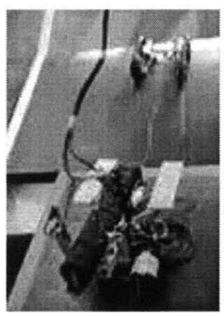


Figure 2.4e Pucks collected.

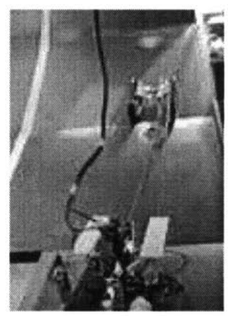


Figure 2.4f Rover ascending.

Approximate Task Time Breakdown

To enable general planning and separation of the requirements for the whole machine into requirements for each functional module, an estimate was made budgeting the 45 seconds of contest time between the different tasks of the strategy. The initial estimate for this time budget is shown in Table 2.1 on page 49. The actual time division between tasks for the finished machine used more time to maneuver the Rover, just about the predicted time or slightly more to winch the Puck Truck, and significantly less time than expected to deposit pucks. The actual (approximate) time breakdown for a contest round can be seen in Table 2.2 on page 49.

TABLE 2.1 Initial planning of time division between tasks for chosen strategy

Time Interval:	**0-15s**	**15-30s**	**30-45s**
Tasks	Rover departs and climbs to top. Collect pucks	Puck Truck winches to top, mates with anchored Rover	Deposit pucks

TABLE 2.2 Actual division of time between tasks for finished machine.

0-15s	15-20s	20-35s	35-42s	42-45s
Rover departs and climbs to top Collect Pucks	Rover maneuvers into position over hole and hooks to top of table	Puck Truck winches to top, mates with anchored Rover	Deposit pucks	Buffer

Figure 2.5 Photo Sequence of Rover anchoring, Puck Truck Ascending and Scoring.

Figure 2.5a Rover Nearing Top.

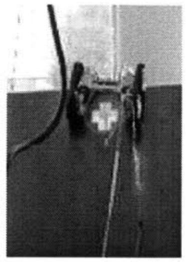


Figure 2.5b Rover Placing Hook.

Figure 2.5c Puck Truck Ascending

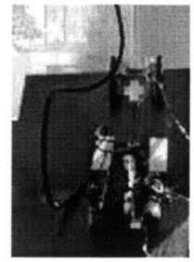


Figure 2.5d Puck Truck Ascending

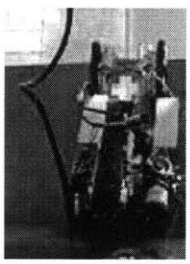


Figure 2.5e Puck Truck Approaching Rover

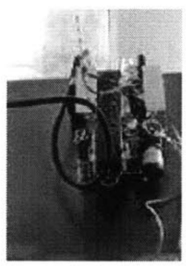


Figure 2.5f Puck Truck Mates to Rover

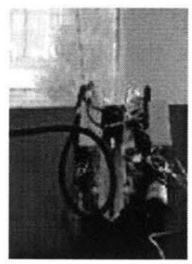


Figure 2.5g Pucks deposited for 75 points.

2.3 The Rover Module

The strategy chosen for the sample machine relies on a small vehicle to climb to the top of the table and anchor itself in position over the 5-point hole. This vehicle is referred to as the Rover or sometimes as the grapple-rover. Once the Rover is in position, the Puck Truck module winches itself up to mate with the Rover and deposit pucks. A view of the final Rover design from its CAD solid model is shown in Figure 2.6.

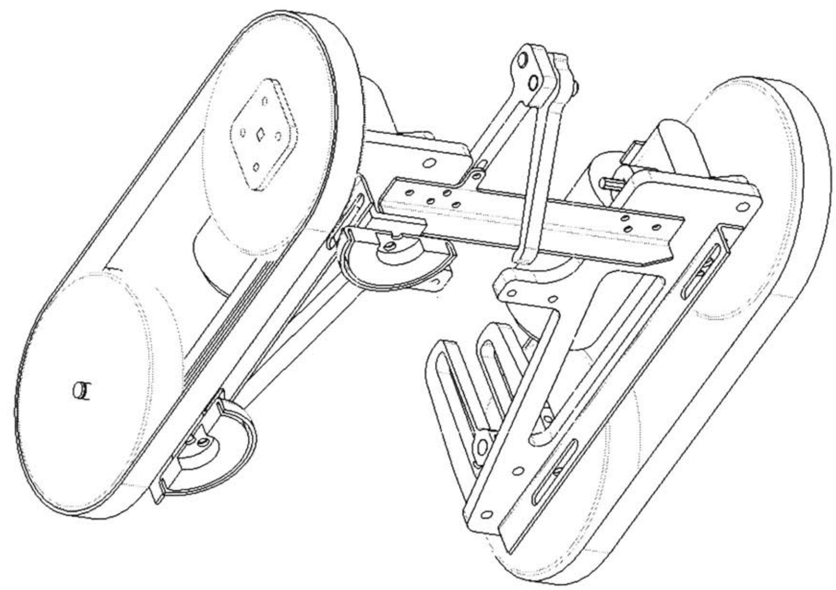


Figure 2.6 View of CAD model of Rover Module. Some symmetrically placed components have been omitted for model simplicity.

Early in the development of the Sample Machine, the Rover was identified as the Most Critical Module. If the Rover module was not able to travel reliably to the top of the table and plant the anchoring hook for the Puck Truck Ascending Winch, then no points would be scored. For this Most Critical Module, a Bench Level Prototype (BLP) was built with simulated rubber-covered wheels and magnets to help increase traction as in the real Rover. The BLP showed that the magnetic traction enhancement was very effective. This was in part because the rubber treads were cleaned with alcohol and tested with a high contact pressure, giving coefficients of friction with the steel table of up to 0.8. The previously assumed value for the tread-table friction coefficient was 0.4 based on tests conducted with uncleaned rubber and lower contact pressures.

Key features of the Rover module include:

- Two independently controlled Bosch motors for steerability
- Polycarbonate chassis with interface for puck truck
- Treads for effective all-wheel drive
- Magnets to enhance traction while climbing the steep sections of the table
- Flexible chassis joiner ("torsional suspension")
- Flexural supports for undriven wheel axles, allowing alignment adjustments
- Passive "grappling" hook to anchor to table top
- Aluminum chassis stiffening rails.

Starting Configuration and "Packaging"

The rules for the contest specify that the starting configuration of a machine must fit inside the green plastic bin in which the kit materials are distributed. These bins measure approximately 20"x11"x10"; the walls are slightly angled and contoured. The Rover module was originally intended to start the round in a vertical orientation on the side of the Puck Truck's puck tray, forward of the large Ford motor for the Ascending Winch. Not only was this difficult to do without violating the size rules, it would have required a complicated departure maneuver, increasing the chances of losing the treads. In the end, a wooden platform was constructed positioning the Rover above the front puck tray at the start. The starting procedure is then to drive straight off a 4-inch drop and continue up the table. The Rover's electrical cable and the ascending winch cord are stored carefully coiled on the table surface under the Puck Truck and reliably follow the Rover up the table. The entire starting configuration fits inside the allowed space, but not with much clearance.

A detailed treatment of the design of the Rover's drivetrain follows in Section 2.3.1. The design of flexural axle supports is presented in Section 2.3.2. The torsional suspension developed to keep all wheels in contact with the table is covered in Section 2.3.4.

2.3.1 Rover Drive System

The Rover's task is to ascend the table, position itself over the 5-point scoring hole and place an anchoring hook over the top edger of the table. Then the Puck Truck ascends to mate with the Rover and deposit pucks. It does this by means of its Ascending Winch, which uses a cord connected to the Rover to pull itself up the table. The mathematical model for the Rover drivetrain was constructed in order to verify that the Bosch motors would be able to do the job, and to select an appropriate wheel diameter. The Bosch motors were chosen because they are especially suitable for powering vehicles. They have convenient surface mounting, a good gear reduction, generous power, and there are standard parts available that make the connection of wheels to these motors very simple.

Mathematical Model for the Rover Drivetrain

The principle parameter that is being chosen with the help of the mathematical model is the appropriate wheel radius for the Rover. A wheel radius that is too large may require too much torque from the motors, or move so fast that it will be hard to control. A wheel radius that is too small will not reach the top of the quickly enough. Due to the nature of the wheel blanks in the kit, there are three different wheel diameters that are convenient to use: 5.5", 4" and 2.5". The use of a spreadsheet is convenient because it instantly reflects the effects of using a different wheel diameter. The spreadsheet in Figure 2.7 on page 54 shows calculations used to choose the medium wheel size of 4".

Modeling the Load

The first step in designing the Rover drivetrain will be to find the load torque and to verify that its motors are strong enough for the job. Then the operating speed corresponding to the load torque can be found. The principle sources of load on the drive motors are assumed to be wheel friction and work done in climbing the table. Because it will consist primarily of motors, wheels and a chassis, it is estimated that the Rover will weigh approximately 2kg.

Driving Friction for Rover						
Inputs						
Mass of machine	2	**kg**				
Weight force per wheel	4.9	**N**	assumes symmetrical load			
Estimated Tread tension	10	**N**	total tension force on one wheel			
Mu bearings	0.2		estimate for Delrin on steel			
Geometry factor	1		cantilever effects, etc.			
# wheels	2		to which friction applies			
Bearing radius r	0.006	**m**	motor's friction included in motor specs)			
Wheel radius R	2.1	**in**				
Wheel radius R	0.054	**m**				
Outputs						
Resultant force per wheel	11.1	**N**	vector sum of forces			
Driving friction force	4.454	**N**	per wheel			
Total Friction torque	0.5	**N-m**	note this is for 2 motors			
INCLINE CLIMBING						
Inputs						
Theta	45	30	15	0	**deg**	incline angle
Theta	0.79	0.52	0.26	0.00	**rads**	
also uses M, g, R						
Output						
Incline driving torque	0.75	0.53	0.27	0.00	**Nm**	note this is for 2 motors
Total driving torque	1.24	1.02	0.77	0.50	**Nm**	note this is for 2 motors
Required Torque	0.62	0.51	0.38	0.25	**Nm**	per motor
Finding the Driving Speed						
Motor characteristics in linear portion of torque-speed curve:						
No load speed	93	**rpm**				
Max torque in linear range	1.34	**Nm**	at	40	**rpm**	
	so w=93-T*(93-40)/1.34				valid for T<1.34Nm	
Speed at torque from abc	68.41	72.7	77.8	83.21	**rpm**	
Translational speed m/s	0.387	0.41	0.44	0.47	**m/s**	
Distance at this angle (in)	30	30	30	30	**in**	
Distance at this angle m	0.76	0.76	0.76	0.76	**m**	
Time	1.97	1.85	1.73	1.62	**s**	
Total (minimum) time	**7.2**	**s**				

Figure 2.7 Spreadsheet model of Rover drivetrain.

Finding the Friction Torque

The torque load on the drive motors due to wheel friction is caused by friction in the motor bearings as well as in the bearings for the rear wheels. In this example, the bearing friction in the motor bearings is ignored because it is known that the motor test data were taken with a large load on the motor bearings, and it is assumed that the friction in those bearings is already accounted for.[1] The friction force in the indirectly driven rear wheels is caused by the net force in the wheel bearings and acts at the radius of the axle. The net force acting on the wheel has two components: one due to the weight of the Rover and one in the form of tread tension. In this machine the axle is fixed and the wheel rotates, so there is no geometric amplification of the friction forces as there would be in the case of a cantilevered wheel.

The Total Torque Required to Climb the Table

The load torque due to bearing friction is assumed to be constant over the Rover's path. The total load torque must also include the torque required to climb the table. As the Rover moves up the inclines on the table, it is acted on by a component of gravity which is parallel to the table surface. The different magnitudes of this load for the different incline angles are shown in the spreadsheet in Figure 2.7. The maximum predicted load torque for driving up the table occurs on the 45 degree incline and is found to be 0.62 Nm per motor. This is well within the motor's capabilities.

Finding the Motor Speed

In order to understand how well the Rover will perform, it is desirable to know not only that it will climb the table successfully, but how quickly it can do so. To find the speed associated with a known load on the motor, the motor's torque-speed characteristics must be known. In the case where a motor exhibits a linear torque-speed curve, this is simple. The torque-speed curve for the Bosch motor (Figure 2.8 on page 56) exhibits linear performance only when the torque is less than approximately 1.34 Nm. This is due to a loss of power under high load, which is likely to be caused by the internal worm gear transmission.

1. A description of the motor testing procedure can be found in Section A.1 on page 131.

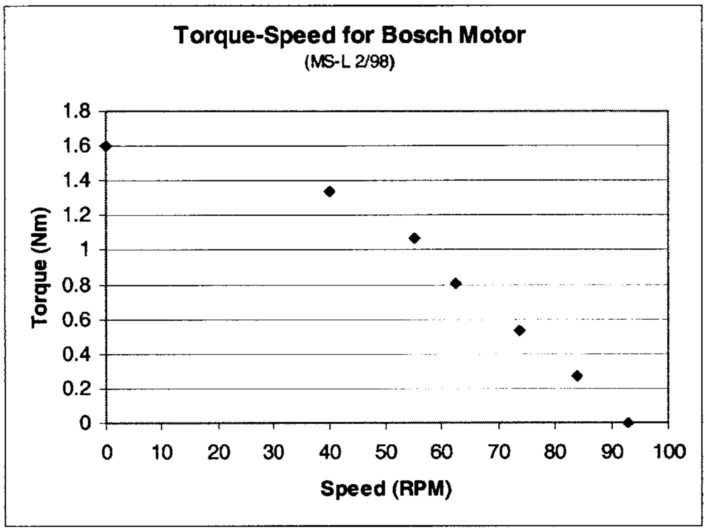


Figure 2.8 Torque-speed data for Bosch motor.

The point in the torque-speed curve after which the motor's performance ceases to be linear is identified as point 1, with speed w_1 and torque T_1. The other endpoint of the linear torque-speed region is the no load speed, w_o which by definition is associated with load torque equal to zero. With the two endpoints known it is possible to find a simple torque-speed relation for the linear region. Equation 2.1 relates the operating speed w to the load torque T.

$$\omega = \frac{\omega_1 - \omega_o}{T_1} \cdot T + \omega_o \tag{2.1}$$

This equation is used in the spreadsheet of Figure 2.7 and gives a different speed for each incline section, since there is a different load torque for each incline. The total time predicted for driving up the table is found to be 7.2 seconds. In order to predict the actual time that the Rover will take to reach the top of the table, the reality of human control must be considered. The Rover must depart from the starting position, travel to the table top while avoiding holes and maneuver with precision at the top of the table. Considering the extra time necessary for maneuvering, the capability to reach the table top in around 7 seconds predicts that the Rover will function well. In testing, the Rover moved relatively quickly, and maneuvering took about as much time as driving up the table. It took the real Rover an average of about 15 seconds to go from departure to being anchored in position over the 5-point scoring hole.

2.3.2 Flexural Axle Supports for Rover

Experience has shown that tread-based vehicles are vulnerable to the loss of their treads. Often this tread loss is brought on by certain maneuvers such as on-the-spot rotation or tackling a difficult obstacle. In addition, insufficient manufacturing accuracy or insufficient rotational rigidity of the axle support blocks can cause an angular error in wheel position and a greater tendency to lose the tread in normal driving. A well-designed, accurate tread system will have fewer problems than one with poor alignment. The flexural axle supports whose design is described in this section allow the fine-tuning of wheel alignment and, to a certain extent, tread tension. Two different flexural axle supports were designed, one to be located closer to the wheel, and one to be closer to the middle of the chassis. Drawings of the final designs can be seen in Figure 2.9 and Figure 2.10.

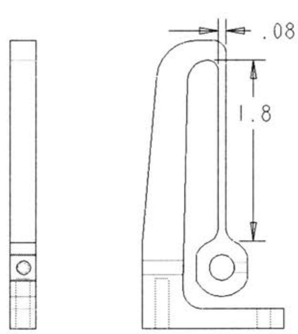


Figure 2.9 Drawing View of Inner Axle Support for Rover.

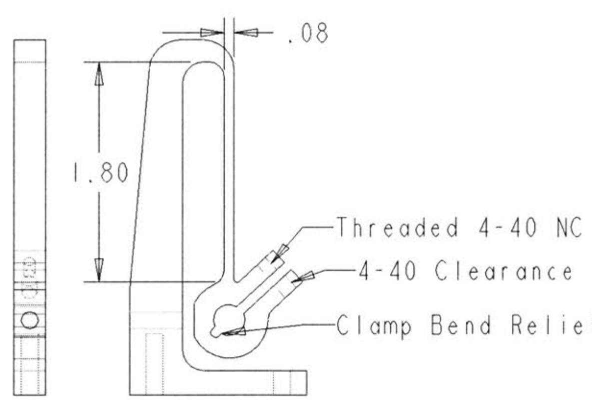


Figure 2.10 Drawing View of Outer Axle Support for Rover.

Purpose of the Flexural Axle Supports as Design Case Study

Especially in hindsight, it is apparent that most of the value of the flexural axle supports in this project is as a general example of flexure design and design for waterjet manufacturing. The real practical benefits of the parts are probably not worth the extra effort required to design and manufacture them compared to a simple machined aluminum bracket. However, this section is not meant to be an example of how to mount wheels most efficiently, but rather demonstrates the use of CAD and CAM tools, flexures, and shaft clamping to achieve a certain precision alignment capability. It also shows the possibilities of and encourages the consideration of non-rectilinear geometry. For the purpose of this design case study, it is assumed that this type of axle support is needed.

Material Selection

- Plate is needed for 2D cutting on waterjet (Section 2.7.2 on page 124)
- Thicker material has better lateral stiffness.
- For a given thickness, higher Young's Modulus means higher ratio of lateral stiffness to flexural stiffness.
- Plate stock in the kit: 1/4" Aluminum 6061 and 0.21" Polycarbonate
- Choose Aluminum for maximum lateral stiffness.

Functional Requirements

Functional Requirements	Possible Design Parameters	Relevant Engineering/ Physics
1. Support vertical loads on 1/4" axle stiffly	2 mounts per axle— cantilever arrangement	Cantilever leverage, Tension and compression, Buckling
2. Allow tensioning of tread	Screw adjustment of flexible beam containing axle hole Beam thickness, Beam length, Deflection magnitude	Beam bending stiffness, stress
3. Allow fine adjustment of wheel angle in horizontal plane	• Pair of flexural wheel supports deflected in opposite directions • Screw adjustment of flexure position from both sides.	Preload from belt tension may overcome need to constrain flexure from both sides— calculate or experiment.
4. Use only available material	Total height Packaging of flexural "mechanism" within part	
5. Show benefits of waterjet part manufacturing	Non-rectilinear geometry	Very little cost for geometric complexity (in 2D)

Revision of Functional Requirements

The flexural axle support parts were originally intended to provide both tread tension adjustment and wheel angle adjustment. However, because the tread material is relatively compliant, the tension increase in the treads that can be effected by an adjustment of the flexural system is not very large. The mounted tread is stretched to approximately 120% of its resting length, resulting in a tension of at least an order of magnitude higher than that which can be added by the modest deflection possible with the flexural mounting system. Thus it was determined that the primary benefit of the flexural wheel mounts would be

- Allow fine adjustment of wheel "twist"

- Demonstrate possibilities created by use of waterjet to make parts
- Demonstrate use of flexures to achieve motion with low parts count.

Design of the Flexural Beam

As a starting point for design, it was determined that 0.1" of deflection of the axle via the flexural beam would be desirable for adjustment purposes. From this starting point, the mount was designed to be as stiff as possible in the lateral direction while avoiding the yielding of any material as the flexure deflects by 0.1". The equations used in these calculations follow, and the actual spreadsheet calculations and values are shown in Figure 2.11 on page 61. A practical constraint on the maximum size of the parts rises since there are only 12" of 1/4" x 2" aluminum bar in the kit. This constraint was treated as a condition to check after other design requirements were satisfied.

The section moment of inertia for the deflection of the beam in the flexural direction is that of a rectangular cross section:

$$I_{flex} = \frac{bh^3}{12} \tag{2.2}$$

where b is 1/4" (plate thickness) and h is the "height" of the section in the direction of bending. For the same section, keeping the definitions of b and h as for the flexural direction, the section moment of inertia in the lateral direction is:

$$I_{lat} = \frac{hb^3}{12} \tag{2.3}$$

and the ratio of lateral stiffness to flexural stiffness is:

$$\text{Stiffness Ratio} = \frac{I_{lat}}{I_{flex}} = \left(\frac{h}{b}\right)^2 \tag{2.4}$$

The required force, F, to achieve a certain deflection δ is:

$$F = \frac{3\delta EI}{L^3} \tag{2.5}$$

where E is the Young's modulus of the material, I is the section moment of inertia, or I_{flex} from above, and L is the length of the beam. For a certain applied load at the beam's tip, the maximum stress is given by:

$$\sigma_{max} = \frac{M_{max}c}{I} \tag{2.6}$$

where M is the maximum moment, $F \cdot L$, and c is the distance to the outermost fiber from the neutral axis. When the resulting stress is safely below the yield stress of the material, a satisfactory

Rover Wheel Mount Flexure				
Material	Aluminum 6061-T6			
E	9.79E+06	**psi**	6.90E+10	**Pa**
Beam width b	0.25	**in**	0.00635	**m**
Beam thickness h	0.08	**in**	0.002032	**m**
Beam length l	1.8	**in**	0.04572	**m**
Moment of Interia, I	1.07E-05	**in^4**	4.44E-12	**m^4**
I lateral	0.000104	**in^4**	4.34E-11	**m^4**
Stiffness Ratio	9.765625		9.765625	
Desired deflection	0.1	**in**	0.00254	**m**
Force required	5.37E+00	**lbf**	2.44E+01	**N**
Sigma max	36274.74	**psi**	2.56E+08	**Pa**
Sigma yield	4.12E+04	**psi**	2.90E+08	**Pa**
Yield safety factor	1.134783		1.134783	**must be >1**
Stiffness	5.37E+01	**lb/in**	9.62E+03	**N/m**
			9.62E+00	**N/mm**

Figure 2.11 Spreadsheet Calculations for Flexural Beam in Rover Axle Support.

solution has been found. The numerical calculations and results for the above equations can be seen in Figure 2.11 on page 61.

Clamping to the Axles

The inner and outer axle mounts are designed to exemplify two different possible axle clamping methods. The inner mount features a set screw for retention of the axle, while the outer mount uses a clamp. The clamp feature was positioned at an angle in order that a drill could make the threaded and clearance holes for the clamping screw.

2.3.3 Rover Wheels: A Redesign Case Study

The kit parts most commonly used as wheels are 5.5" diameter by 1" thick webbed discs intended to be load-bearing spacers for separating stacked pallets of goods. They were donated to the course by Hardigg Industries of South Deerfield, Mass., and save tedious shop work over previous methods used to make wheels. The wheel blanks have holes in the center which are often enlarged to accommodate Delrin^R bushings or specially-made molded flanges which allow a press fit connection to the square shaft of the Bosch motors.

A good example of the realities of the design process can be seen in the evolution of the design for wheels for the Sample Machine's Rover module. This section discusses the design of a lightweight wheel for the Rover module, its tendency to cause the Rover's treads to slip off, a second wheel design which performed better, and a third design which might be the best solution.

Overall Wheel Functional Requirements:

1. Harness all machine weight for traction (4WD or tracks)
2. Radius suitable to climb with most speed
3. Radius suitable for precise control.

The desired wheel diameter is found from the analysis of the Rover drivetrain.

Wheel Design A

The initial design of the Rover's wheel recognized and addressed the following Functional Requirements:

1. **Minimum weight**, since the machine's ability to climb the 45 degree section was unknown.
2. **Minimum width**; this is generally desirable to satisfy size constraints.
3. **Maximum contact pressure**, to reduce the effects of dust and debris on traction.
4. **Able to positively retain tread,** since treads that have slipped off are useless.

The resulting design is shown in Figure 2.12 on page 64.

Effect: In use, the treads slipped off these wheels too easily, evidently due to a crown profile that was too narrow. The wheel's profile was made narrow in the interest of saving weight and having high contact pressure between the rubber tread and the table to minimize the effects of dust and

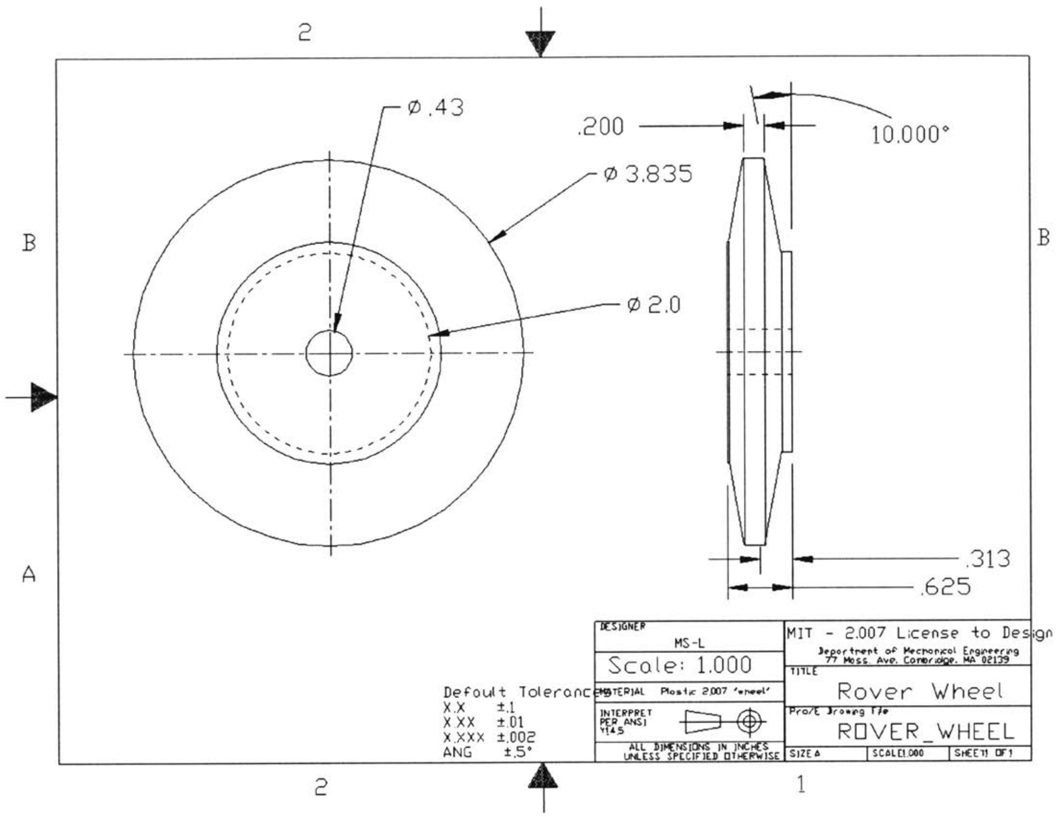


Figure 2.12 Drawing of Rover Wheel Model A.

debris on traction. The function of creating high contact pressure can be achieved with a simple crowned wheel, which approximates point contact. The perception that a narrow wheel would have a traction benefit was not well founded in this situation.

Wheel Design B

After the failure of the first Rover wheel design to retain the treads well, a modified wheel was designed to remedy the situation. This second version Rover wheel is referred to as Wheel B, and is shown in Figure 2.13 on page 65. It is similar to Wheel A in that it also is designed for use with treads to provide the all-wheel-drive effect. Notable features of Wheel Design B are:

- Same width as Wheel A
- Full width tread surface
- Crowned profile
- Same axle mounting geometry as Wheel A

- About twice as heavy as Wheel A.

The wheel's weight, which was a driving factor in the design of Wheel A was not such an issue, because by the time Wheel B was designed, it had been shown that traction was quite sufficient for climbing the 45-degree incline, even with a little extra weight. The primary factor contributing to the underestimate of traction in the early stages of design was the modest friction coefficient used for Buna-N rubber on the steel table. When the rubber treads were cleaned with alcohol and tested with a high contact pressure, the coefficient of friction with the steel table was found to be up to 0.8. The previously assumed value for the tread-table friction coefficient was 0.4 based on tests conducted with uncleaned rubber and lower contact pressures.

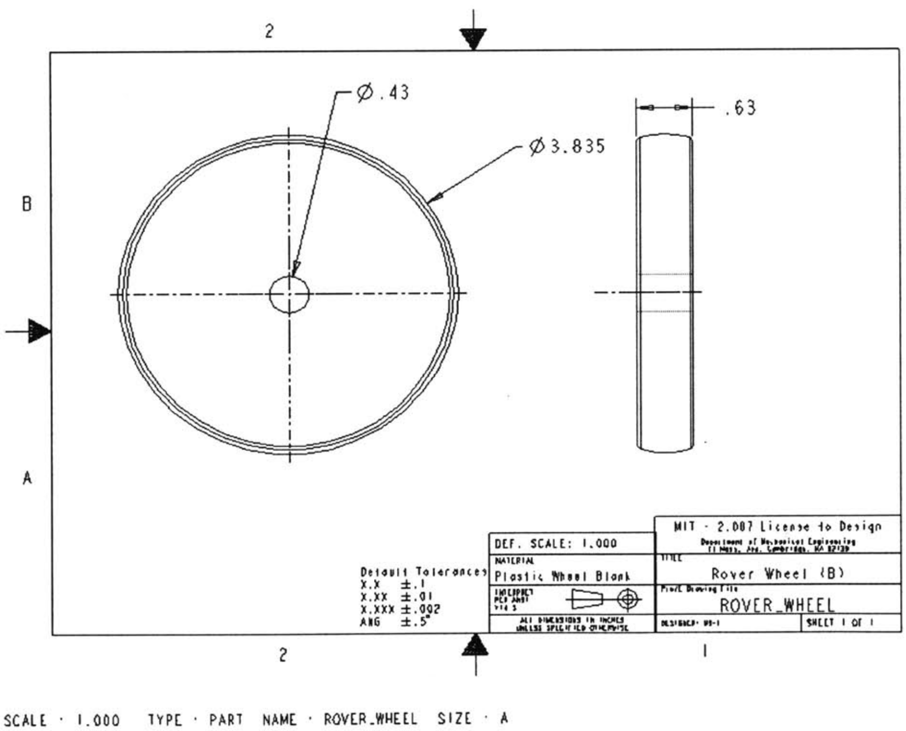


Figure 2.13 Drawing of Rover Wheel Design B.

Results of Using Wheel Design B

Wheel B works reasonably well, though treads are still lost occasionally when trying to rotate the Rover in place or when driving across one of the scoring holes. These maneuvers are very rare and should be completely avoidable in competition, as the Sample Machine generally will compete unopposed. However, there are some things that could help the current system be more reliable:

- More friction at wheel-tread interface
- Wider wheel
- More optimal crown geometry
- Higher tread tension.

The tank-style treads used in the Rover were chosen for their apparent simplicity, and under the assumption that they could be made to work reliably. If none of the above improvements can be harnessed to create a reliable Rover drive system, a different and altogether more robust drive concept can be considered. It is assumed that all wheels will still be driven in order to harness all available traction. Although it is possible that with a strategically placed center of mass and magnets it would be possible to succeed with 2-wheel drive, this opens a whole new set of problems. The problem of lateral forces on treads causing them to slip off may be solved by recognizing and decoupling the two dependent Functional Requirements addressed by the treads, which are:

1. Transfer drive power to undriven wheels
2. Act as traction surface.

Separating these, with one feature of the wheel addressing the transfer of motive power and an independent feature providing the traction, allows each function to be performed more optimally. Wheel design C, shown in Figure 2.14 on page 67, is a concept for an improved wheel for the Rover, to be manufactured and fitted if time allows. The Rover's motive module currently exists and functions, so effort should be focused on finishing a complete working machine before currently functional parts of it are redesigned for optimum performance.

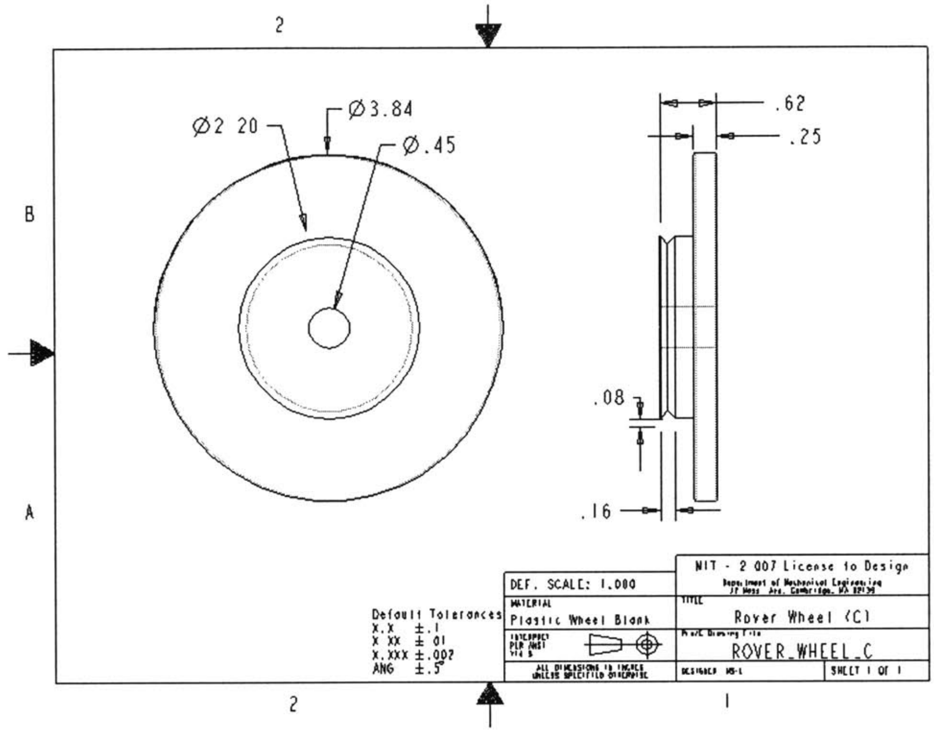


Figure 2.14 Drawing of Rover Wheel design C. Aimed at avoiding failure of Rover due to tread loss by using 4-wheel drive. (Note belt groove for transmission of drive power.)

2.3.4 Torsional "Suspension" for Rover

This section discusses the motivation for and design procedure of a chassis element for the Rover module that acts as a suspension. What is meant here by "suspension" is some system that allows compliance in the chassis specifically in order to allow the Rover's four wheels to stay in contact with the table surface. If the Rover had only three wheels, a suspension wouldn't be necessary, but all-wheel-drive would be more difficult, as would balance and avoiding hang-ups in the scoring holes. The final design and integration into the Rover for the torsionally compliant chassis joiner is visible in Figure 2.6 on page 51.

The Need for a Suspension

The Rover Module can benefit from a suspension system that allows its four wheels to stay in constant contact with the table, even over slightly rough terrain. The Rover uses treads to harness the benefits of all-wheel-drive. Due to its four wheels, it has effectively four points of contact with the surface on which it is driving. In the course of driving up the table it must traverse several 15-degree angles, and barring perfect driving, it may traverse these slope changes at a compound angle (i.e. not perpendicular to the joint). If the Rover had a rigid chassis, one wheel would have to leave the table when traversing a slope change non-perpendicularly. This would cause a problem because the magnet near that wheel would then be pulled farther from the table, resulting in a loss of traction-enhancing magnetism. Also, the work done in resisting the magnetic field by pulling the magnet away from the table would have to come from the drive system, making it momentarily less efficient.

Suspension Concept

The Rover's chassis is made from the stiffest isotropic (non-wood) sheet in the kit that is available in sufficient quantity: 0.21" polycarbonate. Several concepts for the incorporation of compliance to achieve a suspension effect were considered. The general principle to all concepts was similar: a flexural member that allows torsional compliance between the left and right half of the chassis. Among the concepts were several that involved simply thin beams of polycarbonate to allow torsional compliance with minimal bending in the vertical or horizontal planes. These concepts were flawed because the relative thinness of the resulting "torsional beams" possible created some torsional compliance, which was desirable, but also a similar degree of bending compliance, which was not. It was determined that a one-piece solution would not be adequate, and that the torsionally compliant beam would be a distinct part.

Selecting an Appropriate Beam Section

To make an effective suspension, a beam section should be explicitly chosen to have high torsional compliance as well as high bending stiffness. Knowing that open sections have relatively high torsional compliance, this is a good place to start. Then, taking bending stiffness and manufacturing ease into account, an L-beam comes to mind, and can be investigated with the goal of finding a solution that is "good enough." The shape of the final design for this part can be seen in

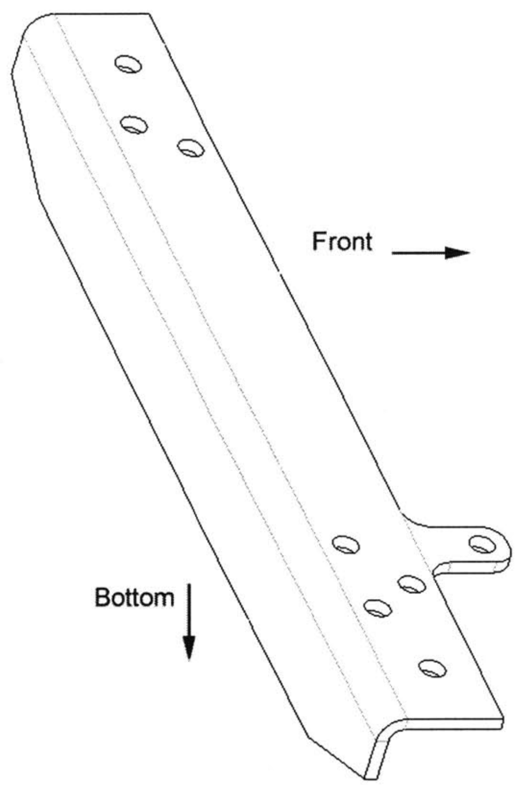


Figure 2.15 Torsion beam solid model part. Protrusion towards front is for mounting of hook support part. Total length is ~5.5"

Figure 2.15 on page 69. There are no definitive metrics that arise easily for determining how stiff the beam should be in bending in the two relevant directions, so it is assumed that symmetry will be acceptable. The stiffness that prevents "sagging" between the two chassis halves is deemed sufficient if it is greater than the stiffness of the solid sheet polycarbonate which would otherwise be there. A 3" wide by 3" long by 0.21" thick section of polycarbonate was the reference for the sagging stiffness—it was found that the torsion beam designed was 9 times stiffer. A numerical form of these calculations for stiffness can be seen in Figure 2.16 on page 70.

Material	AL 5052	
E	6.90E+10	**Pa**
Sigma y	1.60E+08	**Pa**
G	2.83E+10	**Pa**
Thickness	0.0625	**in**
	0.0015875	**m**
Beam Length L	3	**in**
	0.0762	**m**
Section length S	1.2	**in**
	0.03048	**m**
kT	1.51E+01	**Nm/Rad**

Figure 2.16 Spreadsheet excerpt for calculation of torsional stiffness.

Mathematical Model and Sizing of Torsional Beam

The torsional compliance should be such that the magnetic force at a wheel can keep that wheel in contact with the table by deflecting the torsion beam. Torsion depends on a force and a lever arm. The force used is that between one magnet segment and the table. Since most of the weight is in the front of the Rover, it is assumed that the rear wheel is most likely to be found in the air if there were no suspension. For this reason, the lever arm used is that from a front wheel to a rear magnet.

The location of the beam in the chassis is driven largely by packaging constraints. At the time of the design of the chassis, it is unknown exactly what the Rover-Puck Truck interface will be, but provisions are made in the chassis to allow the Puck Truck to reach the scoring hole. The chosen torsion beam location can be seen in the view of the CAD solid model of the Rover in Figure 2.6 on page 51.

The force between one magnet and the table varies greatly with fine-tuned positioning of the magnet. For this study it is assumed that 10N is a representative magnetic force. The moment arm is 6 inches. Next, a desired deflection is necessary to find the required torsional compliance. The four-wheeled, rigid Rover BLP is used on the table to determine what separation exists between a free-hanging wheel and the table for reasonable deviations form a straight-up-the-table course. It is observed that 1" would accommodate all but the worst driving contingencies, but anything over 0.5" will be sufficient for a reasonably practiced driver. Now an analytical model of the beam is needed to design its length, width and height to give suspension performance in the desired range.

Beam Stiffness and Stress

The theoretical torsional stiffness, k_τ, of an open thin section beam is based on the length of the beam, L; the material properties, G; the section thickness t; and the total section length s. Section shape is not a strong driver of torsional stiffness, but does enter to some extent in calculating stress.

$$k_\tau = \frac{st^3G}{3L} \tag{2.7}$$

Finding a beam geometry that is compliant enough in torsion is not the only thing that needs to be done—one must also verify that the desired deflections will not cause the beam to yield. The theoretical formulae for stress in the torsion of an open-section beam are not very exact, in that there are certain stress-concentrating factors in the geometry that are approximated. The formula used is:

$$\tau_{max} = \frac{Mt}{J} \cdot \text{geometry factor} \tag{2.8}$$ [1]

Where M is the applied moment, t is the section thickness as before, J is the section index $\frac{st^3}{3}$ that appeared in equation 2.7, and the *geometry factor* is empirical, representing the stress concentrating effects of bends and corners. In the case of a right angle bend with inside radius equal to the section thickness, Bickford gives a geometry factor of 1.4.

1. From *[Bickford]*

The above relations for stiffness and stress are entered into a spreadsheet to allow comparison of different materials and beam dimensions. It is found that the 5052 aluminum has a better ability to deflect in torsion before yielding than the steel sheet. Therefore, the choice is made for an aluminum L, and since there is only one thickness available, 1/16", those parameters are set. It remains to determine the length L and the section length s. The longer the beam, the more compliant it is, so L is made as large as practical in this case, 3 inches. Then the section length is adjusted until a satisfactory deflection under the applied load is found that is safe with respect to yield. The resultant deflection under load of the chosen geometry is 0.6".

Torsion		
Applied Force	10	**N**
Lever arm	6	**in**
	0.1524	**m**
Applied moment	1.524	**Nm**
Deflection (rad)	1.01E-01	**rad**
Deflection(deg)	5.786216954	**deg**
Deflection (in)	6.06E-01	**in**
Max stress in torsion		
J	4.06476E-11	**m^4**
Tmax torsion	59520119.04	**Pa**
Radius factor	1.4	
Adjusted Tmax	83328166.66	**Pa**
Tyield	1.40E+08	**Pa**
Stress Safety F.	1.68E+00	must be >1

Figure 2.17 Spreadsheet excerpt for stress in torsion for AL 5052 beam with beam geometry given in Figure 2.16 on page 70.

Finite Element Analysis

The simple analytical method of the previous section is more than sufficient for this type of design task, but it is interesting to compare the findings of the pencil and paper (and spreadsheet) to that of a Finite Element Analysis. In this case, the solid modeling software used to model the machine is associated with an FEA package called Pro/Mechanica. Though the FEA package used is integrated in the solid modeling software used, it was necessary to create an auxiliary copy of the torsion beam part specially simplified for the sake of the FEA. Results were achieved that relatively closely match the results given by the analytical formulae. A screen image of the model with load and constraint locations can be seen in Figure 2.18 on page 73.

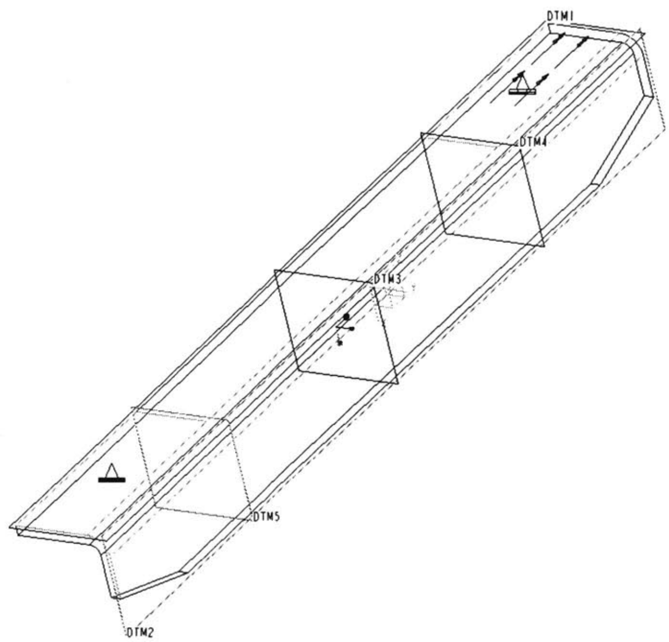


Figure 2.18 Pro/Mechanica FEA Model of Torsion Beam, showing L-shaped beam, datum planes, coordinate system, constraints and loads.

Features and simplifications of the FEA model:

- Constraint 1, towards the bottom of Figure 2.18, is applied to an area corresponding to the rectangular interface area between the beam and the chassis. In reality the connection is made by rivets and screws.
- A moment load is applied to the opposite interface area between the beam and chassis.
- A secondary constraint is added to the load region to keep it flat.

FEA Results

The displacement of the wheel predicted by the FEA under the applied load was 0.65" compared to 0.6" in the analytical model. The FEA model had some localized points of slightly higher stress than predicted by the analytical model, but the average maximum stress was relatively close to that predicted by the analytical model (144 MPa vs. 83 MPa). A screen image of the fringe plot showing stresses for the FEA model part can be seen in Figure 2.19 on page 74. Corresponding to the

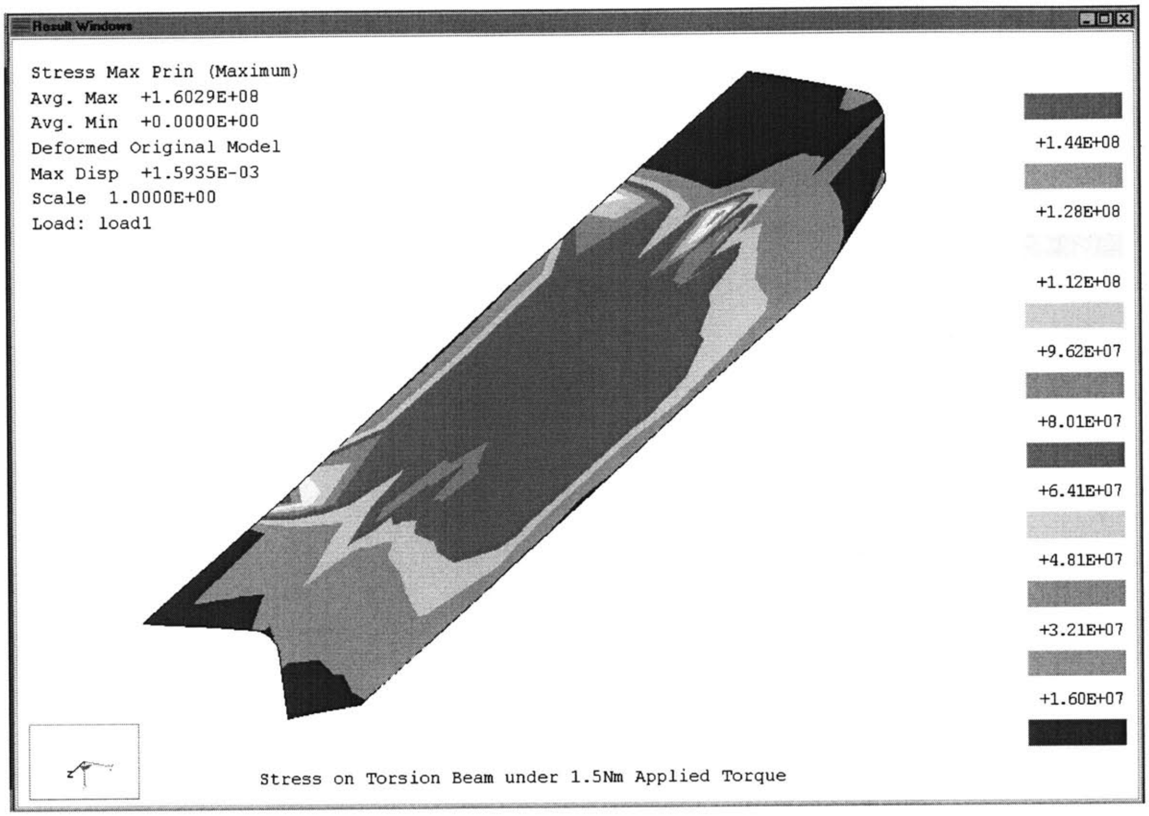


Figure 2.19 Stress And 100% scale deformation results from FEA Analysis.

stress amplification factor used in the analytical model, the FEA model shows the highest stresses in the area of the bend. There may be some high point stresses due to the manner in which the constraints and load were applied. For simplicity, the constraints and loads were evenly distributed about the flat rectangular area that is in contact with the bottom of the Rover's chassis. A more realistic model would constrain only a small disk around the screw/rivet holes, but this would be more complicated and prone to high contact-type stresses which we are not concerned about. (The material can yield a small amount near the rivets without causing a problem in this application.)

Testing

Before the final machine part was made, a test part was made out of scrap sheet metal to validate the results of the design. The test part was clamped to a table, a wooden arm and weight were used to apply a moment to one end of the part, and the deflection was observed to be very close to the expected 0.6". There was no observable yielding of the part, so the design theory was assumed to be validated and the design was finalized.

Deficiencies of Torsional Suspension

One minor deficiency of the torsion beam system is in the slight compliance and misalignment made possible by the mounting screw holes. If the screws are not tight enough, one chassis half can be rotated such that its tread is at a slight angle to the other side's, but only by some large force (usually from handling). If this is checked carefully and the screws tightened and threadlocked, there should be no problem.

2.4 Collecting 10 Additional Pucks

For the 1999 Contest, machines were allowed to start with up to 10 pucks loaded in the machine before the contest. There was also an opportunity to collect 10 additional pucks from a stack in the starting area. A view of the CAD model of the mechanism that was finally designed to collect the 10 additional pucks is shown in Figure 2.20. It is shown in action in Figure 2.21 on page 77.

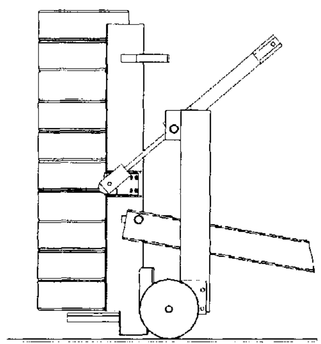


Figure 2.20 Puck Collecting mechanism side view from CAD model.

The vertical stack of 10 additional pucks was supported by a fixture that kept it 1" from the ground and prevented it from tipping over easily. The details of the location of this puck stand were not finalized until a week or two into the course. Together with the technical complexity involved in collecting, and combining the stacked and preloaded pucks into a common depositing system, this caused few students to include the additional pucks in their strategies. Some students did manage to collect the additional pucks effectively, but were not able to score as many points with them as those machine who hauled 10 pucks to the 5-point hole (of which there were about ten out of a class of 140).

In part because of the relative unpopularity of the collection of 10 additional pucks, this was chosen as a good task to use as an example. A sample method for collecting the stack of additional pucks could be covered in detail without providing too much of a prepackaged solution for those lacking the confidence to develop their own.

Figure 2.21 Photo Sequence of Puck Collecting Motion

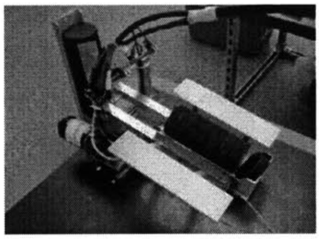


Figure 2.21a Starting configuration for test of puck collecting system.

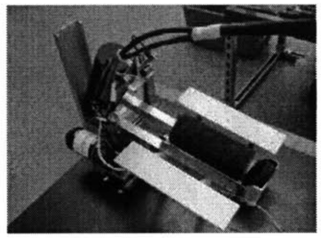


Figure 2.21b Cylinders Retracting.

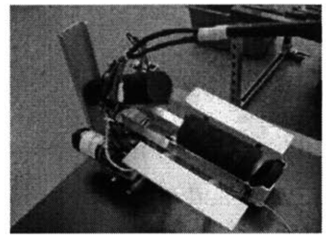


Figure 2.21c Moving through equilibrium position.

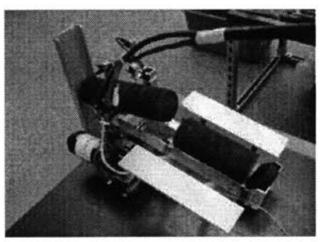


Figure 2.21d Overshoot of equilibrium position.

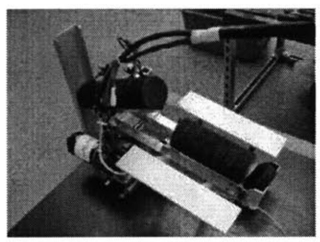


Figure 2.21e At rest at equilibrium position, ready to extend cylinders.

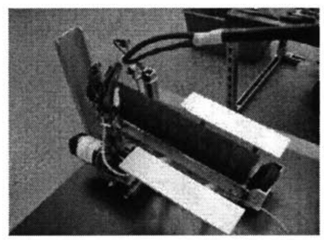


Figure 2.21f Cylinders extended. Collector mated to front puck tray.

2.4.1 Sample Mathematical Model for Collecting Pucks

The remainder of this section is taken primarily from a design example document that was distributed to students as a guide showing the general approach for developing their own mathematical models in problem sets 4 and 5. It was generated quite quickly, and meant to represent as directly as possible the real process used to study the kinematics of puck collecting, hence the hand sketches and handwritten equations.

Basic feasibility analysis:

How much work is required to collect the stack of pucks?

- Assume puck collecting module is a tilting forklift (Figure 2.22):,

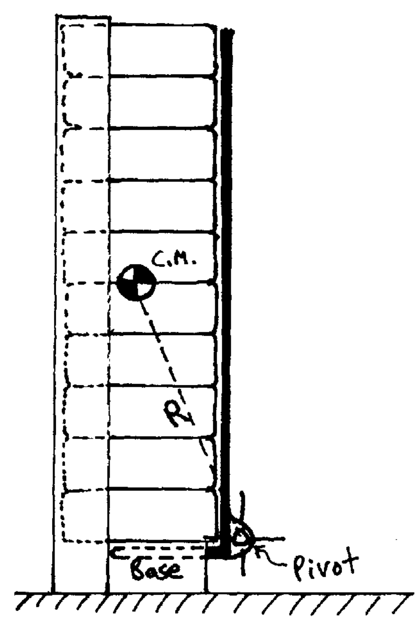


Figure 2.22 Generalized Puck Collecting Geometry

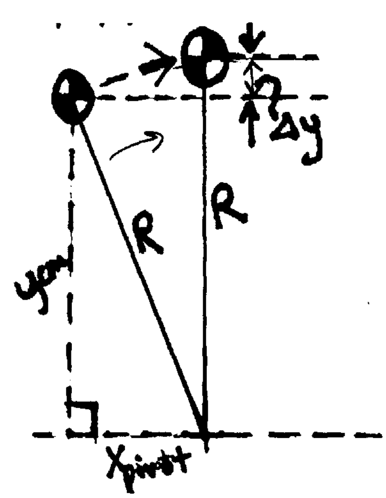


Figure 2.23 Sketch for potential energy change of stacked pucks.

This collection method requires a small increase in height of the pucks which requires a certain amount of energy. The geometric model used to calculate the work required to collect pucks is shown in Figure 2.23. Thinking ahead to possible Design Parameters that can provide the work for the task of collecting pucks, we can compare the amount of Energy required to the Work done by a

2.007 pneumatic piston in one stroke. Spreadsheet calculations for this inquiry are shown in Figure 2.24 on page 79. The result is that a single 2.007 pneumatic cylinder does approximately 9.5 times more work in one stroke than the minimum necessary to collect the stack of pucks. Keeping in mind that the real system may not be able to practically harness all of the available work, a specific method for collecting the puck stack can be sought.

Is DeltaPE of pucks < max piston work (one stroke)?		
Inputs		
Mass of puck	0.165 **kg**	
#pucks	10	
x_pivot	1.75 **in**	Horiz. Dist. to pivot from puck c.m.
Ycm	5 **in**	Vert. Dist. to puck stack c.m.
g	9.8	
Piston Force	27 **N**	(pull)
Piston Stroke	0.045 **m**	
Max Piston Work	**1.215 J**	one stroke
DeltaY	0.30 **in**	
DeltaY	0.008 **m**	
DeltaPE	**0.12 J**	
Ratio of work avail. to delta PE	**9.947**	**must be > 1**

Figure 2.24 Spreadsheet calculations showing that one 2.007 pneumatic cylinder can do enough work to collect 10 pucks in the manner shown in Figure 2.22 on page 78.

This specific method will need to be checked to verify that at all points within the motion there is enough force provided by the piston.

One possible way to harness a single cylinder for this task is sketched below in Figure 2.25 on page 80. The piston pulls horizontally at some height b, and when the stack of pucks crosses a critical point, it falls the rest of the way under the effect of gravity. It is straightforward to find the minimum value of b required to have enough force, and the maximum value of b to have enough piston stroke.

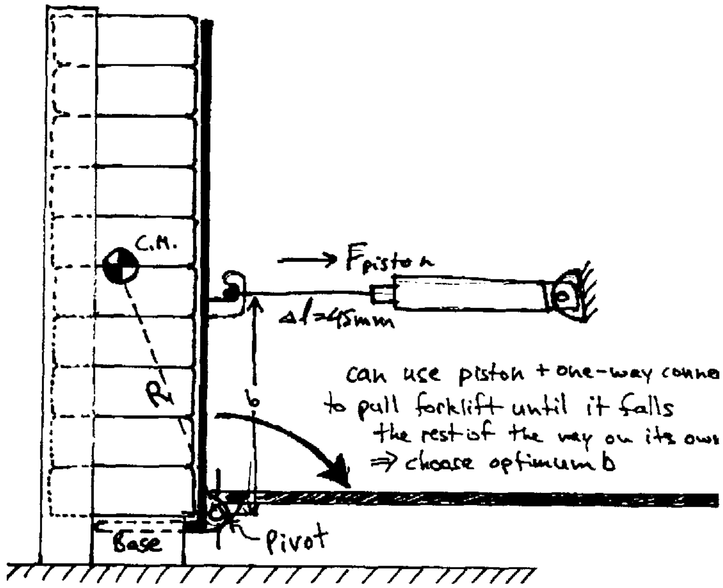


Figure 2.25 Horizontal arrangement of cylinder to initiate free fall of puck stack.

This method may be undesirable because of the free fall of the pucks.

Is there a method with greater control over the puck collector's motion?

Functional Requirement: motion should be calm and under control

--> Keep piston connected at all times-- flow controls can be used to control fall of pucks.

One alternate possibility to the free fall of the puck stack is shown in Figure 2.26 on page 81.

We can use a mathematical model of the generalized puck collection problem to try to answer the question: *Is this the best way to do it?*

The next step is to construct a general geometry/physics model and use a spreadsheet to optimize the function of the mechanism. Figure 2.27 shows the generalized model for the geometry and motion of the puck collector used in developing the spreadsheet model.

The equations that define the model for the geometry (kinematics) are shown in Figure 2.28: Theta is defined (see Figure 2.26 on page 81) as the counterclockwise angle of the long edge of the puck collecting forklift from the horizontal.

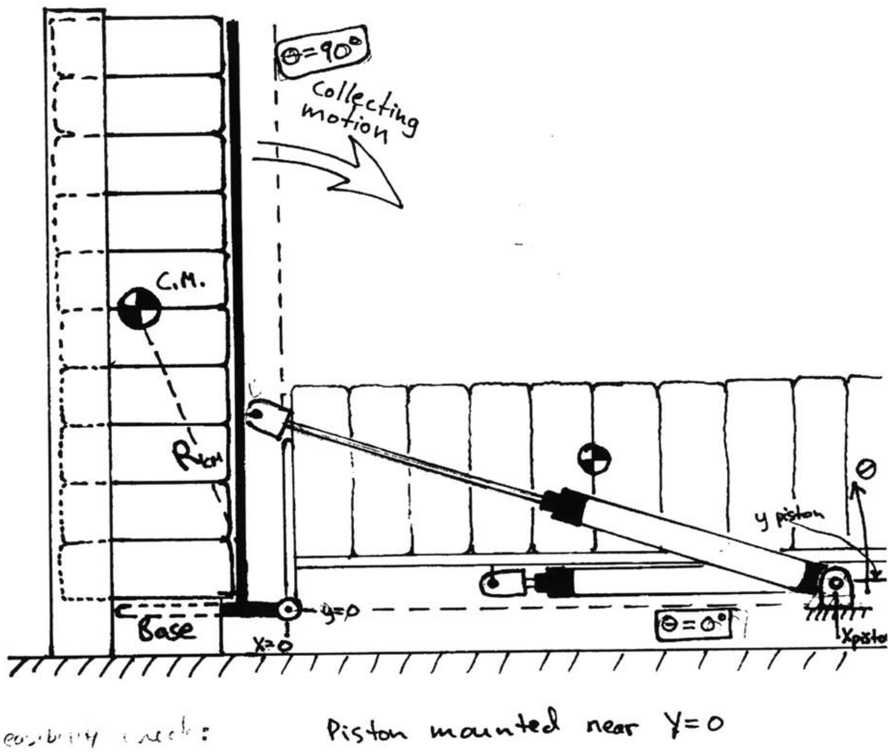


Figure 2.26 Puck collecting cylinder located to avoid free fall of puck stack.

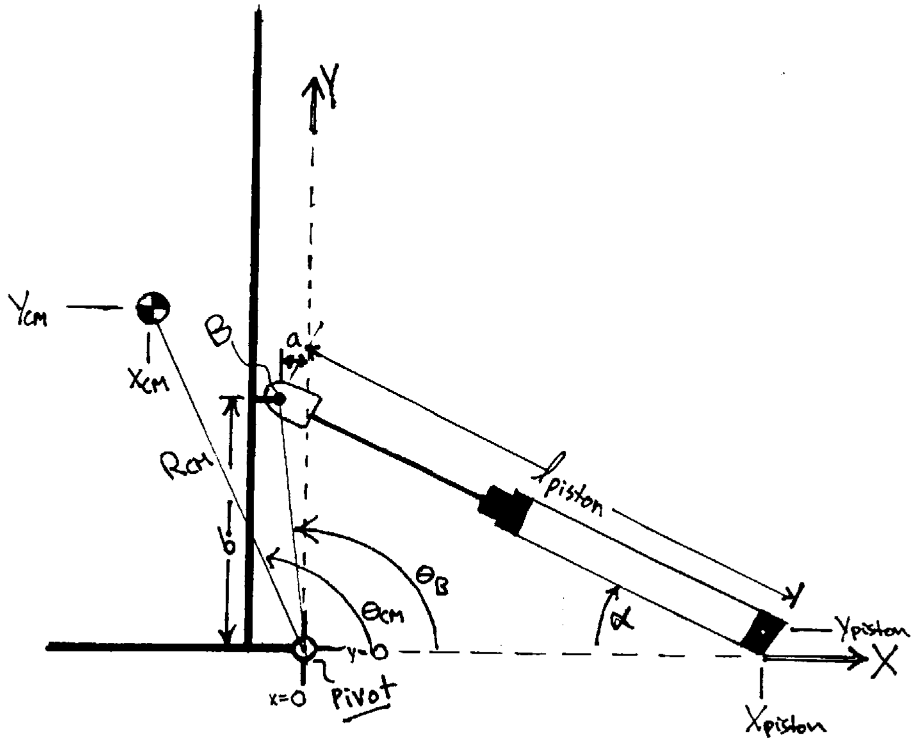


Figure 2.27 Sketch and dimensions for calculations for puck collecting arrangement shown in Figure 2.26 on page 81.

X_{CM_0} – original X-coordinate of Center of Mass of Pucks ~ –2″

Y_{CM_0} " Y-coord. ... $\boxed{Y_{CM_0} \approx 5''}$ $X_{CM_0}\boxed{= -50.4\ mm}$

$$R_{CM} = \sqrt{y_{CM_0}^2 + X_{cm_0}^2}$$

puck collector angle Θ:

$$\Theta_{oCM} = \tan^{-1}\left(\frac{X_{cm_0}}{Y_{cm_0}}\right)$$

$$\boxed{\begin{array}{l}\Theta(t=0) = 90^\circ \\ \Theta(t_f) = 0^\circ\end{array}}$$

$$\Theta_{CM} = \Theta + \Theta_{oCM}$$

Figure 2.28 Sketched equations and specified parameter values for analysis of puck collecting with connected horizontal cylinder arrangement as in Figure 2.26 on page 81.

a - original x-coord. of piston attach point } wrt pivot point
b - " y-coord. " " " "

$$R_B = \sqrt{a^2 + b^2} \qquad X_B(\theta) = R_B \cos\theta_B$$

$$\theta_{oB} = \tan^{-1}\left(\frac{a}{b}\right) \qquad Y_B(\theta) = R_B \sin\theta_B$$

$$\theta_B = \theta + \theta_{oB}$$

$$X_{CM}(\theta) = R_{CM} \cos\theta_{CM}$$

$$Y_{CM}(\theta) = R_{CM} \sin\theta_{CM}$$

Figure 2.29 Sketched relations for puck stack center of mass and cylinder attachment point motions.

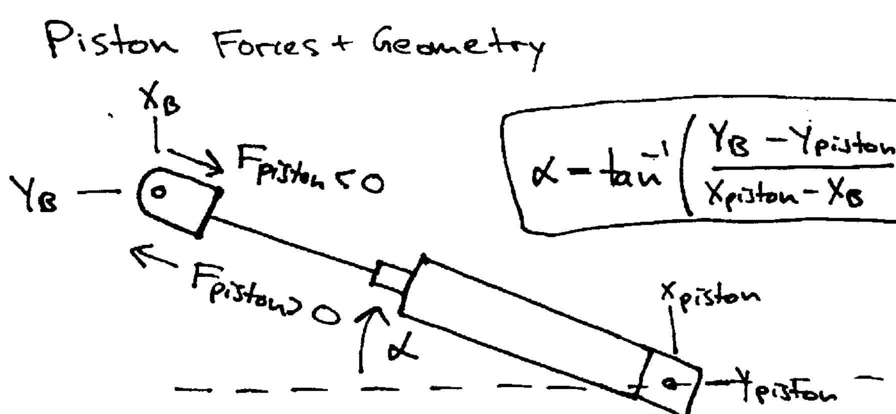


Figure 2.30 Piston Forces and Geometry

The kinematic relations from the model geometry are entered into a spreadsheet...

(Figure 2.31 and Figure 2.32)

Collecting 10 pucks using a tilting forklift

INPUTS	***value***	***units***	***coordinate system: pivot point is (0,0)***
constants			y is + vertical up
weight of 10 pucks	1.65	**kg**	x is + horizontal right
g	9.8	**m/s^2**	
Piston Force @60ps	27.1	**N**	
Lpiston ext	80	**mm**	extended length between mounting hole and clevis hole (.173) (.065)
stroke	45	**mm**	
~constants			
Xcmo	46.74	**mm**	Initial Horizontal distance from pivot to Center of Mass of pucks
Ycmo	51	**mm**	Initial Vertical distance from pivot to Center of Mass of pucks
minor parameters			
a	-35	**mm**	X-position of piston connect point B (note if B to left of pivot, a<0)
Theta	not here, but in series below- values from 90 to (90-puck_tray_angle)= -1(		
pressure	60	**psi**	
key variables:			
b	30	**mm**	vert. Distance from pivot to piston connect point B
Ypiston	77	**mm**	height of piston mount relative to pivot

Intermediate Calculations

Xpiston	29.74	**mm**	Driven by location of B, Ypiston and condition that at theta=90,		
Piston Force	27.1	**N**	at	60 **psi**	piston is fully extended
Lpiston min	35	**mm**			
ThetaCMo	0.742	**rads**	42.5019 **degrees**		
rCM	69.18	**mm**			
ThetaBo	0.862	**rads**	49.3987 **degrees**		
rB (m)	46.1	**mm**			

Remaining Calculations are functions of Theta

Figure 2.31 Spreadsheet calculations for puck collecting with generalized cylinder arrangement as in Figure 2.43 on page 94. The values in this view of the spreadsheet are for the final design.

Remaining Calculations are functions of Theta								
Theta (deg)	90	85	80	75	70	65	60	55
ThetaCM (deg)	132.5	127.5	122.5	117.5	112.5	107.5	102.5	97.5
ThetaB (deg)	139.4	134.4	129.4	124.4	119.4	114.4	109.4	104.4
Ycm(theta) (mm)	51.0	54.9	58.3	61.4	63.9	66.0	67.5	68.6
Xcm(theta) (mm)	-46.7	-42.1	-37.2	-31.9	-26.5	-20.8	-15.0	-9.0
Yb(theta) (mm)	30.0	32.9	35.6	38.0	40.2	42.0	43.5	44.6
Xb(theta) (mm)	-35.0	-32.3	-29.3	-26.0	-22.6	-19.0	-15.3	-11.5
alpha (piston angle)	36.0	35.4	35.0	34.9	35.1	35.7	36.7	38.1
Lpiston(theta) (mm)	80.0	76.1	72.1	68.0	64.0	60.0	56.2	52.4
Stroke(theta) mm	45.0	41.1	37.1	33.0	29.0	25.0	21.2	17.4
puckTorque N-mm	510.6	414.6	323.0	238.5	163.8	101.2	52.4	19.1
puckTorque N-m	0.51	0.41	0.32	0.24	0.16	0.10	0.05	0.02
req'd piston F (N)	**-11.4**	**-9.1**	**-7.0**	**-5.2**	**-3.6**	**-2.2**	**-1.2**	**-0.5**

Figure 2.32 Spreadsheet data calculating motion of final puck collector design, as in Figure 2.43 on page 94.

