THE DESIGN AND MANUFACTURE OF A POWDER DEPOSITION SYSTEM FOR A LARGE POWDER BED ON A THREE DIMENSIONAL PRINTER

by
Benjamin Heywood

Submitted to the Department of Mechanical Engineering
in Partial Fulfillment of the Requirements for the

Degree of

Bachelor of Science

at the

Massachusetts Institute of Technology

May 1993

Signature of Author ______________________________
Department of Mechanical Engineering
May 7, 1993

Certified by ______________________________
Professor Emanuel Sachs
Thesis Supervisor

Certified by ______________________________
Professor Peter Griffith
Chairman, Department Committee

THE DESIGN AND MANUFACTURE OF A POWDER DEPOSITION SYSTEM FOR A LARGE POWDER BED ON A THREE DIMENSIONAL PRINTER

by

Benjamin Heywood

Submitted to the Department of Mechanical Engineering
on May 7, 1993 in partial fulfillment of the requirements for the
Degree of Bachelor of Science in Mechanical Engineering

ABSTRACT

Three Dimensional Printing is a process for the rapid manufacture of tooling and prototype parts directly from a CAD model. Three Dimensional Printing functions by the sequential deposition of powdered material in thin layers and the formation of solid cross-sections of the desired shape by selectively "ink jet" printing a liquid binder into the loose powder. After printing the resulting three-dimensional part is fired and the loose powder is removed. The process may be applied to the production of metal, ceramic, and metal-ceramic parts.

A powder deposition system for a large powder bed has been designed for use on a larger 3D Printer. The design "grates" powder from a hopper, stored in the ceiling above the 3D Printer, into a tube. The tube is guided across the powder bed by a cable drive and a clean line of powder is deposited. To keep up with the goal of technology transfer to industry, the design for the new powder deposition system is suitable for industrial settings. Particularly, the design isolates the powder from the printer, facilitating the control of the powder's environment. The design is capable of handling a variety of materials, including the alumina and stainless steel powders currently used in the 3D Printing process.

Thesis Supervisor: Dr. Emanuel Sachs
Title: Associate Professor of Mechanical Engineering

Acknowledgments

I owe many thanks to the following people for the learning and fun I have had at M.I.T.:

Professor Sachs for introducing me to the world of manufacturing and fostering an interest in bridging the gap between design and manufacturing. 3DP has taught me many valuable lessons.

Dave Brancazio for keeping the lab a fun place to work and most of all for the work you did on my thesis.

Fred Cote for the being a great resource on my trip through M.I.T. Thank you for the wisdom you imparted to me and a place to always feel welcome.

Tim Anderson for your bizarre, abnormal, and peculiar sense of humor and all the help with my thesis, particularly the electronics (yawn).

Harald Tuerck for teaching me how to machine perfectly (almost) in a chaotic world.

Steve Michaels for putting up with me as an annoying UROP student and always providing an entertaining conversation.

All the other people in the lab for providing a fun learning environment.

Vin and Jeff who make up the rest of the Conner III Mech-E Seniors. It has been a great ride from day one.

My parents who I wouldn't be here without. Thanks for the love and support through all the years.

My brothers who have strengthened me through the many battles we have shared.

Erin who made a dorm room a wonderful place to call home.

Table Of Contents

List Of Figures

1. Introduction

1.1. Motivation

Two issues which are key to industrial productivity and competitiveness are the reduction in time to market for new products and the flexible manufacture of products in small quantities. Three Dimensional Printing targets a critical subset of the problems that must be overcome in order to achieve shorter product development cycles and flexible manufacturing for mechanical parts. The problems addressed are rapid prototyping, rapid fabrication of tooling, and the low cost manufacture of tooling.

A major contributor to the time to market for new products is the time required to fabricate prototypes. Rapid prototyping can shorten the product development cycle and improve the design process by providing rapid and effective feedback to the designer. Some applications require rapid prototyping of non-functional parts for use in assessing the aesthetic aspect of a design or the fit and assembly of a design. Other applications require functional parts. Often, it is advantageous if the functional part is fabricated by the same process that will be used in production.