We can use some simple results to check the validity of the model (Figure 2.33):

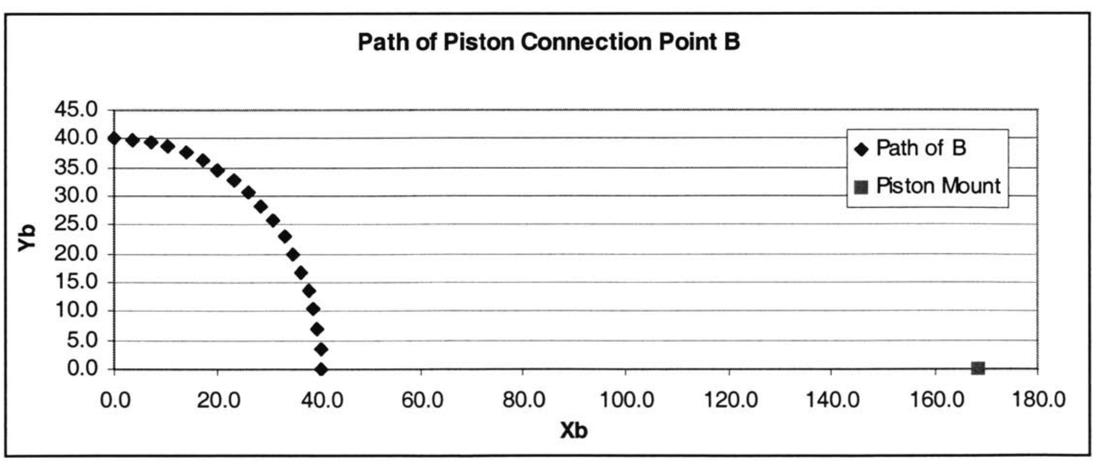


Figure 2.33 Plot of spreadsheet-calculated path of piston attachment point B for arrangement as in Figure 2.26 on page 81.

This shows that, indeed, the point B is rotating about the pivot point (0,0) which signifies that the kinematics model is not completely wrong.

What effect does the motion of the piston attachment point B have on the piston? (see Figure 2.34)

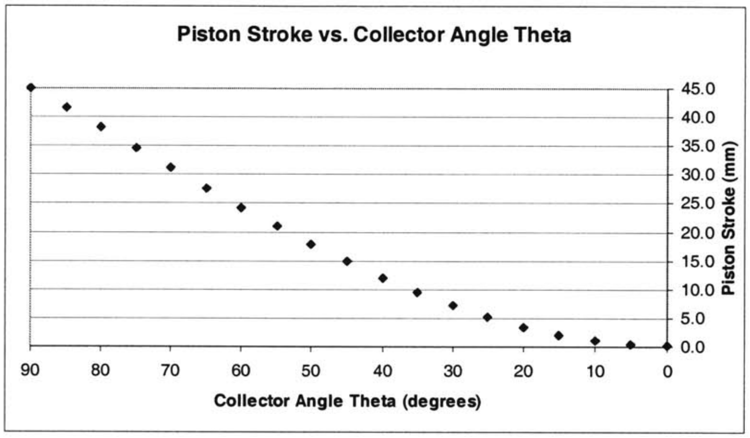


Figure 2.34 Relation between cylinder stroke and puck collection mechanism motion for cylinder located as sketched in Figure 2.26 on page 81 and Figure 2.27 on page 82.

Just the geometry is not enough to check-- Does the piston have enough force when needed?

Torque balance: The torque balance about the pivot point is shown in Figure 2.35.

$$\sum \vec{\tau} = 0$$

watch

$$\Rightarrow \tau_{CM} = -\tau_{piston} \quad \text{(sign convention)}$$

$$\vec{\tau} = \vec{r} \times \vec{F} = r \cdot F \cdot \sin\gamma$$

Figure 2.35 Sketched equations for generalized moment balance about puck collector pivot point.

The torque about the pivot point due to the pucks is derived in Figure 2.36:

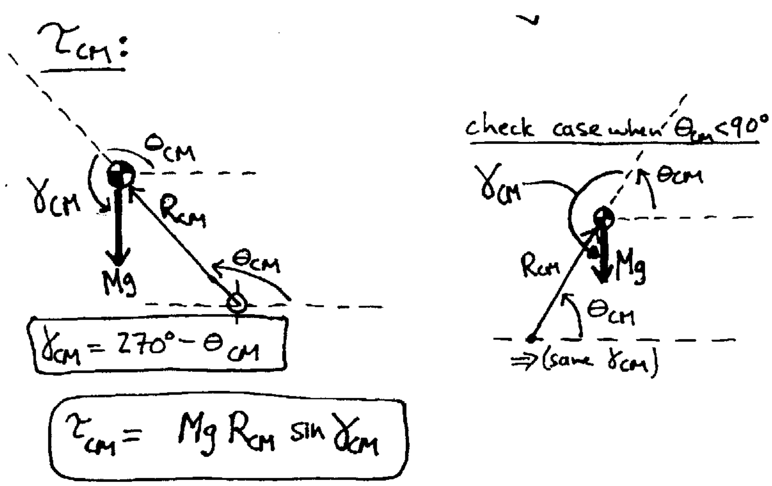
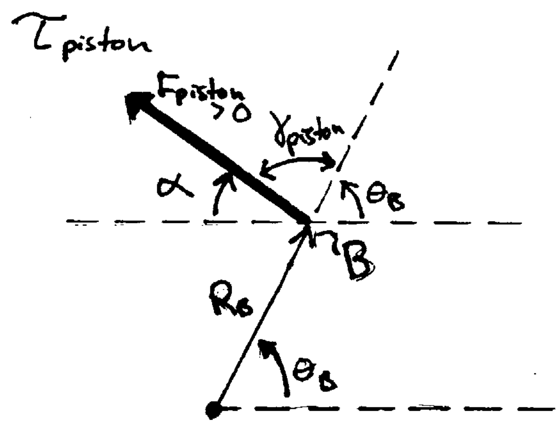


Figure 2.36 Sketched equations for moment about puck collector pivot point due to stack of pucks (acting at center of mass of stack).

The torque about the pivot point due to the Piston is found in Figure 2.37.:



$$\boxed{\gamma_{piston} = 180° - \theta_B - \alpha}$$

$$\boxed{\tau_{piston} = R_B \cdot F_{piston} \cdot \sin \gamma_{piston}}$$

since $\tau_{piston} = -\tau_{CM}$

$$\Rightarrow \boxed{F_{piston} = \frac{-\tau_{CM}}{R_B \sin \gamma_{piston}}}$$

Figure 2.37 Sketched equations for moment about puck collector pivot point due to piston force.

Figure 2.38 plots the force required from the cylinder to initiate (f<0) and then counter the fall

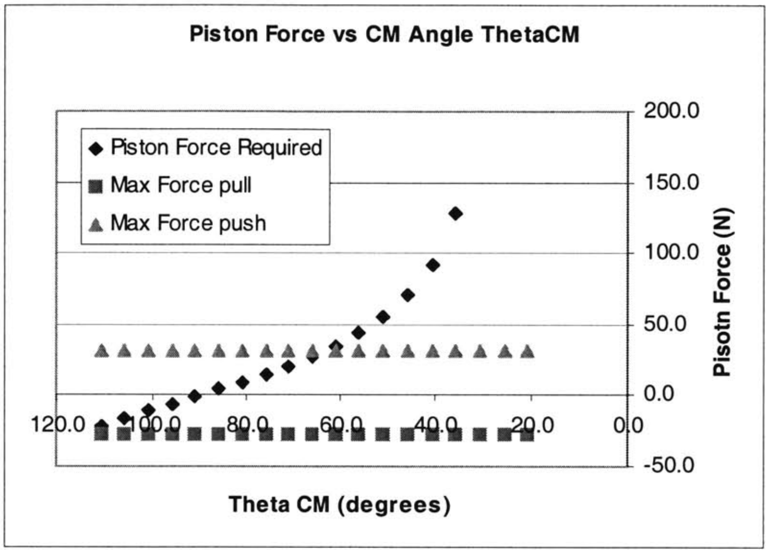


Figure 2.38 Force required from cylinder to counteract fall of puck stack under the influence of gravity for the case where piston's final position is horizontal (Ypiston = 0, Figure 2.26 on page 81).

(f>0) when the piston is located as sketched in Figure 2.26 on page 81

The piston just barely has enough force to start the pucks tipping, then the force on the piston becomes quite large as the collector settles to horizontal. The question arises: *Is there a different arrangement that allows for a "softer" landing?*

Tweaking the parameters b and Ypiston, (Figure 2.39 on page 90) we find a piston placement such that the piston is pulling directly to the right at the beginning, and directly up at the end of the collection motion:

The path of the attachment point and the piston's pivot point are plotted in Figure 2.40 on page 90. Note that for this option, the piston is pivoted at the "nose," and it may be necessary to position the piston off-center to allow the pucks to fall past its mounting point.

Lpiston ext	65 mm	extended length between mounting hole and clevis hole (.
key variables:		
b	60 mm	vert. Distance from pivot to piston connect point B
Ypiston	60 mm	height of piston mount relative to pivot

Figure 2.39 Spreadsheet excerpt showing parameters adjusted to find alternate Piston arrangement

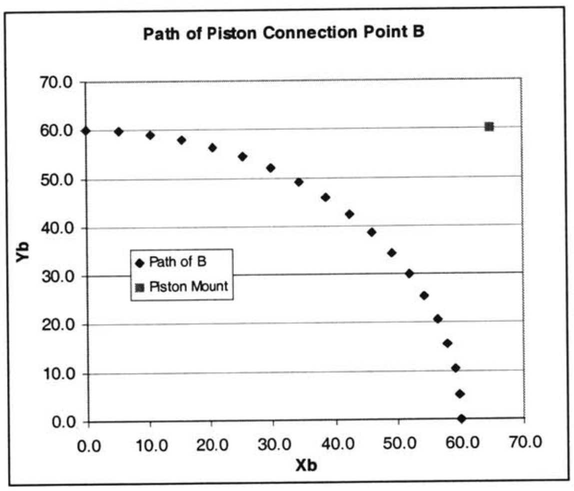


Figure 2.40 Nose-mounted piston pivot point and path of piston attachment point B.

Figure 2.41 on page 91 shows the piston stroke during the motion of the puck collecting system with the cylinders positioned as in the final design shown in Figure 2.43 on page 94. Figure 2.42 on page 92 plots the force required from the cylinder to initiate and then resist the fall of the puck collector for the final design configuration. Although one cylinder is sufficient, the model predicts that if 2 cylinders are used, they will be able to restrain the fall of the stack all the way, keeping the stack in a sort of equilibrium position. As soon as the loaded puck collector's center of mass is past vertical, the piston still has some small lever arm and is still able to pull the collector further. When the piston has reached its minimum length, the puck collector's center of mass will be located such that it will tend to fall and complete the motion under gravity. At this point, extending the cylinders by reversing pressure will push the collector to its final position. This motion can be controlled and slowed by using the exhaust flow control valves to limit the extension speed of the cylinders. In practice, this proved to be a very reliable, but also a very critically balanced system. if one puck is left off the top of the stack, the center of mass of the stack is shifted by 1/2" and the collector is no longer able to move past the cylinder's point of minimum length. The system works very well as designed, but if it didn't, weight could be added to move the center of mass of the loaded collector to an appropriate location. Because it predicts the change in the change in the mechanism's behavior, the spreadsheet model can be used to find a desirable center of mass location.

So the mathematical model has been used to predict with high certainty that the chosen design will

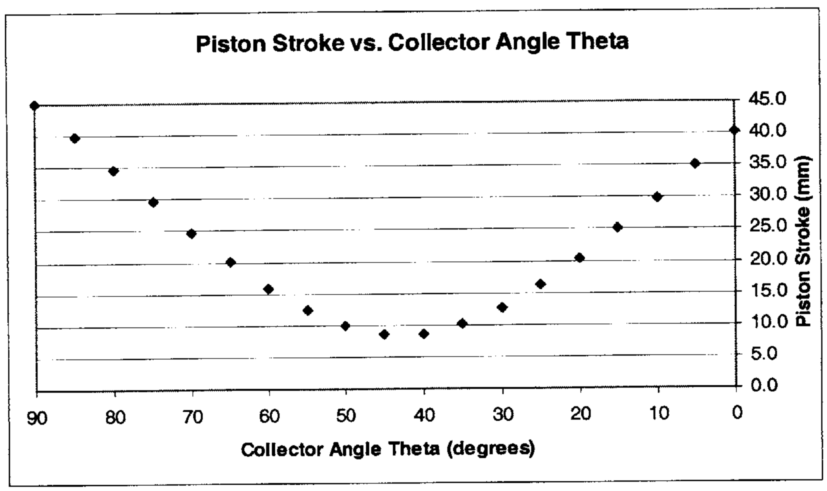


Figure 2.41 Piston stroke during puck collecting motion for piston mounted at nose.

function well enough. It will certainly be better than the two other options considered.

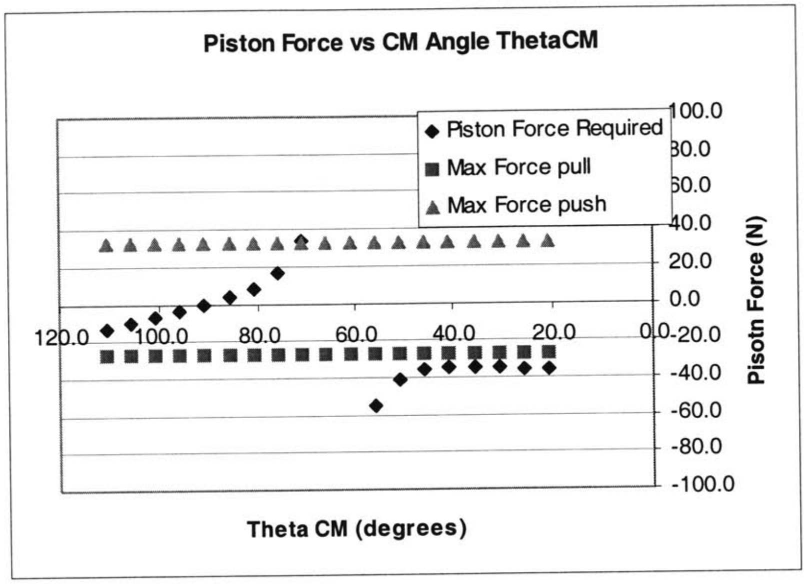


Figure 2.42 Plotted relation between motion of puck collector and force required from cylinder.

Packaging Requirements

It was initially assumed that the pivot point would be located at the bottom corner of the puck collector's tray. However, due to the required protrusion of the puck pusher, the configuration sketched previously wastes valuable starting configuration length, which could be better used to accommodate more pucks in the front tray. When the pivot point is located above the table, and therefore offset from the end of the collector tray, the starting configuration length is reduced by the amount of this offset. Fortunately the mechanism model for the puck collector is very generalized and allows the calculation of the effects of a larger pivot height. A fine balance must then be struck between space saving and mechanism function and reliability, because as the pivot point moves higher and saves more space, the angle of rotation required before the tray's center of mass falls through the mechanism inversion point increases. The mechanism model shows the reduction in gravity-induced moment on the laden puck collector compared to the previous case, where the center of mass of the pucks and collector was located at a much higher point relative to the pivot, and was more inclined to fall on its own after a short pull past a critical angle of approximately 25 degrees. The new space-saving configuration requires a critical angle of nearly 50 degrees to be reached before the puck stack will continue to fall under gravity and push the mechanism through its inversion point.

The Final Puck Collecting System Design

The final design is shown in different stages of the puck collecting motion in Figure 2.43, Figure 2.44 and Figure 2.45. The stroke of the pneumatic cylinders throughout this motion is shown in Figure 2.46 on page 95. The associated force required to effect the motion is shown in Figure 2.47 on page 96.

Conclusion

The Puck Collecting Module represents an interesting design case study. The collection method chosen is very sensitive- it just barely works, but it can be proven that it will just barely work. Because of this sensitivity, many of the parameters governing the operation of the puck collector changed often. The puck collector's exact geometry was important to the function of the CAD solid model of the machine, as the collector need to start vertically in a certain position, and when pivoted to its final position must align and mate with the stationary front puck tray. The handling

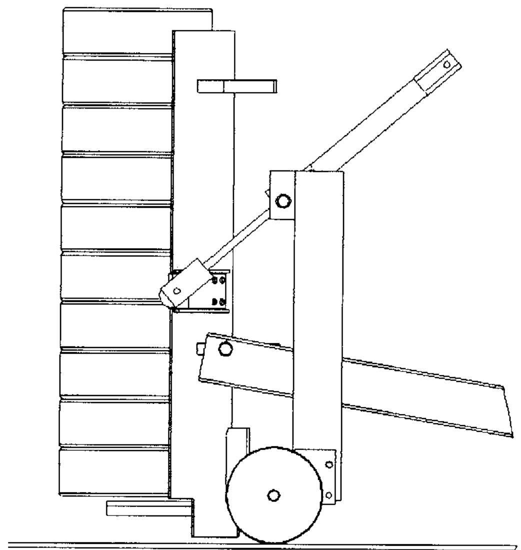


Figure 2.43 Starting Configuration of Puck Collection Module.

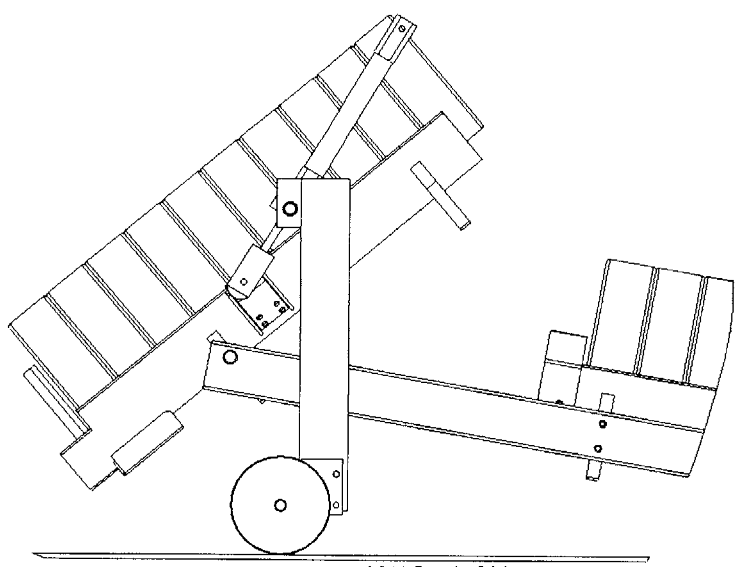


Figure 2.44 Intermediate position of Puck Collecting Module.

of these complicated constraints benefits greatly from a realistic CAD model, as was developed for this machine. Using relations that drive the location of datum planes in the model, parameters of the collection system are given to the CAD software directly from the spreadsheet. Thus the mech-

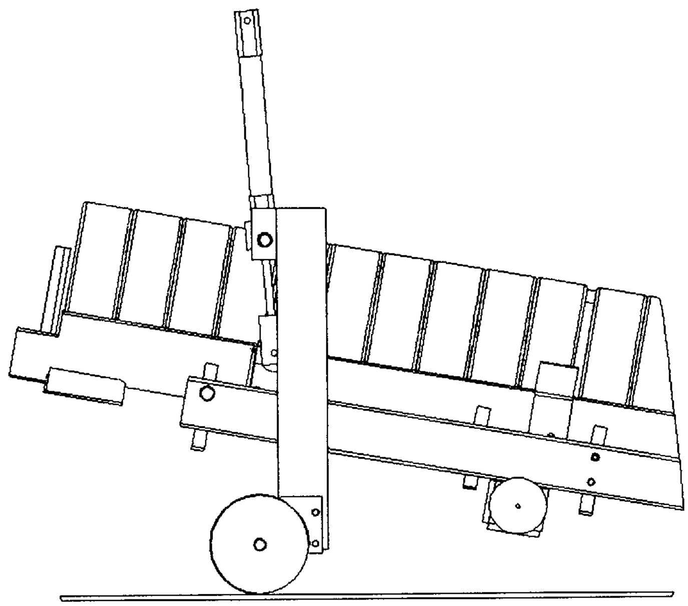


Figure 2.45 Final position of Puck Collecting Module after piston extension from intermediate equilibrium position.

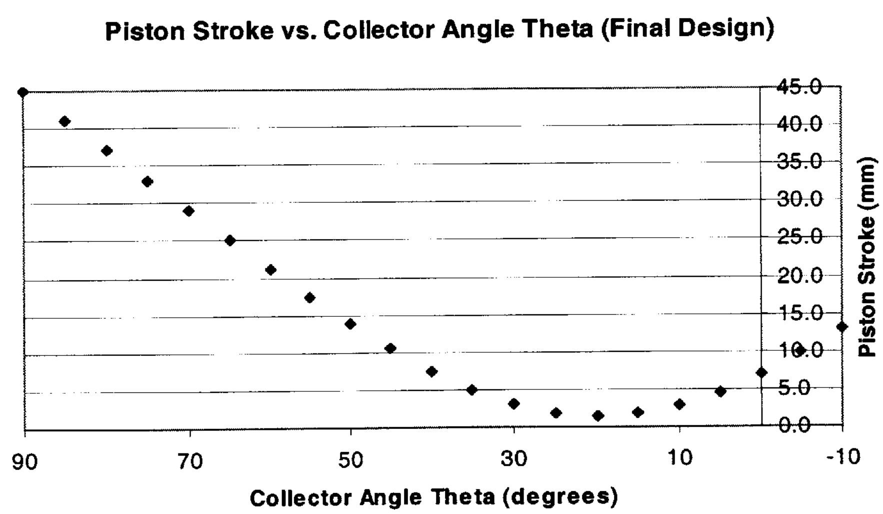


Figure 2.46 Motion of cylinder as a portion of its total stroke while collecting pucks.

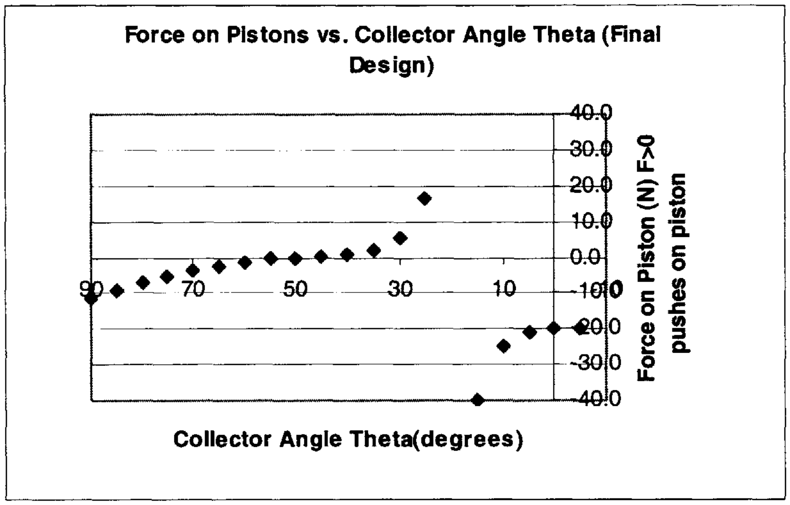


Figure 2.47 Force required from puck collecting pistons. Two pistons used with a combined maximum force of 52N.

anism's performance can be adjusted slightly, and though it requires a manual cut-and-paste operation, the same exact changes can immediately be reflected in the CAD model, and there is no real penalty for repeated adjustment and refinement.

2.5 Design of the Puck Truck Ascending Winch

This design case represents a departure from the pure ideal of optimized design, due to consideration of constraints imposed by the contest (limited materials and time available). This is not necessarily a departure from the real world of design, as there are certain standard sizes of machine components available, not always the exactly optimal size or configuration. The general design process takes the components available into account, and attempts to avoid complexity unless absolutely necessary. The resulting approach is set up to answer the question "will this solution be good enough?" instead of "what is the ideal solution?"

In the chosen strategy, pucks are delivered to the scoring hole by a cargo carrying module called the Puck Truck. It collects, stores, transports and deposits the pucks. An important part of the strategy (described in Section 2.2.1 on page 45) is that the Puck Truck is not self-propelled, but rather winches itself up the incline of the contest table using a string planted securely over the top edge of the table by the Rover module (covered in Section 2.3 on page 51). The Puck Truck then ascends the table by winch, mates with the Rover, which is positioned over the scoring hole, and deposits its load of pucks.

2.5.1 Motor Selection

The selection of a motor for the task of winching the puck truck to the top of the table is the first step in designing the ascending winch system. With a limited set of motors available and multiple motorized systems to design, the choice is not limited only to considerations within the Puck Truck winching system. It is assumed that the Bosch motors will be used for the Rover, as they are the most practical to use for wheeled vehicles and have appropriate power for that task.

Required Power

Without knowing very many details about the final design of the Puck Truck, it is nonetheless desirable to evaluate the approximate power that will be required to run the winch system. A simple first-order model for the power required to move the Puck Truck up the incline can be taken from the work that must be done to bring the Puck Truck from its starting position to its position near the scoring hole. That is, it undergoes a change in elevation, therefore a change in potential energy, which requires work. A time over which that work is done yields an average power that must be input:

$$\text{Average Power} = \frac{\Delta PE}{\Delta t} \tag{2.9}$$

The change in Potential Energy undergone by the Puck Truck is

$$\Delta PE = mg\Delta h \tag{2.10}$$

The Puck Truck weight, *mg,* is found by noting that a load of 20 pucks weighs 32N, and estimating that the weight of the structure and motors will equal this figure, for a total weight of approximately 65N. (See footnote on page 99 for a better model.) Further, the change in height between the initial and final positions of the Puck Truck's center of gravity can be found by measuring the table, yielding a conservative (high) value for the change in height of 40" or 1m. The time over which the power source must do the specified amount of work must be less than the maximum allowable time for this segment of the machine's action—15 seconds. However, to be conservative, it should be noted that under real conditions it is not likely that completing the winching task in 15 seconds will correspond to 15 seconds of maximum average power-- there is the matter of docking to the Rover module, for example. So the selection criterion is that the motor chosen must be able to deliver at least the calculated required power, with a comfortable safety margin.

The minimum required power is

$$\text{Average Power Required} = \frac{65N \cdot 1m}{15s} = 4.33W \tag{2.11}$$

but this is the required OUTPUT power of the system and it is certain that 100% efficiency will not be achieved. There will be losses in the wrapping of string around the pulley itself, as well as friction between the string and any guides necessary to route the string along an appropriate path inside the machine. An estimate is made that in order to power the winch system, a motor must be able to supply at least 25% more power than that required as output. That is, the motor must be able to be used in an 80% efficient system and still produce the required output power.

$$\text{Required Motor Power} = \frac{\text{Output Power}}{\text{predicted } \eta} = \frac{4.33W}{0.8} = 5.4W \tag{2.12}$$

TABLE 2.3 Properties of motors available for use in ascending winch system.

Motor	Stall Torque (Nm)	No Load Speed (rpm)	Max. Power (W)	Mass (kg)
Ford (black and yellow leads, clockwise rotation)	7.5	81	15.9	1.4
Black and Decker with gears (5V)	0.83	200	4.34	~0.2
Geared Maxon	0.32	580	4.9	~0.2

Other Factors Involved in Motor Selection. In order to be able to acknowledge explicitly some of the non-numerical factors that may go into the selection of the motor for this system, it is a good idea to consider the system's overall Functional Requirements.

The Puck Truck winch system must:

- Winch Puck Truck to top hole in as little time as possible, must be <15s
- Fit within the size constraints
- Be easy to manufacture
- Be robust
- Be reliable
- Not negatively affect stability of Puck Truck (center of mass location)
- Not damage Rover or Puck Truck when a hard stop is reached.

Dismissing Direct Drive Motors. Making the judgement that without a custom geartrain (undesirable added complexity and manufacturing effort), the small direct drive DC motors will lack the torque required for this task, one is left with three motor options: the Ford windshield wiper motor, green Maxon gearmotor, or Black and Decker screwdriver motor with gearbox.

Dismissing Geared Maxon and Black and Decker Motors. As seen in Table 2.3 on page 99, the geared Maxon motor is not quite powerful enough to complete the task. Even if the assumptions are scrutinized and the estimated weight of the Puck Truck is reduced to account for the lighter motor[1], there will be an insufficient margin of safety with respect to power to accom-

1. This points out that a better procedure here would take the motor's weight into account in determining the power needed from different motors. Still, the heaviest motor is only about 25% of the final Puck Truck weight, and the discovery of a better model after the fact just highlights the nature of design.

modate design freedom and any system inefficiencies. The Black and Decker motor clearly has insufficient power at 5 Volts. Using the Black and Decker motor on the 12V circuits would give it about twice the power, but is undesirable because the motor is wound for 3.6V, and already shows signs of excessive brush wear and overheating when driven at 5V and moderately loaded. The general robustness and suitability of these motors was found to be questionable, though some students managed to use them very effectively, even at 12 Volts.

Selecting Ford Motor. The Ford motor is chosen because it easily has enough power, allowing freedom in design because efficiency is not critically important. The design freedom allowed by a generous excess of power will play a role later in the design of the winch pulley. The references to lead wire color and direction of rotation in the entry for the Ford motor in Table 2.3 are necessary because the motor is designed for efficient operation in one direction only, and has different speeds based on the input leads used. The data in Table 2.3 are for the configuration with the highest speed.

2.5.2 Winch Design and Mathematical Model

The steps in the design of the winch to harness the selected Ford motor are shown in Figure 2.48 on page 101. The diameter of the winch pulley turns out to be critical; the largest diameter round stock remaining in the kit after the Rover wheels have been made is just barely large enough to pull the Puck Truck to the top of the table quickly enough. One early design concept considered to increase the speed of the pulley system was the use of the 24 pitch nylon gears supplied in the kit. However, past modeling of the stresses on the gear teeth by a student found that even two gears harnessed side by side would fail at the Ford motor's maximum torque. Therefore, the mathematical model (depicted in Figure 2.49 on page 102) was set up to verify whether or not the simple mechanical design concept would be good enough, rather than trying to find a more difficult-to-implement optimum solution. Note that an advantage of using mathematical models in spreadsheet format is that the model can easily be rearranged slightly to find the optimum design.

Detailed Mathematical Model

Once a motor is selected, it becomes easier to develop a more complete mathematical model of the Ascending Winch system. The weight of the Puck Truck can be estimated with more certainty, and one can begin to work on the mechanical details of mounting, packaging, and integration in the

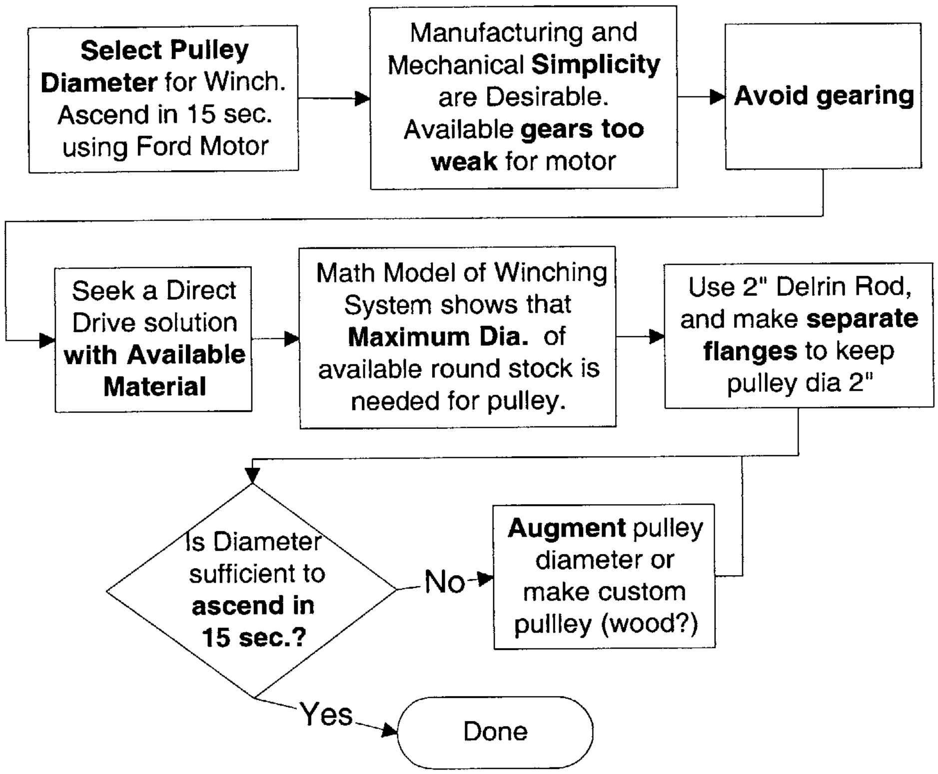


Figure 2.48 Process used to select pulley diameter for Ascending Winch

concurrently-developed solid (CAD) model. As the CAD model becomes more detailed and complete, it may lead to further refinements in the mathematical model, such as better estimates of efficiency and weight.

One slightly complicating factor in the model is the fact that the force required to pull the Puck Truck was initially calculated as if it would be parallel to the table's surface. In reality, the winch cord is at an angle with respect to the table's surface, because it is anchored at the top of the table. Figure 2.50 on page 103 shows a dimensioned side view of the table. Simple trigonometry is used in order to make the transition from force required parallel to the table surface to tension required in the string (which is really what the winch produces). The relatively small effects of this calculation can be seen in Figure 2.49 on page 102.

Evaluation of Ford motor for ascending winch						
Black and yellow wires, clockwise...						
Stall torque	7.5				**Nm**	
No Load speed	8.482	**rad/s**	81 **rpm**			
Max. power	15.9	**Watts**	Assumes linear torque-speed curve			
Power and Torque required to winch machine						
Truck weight	61.29 **N**		13.5 **lb**			
Wheel mu	0.3					
Angle	0	15	30	45	**Degrees**	
Distance @ angle	15	30	30	30	**in**	
Distance @ angle	0.38	0.76	0.76	0.76	**m**	
Req'd Parallel pull force	18.39	33.62	46.57	56.34	**N**	
Effects of winch string not pulling parallel to table surface						
X dist to attch point	106.2	76.1	47.1	21.2	**in**	
Y dist to attch point	46.8	43.9	36.1	21.2	**in**	
Max Angle of pull string	23.8	30.0	37.5	45	**Degrees**	
String Angle rel. to vehicle	23.8	15.0	7.5	0	**Degrees**	
Geometric Force amplifier	1.09	1.04	1.01	1.00	-	conservative
String pull force	20.1	34.8	47.0	56.3	**N**	
Approx. system efficienc	**0.8**				-	Friction losses in eyelets, etc.
Pulley pull force	25.1	43.5	58.7	70.4	**N**	
Pulley radius	0.025				**m**	
Motor torque	0.64	1.11	1.49	1.79	**Nm**	
Motor speed*	7.76	7.23	6.80	6.46	**rad/s**	*from linear Torque-Speed curve
	74.1	69.1	64.9	61.7	**rpm**	
String speed	0.197	0.184	0.173	0.164	**m/s**	
Time each section	1.93	4.15	4.41	4.64	**s**	
Total time to top	**15.14 s**		**Predicted**			
Real winching time	~15 s		!			

Figure 2.49 Spreadsheet calculations for Ford motor and Ascending Winch.

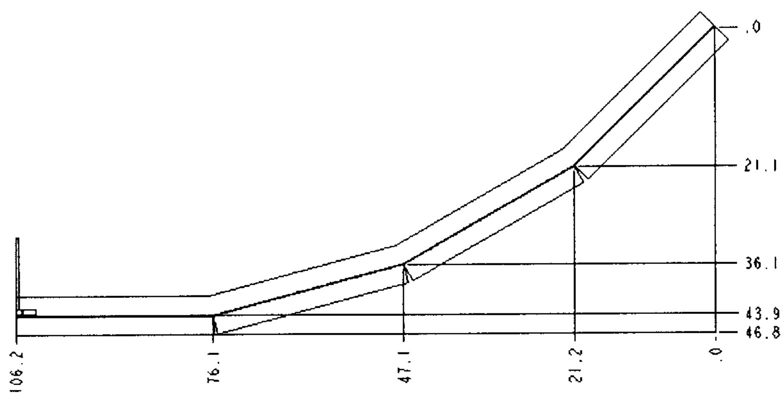


Figure 2.50 Side view of 1999 Contest Table. Dimensions in inches.

Technical Note: The CAD model is used to calculate an accurate weight estimate based on densities. For parts like motors, densities are derived from the known weight and the CAD part's volume.

Concurrency. The design of each module in this machine is approached in a relatively concurrent manner. Other modules are evolving and it is almost unavoidable for modules to affect each other. The use of a parametric CAD solid model can be of great help when modules have spatial interdependencies. Packaging rearrangements can be made easily, and in a carefully constructed model, hole locations, and other features that represent dependencies of one part on another, can update automatically. An example of this is the coupling between the Ford motor's location, the Puck Tray's angle, the machine's center of mass, and the load on the Puck Depositing system. The Puck Truck Ascending Winch system is located under the rear Puck Tray. The further back it is moved (to allow space from which the Rover will start and to put the center of mass rearward for directional stability while ascending), the shallower the angle of the Puck Tray can be. This directly affects the incline angle up which the depositing system must push the pucks, as well as the height of the Puck Collecting system's pivot point and the overall machine's center of gravity. These complicated dependencies work in the other direction to some extent as well. Having to balance and package these interdependent modules made the use of a detailed parametric CAD model very important.

Winch cord routing

Since the motor and pulley for the Ascending Winch are located towards the rear of the machine, winch cord guides are used to route the cord such that it effectively pulls from the front. A pair of guides are formed by bending 1/8" welding rod, as shown in Figure 2.51. These guides are placed to guide the winch cord along a desired path within the Puck Truck, and to create an appropriate effective pulling point location at the front of the truck. The originally intended winch cord routing is sketched a view of the CAD model in Figure 2.52. After testing, the location of the guides was changed in order to move the effective pulling point higher.

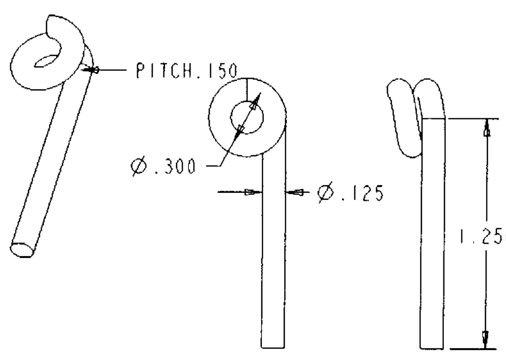


Figure 2.51 Design for one of the welding rod eyelets used as guides for the Ascending Winch string.

In the preliminary stages of the design of the Ascending Winch it was assumed that the winch cord could be routed as necessary to accommodate the differences between spool location and desired effective pulling point. The effective pulling point is the last constraint of the string before its free length. Simple experiments with trial models and prototypes showed that the lateral location of the effective pulling point should correspond to the lateral location of the center of gravity of the Puck Truck. As noted in the Testing Section (Section 2.8 on page 125), there was an oversight made in that the vertical position of the effective pulling point was not considered. Trial runs showed that the effective pulling point's height is quite important. With the effective pulling point too low, as it was at first, the front wheels of the truck are raised and it no longer correctly mates with the Rover at the top of the incline. The reason for this is a force couple created between the up-slope winch cord tension and the down-slope component of the weight of the machine. The effective moment

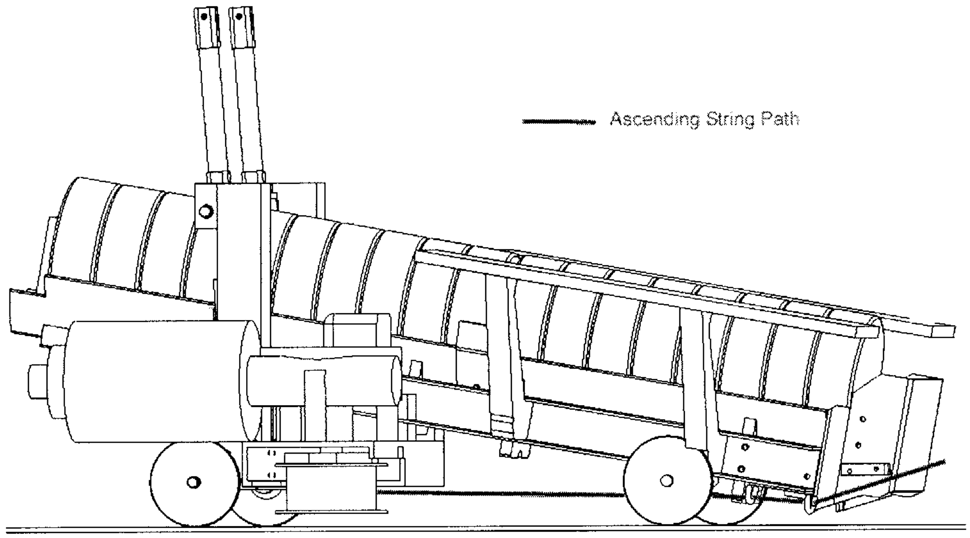


Figure 2.52 Side View of Puck Truck model showing integration of Ascending Winch Module and String Path.

created by these forces is directly related to the distance, in the direction perpendicular to the table surface, between the pulling point and the machine's center of gravity. In order to get this part of the design right before building it, the CAD model could be used to align the string guides with the center of gravity.

2.6 Puck Depositing Mechanism

An important part of the Sample Machine's strategy as introduced in Section 2.2.1 involves the depositing of pucks in the uppermost scoring hole, for 5 points each. This section briefly discusses the conceptual design of the puck depositing system, then goes into detail about some engineering details involving the puck depositing module. The selection of a motor is covered in Section 2.6.1. Further details of the mathematical model for this module are covered in Section 2.6.2. In the course of the design of this module, a flexible coupling was developed that may find use in the future as a stock design part for the course. It fills a valuable functional need and communicates good design practice even without being designed from scratch by each student, and is the topic of Section 2.6.3. The final Puck Depositing system is shown depositing pucks in Figure 2.53 on page 106. A view from the CAD model of the final design for the winch system powering this module is shown in Figure 2.65 on page 118.

Figure 2.53 Photo Sequence of Puck Depositing.

Figure 2.53a Puck Truck mated with Rover and positioned over 5-point hole.

Figure 2.53b Beginning to deposit.

Figure 2.53c 8 pucks deposited, 8 more to go.

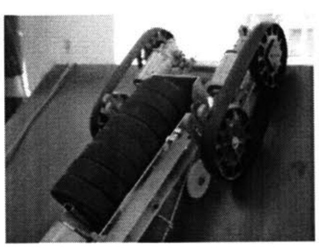


Figure 2.53d 10 pucks deposited.

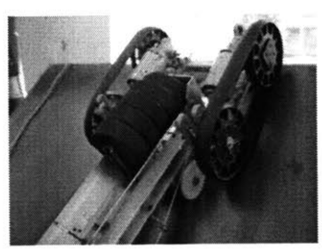


Figure 2.53e Last 3 pucks. Note topmost puck beginning to fall.

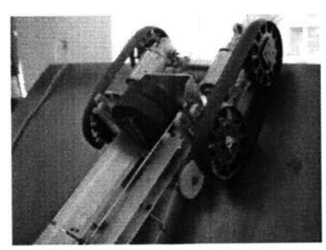


Figure 2.53f Depositing complete. Last 2 pucks are not deposited because slider has reached hard stop. Elapsed time: ~**4.3s**

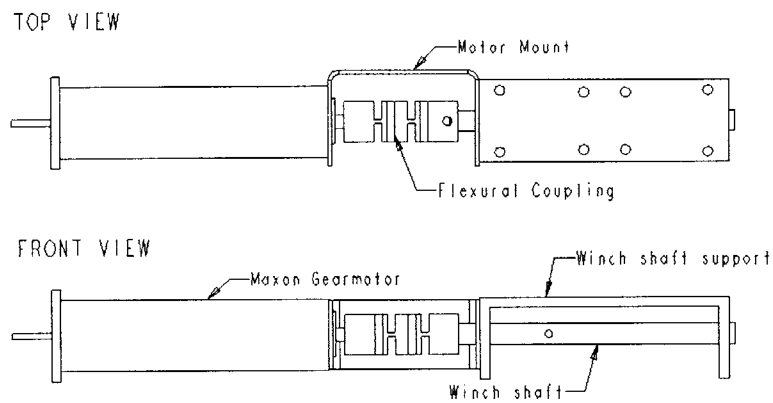


Figure 2.54 Side and top views of CAD model of Maxon Gearmotor assembly for Puck Depositing Module.

Puck Depositing Geometry

The MechEverest scoring holes are plus-shaped, allowing pucks to be deposited in an orientation corresponding to a rectangular cross-section only. The pucks cannot enter the scoring hole in the orientation corresponding to their circular cross-section. The depositing of pucks in these scoring holes requires precision since the holes are sized only ~1/4" larger than the pucks on all sides. For easy depositing the pucks (usually at least 10) are stored such that one simple motion can deposit them all, one after the other. There are several possible arrangements of pucks within a machine that can be used in order to deposit them correctly. The two most common such arrangements place pucks in a row, either face to face or, less frequently, tangent to each other. The primary benefit of the former is better puck storage density, while the latter allows pucks to roll. For this machine, the goal of depositing the highest possible number of pucks makes the face-to-face configuration desirable.

Tray Profile Functional Requirements

- Allows pucks to be deposited
- Allows additional pucks to be collected
- Holds and deposits maximum possible number of pucks
- Fits in space constraint
- Functions Reliably
- Makes efficient use of power (has low friction)

Choosing the Tray Profile

The Puck Tray essentially consists of two linear bearing systems. The more obvious one includes the slot and slider. But the tray also acts as a linear bearing for the stack of pucks. As such, it is desirable to bring all forces acting on the pucks as close together as possible, to minimize the problems created by force couples. General machine design practices encourage the collocation of the centers of stiffness, mass and friction with the actuation force. In this case, however, inertial effects are neglected, making alignment with the center of mass less important. In addition, the geometry of the tray plays a role. A shallow V is less stable but minimizes distance between the bearing and load for the slider system. A steeper V has more friction, as can be calculated by breaking the normal force on the puck tray into components, the vertical of which must balance the weight of the puck. The effects of the tray geometry are included in the mathematical model (Figure 2.58 on page 112) in two ways. The first is in the simple vector amplification of normal force on the puck, and the second involves the slider bearing geometry. The effective offsets from the slider bearing to the points where forces act on it affect the normal forces contributing to bearing friction in the slider. A schematic representation of these bearing forces is shown in Figure 2.55 on page 109. In order to minimize the amplification of friction forces in the bearing, the bearing is made as long as practical without sacrificing puck capacity. The calculations are made by summing moments, and are shown numerically in Figure 2.58 on page 112.

The mathematical model will be used to verify that the 90-degree V tray profile, chosen by estimate-based evaluation, will allow the module to function sufficiently well. The design chosen for the Puck Tray can be seen in Figure 2.56 and Figure 2.65 on page 118..

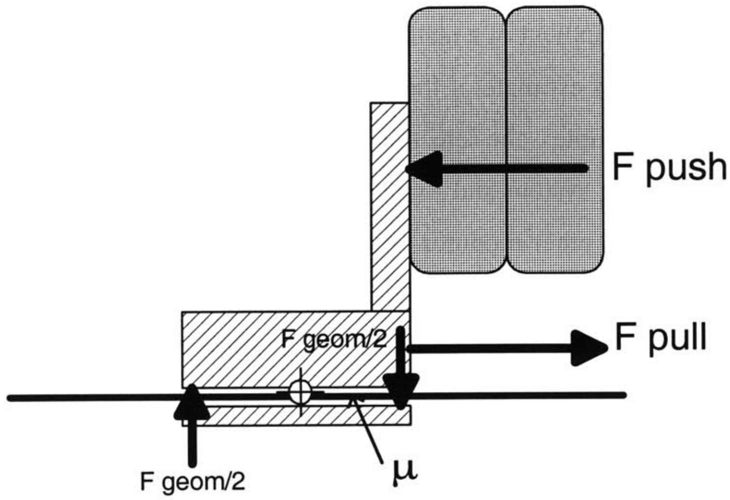


Figure 2.55 Schematic diagram for forces on puck tray slider used to calculate bearing friction force F_{geom} induced by off-axis loads F_{push} and F_{pull}.

Figure 2.56 CAD end view of Puck Tray profile.

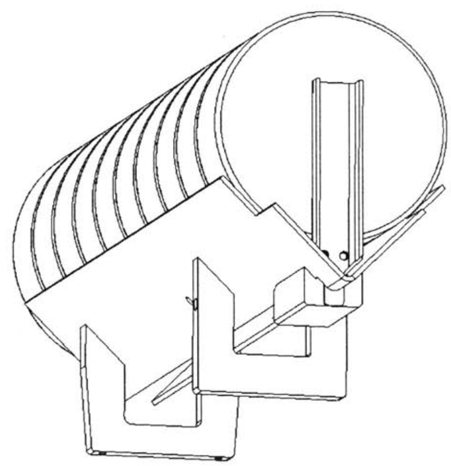


Figure 2.57 CAD view of Rear Puck Tray with 10 Pucks, showing the Puck Tray Slider and attached Puck Pusher.

2.6.1 Motor Selection

At the beginning of the development of a mathematical model for the Puck Depositing system, it is desirable to obtain a first-pass estimate of the power required to deposit the pucks. As the model evolves and become more complex, the selection of an appropriate motor from a first-pass analysis helps guide the design of the system and its model. Of course, at this point, several of the kit's motors have been assigned to other modules. The primary choices available are the Maxon Gearmotor, the Black and Decker motor with gearbox, or any of the 3 small direct drive motors available. The first pass estimate of the load represented by the task of pushing pucks along the Puck Tray when at the top of the table reveals that a force of over 50N will be required, meaning that direct drive motors would need a custom gearing system and can be eliminated since two geared motor types are available. Their properties are tabulated in Table 2.4, where the figure for maximum power is found assuming a linear torque-speed curve:

$$MaxMotorPower = \frac{w_O}{2} \cdot \frac{T_S}{2} \tag{2.13}$$

TABLE 2.4 Properties of candidate motors for Puck Depositing system.

Motor	Stall Torque (Nm)	No Load Speed (rpm)	Max. Power (W)
Black and Decker w/ gears (5V)	0.83	200	4.34
Geared Maxon	0.32	580	4.9

The mathematical model (Figure 2.58 on page 112) predicts a load associated with the task of depositing the pucks, and both motors would be powerful enough to complete the task well. However, the Black and Decker motor is a second choice to the Maxon gearmotor for several practical reasons. It must be used on a special 5V circuit in order to avoid damage to the brushes (it is wound for 3.6V) and implementation of this 5V circuit in the control system is such that only a pair of motor circuits together can be switched to 5 Volts. This would force one motor system that is meant to run on 12 Volts to run on 5, which is sufficiently undesirable to avoid the use of the Black and Decker motor at 5 Volts.

Using the Black and Decker motor on the 12V circuits would give it about twice the power, but is undesirable because the motor is wound for 3.6V, and already shows signs of excessive brush wear and overheating when driven at 5V and moderately loaded. The general robustness and suitability of these motors was found to be questionable, though several students did manage to use them effectively, even at 12 Volts.

2.6.2 Mathematical Model for Puck Depositing System

This section discusses parts of the mathematical model developed to predict and ensure the performance of the puck depositing system. The mathematical modeling done to determine a condition for the avoidance of possible jamming of this system is covered in some detail, as is the tendency of off-axis forces to increase bearing friction. The complete mathematical model for this module is presented in spreadsheet form, and predicts quite powerful performance of this system with the Maxon Gearmotor. The system as built performed very well, closely matching the predictions of the mathematical model, which is shown in Figure 2.58 on page 112.

Bounding the Problem

Sometimes it is difficult to know where to begin, or what results from a mathematical model mean. To address this, one can often find limiting values that frame the range of acceptable results. In this case, we have many tasks to accomplish in 45 seconds, and are concerned with the time it will take to deposit the pucks. Though originally intending to deposit 18 to 20 pucks, space and practical concerns limit the number to 16 in the final design, so the model will address the depositing of 16 pucks into the scoring hole.

Based on the approximate division of the available time between tasks (Table 2.1 on page 49) we know that the 16 pucks must be deposited in a total time of less than 15 seconds. This creates an upper bound on average time per puck of about 1s, and a corresponding lower bound on speed. There is also an upper bound on speed. With infinite power, the pucks can not be delivered infinitely quickly. The limiting factor arises from the reliance on gravity to propel the pucks into the scoring hole once they are free from the tray. If the puck stack is pushed too quickly, there may not be enough time for one puck to fall clear of the one behind it, resulting in a jam as the first puck is pressed against the wall of the Puck Depositing Guide.

Evaluation of Green Maxon Motor for Puck Depositing							
Stall torque	0.32	**Nm**					
No Load speed	60.737	**rad/s**	580 **rpm**				
Max Motor Power	4.859	**Watts**	assumes linear torque-speed curve				
Power required to deposit pucks							
Mass per puck	0.16	**kg**					
Mu puck-Al	0.4						
incline Angle of tray	35	**degrees**					
Mu delrin-Al	0.3						
Calculating sliding bearing geometry factor							
H	0.75	**in**	height of puck-pushing force wrt bearing contact point				
I	0.2	**in**	height of string-pulling point wrt bearing contact point				
Assumed Fpull/Fpush	1.2		Estimate for iteration- adjust to match B37				
L	1.5	**in**	bearing length				
Fgeom/Fpush	0.68	bearing geometry factor					
Force required to push N pucks							
N	18			17	16	15	14
Tray V angle	90	**Degrees**					
Friction factor	1.41	due to V shape					
F friction	15.97	**N**		15.08	14.19	13.30	12.42
F gravity	16.19	**N**		15.29	14.39	13.49	12.59
Constant F	5	**N**		5	5	5	5
	*Keeps Fpush from going to 0						
(F push)	37.15	**N**		35.37	33.58	31.80	30.01
Bearing geometry friction	7.58	**N**		7.22	6.85	6.49	6.12
Total F (F pull)	44.73	**N**		42.58	40.43	38.28	36.13
Actual Fpull/Fpush	1.20		iterate to match assumed Fpull/Fpush at B17				
Est. system efficiency	0.75						
Net F required	**59.65**	**N**		**56.78**	**53.91**	**51.04**	**48.17**
Pulley radius	0.0035	**m**					
Motor torque	0.209	**Nm**		0.199	0.189	0.179	0.169
Motor speed	21.11	**rad/s**		23.02	24.92	26.83	28.73
Motor speed	201.6	**rpm**		219.8	238.0	256.2	274.4
	From linear Torque-Speed curve						
String speed	0.074	**m/s**		0.081	0.087	0.094	0.101
Time/puck at max. speed	0.344	**s**		0.315	0.291	0.270	0.253
Min time/puck to avoid jam	0.230	**s**		0.230	0.230	0.230	0.230
Based on acceleration with which puck clears mouth of tray							
Min. time this puck	0.344			0.315	0.291	0.270	0.253
Calc. time for 16 pucks:	3.51	**s**	Model validation opportunity: under fu				
Min. time 16 pucks no jam	**4.01**	**s**					
In reality:	**4.3**	**seconds for 16 pucks under manual speed control**					

Figure 2.58 Spreadsheet used to calculate mathematical model of Puck Depositing System.

Finding The Maximum Safe Speed to Avoid Jamming

To find the maximum safe speed to prevent the jamming described above, a simple model is developed for the falling of pucks off the end of the tray. The relevant geometry is sketched in Figure 2.59 on page 113.

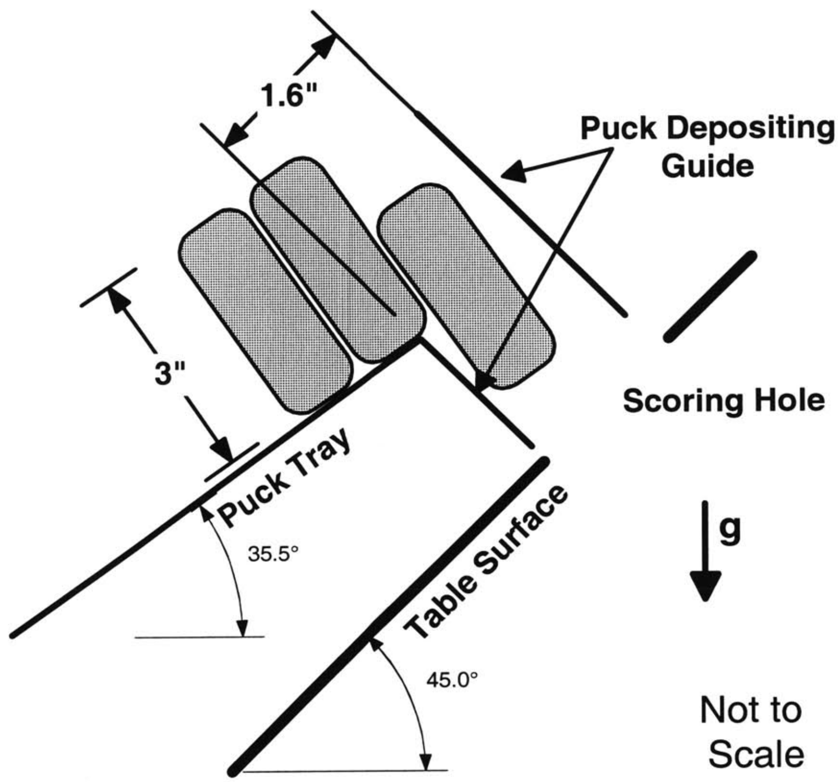


Figure 2.59 Sketch for calculating maximum puck depositing rate to avoid jamming against surface of Puck Depositing Guide.

The first step in modeling the acceleration of a falling/sliding puck is to determine the net force acting on it. The net force on the puck is in the direction that the puck will travel, i.e. along the surface of the puck behind it and the vertical face of the front puck tray. The component of the force due to gravity is balanced by a friction force in the opposite direction:

$$F_{net} = Mg\cos\theta - \mu Mg\sin\theta \tag{2.14}$$

The coefficient of friction μ between the puck and the surface along which it slides is found experimentally by placing 2 pucks on top of each other on an incline and measuring the angle at which the top one slips. When α is the angle of the incline from the horizontal,

$$\mu = \tan\alpha \tag{2.15}$$

from which μ was found to be 0.4. In order to keep the model conservative with respect to the uncertainty in the actual value of μ under operating conditions, a safety factor of 1.5 was applied to the experimental value for μ.

Using the fact that the angle of the tray is 35 degrees from the horizontal when on the 45 degree incline, and that the puck weighs ~1.6N, the resulting net force is found:

$$F_{net} = 0.57N \tag{2.16}$$

The next step is to calculate the time required for a puck to fall clear under the effect of this net force. The net force creates an acceleration of the puck by:

$$F = ma \tag{2.17}$$

or

$$a_{puck} = \frac{F_{net}}{m_{puck}} \tag{2.18}$$

The pucks have a diameter of 3", and to keep the model conservative with respect to the falling distance, the height y that the puck needs to drop in order to make a clear path for the next puck was taken as 4". The relation between the drop distance and the acceleration is

$$y = \frac{at^2}{2} \tag{2.19}$$

which rearranges to

$$t_{drop} = \sqrt{\frac{2y}{a_{puck}}} \tag{2.20}$$

which was found to have a value of $t_{drop} = 0.23s$.

This value was included in the mathematical model (Figure 2.58 on page 112) as a minimum time that would be need for each puck to be deposited, even when the winch system could technically propel the puck faster. In order to prevent jamming, the speed of the depositing winch must be carefully regulated during depositing. This requires the use of one of the variable speed control circuits to manually ensure that the system does not move too fast as fewer and fewer pucks remain part of the load. A closer view of the Puck Depositing System is shown in Figure 2.60 and Figure 2.61.

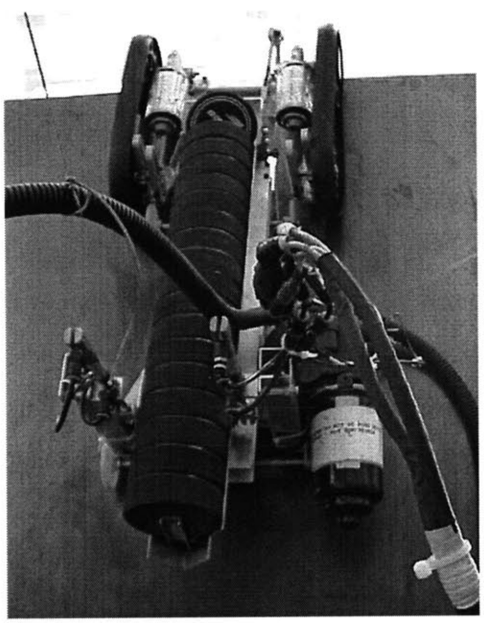


Figure 2.60 Puck Truck in scoring position, interfacing with Rover.

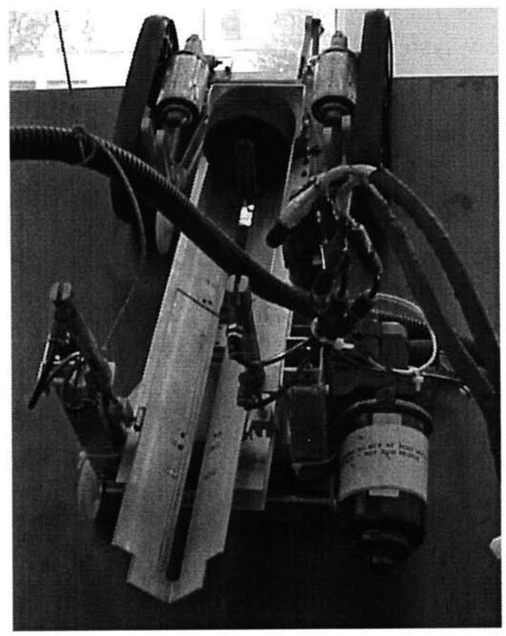


Figure 2.61 View of Puck Truck in scoring position after depositing it maximum, 16 pucks.

2.6.3 Flexural Coupling

This section covers the need for a high-torque flexible coupling to connect motors to fully supported shafts, and presents a solid plastic part to serve this purpose that makes use of flexures and the toughness of UHMW-polyethylene.

Maxon Gearmotor Background

The green Maxon Gearmotor is a popular motor in the 2.007 kit because of its high power density and torque (due to its efficient planetary gearbox). Because there is only one in the kit, and other motors are often used for propulsion of a vehicle, this motor is commonly used for winches and leadscrew systems.

Motor-Shaft Couplings in 2.007

The avoidance of overconstraint, especially of motor shafts, is stressed in the teaching of 2.007. Traditionally, flexible PVC or Tygon^{R} tubing has been provided to make easy shaft couplings for 2.007 motors. As the contest tasks become more demanding (illustrated by the evolution from the handling of ping-pong balls in 1995 to hockey pucks in 1999), more and more machines rely on the ability to harness the full torque of these motors. Especially in the case of the Maxon motor, the flexible tubing couplings can be inadequate. The standard tubing-based coupling with one piece of 1/8" ID tubing fails by slipping or twisting at these torques. In fact, the only tubing-based coupling able to handle the stall torque of the Maxon gearmotor required the use of 1/2" ID tubing, very tight tie wraps to apply pressure to the motor shaft, adhesive to ensure non-slip connection to the load shaft, and a very small gap between the ends of the shafts.

The inability of flexible tubing couplings to handle torque points out the need for a solid flexible coupling that can be made from the kit parts. Several efficient but complicated couplings were made by the course staff as demonstration items. These included a very nice twin universal joint coupling (by Joachim Sihler), a slotted socket and "dog bone" coupling (MS-L), and a hexagonal socket and "dog bone" coupling (MS-L). Both were able to handle the maximum stall torque of the motor, and rather large angular and parallel misalignments. They were far too complex to be adopted by students, however. This provided the context for the design of the flexural coupling used in the sample machine.

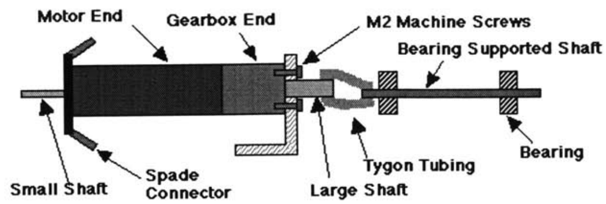


Figure 2.62 "How-to" sketch from 2.007 web site, by Roger Cortesi.

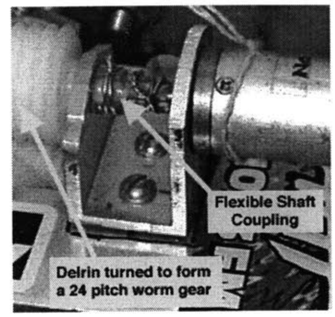


Figure 2.63 Typical student application of flexible tubing as motor-shaft coupling.

Alternatives to the Use of a Flexible Coupling

It is interesting to note that the difficulty of incorporating a sufficiently strong flexible coupling led many students to avoid using a coupling altogether. It was common in 1999 for students with lead-screw systems to connect their ~12" screws directly to the motor output shaft and loosely support only the far end of the screw. These systems were over constrained and inaccurate, but were also usually sufficient for the application.

Design of the Flexural Coupling

An experimental coupling was designed which consists of a pair of flexural universal joints. Table 2.5 lists the Functional Requirements identified and addressed by this part. The final part is

TABLE 2.5 Functional Requirements, Design Parameters and Physics for Flexible Coupling

Functional Requirements	Possible Design Parameters	Relevant Physics
Allow angular misalignment	One set of flexures—horizontal and vertical	Beam bending with various boundary conditions related to mode of deflection; Fatigue
Allow parallel misalignment	Second set of flexures	"
Easy to manufacture	Required accuracy of slots	Sensitivity to slot width and depth
Use only kit parts		

shown in CAD form in Figure 2.64. Its location between the motor and shaft of the Puck

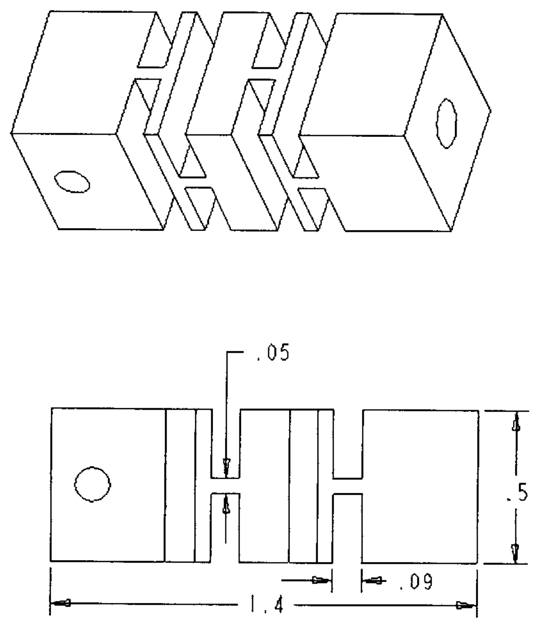


Figure 2.64 CAD drawing of experimental flexural coupling. Dimensions in inches.

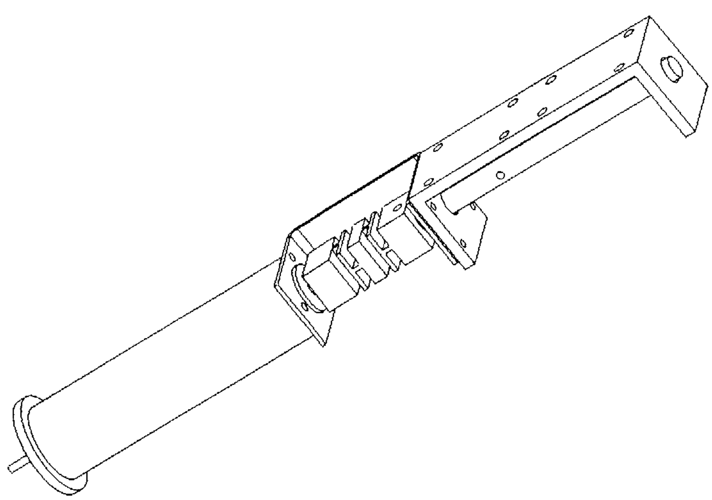


Figure 2.65 View of CAD model of Maxon motor assembly for Puck Depositing Module

Depositing winch system is shown in Figure 2.65 on page 118.

The prototype part was manufactured using a milling machine and a 3/32" endmill. To be successful as a stock design for 2.007, the flexural coupling should ideally be manufacturable without the use of a mill, as mills are in high demand among students, and for inexperienced machinists have a relatively high time overhead in setup and use. The coupling will likely be successful if it can be made to function well with slots cut by bandsaw. Positioning the cuts and controlling depth can be done manually by using full scale printed side and top views from the CAD file as templates.

Material Selection

As a material for use in creating flexures, the Ultra High Molecular Weight Polyethylene in the kit was chosen for its high ultimate strength, but even more so for its high elongation before failure. These properties give it a long life expectancy even under plastic deformation. This material has an ultra-high molecular weight not because its molecules have a high density, but because they are very large. The molecules making up this type of polyethylene are very long polymer chains causing this material to have different properties from Low Density Polyethylene, for example. The relevant material properties for UHMW-Polyethylene are listed in Table 2.6.

FEA study

In order to verify that the flexible coupling's flexures will not fail, a simplified model is subjected to a simple finite element analysis (FEA) test. In this case, the problem is not so complex that FEA is necessary because standard calculations would fail, but it presents itself as a simple tool for a quick investigation of stress and strain in the plastic part.

TABLE 2.6 Mechanical Properties of UHMW-Polyethylene[a]

Young's Modulus, E	Tensile Strength at Yield	Tensile Strength at Break	Elongation at Break
690 MPa	21 MPa	48 MPa	350%

a. Data from *[Crown Plastics]*

The FEA model features displacement constraints to simulate parallel shaft misalignment. Various magnitudes of displacement are applied, always in equal magnitudes in the Y and Z directions (across a diagonal of the coupling's end face). A fringe plot of typical FEA results for von Mises stress can be seen in Figure 2.66 on page 120. Figure 2.67 on page 120 shows the corresponding maximum principal strain. The units of stress are KPa, and strain is elongation per unit length.

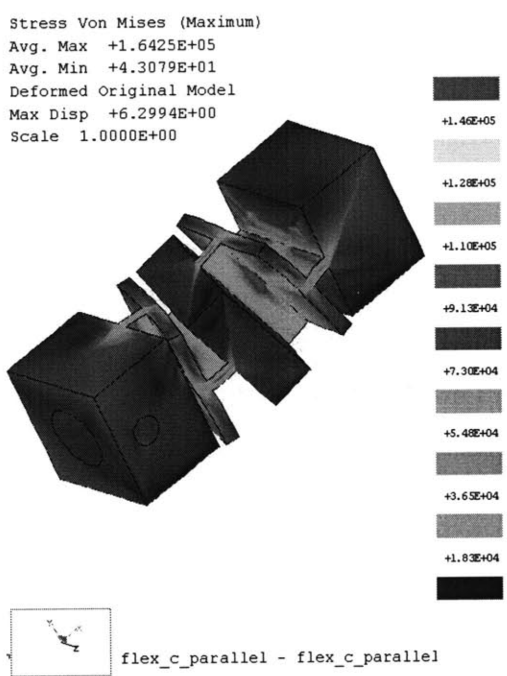


Figure 2.66 Stress calculated by linear FEA for flexural coupling under parallel misalignment of 4.2mm. Units are KPa.

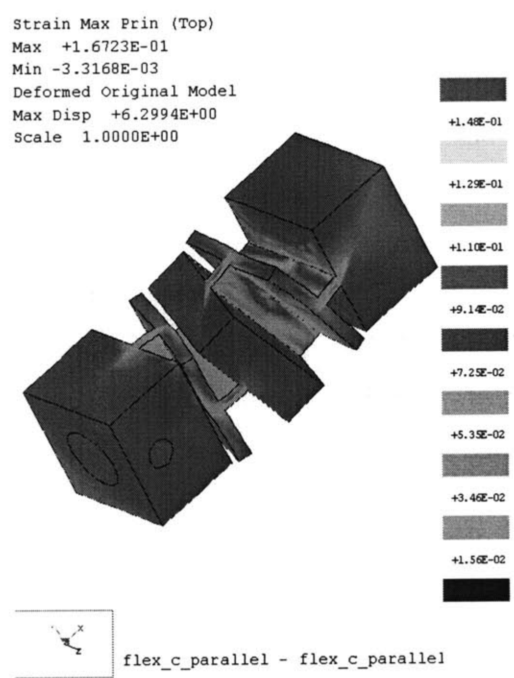


Figure 2.67 Strain calculated by linear FEA for flexural coupling under parallel misalignment of 4.2mm. Units are elongation/length.

Several analyses of this type of loading were performed, and results are tabulated in Table 2.7 on page 121. In use the coupling will see angular as well as parallel shaft misalignment. Due to the nature of the constraints in the FEA program, it is easiest to estimate a relationship between a parallel offset condition and an angular condition. Figure 2.68 on page 121 shows the simplified geometry used to model the coupling during parallel misalignment. By arguments of symmetry, a similar maximum stress will exist in the part if it is deflected to a total angle of twice the flexural angle α. The angle α is found from the simplified geometry by

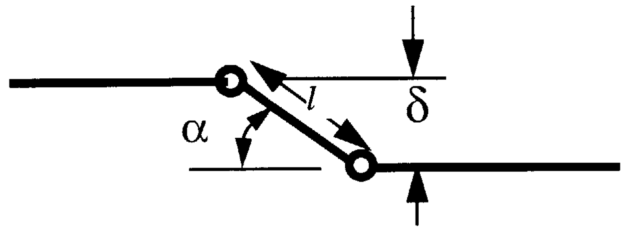


Figure 2.68 Sketch used to calculate approximate relation between angular and parallel misalignment of flexural coupling.

$$\alpha = \operatorname{asin}\left(\frac{\delta}{l}\right) \tag{2.21}$$

The total angular deflection possible will be twice α, and this is what is tabulated in Table 2.7.

TABLE 2.7 FEA-calculated stress and strain states in flexural coupling for various deflection limits.

Parallel Misalignment δ	0.5 mm	1.1 mm	4.2 mm
Angular Equivalent	5.7°	12.6°	50°
Stress	21 MPa	47 MPa	164 MPa*
Strain	2.4%	~4%	12%
Condition	No yielding	All stress below ultimate stress	Maximum possible deflection

Analysis of FEA results

In order for the coupling to operate most efficiently, no material should yield. Table 2.7 shows that the maximum parallel shaft offset to avoid yield is 0.5mm. This is somewhat small, but well within the capabilities of manufacturing. the points were yielding will occur are the sharp corners at the roots of the flexures. If they do yield, there will not be much strain energy absorbed, and certainly the coupling will not fail, so it can operate safely to misalignments of 1.1mm. Any greater misalignment should not be experienced, but if it is, the FEA predicts that stresses beyond the material's ultimate tensile strength will occur.

In the case of maximum deflection, the maximum von Mises stress found by the FEA is approximately 160MPa, or about 3.5 times the failure stress for this material tabulated in Table 2.6 on page 119. This result would seem to indicate that the flexures in the part will fail if bent to their geometric maximum deflection. However, this is an experimental part, and a prototype exists. It is known from experimentation with the prototype that plastic deformation, but no failure occurs. Taking a look at the strain situation can shed some light on this, especially when keeping in mind that the FEA program used is capable only of predicting linear behavior in materials. The maximum elongation shown in Figure 2.67 is 12%, whereas the elongation of a tensile specimen at failure was 350% (Table 2.6). So, although the material is locally yielding (not really a problem for plastics) it is really a displacement condition that will break the part, and in that respect we are quite safe. Adding to this the fact that in most applications the amount of misalignment will be much smaller than the worst case studied, it is not likely that it will even yield in normal use.

Fatigue. If this part were to be used over long periods of time, it would be good to check for the effects of fatigue. A generally good design rule would be to keep all stresses below half the yield stress, but for plastics it is often necessary to study the specific behavior of the material. In this case, where the period of use will be brief, and fatigue will be visible before it causes failure, it is ignored.

Conclusion

This simple FEA investigation highlights several important points to consider regarding the use of FEA. It shows that the interpretation of FEA results is a very important part of the process. It also shows that with careful interpretation, FEA methods can be used to efficiently reduce uncertainty, a primary goal in the design of machines for the course.

Manufacturing the Flexural Coupling

Manufacturing drawings and process plans for the flexural coupling can be seen in Appendix B. There are two process plans provided, one for the use of a mill to cut the flexures, and one for the use of a bandsaw. The bandsaw-cut coupling may be of slightly inferior quality of finish, but may also save a lot of time in manufacturing.

2.7 Manufacturing

Because student must not only design but manufacture the parts for their machines, manufacturing methods are an important part of the course. Most students learn concepts like Design for Manufacturing, Design for Assembly, Design for Serviceability, etc. by doing, and often by wishing they had done differently. Students have access to a traditional machine shop, as well as certain CNC machines by special arrangement.

2.7.1 Design and Manufacturing of Accurate Sheet Metal Parts

Because of its low cost and versatility, the 2.007 kit contains a relative abundance of sheet material. Included are an 18" x 18" sheet of 1/16" thick 5052 aluminum and a 12" square and 36" x 1" strip of 18 gauge mild steel. In order to create stiffer, more 3-dimensional parts with sheet metal, parts are often designed to be bent or formed. The accurate design of formed sheet metal parts is made easier by the use of a parametric 3D CAD system with some basic sheet metal modeling features. The classic case where good CAD solid modeling helps design sheet metal parts is when a part is bent and formed, and the formed part is related to other parts in an assembly. The power of 3D solid modeling is most evident when a 2D "unbent" instance of the part can be generated that is linked to changes made in the 3D geometry. This 2D geometry is easily exported for CNC machining (see below) or more manual methods, such as using a full scale plot as a template for cutting and punching holes.

One common type of feature in sheet metal parts is a hole whose position depends on the relationship between the fully formed sheet metal part and other parts. For example, a sheet metal bracket may be designed with holes in several bent tabs for mounting to holes in other parts. In this case, the holes can be made in the bent tab such that they correspond to the location of holes in the reference part, and the CAD system can de used to indicate where to punch the holes in the flat sheet before bending. Another common way that formed sheet metal parts are dependent on the relation between the formed geometry and other parts is when they are created to "fill the gap" between components that are located with respect to each other and the machine, but not yet physically connected. Examples of parts designed in this manner are the Maxon Gearmotor Mount and the Puck Depositing Guide. It should be noted that 2D geometry resulting from "unbend" operations is dependent on parameters of the forming process, most notably the bend radius. The parametric solid modelling software used in the design of this machine is Pro/Engineer, though SolidWorks and other high end 3D CAD packages have similar functionality.

2.7.2 Use of CNC Abrasivejet Machining Center

The vast majority of the two-dimensional (sheet) parts for the sample machine were manufactured using an OMAX Jetmachining center, referred to commonly as a waterjet or abrasivejet cutter (Figure 2.69). It cuts materials by generating a stream of water that is approximately 0.028" in diameter (at about 40,000 psi), which then passes through a venturi where it draws in a garnet abrasive. The resulting abrasive jet stream can cut materials in excess of 1" thick aluminum plate. The apparent extravagance of using a CNC machine like the waterjet for the construction of a 2.007 sample machine is justified not only by its convenience, but also by the fact that a waterjet machine will be available for use by 2.007 students in the immediate future.

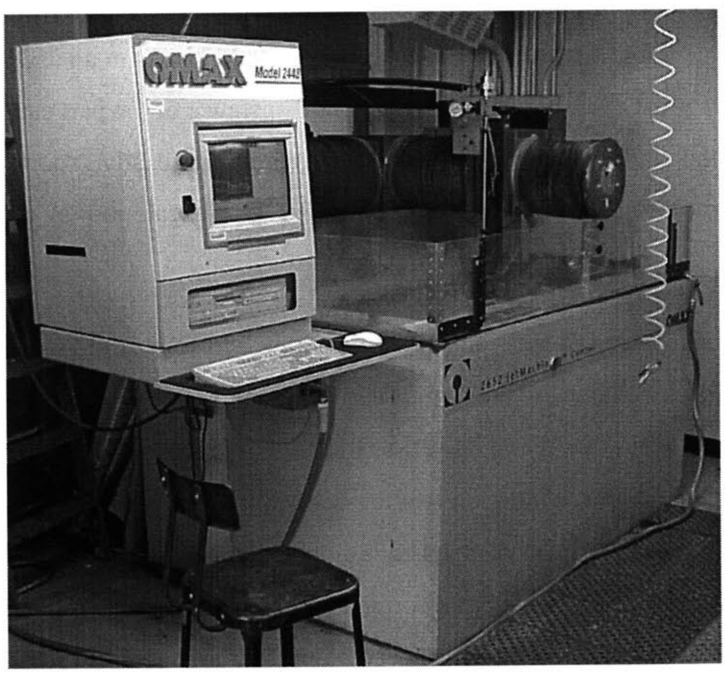


Figure 2.69 OMAX, Inc. Abrasivejet machine in the shop of MIT's Laboratory for Manufacturing and Productivity.

Key advantages of using the waterjet cutter:

- Easy to use
  - only 2D toolpath
  - takes DXF files from any CAD system
  - absence of lateral cutting forces makes it easy to fixture stock
- Accurate (tolerances of +/- 0.005" easily achievable in thin sheet parts)
- No manufacturing penalty for complex geometry
  - allows non-rectilinear part shapes
  - as a teaching tool, this encourages optimal part design.

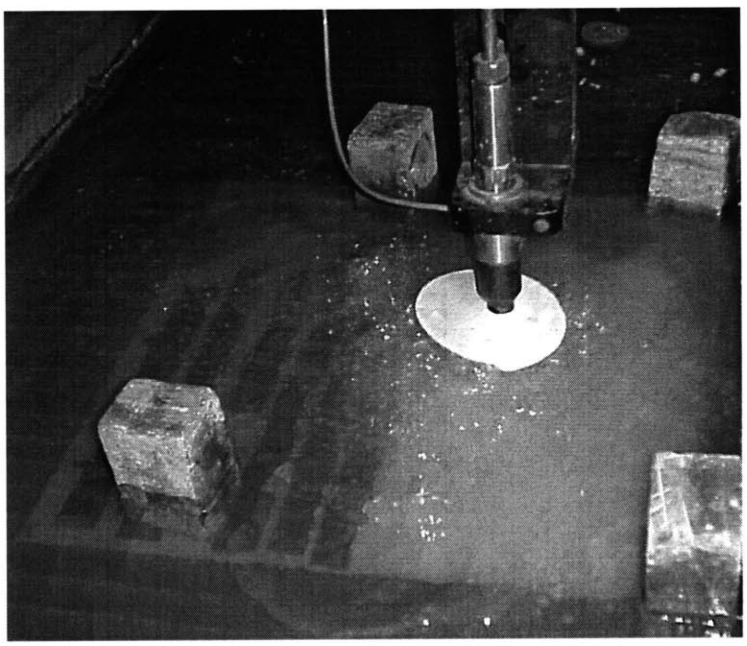


Figure 2.70 Abrasivejet nozzle cutting part in submersed 1/16" Aluminum sheet.

A typical toolpath for waterjet cutting of half of the Rover's chassis is shown in Figure 2.71 on page 126.

2.8 Testing the Sample Machine

Individual modules were tested as they were completed. The Rover was the first module completed, then the Puck Depositing system, the Puck Collecting system, and finally the Ascending Winch were tested. Then the entire system was tested, and a few problems discovered. In general, however, the number and scope of problems encountered was very low, requiring only a few hours

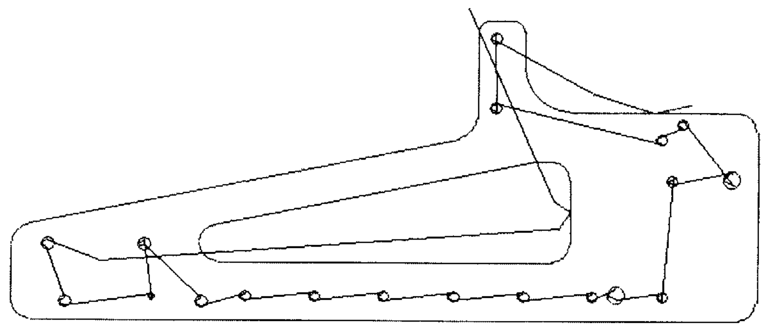


Figure 2.71 Typical DXF toolpath used by abrasivejet cutter's software to cut a part, in this case half of Rover's chassis. Small holes are 1/8" diameter.

to correct. This shows the practical benefits of detailed mathematical and solid modeling. For reference, the typical sequence of events during a round is shown in Table 2.8.

TABLE 2.8 Typical Contest Round Sequence of Events

0-15s	15-20s	20-35s	35-42s	42-45s
Rover departs and climbs to top	Rover maneuvers into position over hole and hooks to top of table	Puck Truck winches to top, mates with anchored Rover	Deposit pucks	Buffer
collect pucks		Take up slack in puck depositing string		

2.8.1 Problems Encountered

- Umbilical sometimes wedged between front of Puck Truck and Rover, preventing proper mating.
  Cause: Umbilical was allowed to droop over front of Puck Truck
  Remedy: Welding rod hook to route umbilical to side of Rover Ramp.
- Rover Ramp supports interfered with Rover wheels during mating
  Cause: Lack of interference check in CAD side view of scoring position.
  Remedy: Repositioning of supports.
- Umbilical Tension pulled Puck Truck forward from starting position.
  Cause: Rear location of umbilical connector, Umbilical weight, Umbilical tower position
  Remedy: Include in the starting configuration a wheel chock which prevents free rolling of Puck Truck but which is easily overcome when the Ascending Winch is activated.

- Topmost puck from collected stack occasionally lost during motion of Rear Puck Tray.
  Cause: Air in unpressurized side of cylinders, with restricted exit orifice for slower motion, acted as air spring. Size constraints require top puck to be supported only to 1/2" of its height.
  Remedy: Exit orifices carefully adjusted to be even slower (smoother). Not a critical problem, as lost puck usually falls harmlessly on table.
- Frontmost Puck occasionally lost when Puck Truck shaken/jostled.
  Cause: Rover departure or passing of wheel over a scoring hole. First puck is supported half by puck tray, half by front surface of the puck depositing guide due to tray length constraints.
  Remedy: Usually not a critical problem; puck is either lost on way up slope or stays constrained within puck depositing guide. If problem persists, consider removing this puck.
- Rover becomes stuck in hole.
  Cause: Wheel traversing an intermediate scoring hole causes at least one magnet to become closer to the table, usually by enough to transition to full contact with the table.
  Remedy: Maneuver to avoid driving through scoring holes. This may require practice.
- Rover's magnets become stuck to table.
  Cause: If magnets are too close to the table, small perturbations may cause them to come close enough to the table to override the stiffness of the chassis. The mode of compliance in the chassis is principally torsion.
  Remedy: Reduce relevant lever arms in magnet mounting, position magnets further from table.
- Puck deposition (Maxon motor) pulley system jams.
  Cause: Misrouted string in setup.
  Remedy: Strictly verify proper setup.
- Puck Collection fails— stack falls backwards or to side
  Cause: Improper setup. The puck collection system is sensitive for several reasons: 1) **slop** in the linear bearing system, allowing the puck pusher (forklift prong) to have slight negative angle; 2) puck pusher is very **narrow**, 3) the puck tray is not very effective at constraining pucks from falling to the side until they are partially resting on the tray.
  Remedy: Set up carefully. Experiment with effect of shim on tip of puck pusher to effectively reduce negative angle. Beware of trade-off with linear bearing efficiency while depositing pucks, as this may also raise the effective contact point with respect to the sliding bearing and increase bearing friction forces.
- Puck truck travels with only rear wheels on table— front end ~1/2" above table.
  Cause: Initial disregard for to vertical-plane effects of effective winch pulling force location. The location of the effective pulling point lower than the center

of gravity creates a force couple which tends to rotate the Puck Truck's front end away from the table.

Remedy: Relocate winch string guides on Puck Truck and anchor point on Rover. Higher winch string guide location counteracts lifting. The force couple continues to lift the front end until equilibrium is reached. When the front wheels are in the air and at equilibrium, the height of the effective pulling point from the table should be noted. The string guides should be relocated such that the effective pulling point is at least this distance from the table surface with all wheels on the ground.

2.9 Conclusion

This project aims to be useful by providing a concrete basis for design case studies in engineering design for the 2.007 course. The outlook is good for creation of an easily accessible set of examples to allow students to become familiar with the type of analysis they may do in designing their machines. Some of the most useful parts of the examples may be the way design choices are made by estimation. In the case of open-ended design problems like those encountered in 2.007, the posing of the problem is often at least as important as its solution.

The practical embodiment of the Sample Machine as a set of design case studies will likely be in the form of a tutorial section on the 2.007 world wide web page. The examples from the design of the Sample Machine may also be useful in teaching recitation sections, since the details can be covered in depth and questions can be answered in person. The design case studies for individual modules can be used independently, perhaps to demonstrate specific methods and tools. However, there is already too much material to be covered in lecture and lab meetings, so making the material available on the web page would likely give the best access to those students who feel they would benefit from it. In further support of the publishing of these examples on the 2.007 web page, the course evaluation forms distributed at the end of the semester showed that student reactions to the 1999 web page were positive. They also support the addition of more technical content to the web page.

As a final word, some recurring themes in the teaching (and practicing) of mechanical engineering design, and perhaps design in general, are listed below:

- Know what is optimal, and also what is sufficient.
- Good enough is good enough, as long as you prove it.

- Always ask yourself Why? Why? Why?
- A design is perfect not when there is nothing left to add, but rather when there is nothing left to remove.[1]
- It always pays to do it right the first time.
- In case of doubt, methodically eliminate uncertainty

1. Paraphrase of a quote of unknown source, perhaps itself a paraphrase of comments regarding sculpture that are attributed to Michelangelo.

Appendix A
MOTOR PROPERTIES

A.1 Bosch Motor

The most widely used motors in this course are of a wormgear type donated by Bosch that is used for automotive applications like power seat control. To find the Bosch motor's Torque-Speed properties, A 1.5- inch diameter pulley was attached to the output shaft. A string with varying weight attached (in the form of up to 6 Ford motors) was winched vertically up while an opto-electronic tachometer was used to measure the pulley's speed. The known weight at a known radius gave the torque, and the speed was measured directly. An interesting detail to keep note of is that the testing setup imposed a cantilevered load on the output shaft bearings, so modeling bearing losses in the motor will likely be unnecessary to predict its performance. The Bosch motor's Torque-Speed curve is shown in Figure A.1 on page 132. The raw data and calculations from which the Torque-Speed curve was plotted are shown in Figure A.2 on page 133.

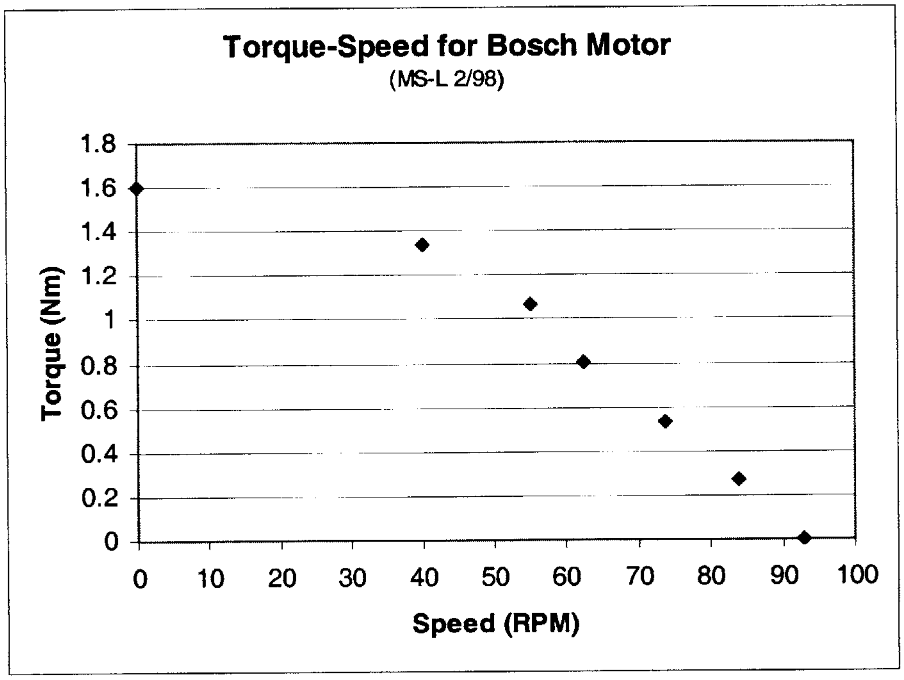


Figure A.1 Experimental Torque-speed data for Bosch Motor.

Bosch Motor

Winch radius	0.019	**m**
Ford motor mass	1.43	**kg**

Load **# Ford motors**	Load **N**	Torque **Nm**	Speed **rpm**	avg speed **rpm**	Torque **Nm**
0	0	0	92		0
0	0	0	93		0
0	0	0	94	93.0	0
1	14.03	0.27	84		0.27
1	14.03	0.27	84	84.0	0.27
2	28.06	0.53	73		0.53
2	28.06	0.53	74		0.53
2	28.06	0.53	74		0.53
2	28.06	0.53	74	73.8	0.53
3	42.09	0.80	61		0.80
3	42.09	0.80	62		0.80
3	42.09	0.80	64	62.3	0.80
4	56.11	1.07	55	55.0	1.07
5	70.14	1.34	40		1.34
5	70.14	1.34	40	40.0	1.34
6	84.17	1.60	0	0.0	1.60

Figure A.2 Spreadsheet showing raw data and calculations for Bosch motor Torque-Speed.

A.2 Ford Motor

These motors were donated to the course by the Ford Motor Company, and are normally used to power windshield wipers in cars. They feature a very efficient wormgear drive using a metal double-helix worm and a conformal plastic worm gear. The relative efficiency of this system compared to most wormgear drives is evidenced by the fact that it is back-drivable. The motor is intended to run in one direction only (the reciprocating action of the wipers is achieved mechanically) and therefore is more powerful in its intended "forward" direction, which is clockwise as viewed from the motor's point of view. This is likely due to lack of a good thrust bearing on the worm/motor shaft for operation in the CCW direction, and makes the Ford motors difficult to use as a matched pair for powering symmetrically vehicles.

A.2.1 Experimental Data

To find the Ford motor's Torque-Speed properties, A 6 inch pulley was attached to the output shaft. A string with varying weight attached (in the form of up to 14 Ford motors) was winched vertically up while an opto-electronic tachometer was used to measure pulley speed. The known weight at a known radius gave the torque, and the speed was measured directly. Torque-Speed data taken for this motor are shown in Figure A.3 on page 135, Figure A.4 on page 135 and Figure A.5 on page 136. It is assumed that the relative power loss for counterclockwise operation in low speed mode is similar to that seen in High Speed mode.

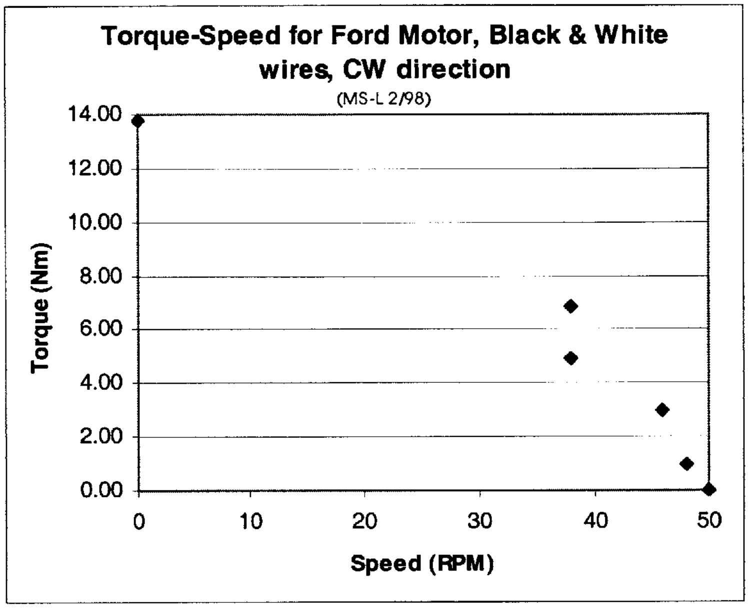


Figure A.3 Experimental Torque-Speed data for Ford motor in Low Speed mode.

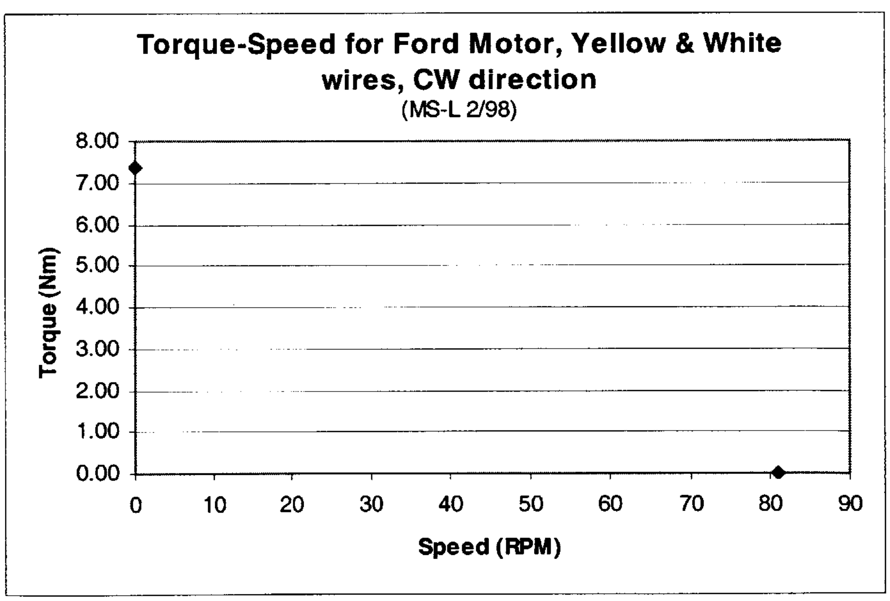


Figure A.4 Experimental Torque-Speed data for Ford motor in High Speed mode, Clockwise operation.

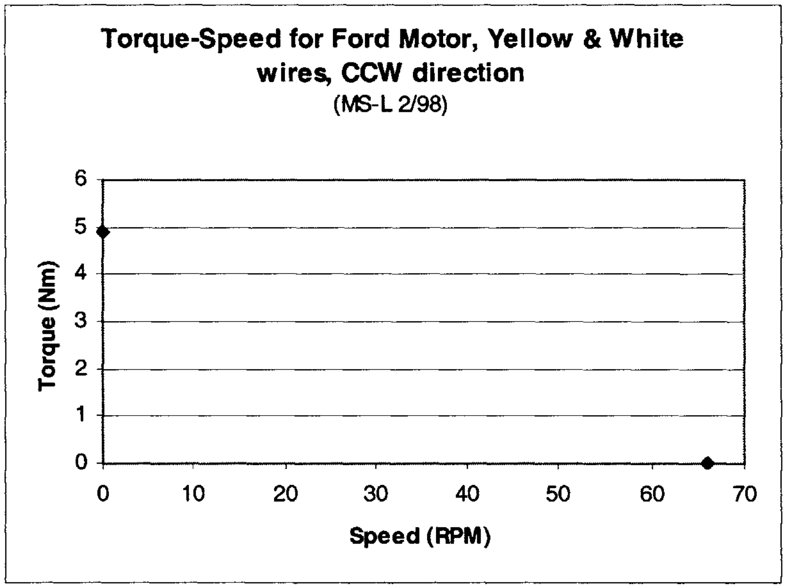


Figure A.5 Experimental Torque-Speed data for Ford motor in High Speed mode, Counterclockwise operation.

A.3 Green Maxon Gearmotor

Each kit contains one small coreless DC planetary gearmotor donated by Maxon. These motors are fast, efficient and relatively powerful and are often used to power winches and leadscrew systems. To find the Maxon gearmotor's Torque-Speed properties, the motor was connected to an independently supported 1.75-inch diameter pulley with a flexible coupling. A string with varying weight attached was winched vertically up while an electronic tachometer was used to measure pulley speed. The known weight at a known radius gave the torque, and the speed was measured directly. Torque-Speed data taken for this motor are shown in Figure A.6 on page 137. The raw data from which the Torque-Speed curve was plotted are shown in Figure A.7 on page 138.

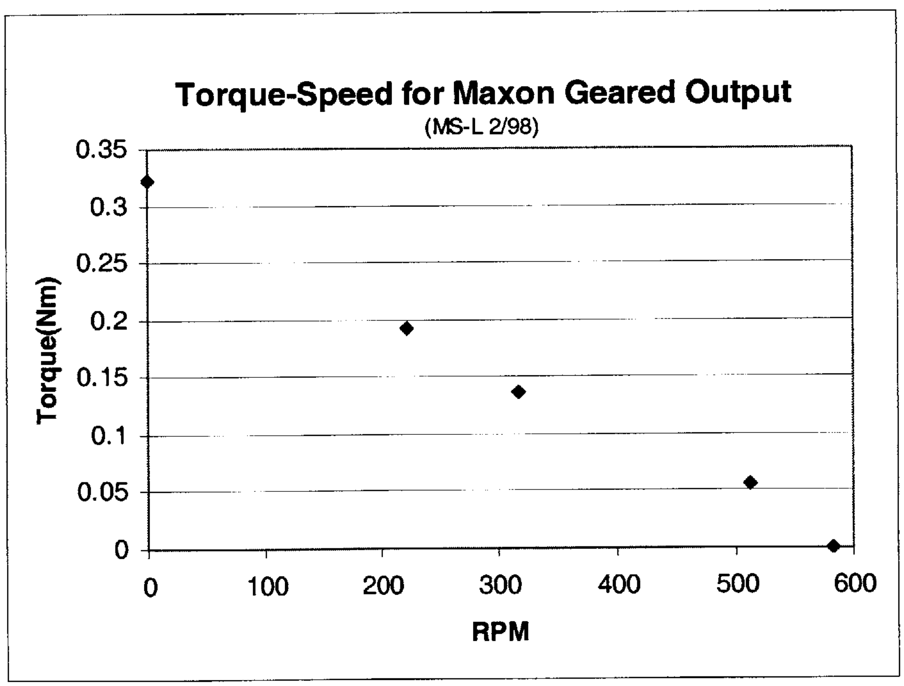


Figure A.6 Experimental Torque-Speed data for Maxon Gearmotor at geared output shaft. Note linearity of curve due to efficient gearbox.

Maxon Gearmotor Geared Output

Load	Torque	Speed	
kg	**Nm**	**rpm**	Test Voltage
0.88	0.19	184	13.8 **V**
0.88	0.19	213	
0.88	0.19	188	
0.88	0.19	216	
0.88	0.19	222	
0.88	0.19	248	
0.88	0.19	228	
0.88	0.19	245	
0.88	0.19	240	
0.88	0.19	233	
0.88	0.19	233	
0.00	0.00	594	
0.00	0.00	591	
0.00	0.00	564	
0.26	0.06	375	
0.26	0.06	512	
0.26	0.06	512	
0.26	0.06	512	
0.62	0.14	331	
0.62	0.14	328	
0.62	0.14	302	
0.62	0.14	313	
0.62	0.14	308	
0.62	0.14	294	
0.62	0.14	291	

Avg speed	Torque
rpm	**Nm**
222.7	0.19
583.0	0.00
512.0	0.06
316.4	0.14
0	0.32

Figure A.7 Spreadsheet showing raw data and calculations for Torque-Speed curve for Maxon gearmotor geared output.

A.4 Black and Decker Motor

These motors were donated to the course by Black and Decker and are from small cordless power screwdrivers from the popular VersaPak line. The motor is a small 3.6V DC motor manufactured by Johnson Controls, of the same size as the common Mabuchi 380 series. The screwdrivers achieve the torque required to drive screws by incorporating a 2-stage planetary gearbox with an 81:1 reduction ratio. In order to use the motor with the gearbox, it is usually necessary to remove the rest of the plastic housing (battery compartment and switch) to save space.

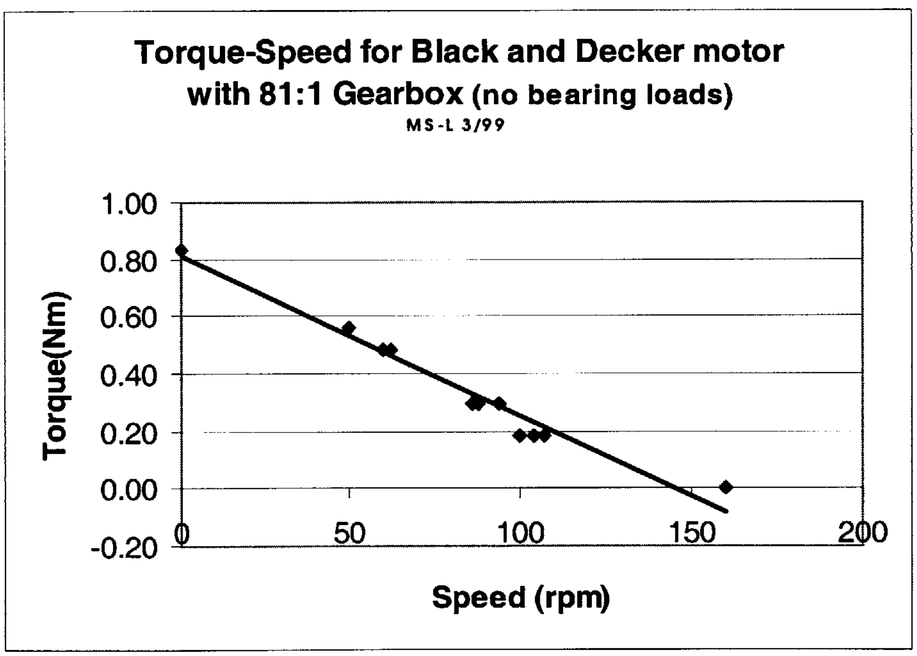


Figure A.8 Torque-speed data taken for Black and Decker motor with gearbox at 5V.

Black and decker motor with Gearbox 81:1

At	5	**V**	Kv	40	
Stall torque	0.828	**Nm**			
No load speed	200	**rpm**			
Max power	4.3354	**W**			
Without gearbox:					
Electrical power tests					
speed	no load	stall	inbetweer	inbetwee	inbetween
Terminal **Volts**	5	1	3	4	2
Current **(A)**	0.85	4.8	2	1.36	3.25
Armature resistance		0.21	**Ohms**		
Spool radius	0.75	**in**			
	0.0191	**m**			

tests on 3/22/99 with spool on output shaft

weight per motor 0.4 kg

# motors lifted	Torque **Nm**	length **in**	length **m**	time **s**	speed **rpm**
1	0.07	30	0.76	3.5	109.13
1	0.07	30	0.76	3.5	109.13
1	0.07	30	0.76	3.5	109.13
2	0.15	29	0.74	4	92.31
2	0.15	29	0.74	3.7	99.79
2	0.15	29	0.74	3.8	97.17
3	0.22	29	0.74	4.2	87.91
3	0.22	29	0.74	3.8	97.17
3	0.22	29	0.74	4.1	90.06
3	0.22	29	0.74	4	92.31
5	0.37	54	1.37	9.8	70.16
5	0.37	56	1.42	9	79.22
5	0.37	54	1.37	9.3	73.93
5	0.37	59	1.50	10.2	73.65

Figure A.9a

Spool radius	0.8 **in**				
	0.0203 **m**				

tests on 3/25/99 with spool on bearings and coupling to motor

mass (kg)

0	0.00				160.00
1	0.19	63	1.60	8	100.27
1	0.19	63	1.60	7.7	104.17
1	0.19	63	1.60	7.5	106.95
1.6	0.30	59	1.50	8	93.90
1.6	0.30	59	1.50	8.5	88.38
1.6	0.30	59	1.50	8.7	86.35
2.6	0.49	59	1.50	12	62.60
2.6	0.49	59	1.50	12.5	60.10
3	0.56	59	1.50	15	50.08
	0.83				0.00

Averaged number motors lifted	Torque **Nm**	avgspee **rpm**	Power **W**
1	0	200	0
2	0.07	109.13	0.85344
3	0.15	96.424	1.50808
5	0.22	91.863	2.15511
	0.37	74.24	2.9028
	0.828	0	0

Figure A.9b

A.5 Polaroid Motor

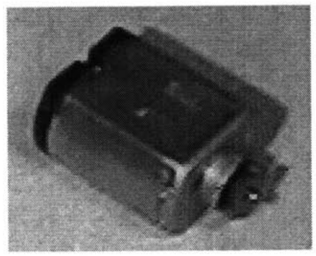


Figure 2.72 Polaroid motor for 2.007

This small DC motor is called the Polaroid motor because it was donated by Polaroid, and

TABLE 2.9 Data for Polaroid motor at 13.8V

No Load Speed	**Stall Torque**	**Length**	**Dia.**	**Shaft Dia.**
19000 rpm	0.0722 Nm	54 mm	40 mm	3 mm

is usually found in Polaroid cameras. Each kit contains two motors, one mounted in a complex camera geartrain. These motors are meant for use at lower voltages and are in danger of burning out at the 13.8V that comes from teh power supplies. However, with very efficient bearings, they have been used to spin cylindrical flywheels and thereby shoot street hockey balls up to 8 feet.

A.6 Silver Maxon Motor

This motor is used relativley rarely. It has low torque, but operates efficiently.

TABLE 2.10 Data for Silver Maxon at 13.8V

No Load Speed	Stall Torque	Length	Dia.	Shaft Dia.
3750 rpm	0.0722 Nm	54 mm	40 mm	3 mm

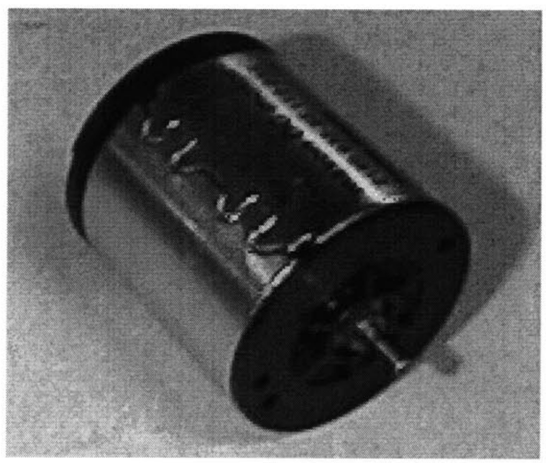


Figure 2.73 Silver Maxon DC motor.

Appendix B

1999 PROBLEM SETS

B.1 Problem Sets

Problem Sets- weekly homework assignment to be turned in for evaluation-- were a rarity for this course until relatively recently. The problem sets have evolved over the past 5 years to become what is hopefully a cohesive set of tasks that tracks the design process taught in class.

1999 Problem Set Development Team

Part of the author's role as a Teaching Assistant for 2.007 in the Spring of 1999 involved updating, revising and publishing Problem Sets. No further major revisions in the Problem Sets are planned.

These Problem Sets represent the latest edition of a body of assignments that was originally created around 1996 by course staff. Joachim Sihler also contributed to the development of the 1999 Problem Sets. The team responsible for the 1998 problem sets included Eberhard Bamberg, Roger Cortesi, and the author.

Copies of the Problem Sets as they were distributed for 1999 follow. Each Problem Set is followed by a paragraph written in retrospect about its effectiveness.

Major Changes from Previous Versions

Several changes were made between the previous version of the Problem Sets and the version for 1999. New examples were integrated into Problem Sets 1 and 2, technical examples were published as accompaniments to Problem Sets 4 and 5, and new tasks were added in the final construction and testing phase of the project (Problem sets 10 and 11).

In addition, the scheduling of the steps in concept generation and selection was condensed. The goal of this was to allow more time for actual design, engineering and manufacturing. This condensing of the concept selection process was done in response to observed reality that students often selected their favorite designs even when the Problem Sets still asked them to evaluate different ones. The carrying along of already dismissed concepts to satisfy the Problem Sets is undesirable. The principle goal of the concept selection phase in this course is to arrive at a concept that the student can use to learn the remaining steps of the design process.

B.2 1999 Problem Set 1

2.007 Problem Set 1

"Learning From the Past; Designing for the Future"

Due Week 2 (2/8 - 2/12, 1999)

Objective

The objective of this problem set is to study a former contest (Ballcano), reverse the engineering process, and perform a trial run at the design process that you will be learning this semester. Learning from the past is an invaluable tool for designing for the future.In addition, you will begin to develop strategy and machine concepts for this year's contest, MechEverest.

Grading

You will be part of a 3 person grading team: each person will review and make comments and grade each other person's problem sets. Your section instructor will review the grading. Your grade for the course will be affected by how well you evaluate the work of others (a critical engineering function). Please make sure your section instructor can tell which comments were made by whom (use different colors, for example).

Grader	Problem 1 (10 pts.)	Problem 2 (10 pts.)	Problem 3 (10 pts.)	Problem 4 (10 pts.)	Manufacturing Q's (10 pts.)	Total
Instructor						
Group Grading Total						

Problem 1 (10 points)

Review the description of last year's contest, Ballcano. As part of the first lecture you will also watch the video. List various strategies you observed and develop a set of criteria that you would use to judge the strategies shown (i.e. how much does it depend on driving skill, how crucial is the timing, how vulnerable is it, how flexible it is, what is the scoring potential, etc.)
Pick three different ones and apply your criteria. Which strategy would you chose, and why? (Not necessarily the winning strategy).

There are five copies of the video at Barker Engineering Library, and it can be reviewed during their normal hours (Monday - Thursday 9am - 8pm, Friday 9am - 6pm, Saturday 11am - 6pm, Sunday 1pm - 8pm).

EXAMPLE STRATEGIES

Strategy 1: Dumptruck
Drive to base of hill, wait for balls to fill up in bucket. Drive to 2-point (raised) hole and dump. If time allows, repeat.
Strategy 2 : Ballthrower
Start out on top of 2 point hole. Drive to base of hill, leaving a big funnel behind. Use ramp to gather balls from hill, shoot at funnel, which diverts balls into hole.
Strategy 3: Forklift
Try to disable the opponent by flipping over, etc. Then go get a point or 2.

EXAMPLE CRITERIA used to evaluate various strategies

TABLE B.1 Example Criteria

Criteria	Descriptions
Potential to score	Does the strategy lend itself to scoring many points during the contest time?
DefensiveCapability	How well can the strategy defend against an attacking opponent?
OffensiveCapability	How well can the strategy, within the scope of the rules, successfully impede the opponent?
Tolerance for inaccuracies	How crucial is accuracy in your manufactured parts?
Technical simplicity	How easy is it to design and build a machine for this strategy?

TABLE B.1 Example Criteria

Criteria	Descriptions
Operational simplicity	How easy will it be to drive the machine?
Flexibility	How well can the strategy deal with different opponents and their attempts to win?
Robustness	How resistant is the strategy to disturbances? (attacking opponents, difference between tables, etc)
Potential to get a high seeding score	During the in-lab contest, the seeding for the first night will be determined by having an individual machine running against time only. Number of points scored here determines seeding (best vs. worst in 1st round)

EXAMPLE Evaluation of the strategies

TABLE B.2 Sample Strategy Evaluation

scoring: low: 0-1 points, medium: 2-3 points, high: 4-5 points, excellent: 6			
Criteria	Strategy1: Dumptruck	Strategy 2: Ballthrower	Strategy 3: Forklift
Potential to Score	4	5	1
Defensive Capability	2	2	2
Offensive Capability	2	2	4
Tolerance for inaccuracies	3	2	3
Technical simplicity	4	2	3
Operational simplicity	3	2	4
Flexibility	3	1	4
Robustness	4	3	5
Potential to get a high seeding score	5	5	1
Total	30	24	27

Problem 2 (10 points)

Talk to some former 2.007 students (e.g. your UAs, people in your living group, etc.) and ask them about their experiences with 2.007. Ask them about their machines and how they performed, and the design process they followed, etc.

What did you learn from talking to former 2.007 students?

Some Possible Questions:

1. What kind of strategy did you use? How important is it to find a good strategy?

2. Could you finish your machine in time?

3. Did you think that following the problem sets helped / would have helped finishing your machine in time?

4. How well did you perform during the contest?

5. If you had to do this course again, what would you do differently?

6. Is there any part of the design process that you feel you should have spent more time on?

7. What were your greatest difficulties?

8. Did you use any software tools to design your machine? If so, do you think they helped?

Problem 3 (10 points)

Review the description of this year's contest, MechEverest. List a set of at least 5 possible strategies (things a machine might be designed to do) and briefly discuss them in terms of complexity/simplicity, robustness/vulnerability, feasibility, and scoring potential.

Note: When describing strategies, list them in a play-by-play manner using numbered sentences (a list). This makes them easy to reference. The strategy should read like a script for a play. Number drawings so that they can be referenced later.

Develop a list Functional Requirements and possible Design Parameters for each strategy (see p4 for DP examples)

EXAMPLE: If your strategy were to ballistically deposit pucks into a scoring slot, these might be some of your FR's:

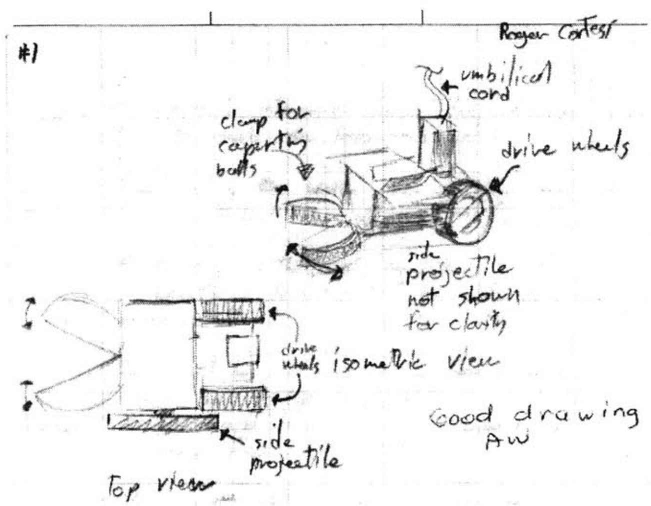
1. Able to project a puck to a height of Y and a range of X
2. Repeatable/accurate enough to have puck actually enter slot.
3. Able to throw multiple pucks
4. Uses only available parts and material
5. Operated by 1 person
6. Easy to set up for contest

Problem 4 (10 points)

Make simple isometric sketches of at least 5 machine concepts that could execute one or several of the strategies from Problem3.

For each of the sketched designs, develop a list of Functional Requirements, possible Design Parameters, and Dominant Physics (e.g. F=ma, Power = force * velocity, Sigma=Mc/I)

EXAMPLES:



This is the type of sketch we're looking for here: 3-D, with functionality communicated by simple labels.

EXAMPLES:

Here are some simple examples of FRDPPh that might need to be considered for your concepts:

TABLE B.3 FRDPPh Examples

Functional Requirement	Possible Design Parameters	Relevant Physics
Be able to push opponent out of the way	Number of driven wheels; Traction material	Traction2wd:F=mu(tire)*Mg/~2 4wd:F=mu(tire)*Mg ; Motor: F=T/r, T - stall torque of motor, r - wheel radius
Lift opponent machine of mass M	Forklift	F=M*g

TABLE B.3 FRDPPh Examples

Functional Requirement	Possible Design Parameters	Relevant Physics
Prevent machine of mass m from tipping over when lifting opponent of mass M	Counterweight, Length of forklift prongs	m*L1 > M*L2, L1 - distance of machine's C.G. to pivot point L2 - distance of C.G. of load to pivot point
Reliably climb an incline plane without skidding wheels	Traction material, Extra normal force	no extra normal force: tan (phi) < mu, phi - incline angle; mu*(N +Mg*cos(phi)) >Mg*sin(phi) N - extra normal force, Mg weight of machine --Watch out for reaction torque... -Calculate as leverage
Limit deflection of an extended arm when a force is applied at its tip	Beam thickness, section (I-beam, sandwich structure) Youngs modulus	x=FL3/3EI, L - length of arm, E - young's modulus, I - section moment of inertia.
Drive quickly to the ramp	Wheel size, Motor speed, Gear ratio	v=pi*d*n d - diameter of wheel, n - no load speed of motor
Highly precise control of a motor	Gear ratio, Control circuit (on/off or variable)	Gearing: n1*w1=n2*w2 n - # teeth, w - rotational velocity
Limit stress of a structure in bending	height and width of cross sectional area, Young's modulus	sigma=Mc/I M - max. moment, I - moment of inertia c - distance from neutral axis to most stressed material

General Design Questions (10 points)

The answers to most of these question can be found in the 2.007 materials handouts. More detailed information can be found in Machinery's Handbook or similar references.

1. Why should you always be wearing safety glasses and closed shoes (no sandals!) in lab?

2. What are the important parameters for selecting cutting speeds and feed rates for machining?
3. What is a good speed (rpm) for drilling a 1/4" hole into a mild steel using a HSS drill bit? How does this change when drilling the same hole into Aluminum? (hint: Check out Machinery's Handbook or similar resources)

- Enabling Grade for ME students: In order to receive your grade for your problem set, you must have satisfactorily completed the portfolio assignment from 2.670, and turn in a hardcopy with this problem set.

B.2.1 Observations Regarding Problem Set 1

This problem set was published with extensive examples to communicate the concepts that students were asked to apply, and to give a general impression of the level of detail expected. Unfortunately, a large number of students turned in solutions to Problem 1 using remarkably similar selection criteria to those in the examples. This most likely indicates a perception among students that they couldn't come up with any better criteria, though the examples were far form perfect. Still, most students did add several original criteria. With more experience about what works, what fails unexpectedly, etc.- such as students have at the end of the course, it is likely easier to come up with an original set of evaluation criteria. So it is not entirely clear whether the amount of example-emulation was due to unfamiliarity with the material or the content, style and presentation of the examples. As a reaction, the amount of detail in the examples was reduced in later problem sets, and focus shifted from providing complete sample solutions to simple illustrative examples of key points only.

B.3 1999 Problem Set 2

2.007 Problem Set 2

"Selecting and Refining Concepts"

Due Week 3 (2/15 - 2/19, 1999)

Objective

The objective of this problem set is to continue to develop concepts and possible machine modules for this year's contest. You will put the modules together to create suitable machines, create simple sketch (3-D) models of your concepts, and identify points of risk. You should not discuss this problem set with your grading partners, (or else you will not be able to cross pollinate well). Feel free to discuss ideas and thoughts with other people. Your section instructor will be most displeased if four people turn in the same problem set!

Grading

You are responsible for using the Rohrbach method for grading your problem sets. You will be part of a 3 person grading team. Each person will review, make comments and grade each other person's problem set. Group grading is expected to take at most one hour, and should be completed before lab. Evaluating the work of others is a critical engineering function, so your section instructor will be looking for constructive comments and realistic assignment of grades from everyone. The grading group as a whole will receive a grade based on the quality of their group grading. Your section instructor will appreciate being able to tell who made which comments, so please initial them or use a unique color.

Grader	Problem 1 (10 pts.)	Problem 2 (10 pts.)	Problem 3 (10 pts.)	Problem 4 (10 pts.)	Manufacturing Q's (10 pts.)	Total
Instructor						
Group Grading						
Total						

Problem 1 (12 points)

* If you have come up with any new machine or module concepts, please introduce them here with a simple isometric sketch, and briefly cover PS1 problems 3 and 4 for those new concepts.

Develop a list of criteria useful to assess all possible aspects of your designs. Examples are scoring potential, ease of manufacture, number of different parts required, flexibility of strategy, etc. Using the concepts created in Problem 4 of Problem Set 1, create a Pugh Chart with the above found criteria. To do so, pick one design as a baseline by which the remaining ones are measured. Note that not all criteria are equally important. You may therefore want to implement weighting factors to describe the relevance of individual criteria.

Use the Pugh chart to select the 2 most promising concepts for more detailed study. One of these concepts will become your machine!

Example for a (weighted) Pugh Chart from Lecture 3:.:

Functional requirement	**Weight**	**Design 1** (Baseline)	**Design 2**	**Design 3**	**Design 4**
Accuracy	**3**	**0**	**+**	**0**	**+**
Ergonomics	**1**	**0**	**-**	**-**	**+**
Cost	**1**	**0**	**0**	**+**	**+**
Flexibility	**1**	**0**	**0**	**-**	**+**
Robustness	**2**	**0**	**+**	**-**	**-**
Manufacturability	**1**	**0**	**+**	**0**	**-**
Serviceability	**1**	**0**	**+**	**+**	**0**
Total + and -		**0**	**6**	**-2**	**3**

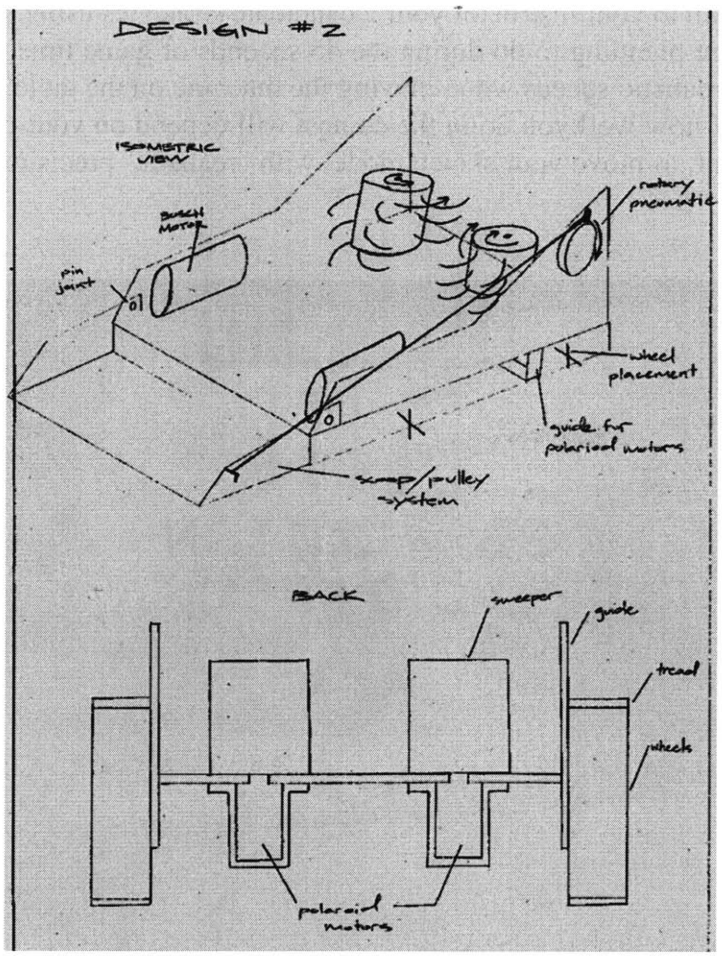
The criteria in this example are very generalized-- your criteria should be more specific. Please make sure your criteria are easily understood- use brief explanations below each criterion if necessary.

Problem 2 (13 points)

For your 2 candidate designs selected in Problem 1, identify the different modules and list their FR's.

Make larger, more detailed isometric sketches of your 2 candidate concepts (8x10 inch sketches are good here) Pay attention to scale, label actuators, and show the different modules by using a different color for each module

Example:



Sample sketch (yours should have color!) taken from
Geoffrey Wilson's Portfolio from last year (Ballcano)

Problem 3 (10 points)

Using cardboard, welding rod, tape, glue or any other available materials, make sketch models of your 2 candidate concepts that exhibit the basic functionalities of your proposed machine. Verify that your machine fits within the size constraints as given by the contest rules.

It is generally a good idea to keep a safety margin for the overall dimensions. We have already seen too many students trying to make their machines fit by using hack saws, sanders, etc.

At the table, explain to your instructor your 2 candidate strategies using the sketch models. Show what you are planning to do during the 45 seconds of game time. Try to mimic the real motions and realistic speeds when moving the machine on the table.

A good portion of how well you do in the contest will depend on your driving skills. It is therefore important, to move your sketch model with "realistic" precision.

Example:

This is a very nice cardboard sketch model by Pablo (Ballcano 1998)

This year, we are asking you to make 2 sketch models, so you don't need to get this fancy in PS2--the models need only be detailed enough to allow a basic demonstration of their strategies.

Problem 4 (10 points)

Points of Risk

For each of your 2 candidate machine concepts, identify the areas of greatest risk to your machine's ability to perform well. Consider not only **Technical** risks, but also **Strategy**, **Human Factors**, **Project Management** and other risks.

Examples:

1.) Very high accuracy required to throw a puck into the top slot
2.) Machine requires a lot of operator skill (remote controlling can be difficult!)
3.) Very sensitive to differences between tables
4.) Strategy is vulnerable to interference
5.) Machine has too many complicated parts for designer/builder's courseload

For each of your 2 candidate machine concepts, identify the Most Critical Module. (The "most critical module" has the greatest risk of not working well enough to satisfy its FR's. Perhaps it is the module with the most complicated physics, the most stringent machining tolerances, the most convoluted geometry, etc.)

General Design Questions (5 points)

The answers to most of these question can be found in the 2.007 materials handouts. More detailed information can be found in the Machinery's Handbook or similar references.

How can you improve the stiffness of thin structures (i.e. structures made from sheet metal)?
What is the modulus of elasticity (Young's modulus) of steel?
What is the modulus of elasticity of Aluminum?
How will you have to change your design when switching from steel to Aluminum in order to maintain its stiffness?

B.3.1 Observations Regarding Problem Set 2

Problems 3 and 4 are mostly new this year. The simple sketch models asked for in Problem 3 were incredibly valuable in lab sections, as they served as props for peer evaluation of various strategies and catalyzed a lot of brainstorming. They also provided a good means for introducing the ideas of pragmatism and realistic mechanical possibilities early in the design process. Problem 4 gets students thinking about minimizing risks from an early stage.

This problem set also shows the condensed schedule for concept selection, asking students to eliminate all but two of their concepts already. This was done to keep the workload reasonable (as compared to doing the same steps for 3 or 4 concepts) and in response to perceived reality of students' approach to this course. When they were asked to continue to evaluate more than 2 concepts in the past, it was obvious that many were keeping several concepts alive just to fulfill that requirement.

B.4 1999 Problem Set 3

2.007 Problem Set 3

"Selecting and Refining Concepts"

Due Week 4 (2/22 - 2/26, 1999)

Objective

The objective of this problem set is to further define and develop the concepts that you started creating in Problem Set 2, and then select an **ultimate concept**. You should not discuss this problem set with your grading partners, (or else you will not be able to cross pollinate well). Feel free to discuss ideas and thoughts with other people. Your section instructor will be most displeased if three people turn in the same problem set!

Grading

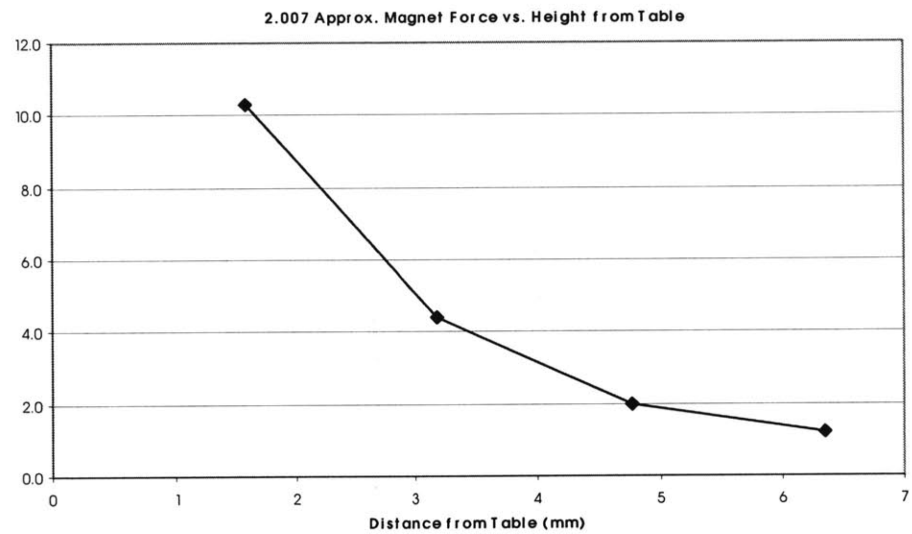
You are responsible for using the Rohrbach method for grading your problem sets. You will be part of a 3 person grading team. Each person will review, make comments and grade each other person's problem set. Group grading is expected to take at most one hour, and should be completed before lab. Evaluating the work of others is a critical engineering function, so your section instructor will be looking for constructive comments and realistic assignment of grades from everyone. The grading group as a whole will receive a grade based on the quality of their group grading. Your section instructor will appreciate being able to tell who made which comments, so please initial them or use a unique color.

Grader	Problem 1 (15 pts.)	Problem 2 (10 pts.)	Problem 3 (10 pts.)	Problem 4 (10 pts.)	GD Q's (5 pts.)	Total
Instructor						
Group Grading						
Total						

Problem 1 (15 points)

Design and carry out one or 2 simple physical experiments to gather experience to indicate whether or not you will be able to make your most critical modules work. This information will help you choose between your 2 candidate concepts.

Example:
For exploring feasibility of magnetic traction enhancement, a simple experiement with one of the kit magnets was performed. The magnet was placed on various thicknesses of rubber on top of the table, and maximum pull was measured using a spring scale.



Now real numbers can be used to determine what conditions need to be met (max. distance of magnet from table) to allow a magnet-rover to climb the 45-degree incline.

Problem 2 (10 points)

Using information gained from your physical experiements, revisit the Pugh chart to compare your 2 candidate concepts. You may use your criteria from PS2, Problem1, but you may find it necessary to use more detailed criteria at this stage.
Determine your Ultimate Concept--it may be one of your candidate concepts, or, if Pugh chart/BLP support it, some modular combination of your 2 candidate concepts.

Problem 3 (10 points)

Create a detailed, isometric sketch of this "ultimate" design and be sure to scale all modules according to their actual proportions. Trace over each module with a colored pencil so you can better see the function and connectivity of each module. Check that the proposed design does indeed satisfy the Functional Requirements, otherwise modify the list of Fr's and see if you are happy with it.

Problem 4(10 points)

- For your selected concept, prepare a general Bill of Materials (a table arranged by major parts and subassemblioes) What kit parts, actuators, etc, will be used, and do you have enough?
- Check your Power Budget -- will your actuators have the power to do what you want? Does the Power System supply enough power for your actuators to do what you want? (Abs. Max. electrical power input =13V*7A= 91Watts) See the web page for actuator data.
- Identify the Most Critical Module of your ultimate concept. (The "most critical module" has the greatest risk of not working well enough to satisfy its FR's. Perhaps it is the module with the most complicated physics, the most stringent machining tolerances, the most convoluted geometry, the highest stresses, etc.)

General Design Questions (5 points)

The answers to most of these questions can be found in Machinery's Handbook or similar references.

1.A 30" long steel bar with a square cross-section of 1" x 1" is firmly held at one end while a load of 5000 N is applied to its other end. Calculate the maximum bending moment and the location of its occurrence. What is the maximum deflection of the beam and where does it occur?

2.How could you improve the above described bar's stiffness without adding more weight to it (assume the load to have one distinct direction). Hint: what is the equation for calculating the moment of inertia.

3.What are the basic steps of tapping?

B.4.1 Observations Regarding Problem Set 3

In planning the problem sets and the course syllabus, it always seems like there isn't enough time for everything. Often material is applied before it has been covered in detail, necessitated by the pace of the course. This problem set deliberately puts the selection of a concept one problem set earlier than the previous year. This is an indication of the greater emphasis being put on mathematical and solid modeling, essentially getting those time-consuming parts of the process started as soon as possible. It also is a reaction to the fact that the complexity of the machines has increased every year, leading to a greater need for detailed design and manufacturing time. The loss of a week in the concept selection process was acceptable, and helped by the fact that the contest rules and kit contents were public form the beginning of the course.

B.5 1999 Problem Set 4

2.007 Problem Set 4

"Models-- Mathematical, Digital and Physical"

Due Week 5 (3/1-3/5, 1999)

Objective

The objective of this problem set is to justify the physics of the design with a mathematical model, and to begin to create a solid model of the design created in Problem Set 3. These models will allow you to design the details of your modules, and may point out areas that will require extra attention to ensure functionality.

Grading

You are responsible for using the Rohrbach method for grading your problem sets. You will be part of a 3 person grading team. Each person will review, make comments and grade each other person's problem set. Group grading is expected to take at most one hour, and should be completed before lab. Evaluating the work of others is a critical engineering function, so your section instructor will be looking for constructive comments and realistic assignment of grades from everyone. The grading group as a whole will receive a grade based on the quality of their group grading. Your section instructor will appreciate being able to tell who made which comments, so please initial them or use a unique color.

Grader	Problem 1 (20 pts.)	Problem 2 (20 pts.)	Problem 3 (10 pts.)			Total
Instructor						
Group Grading						
Total						

Problem 1 (20 points)

Create a Mathematical Model for your machine's Most Critical Module.* Outline and solve the basic physics to verify the performance of your Most Critical Module. We encourage you to use spreadsheets so you can very quickly redo your calculation as the design evolves.

*If you have no module which is more critical than the others, you may choose to do a first-pass treatment of your overall machine instead. You may also just pick one of your equally critical modules to model this week.

Please make sure that your grading team and instructor can easily follow what your mathematical model is. Don't just give them a printed spreadsheet-- make sketches that define your parameters and variables, and show which equations and principles you used to create your model.

Note that rather than just verifying the feasibility, you may find yourself using the physics models and spreadsheets to optimize certain design parameters.

See the web page's Handouts and Useful Info section for tips about doing calculations.

Examples of questions you may use your mathematical model to solve:

How much normal force is needed to allow the machine to climb 30, 45 degree inclines? Will the machine tip over if an arm is extended? For a bucket-dumping motion of 90 degrees, where should pistons be connected? Will they have enough force to do the job?

Calculations in design are very often iterative because they usually depend on many independent parameters. Using a spreadsheet whereby changing a number immediately updates the entire calculation can save you a lot of time. This way it's also much more fun to play around with the design parameters in order to "tweak" the machine's performance.

Problem 2 (20 points)

Using data from your mathematical model, create a model of your **Most Critical Module**.It may be...

...a digital solid model (Pro/Engineer is the only program officially supported for this class, but you may use any available 3-D CAD software)

OR

...a detailed physical model using cardboard, foam, foamcore, etc. AND a high-quality pencil and paper or CAD-drawn isometric.

OR

A high-quality set of hand-drawn three-view and isometric drawings

Future problem sets will ask you to update your model and drawing to correspond to as-built condition.

Problem 3 (10 points)

Create manufacturing drawings and process plans for a Bench Level Prototype of your Most Critical Module.

The best way to clarify what is meant by a BLP is: if you do it well, you should be able to incorporate your BLP into your final machine.

Design a BLP experiment that will allow you to verify the functionality of your MCM.

Build the BLP. (should be completed by week 6)

Example: Make drawings and begin to build a ball-shooter module. Your experiment could be to fixture the module in a vise, hook it up to power, and see how it works. Do you burn up the motors? does lube help? do you have vibration problems? can you shoot a ball? what spacing between rollers is optimal? etc...

B.5.1 Observations Regarding Problem Set 4

The idea of a Bench Level Prototype as presented in this problem set is a good one, but in general is not quite carried out in practice. At this stage of the course, many students are not sure of the final shape their machine will take, having little experience about what is feasible and how to integrate their different functional modules. However, many students do build things here that help a great deal at least in realizing how much time it takes to manufacture parts.

B.6 1999 Problem Set 5

2.007 Problem Set 5

"Complete Models-- Mathematical, Digital and Physical"

Due Week 6 (3/8-3/12, 1999)

Objective

The objective of this problem set is to justify the physics of the design with a mathematical model, and to finish creating the solid model you began in Problem Set 4.

Grading

You are responsible for using the Rohrbach method for grading your problem sets. You will be part of a 3 person grading team. Each person will review, make comments and grade each other person's problem set. Group grading is expected to take at most one hour, and should be completed before lab. Evaluating the work of others is a critical engineering function, so your section instructor will be looking for constructive comments and realistic assignment of grades from everyone. The grading group as a whole will receive a grade based on the quality of their group grading. Your section instructor will appreciate being able to tell who made which comments, so please initial them or use a unique color.