Two issues of current prototyping are tooling lead time and tooling cost. The combination of long lead times and high cost make it impractical to fabricate preproduction prototypes by the same process that will be used in production.

A second major contributor to the time to market is the time required to develop tooling, such as mold and dies. For some types of tooling, such as injection molding dies, the turnaround time for the design and fabrication of a tool routinely extends to several months. The long lead times are due to the fact that the tooling is generally one of a kind and can be extremely complex, resulting in high tooling costs.

Current options do not provide a satisfactory solution to the demand for rapid and flexible manufacturing. The goal of 3D Printing is to produce complex three-dimensional parts directly from CAD models, with no part specific tooling required. This process will be used to produce both functional parts and tooling for prototypes and small batch production.

1.2. The 3D Printing Process

Three Dimensional Printing is a manufacturing process that fabricates solid objects directly from computer models by "printing" sequential two dimensional layers. Each layer begins with fine powder spread into a thin distribution. From a CAD file of the desired part, a slicing algorithm draws detailed information for every layer. Using a technology similar to ink-jet printing, a raster-scanning printhead selectively applies a binder material to join particles where the objects is to be formed. A line of powder is deposited, and a piston that supports the powder bed lowers so that the next powder layer can be leveled and selectively joined. This layer-by-layer process repeats until the part is completed (Figure 1). Unbound powder is removed after heat treatment, leaving the fabricated part.

Three Dimensional Printing applies to a wide variety of materials, including ceramics, metals, metal-ceramic composites, and polymers. Currently, the two main applications of 3D Printing are aluminum oxide powder bound by colloidal silica binder and stainless steel powder bound by latex binder.

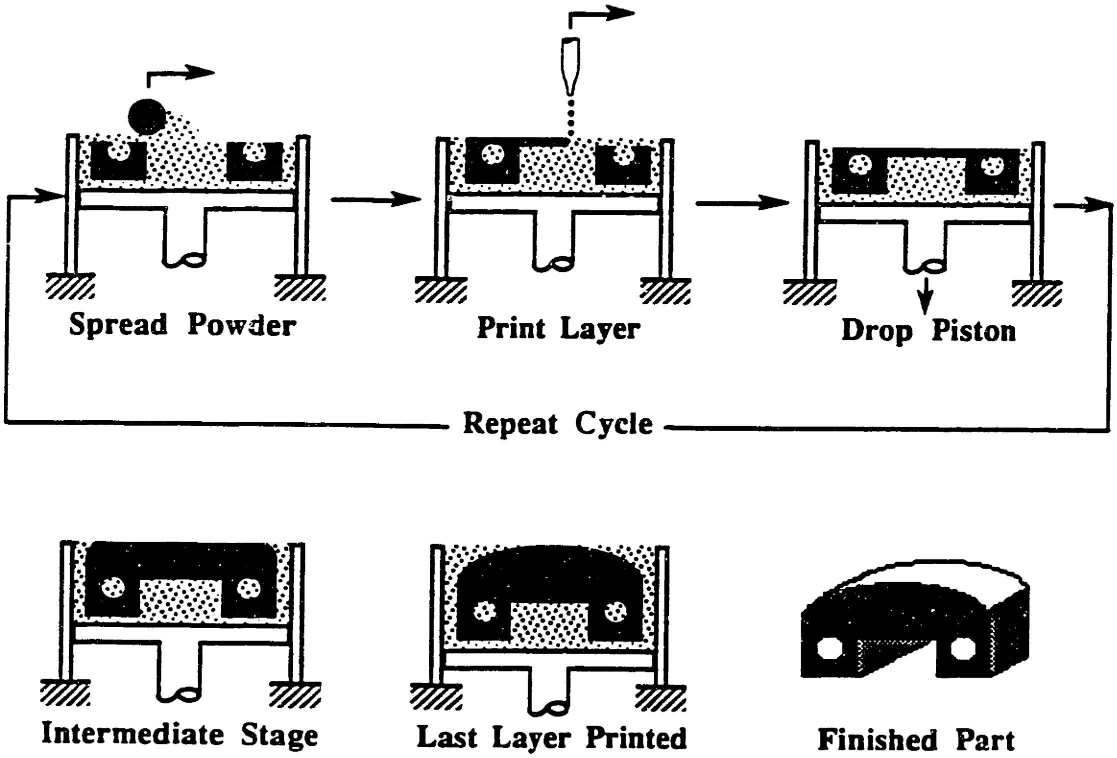


Figure 1 - The 3D Printing Process

1.3. Automating the Alpha 3D Printer

In the summer of 1992, a Alpha 3D Printer was built. The main objective of the new machine was to increase the size of the powder bed allowing for the fabrication of larger parts. The size of the powder bed was increased from 3"x3"x3" to 6"x12"x12". The previous version of the 3D Printer utilized a paddle wheel system for powder deposition, which worked using volume displacement principles. However, expanding the paddle wheel for the Alpha Printer would have been impractical.

Manual powder spreading greatly delayed the production of parts on the Alpha 3D Printer. Therefore, to fully automate the Printer and increase production, a new powder deposition system had to be designed and implemented.

2. Design of Powder Deposition System for a Large Powder Bed

In order to fully automate the Alpha 3D Printer, a new powder deposition system had to be developed which would incorporate the larger print volume. The following is a list of the design criteria used in the development of the new powder deposition system.

Design Criteria

- applicable in industrial settings
- robust
- isolate powder
- suitable for different powders
- printer layout considerations
- low profile

2.1. Industrial Settings

To keep up with the goal of technology transfer to industry, the design for the new powder deposition system must be suitable for industrial settings. Since a present version of the printer is currently being manufactured for industry, all new components must consider the eventual use in industry as a important design criterion.

2.2. Robust

Any powder deposition system implemented on the Alpha Printer must be able to deposit up to 2000 layers without failing. As with any high precision machine, the 3D Printer has many different components which can fail. The printing of complicated parts can run upwards of 12 hours, and a successful printing requires that the printer run smoothly throughout. Therefore, all components of the printer must be robust and operate without failing during printing.

2.3. Isolate Powder

The different powders utilized on the 3D Printer are affected by their environment. In particular, the alumina powder does not flow well in high humidity. To prevent any variation in powder characteristics, the powder should be stored in a controlled environment. Separating the powder from the printer allows for greater control of the powder environment. Isolating the powder would also protect against contamination by printer chemicals. The powder can be kept in a controlled environment until seconds before spreading.

In industry, isolating the powder would allow companies to store the powder in a gray space. It would allow for large volumes of powder to be stored away from the printer. Also, separating the powder from the printer significantly reduces the foot print of the printer.

2.4. Different Powders

Currently, the 3D Printing Lab is utilizing two main powders for printing, alumina oxide and stainless steel. The alumina powder is used to create ceramic molds or ceramic parts directly. The ceramic molds are then cast to make metal parts. The stainless steel parts are intended for use as injection molding inserts. These inserts would allow for quick production of dies for plastic parts. The powder deposition system has to be capable of handling a wide variety of materials, particularly the alumina and stainless steel powders currently used in production.

One application of 3D Printing that has yet to be explored is multiple material parts. In the future, customers could ask for parts made from more than one material. This would require the powder deposition system to deposit different materials in a closed loop system. The design should allow for several different powders to be stored for quick material changes on the printer. Therefore, the system must be expandable to handle these needs.

2.5. Printer Layout Considerations

One important consideration when designing the new powder deposition system is the layout of the printer. Since powder deposition is one of the last systems implemented to fully automate the printer, the layout of the other elements of the machine is already fixed. The design has to fit within the footprint of the current machine.