Grader	Problem 1 (20 pts.)	Problem 2 (20 pts.)	Problem 3 (10pts.)			Total
Instructor						
Group Grading						
Total						

Problem 1 (20 points)

Complete the Mathematical model of your machine that you began in PS4, Problem 1. (Different machine designs and different PS4's will require different specific approaches)

Calculations in design are very often iterative because they usually depend on many independent parameters. Using a spreadsheet whereby changing a number immediately updates the entire calculation can save you a lot of time. This way it's also much more fun to play around with the design parameters in order to "tweak" the machine's performance.

Problem 2 (20 points)

Using data from your mathematical model, make a solid model of your entire machine.
.Please create either...
A digital solid model (Pro/Engineer is the only program officially supported for this class, but you may use any available 3-D CAD software) For this option, please make sure to submit useful printed views of your model.
OR
A detailed physical model using cardboard, foam, foamcore, etc. **and** a high-quality pencil and paper or CAD-drawn isometric.
OR
A high-quality set of hand- or CAD-drawn three-view **and** isometric drawings.
Future problem sets will ask you to update your model and drawing to correspond to as-built condition.

Problem 3 (10 points)

Continue to create manufacturing drawings and process plans for the parts of your BLP. Build the BLP, and be prepared to show it to your instructor during lab in week 6 (when this PS is Due.)

B.6.1 Observations Regarding Problem Set 5

The use of digital solid modeling tools (i.e. 3D solid model CAD) is strongly encouraged here. The opinions among students about the effectiveness of its use are varied. Most agree that learning to use this type of software will be important in their mechanical engineering academic and professional careers. The specific software supported was Pro/Engineer, the use of which is introduced to all 2.007 students in the Independent Activities Period course 2.670 Mechanical Engineering Tools in January. SolidWorks was also available and was used by a number of students for its relatively faster learning curve. Many students swore by the use of CAD solid models- several relying on it to determine hole locations needed in flat sheets of metal before forming them into complex boxes, etc. Some students found the use of these CAD systems tedious and difficult, and poor uses of time compared to manufacturing, though these were certainly in the minority to those who used CAD and found it valuable. Of course some likely found it valuable because of its positive effects on grading, but in general there was a feeling of mild awe as students created corresponding digital and physical machines.

B.7 1999 Problem Set 6

2.007 Problem Set 6

"Manufacturing and Schedule I"

Due Week 7 (3/15-3/19, 1999)

Objective

The objective of this problem set is to produce drawings from which you will make parts for your machine. If you can create drawings on a CAD system fast and efficiently, then you should. If you are not CAD comfortable, a hand sketch is acceptable. *But before you cut anything, you must at least have a hand drawn sketch of what you want to do, when you step up to the machine to start cutting! Your grade will be severely truncated if you chop and build.*

Grading

You are responsible for using the Rohrbach method for grading your problem sets. You will be part of a 3 person grading team. Each person will review, make comments and grade each other person's problem set. Group grading is expected to take at most one hour, and should be completed before lab. Evaluating the work of others is a critical engineering function, so your section instructor will be looking for constructive comments and realistic assignment of grades from everyone. The grading group as a whole will receive a grade based on the quality of their group grading. Your section instructor will appreciate being able to tell who made which comments, so please initial them or use a unique color.

Grader	Problem 1 (10 pts.)	Problem 2 (20 pts.)	Problem 3 (10 pts.)	Problem 4 (10 pts.)		Total
Instructor						
Group Grading						
Total						

Problem 1 (10 points)

Make a Manufacturing Schedule listing all the parts in your machine, when you will make them, the material they will be made of, and how long you think it will take to manufacture them.

Problem 2 (20 points)

Prepare part drawings for parts to be presented in lab during week7. Engineering drawings would be great, but hand sketches are fine. Make sure to include the type of material and every relevant dimension such that a machinist with no prior knowledge of your design could machine the part correctly.

Problem 3 (10 points)

For every part from Problem 2, make a detailed process plan which describes step by step the fabrication of the part.

Problem 4 (10 points)

Manufacture the parts listed in Problem 2 and show them (with drawings) to your section instructor in lab during week 7.

How long did it actually take to make the parts compared to your plan in Problem 1?

B.7.1 Observations Regarding Problem Set 6

Problem set 6 kicks off the manufacturing part of the course and is due the week before spring break. At this stage, students are encouraged to manufacture their most critical module first. This encourages the tackling of the most risky technical problems up front, to prevent them from scuttling an almost-complete design in the end of the course. All students manufacture a Stirling engine as part of 2.670 in January, but for many this will be the first experience with making a part without instructions and machine setup for them, etc. As such, it is often encouraged that students begin to machine one or two simple parts that they know they will need at this point to get them accustomed to working in the shop.

The grading of parts by the section instructor is in practice more complicated than is stated in the problem set. The details are left up to the section instructor, and 2 different strategies are most common:

1. Students submit drawings in week 6 for parts they will make in week 7. Drawings are checked and approved by section staff and returned. This is a very time-consuming plan for the section staff.
2. Students submit parts and the drawings form which they were made for inspection by section staff in lab when the problem set is due. This is efficient for the section staff, as they need to keep up to date with the status of machines in any case. It does not quite guarantee that drawings shown were made before material was cut, but there is generally no need for suspicion in this matter.

B.8 1999 Problem Set 7

2.007 Problem Set 7

"Manufacturing and Schedule 2"

Due Week 9 (3/29-4/2, 1999)

Objective

The objective of this problem set is to produce drawings from which you will make parts for your machine. If you can create drawings on a CAD system fast and efficiently, then you should. If you are not CAD comfortable, a hand sketch is acceptable. *But before you cut anything, you must at least have a hand drawn sketch of what you want to do, when you step up to the machine to start cutting! Your grade will be severely truncated if you chop and build.*

Grading

You are responsible for using the Rohrbach method for grading your problem sets. You will be part of a 3 person grading team. Each person will review, make comments and grade each other person's problem set. Group grading is expected to take at most one hour, and should be completed before lab. Evaluating the work of others is a critical engineering function, so your section instructor will be looking for constructive comments and realistic assignment of grades from everyone. The grading group as a whole will receive a grade based on the quality of their group grading. Your section instructor will appreciate being able to tell who made which comments, so please initial them or use a unique color.

Grader	Problem 1 (10 pts.)	Problem 2 (20 pts.)	Problem 3 (10 pts.)	Problem 4 (10 pts.)		Total
Instructor						
Group Grading						
Total						

Problem 1 (10 points)

Update your Manufacturing Schedule (listing all the parts in your machine, when you will make them, the material they will be made of, and how long you think it will take to manufacture them.)

Problem 2 (20 points)

Prepare part drawings for parts to be presented in lab during week9. Engineering drawings would be great, but hand sketches are fine. Make sure to include the type of material and every relevant dimension such that a machinist with no prior knowledge of your design could machine the part correctly.

Problem 3 (10 points)

For every part from Problem 2, make a detailed process plan which describes step by step the fabrication of the part.

Problem 4 (10 points)

Manufacture the parts listed in Problem 2 and show them (with drawings) to your section instructor in lab during week 9.

B.8.1 Observations Regarding Problem Set 7

This problem covers parts manufactured during spring break. A small enthusiastic minority of students will make good use of the week of spring break to get a head start in manufacturing, though some need it to remedy fundamental design problems or complete the mathematical and solid models from problem sets 4 and 5.

B.9 1999 Problem Set 8

2.007 Problem Set 8

"Manufacturing and Schedule 3"

Due Week 10 (4/5-4/9, 1999)

Objective

The objective of this problem set is to produce drawings from which you will make parts for your machine. If you can create drawings on a CAD system fast and efficiently, then you should. If you are not CAD comfortable, a hand sketch is acceptable. *But before you cut anything, you must at least have a hand drawn sketch of what you want to do, when you step up to the machine to start cutting! Your grade will be severely truncated if you chop and build.*

Grading

You are responsible for using the Rohrbach method for grading your problem sets. You will be part of a 3 person grading team. Each person will review, make comments and grade each other person's problem set. Group grading is expected to take at most one hour, and should be completed before lab. Evaluating the work of others is a critical engineering function, so your section instructor will be looking for constructive comments and realistic assignment of grades from everyone. The grading group as a whole will receive a grade based on the quality of their group grading. Your section instructor will appreciate being able to tell who made which comments, so please initial them or use a unique color.

Grader	Problem 1 (10 pts.)	Problem 2 (20 pts.)	Problem 3 (10 pts.)	Problem 4 (10 pts.)		Total
Instructor						
Group Grading						
Total						

Problem 1 (10 points)

Update your Manufacturing Schedule (listing all the parts in your machine, when you will make them, the material they will be made of, and how long you think it will take to manufacture them.)

Problem 2 (20 points)

Prepare part drawings for parts to be presented in lab during week 10. Engineering drawings would be great, but hand sketches are fine. Make sure to include the type of material and every relevant dimension such that a machinist with no prior knowledge of your design could machine the part correctly.

Problem 3 (10 points)

For every part from Problem 2, make a detailed process plan which describes step by step the fabrication of the part.

Problem 4 (10 points)

Manufacture the parts listed in Problem 2 and show them (with drawings) to your section instructor in lab during week 10.

B.9.1 Observations Regarding Problem Set 8

At this point, students are for the most part realizing how little time they have left to finish their parts, and manufacturing efficiency dominates their concerns.

B.10 1999 Problem Set 9

2.007 Problem Set 9

"Manufacturing and Schedule 3"

Due Week 11 (4/12-4/16, 1999)

Objective

The objective of this problem set is to produce drawings from which you will make parts for your machine. If you can create drawings on a CAD system fast and efficiently, then you should. If you are not CAD comfortable, a hand sketch is acceptable. *But before you cut anything, you must at least have a hand drawn sketch of what you want to do, when you step up to the machine to start cutting! Your grade will be severely truncated if you chop and build.*

Grading

You are responsible for using the Rohrbach method for grading your problem sets. You will be part of a 3 person grading team. Each person will review, make comments and grade each other person's problem set. Group grading is expected to take at most one hour, and should be completed before lab. Evaluating the work of others is a critical engineering function, so your section instructor will be looking for constructive comments and realistic assignment of grades from everyone. The grading group as a whole will receive a grade based on the quality of their group grading. Your section instructor will appreciate being able to tell who made which comments, so please initial them or use a unique color.

Grader	Problem 1 (10 pts.)	Problem 2 (20 pts.)	Problem 3 (10 pts.)	Problem 4 (10 pts.)		Total
Instructor						
Group Grading						
Total						

Problem 1 (10 points)

Update your Manufacturing Schedule (listing all the parts in your machine, when you will make them, the material they will be made of, and how long you think it will take to manufacture them.)

Problem 2 (20 points)

Prepare part drawings for parts to be presented in lab during week 11. Engineering drawings would be great, but hand sketches are fine. Make sure to include the type of material and every relevant dimension such that a machinist with no prior knowledge of your design could machine the part correctly.

Problem 3 (10 points)

For every part from Problem 2, make a detailed process plan which describes step by step the fabrication of the part.

Problem 4 (10 points)

Manufacture the parts listed in Problem 2 and show them (with drawings) to your section instructor in lab during week 11.

B.10.1 Observations Regarding Problem Set 9

At this point, most students are scrambling to finish machining. There are some who are on schedule and putting finishing touches on their machines, some with finished machines that need redesign and new parts to function properly, and some who are looking at ways to remove complexity from what remains to manufacture, often sacrificing some module or function which was deemed to be optional. Most students have tested at least one major module at this point.

B.11 1999 Problem Set 10

2.007 Problem Set 10

"Manufacturing and Schedule 4"

Due Week 12 (4/19-4/23, 1999)

Objective

The objective of this problem set is to finish the manufacturing of your machine, and begin to practice and conduct objective testing. The testing may guide you to areas where a small improvment can yield an important overall performance improvement.

Grading

You are responsible for using the Rohrbach method for grading your problem sets. You will be part of a 3 person grading team. Each person will review, make comments and grade each other person's problem set. Group grading is expected to take at most one hour, and should be completed before lab. Evaluating the work of others is a critical engineering function, so your section instructor will be looking for constructive comments and realistic assignment of grades from everyone. The grading group as a whole will receive a grade based on the quality of their group grading. Your section instructor will appreciate being able to tell who made which comments, so please initial them or use a unique color.

Grader	Problem 1 (15 pts.)	Problem 2 (15 pts.)	Problem 3 (10 pts.)	Problem 4 (10 pts.)		Total
Instructor						
Group Grading						
Total						

Problem 1 (15 points)

Update your Schedule to include all remaining tasks before the end of the course. (list all the parts in your machine, when you will make them, the material they will be made of, and how long you think it will take to manufacture them.)

As your focus shifts from manufacturing to practicing driving, debugging and packaging your machine, include these tasks in your schedule.

If you have needed to alter your design for practical reasons or needed to make trade-offs to allow the on-time completion of your machine, describe the motivation for these changes, and update your solid and physics models to reflect your changes.

Problem 2 (15 points)

As you practice with your machine, try to practice under as real conditions as possible.

Keep a brief log of what happens during each run. Try to objectively analyze the performance of your machine in practice. For example, you might consider:

- What is your machine's average score?
- How repeatable is it? (standard deviation?)
- How sensitive is your machine to less-than-ideal situations? (umbilical, interference from opponent, driving errors, which side of the table it runs on, etc.)
- What specific problems have the greatest impact on your machine's performance? Try to use your test data to find the quantitative effects of each specific problem you identify.

Example:
When a friend guides the umbilical for you, your average score over 10 runs is 18 points. When the umbilical is not handled for you (i.e. contest conditions) your machine's average score over 10 runs is 12 points. Here the effect of the umbilical is an average of -6 points.

Are there any simple things you can do to improve the performance of your machine?

What are the Pros and Cons?

If you make modifications, describe the reasons for making them and study their effects (compare "before" and "after" data).

Problem 3 (10 points)

Prepare part drawings and process plans for parts to be presented in lab during week 12. Engineering drawings would be great, but hand sketches are fine. Make sure to include the type of material and every relevant dimension such that a machinist with no prior knowledge of your design could machine the part correctly.

If you are done with manufacturing, you get full credit for this problem.

Problem 4 (10 points)

Manufacture the parts listed in Problem 3 and show them (with drawings) to your section instructor in lab during week 12.

If you are done with manufacturing, you get full credit for this problem.

B.11.1 Observations Regarding Problem Set 10

Problem Set 10 contains new material in question 2. The explicit emphasis on structured testing was made because machines in general were not as close to completion as at this point of the course in previous years. For the most part, this was due to greater mechanical complexity of the average machine- it seems that the simplest machines possible for the 1999 contest were more complex than the simplest machines of previous years.

B.12 1999 Problem Set 11

2.007 Problem Set 11

"Final Preparation"

Due Week 13 (4/26-4/30, 1999)

Objective

The objective of this problem set is to conclude practicing and testing, and prepare the completed machine for shipping and competition.

Grading

You are responsible for using the Rohrbach method for grading your problem sets. You will be part of a 3 person grading team. Each person will review, make comments and grade each other person's problem set. Group grading is expected to take at most one hour, and should be completed before lab. Evaluating the work of others is a critical engineering function, so your section instructor will be looking for constructive comments and realistic assignment of grades from everyone. The grading group as a whole will receive a grade based on the quality of their group grading. Your section instructor will appreciate being able to tell who made which comments, so please initial them or use a unique color.

Grader	Problem 1 (10 pts.)	Problem 2 (15 pts.)	Problem 3 (10 pts.)	Problem 4 (15 pts.)		Total
Instructor						
Group Grading						
Total						

Problem 1 (10 points)

Update your Schedule to include all remaining tasks before the end of the course.

As your focus shifts from manufacturing to practicing driving, debugging and packaging your machine, include these tasks in your schedule.

If you have needed to alter your design for practical reasons or needed to make trade-offs to allow the on-time completion of your machine, describe the motivation for these changes, and update your solid and physics models to reflect your changes.

Problem 2 (15 points)

Continue to gather test data, perhaps with some of the problems you found last week resolved.

As you practice with your machine, try to practice under as real conditions as possible.

Keep a brief log of what happens during each run. Try to objectively analyze the performance of your machine in practice. For example, you might consider:

- What is your machine's average score?
- How repeatable is it? (standard deviation?)
- How sensitive is your machine to less-than-ideal situations? (umbilical, interference from opponent, driving errors, which side of the table it runs on, etc.)
- What specific problems have the greatest impact on your machine's performance? Try to use your test data to find the quantitative effects of each specific problem you identify.

Example:
When a friend guides the umbilical for you, your average score over 10 runs is 18 points. When the umbilical is not handled for you (i.e. contest conditions) your machine's average score over 10 runs is 12 points. Here the effect of the umbilical is an average of -6 points.

Are there any simple things you can do to improve the performance of your machine?

At this point in the game, weigh carefully the benefits and risks of modifying your machine.

If you make modifications, describe the reasons for making them, and describe their effects (compare "before" and "after" data).

Problem 3 (10 points)

Prepare part drawings for any last-minute parts or modifications to be presented in lab during week 13. Engineering drawings would be great, but hand sketches are fine. Make sure to include the type of material and every relevant dimension such that a machinist with no prior knowledge of your design could machine the part correctly.

Make a detailed process plan which describes step by step the fabrication of the part.

Manufacture the parts and show them (with drawings) to your section instructor in lab during week 13.

If you are done with manufacturing, you get full credit for this problem.

Problem 4 (15 points)

- Plan the steps you will need to take to prepare your machine for "shipping".

How will you store your machine in the kit bin? (Past contestants have noted that Buna-N rubber has a tendency to creep if left tensioned for a week.)
Are there any parts in your machine that wear quickly? Do you have fresh ones to use for the contest?
Have you done all the things you planned to leave until the end-- tightening fasteners, applying thread locker (red Loctite bottle)?

- Write a pre-contest checklist covering the things you will verify after unpacking your machine.

Example:
Check all fasteners for snugness. Tighten if necessary. Apply thread locker where necessary.
Check all wiring for damaged or loose connections.
Test run all motors using test station (there will be one in Ice Rink to allow resetting of machines without power from the table).

B.12.1 Observations Regarding Problem Set 11

This Problem Set contains new material in Problems 2 and 4. The explicit emphasis on structured testing and planning was made because machines in general were not ready as early this year as in past years. For the most part, this was due to greater mechanical complexity of the average machine- it seems that the simplest machines possible for the 1999 contest were more complex than the simplest machines of previous years. The emphasis on efficient testing and preparation were intended to help counter some of the effects of the late completion of manufacturing.

B.13 1999 Problem Set 12

2.007 Problem Set 12

"Portfolio"

Due Monday 5/10/99

Objective

Designers, artists, architects, etc. very often prepare a collection of their ideas and projects to present them to customers, future employers, etc.
This portfolio will serve as documentation for your instructor of the totality of your 2.007 design effort, and should serve you well in job interviews, etc.

Problem 1 (50 points)

You are asked to outline the complete design process starting with the definition of the problem and going all the way to the finished machine. It is vital that you present the entire process including:

- definition of the problem
- finding the right strategy
- concept generation and selection
- detailed physics
- proof of concept
- design optimization
- manufacturing drawings
- testing
- finished "product"
- contest

Take a few photos of your machine and use them to explain the functionality of your design. You may also want to include pictures of you during the contest or while in the machine shop.
Tell us how your machine performed and what you would do differently if you had to do this course over again.
Ideally, you would have this portfolio published on the web, and hand in a hardcopy along with the URL to your instructor. A hardcopy-only portfolio is acceptable also.
Examples:

There is a good how-to document (MS Powerpoint presentation) available covering the creation of a portfolio. It can be found in the examples column on the problem sets page of the web site.
Student Portfolios from 1998
http://web.mit.edu/jnavarro/www/portfolio/2.007/
http://web.mit.edu/erios/
http://web.mit.edu/vinod/www/portfolio/ballcano/
http://duct-tape.mit.edu/mobius/projects/hod/

B.13.1 Observations Regarding Problem Set 12

Most students were glad to create a portfolio- many published them on their personal web pages. Describing the design and implementation of a project like this after completion is often beneficial. It can reveal more clearly the logical path followed, and point out areas needing improvement in the future. As such it is a very valuable part of the 2.007 experience, encouraging a retrospective assessment of the semester's work and cementing what was learned.

Appendix C

MANUFACTURING DRAWINGS AND PROCESS PLANS

C.1 Format of Drawings and Process Plans

The Mechanical Drawings and Process Plans for the construction of the sample machine are included here. In most cases, the parts were made by the author, and the included drawings were considered invaluable. Process plans were created once the drawing was complete, and in several cases, the exercise of developing a process plan highlighted required design changes in the part for manufacturing purposes. Drawings were generated from the solid geometry in Pro/Engineer, and by default are size A. Reproduction of drawings for this thesis causes the scale values to be unreliable. For parts that have 2D views generated for export to the CNC abrasivejet cutting machine, a full scale view is included as one drawing sheet with no frame or text- this indicates which geometry was sent to the waterjet cutter, and does not represent a formatting error.

The structure of the Pro/Engineer Assembly model is represented by the text version of its model tree. The organization of the drawings in this appendix attempts to track the structure of the model, making some exceptions by grouping related parts together.

C.2 Model Tree

The Model Tree is a symbolic representation in Pro/Engineer of the structure of an assembly model. Text versions of the model trees for the Puck Truck and the Rover assemblies are included here, and serve as a loose index for the order of the manufacturing drawings and process plans that follow.

C.2.1 Rover

Model Name

```
ROVER.ASM
    ROVER_CHASSIS.PRT
    BOSCH.PRT
    ROVER_WHEEL.PRT
    BOSCH_FLANGE.PRT
    ROVER_WHEEL.PRT
    FLEX_WHEEL_MT_O.PRT
    FLEX_WHEEL_MT_I.PRT
    TORSION_BEAM.PRT
    BOSCH.PRT
    HALF_MAGNET.PRT
    HOOK_MOUNT.PRT
    SQUARE_SHAFT.PRT
    ROVER_AXLE.PRT
    ROV_CHASS_BRACE_SHT.PRT
    ROV_CHASS_BRACE_SHT_L.PRT
    MAGNET_MT.PRT
    HALF_MAGNET.PRT
    MAGNET_MT_REAR.PRT
    ROVER_HOOK_PIN.PRT
    ROVER_HOOK_2.PRT
    ROVER_HOOK_STOP_PIN.PRT
```

ROVER_TREAD_2.PRT
FLEX_MT_I_MIRROR.PRT
FLEX_MT_O_MIRROR.PRT
ROVER_AXLE.PRT
ROVER_WHEEL.PRT
SQUARE_SHAFT_MIRROR.PRT
BOSCH_FLANGE_MIRROR.PRT
ROVER_WHEEL.PRT
ROVER_TREAD_2_MIRROR.PRT

C.2.2 Puck Truck

```
        Model Name
------------------------------------
PUCK_TRUCK3.ASM
        SKELETON3.PRT
        FLAT_PLATE.PRT
        PUCK_TRAY_REAR.PRT
        PUCK_TRAY_FRONT.PRT
        Pattern (PUCK.PRT)
                PUCK.PRT
                PUCK.PRT
                PUCK.PRT
                PUCK.PRT
                PUCK.PRT
                PUCK.PRT
                PUCK.PRT
                PUCK.PRT
                PUCK.PRT
                PUCK.PRT
        Pattern (PUCK.PRT)
                PUCK.PRT
                PUCK.PRT
                PUCK.PRT
                PUCK.PRT
```

PUCK.PRT
PUCK.PRT
PUCK.PRT
PUCK.PRT
PUCK_PUSHER.PRT
PUCK_TRAY_SLIDER.PRT
PUCK_TRAY_BRACE.PRT
PUCK_TRAY_BRACE.PRT
PUCK_TRAY_BRACE_PIV.PRT
PUCK_GUIDE_2.PRT
PISTON_ATTACH_2.PRT
PISTONPLNGR.PRT
CYLINDER.ASM
PISHOUSING.PRT
PISTON_NOSE_MOUNT.PRT
PUCK_TRAY_STOP.PRT
PUCK_PULL_PULLEY.PRT
TRAY_PIVOT_PIN.PRT
PUCK_TRAY_BRACE_FRONT.PRT
UCHANNEL.PRT
MAXON_PULLEY_2.PRT
PUCK_TRAY_BRACE_REAR.PRT
UCHANNEL_MIRROR_2.PRT
FORD.ASM
FORD.PRT
FORDFLANGE.PRT
FORD_PULLEY_FLANGE.PRT
FORD_PULLEY.PRT
FORD_PULLEY_FLANGE_O.PRT
1X3BOX.PRT
FORD_MOUNT_BLOCK.PRT
1X1BOX.PRT
MAXON.ASM
GMAXON.PRT

FLEX_COUPLING.PRT
MAXON_WINCH_SHAFT.PRT
MAXON_MOUNT.PRT
MAXON_WINCH_SHAFT_SUPPORT.PRT
PISTON_NOSE_MOUNT_MIRROR.PRT
PISHOUSING_MIRROR.PRT
PISTON_ATTACH_2_MIRROR.PRT
PISTONPLNGR_MIRROR.PRT
1X1BOX_MIRROR.PRT
PUCK_TRUCK_WHEEL.PRT
PUCK_TRUCK_WHEEL_BRACKET.PRT
PUCK_TRUCK_REAR_AXLE.PRT
PUCK_TRUCK_WHEEL.PRT
PUCK_TRUCK_WHEEL_BRACKET.PRT
PUCK_TRAY_STOP_MIRROR.PRT
FORD_MOUNT_BLOCK.PRT
TRUCK_ROVER_MATING_GUIDE.PRT
PUCK_ROVER_MATING_GUIDE_MIRROR.PRT
PISOTN_PIVOT_PIN.PRT
PISTON_PIVOT_BLOCK.PRT
PISTON_PIVOT_BLOCK_MIRROR.PRT
PUCK_TRUCK_WHEEL.PRT
PUCK_TRUCK_WHEEL_MIRROR_F.PRT
PUCK_TRUCK_FRONT_WHEEL_BLOCK.PRT

C.3 Relations Files

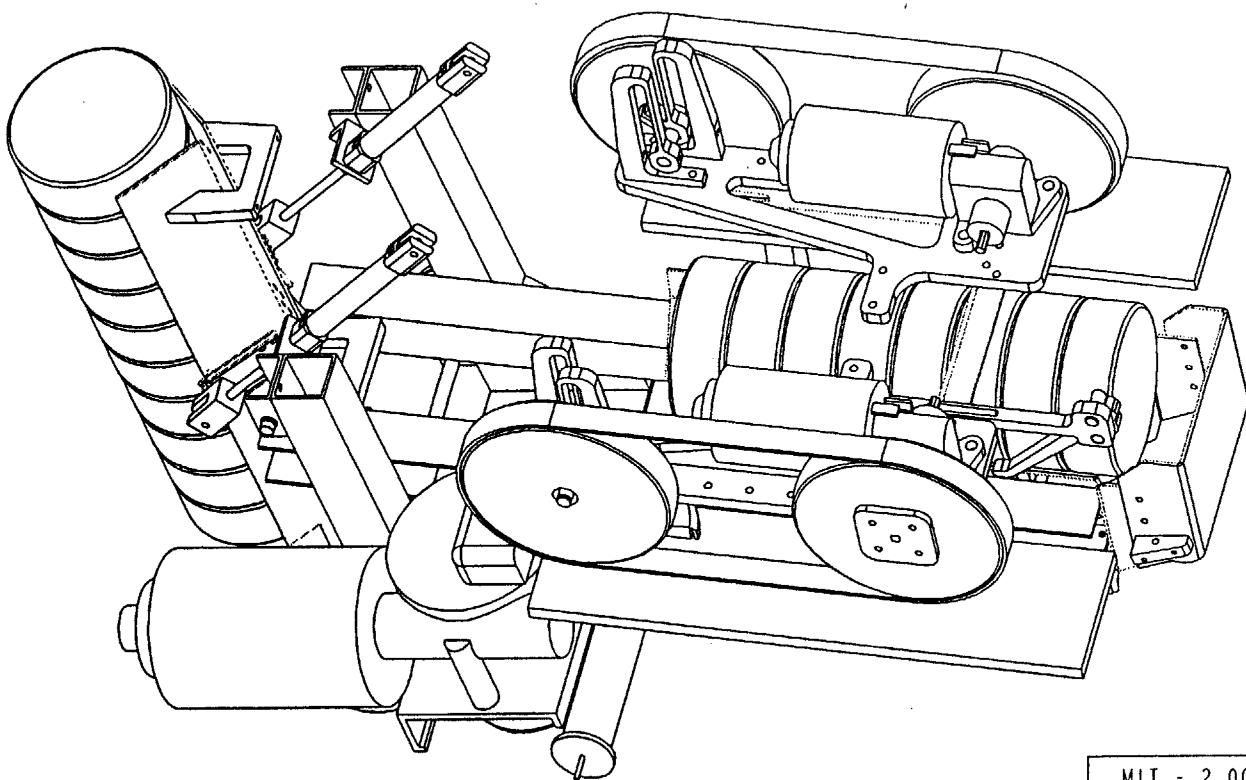
The Puck Truck assembly's relations file contains the "behind-the-scenes" formulas linking various parameters and dimension values in the model. In the case of this model, the most common use for relations is to force several dimensions to always have the same value without changing them all at the same time manually. The other, more interesting set of relations ensures that the Pro/Engineer model of the puck collection mechanism corresponds exactly in geometry with the mathematical (spreadsheet) model which is used to predict whether or not the mechanism will function correctly.

C.3.1 Puck Truck Relations

```
/* CODING TABLE  SESSION ID   MODEL NAME
/* CODING TABLE      3       PUCK_TRUCK3.ASM
/* CODING TABLE     50       SKELETON3.PRT
/* CODING TABLE     54       PUCK_TRAY_REAR.PRT
/* CODING TABLE     84       PUCK_TRAY_BRACE_FRONT.PRT
/* CODING TABLE     64       PUCK_TRAY_BRACE.PRT
/* CODING TABLE    106       FORD_MOUNT_BLOCK.PRT
/* CODING TABLE     66       PUCK_TRAY_BRACE_PIV.PRT
/* CODING TABLE

/*paste the following from puck-collection-mm.xls
a       =   1.377952756
b       =   1.181102362
Ypiston=    3.031496063
Lpiston=    3.149606299
Xpiston=    1.170784773

tray_angle=100
rear_tray_angle=0
/*rear_tray_angle=tray_angle
```

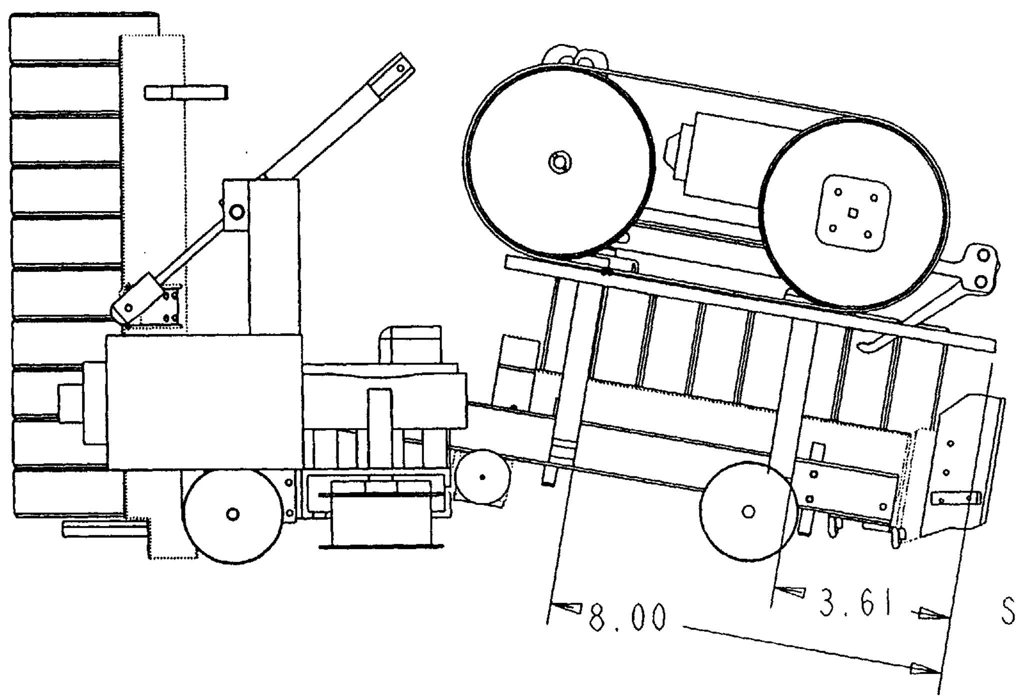
```
pivot_offset=.37
pivot_height=4

D1:50=tray_angle
D0:50=pivot_height
D4:50=pivot_offset
D5:50=pivot_height-delta
D3:50=rear_tray_angle
big_L=D2:54-D5:50
D2:3=big_L+tray_gap

D6:50=pivot_offset
D13:50=a
D9:50=b
D10:50=Ypiston

D12:50=Xpiston
D27:84=D27:64
D26:84=D26:64
D25:84=D25:64
D28:84=D28:64
D14:84=D14:64
D9:84=D9:64
D10:84=D10:64
D11:84=D11:64
D12:84=D12:64
D29:84=D29:64
D16:84=D16:64

D11:106=tray_angle
D11:66=D9:64
```

C.4 Drawings and Process Plans



Default Tolerances
X.X ±.1
X.XX ±.01
X.XXX ±.002
ANG ±.5°

	MIT - 2.007 License to Design Department of Mechanical Engineering 77 Mass. Ave, Cambridge, MA 02139
MATERIAL	TITLE 2.007 Sample Machine
INTERPRET PER ANSI Y14.5	Pro/E Drawing File PUCK_TRUCK3_ASM
ALL DIMENSIONS IN INCHES UNLESS SPECIFIED OTHERWISE	DESIGNER: | SCALE 0.350 | SHEET 1 OF 5



Default Tolerances
X.X ±.1
X.XX ±.01
X.XXX ±.002
ANG ±.5°

MATERIAL

INTERPRET PER ANSI Y14.5

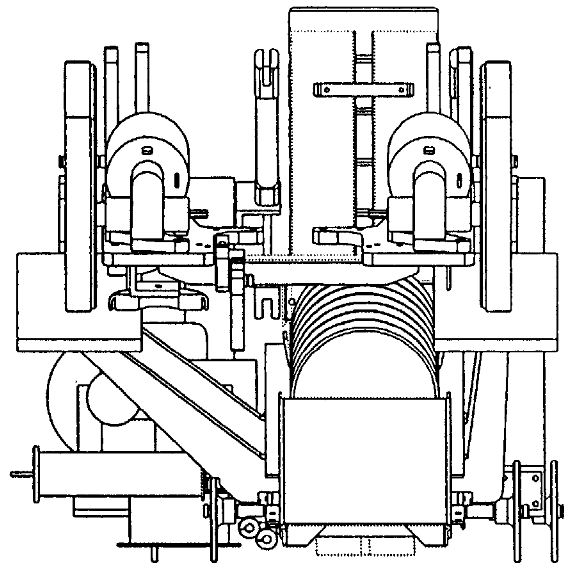
ALL DIMENSIONS IN INCHES UNLESS SPECIFIED OTHERWISE

MIT - 2.007 License to Design
Department of Mechanical Engineering
77 Mass. Ave, Cambridge, MA 02139

TITLE
Sample Machine

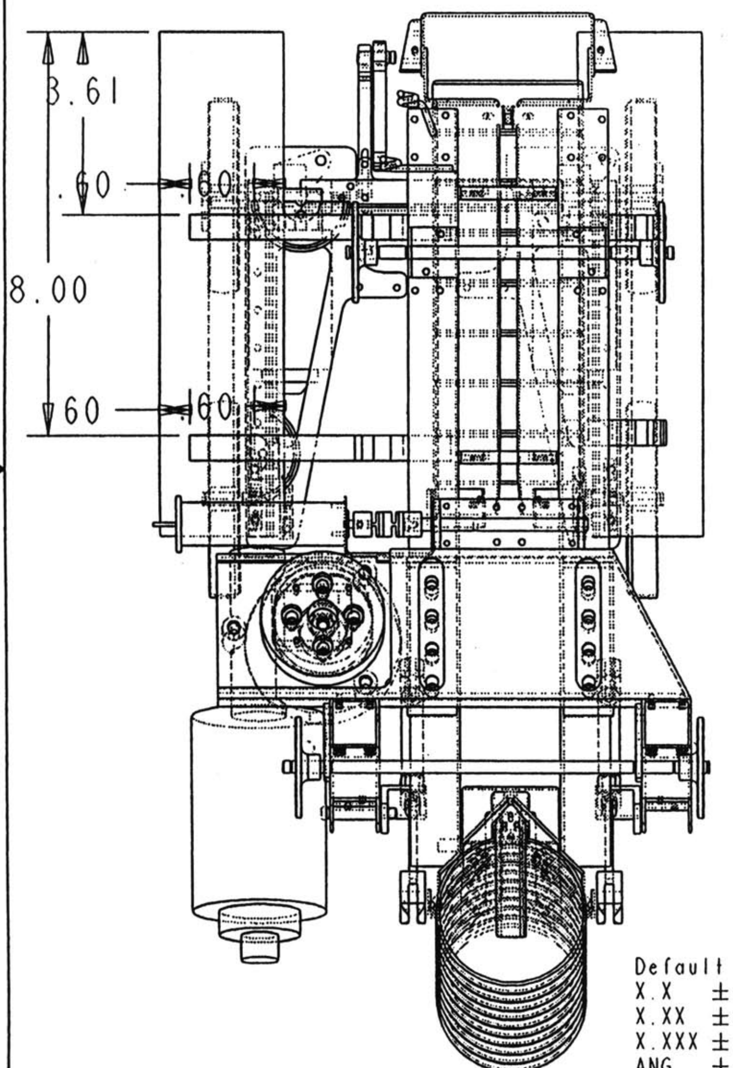
Pro/E Drawing File
PUCK_TRUCK3_ASM

DESIGNER: | SCALE 0.091 | SHEET 2 OF 5



Default Tolerances
X.X ±.1
X.XX ±.01
X.XXX ±.002
ANG ±.5°

MATERIAL &MATERIAL	MIT - 2.007 License to Design Department of Mechanical Engineering 77 Mass. Ave, Cambridge, MA 02139
INTERPRET PER ANSI Y14.5	TITLE &TITLE
ALL DIMENSIONS IN INCHES UNLESS SPECIFIED OTHERWISE	Pro/E Drawing File PUCK_TRUCK3_ASM
	DESIGNER: · SCALE 0.120 · SHEET 3 OF 5

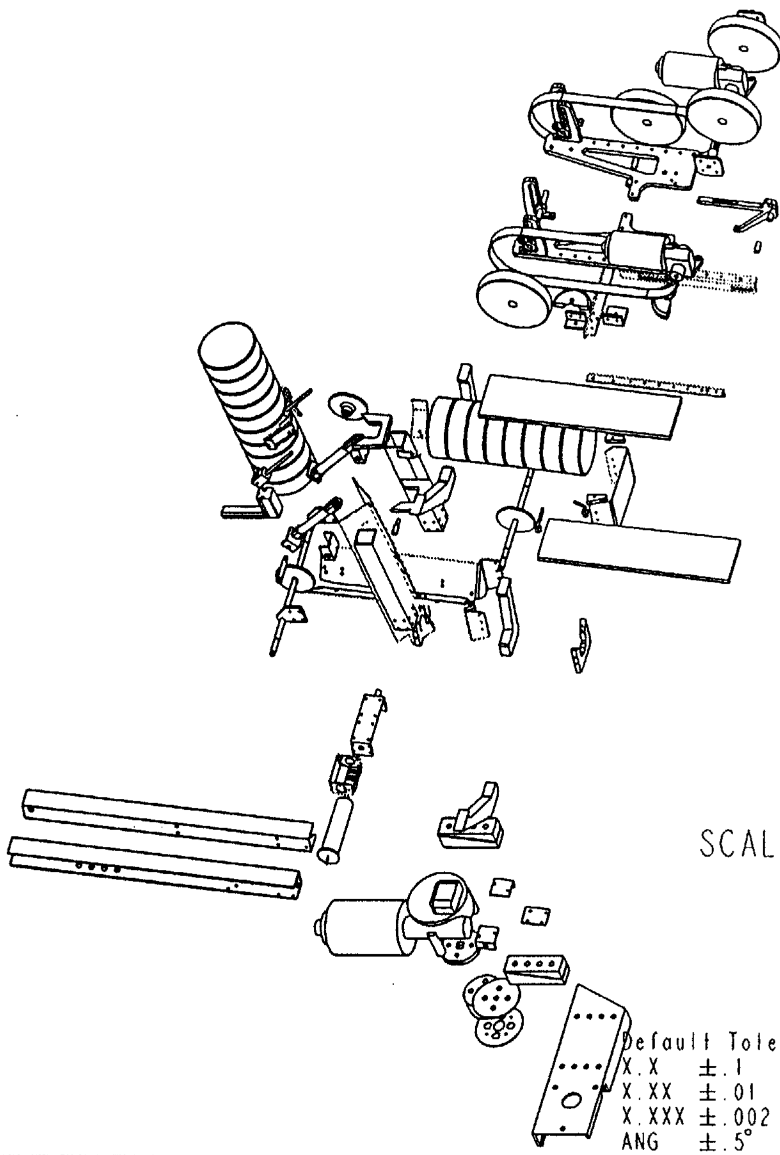


SCALE 0.300

Default Tolerances
X.X ±.1
X.XX ±.01
X.XXX ±.002
ANG ±.5°

	MIT - 2.007 License to Design Department of Mechanical Engineering 77 Mass. Ave, Cambridge, MA 02139
MATERIAL	TITLE Sample Machine
INTERPRET PER ANSI Y14.5	Pro/E Drawing File PUCK_TRUCK3_ASM
ALL DIMENSIONS IN INCHES UNLESS SPECIFIED OTHERWISE	DESIGNER: | SCALE 0.091 | SHEET 4 OF 5

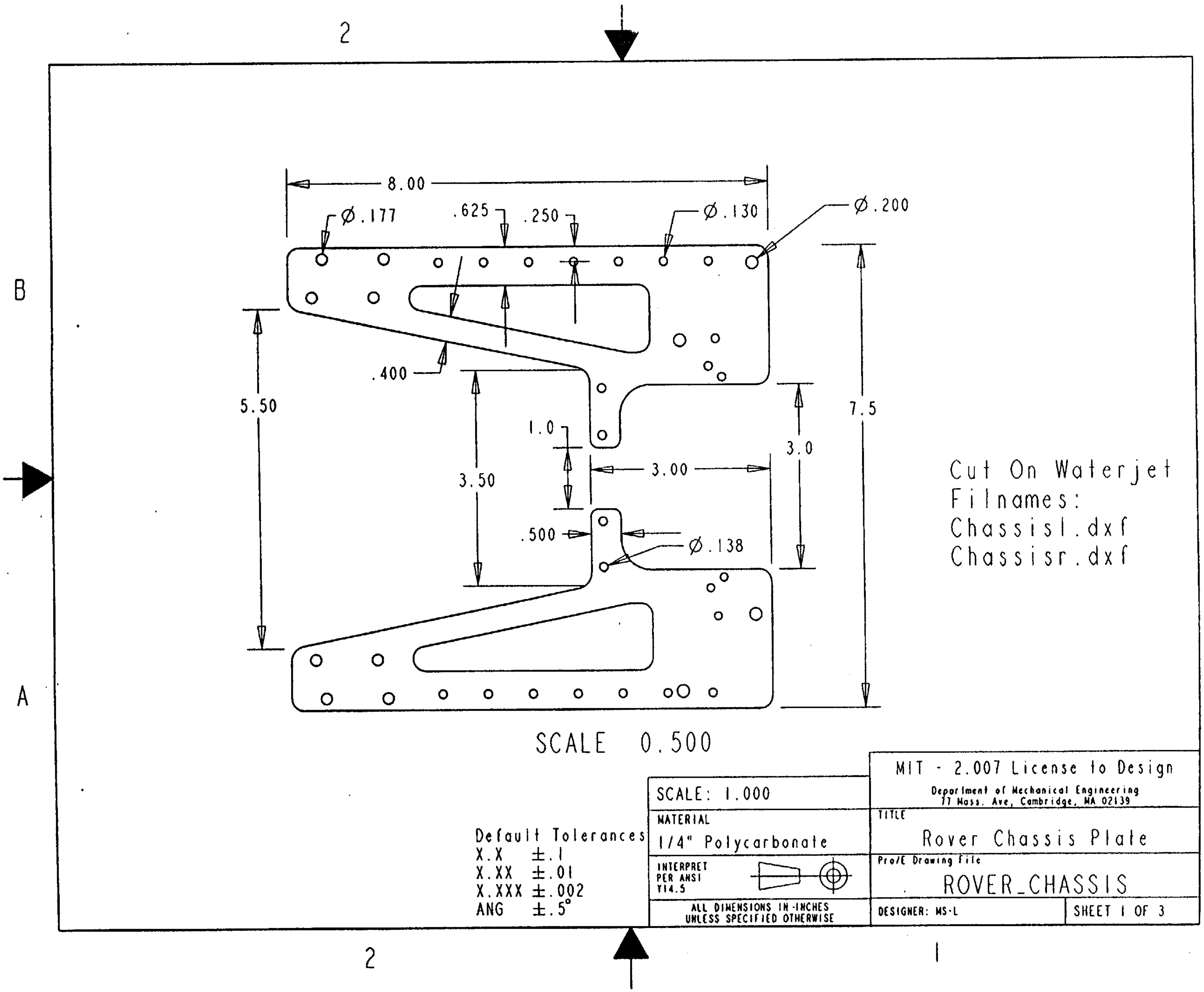
2 B A 2 1 B

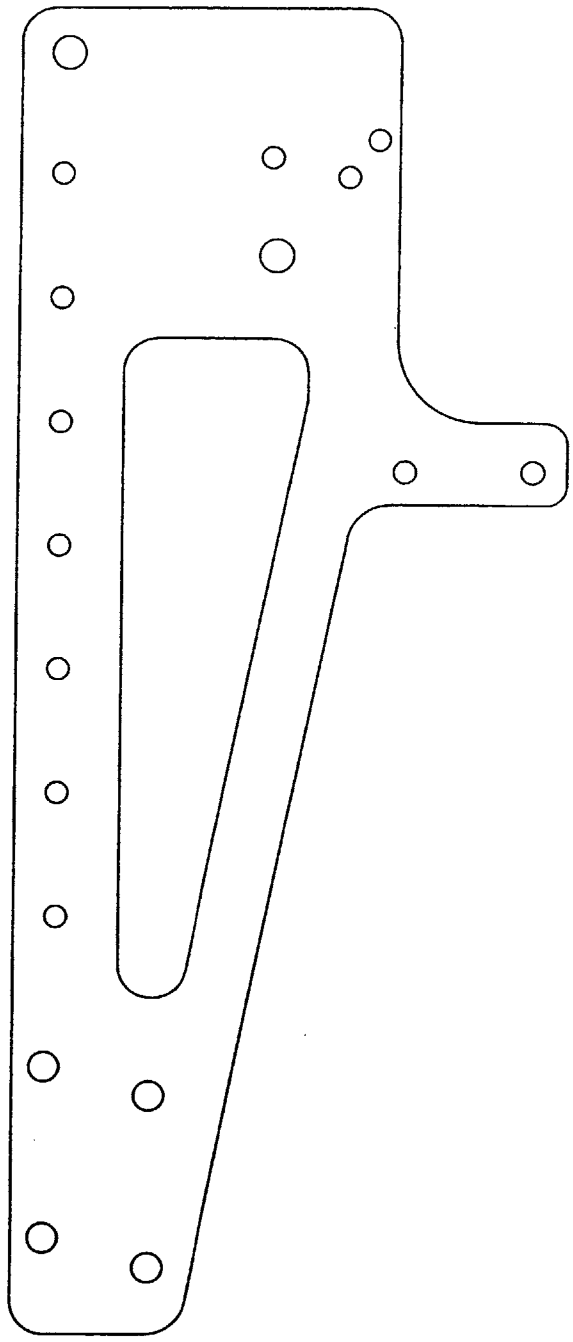


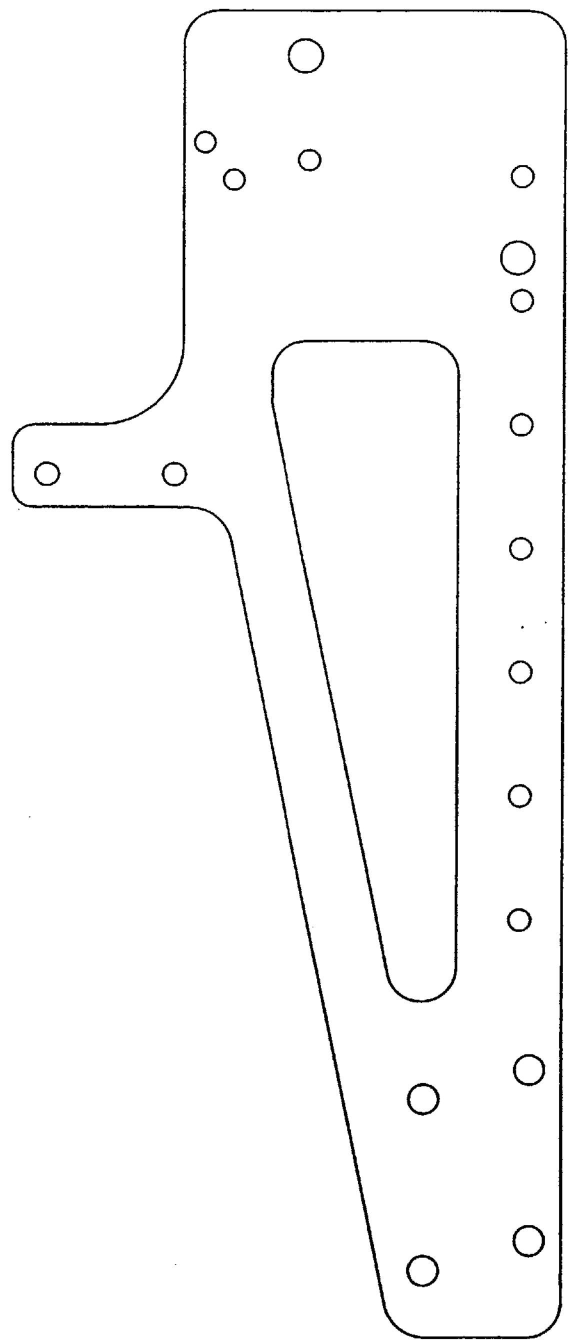
SCALE 0.120

Default Tolerances
X.X ±.1
X.XX ±.01
X.XXX ±.002
ANG ±.5°

	MIT - 2.007 License to Design Department of Mechanical Engineering 77 Mass. Ave, Cambridge, MA 02139
MATERIAL	TITLE Exploded View
INTERPRET PER ANSI Y14.5	Pro/E Drawing File PUCK_TRUCK3_ASM
ALL DIMENSIONS IN INCHES UNLESS SPECIFIED OTHERWISE	DESIGNER: · SCALE 0.091 · SHEET 5 OF 5

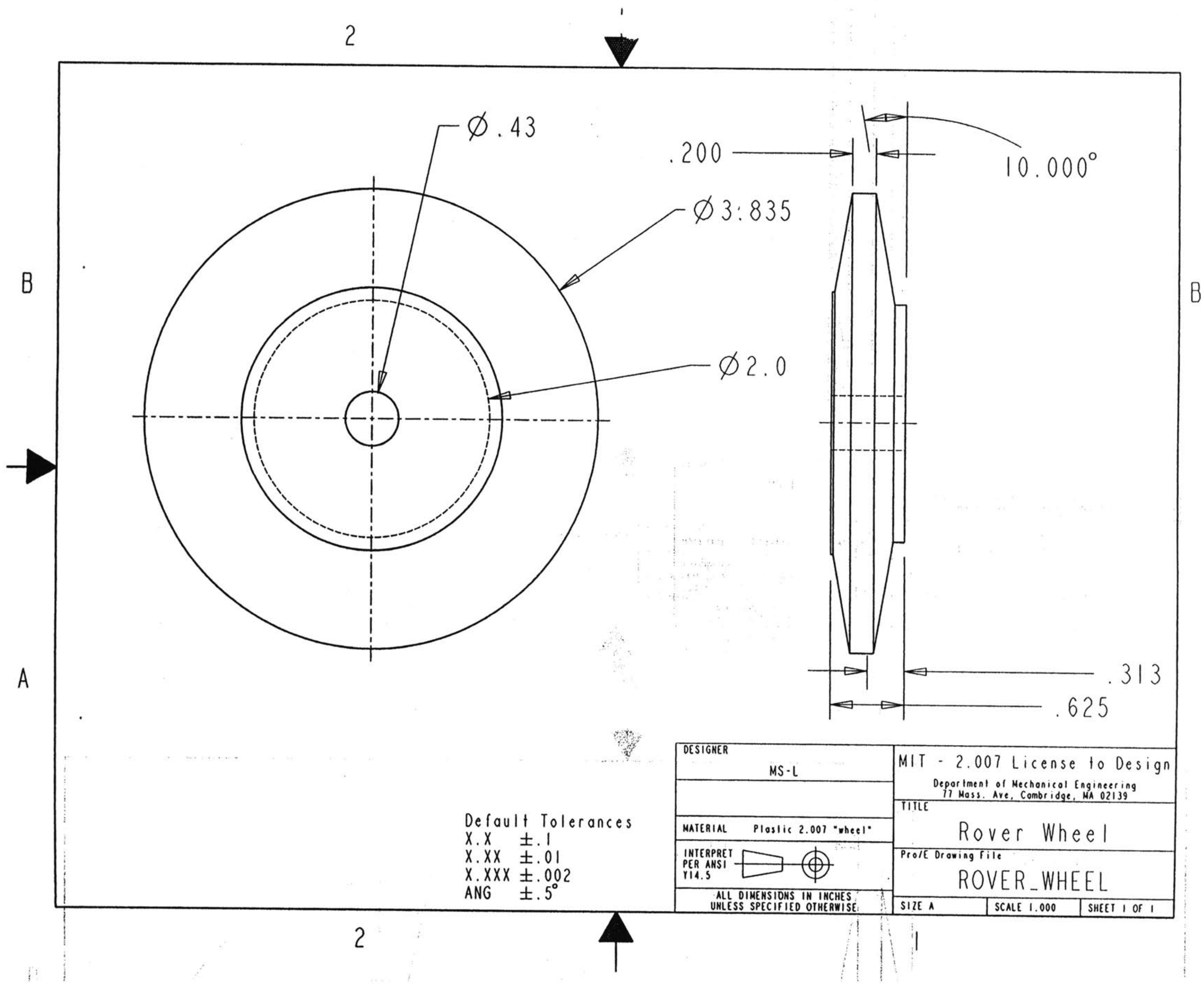

8.00
Ø.177
.625
.250
Ø.130
Ø.200
.400
5.50
7.5
1.0
3.50
3.0
3.00
.500
Ø.138
Cut On Waterjet
Filnames:
Chassisl.dxf
Chassisr.dxf
SCALE 0.500
Default Tolerances
X.X ±.1
X.XX ±.01
X.XXX ±.002
ANG ±.5°
SCALE: 1.000
MATERIAL
1/4" Polycarbonate
INTERPRET PER ANSI Y14.5
ALL DIMENSIONS IN INCHES UNLESS SPECIFIED OTHERWISE
MIT - 2.007 License to Design
Department of Mechanical Engineering
77 Mass. Ave, Cambridge, MA 02139
TITLE
Rover Chassis Plate
Pro/E Drawing File
ROVER_CHASSIS
DESIGNER: MS-L
SHEET 1 OF 3
2
B
A
1



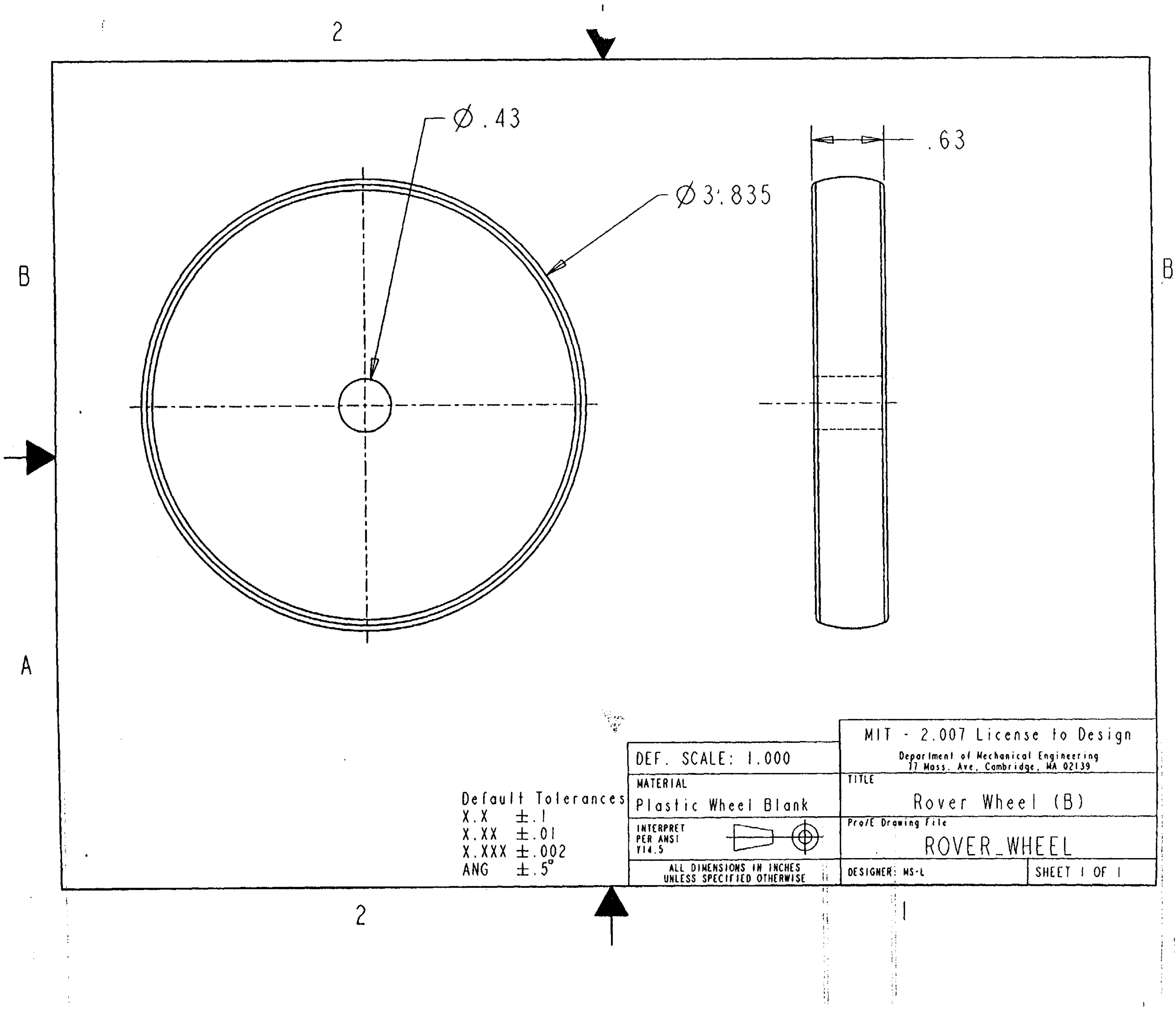


Process Plan for Rover Chassis

Step	Tools	Note
1. Import to Waterjet and add traverses	.dxf file, Waterjet PC	2 DXF files- left and right chassis half.
2. Cut on waterjet	OMAX Abrasivemachining center ("waterjet")	Verify correct offset for jet diameter (iterate if nec.)
3. Clean up edges	File	

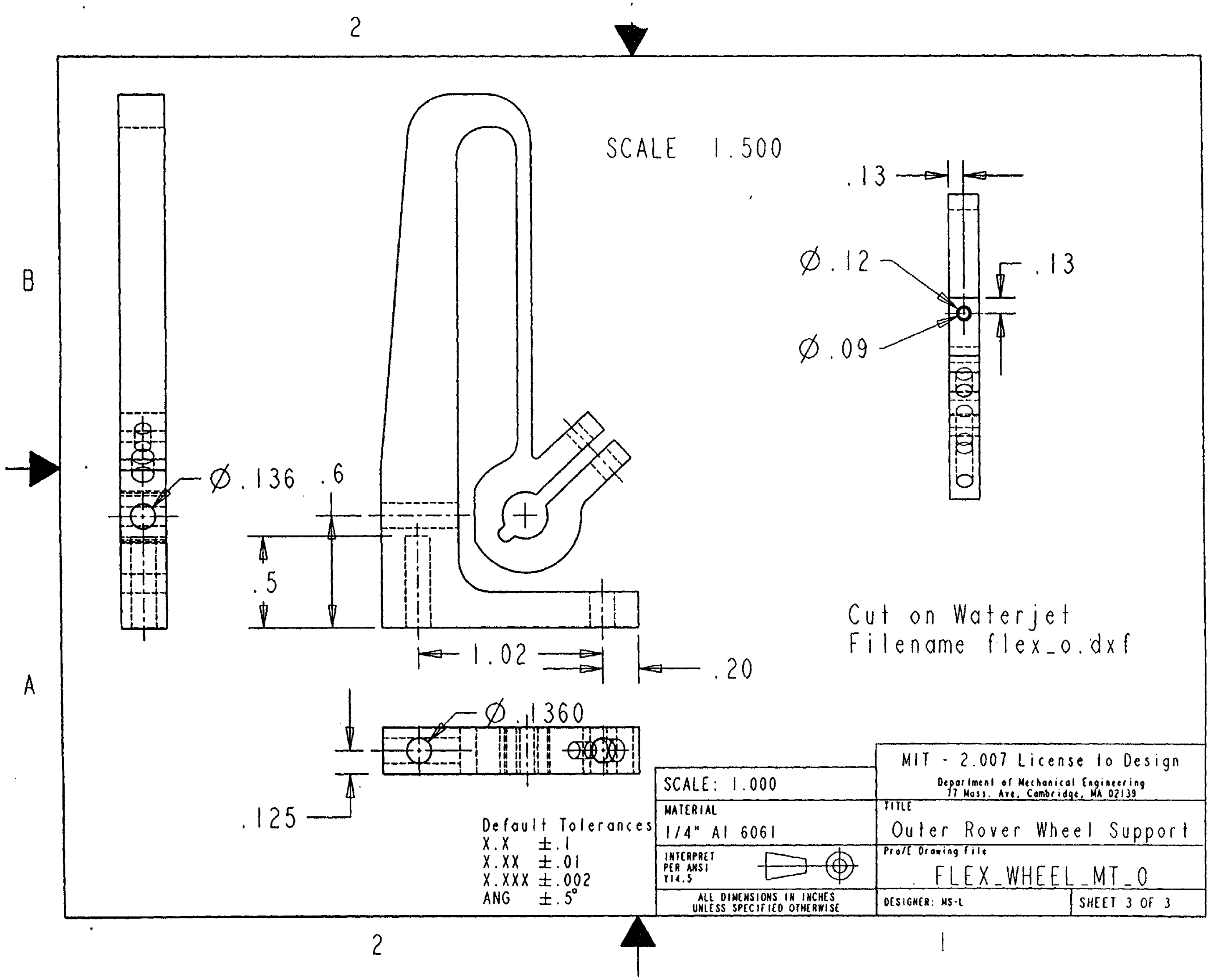


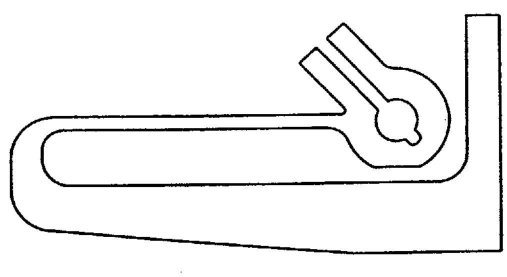
Ø.43
Ø3.835
Ø2.0
.200
10.000°
.313
.625
2
B
A
1
Default Tolerances
X.X ±.1
X.XX ±.01
X.XXX ±.002
ANG ±.5°
DESIGNER
MS-L
MATERIAL Plastic 2.007 "wheel"
INTERPRET PER ANSI Y14.5
ALL DIMENSIONS IN INCHES UNLESS SPECIFIED OTHERWISE
MIT - 2.007 License to Design
Department of Mechanical Engineering
77 Mass. Ave, Cambridge, MA 02139
TITLE
Rover Wheel
Pro/E Drawing File
ROVER_WHEEL
SIZE A
SCALE 1.000
SHEET 1 OF 1

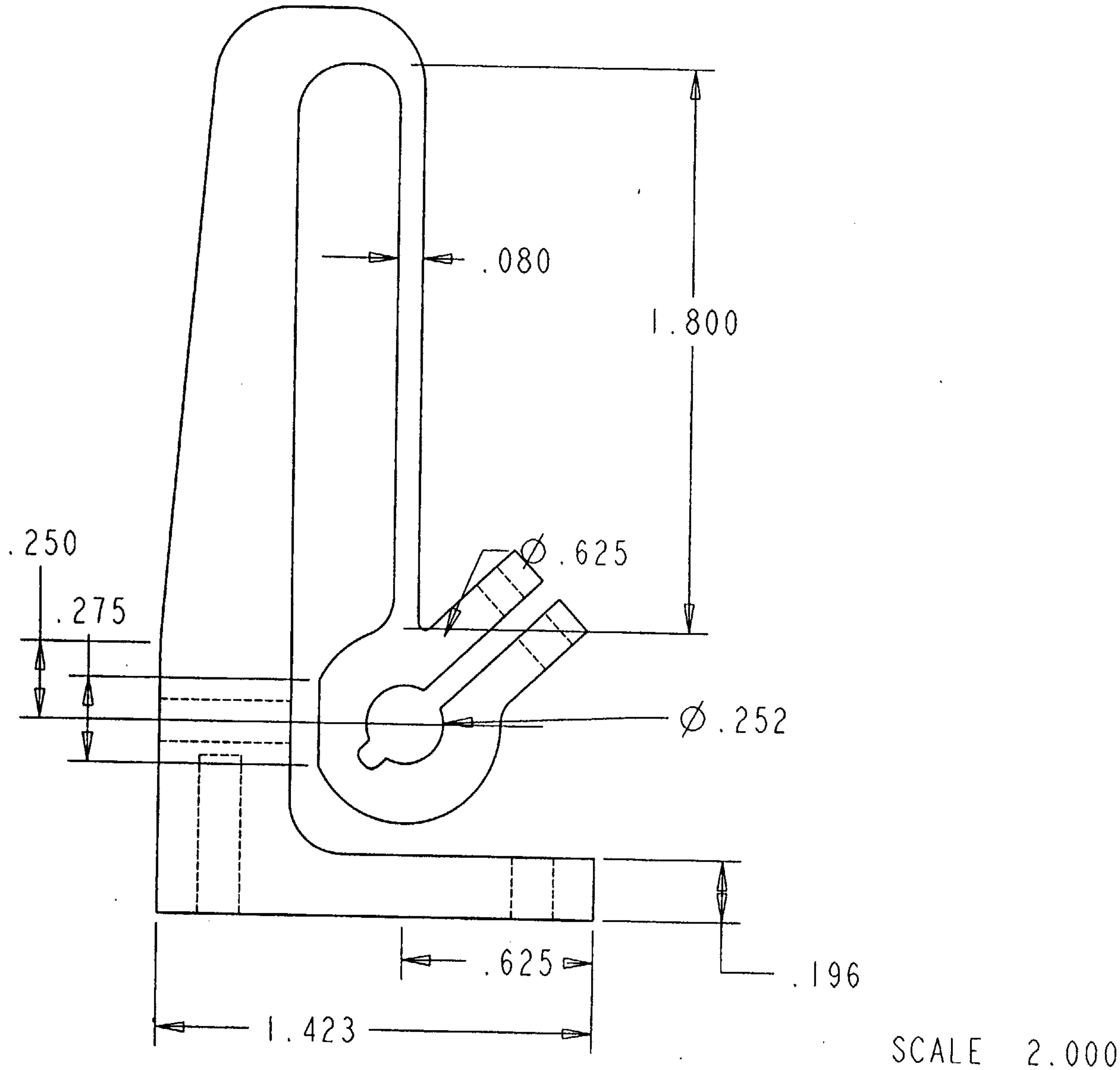

2
Ø .43
.63
Ø 3.835
B
B
A
2
1
Default Tolerances
X.X ±.1
X.XX ±.01
X.XXX ±.002
ANG ±.5°
DEF. SCALE: 1.000
MATERIAL
Plastic Wheel Blank
INTERPRET PER ANSI Y14.5
ALL DIMENSIONS IN INCHES UNLESS SPECIFIED OTHERWISE
MIT - 2.007 License to Design
Department of Mechanical Engineering
77 Mass. Ave, Cambridge, MA 02139
TITLE
Rover Wheel (B)
Pro/E Drawing File
ROVER_WHEEL
DESIGNER: MS-L
SHEET 1 OF 1

Process Plan for Rover Wheel (Version B)

Step	Tools	Note
1. Mount in lathe	Lathe, special fixture	
2. Cut to "medium" diameter	Lathe, normal cutting tool	Keep cutting forces constant and low to avoid damage to center of wheel that is held in fixture
3. Mark desired width on wheel rim	Dial caliper or height gauge	
4. Cut to width	Lathe, normal cutting tool	Replace knurled fastening knob on fixture with washer and nut to cut close to the center.
5. Create half of crown by cutting wheel surface at 10 degree angle	Lath, normal cutting tool	rotate secondary crossfeed axis to appropriate angle.
6. Remove from lathe		
7. Cut center flush to width	Hacksaw Alt: lathe and external jaws on chuck	Bandsaw unnecessary
8. Remount in fixture and cut other half of "crown"	Lath, normal cutting tool	
9. Round over crown	Lathe, (long) file	Be very careful when using hand near turning chuck- use low speed

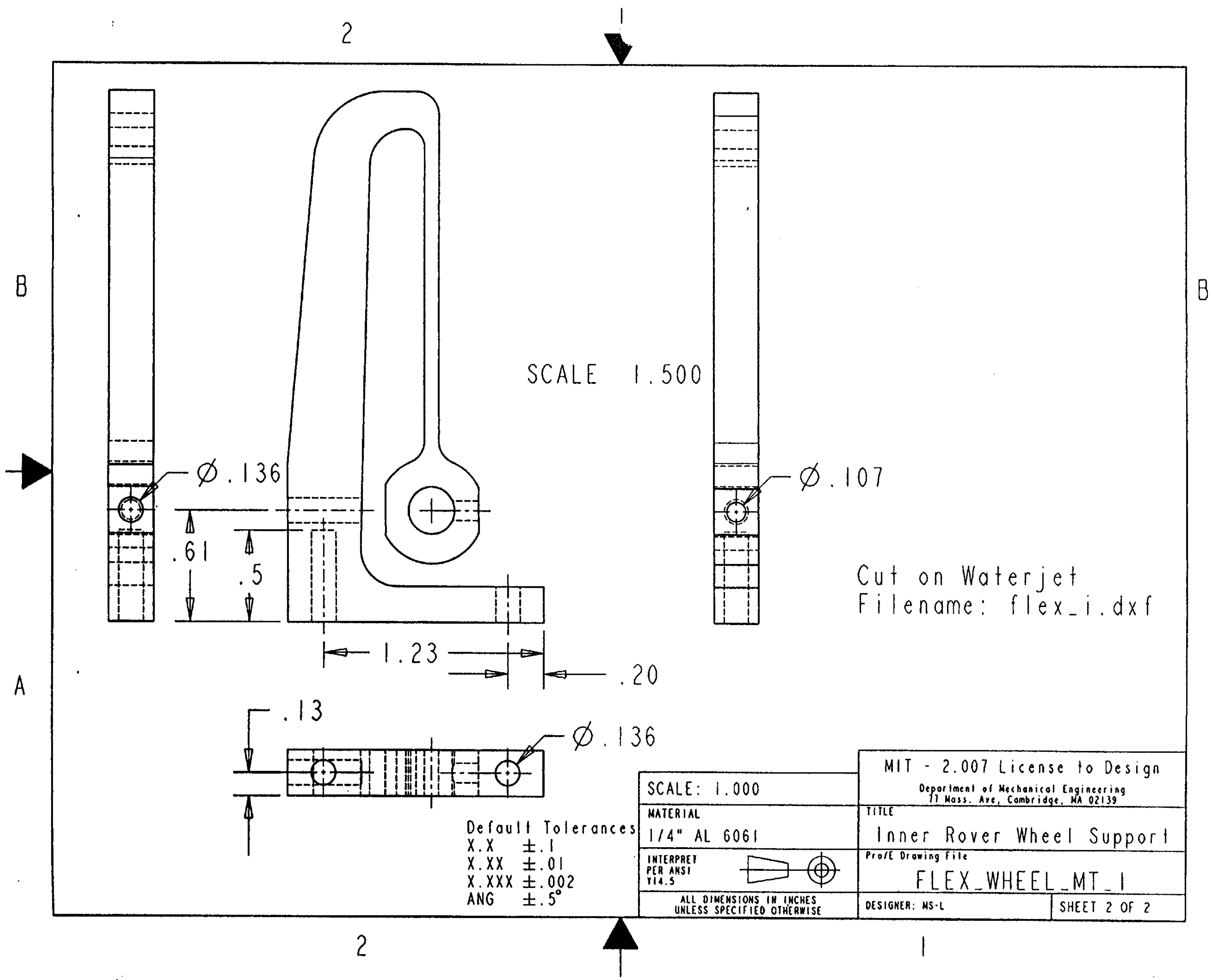

SCALE 1.500
.13
Ø.12
.13
Ø.09
Ø.136 .6
.5
1.02
.20
Cut on Waterjet
Filename flex_o.dxf
Ø.1360
.125
Default Tolerances
X.X ±.1
X.XX ±.01
X.XXX ±.002
ANG ±.5°
SCALE: 1.000
MATERIAL
1/4" Al 6061
INTERPRET PER ANSI Y14.5
ALL DIMENSIONS IN INCHES UNLESS SPECIFIED OTHERWISE
MIT - 2.007 License to Design
Department of Mechanical Engineering
77 Mass. Ave, Cambridge, MA 02139
TITLE
Outer Rover Wheel Support
Pro/E Drawing File
FLEX_WHEEL_MT_0
DESIGNER: MS-L
SHEET 3 OF 3
2
B
A
1

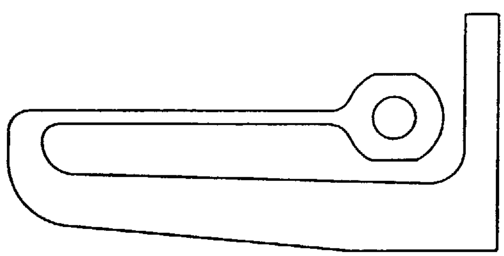



.080
1.800
.250
.275
Ø.625
Ø.252
.625
.196
1.423
SCALE 2.000

Process Plan for Outer Rover Axle Support

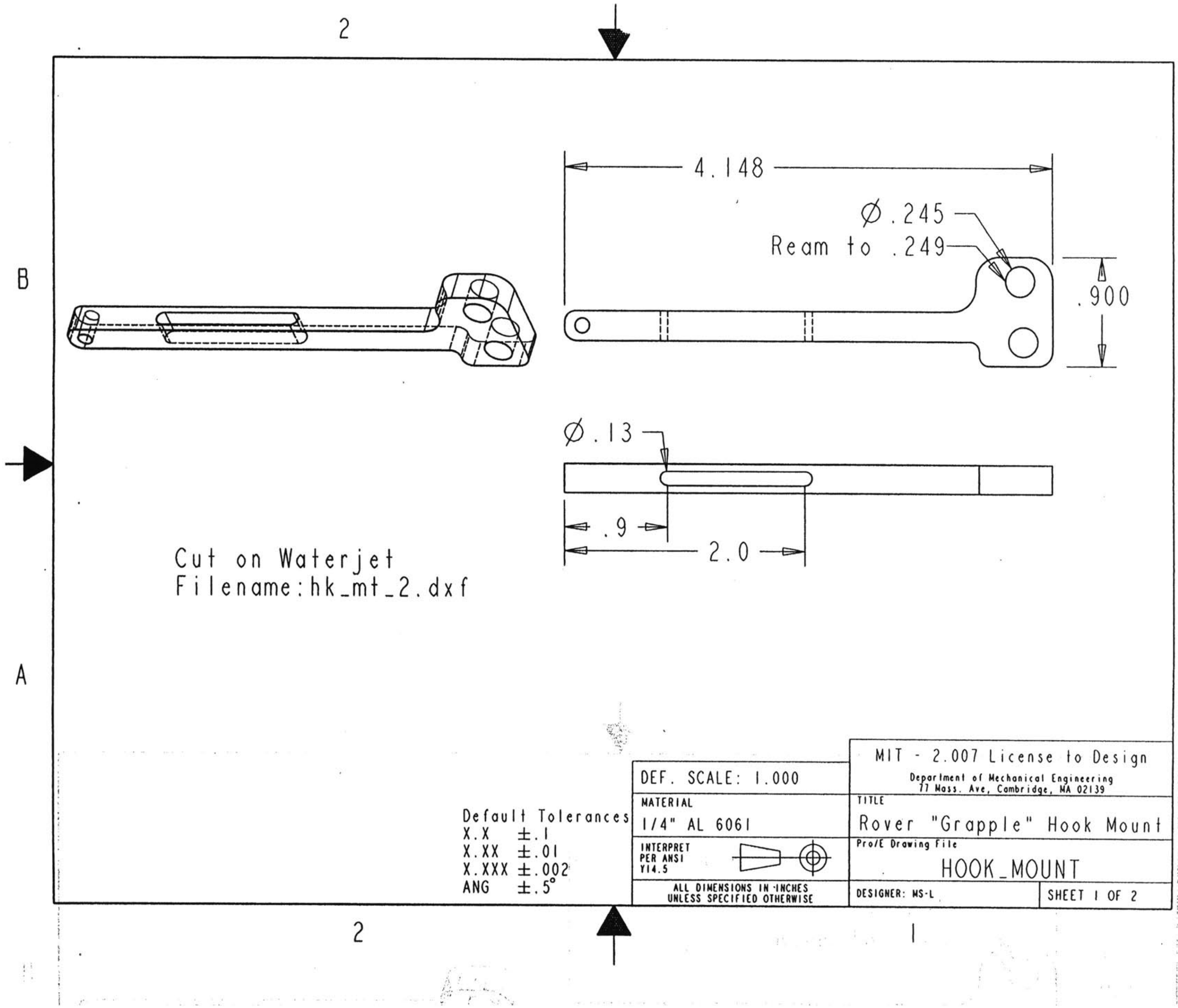
Step	Tools	Note
1. Import to Waterjet and add traverses	.dxf file, Waterjet PC	
2. Cut on waterjet	OMAX Abrasivemachining center ("waterjet")	Verify correct offset for jet diameter (iterate if nec.)
3. Clean up edges	File	
4. Mark and drill mounting holes	Dial caliper, drill press, machinist's vise, square, centerdrill, drill	
5. Mark and drill preload/ positioning hole	as above	
6. Mark clamp hole location	Dial caliper	
7. Drill clamp hole 0.089" through both clamp arms	Drill press, machinist's vise, centerdrill, #43 drill	
8. Enlarge hole in bottom clamp arms for screw clearance	Drill press, 0.12" or 1/8" drill bit	
9. Ream axle hole to 0.251"	Drill press, machinist's vise, reamer, coolant	Use a very slow speed for reaming
10. Thread all holes	Taps and handle, tapping fluid, vise	

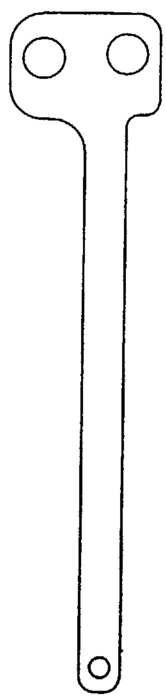

2
1
B
A
SCALE 1.500
Ø .136
.61
.5
1.23
.20
.13
Ø .136
Ø .107
Cut on Waterjet
Filename: flex_i.dxf
Default Tolerances
X.X ±.1
X.XX ±.01
X.XXX ±.002
ANG ±.5°
SCALE: 1.000
MATERIAL
1/4" AL 6061
INTERPRET PER ANSI Y14.5
ALL DIMENSIONS IN INCHES UNLESS SPECIFIED OTHERWISE
MIT - 2.007 License to Design
Department of Mechanical Engineering
77 Mass. Ave, Cambridge, MA 02139
TITLE
Inner Rover Wheel Support
Pro/E Drawing File
FLEX_WHEEL_MT_1
DESIGNER: MS-L
SHEET 2 OF 2



Process Plan for Inner Rover Axle Support

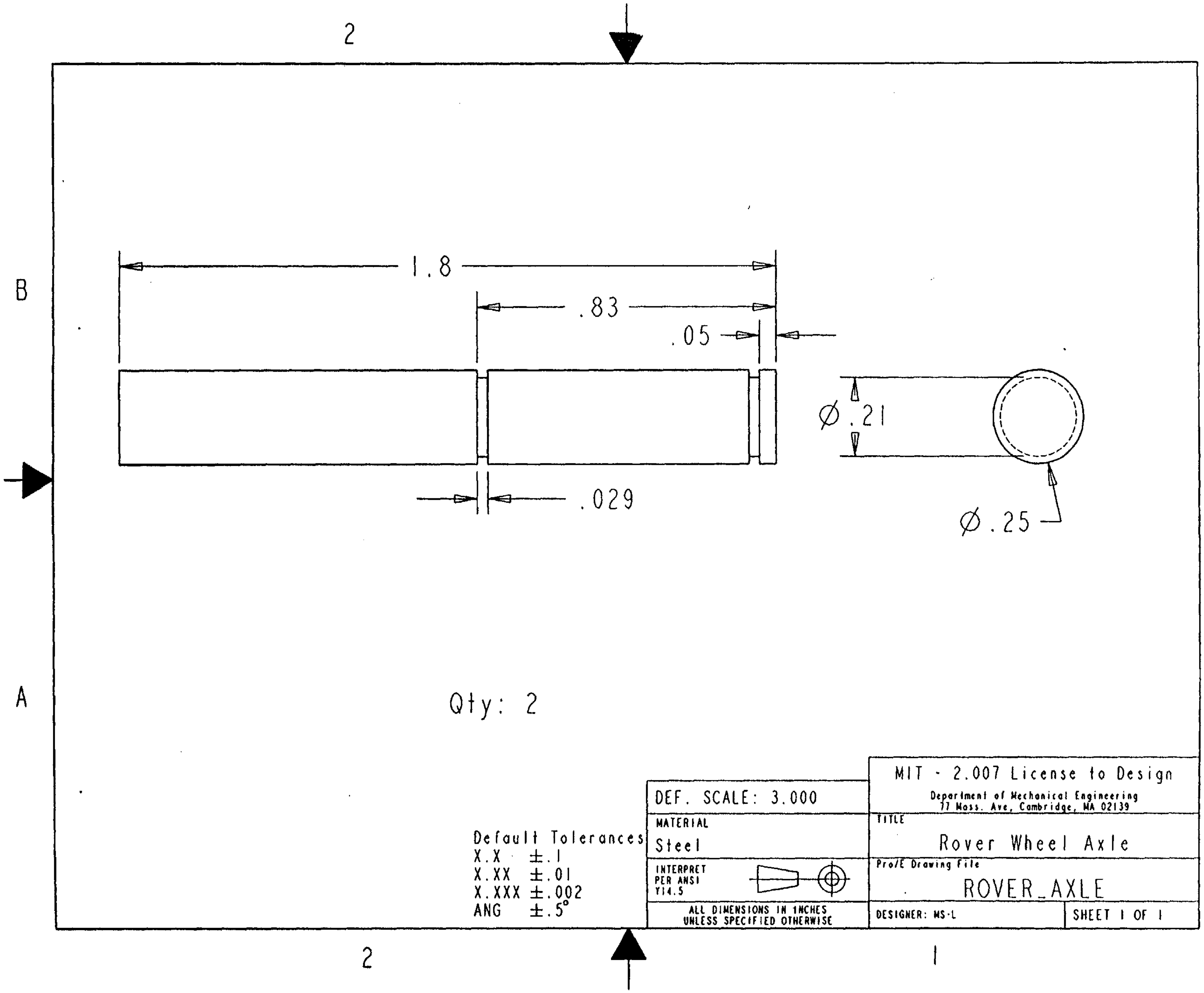
Step	Tools	Note
1. Import to Waterjet and add traverses	.dxf file, Waterjet PC	
2. Cut on waterjet	OMAX Abrasivemachining center ("waterjet")	Verify correct offset for jet diameter (iterate if nec.)
3. Clean up edges	File	
4. Mark and drill mounting holes	Dial caliper, drill press, machinist's vise, square, centerdrill, drill	
5. Mark and drill preload/ positioning hole	as above	
6. Mark set screw hole location	Dial caliper	
7. Drill set screw hole 0.089" through both clamp arms	Drill press, machinist's vise, centerdrill, #43 drill	The area where the hole is being drilled must be securely held--(deflection of the flexure will cause difficulty in drilling.) Some scrap paper or tape may be used to force the vise's clamping pressure to be applied to the axle hole area.
8. Ream axle hole to 0.251"	Drill press, machinist's vise, reamer, coolant	Use a very slow speed for reaming
9. Thread all holes	Taps and handle, tapping fluid, vise	


4.148
Ø.245
Ream to .249
.900
Ø.13
.9
2.0
Cut on Waterjet
Filename:hk_mt_2.dxf
Default Tolerances
X.X ±.1
X.XX ±.01
X.XXX ±.002
ANG ±.5°
DEF. SCALE: 1.000
MATERIAL
1/4" AL 6061
INTERPRET PER ANSI Y14.5
ALL DIMENSIONS IN INCHES UNLESS SPECIFIED OTHERWISE
MIT - 2.007 License to Design
Department of Mechanical Engineering
77 Mass. Ave, Cambridge, MA 02139
TITLE
Rover "Grapple" Hook Mount
Pro/E Drawing File
HOOK_MOUNT
DESIGNER: MS-L
SHEET 1 OF 2



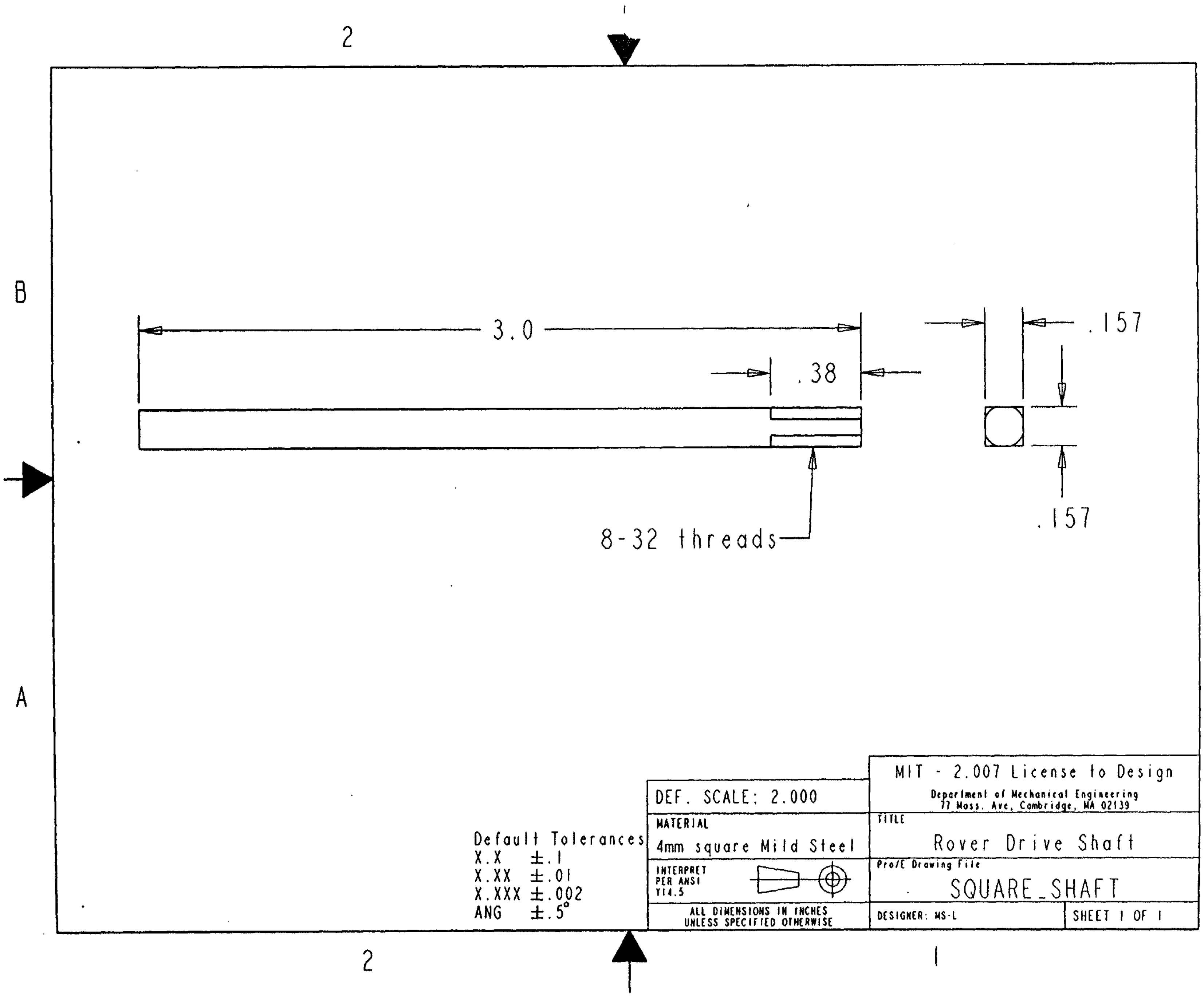
Process Plan for Rover "Grappling" Hook Mount

Step	Tools	Note
1. Import to Waterjet and add traverses	.dxf file, Waterjet PC	
2. Cut on waterjet	OMAX Abrasivemachining center ("waterjet")	Verify correct offset for jet diameter (iterate if nec.)
3. Clean up edges	File	
4. Ream pin holes to 0.249"	Drill press, machinist's vise, reamer, coolant	Use a very slow speed for reaming
5. Cut slot	Mill, parallels, edge finder, 1/8" endmill, colant	


2
B
A
1.8
.83
.05
⌀.21
⌀.25
.029
Qty: 2
Default Tolerances
X.X ±.1
X.XX ±.01
X.XXX ±.002
ANG ±.5°
DEF. SCALE: 3.000
MATERIAL
Steel
INTERPRET PER ANSI Y14.5
ALL DIMENSIONS IN INCHES UNLESS SPECIFIED OTHERWISE
MIT - 2.007 License to Design
Department of Mechanical Engineering
77 Mass. Ave, Cambridge, MA 02139
TITLE
Rover Wheel Axle
Pro/E Drawing File
ROVER_AXLE
DESIGNER: MS-L
SHEET 1 OF 1
1

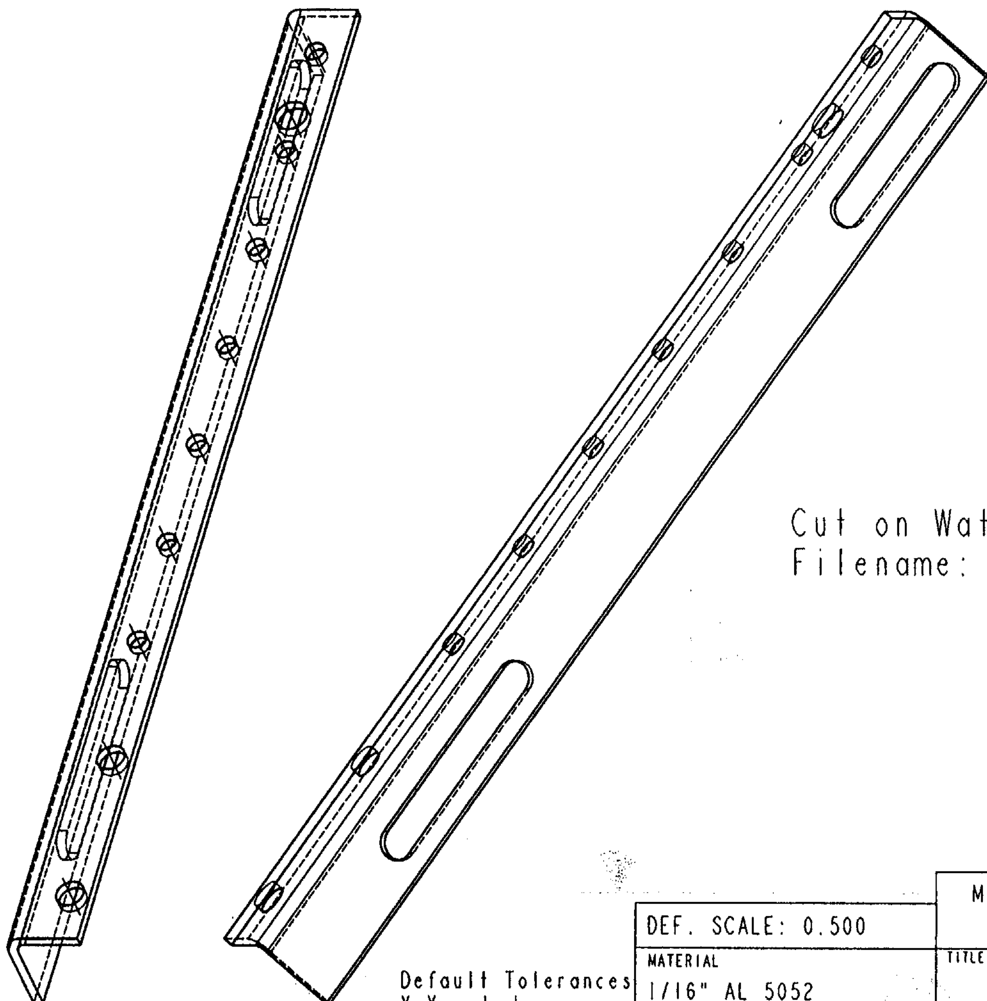
Process Plan for Rover Axle

Step	Tools	Note
1. Mark and cut 1/4" Steel rod to length +1/8"	Calipers, Dykem Steel Blue, Hacksaw	Hacksaw much better than Bandsaw here.
2. Clean and face ends, turn to length	Lathe, normal cutting tool, cutting oil, file, dial caliper	
3. Mark groove location	Calipers, Dykem Steel Blue	
4. Cut grooves	Lathe, grooving tool, cutting oil	Use an E-clip to test for fit.


3.0
.38
.157
.157
8-32 threads
Default Tolerances
X.X ±.1
X.XX ±.01
X.XXX ±.002
ANG ±.5°
DEF. SCALE: 2.000
MATERIAL
4mm square Mild Steel
INTERPRET PER ANSI Y14.5
ALL DIMENSIONS IN INCHES UNLESS SPECIFIED OTHERWISE
MIT - 2.007 License to Design
Department of Mechanical Engineering
77 Mass. Ave, Cambridge, MA 02139
TITLE
Rover Drive Shaft
Pro/E Drawing File
SQUARE_SHAFT
DESIGNER: MS-L
SHEET 1 OF 1

Process Plan for Rover Drive Shaft

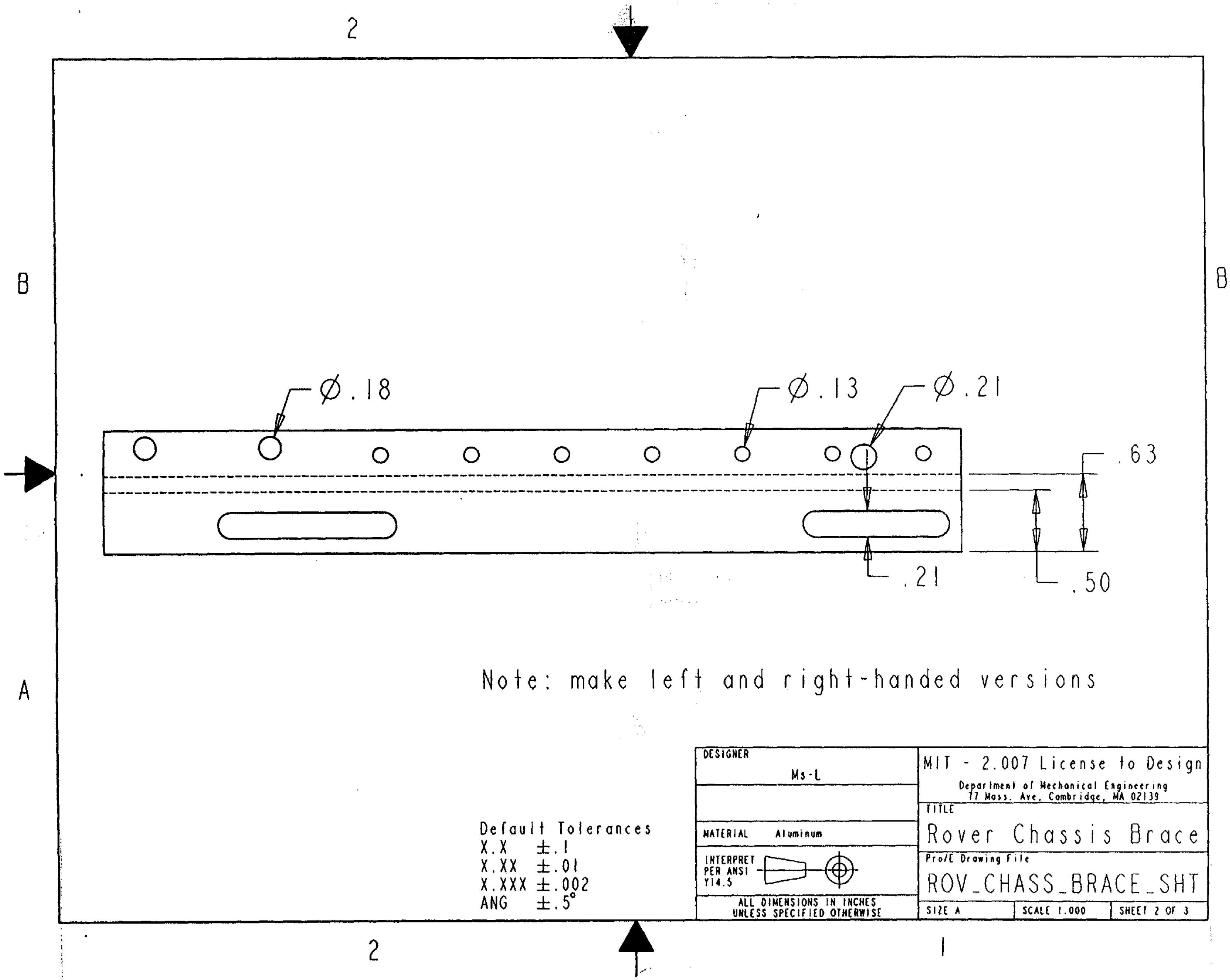
Step	Tools	Note
1. Mark and cut 4mm square Steel rod to length +1/8"	Calipers, Dykem Steel Blue, Hacksaw	Hacksaw much better than Bandsaw here.
2. Clean ends	File, Belt sander	
3. Mark thread depth	Calipers, Dykem Steel Blue,	
4. Thread end	8-32 die, handle, cutting fluid	A lathe (with 4mm or 3/16" square collet) may be useful as a threadcutting aid. With the shaft in the collet, the tailstock may be used to brace the diehandle, ensuring that the threads are cut straight.



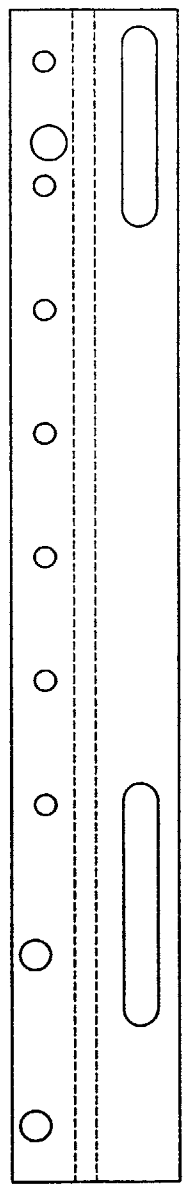
Cut on Waterjet
Filename: chas_br.dxf

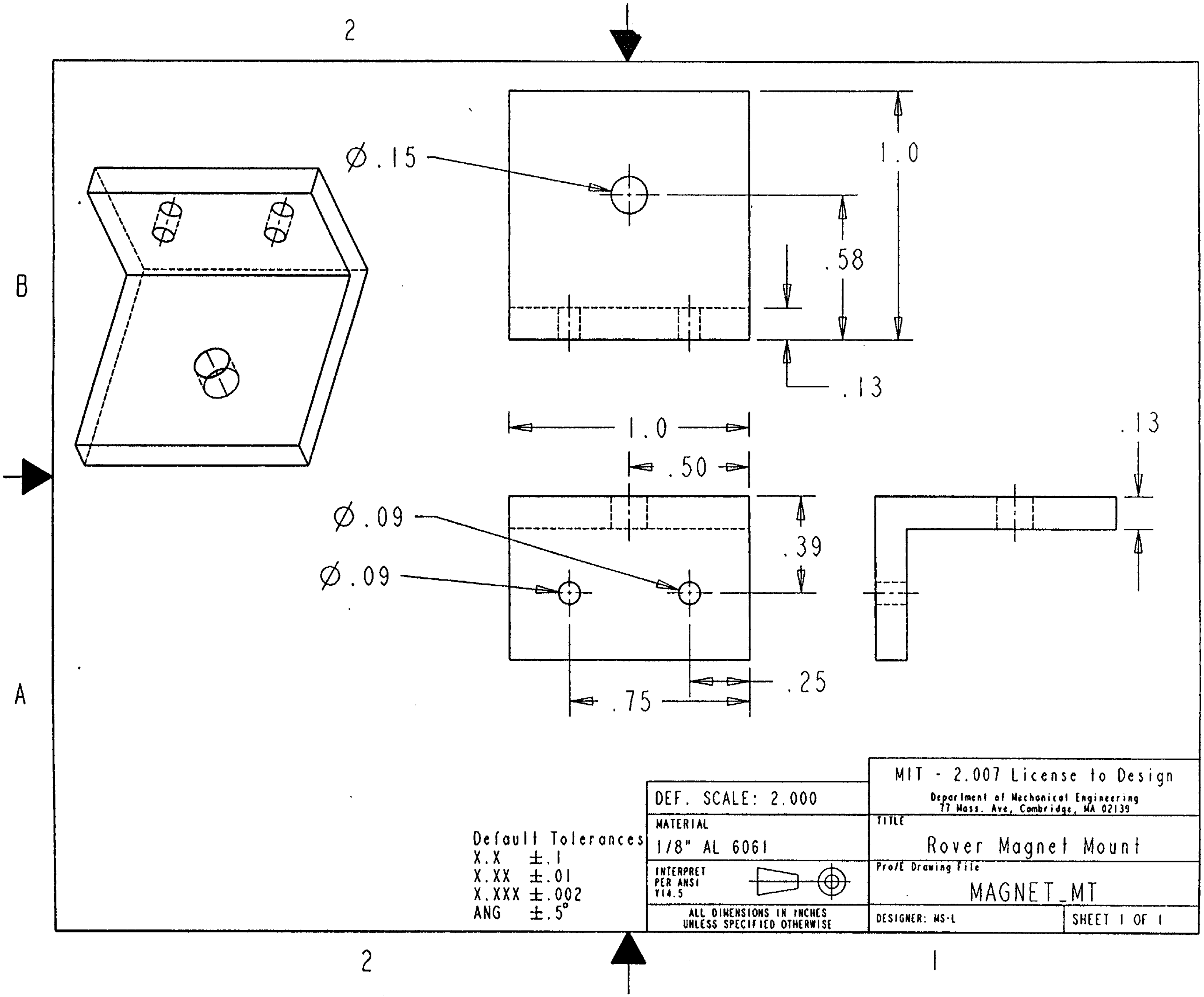
Default Tolerances
X.X ±.1
X.XX ±.01
X.XXX ±.002
ANG ±.5°

DEF. SCALE: 0.500	MIT - 2.007 License to Design Department of Mechanical Engineering 77 Mass. Ave, Cambridge, MA 02139
MATERIAL 1/16" AL 5052	TITLE Rovers Chassis Brace
INTERPRET PER ANSI Y14.5	Pro/E Drawing File ROV_CHASS_BRACE_SHT
ALL DIMENSIONS IN INCHES UNLESS SPECIFIED OTHERWISE	DESIGNER: MS-L — SHEET 1 OF 3



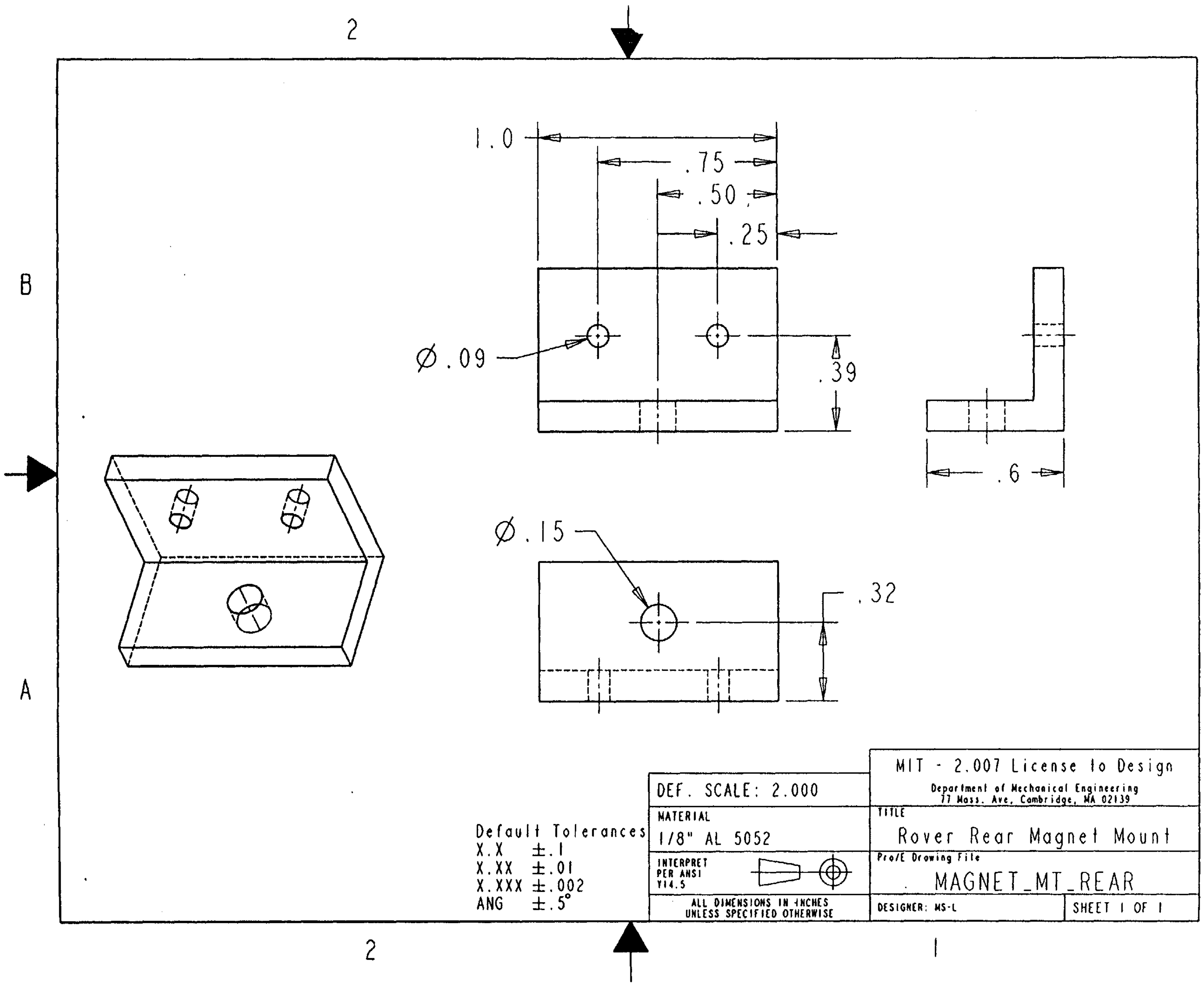
2
B
A
Ø.18
Ø.13
Ø.21
.63
.50
.21
Note: make left and right-handed versions
Default Tolerances
X.X ±.1
X.XX ±.01
X.XXX ±.002
ANG ±.5°
DESIGNER
Ms-L
MATERIAL Aluminum
INTERPRET PER ANSI Y14.5
ALL DIMENSIONS IN INCHES UNLESS SPECIFIED OTHERWISE
MIT - 2.007 License to Design
Department of Mechanical Engineering
77 Mass. Ave, Cambridge, MA 02139
TITLE
Rover Chassis Brace
Pro/E Drawing File
ROV_CHASS_BRACE_SHT
SIZE A
SCALE 1.000
SHEET 2 OF 3
1




2
B
A
Ø.15
1.0
.58
.13
1.0
.50
.13
Ø.09
Ø.09
.39
.25
.75
Default Tolerances
X.X ±.1
X.XX ±.01
X.XXX ±.002
ANG ±.5°
DEF. SCALE: 2.000
MATERIAL
1/8" AL 6061
INTERPRET PER ANSI Y14.5
ALL DIMENSIONS IN INCHES UNLESS SPECIFIED OTHERWISE
MIT - 2.007 License to Design
Department of Mechanical Engineering
77 Mass. Ave, Cambridge, MA 02139
TITLE
Rover Magnet Mount
Pro/E Drawing File
MAGNET_MT
DESIGNER: MS-L
SHEET 1 OF 1
2
1
B

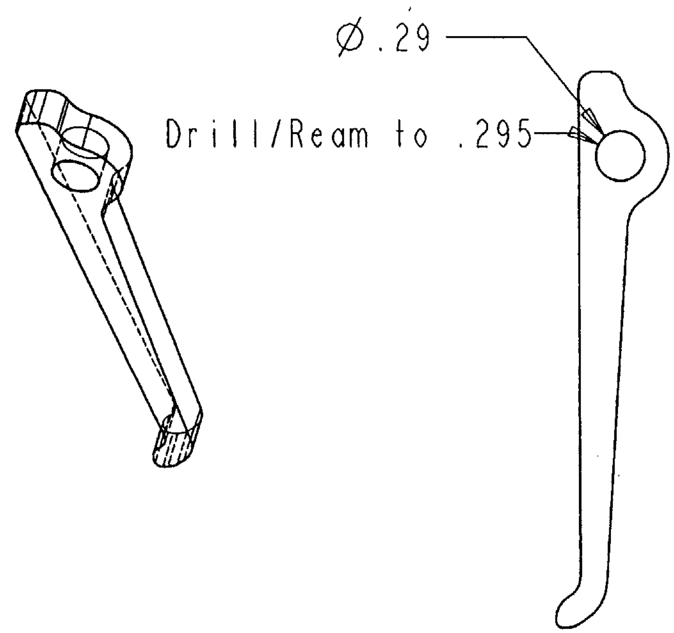
Process Plan for Rover Front Magnet Mount

Step	Tools	Note
1. Mark part size +1/16" on scrap piece of 1x3" box extrusion	Dykem steel blue, ruler, combination square or dial caliper	
2. Cut from stock	Bandsaw or hacksaw	Use fine toothed blade (2 or more teeth engaged in thickness of part at all times)
3. Clean up edges	Mill or Sander or File	Sander or file may be used if squareness is not very important.
4. Mark hole locations	Dial caliper	Use consistent reference edges
5. Drill holes	Drill press, machinist's vise, centerdrill, drills	
6. Debur holes	Drill press, countersink	Use low speed


2
B
A
1.0
.75
.50
.25
Ø.09
.39
.6
Ø.15
.32
Default Tolerances
X.X ±.1
X.XX ±.01
X.XXX ±.002
ANG ±.5°
DEF. SCALE: 2.000
MATERIAL
1/8" AL 5052
INTERPRET PER ANSI Y14.5
ALL DIMENSIONS IN INCHES UNLESS SPECIFIED OTHERWISE
MIT - 2.007 License to Design
Department of Mechanical Engineering
77 Mass. Ave. Cambridge, MA 02139
TITLE
Rover Rear Magnet Mount
Pro/E Drawing File
MAGNET_MT_REAR
DESIGNER: MS-L
SHEET 1 OF 1
1

Process Plan for Rover Rear Magnet Mount

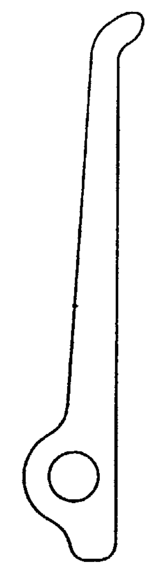
Step	Tools	Note
1. Mark part size +1/16" on scrap piece of 1x3" box extrusion	Dykem steel blue, ruler, combination square or dial caliper	
2. Cut from stock	Bandsaw or hacksaw	Use fine toothed blade (2 or more teeth engaged in thickness of part at all times)
3. Clean up edges	Mill or Sander or File	Sander or file may be used if squareness is not very important.
4. Mark hole locations	Dial caliper	Use consistent reference edges
5. Drill holes	Drill press, machinist's vise, centerdrill, drills	
6. Debur holes	Drill press, countersink	Use low speed



Cut on Waterjet
Filename: Hook2.dxf

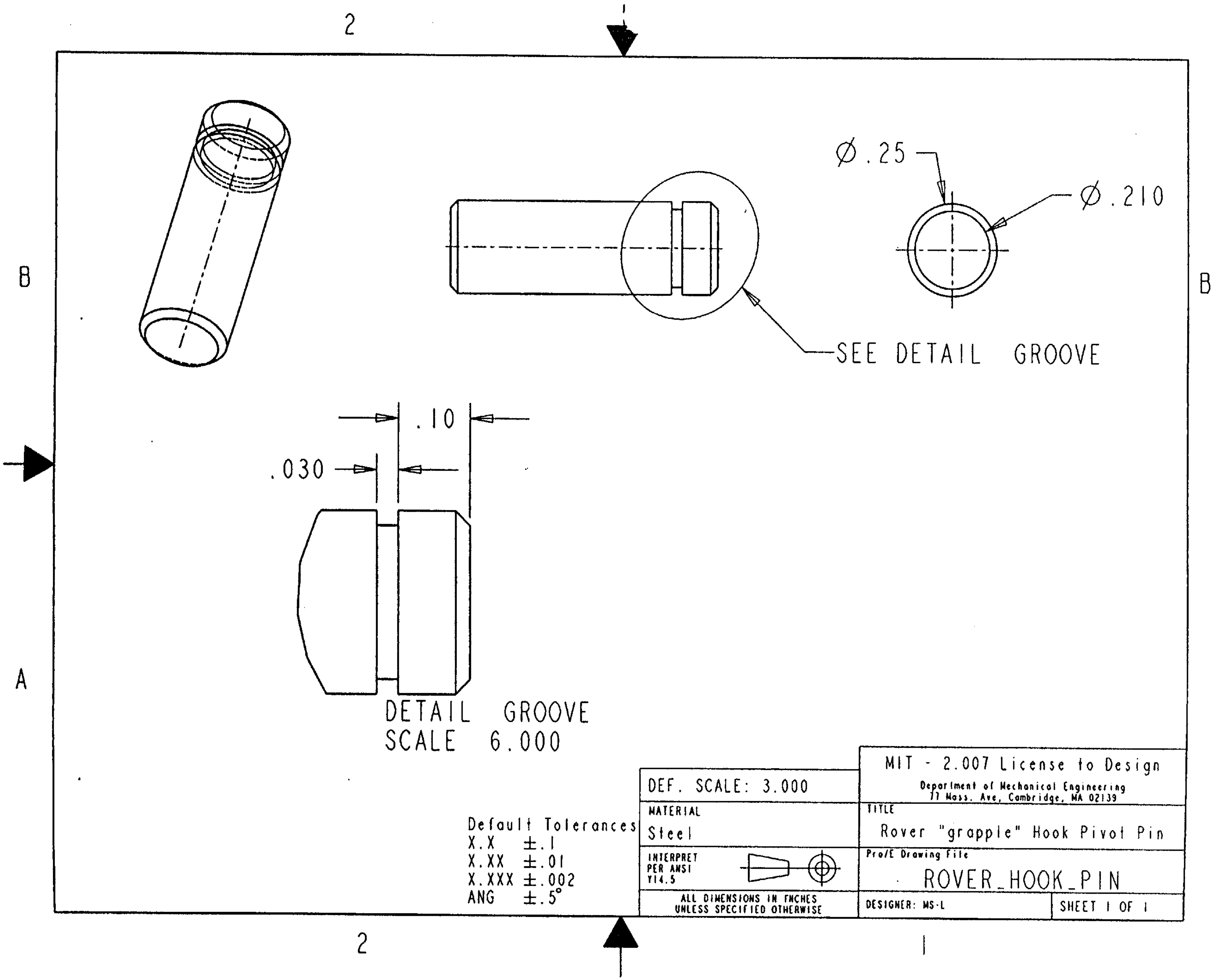
Default Tolerances
X.X ±.1
X.XX ±.01
X.XXX ±.002
ANG ±.5°

DEF. SCALE: 1.000	MIT - 2.007 License to Design Department of Mechanical Engineering 77 Mass. Ave, Cambridge, MA 02139
MATERIAL 1/4" AL 6061	TITLE Rover "grapple" Hook
INTERPRET PER ANSI Y14.5	Pro/E Drawing File ROVER_HOOK_2
ALL DIMENSIONS IN INCHES UNLESS SPECIFIED OTHERWISE	DESIGNER: MS-L — SHEET 1 OF 2



Process Plan for Rover "Grappling" Hook

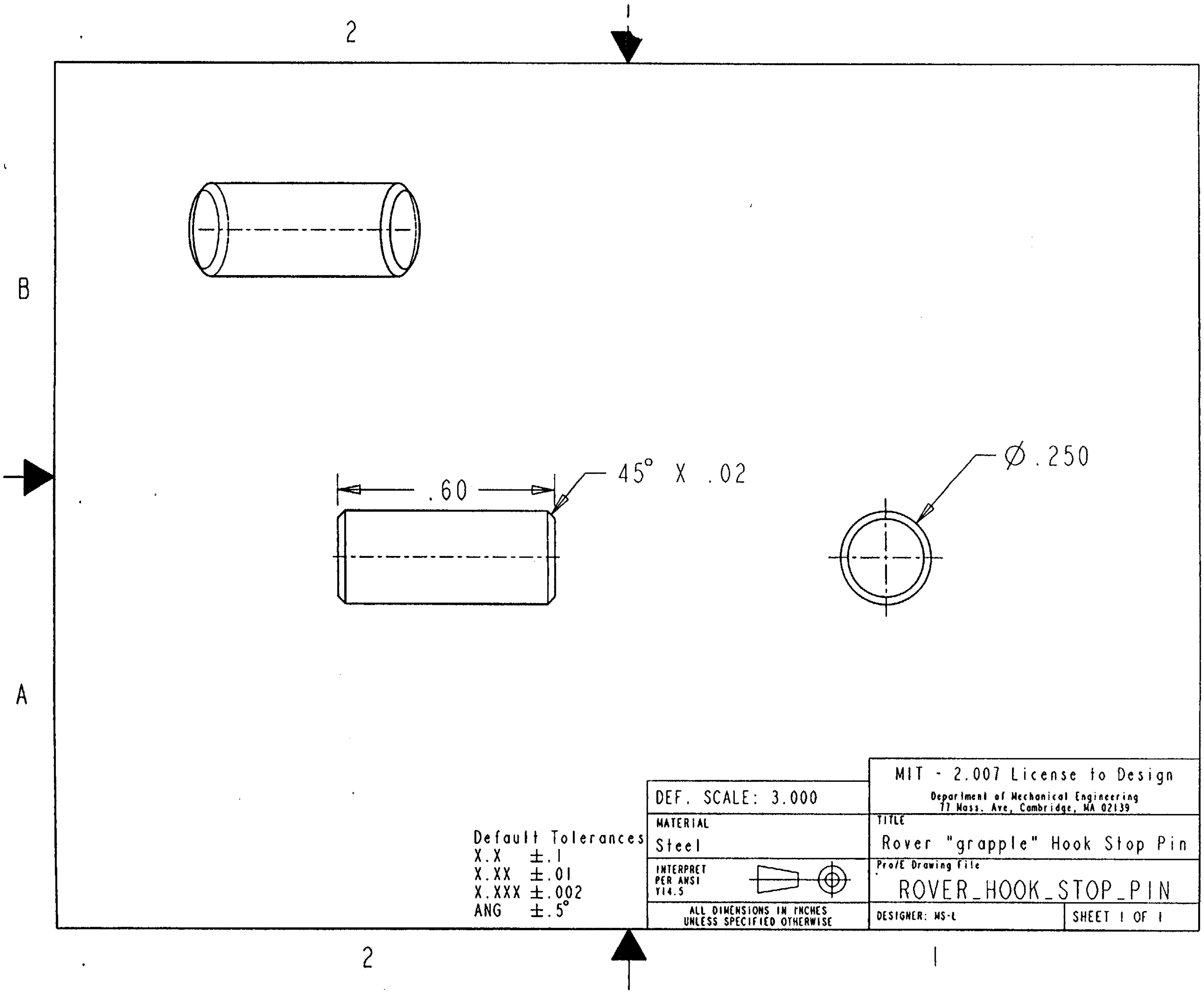
Step	Tools	Note
1. Import to Waterjet and add traverses	.dxf file, Waterjet PC	2 DXF files- left and right chassis half.
2. Cut on waterjet	OMAX Abrasivemachining center ("waterjet")	Verify correct offset for jet diameter (iterate if nec.)
3. Debur edges	File	
4. Enlarge hole to .297" to fit bearing and pin	Drill Press, 0.297" drill, cutting fluid	



2
B
A
Ø.25
Ø.210
SEE DETAIL GROOVE
.10
.030
DETAIL GROOVE
SCALE 6.000
Default Tolerances
X.X ±.1
X.XX ±.01
X.XXX ±.002
ANG ±.5°
DEF. SCALE: 3.000
MATERIAL
Steel
INTERPRET PER ANSI Y14.5
ALL DIMENSIONS IN INCHES UNLESS SPECIFIED OTHERWISE
MIT - 2.007 License to Design
Department of Mechanical Engineering
77 Mass. Ave, Cambridge, MA 02139
TITLE
Rover "grapple" Hook Pivot Pin
Pro/E Drawing File
ROVER_HOOK_PIN
DESIGNER: MS-L
SHEET 1 OF 1
1

Process Plan for Rover Hook Pivot Pin

Step	Tools	Note
1. Mark and cut 1/4" Steel rod to length +1/8"	Calipers, Dykem Steel Blue, Hacksaw	Hacksaw much better than Bandsaw here.
2. Clean and face ends, turn to length	Lathe, normal cutting tool, cutting oil, file, dial caliper	
3. Mark groove location	Calipers, Dykem Steel Blue	
4. Cut groove	Lathe, groove cutting tool, cutting oil	Use an E-clip to test for fit.


2
1
B
A
.60
45° X .02
Ø.250
Default Tolerances
X.X ±.1
X.XX ±.01
X.XXX ±.002
ANG ±.5°
DEF. SCALE: 3.000
MATERIAL
Steel
INTERPRET PER ANSI Y14.5
ALL DIMENSIONS IN INCHES UNLESS SPECIFIED OTHERWISE
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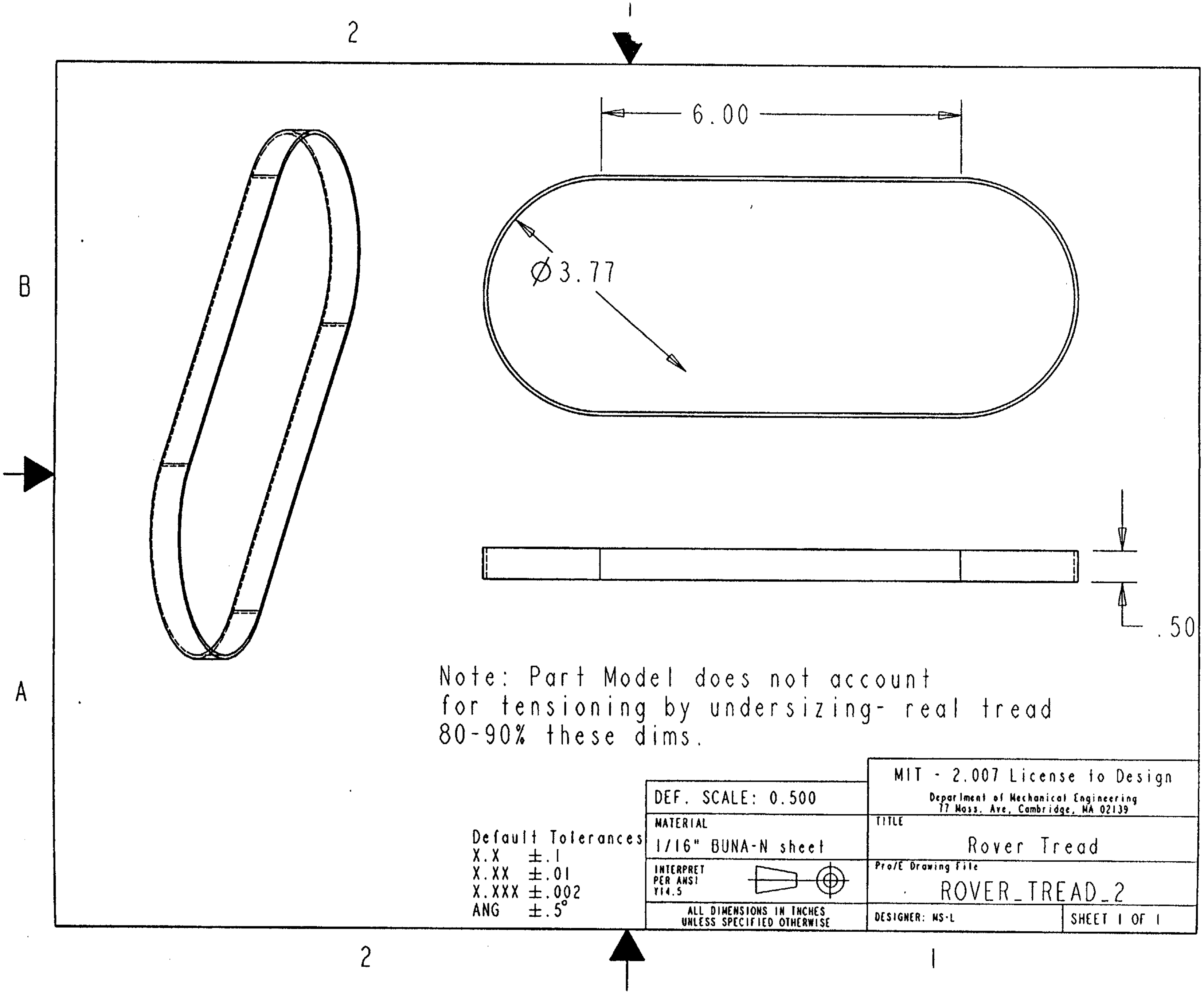
Department of Mechanical Engineering
77 Mass. Ave, Cambridge, MA 02139
TITLE
Rover "grapple" Hook Stop Pin
Pro/E Drawing File
ROVER_HOOK_STOP_PIN
DESIGNER: MS-L
SHEET 1 OF 1

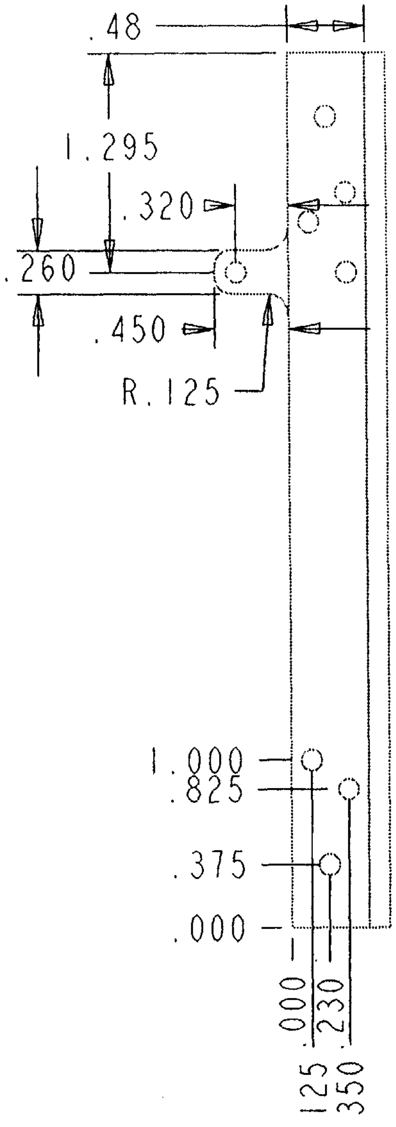
Process Plan for Rover Hook Stop Pin

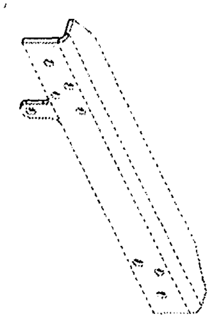
Step	Tools	Note
1. Mark and cut 1/4" Steel rod to length +1/8"	Calipers, Dykem Steel Blue, Hacksaw	Hacksaw much better than Bandsaw here.
2. Clean and face ends, turn to length, chamfer ends	Lathe, normal cutting tool, cutting oil, file, dial caliper	


6.00
Ø3.77
.50
Note: Part Model does not account
for tensioning by undersizing- real tread
80-90% these dims.
Default Tolerances
X.X ±.1
X.XX ±.01
X.XXX ±.002
ANG ±.5°
DEF. SCALE: 0.500
MATERIAL
1/16" BUNA-N sheet
INTERPRET PER ANSI Y14.5
ALL DIMENSIONS IN INCHES UNLESS SPECIFIED OTHERWISE
MIT - 2.007 License to Design
Department of Mechanical Engineering
77 Mass. Ave, Cambridge, MA 02139
TITLE
Rover Tread
Pro/E Drawing File
ROVER_TREAD_2
DESIGNER: MS-L
SHEET 1 OF 1
2
1
B
A

Process Plan for Rover Treads

Step	Tools	Note
1. Cut Buna-N rubber stock to width	Ruler, sharp knife, straightedge	Use straightedge to keep sheet flat and cut straight.
2. Cut 2 strips to 90% of stretched tread length.	Ruler or tape measure, sharp knife	
3. Lay strip into loop, overlapping ends.		
4. Cut diagonally across overlapped ends (~45 deg.)	straightedge, clean sharp knife	Make cut as clean and straight as possible
5. Apply Loctite (super-) glue to one cut diagonal edge, evenly but sparingly.	Loctite CA (Cyanoacrylate) glue from white bottle	
6. Bring edges to gether on flat smooth surface (scrap Al) and press together fro 30 sec., keeping joint flat.	Scrap aluminum sheet	CA (super-) glues bond to skin very well, so you may wish to wear gloves to avoid the discomfort of a layer of hardened glue on your fingertips. Acetone or nail polish remover containing acetone may be used to help dissolve CA.





Cut flat part on Waterjet
Filename: torsion.dxf

SCALE 1.000

Default Tolerances
X.X ±.1
X.XX ±.01
X.XXX ±.002
ANG ±.5°

MATERIAL	1/16" AL 5052
INTERPRET PER ANSI Y14.5	
ALL DIMENSIONS IN INCHES UNLESS SPECIFIED OTHERWISE	

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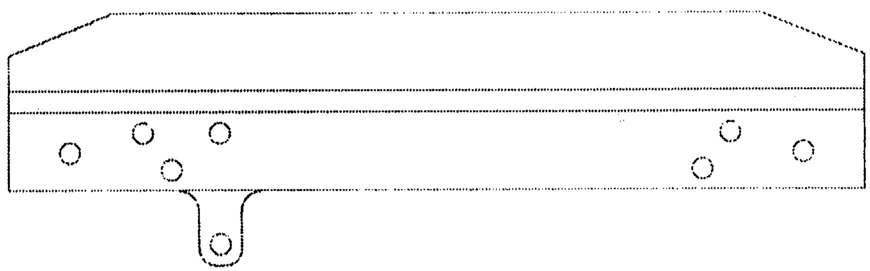
TITLE
Rover Chassis Torsional Beam

Pro/E Drawing File
TORSION_BEAM

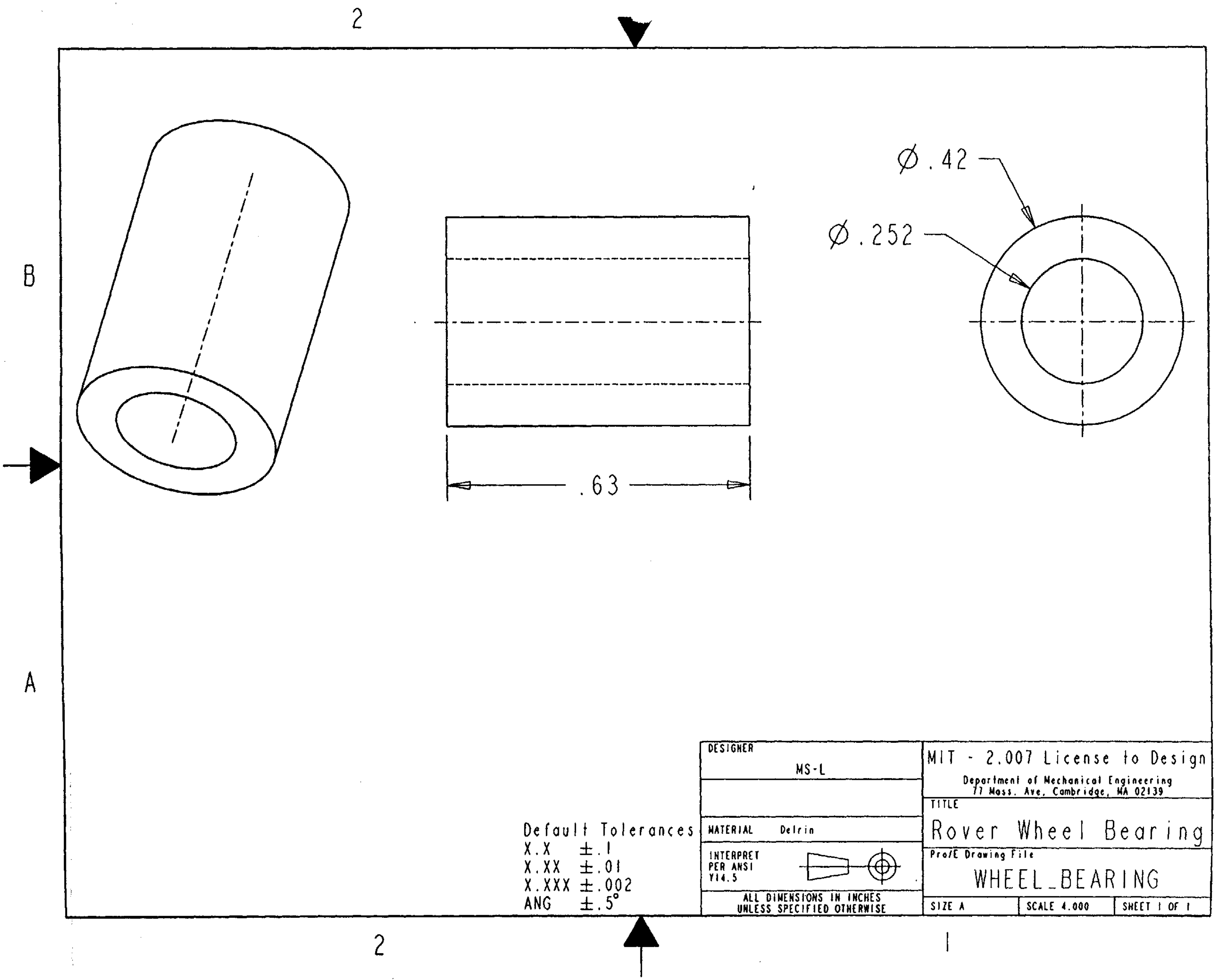
DESIGNER:	SCALE 0.500	SHEET 2 OF 3



SCALE 1.000

Process Plan for Rover Torsionally Compliant Chassis Connector

Step	Tools	Note
1. Import to Waterjet and add traverses	.dxf file, Waterjet PC	2 DXF files- left and right chassis half.
2. Cut on waterjet	OMAX Abrasivemachining center ("waterjet")	Verify correct offset for jet diameter (iterate if nec.)
3. Debur edges and hole	File, countersink	
4. Mark and Bend	Dial Caliper, Brake, square	



2
B
A
2
1
B
Ø .42
Ø .252
.63
Default Tolerances
X.X ±.1
X.XX ±.01
X.XXX ±.002
ANG ±.5°
DESIGNER
MS-L
MATERIAL Delrin
INTERPRET PER ANSI Y14.5
ALL DIMENSIONS IN INCHES UNLESS SPECIFIED OTHERWISE
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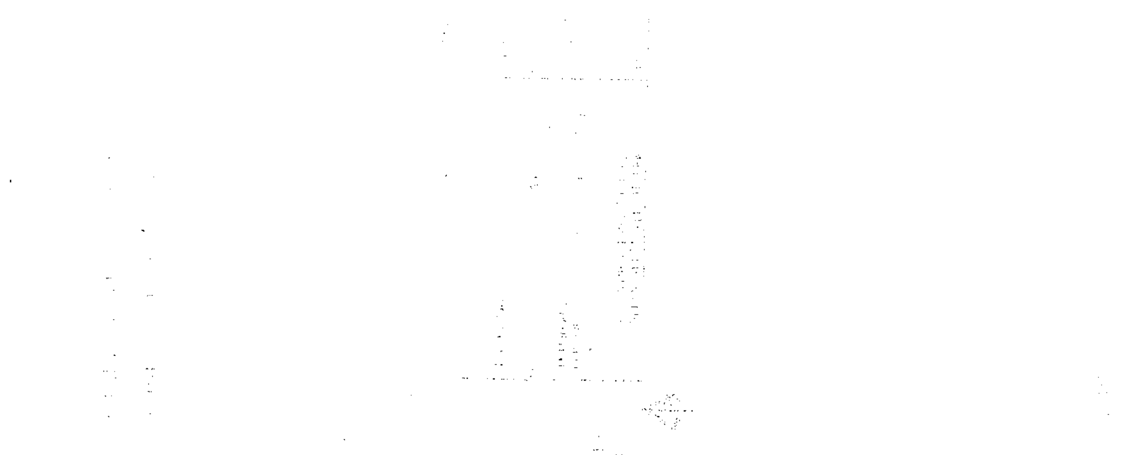
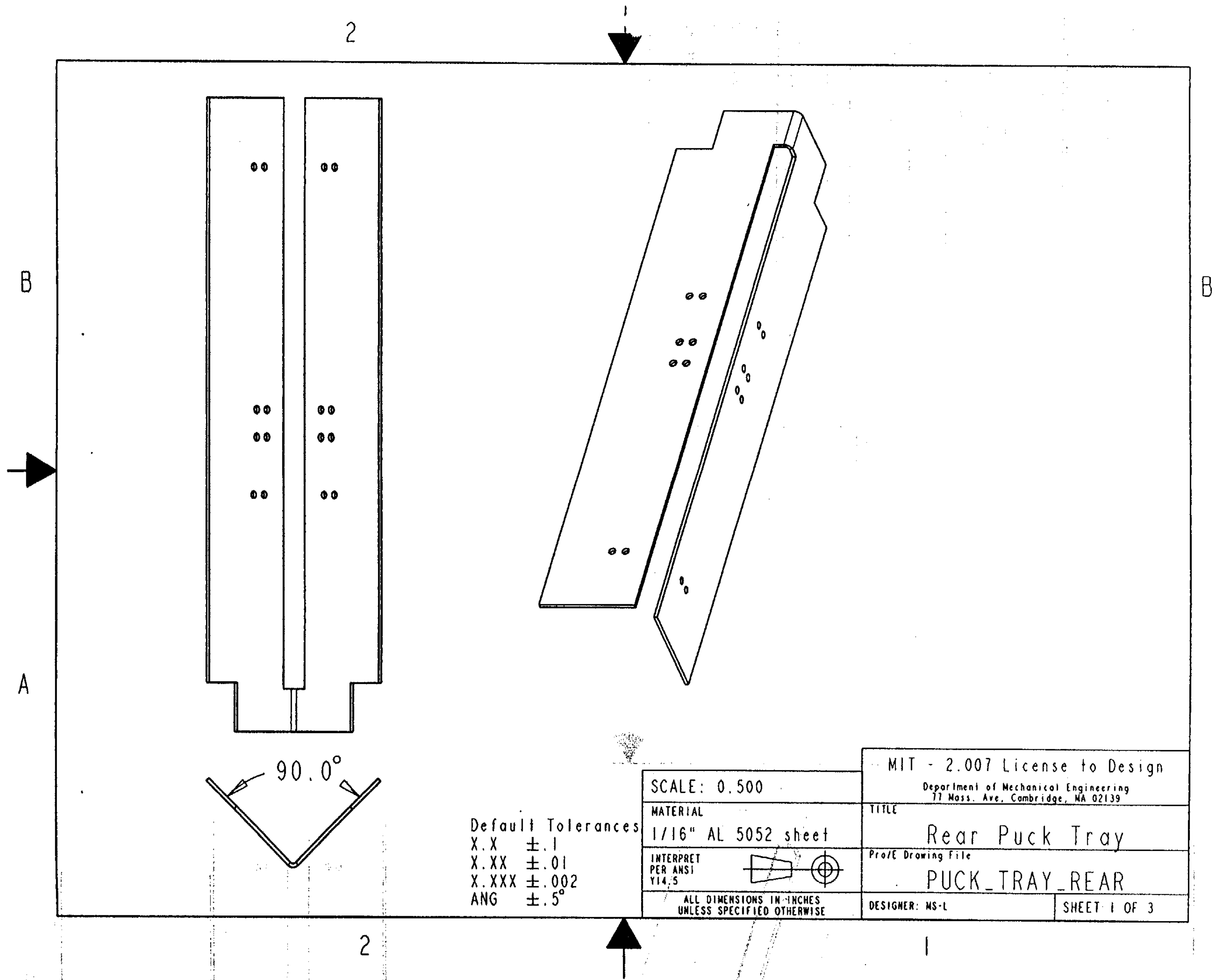
Department of Mechanical Engineering
77 Mass. Ave, Cambridge, MA 02139
TITLE
Rover Wheel Bearing
Pro/E Drawing File
WHEEL_BEARING
SIZE A
SCALE 4.000
SHEET 1 OF 1

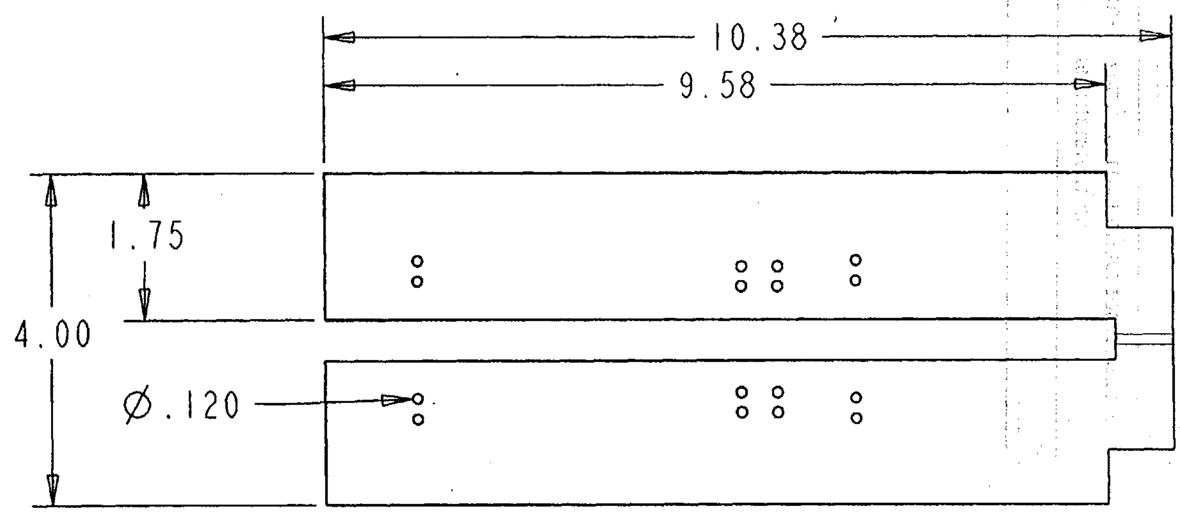
Process Plan for Rover Wheel Bearing

Step	Tools	Note
1. Chuck 1" dia. x >2" length Delrin in Lathe	Lathe	
2. Face and chamfer one end	Lathe, Normal cutting tool, File	
3. Drill Center Hole	Lathe, Drill chuck, Centerdrill, 1/4" drill	
4. Measure and cut off to length + ~0.1"	Lathe, Dykem steel blue dye, Calipers, Parting tool	
5. Face cut and chamfer the recently cutoff face to length	Lathe, Normal cutting tool, Calipers or Micrometer, Dykem steel blue dye, File	Depending on accuracy required, Measure and mark with dye, or calculate material to be removed and use dial gauge on Lathe bed.