2.6. Low Profile

For smooth operation of the printer, it is important that the print head be kept visible. Keeping the print head visible facilitates its upkeep and maintenance, including nozzle and catcher operation. The printer, without the powder deposition system, allows the operator adequate visual access to the print head. The new powder deposition system should not compromise that visibility.

3. Description of Powder Deposition System Design

Figure 2 shows the overall configuration of the powder deposition system as implemented on the Alpha 3D Printer. The powder hopper contains the current powder being used for printing. Once the hopper is hoisted up to its rest position in the ceiling, the powder is sealed from the outside environment. The DC motor turns a stainless steel mesh which grates the powder from the bottom of the hopper. The resulting shower of powder is caught and funneled down a tube attached to a cable drive on the printer.

When powder deposition is necessary, the DC motor is started by the printer's controller, and the stepper motor is activated. The tube is guided across the powder bed by the cable drive and a clean line of powder is deposited. Any clouding of the powder is vacuumed up by a suction line attached to an air evacuation line.

This design accomplishes all of the design goals intended for the system. The powder is isolated in a hopper away from the printer (in the ceiling). The environment of the powder could be controlled by pumping the desired environment into the hopper (e.g. dry air to keep the powder dry). The design is low profile, only adding a thin cable in front of the print head, and all components of the design stay within the foot print of the printer.

The following sections contain detailed descriptions of the individual components of the powder deposition system. All parts drawings are found in Appendix A.