2
B
A
90.0°
Default Tolerances
X.X ±.1
X.XX ±.01
X.XXX ±.002
ANG ±.5°
SCALE: 0.500
MATERIAL
1/16" AL 5052 sheet
INTERPRET PER ANSI Y14.5
ALL DIMENSIONS IN INCHES UNLESS SPECIFIED OTHERWISE
MIT - 2.007 License to Design
Department of Mechanical Engineering
77 Mass. Ave, Cambridge, MA 02139
TITLE
Rear Puck Tray
Pro/E Drawing File
PUCK_TRAY_REAR
DESIGNER: MS-L
SHEET 1 OF 3
1



NOTE: Cut on Waterjet

DXF Filename: reartray.dxf

Default Tolerances
X.X ±.1
X.XX ±.01
X.XXX ±.002
ANG ±.5°

SCALE: 0.500	MIT - 2.007 License to Design Department of Mechanical Engineering 77 Mass. Ave, Cambridge, MA 02139
MATERIAL	TITLE Rear Puck Tray
INTERPRET PER ANSI Y14.5	Pro/E Drawing File PUCK_TRAY_REAR
ALL DIMENSIONS IN INCHES UNLESS SPECIFIED OTHERWISE	DESIGNER: MS-L — SHEET 2 OF 3

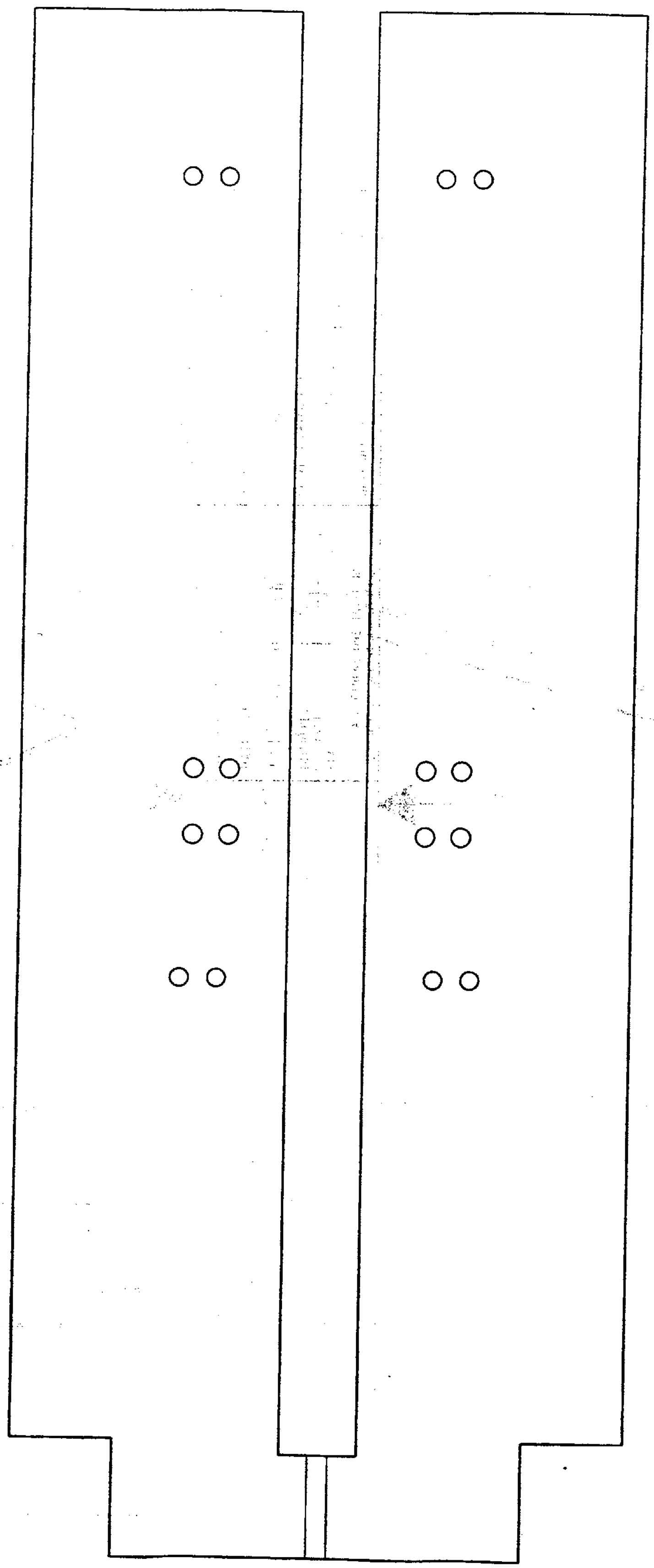
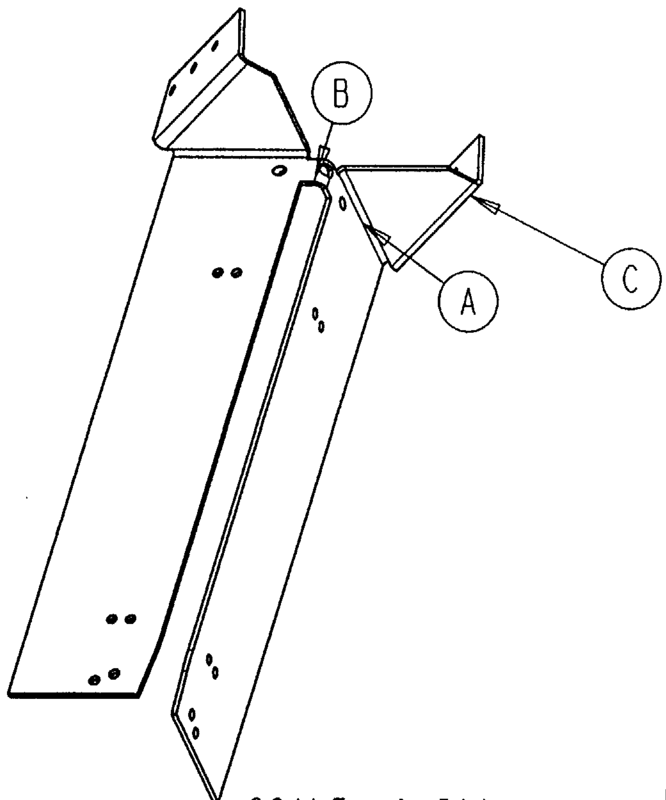


Table 1: Process Plan for Rear Puck Tray

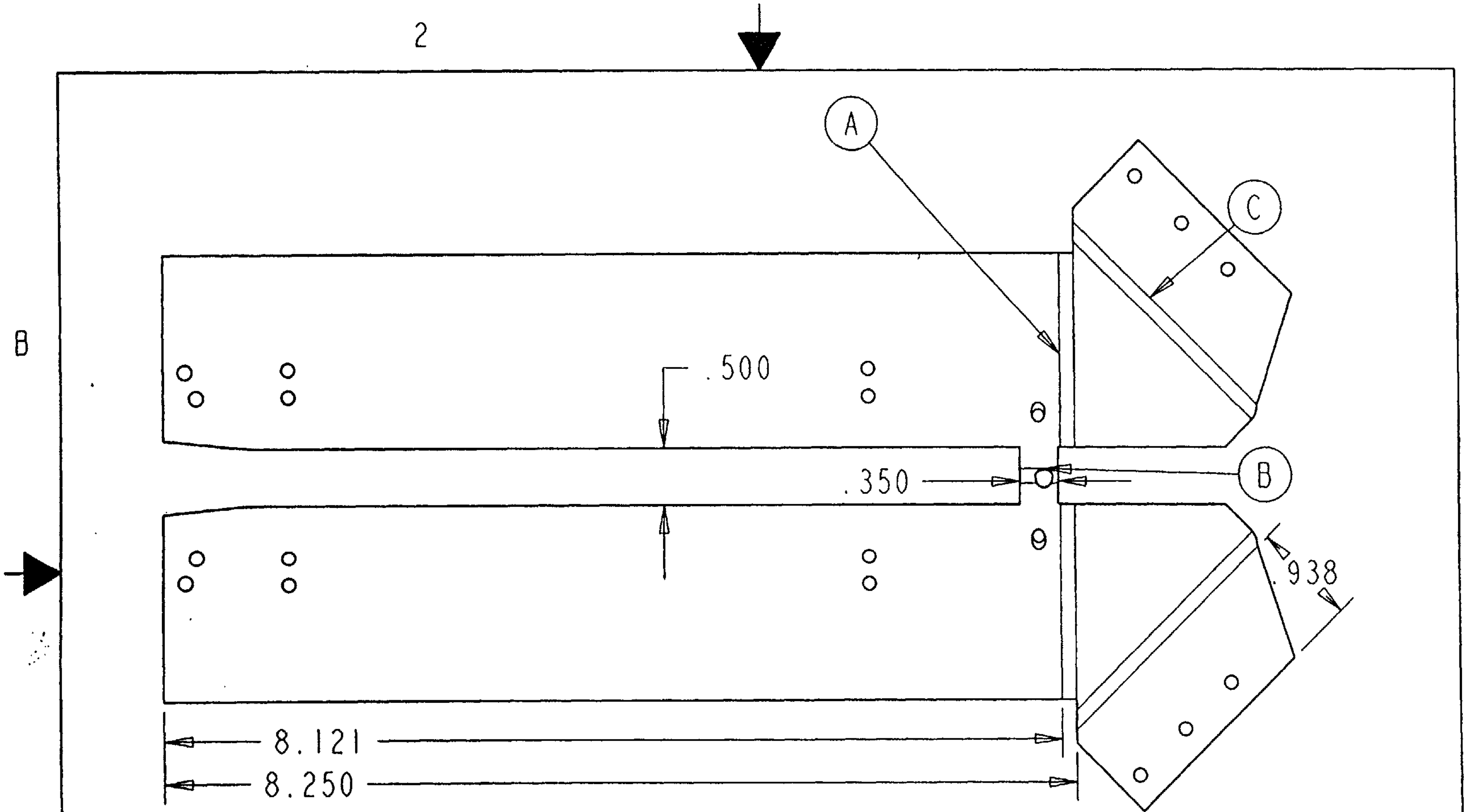
Step	Tools	Note
1. Import to Waterjet and add traverses	.dxf file, Waterjet PC	
2. Cut on waterjet	OMAX Abrasivemachining center ("waterjet")	Verify correct offset for jet diameter (iterate if nec.)
3. Clean up edges	File	
4. Debur and Countersink screw holes	Drill press, Countersink	
5. Mark Bend line	Calipers, Scribe, etc.	
6. Bend	Brake, square	use square to verify angle



SCALE 0.500

Default Tolerances
X.X ±.1
X.XX ±.01
X.XXX ±.002
ANG ±.5°

SCALE: 1.000	MIT - 2.007 License to Design Department of Mechanical Engineering 77 Mass. Ave, Cambridge, MA 02139
MATERIAL 1/16" AL 5052 sheet	TITLE Front Puck Tray
INTERPRET PER ANSI Y14.5	Pro/E Drawing File PUCK_TRAY_FRONT
ALL DIMENSIONS IN INCHES UNLESS SPECIFIED OTHERWISE	DESIGNER: MS-L SHEET 1 OF 3



SCALE 0.750

NOTE: Make Bends A,B,C
in alph. order

DXF Filename: Tray_f.dxf

Default Tolerances
X.X ±.1
X.XX ±.01
X.XXX ±.002
ANG ±.5°

SCALE: 1.000	MIT - 2.007 License to Design Department of Mechanical Engineering 77 Mass. Ave, Cambridge, MA 02139
MATERIAL 1/16" AL 5052 sheet	TITLE Front Puck Tray
INTERPRET PER ANSI Y14.5	Pro/E Drawing File PUCK_TRAY_FRONT
ALL DIMENSIONS IN INCHES UNLESS SPECIFIED OTHERWISE	DESIGNER: HS-L SHEET 2 OF 3

2 1

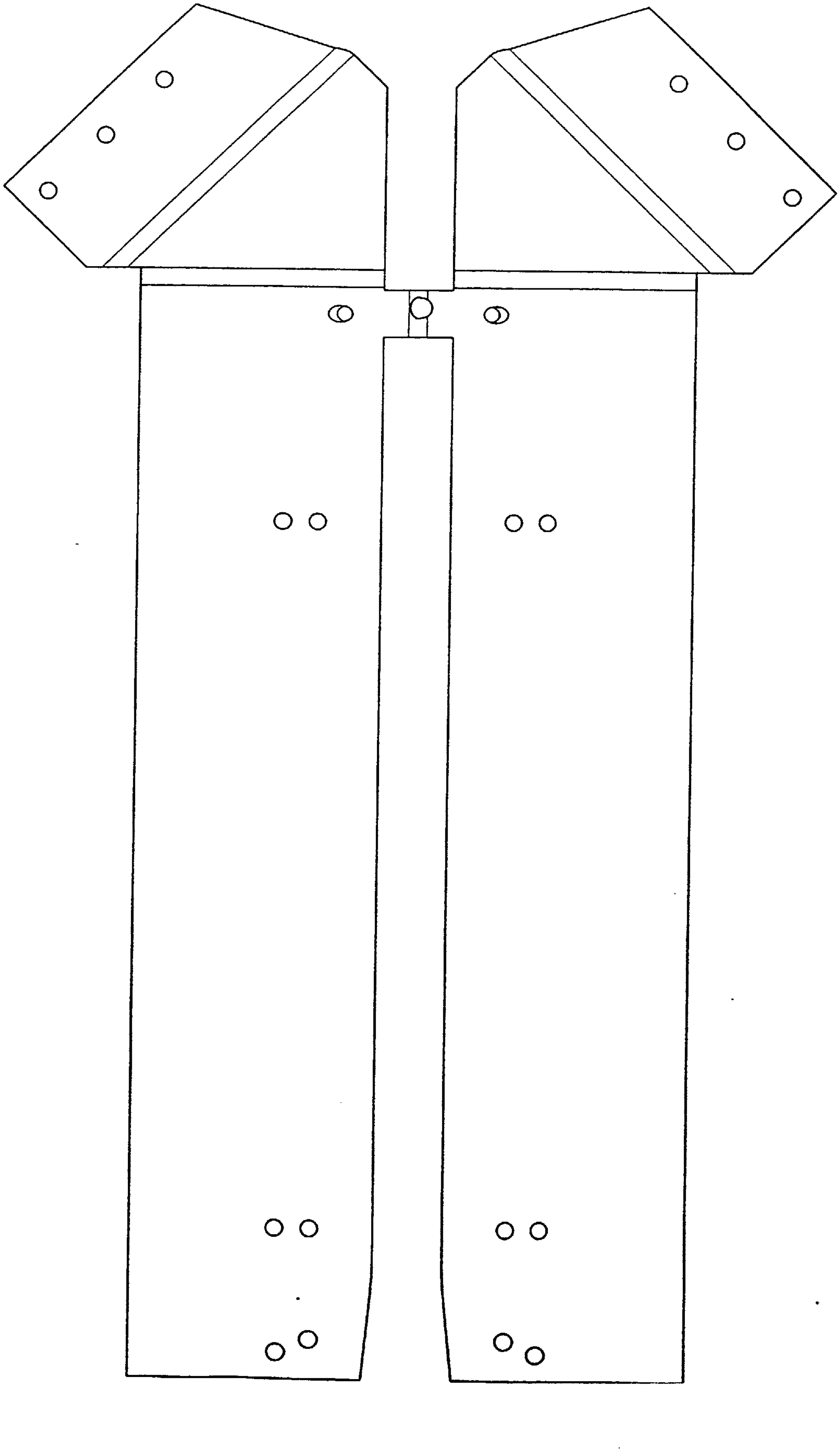
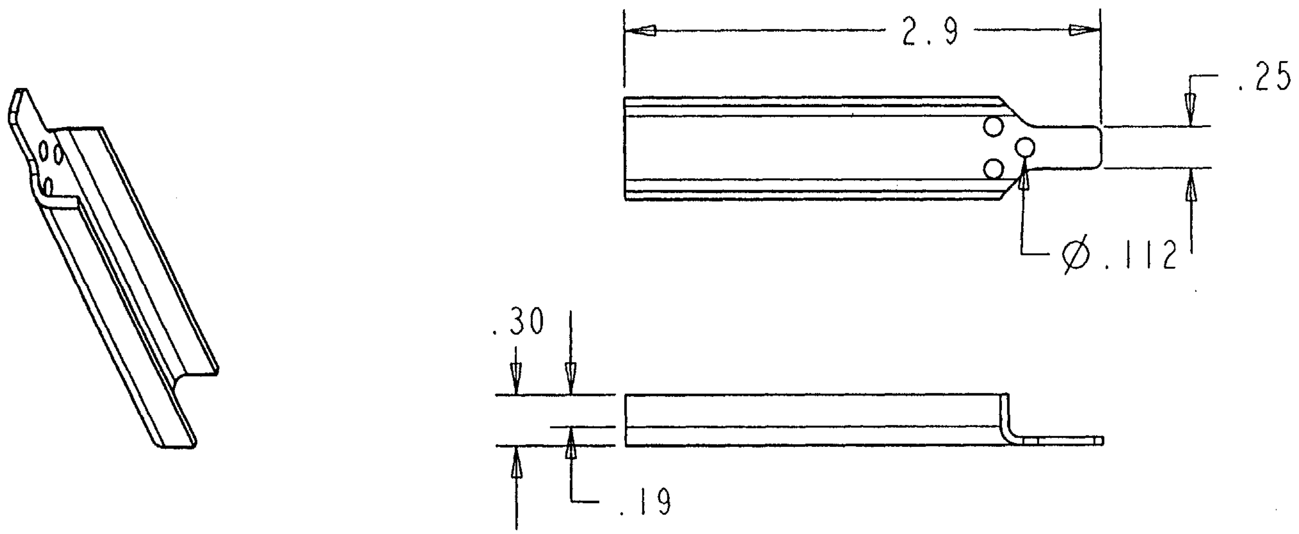


Table 1: Process Plan for Front Puck Tray

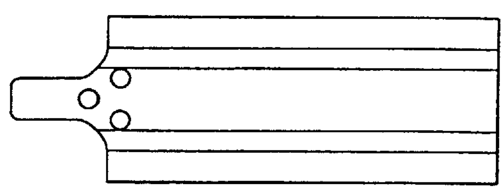
Step	Tools	Note
1. Import to Waterjet and add traverses	.dxf file, Waterjet PC	
2. Cut on waterjet	OMAX Abrasivemachining center ("waterjet")	Verify correct offset for jet diameter (iterate if nec.)
3. Clean up edges	File	
4. Debur and Countersink screw holes	Drill press, Countersink	
5. Mark Bend lines	Calipers, Scribe, etc.	
6. Bend both bends A	Brake, square	use square to verify angle
7. Bend B	Freehand (little material)	
8. Bend both bends C	Vise, Scrap wood, Mallet, Pliers, Square	Hold flap in vise



Cut flat part on Waterjet
DXF Filnename: pusher.dxf

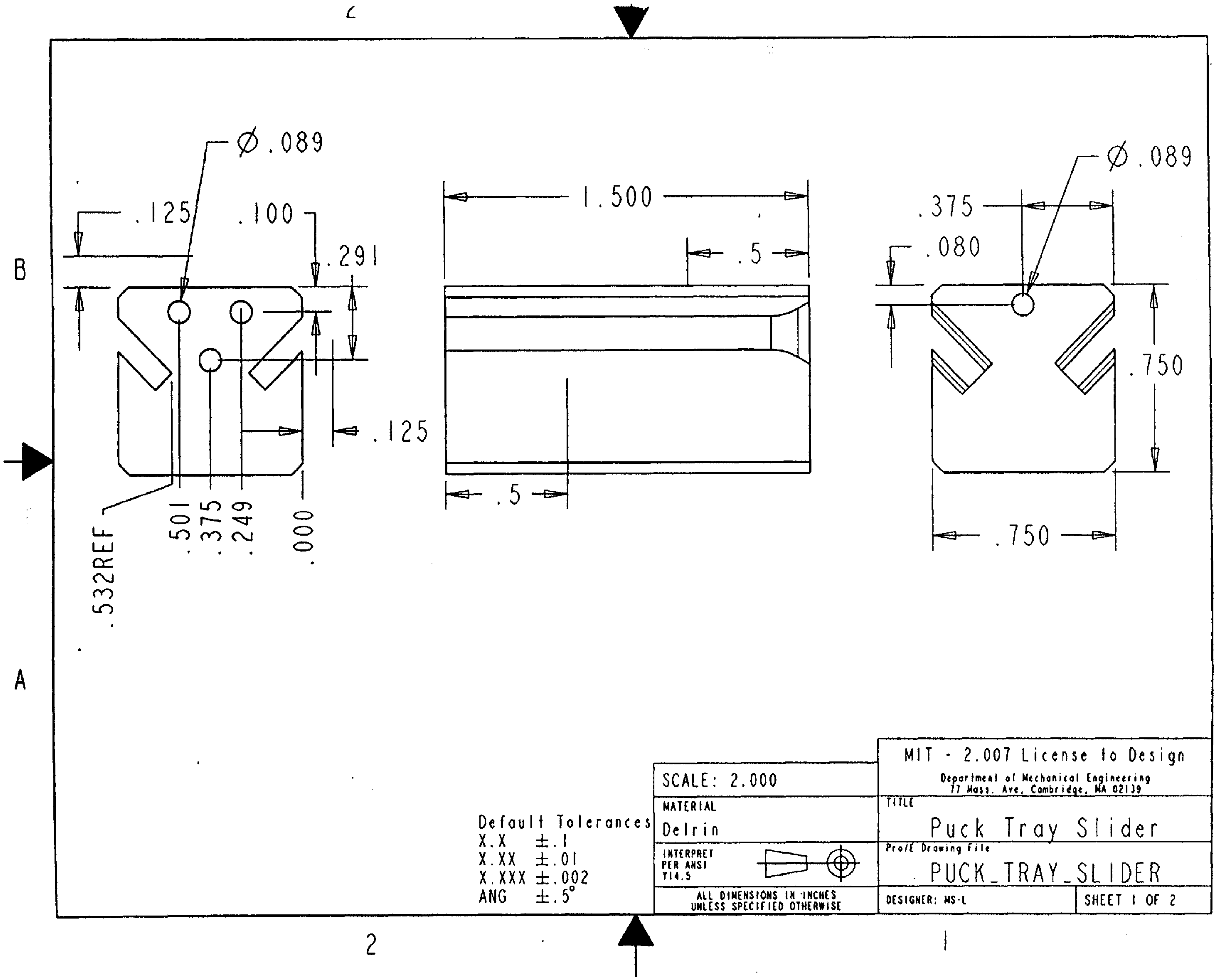
Default Tolerances
X.X ±.1
X.XX ±.01
X.XXX ±.002
ANG ±.5°

SCALE: 1.000	MIT - 2.007 License to Design Department of Mechanical Engineering 77 Mass. Ave, Cambridge, MA 02139
MATERIAL 18 ga. Mild Steel	TITLE Puck Pusher
INTERPRET PER ANSI Y14.5	Pro/E Drawing File PUCK_PUSHER
ALL DIMENSIONS IN INCHES UNLESS SPECIFIED OTHERWISE	DESIGNER: MS-L — SHEET 1 OF 2



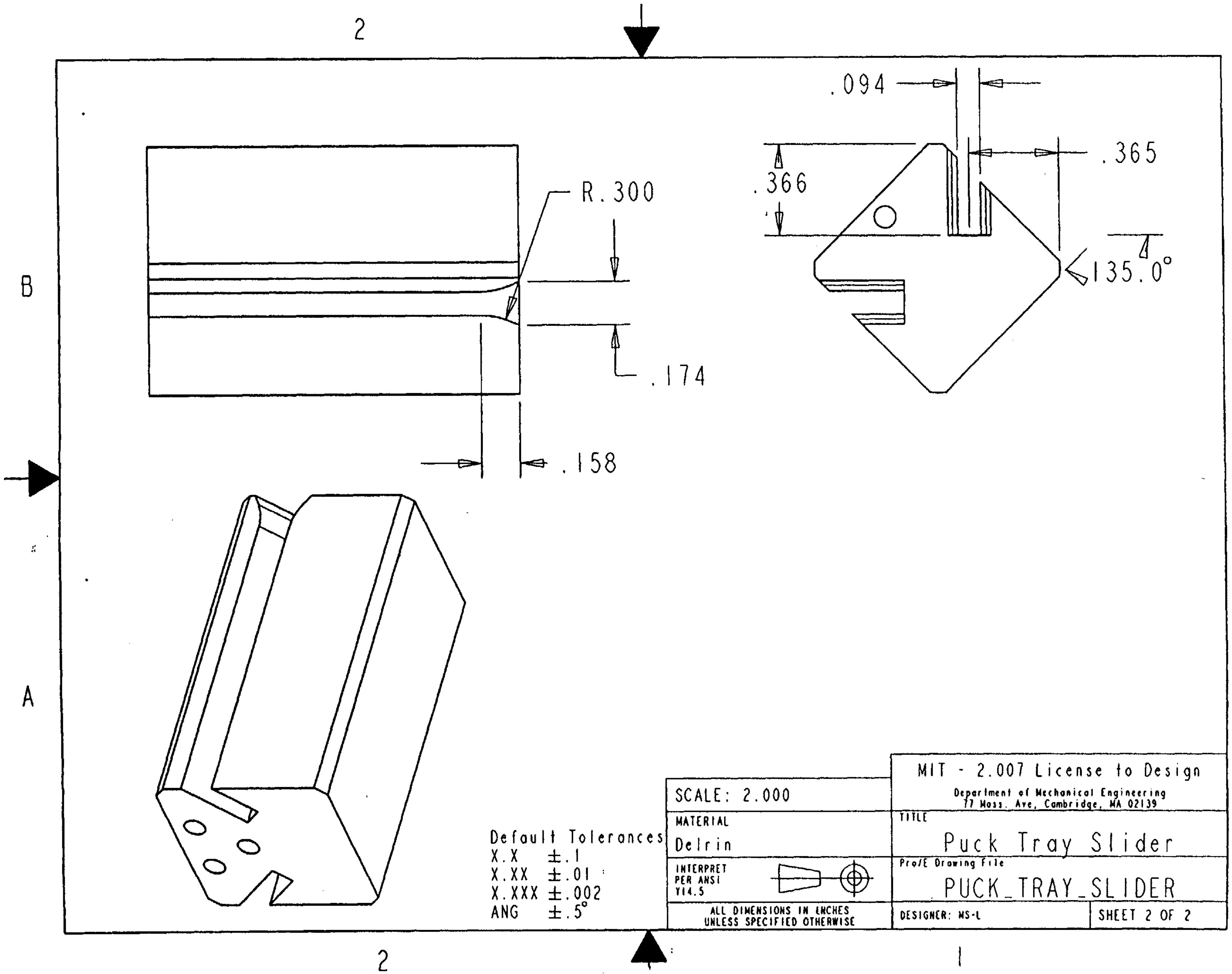
Process Plan for Puck Pusher

Step	Tools	Note
1. Import to Waterjet and add traverses	.dxf file, Waterjet PC	
2. Cut on waterjet	OMAX Abrasivemachining center ("waterjet")	Verify correct offset for jet diameter (iterate if nec.)
3. Clean up edges	File	
4. Debur screw holes	Drill press, Countersink	
5. Mark Bend lines	Calipers, Scribe, etc.	
6. Make Bends	Brake	



Default Tolerances
X.X ±.1
X.XX ±.01
X.XXX ±.002
ANG ±.5°

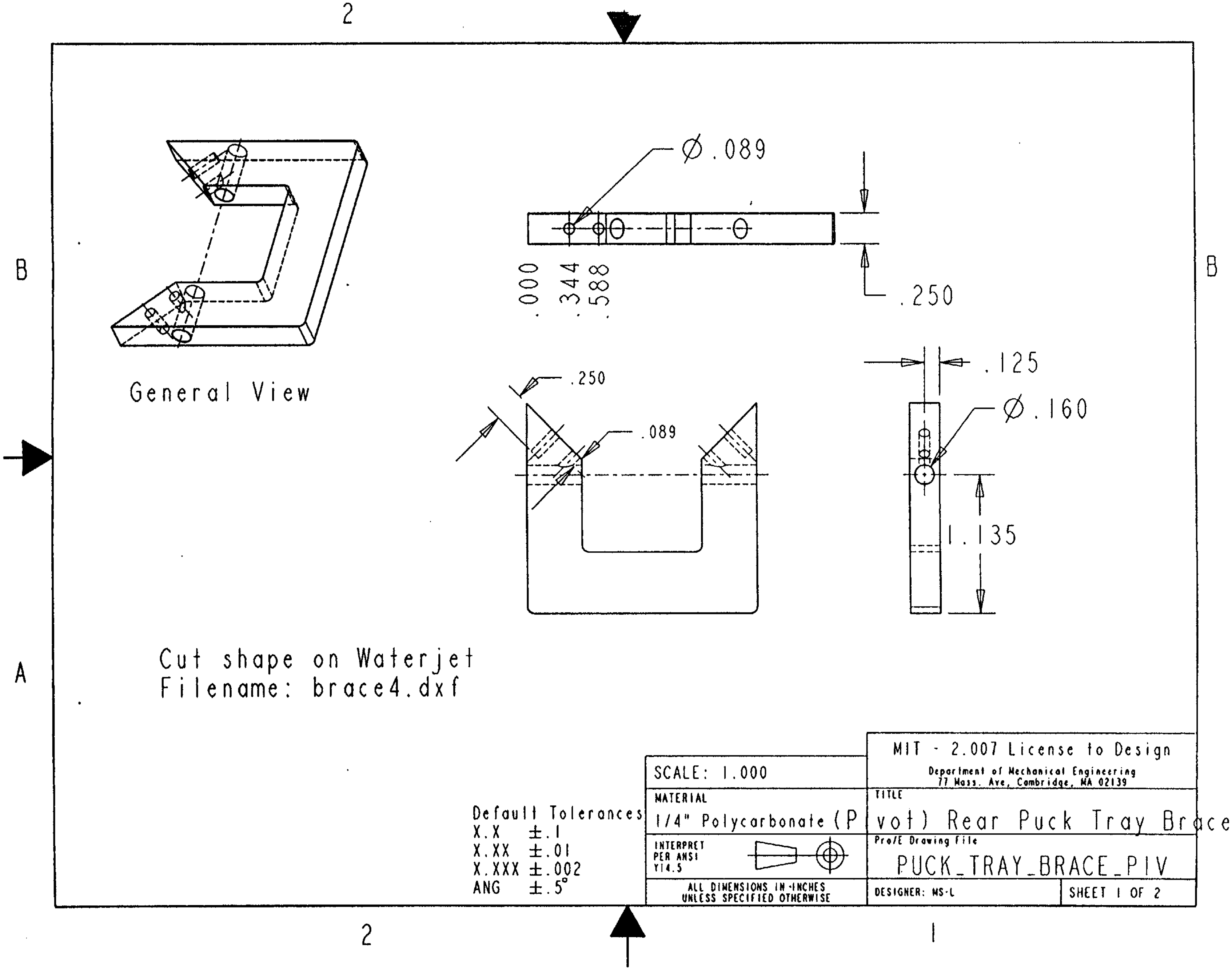
SCALE: 2.000	MIT - 2.007 License to Design Department of Mechanical Engineering 77 Mass. Ave, Cambridge, MA 02139
MATERIAL Delrin	TITLE Puck Tray Slider
INTERPRET PER ANSI Y14.5	Pro/E Drawing File PUCK_TRAY_SLIDER
ALL DIMENSIONS IN INCHES UNLESS SPECIFIED OTHERWISE	DESIGNER: MS-L · SHEET 1 OF 2



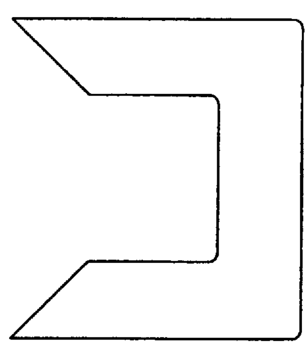
2
B
A
2
1
B
.094
.365
.366
135.0°
R.300
.174
.158
Default Tolerances
X.X ±.1
X.XX ±.01
X.XXX ±.002
ANG ±.5°
SCALE: 2.000
MATERIAL
Delrin
INTERPRET PER ANSI Y14.5
ALL DIMENSIONS IN INCHES UNLESS SPECIFIED OTHERWISE
MIT - 2.007 License to Design
Department of Mechanical Engineering
77 Mass. Ave, Cambridge, MA 02139
TITLE
Puck Tray Slider
Pro/E Drawing File
PUCK_TRAY_SLIDER
DESIGNER: MS-L
SHEET 2 OF 2

Process Plan for Puck Tray Slider

Step	Tools	Note
1. Cut 1" Delrin rod to length + .25"	Calipers, Hacksaw	Round stock is often dangerous to bandsaw, it may catch a sawtooth and spin....
2. Cut square from 1" Delrin Rod	Mill, V-block, 2-flute endmill ~1/2", coolant	Bring cutter to just touching round surface, then use graduations on mill's bed raising crank to cut required amount from each of 4 sides.
3. Cut to length	Mill, Parallels, e-mill, calipers	
4. Cut bearing slots	Mill, V-block, Edgefinder, coolant 3/32 2-flute e-mill	Verify depth of cut this e-mill is capable of (enough cutting heght?)
5. Drill screw holes	Mill, edgefinder, center-drill, #43 drill, coolant	
6. Tap screw holes	4-40 tap	Holes can be arbitrarily deep so no bottoming tap should be necessary
7. Cut widening of bearing slots	X-acto knife, small file	

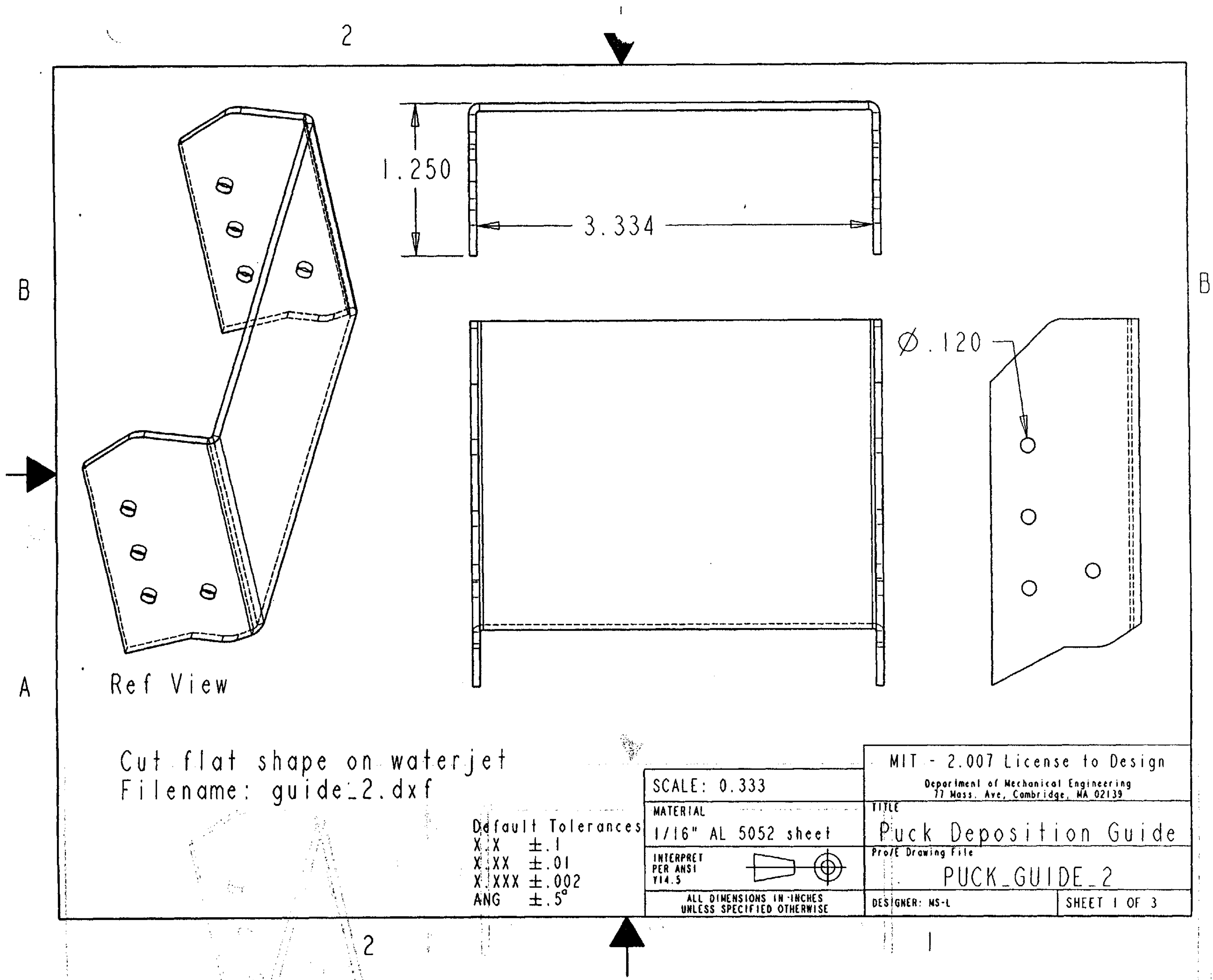


2
B
A
Ø.089
.000
.344
.588
.250
.125
Ø.160
.250
.089
1.135
General View
Cut shape on Waterjet
Filename: brace4.dxf
Default Tolerances
X.X ±.1
X.XX ±.01
X.XXX ±.002
ANG ±.5°
SCALE: 1.000
MATERIAL
1/4" Polycarbonate (Pivot) Rear Puck Tray Brace
INTERPRET PER ANSI Y14.5
ALL DIMENSIONS IN INCHES UNLESS SPECIFIED OTHERWISE
MIT - 2.007 License to Design
Department of Mechanical Engineering
77 Mass. Ave, Cambridge, MA 02139
TITLE
Pro/E Drawing File
PUCK_TRAY_BRACE_PIV
DESIGNER: MS-L
SHEET 1 OF 2
1

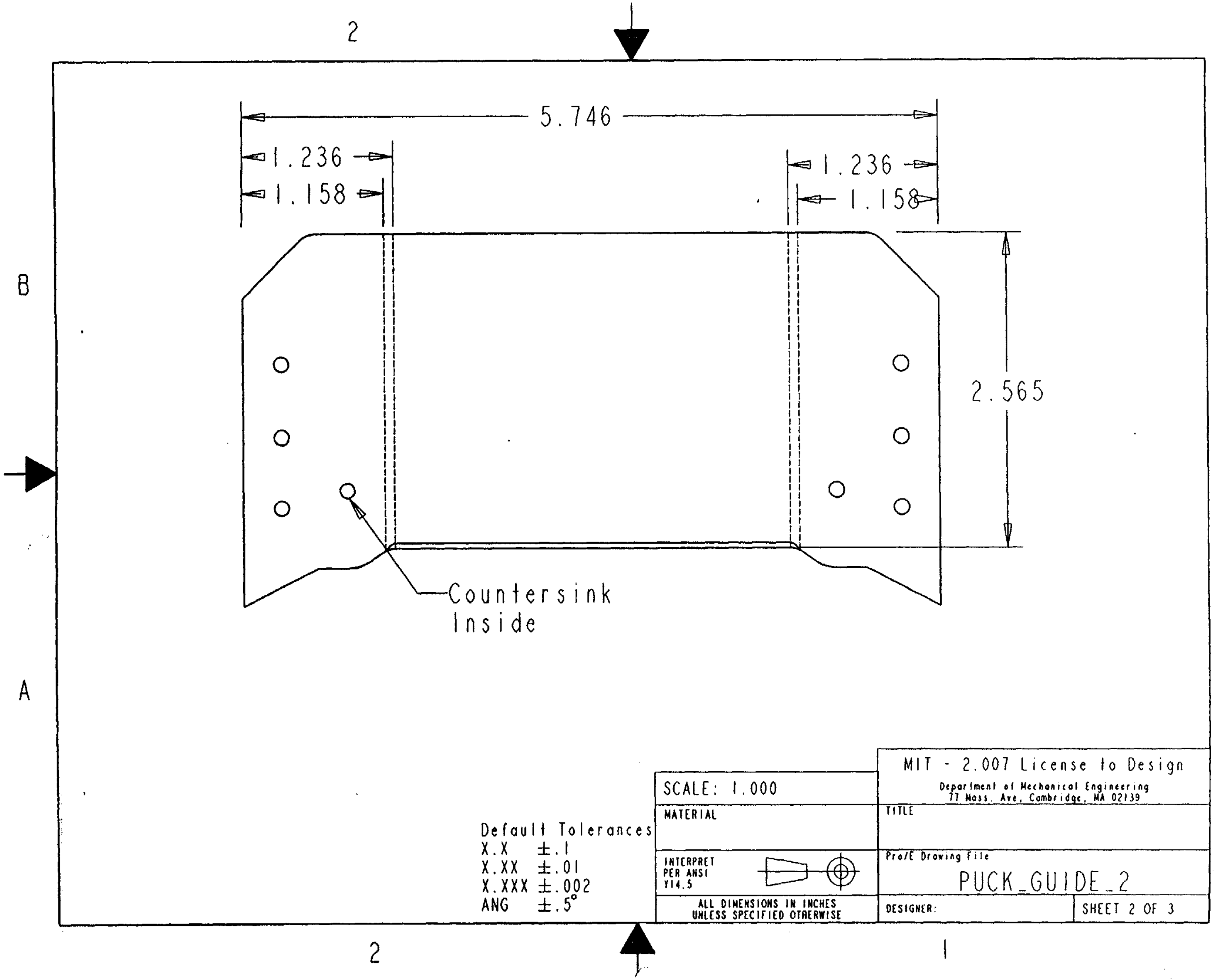


Process Plan for (Pivot) Rear Puck Tray Brace

Step	Tools	Note
1. Import to Waterjet and add traverses	.dxf file, Waterjet PC	
2. Cut on waterjet	OMAX Abrasivemachining center ("waterjet")	Verify correct offset for jet diameter (iterate if nec.)
3. Clean up edges	File	
4. Drill screw holes in angled surfaces	Mill, V-Block, Edgefinder, Centerdrill, Drill #43, Coolant	Concurrent with other Tray Brace parts (same or similar setup) Use Vise Stop to create repeatable positionining of same part flipped, and other parts with same dims
5. Drill Pivot Hole	Mill, Edgefinder, Parallels, Centerdrill, Drill for .160, coolant	Can use Vise Stop to flip part without rezeroing readout
6. Tap screw holes	4-40 tap, 4-40 bottoming tap, tap cutting fluid	



2
B
A
Ref View
1.250
3.334
Ø.120
B
Cut flat shape on waterjet
Filename: guide_2.dxf
Default Tolerances
X.X ±.1
X.XX ±.01
X.XXX ±.002
ANG ±.5°
SCALE: 0.333
MATERIAL
1/16" AL 5052 sheet
INTERPRET PER ANSI Y14.5
ALL DIMENSIONS IN INCHES UNLESS SPECIFIED OTHERWISE
MIT - 2.007 License to Design
Department of Mechanical Engineering
77 Mass. Ave, Cambridge, MA 02139
TITLE
Puck Deposition Guide
Pro/E Drawing File
PUCK_GUIDE_2
DESIGNER: MS-L
SHEET 1 OF 3
2
1



5.746
1.236
1.158
1.236
1.158
2.565
Countersink
Inside
2
2
1
B
B
A
Default Tolerances
X.X ±.1
X.XX ±.01
X.XXX ±.002
ANG ±.5°
SCALE: 1.000
MATERIAL
INTERPRET PER ANSI Y14.5
ALL DIMENSIONS IN INCHES UNLESS SPECIFIED OTHERWISE
MIT - 2.007 License to Design
Department of Mechanical Engineering
77 Mass. Ave, Cambridge, MA 02139
TITLE
Pro/E Drawing File
PUCK_GUIDE_2
DESIGNER:
SHEET 2 OF 3

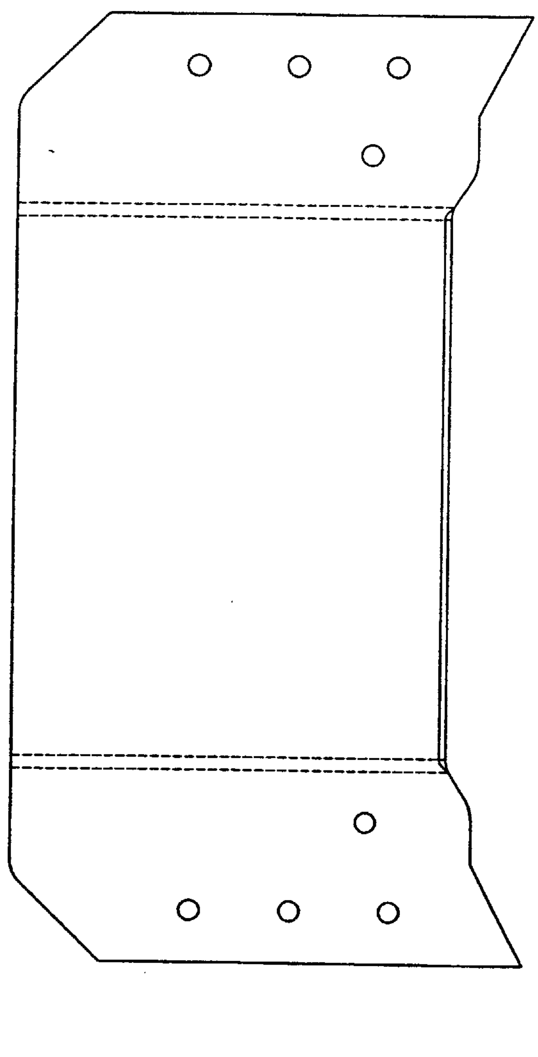
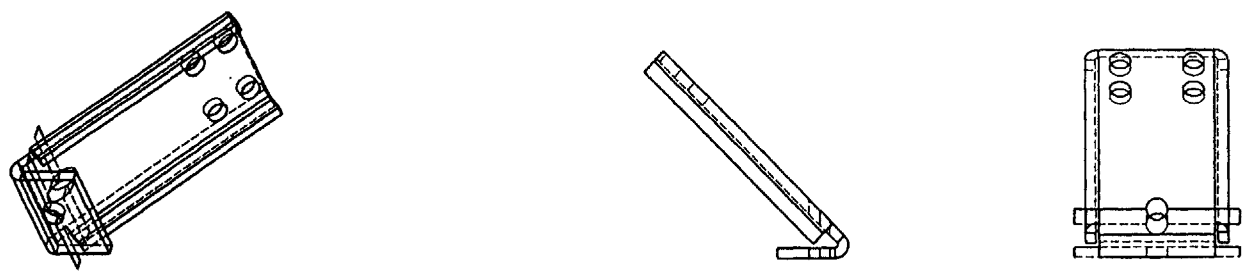


Table 1: Process Plan for Puck Deposition Guide

Step	Tools	Note
1. Import to Waterjet and add traverses	.dxf file, Waterjet PC	
2. Cut on waterjet	OMAX Abrasivemachining center ("waterjet")	Verify correct offset for jet diameter (iterate if nec.)
3. Clean up edges	File	
4. Debur and Countersink indicated screw holes	Drill press, Countersink	
5. Mark Bend lines	Calipers, Scribe, etc.	
6. Bend both bends	Brake, square	use square to verify angle



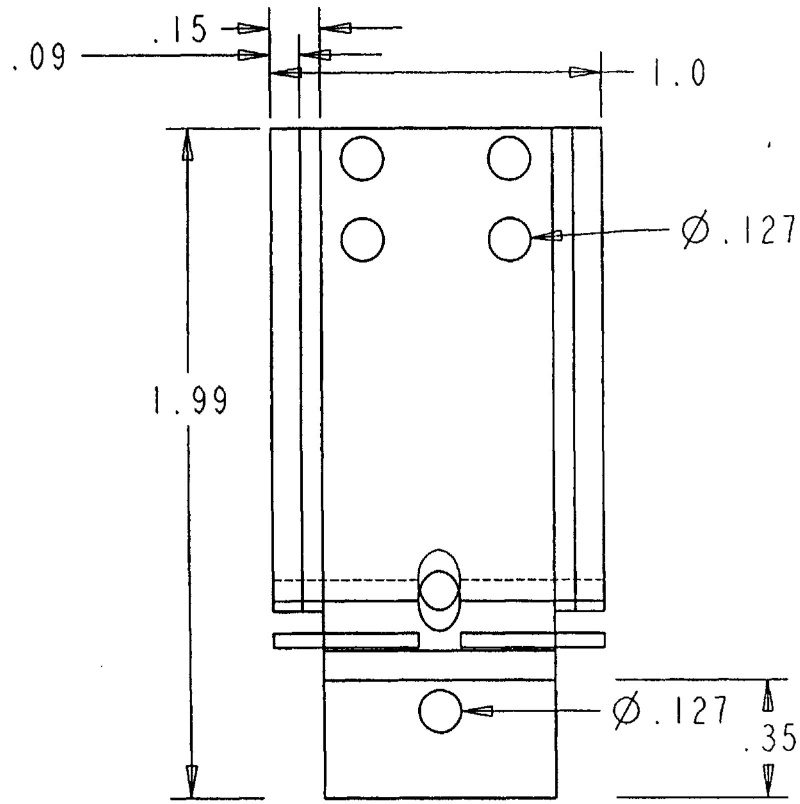
Cut flat shape on Waterjet
Filename: attach.dxf

Default Tolerances
X.X ±.1
X.XX ±.01
X.XXX ±.002
ANG ±.5°

SCALE: 1.000	MIT - 2.007 License to Design Department of Mechanical Engineering 77 Mass. Ave, Cambridge, MA 02139
MATERIAL 18 ga. Mild Steel	TITLE Piston Attach Point Bracket
INTERPRET PER ANSI Y14.5	Pro/E Drawing File PISTON_ATTACH_2
ALL DIMENSIONS IN INCHES UNLESS SPECIFIED OTHERWISE	DESIGNER: MS-L — SHEET 1 OF 3

2

B



B

A

Default Tolerances
X.X ±.1
X.XX ±.01
X.XXX ±.002
ANG ±.5°

SCALE: 2.000	MIT - 2.007 License to Design Department of Mechanical Engineering 77 Mass. Ave, Cambridge, MA 02139
MATERIAL 18 ga. Mild Steel	TITLE Piston Attach Point Bracket
INTERPRET PER ANSI Y14.5	Pro/E Drawing File PISTON_ATTACH_2
ALL DIMENSIONS IN INCHES UNLESS SPECIFIED OTHERWISE	DESIGNER: MS-L / SHEET 2 OF 3

2

1

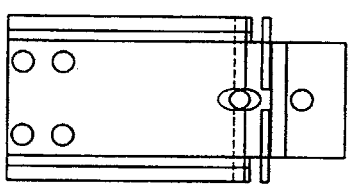
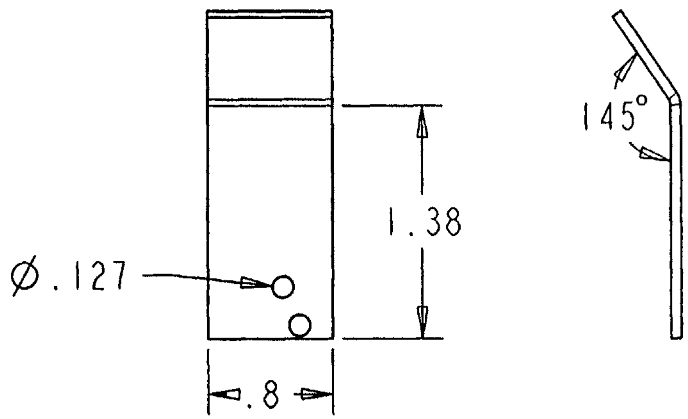


Table 1: Process Plan for Piston Attach Point Bracket

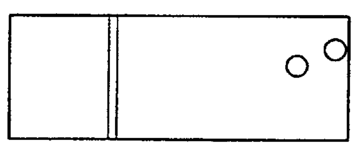
Step	Tools	Note
1. Import to Waterjet and add traverses	.dxf file, Waterjet PC	
2. Cut on waterjet	OMAX Abrasivemachining center ("waterjet")	Verify correct offset for jet diameter (iterate if nec.)
3. Clean up edges	File	
4. Debur and Countersink indicated screw holes	Drill press, Countersink	
5. Mark Bend lines	Calipers, Scribe, etc.	
6. Bend 45 deg. angle	Brake	use drawing to verify angle
7. Bend Stiffening Bends	Brake	Take care to leave clearance around holes for nuts/rivets



make 2 mirror image parts
Waterjet Filename: traystop.dxf

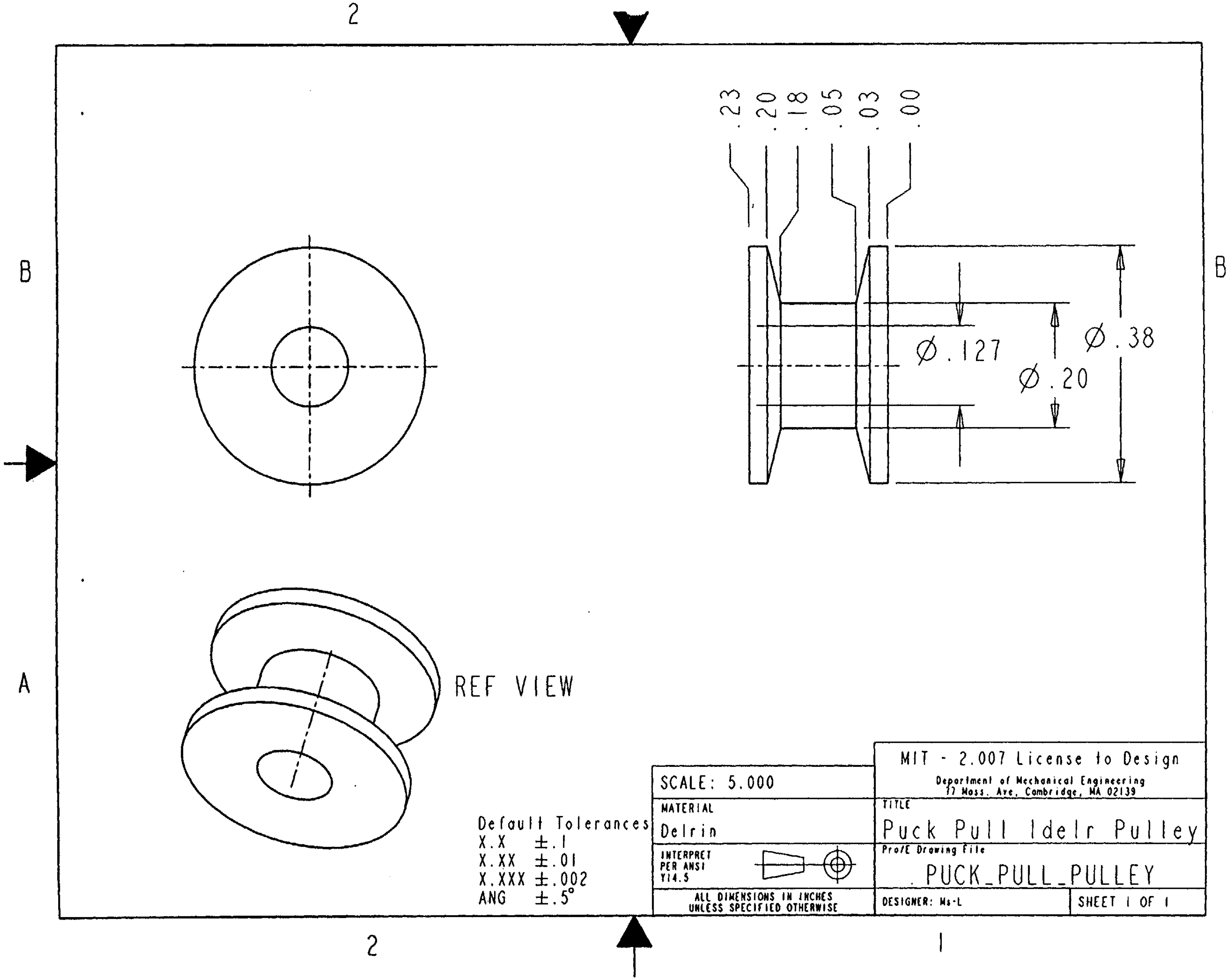
Default Tolerances
X.X ±.1
X.XX ±.01
X.XXX ±.002
ANG ±.5°

	MIT - 2.007 License to Design Department of Mechanical Engineering 77 Mass. Ave, Cambridge, MA 02139
SCALE: 1.000	
MATERIAL 18 ga. Mild Steel	TITLE Rear Puck Tray Stop
INTERPRET PER ANSI Y14.5	Pro/E Drawing File PUCK_TRAY_STOP
ALL DIMENSIONS IN INCHES UNLESS SPECIFIED OTHERWISE	DESIGNER: MS-L | SHEET 1 OF 2



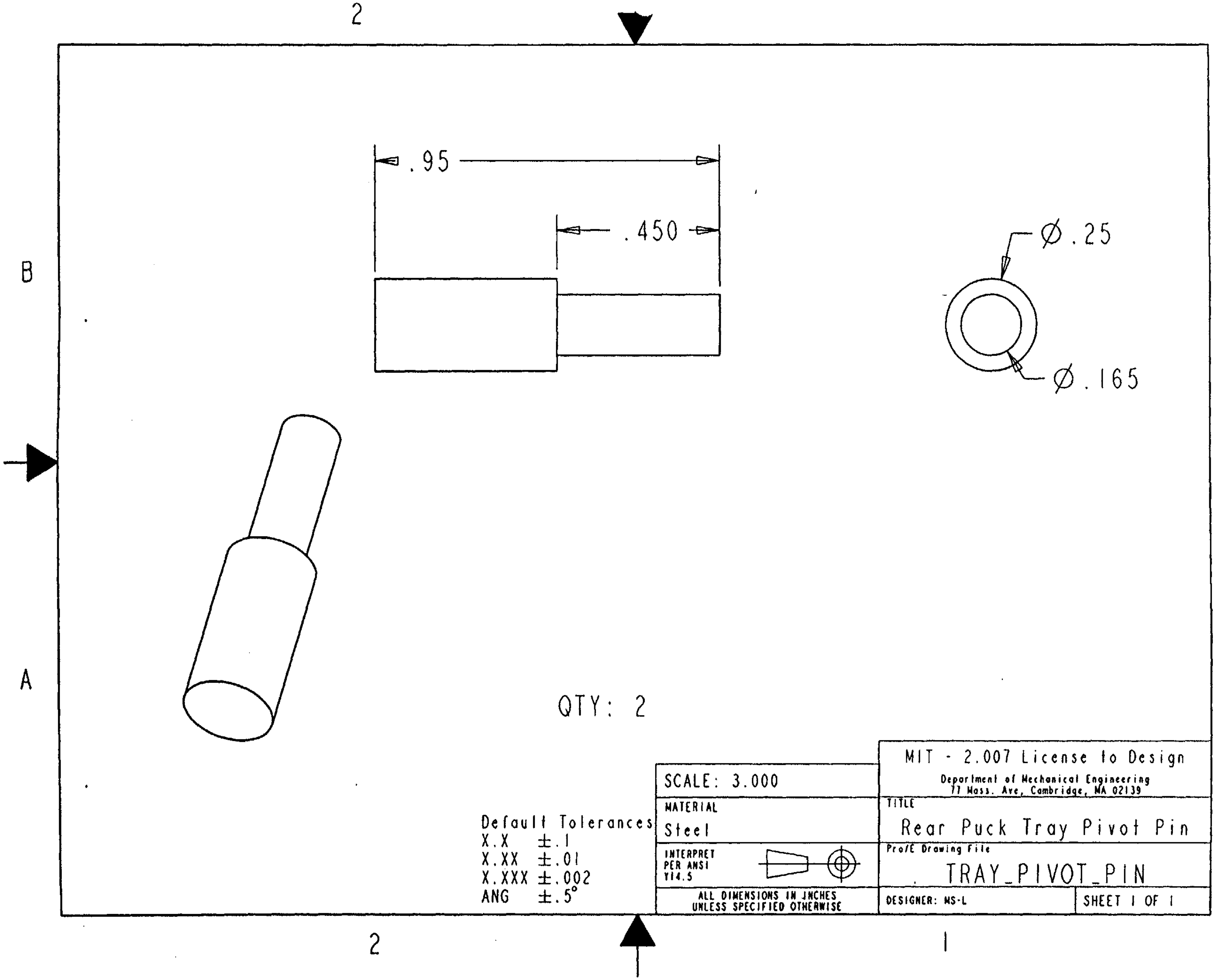
Process Plan for Puck Tray Stop

Step	Tools	Note
1. Import to Waterjet and add traverses	.dxf file, Waterjet PC	make 2 mirror parts
2. Cut on waterjet	OMAX Abrasivemachining center ("waterjet")	Verify correct offset for jet diameter (iterate if nec.)
3. Clean up edges	File	
4. Debur and holes	Drill press, Countersink	
5. Mark Bend line	Calipers, Scribe, etc.	
6. Bend 45 deg. angle	Brake	use drawing to verify angle


2
2
1
B
B
A
.23
.20
.18
.05
.03
.00
Ø.127
Ø.20
Ø.38
REF VIEW
Default Tolerances
X.X ±.1
X.XX ±.01
X.XXX ±.002
ANG ±.5°
SCALE: 5.000
MATERIAL
Delrin
INTERPRET PER ANSI Y14.5
ALL DIMENSIONS IN INCHES UNLESS SPECIFIED OTHERWISE
MIT - 2.007 License to Design
Department of Mechanical Engineering
77 Mass. Ave, Cambridge, MA 02139
TITLE
Puck Pull Idelr Pulley
Pro/E Drawing File
PUCK_PULL_PULLEY
DESIGNER: Ms-L
SHEET 1 OF 1

Process Plan for Puck Pull Idler Pulley

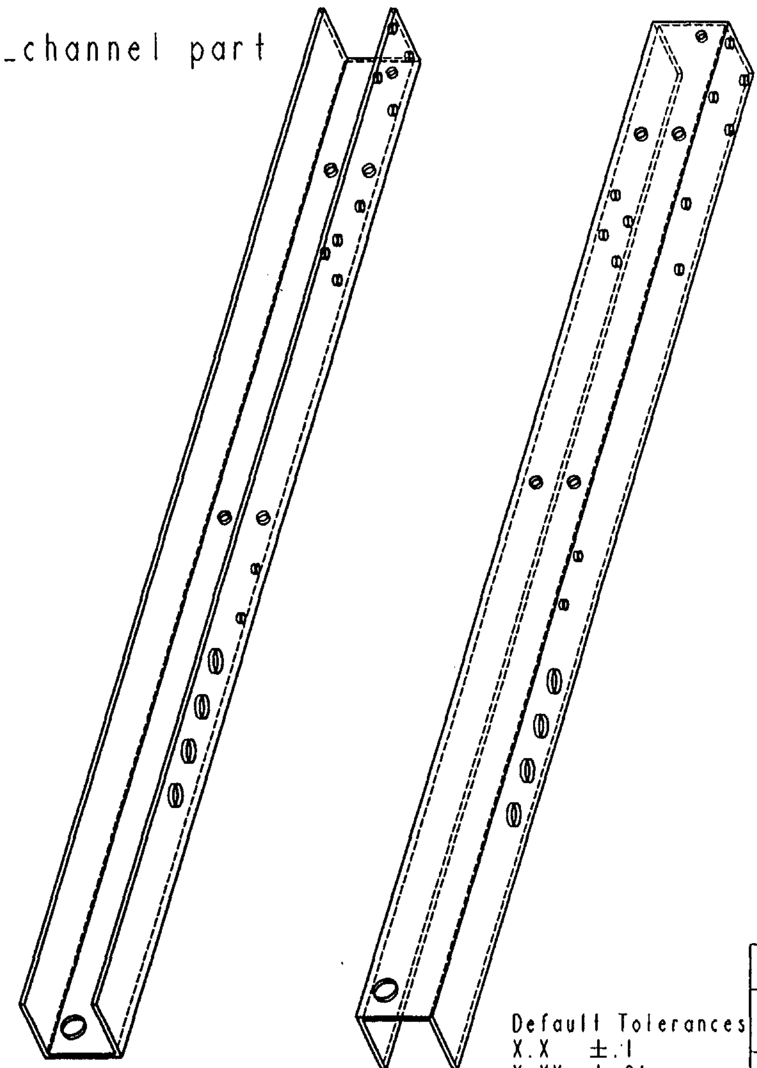
Step	Tools	Note
1. Turn 1" dia Delrin rod to pulley OD x ~4 pulleys long	Lathe, Calipers	
2. Drill axle hole through length of stock	Drill chuck, centerdrill, 1/8" drillbit, coolant	
3. Mark locations where flanges will remain	Calipers	
4. Cut pulley grooves	Lathe, Cutoff tool	Cutoff tools should be used to cut radially only. Record dial position at desired groove depth- this can be returned to for subsequent pulleys cut in the exact same setup
5. Cut off pulley	Lathe, Cutoff tool	
6. Make 1-2 more pulleys		



.95
.450
Ø.25
Ø.165
QTY: 2
Default Tolerances
X.X ±.1
X.XX ±.01
X.XXX ±.002
ANG ±.5°
SCALE: 3.000
MATERIAL
Steel
INTERPRET PER ANSI Y14.5
ALL DIMENSIONS IN INCHES UNLESS SPECIFIED OTHERWISE
MIT - 2.007 License to Design
Department of Mechanical Engineering
77 Mass. Ave, Cambridge, MA 02139
TITLE
Rear Puck Tray Pivot Pin
Pro/E Drawing File
TRAY_PIVOT_PIN
DESIGNER: MS-L
SHEET 1 OF 1

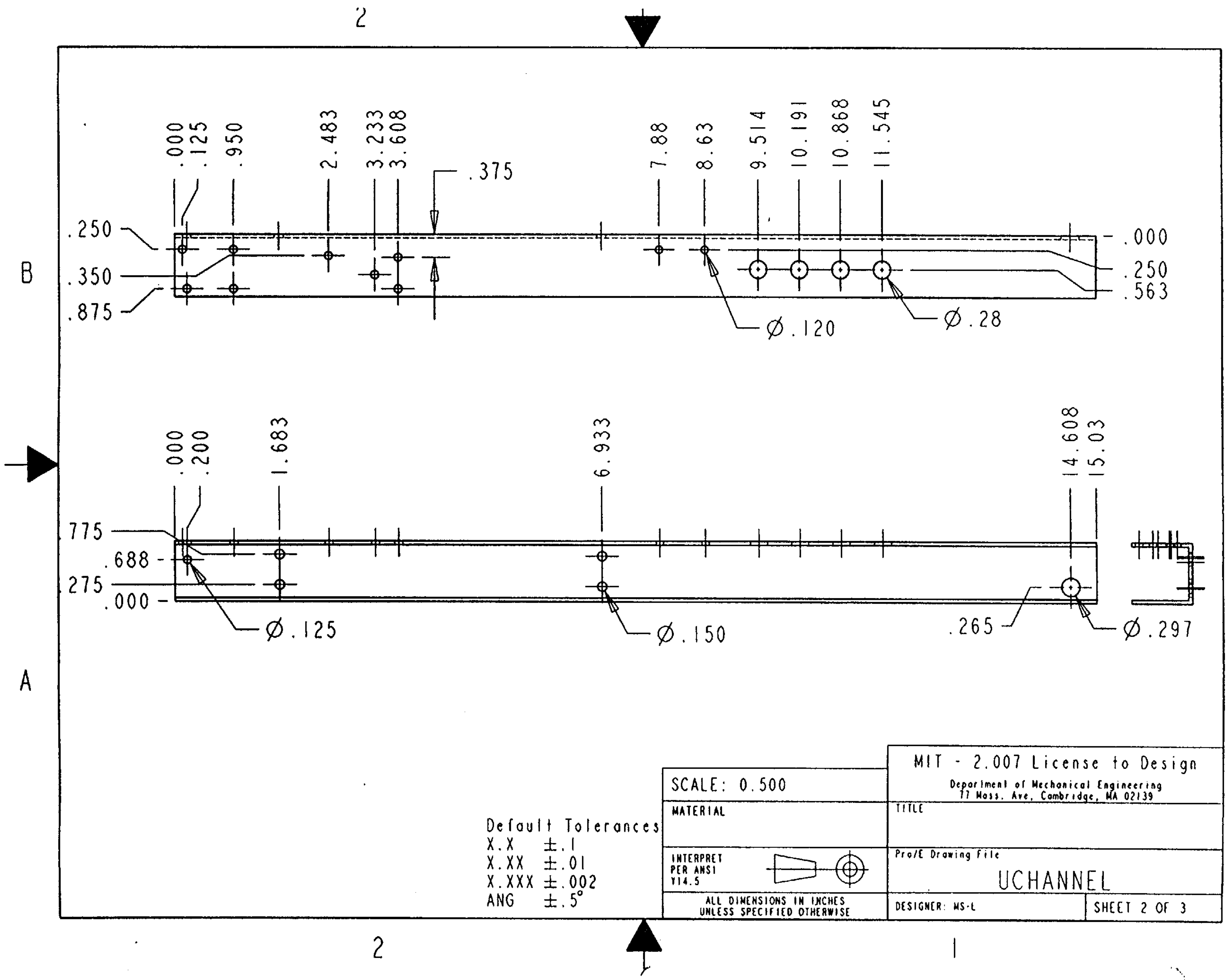
Process Plan for Puck Tray Pivot Pin

Step	Tools	Note
1. Cut 1/4" Steel rod to length +1/8"	Calipers, Dykem Steel Blue, Hacksaw	Hacksaw much better than Bandsaw here.
2. Face and clean ends	Lathe, normal cutting tool, file	
3. Cut shoulder	Lathe, cutting tool with close to square corner, light oil as coolant, Dial gauge	Speed around 300-400 rpm Comfortable depth of cut is one that causes cutting oil to smoke lightly. Keep cutting tip oiled. A dial gauge can be mounted (usually magnetically) to the bed of lathe to measure the length of the shoulder cut, and ensure that each cut ends at the same spot.
4. Face cut to length	Lathe, Calipers, normal cutting tool	
5. Chamfer ends	Lathe, File	

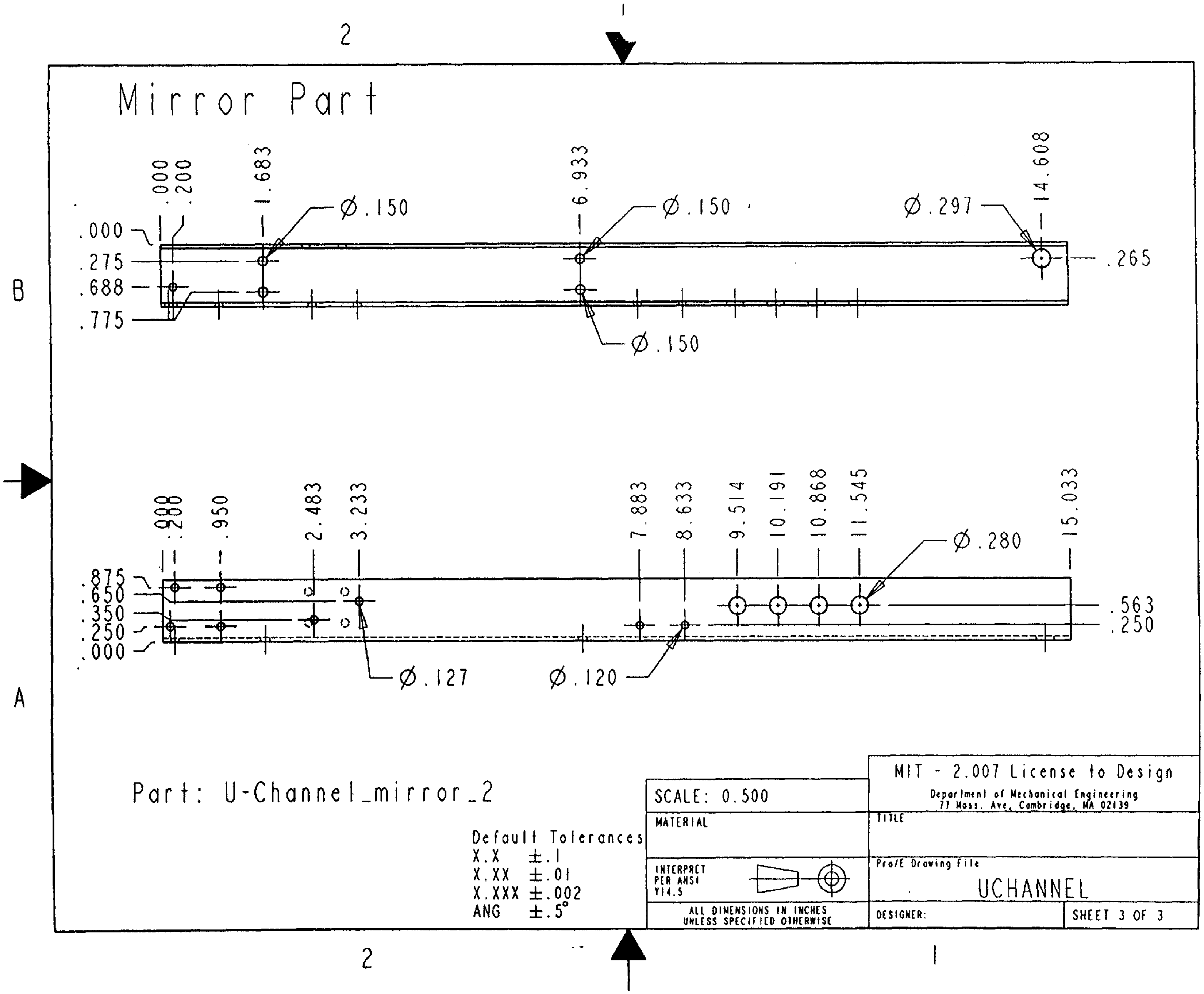


Default Tolerances
X.X ±.1
X.XX ±.01
X.XXX ±.002
ANG ±.5°

SCALE: 0.500	MIT - 2.007 License to Design Department of Mechanical Engineering 77 Mass. Ave, Cambridge, MA 02139
MATERIAL 1/16" AL 6061 U-channel	TITLE U-Channel Structural Members
INTERPRET PER ANSI Y14.5	Pro/E Drawing File UCHANNEL
ALL DIMENSIONS IN INCHES UNLESS SPECIFIED OTHERWISE	DESIGNER: Ms-L — SHEET 1 OF 3



.000
.125
.950
2.483
3.233
3.608
.375
7.88
8.63
9.514
10.191
10.868
11.545
.250
.350
.875
.000
.250
.563
Ø.120
Ø.28
.000
.200
1.683
6.933
14.608
15.03
.775
.688
.275
.000
Ø.125
Ø.150
.265
Ø.297
A
B
2
1
Default Tolerances
X.X ±.1
X.XX ±.01
X.XXX ±.002
ANG ±.5°
SCALE: 0.500
MATERIAL
INTERPRET PER ANSI Y14.5
ALL DIMENSIONS IN INCHES UNLESS SPECIFIED OTHERWISE
MIT - 2.007 License to Design
Department of Mechanical Engineering
77 Mass. Ave, Cambridge, MA 02139
TITLE
Pro/E Drawing File
UCHANNEL
DESIGNER: MS-L
SHEET 2 OF 3


Mirror Part
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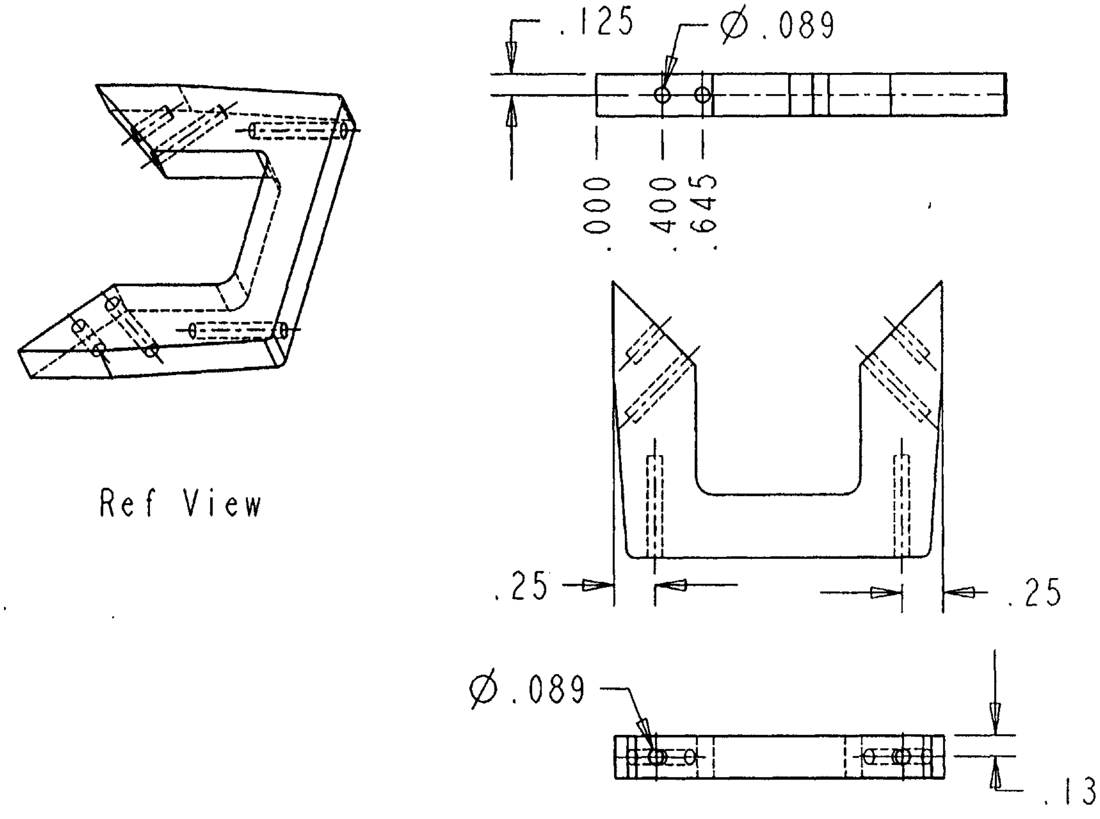
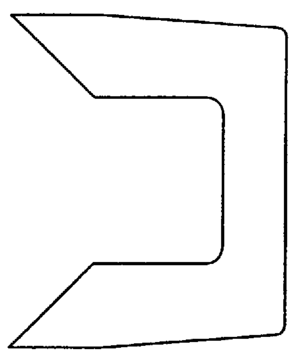
.200
1.683
6.933
14.608
Ø.150
Ø.150
Ø.297
.000
.275
.688
.775
.265
Ø.150
.000
.200
.950
2.483
3.233
7.883
8.633
9.514
10.191
10.868
11.545
15.033
Ø.280
.875
.650
.350
.250
.000
.563
.250
Ø.127
Ø.120
Part: U-Channel_mirror_2
Default Tolerances
X.X ±.1
X.XX ±.01
X.XXX ±.002
ANG ±.5°
SCALE: 0.500
MATERIAL
INTERPRET PER ANSI Y14.5
ALL DIMENSIONS IN INCHES UNLESS SPECIFIED OTHERWISE
MIT - 2.007 License to Design
Department of Mechanical Engineering
77 Mass. Ave, Cambridge, MA 02139
TITLE
Pro/E Drawing File
UCHANNEL
DESIGNER:
SHEET 3 OF 3



Cut Shape on Waterjet
Filename: brace3.dxf

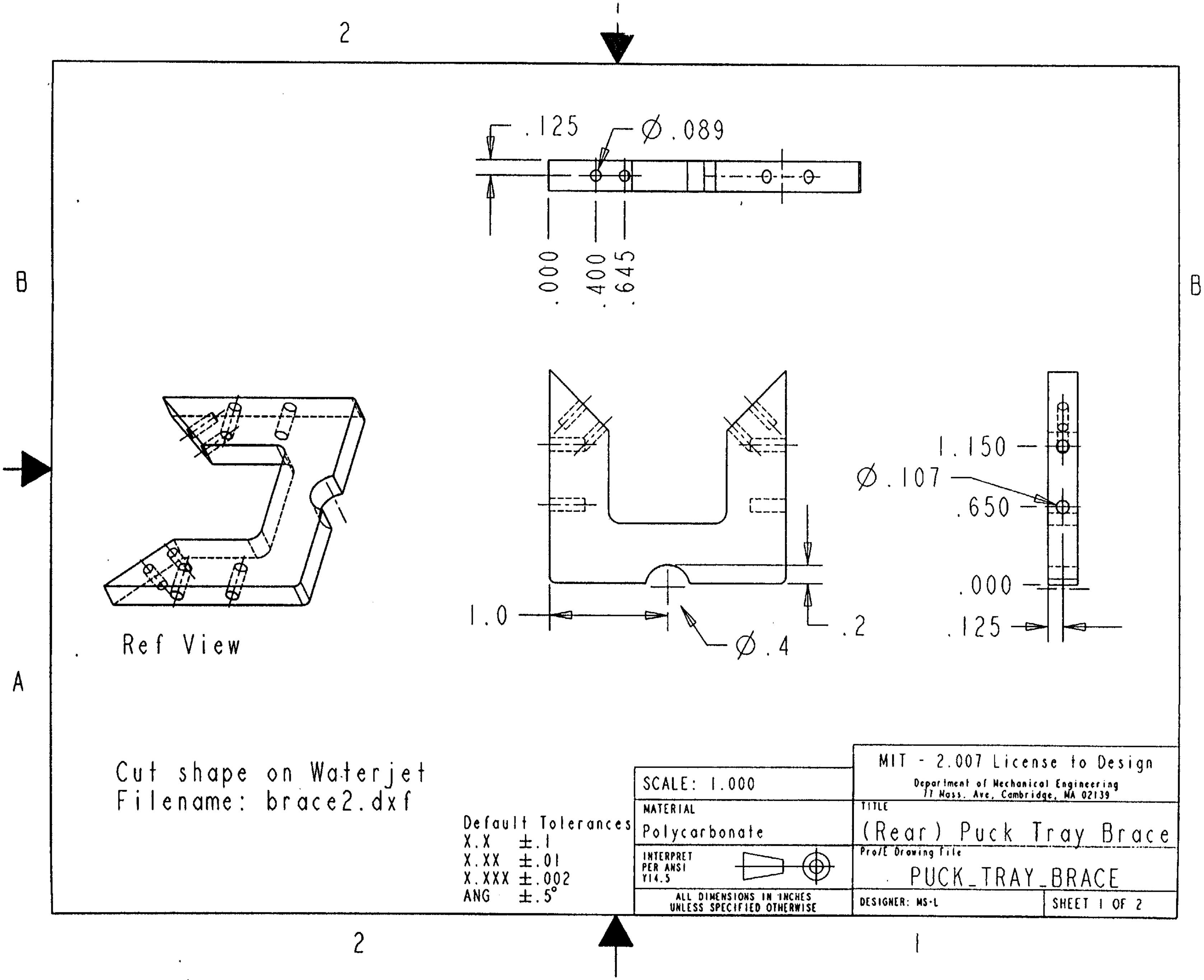
Default Tolerances
X.X ±.1
X.XX ±.01
X.XXX ±.002
ANG ±.5°

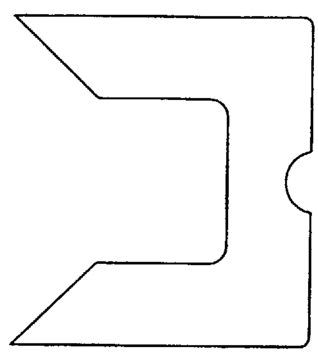
SCALE: 1.000	MIT - 2.007 License to Design Department of Mechanical Engineering 77 Mass. Ave, Cambridge, MA 02139
MATERIAL 1/16" AL 5052 sheet	TITLE Rear Puck Tray Front Brace
INTERPRET PER ANSI Y14.5	Pro/E Drawing File PUCK_TRAY_BRACE_REAR
ALL DIMENSIONS IN INCHES UNLESS SPECIFIED OTHERWISE	DESIGNER: MS-L — SHEET 1 OF 2



Process Plan for Rear Puck Tray Front Brace

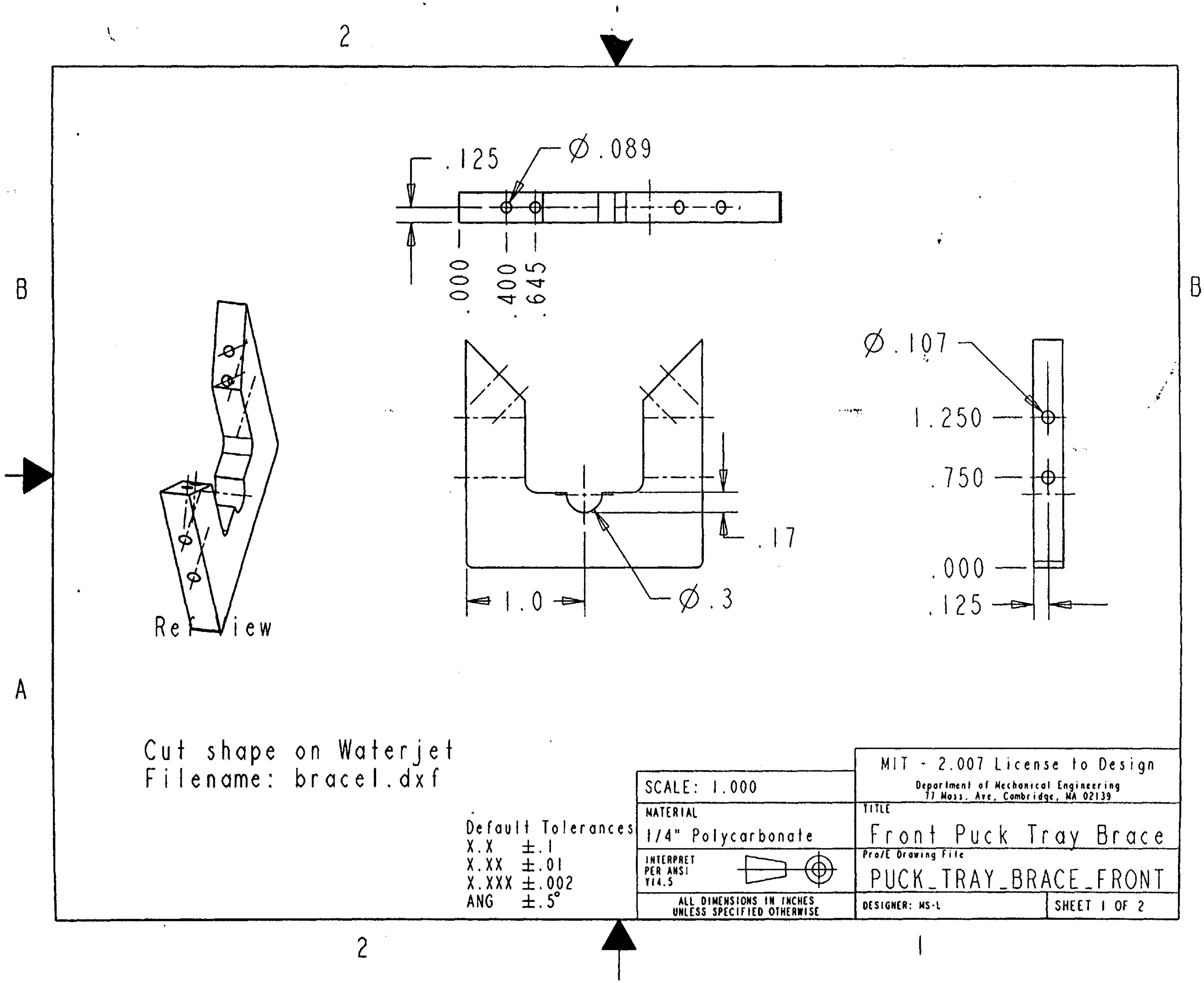
Step	Tools	Note
1. Import to Waterjet and add traverses	.dxf file, Waterjet PC	
2. Cut on waterjet	OMAX Abrasivemachining center ("waterjet")	Verify correct offset for jet diameter (iterate if nec.)
3. Clean up edges	File	
4. Drill screw holes in angled surfaces	Mill, V-Block, Edgefinder, Centerdrill, Drill #43, Coolant	Concurrent with other Tray Brace parts (same or similar setup) Use Vise Stop to create repeatable positionining of same part flipped, and other parts with same dims
5. Drill bottom screw holes	Mill, Centerdrill, #43 drill, coolant	Can use vise stop for symmetry as above
6. Tap screw holes	4-40 tap, 4-40 bottoming tap, tap cutting fluid	


.125
Ø.089
.000
.400
.645
1.150
Ø.107
.650
.000
.125
1.0
Ø.4
.2
Ref View
Cut shape on Waterjet
Filename: brace2.dxf
Default Tolerances
X.X ±.1
X.XX ±.01
X.XXX ±.002
ANG ±.5°
SCALE: 1.000
MATERIAL
Polycarbonate
INTERPRET PER ANSI Y14.5
ALL DIMENSIONS IN INCHES UNLESS SPECIFIED OTHERWISE
MIT - 2.007 License to Design
Department of Mechanical Engineering
77 Mass. Ave. Cambridge, MA 02139
TITLE
(Rear) Puck Tray Brace
Pro/E Drawing File
PUCK_TRAY_BRACE
DESIGNER: MS-L
SHEET 1 OF 2
2
B
A
1

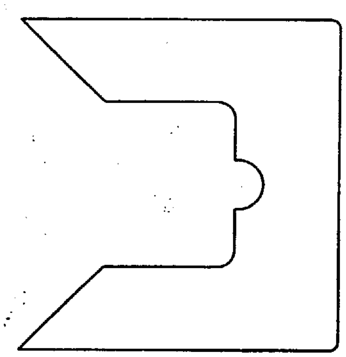


Process Plan for Front Puck Tray Rear Brace

Step	Tools	Note
1. Import to Waterjet and add traverses	.dxf file, Waterjet PC	
2. Cut on waterjet	OMAX Abrasivemachining center ("waterjet")	Verify correct offset for jet diameter (iterate if nec.)
3. Clean up edges	File	
4. Drill screw holes in angled surfaces	Mill, V-Block, Edgefinder, Centerdrill, Drill #43, Coolant	Concurrent with other Tray Brace parts (same or similar setup) Use Vise Stop to create repeatable positionining of same part flipped, and other parts with same dims
5. Drill side screw holes	Mill, edgefinder, Vise Stop, Centerdrill, #43 drill, coolant	Can use vise stop for symmetry as above
6. Tap screw holes	4-40 tap, 4-40 bottoming tap, tap cutting fluid	

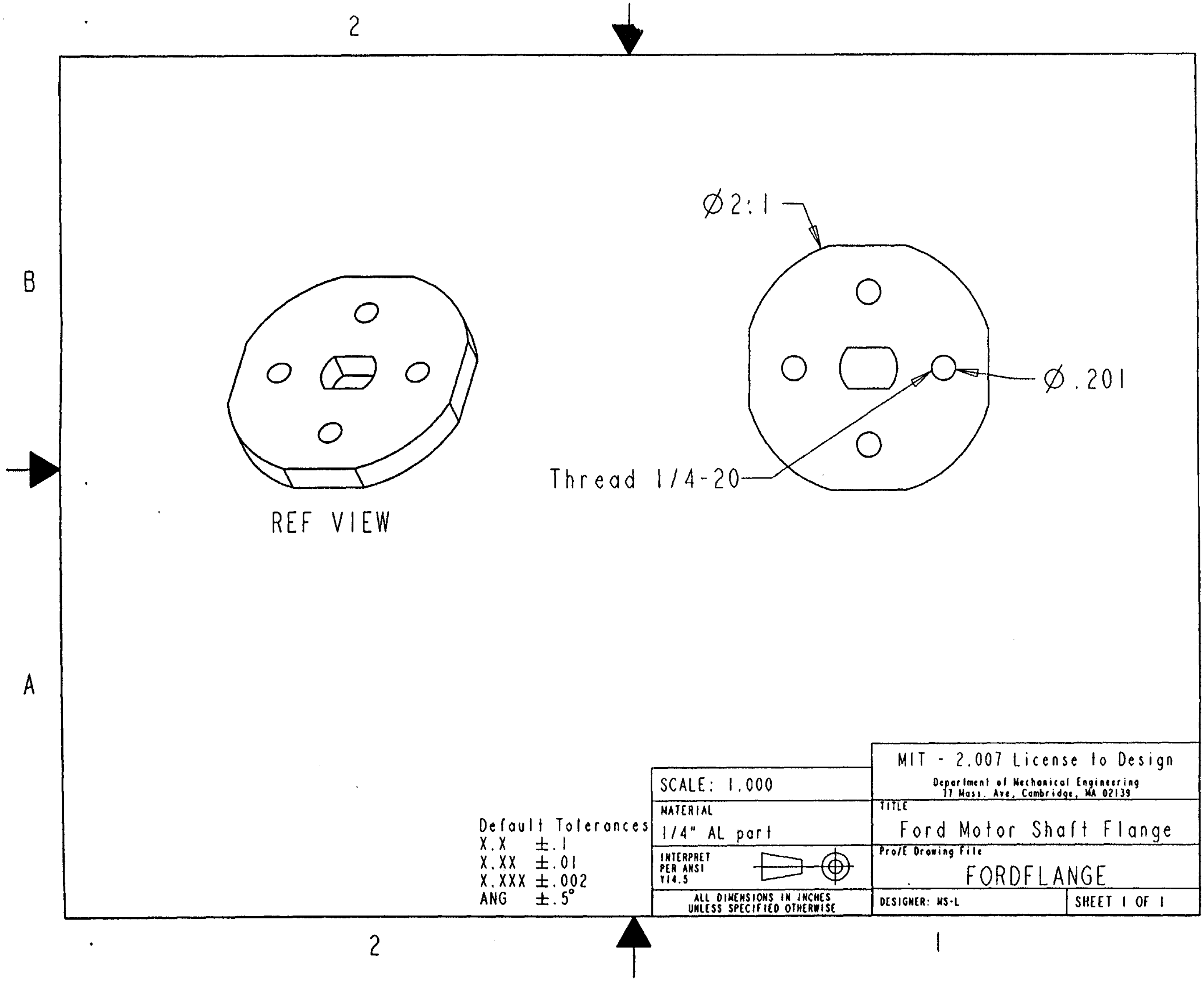


Ø .089
.125
.000
.400
.645
Ø .107
1.250
.750
.000
.125
.17
1.0
Ø .3
Ref View
Cut shape on Waterjet
Filename: bracel.dxf
Default Tolerances
X.X ±.1
X.XX ±.01
X.XXX ±.002
ANG ±.5°
SCALE: 1.000
MATERIAL
1/4" Polycarbonate
INTERPRET PER ANSI Y14.5
ALL DIMENSIONS IN INCHES UNLESS SPECIFIED OTHERWISE
MIT - 2.007 License to Design
Department of Mechanical Engineering
77 Mass. Ave, Cambridge, MA 02139
TITLE
Front Puck Tray Brace
Pro/E Drawing File
PUCK_TRAY_BRACE_FRONT
DESIGNER: MS-L
SHEET 1 OF 2



Process Plan for Front Puck Tray Front Brace

Step	Tools	Note
1. Import to Waterjet and add traverses	.dxf file, Waterjet PC	
2. Cut on waterjet	OMAX Abrasivemachin-ing center ("waterjet")	Verify correct offset for jet diame-ter (iterate if nec.)
3. Clean up edges	File	
4. Drill screw holes in angled surfaces	Mill, V-Block, Edgefinder, Centerdrill, Drill #43, Coolant	Concurrent with other Tray Brace parts (same or similar setup) Use Vise Stop to create repeatable positionining of same part flipped, and other parts with same dims
5. Drill side screw holes	Mill, edgefinder, Vise Stop, Centerdrill, #43 drill, coolant	Can use vise stop for symmetry as above
6. Tap screw holes	4-40 tap, 4-40 bottoming tap, tap cutting fluid	


2
B
A
REF VIEW
Ø2:1
Ø.201
Thread 1/4-20
Default Tolerances
X.X ±.1
X.XX ±.01
X.XXX ±.002
ANG ±.5°
SCALE: 1.000
MATERIAL
1/4" AL part
INTERPRET PER ANSI Y14.5
ALL DIMENSIONS IN INCHES UNLESS SPECIFIED OTHERWISE
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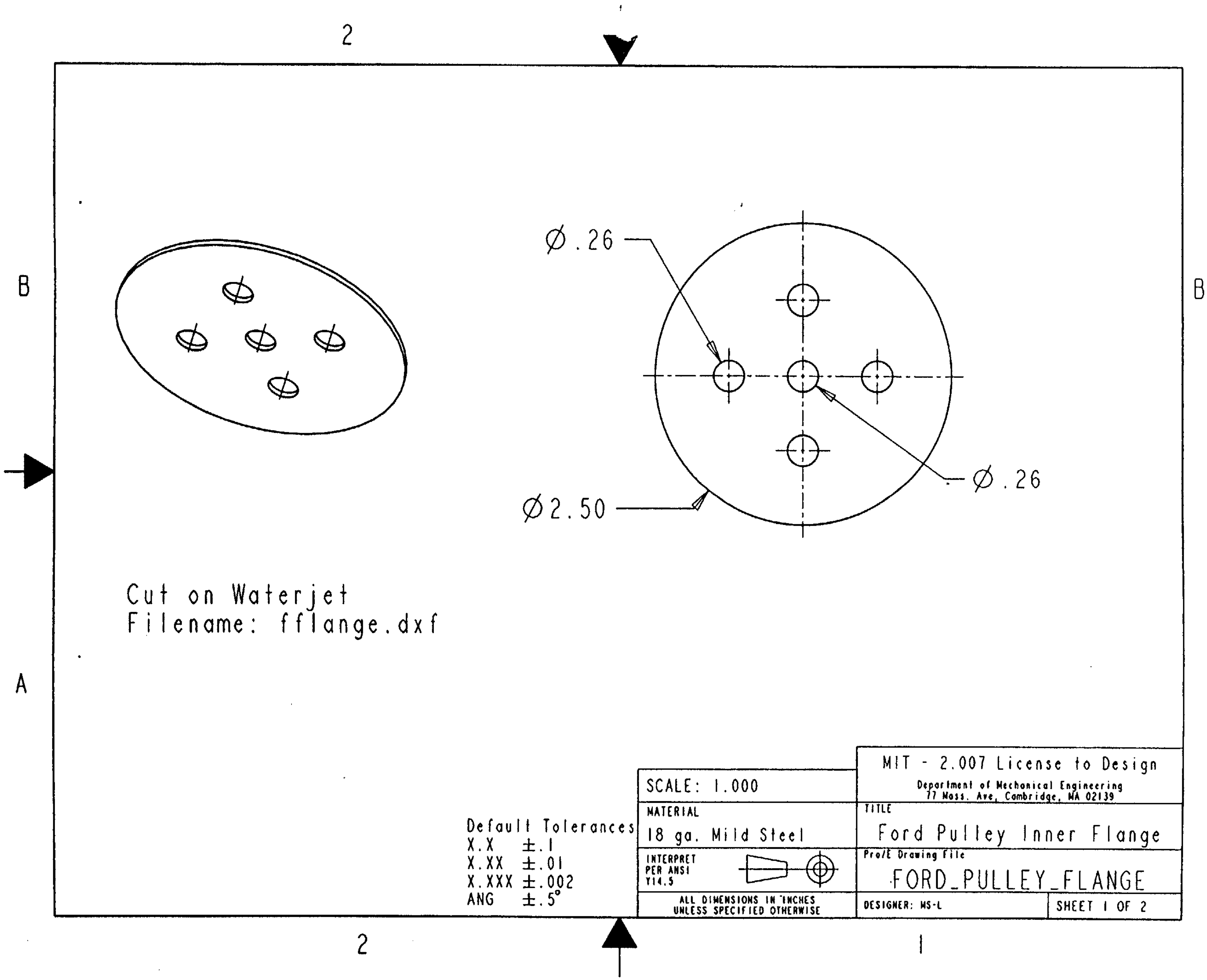
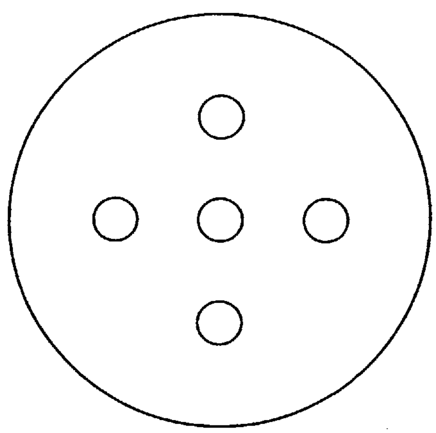
Department of Mechanical Engineering
77 Mass. Ave, Cambridge, MA 02139
TITLE
Ford Motor Shaft Flange
Pro/E Drawing File
FORDFLANGE
DESIGNER: MS-L
SHEET 1 OF 1
1

Process Plan for Ford Motor Shaft Mounting Flange

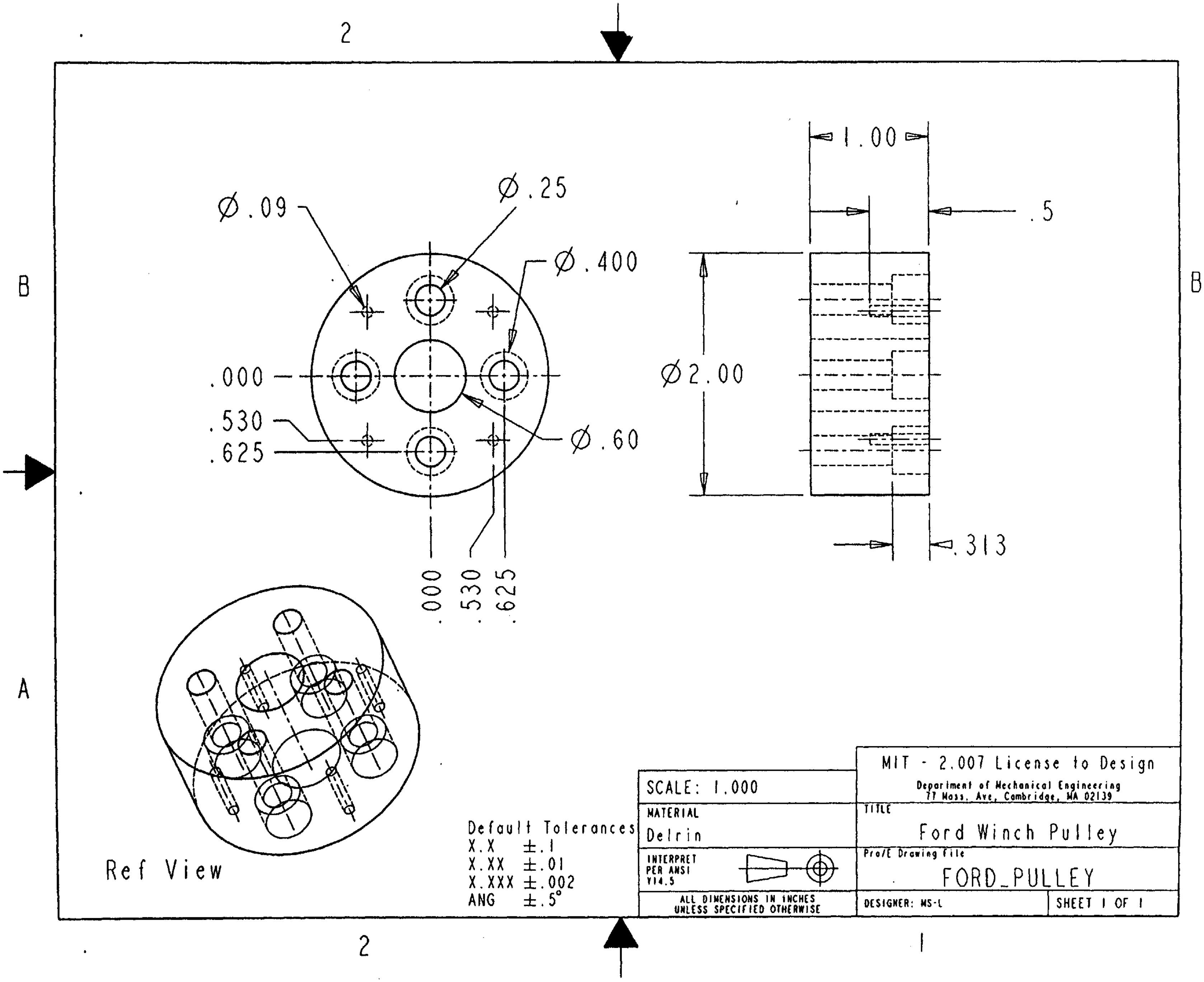
Step	Tools	Note
1. Transfer edge roundoff pattern from drawing to part	Scissors/knife Removable adhesive	Accuracy is not imp't - can do freehand if necessary.
2. Cut square corners to marked round	Large Bandsaw	Coolant may be necessary
3. Enlarge holes	Drillpress, 0.21" drill, machinist's vise	
4. Thread holes	1/4-20 tap, tap handle or tapping station, tapping fluid	


2
B
A
Ø.26
Ø.26
Ø2.50
Cut on Waterjet
Filename: fflange.dxf
Default Tolerances
X.X ±.1
X.XX ±.01
X.XXX ±.002
ANG ±.5°
SCALE: 1.000
MATERIAL
18 ga. Mild Steel
INTERPRET PER ANSI Y14.5
ALL DIMENSIONS IN INCHES UNLESS SPECIFIED OTHERWISE
MIT - 2.007 License to Design
Department of Mechanical Engineering
77 Mass. Ave, Cambridge, MA 02139
TITLE
Ford Pulley Inner Flange
Pro/E Drawing File
FORD_PULLEY_FLANGE
DESIGNER: MS-L
SHEET 1 OF 2
1



Process Plan for Inner Ford Motor Pulley Flange

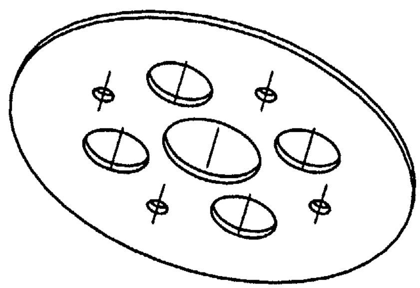
Step	Tools	Note
1. Import to Waterjet and add traverses	.dxf file, Waterjet PC	
2. Cut on waterjet	OMAX Abrasivemachining center ("waterjet")	Verify correct offset for jet diameter (iterate if nec.)
3. Clean up edges	File	
4. Debur holes	Drill Press, Countersink	

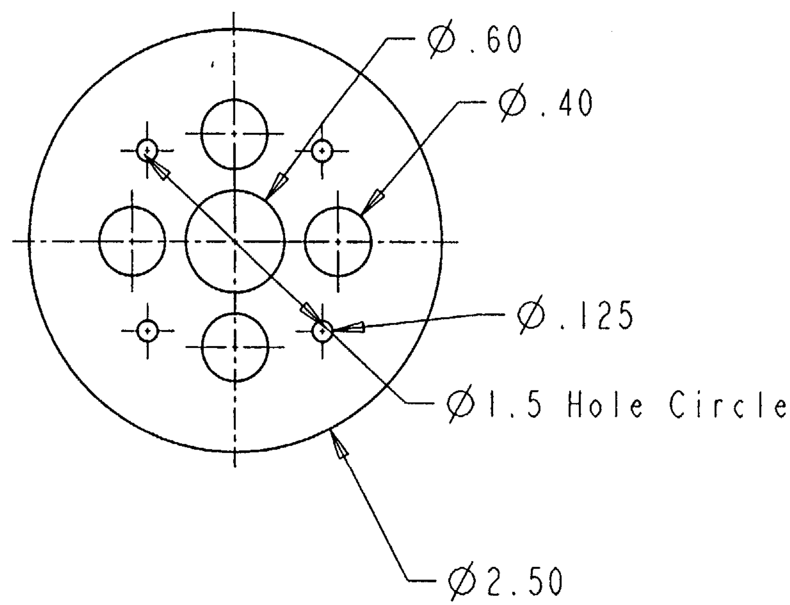


Ø.09
Ø.25
Ø.400
.000
.530
.625
Ø.60
.000
.530
.625
1.00
.5
Ø2.00
.313
Ref View
Default Tolerances
X.X ±.1
X.XX ±.01
X.XXX ±.002
ANG ±.5°
SCALE: 1.000
MATERIAL
Delrin
INTERPRET PER ANSI Y14.5
ALL DIMENSIONS IN INCHES UNLESS SPECIFIED OTHERWISE
MIT - 2.007 License to Design
Department of Mechanical Engineering
77 Mass. Ave, Cambridge, MA 02139
TITLE
Ford Winch Pulley
Pro/E Drawing File
FORD_PULLEY
DESIGNER: MS-L
SHEET 1 OF 1

Process Plan for Ford Winch Pulley

Step	Tools	Note
1. Chuck 2" dia. x >2" length Delrin in Lathe	Lathe	
2. Face one end	Lathe, Normal cutting tool	
3. Drill Center Hole	Lathe, Drill chuck, Centerdrill, Drills: ~1/4, ~3/8, ~ 1/2, ~.6"	Approach final hole diameter in steps.
4. Measure and cut off to length + ~0.1"	Lathe, Dykem steel blue dye, Calipers, Parting tool	
5. Face cut recently cutoff face to length	Lathe, Normal cutting tool, Calipers or Micrometer, Dykem steel blue dye	Depending on accuracy required, Measure and mark with dye, or calculate material to be removed and use dial gauge on Lathe bed.
6. Drill 1/4" Screw Holes	Mill, Parallels, V-block, Edge finder, Centerdrill, 1/4" drill	To locate center of cylindrical part on mill: A) use dial indicator in spindle and run around edge of cylinder or center hole until dial deflection is constant, OR B) use edge finder on vise to get Y-zero, then use Y-position of center of hole to get X-position of edge of cylinder. Now X,Y of center of cylinder are known.
7. Counterbore Screw holes	Drill press, Counterbore for 1/4"	Can control depth by marking Counterbore bit with marker at appropriate depth.
8. Drill flange mounting holes	Drill press, #43 Drill, PART Outer Ford Flange, adhesive or double-sided tape	Use flange Part, centered on other holes, as guide for mounting hole placement
9. Tap flange mounting holes	4-40 tap and handle, tapping fluid	

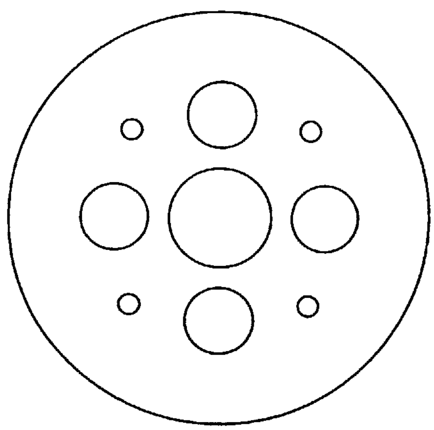




Cut On Waterjet from CAD File
Filename: fflang02.dxf

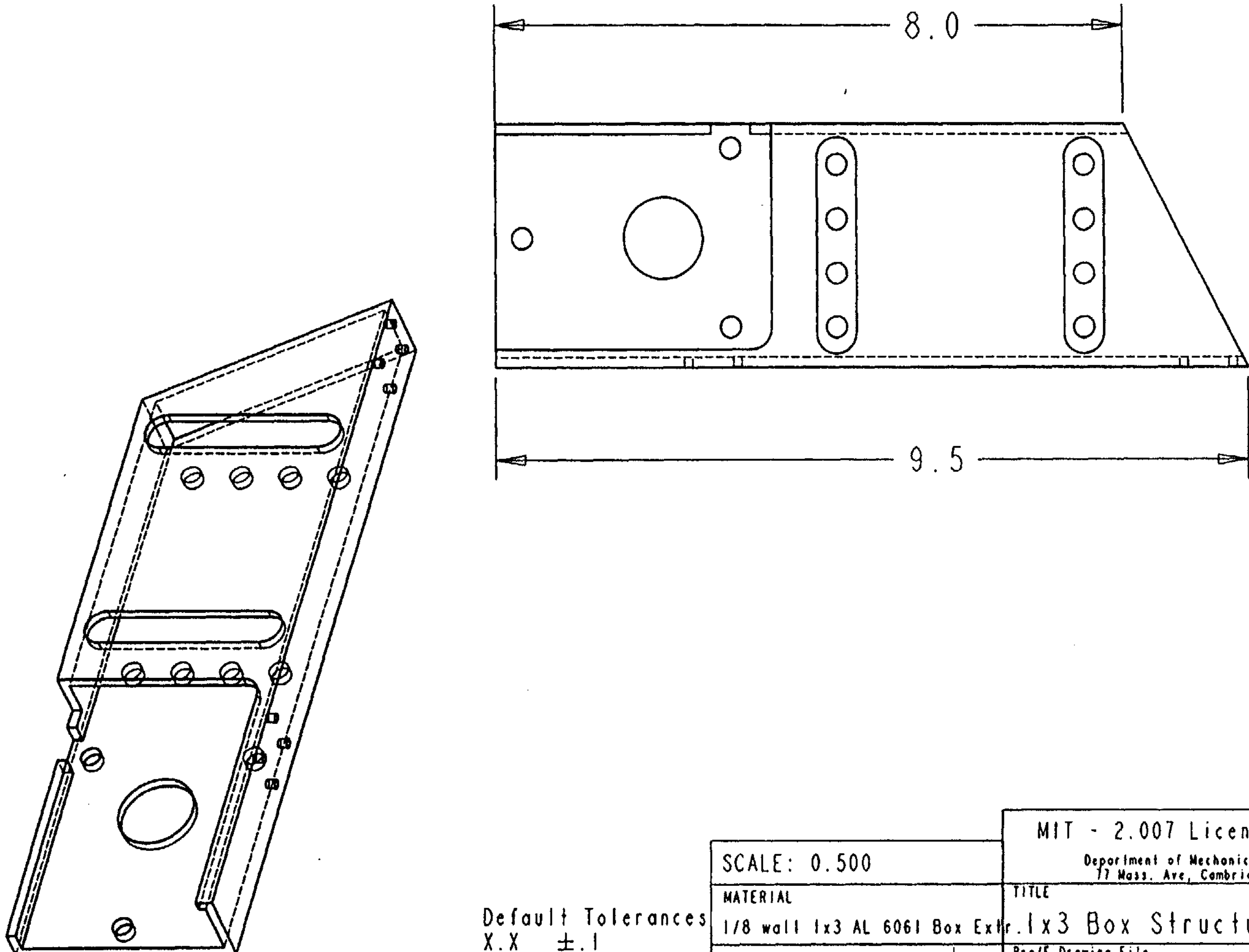
Default Tolerances
X.X ±.1
X.XX ±.01
X.XXX ±.002
ANG ±.5°

SCALE: 1.000	MIT - 2.007 License to Design Department of Mechanical Engineering 77 Mass. Ave, Cambridge, MA 02139
MATERIAL 18 ga. Mild Steel	TITLE Outer Ford Pulley Flange
INTERPRET PER ANSI Y14.5	Pro/E Drawing File FORD_PULLEY_FLANGE_O
ALL DIMENSIONS IN INCHES UNLESS SPECIFIED OTHERWISE	DESIGNER: MS-L — SHEET 1 OF 2



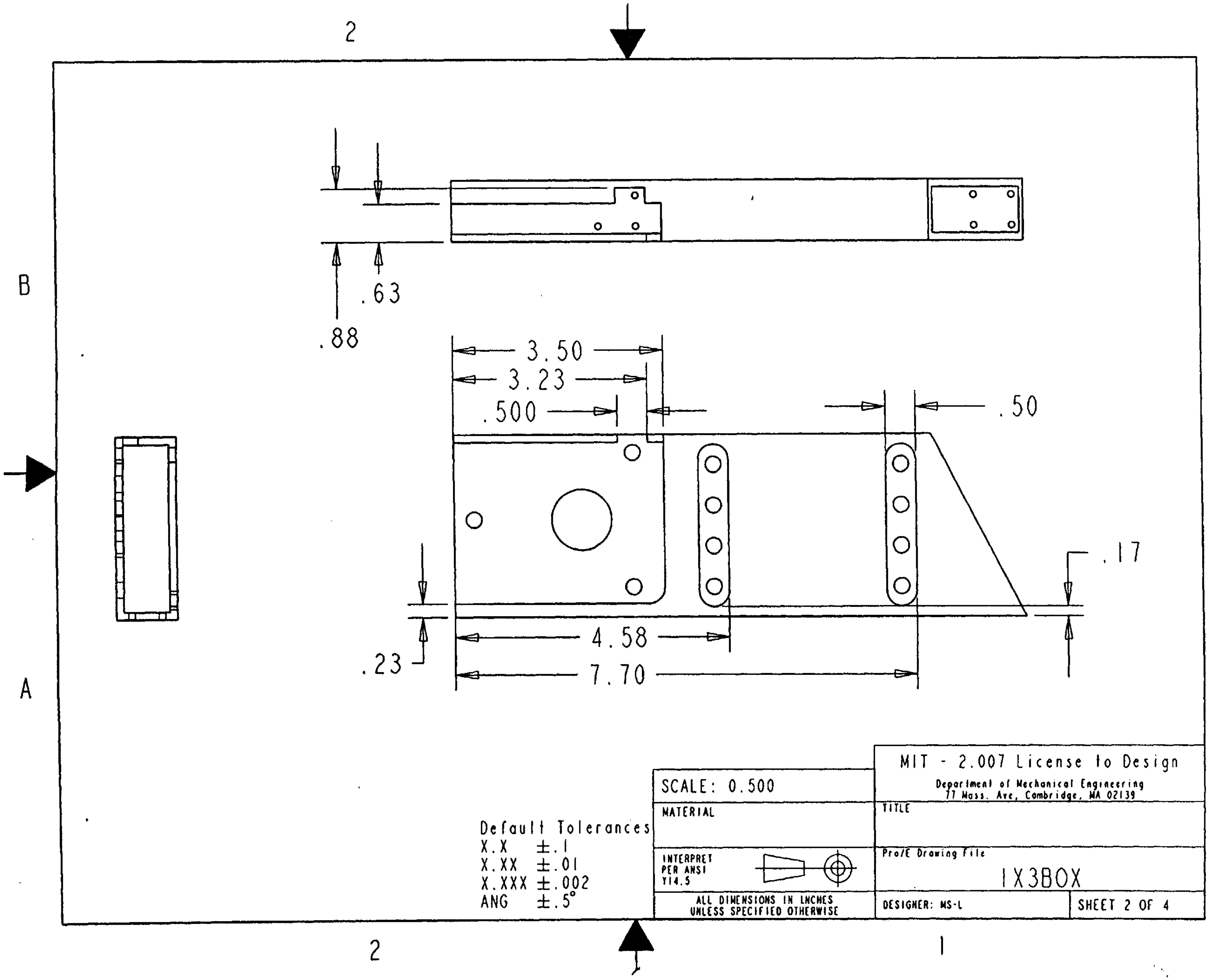
Process Plan for Outer Ford Motor Pulley Flange

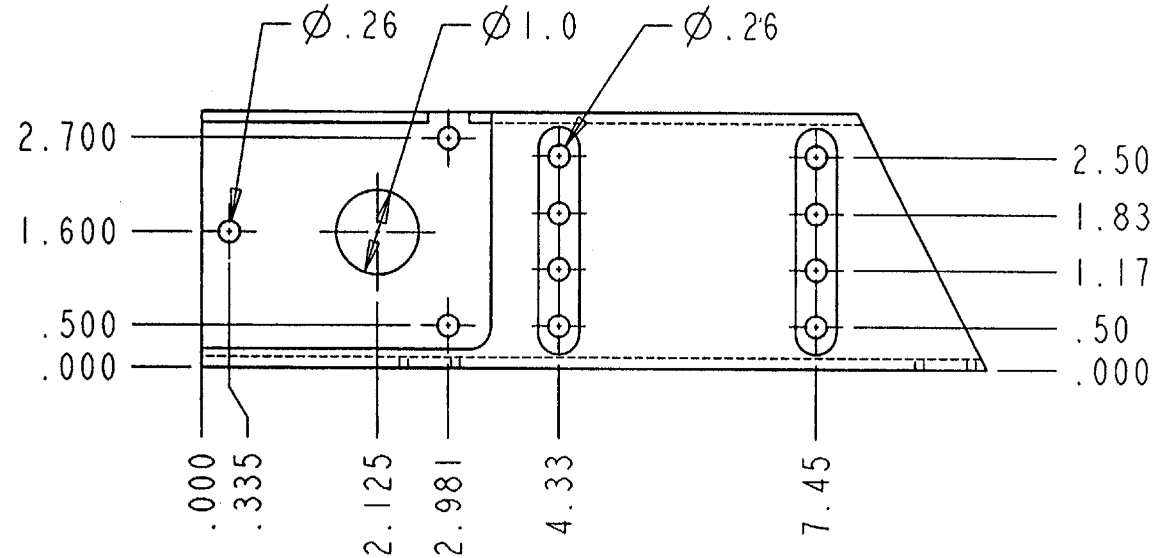
Step	Tools	Note
1. Import to Waterjet and add traverses	.dxf file, Waterjet PC	
2. Cut on waterjet	OMAX Abrasivemachining center ("waterjet")	Verify correct offset for jet diameter (iterate if nec.)
3. Clean up edges	File	
4. Debur holes	Drill Press, Countersink	



Default Tolerances
X.X ±.1
X.XX ±.01
X.XXX ±.002
ANG ±.5°

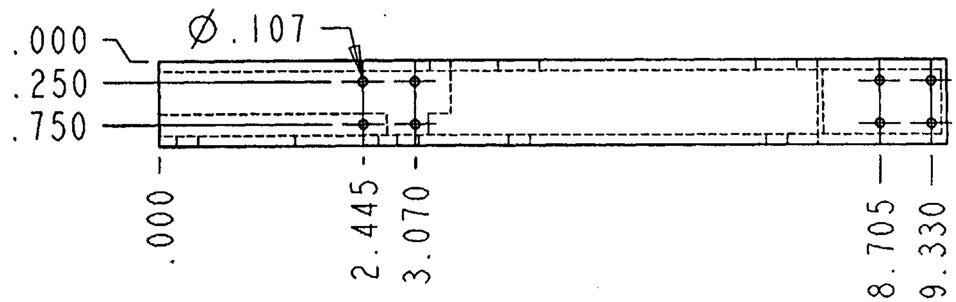
SCALE: 0.500	MIT - 2.007 License to Design Department of Mechanical Engineering 77 Mass. Ave, Cambridge, MA 02139
MATERIAL 1/8 wall 1x3 AL 6061 Box Extr.	TITLE 1x3 Box Structural Member
INTERPRET PER ANSI Y14.5	Pro/E Drawing File 1X3BOX
ALL DIMENSIONS IN INCHES UNLESS SPECIFIED OTHERWISE	DESIGNER: MS-L — SHEET 1 OF 4


2
B
A
.63
.88
3.50
3.23
.500
.50
.17
.23
4.58
7.70
Default Tolerances
X.X ±.1
X.XX ±.01
X.XXX ±.002
ANG ±.5°
SCALE: 0.500
MATERIAL
INTERPRET PER ANSI Y14.5
ALL DIMENSIONS IN INCHES UNLESS SPECIFIED OTHERWISE
MIT - 2.007 License to Design
Department of Mechanical Engineering
77 Mass. Ave, Cambridge, MA 02139
TITLE
Pro/E Drawing File
1X3BOX
DESIGNER: MS-L
SHEET 2 OF 4
1



Default Tolerances
X.X ±.1
X.XX ±.01
X.XXX ±.002
ANG ±.5°

SCALE: 0.500	MIT - 2.007 License to Design Department of Mechanical Engineering 77 Mass. Ave, Cambridge, MA 02139
MATERIAL	TITLE
INTERPRET PER ANSI Y14.5	Pro/E Drawing File 1X3BOX
ALL DIMENSIONS IN INCHES UNLESS SPECIFIED OTHERWISE	DESIGNER: SHEET 3 OF 4

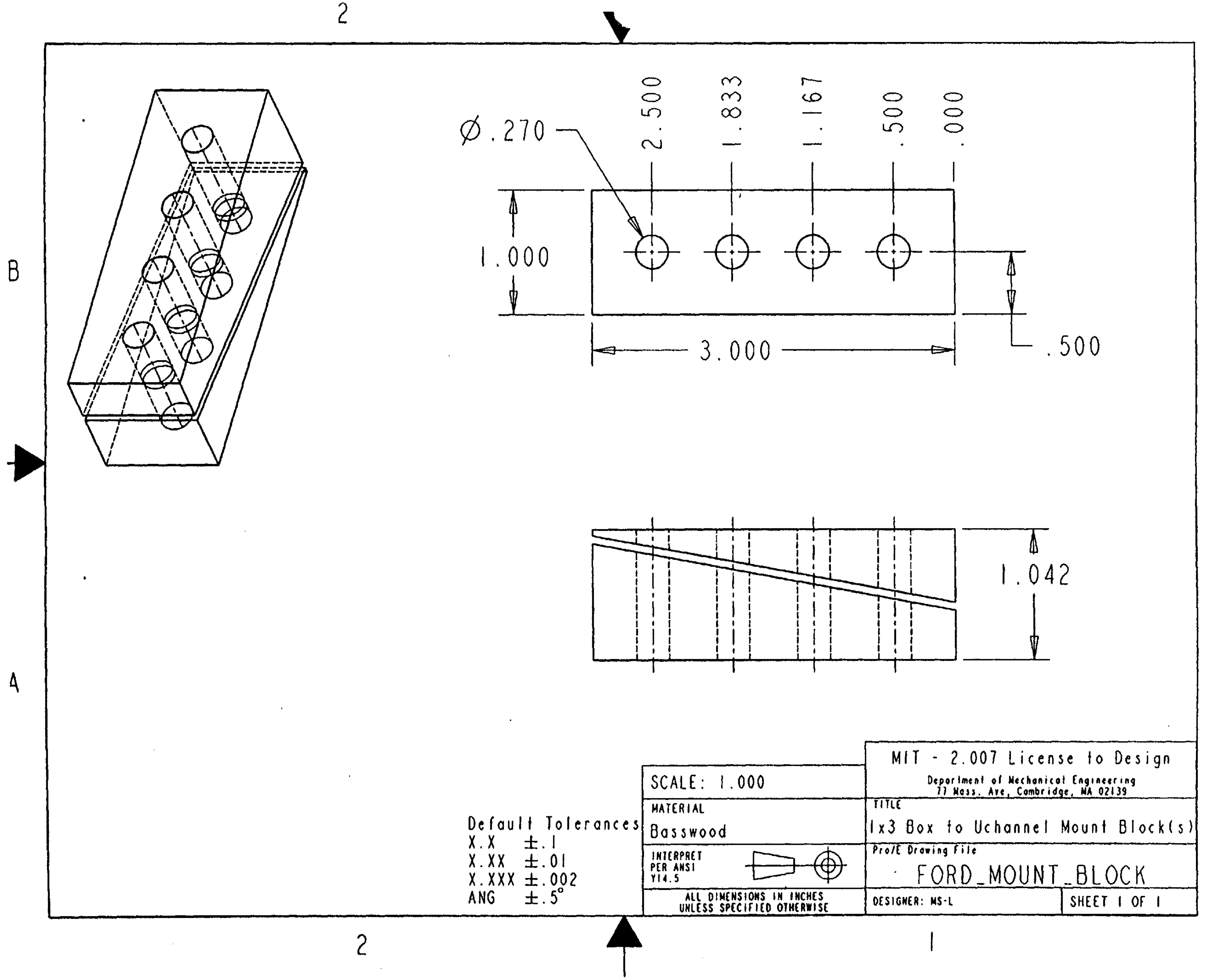


Default Tolerances
X.X ±.1
X.XX ±.01
X.XXX ±.002
ANG ±.5°

SCALE: 0.500	MIT - 2.007 License to Design Department of Mechanical Engineering 77 Mass. Ave, Cambridge, MA 02139
MATERIAL	TITLE
INTERPRET PER ANSI Y14.5	Pro/E Drawing File 1X3BOX
ALL DIMENSIONS IN INCHES UNLESS SPECIFIED OTHERWISE	DESIGNER: SHEET 4 OF 4

Process Plan for 1x3 Box Structural Member

Step	Tools	Note
1. Mark and Cut to basic shape	Calipers, Blue dye, Bandsaw	Leave extra material on square (reference) end to create nice ref. surface in mill.
2. Clean Reference Face	Mill, 1/2" 2-flute end-mill, water based coolant	
3. In same setup, make large top surface cut and slots	Mill, 1/2" 2-flute end-mill, water based coolant	Pay attention to workholding issues, and avoid having to mill large floppy hanging plate (vibration)
4. In same setup, drill 8 .26" mounting holes	Drill Chuck, Centerdrill, ~0.2", 0.26" drills	Use at least one intermediate drill before reaching final hole size-otherwise risk chatter and poor accuracy.
5. Change Setup-- Drill small 1x1 box attach screw holes	Drill Chuck, Centerdrill, .106" drill	
6. Tap holes from step 5	6-32 tap and handle, tapping fluid	

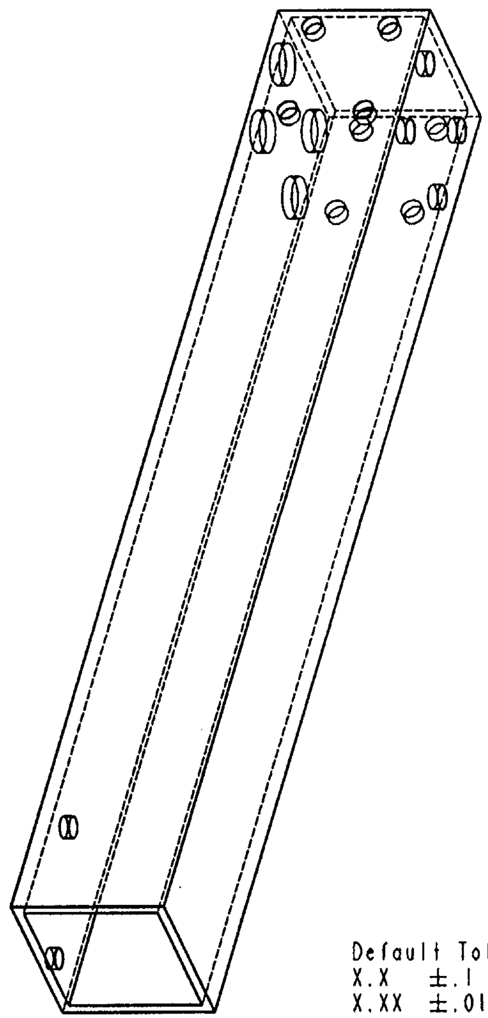

Ø .270
2.500
1.833
1.167
.500
.000
1.000
3.000
.500
1.042
Default Tolerances
X.X ±.1
X.XX ±.01
X.XXX ±.002
ANG ±.5°
SCALE: 1.000
MATERIAL
Basswood
INTERPRET PER ANSI Y14.5
ALL DIMENSIONS IN INCHES UNLESS SPECIFIED OTHERWISE
MIT - 2.007 License to Design
Department of Mechanical Engineering
77 Mass. Ave, Cambridge, MA 02139
TITLE
1x3 Box to Uchannel Mount Block(s)
Pro/E Drawing File
FORD_MOUNT_BLOCK
DESIGNER: MS-L
SHEET 1 OF 1
2
B
A
1

Process Plan for Angled Connector Block between 1x3 Box and U-channel

Step	Tools	Note
1. Laminate 2 1/2" thick pieces of basswood to make 1" thick piece large enough to make 2 blocks	Bandsaw, wood glue, scrap wood, clamps or vise	Use scrap wood to preotect good wood from being marred during clamping
2. Adhere side view templates to 1" wood stock	100% scale drawing, scissors or knife, removable (spray) adhesive.	Verify drawing scale by measuring Make 2 parts
3. Cut side profile, leaving ~.1" extra on all sides	Bandsaw	
4. Sand cut faces to size and square	Belt sander, Square	Verify squareness of sander table and adjust if necessary
5. Apply top view templates to parts	100% scale drawing, scissors or knife, removable (spray) adhesive.	
6. Drill holes as indicated by template	Drill press, drills	High speed is best for drilling wood.
7. Cut part in two at angle, as indicated by side view template	Bandsaw	
8. Remove templates		
9. Sand flat and smooth, remove sharp corners	Belt sander	
10. Seal and protect with one thin coat of ployurethane	Polyurethane, clean rag	very optional, but effect is nice

2

B



General View

A

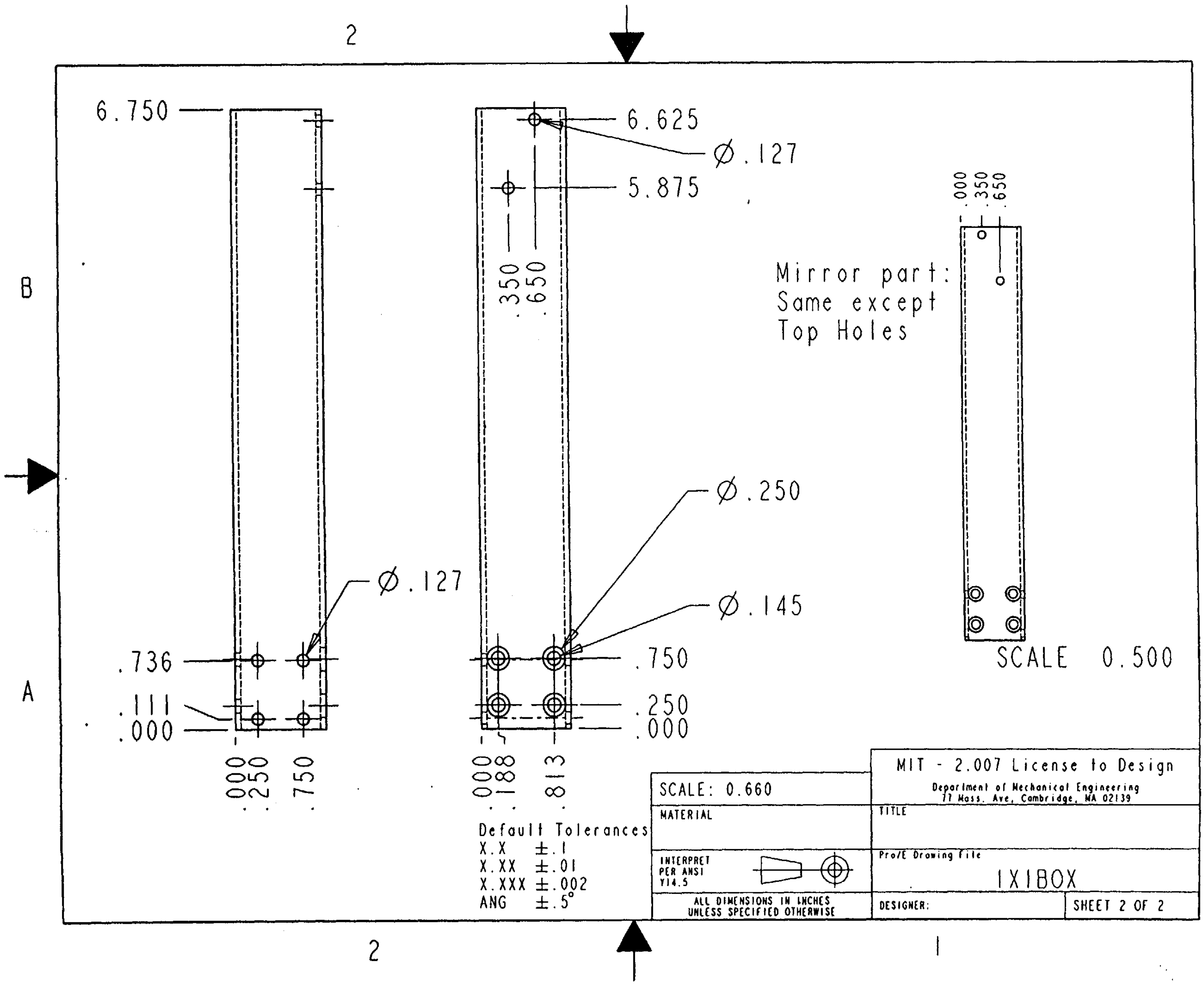
Default Tolerances
X.X ±.1
X.XX ±.01
X.XXX ±.002
ANG ±.5°

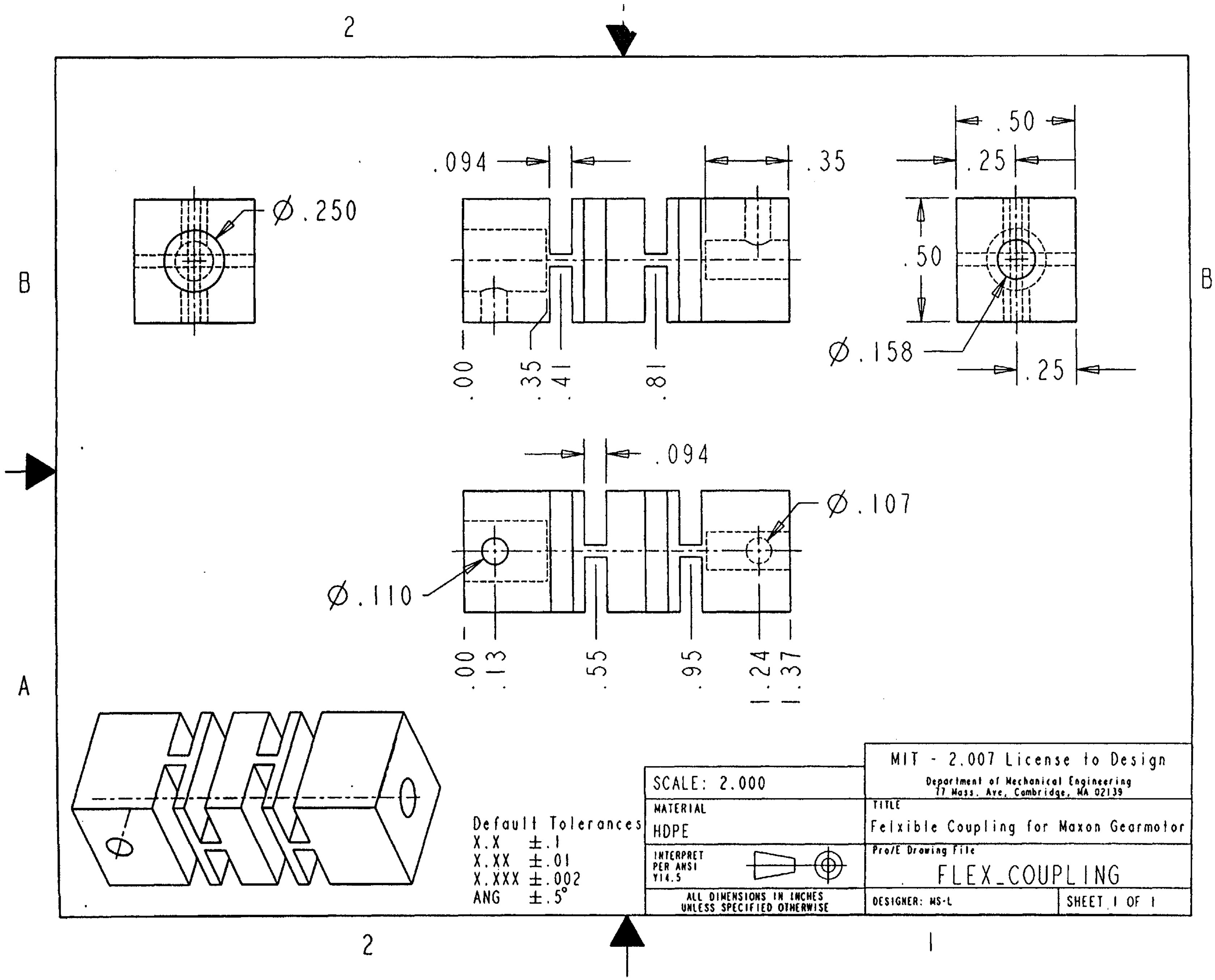
SCALE: 0.660	MIT - 2.007 License to Design Department of Mechanical Engineering 77 Mass. Ave. Cambridge, MA 02139
MATERIAL 1x1 1/16" wall AL 6061	TITLE 1x1 Box Piston Mount Post
INTERPRET PER ANSI Y14.5	Pro/E Drawing File 1X1BOX
ALL DIMENSIONS IN INCHES UNLESS SPECIFIED OTHERWISE	DESIGNER: MS-L SHEET 1 OF 2

B

2

1


2
6.750
6.625
Ø.127
5.875
.350
.650
.000
.350
.650
Mirror part:
Same except
Top Holes
B
B
Ø.250
Ø.127
Ø.145
.736
.750
SCALE 0.500
A
.111
.000
.250
.000
.000
.250
.750
.000
.188
.813
MIT - 2.007 License to Design
Department of Mechanical Engineering
77 Mass. Ave, Cambridge, MA 02139
SCALE: 0.660
MATERIAL
TITLE
Default Tolerances
X.X ±.1
X.XX ±.01
X.XXX ±.002
ANG ±.5°
INTERPRET
PER ANSI
Y14.5
Pro/E Drawing File
1X1BOX
ALL DIMENSIONS IN INCHES
UNLESS SPECIFIED OTHERWISE
DESIGNER:
SHEET 2 OF 2
2
1


Ø.250
.094
.35
.50
.25
.50
Ø.158
.25
.00
.35
.41
.81
.094
Ø.107
Ø.110
.00
.13
.55
.95
1.24
1.37
Default Tolerances
X.X ±.1
X.XX ±.01
X.XXX ±.002
ANG ±.5°
SCALE: 2.000
MATERIAL
HDPE
INTERPRET PER ANSI Y14.5
ALL DIMENSIONS IN INCHES UNLESS SPECIFIED OTHERWISE
MIT - 2.007 License to Design
Department of Mechanical Engineering
77 Mass. Ave, Cambridge, MA 02139
TITLE
Felxible Coupling for Maxon Gearmotor
Pro/E Drawing File
FLEX_COUPLING
DESIGNER: MS-L
SHEET 1 OF 1

Process Plan for Flexible Coupling for Green Gearmotor

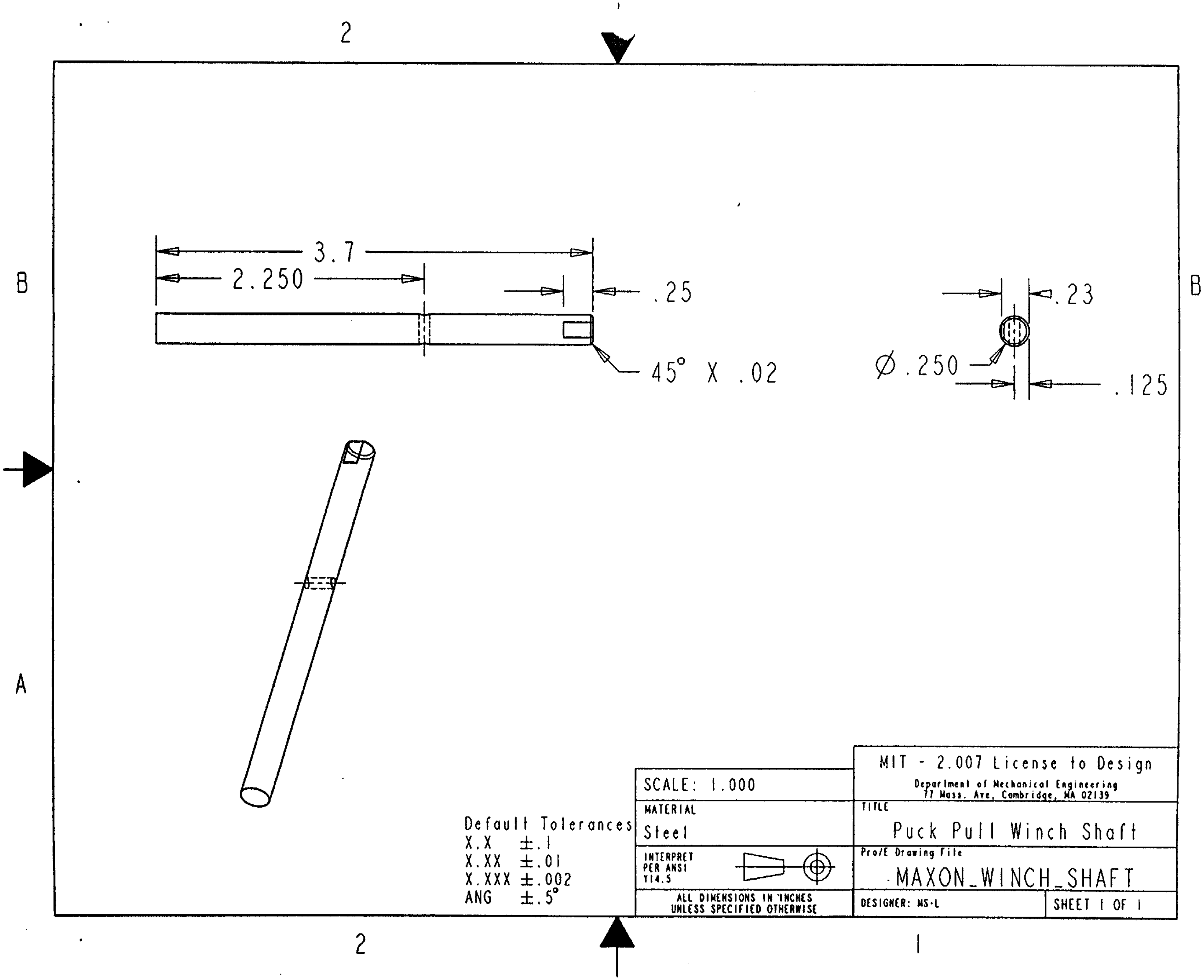
Step	Tools	Note
1. Cut 1/2" square UHMW PE rod to length + ~1/8"	Dial caliper, hacksaw or bandsaw	
2. Cut to length	Mill, parallels, endmill, dial caliper	
3. Cut one set of slots	Mill with digital readout, parallels, edgefinder, coolant 3/32" 2-flute endmill	Verify depth of cut this e-mill is capable of (enough cutting heght?)
4. Rotate part 180 deg., rezero readout (if nec.) and cut other side of slots from step 3.	Same	*Use of a vise stop or other reference point for repeatable alignment of part in vise will eliminate need to repeatedly find the lateral edge and rezero the readout.
5. Rotate part 90 deg., rezero readout (if nec.) and cut second set of slots.	Same	
6. Rotate part 180 deg., rezero readout (if nec.) and cut other side of slots from step 5.	Same	
7. Debur edges	File, sharp knife	
8. Drill motor shaft hole	Lathe, centerdrill, drills	Use tailstock to measure depth of hole
9. Drill pulley shaft hole	Lathe, centerdrill, 1/4" drill	
10. Mark and drill set screw holes	Dykem steel blue, dial caliper, drill press, drills	

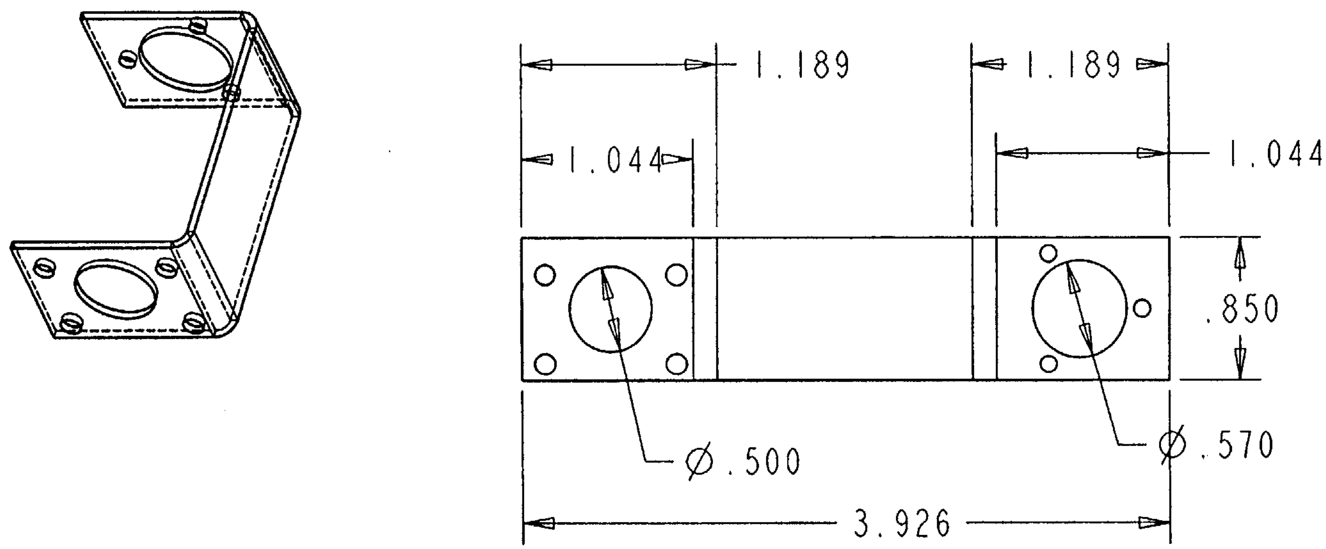
Process Plan for Flexible Coupling for Green Gearmotor

Step	Tools	Note
11. Thread set screw holes	Tap and handle	Tapping fluid shouldn't be necessary in plastic, but may help. Tapping too aggressively may cause localized melting and a poor quality thread..

Process Plan for Flexible Coupling for Green Gearmotor
No-Mill Version

Step	Tools	Note
1. Cut 1/2" square UHMW PE rod to length	Dial caliper, hacksaw or bandsaw	
2. Prepare full scale drawing views from all sides of part and affix to stock	Drawings, knife or scissors, removable adhesive	Spray adhesive is best because it allows repositioning.
3. Cut slots where indicated by templates, from all 4 sides.	Bandsaw or hacksaw, coolant	Fine depth control is important. As always, make sure the smallest possible amount of the blade is exposed.
4. Debur edges	File, sharp knife	
5. Fixture part in lathe and face ends	Lathe, collet chuck, 1/2" square collet	
6. Drill motor shaft hole	Lathe, centerdrill, drills	Use tailstock to measure depth of hole
7. Drill pulley shaft hole	Lathe, centerdrill, 1/4" drill	
8. Mark and drill set screw holes	Dykem steel blue, dial caliper, drill press, drills	
9. Thread set screw holes	Tap and handle	Tapping fluid shouldn't be necessary in plastic, but may help. Tapping too aggressively may cause localized melting and a poor quality thread..

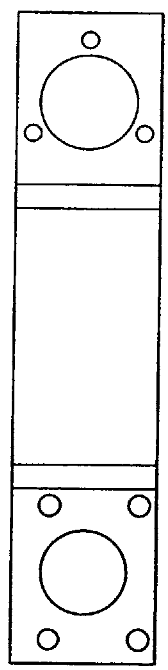

3.7
2.250
.25
45° X .02
.23
Ø.250
.125
Default Tolerances
X.X ±.1
X.XX ±.01
X.XXX ±.002
ANG ±.5°
SCALE: 1.000
MATERIAL
Steel
INTERPRET PER ANSI Y14.5
ALL DIMENSIONS IN INCHES UNLESS SPECIFIED OTHERWISE
MIT - 2.007 License to Design
Department of Mechanical Engineering
77 Mass. Ave, Cambridge, MA 02139
TITLE
Puck Pull Winch Shaft
Pro/E Drawing File
MAXON_WINCH_SHAFT
DESIGNER: MS-L
SHEET 1 OF 1

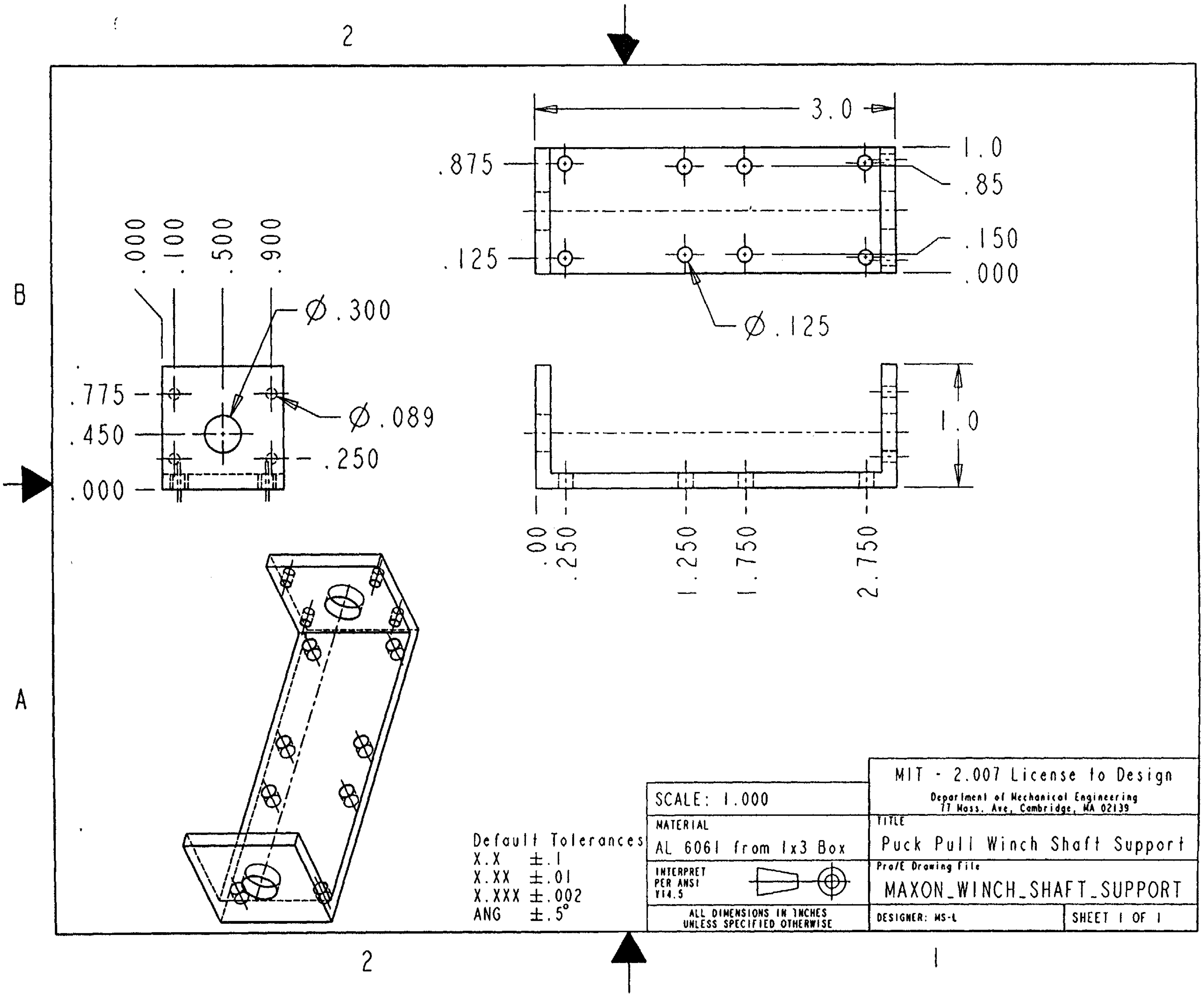


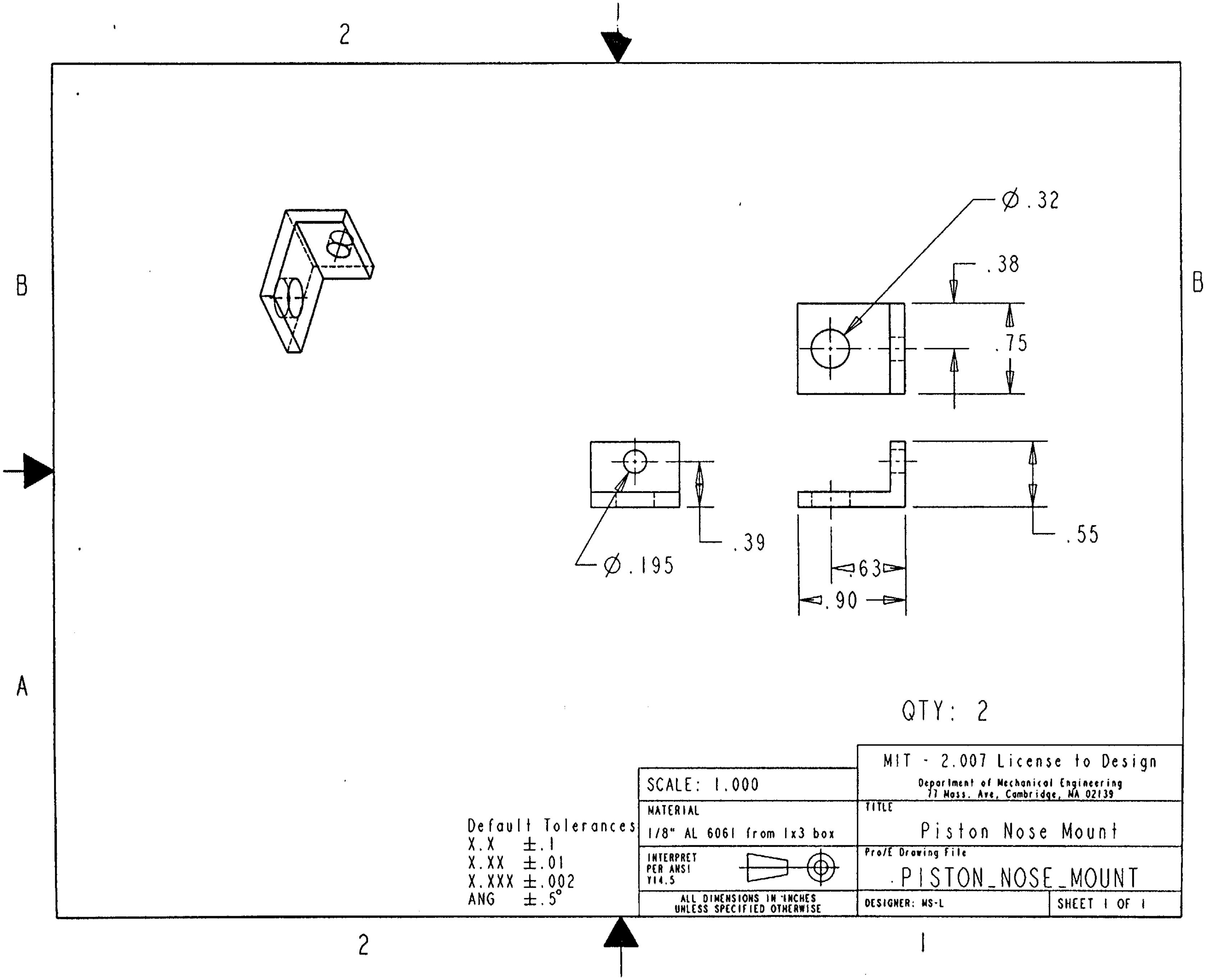
Cut flat shape on Waterjet
Filename: maxmt.dxf

Default Tolerances
X.X ±.1
X.XX ±.01
X.XXX ±.002
ANG ±.5°

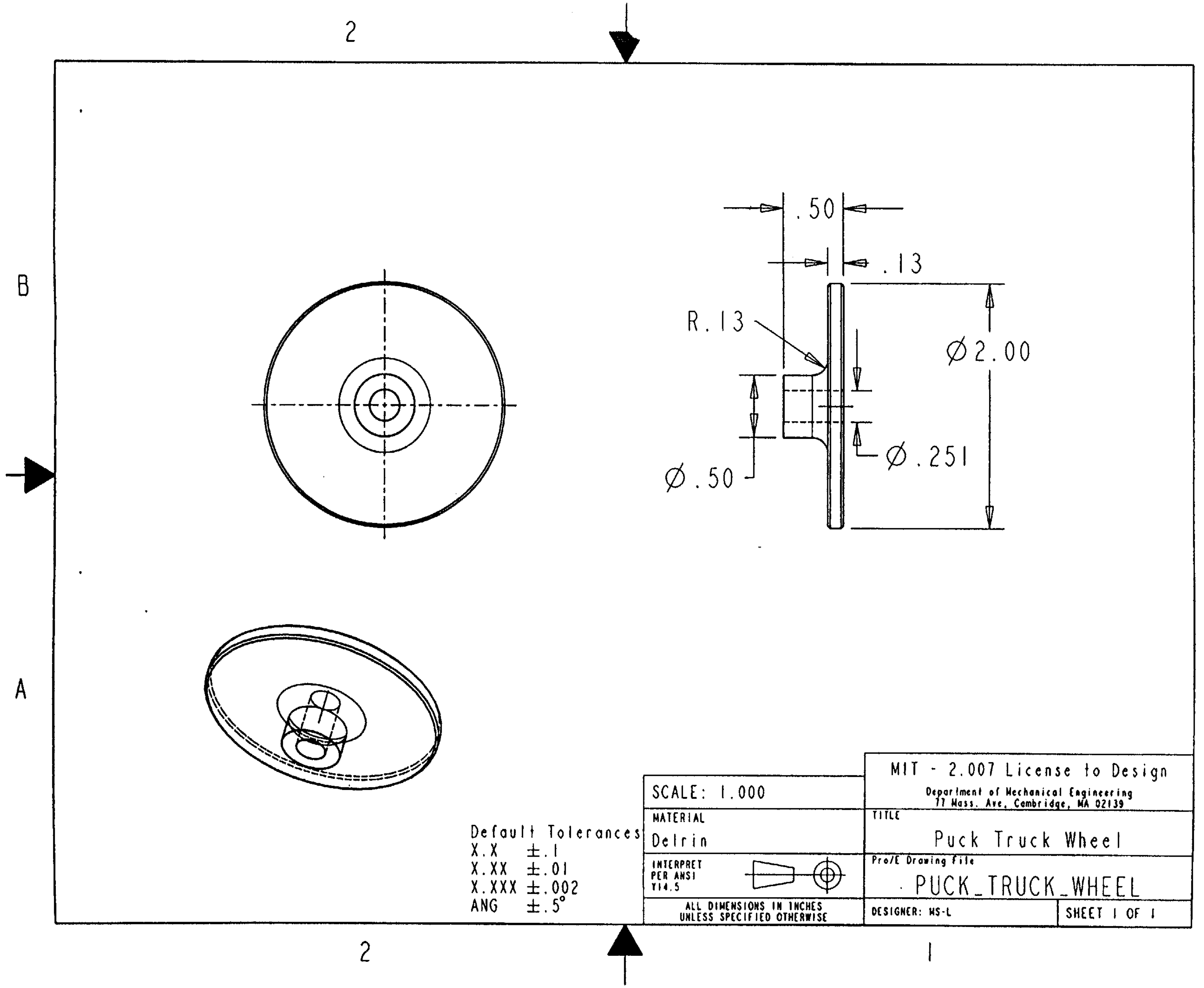
SCALE: 1.000	MIT - 2.007 License to Design Department of Mechanical Engineering 77 Mass. Ave, Cambridge, MA 02139
MATERIAL 18 ga. Mild Steel	TITLE Maxon Gearmotor Mount
INTERPRET PER ANSI Y14.5	Pro/E Drawing File MAXON_MOUNT
ALL DIMENSIONS IN INCHES UNLESS SPECIFIED OTHERWISE	DESIGNER: MS-L — SHEET 1 OF 2



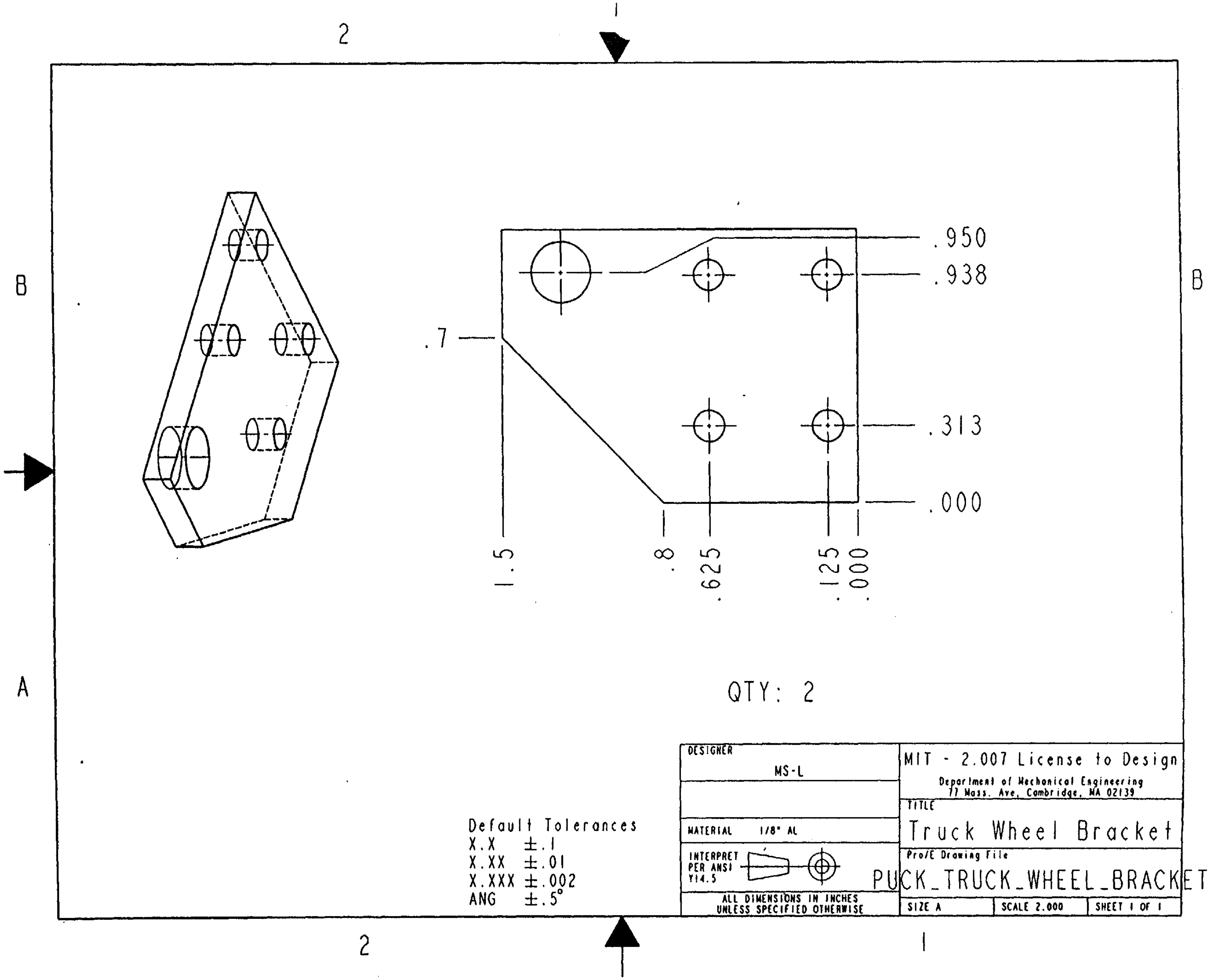

3.0
1.0
.875
.85
.125
.150
.000
Ø.125
.000
.100
.500
.900
Ø.300
.775
Ø.089
.450
.250
.000
1.0
.00
.250
1.250
1.750
2.750
Default Tolerances
X.X ±.1
X.XX ±.01
X.XXX ±.002
ANG ±.5°
SCALE: 1.000
MATERIAL
AL 6061 from 1x3 Box
INTERPRET PER ANSI Y14.5
ALL DIMENSIONS IN INCHES UNLESS SPECIFIED OTHERWISE
MIT - 2.007 License to Design
Department of Mechanical Engineering
77 Mass. Ave, Cambridge, MA 02139
TITLE
Puck Pull Winch Shaft Support
Pro/E Drawing File
MAXON_WINCH_SHAFT_SUPPORT
DESIGNER: MS-L
SHEET 1 OF 1



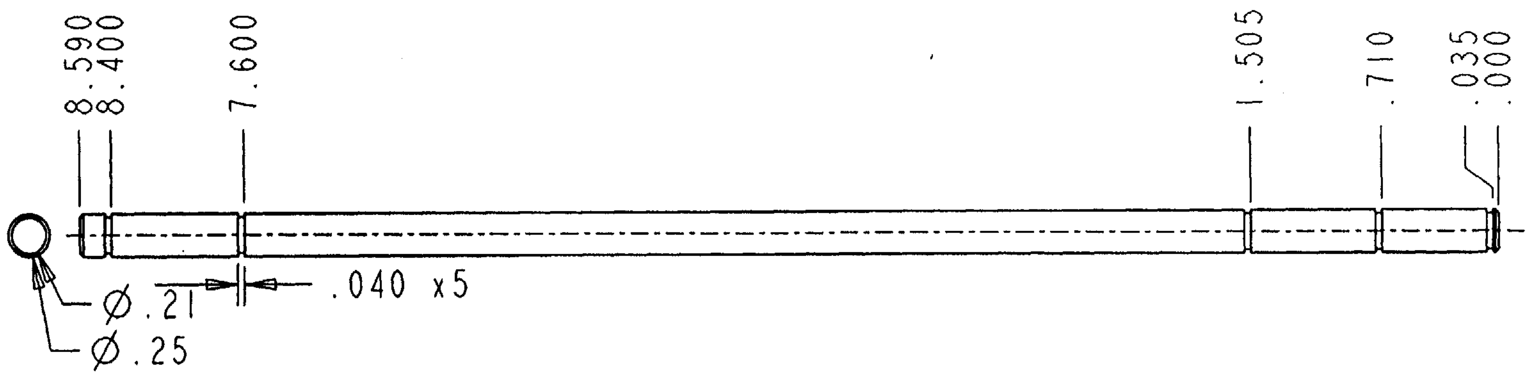
2
1
B
A
Ø .32
.38
.75
Ø .195
.39
.55
.63
.90
QTY: 2
Default Tolerances
X.X ±.1
X.XX ±.01
X.XXX ±.002
ANG ±.5°
SCALE: 1.000
MATERIAL
1/8" AL 6061 from 1x3 box
INTERPRET PER ANSI Y14.5
ALL DIMENSIONS IN INCHES UNLESS SPECIFIED OTHERWISE
MIT - 2.007 License to Design
Department of Mechanical Engineering
77 Mass. Ave, Cambridge, MA 02139
TITLE
Piston Nose Mount
Pro/E Drawing File
PISTON_NOSE_MOUNT
DESIGNER: MS-L
SHEET 1 OF 1



.50
.13
R.13
Ø2.00
Ø.251
Ø.50
Default Tolerances
X.X ±.1
X.XX ±.01
X.XXX ±.002
ANG ±.5°
SCALE: 1.000
MATERIAL
Delrin
INTERPRET PER ANSI Y14.5
ALL DIMENSIONS IN INCHES UNLESS SPECIFIED OTHERWISE
MIT - 2.007 License to Design
Department of Mechanical Engineering
77 Mass. Ave, Cambridge, MA 02139
TITLE
Puck Truck Wheel
Pro/E Drawing File
PUCK_TRUCK_WHEEL
DESIGNER: WS-L
SHEET 1 OF 1

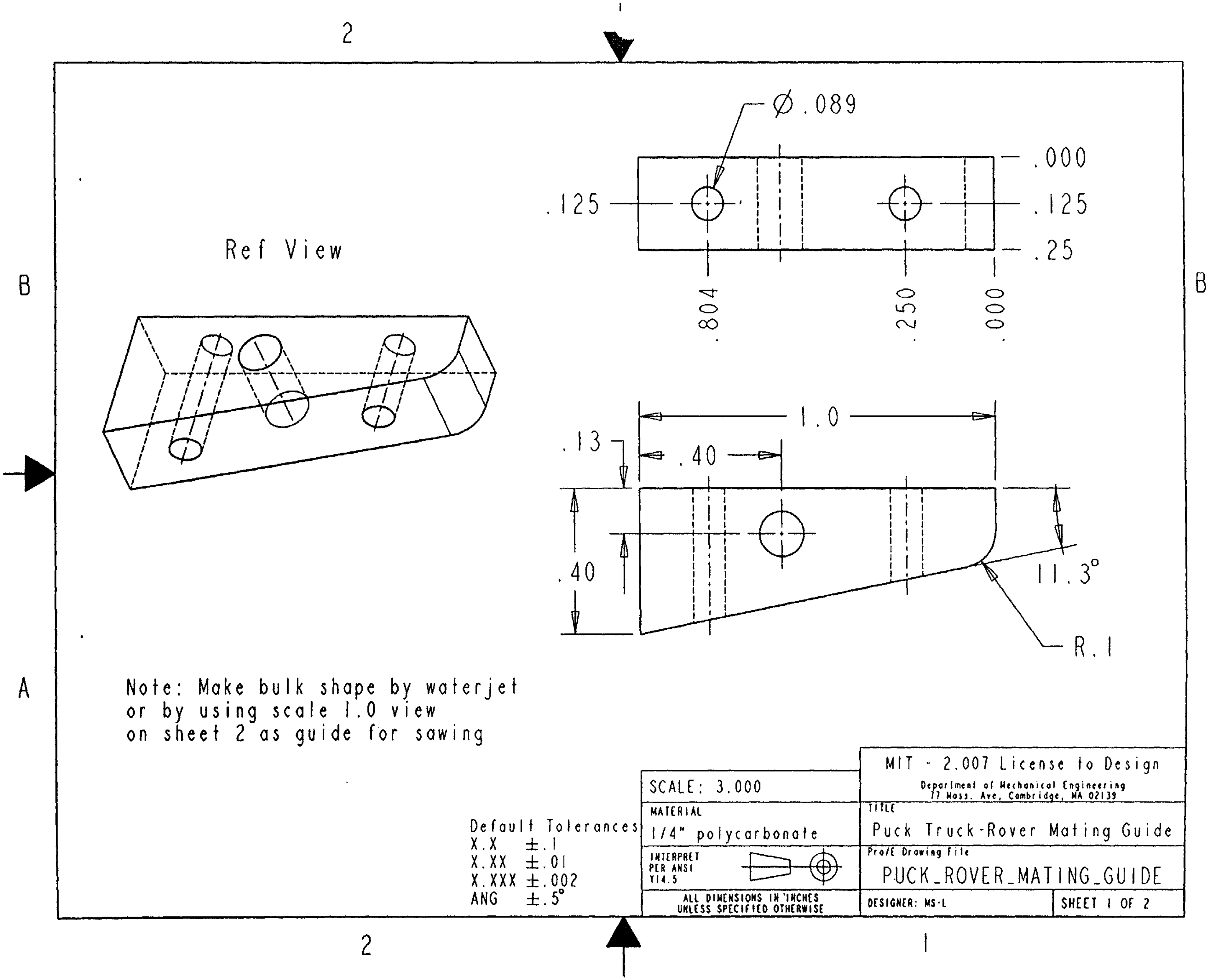


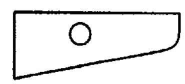
2
1
B
B
A
2
1
.950
.938
.7
.313
.000
1.5
.8
.625
.125
.000
QTY: 2
Default Tolerances
X.X ±.1
X.XX ±.01
X.XXX ±.002
ANG ±.5°
DESIGNER
MS-L
MATERIAL 1/8" AL
INTERPRET PER ANSI Y14.5
ALL DIMENSIONS IN INCHES UNLESS SPECIFIED OTHERWISE
MIT - 2.007 License to Design
Department of Mechanical Engineering
77 Mass. Ave, Cambridge, MA 02139
TITLE
Truck Wheel Bracket
Pro/E Drawing File
PUCK_TRUCK_WHEEL_BRACKET
SIZE A
SCALE 2.000
SHEET 1 OF 1



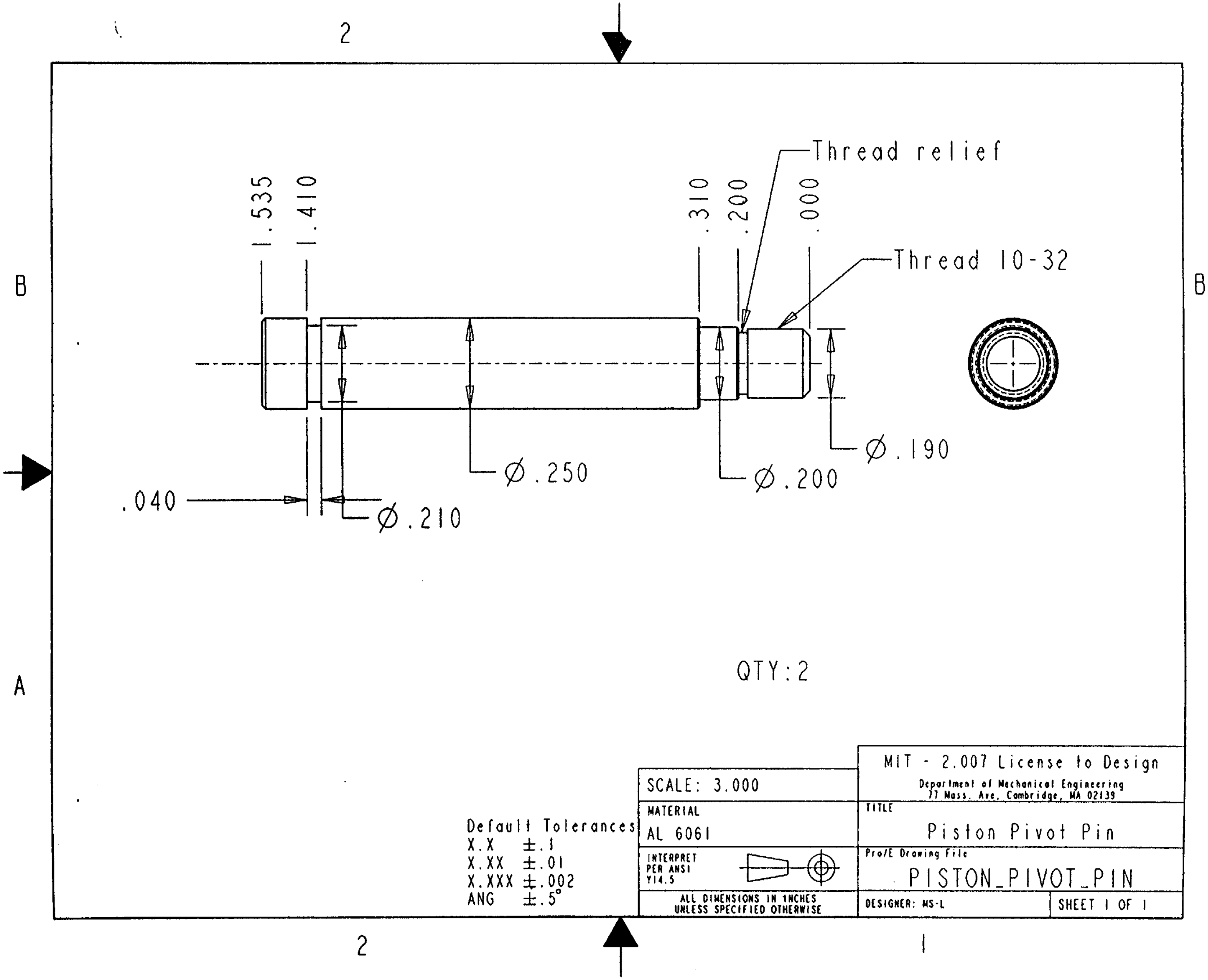
Default Tolerances
X.X ±.1
X.XX ±.01
X.XXX ±.002
ANG ±.5°

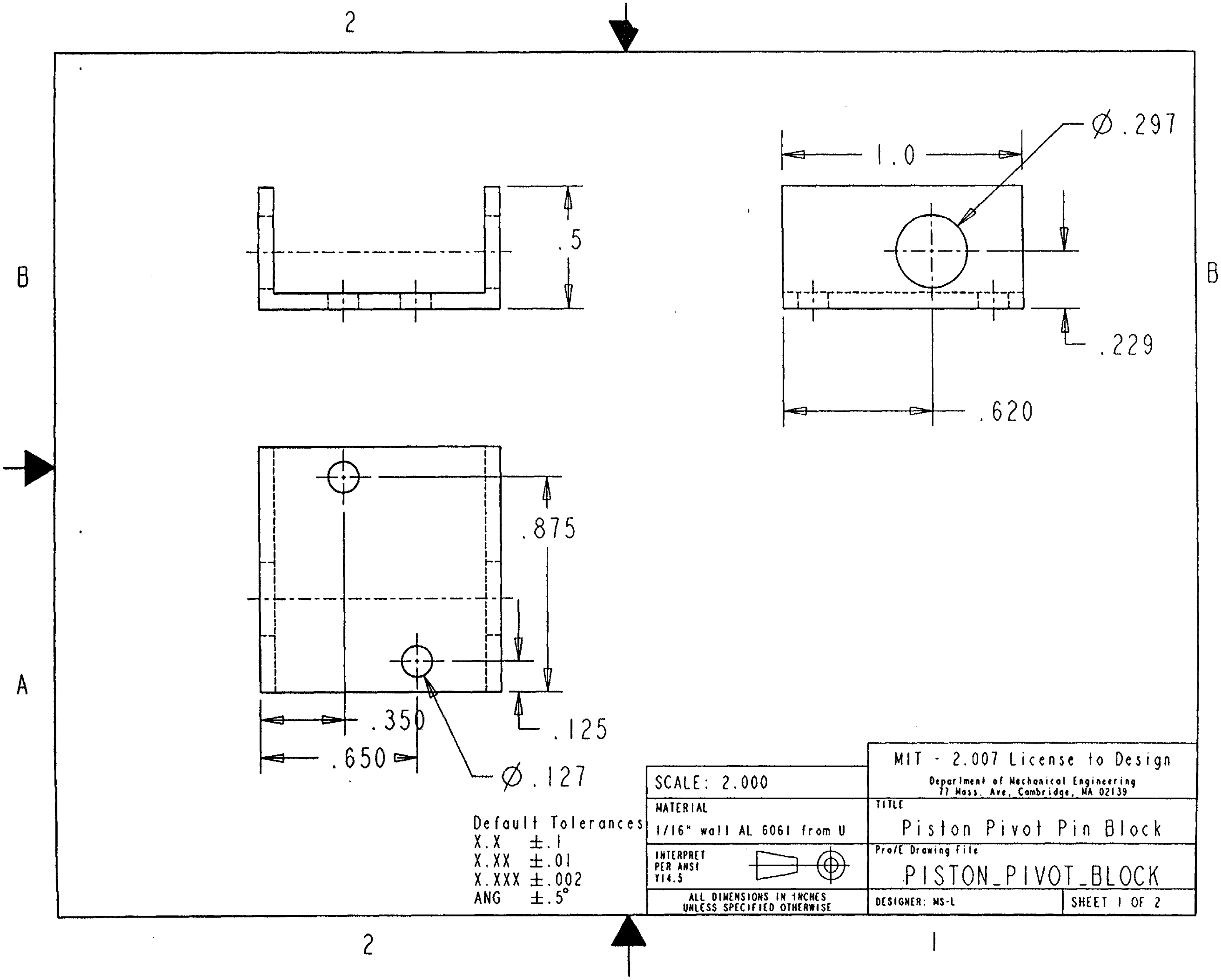
SCALE: 1.000	MIT - 2.007 License to Design Department of Mechanical Engineering 77 Mass. Ave, Cambridge, MA 02139
MATERIAL Steel	TITLE Puck Truck Rear Axle
INTERPRET PER ANSI Y14.5	Pro/E Drawing File PUCK_TRUCK_REAR_AXLE
ALL DIMENSIONS IN INCHES UNLESS SPECIFIED OTHERWISE	DESIGNER: MS-L — SHEET 1 OF 1


Ref View
Ø .089
.125
.000
.125
.25
.804
.250
.000
1.0
.13
.40
.40
11.3°
R.1
Note: Make bulk shape by waterjet
or by using scale 1.0 view
on sheet 2 as guide for sawing
Default Tolerances
X.X ±.1
X.XX ±.01
X.XXX ±.002
ANG ±.5°
SCALE: 3.000
MATERIAL
1/4" polycarbonate
INTERPRET PER ANSI Y14.5
ALL DIMENSIONS IN INCHES UNLESS SPECIFIED OTHERWISE
MIT - 2.007 License to Design
Department of Mechanical Engineering
77 Mass. Ave, Cambridge, MA 02139
TITLE
Puck Truck-Rover Mating Guide
Pro/E Drawing File
PUCK_ROVER_MATING_GUIDE
DESIGNER: MS-L
SHEET 1 OF 2



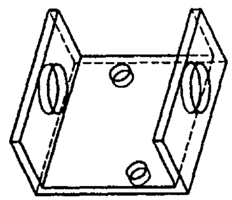
SCALE 1.000


2
B
A
2
1
B
1.535
1.410
.310
.200
.000
Thread relief
Thread 10-32
Ø.250
Ø.200
Ø.190
.040
Ø.210
QTY:2
Default Tolerances
X.X ±.1
X.XX ±.01
X.XXX ±.002
ANG ±.5°
SCALE: 3.000
MATERIAL
AL 6061
INTERPRET PER ANSI Y14.5
ALL DIMENSIONS IN INCHES UNLESS SPECIFIED OTHERWISE
MIT - 2.007 License to Design
Department of Mechanical Engineering
77 Mass. Ave, Cambridge, MA 02139
TITLE
Piston Pivot Pin
Pro/E Drawing File
PISTON_PIVOT_PIN
DESIGNER: MS-L
SHEET 1 OF 1


2
2
B
B
A
2
1
.5
1.0
Ø .297
.229
.620
.875
.125
.350
.650
Ø .127
Default Tolerances
X.X ±.1
X.XX ±.01
X.XXX ±.002
ANG ±.5°
SCALE: 2.000
MATERIAL
1/16" wall AL 6061 from U
INTERPRET PER ANSI Y14.5
ALL DIMENSIONS IN INCHES UNLESS SPECIFIED OTHERWISE
MIT - 2.007 License to Design
Department of Mechanical Engineering
77 Mass. Ave, Cambridge, MA 02139
TITLE
Piston Pivot Pin Block
Pro/E Drawing File
PISTON_PIVOT_BLOCK
DESIGNER: MS-L
SHEET 1 OF 2

2

B



Mirror Part

B

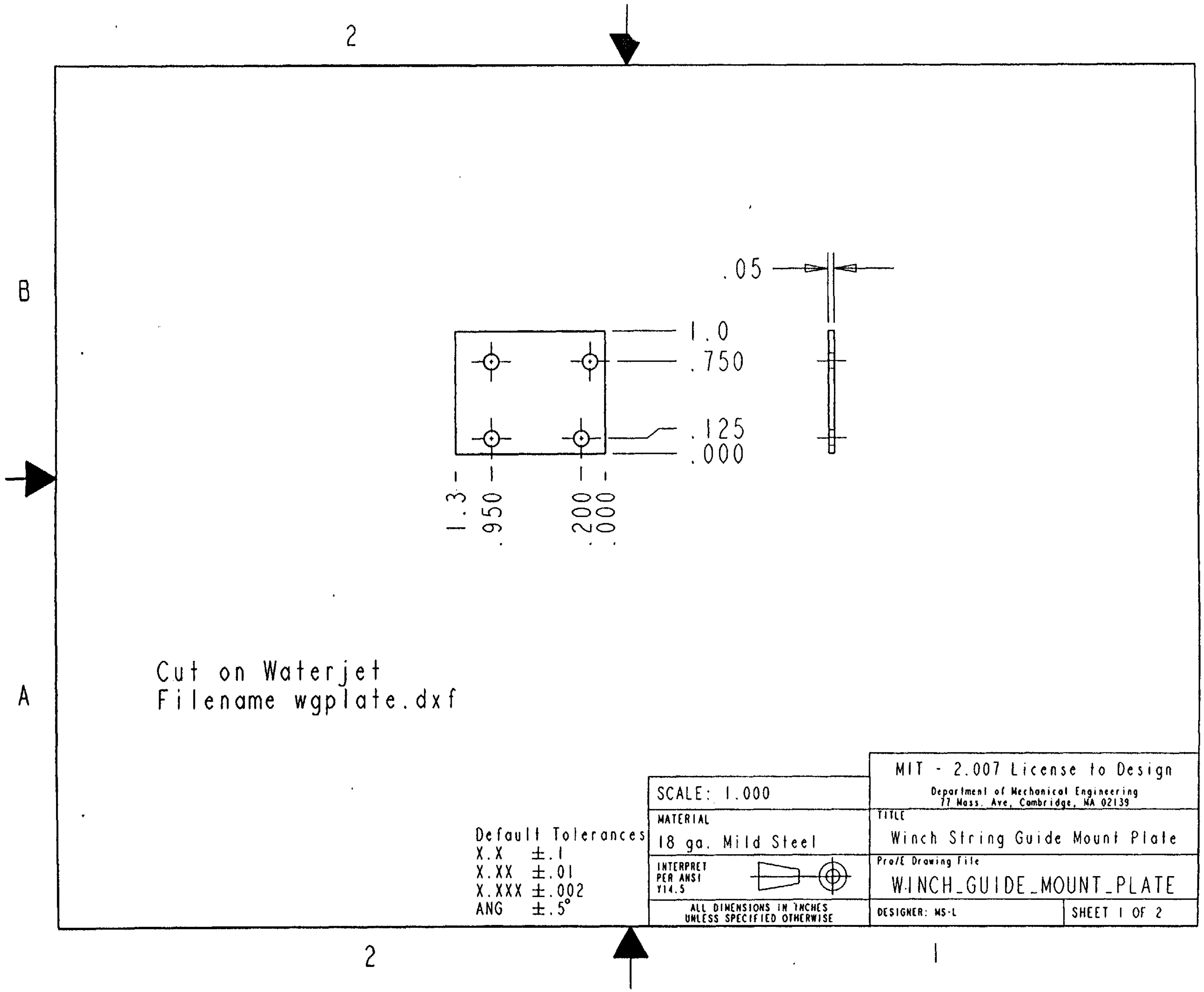
A

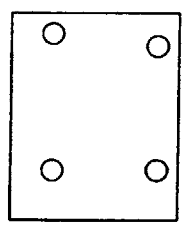
Default Tolerances
X.X ±.1
X.XX ±.01
X.XXX ±.002
ANG ±.5°

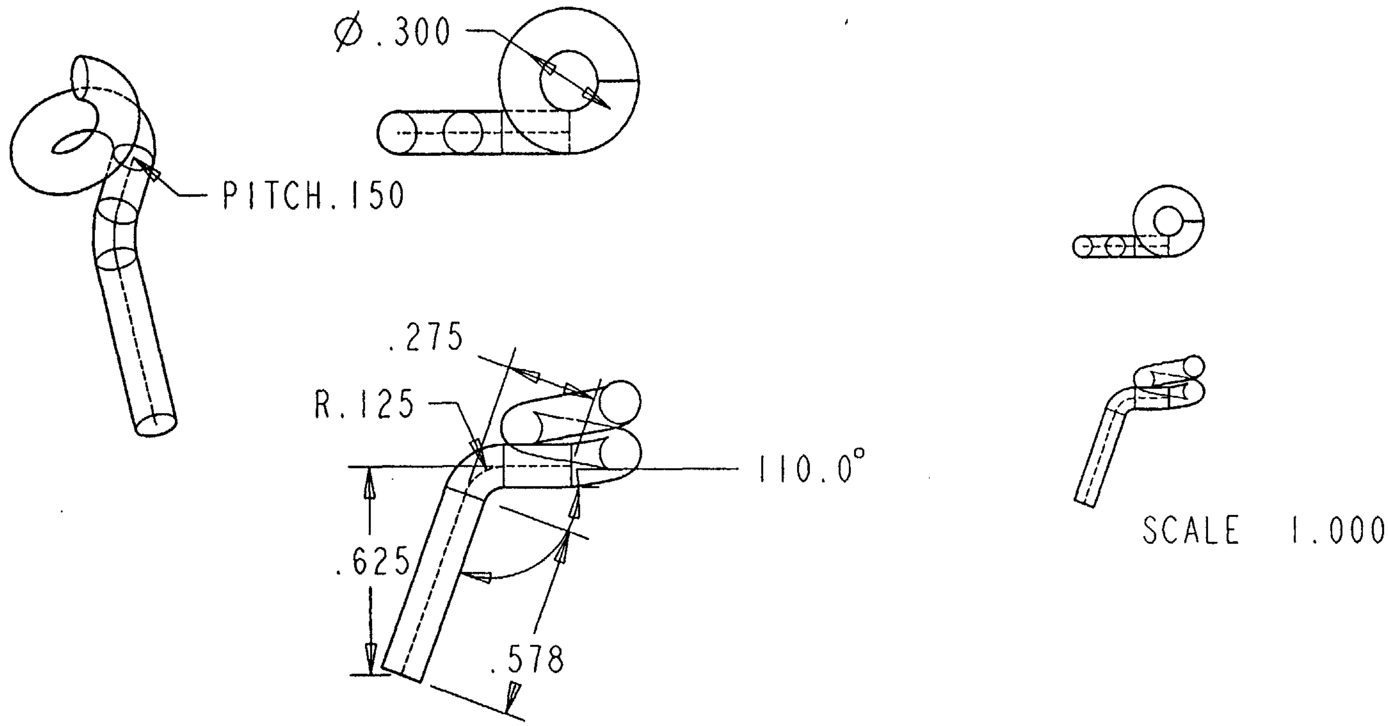
SCALE: 2.000	MIT - 2.007 License to Design Department of Mechanical Engineering 77 Mass. Ave, Cambridge, MA 02139
MATERIAL &MATERIAL	TITLE &TITLE
INTERPRET PER ANSI Y14.5	Pro/E Drawing File PISTON_PIVOT_BLOCK
ALL DIMENSIONS IN INCHES UNLESS SPECIFIED OTHERWISE	DESIGNER: &Designer — SHEET 2 OF 2

2

1

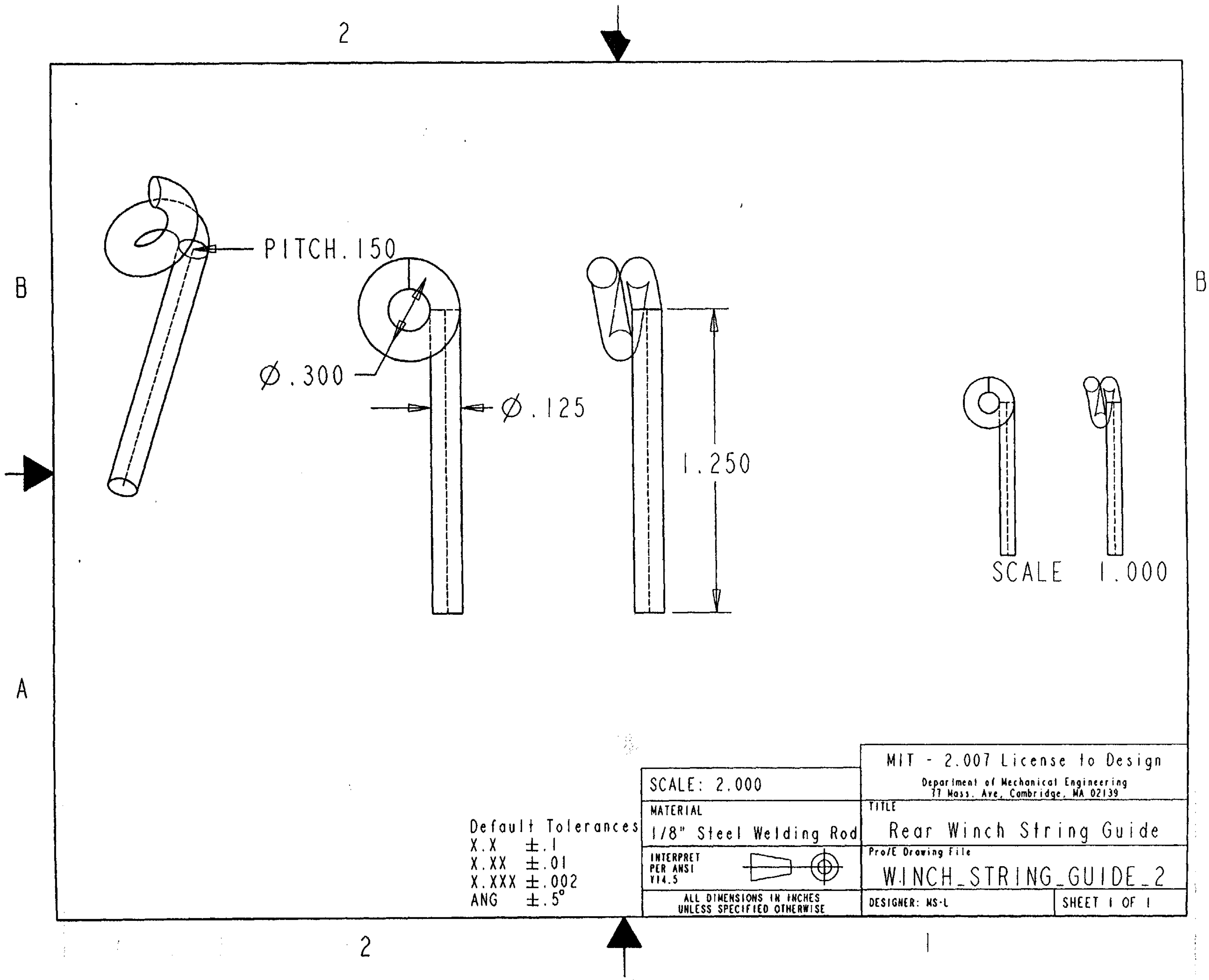

.05
1.0
.750
.125
.000
1.3
.950
.200
.000
Cut on Waterjet
Filename wgplate.dxf
Default Tolerances
X.X ±.1
X.XX ±.01
X.XXX ±.002
ANG ±.5°
SCALE: 1.000
MATERIAL
18 ga. Mild Steel
INTERPRET PER ANSI Y14.5
ALL DIMENSIONS IN INCHES UNLESS SPECIFIED OTHERWISE
MIT - 2.007 License to Design
Department of Mechanical Engineering
77 Mass. Ave, Cambridge, MA 02139
TITLE
Winch String Guide Mount Plate
Pro/E Drawing File
WINCH_GUIDE_MOUNT_PLATE
DESIGNER: MS-L
SHEET 1 OF 2
2
B
A
1

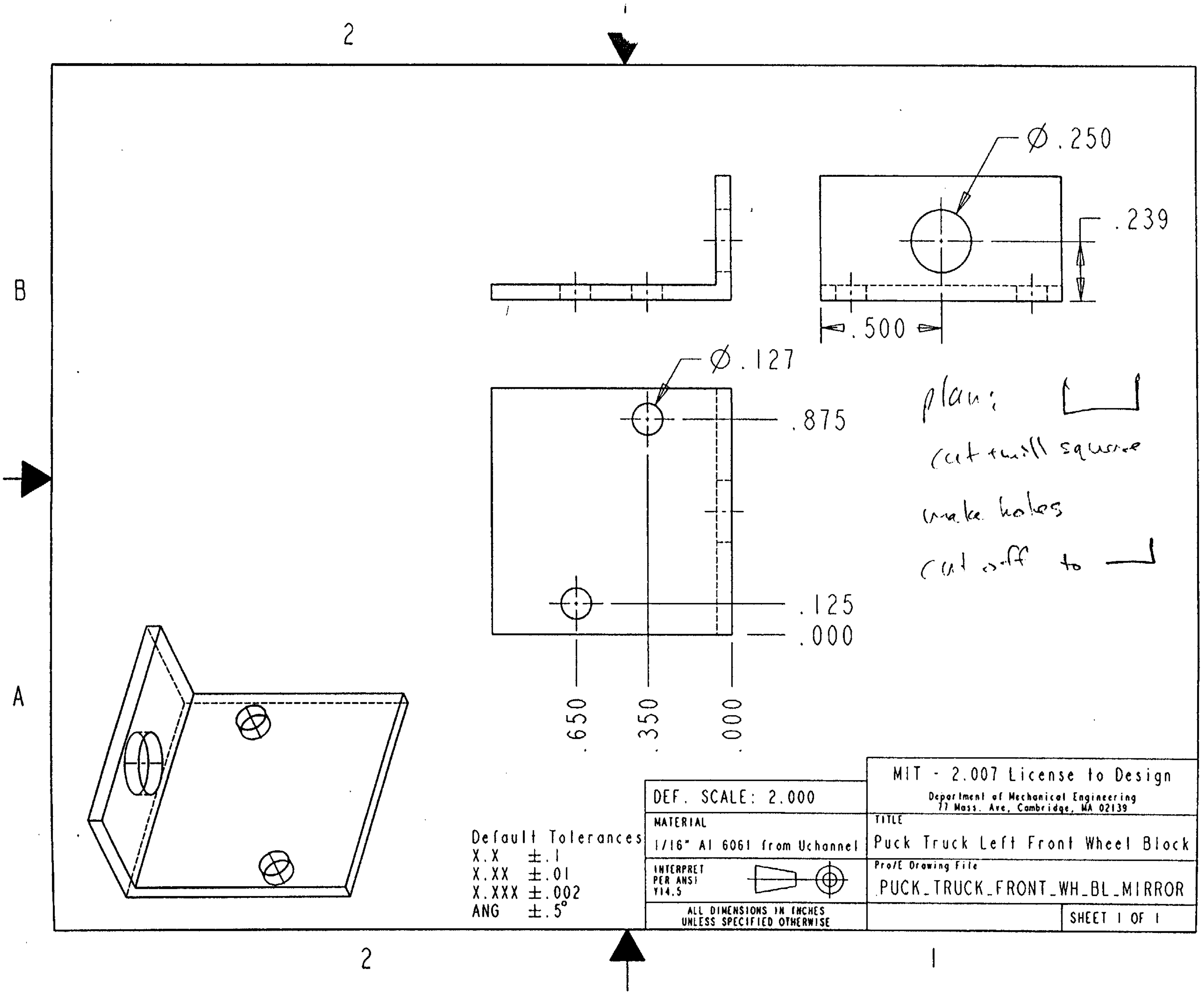




Default Tolerances
X.X ±.1
X.XX ±.01
X.XXX ±.002
ANG ±.5°

SCALE: 2.000	MIT - 2.007 License to Design Department of Mechanical Engineering 77 Mass. Ave, Cambridge, MA 02139
MATERIAL 1/8" Steel Welding Rod	TITLE Front Winch String Guide
INTERPRET PER ANSI Y14.5	Pro/E Drawing File WINCH_STRING_GUIDE
ALL DIMENSIONS IN INCHES UNLESS SPECIFIED OTHERWISE	DESIGNER: MS-L · SHEET 1 OF 1


PITCH.150
Ø.300
Ø.125
1.250
SCALE 1.000
Default Tolerances
X.X ±.1
X.XX ±.01
X.XXX ±.002
ANG ±.5°
SCALE: 2.000
MATERIAL
1/8" Steel Welding Rod
INTERPRET PER ANSI Y14.5
ALL DIMENSIONS IN INCHES UNLESS SPECIFIED OTHERWISE
MIT - 2.007 License to Design
Department of Mechanical Engineering
77 Mass. Ave, Cambridge, MA 02139
TITLE
Rear Winch String Guide
Pro/E Drawing File
WINCH_STRING_GUIDE_2
DESIGNER: MS-L
SHEET 1 OF 1
2
B
A
1



2
B
A
2
1
B
Ø.250
.239
.500
Ø.127
.875
.125
.000
.650
.350
.000
plan:
cut to ill square
make holes
cut off to
Default Tolerances
X.X ±.1
X.XX ±.01
X.XXX ±.002
ANG ±.5°
DEF. SCALE: 2.000
MATERIAL
1/16" Al 6061 from Uchannel
INTERPRET PER ANSI Y14.5
ALL DIMENSIONS IN INCHES UNLESS SPECIFIED OTHERWISE
MIT - 2.007 License to Design
Department of Mechanical Engineering
77 Mass. Ave, Cambridge, MA 02139
TITLE
Puck Truck Left Front Wheel Block
Pro/E Drawing File
PUCK_TRUCK_FRONT_WH_BL_MIRROR
SHEET 1 OF 1

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