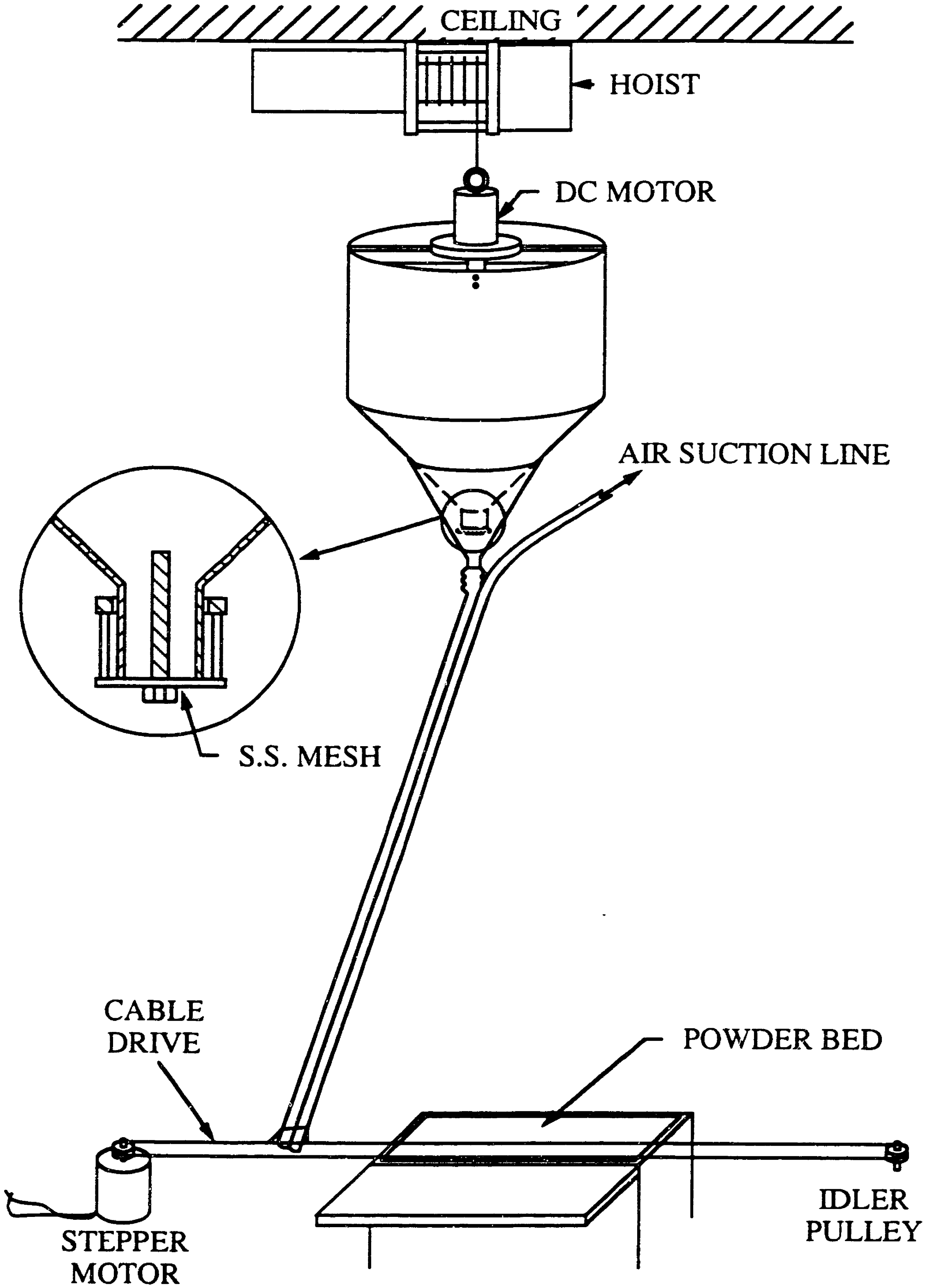


Figure 2 - Overall Configuration of Powder Deposition System

3.1. Ceiling Structure and Hoist

The ceiling above the chosen location for the 3D Printer was not ideal for the implementation of the powder deposition system. In order to avoid the pipes above the machine, the structure shown in Figure 3 was attached to the ceiling. The ceiling structure provided a solid base against which the powder hopper could dock and a sturdy mounting plate for the hoist.

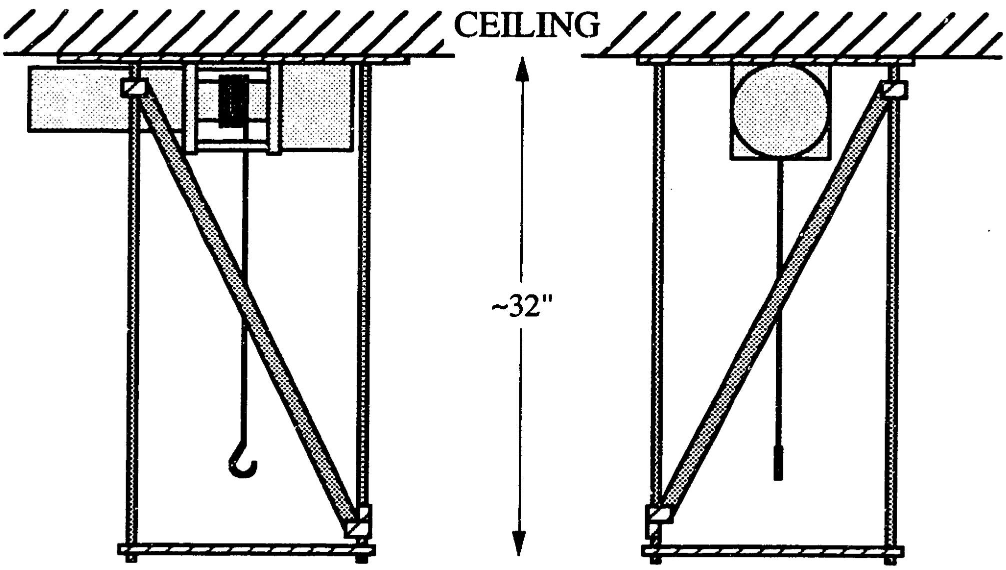


Figure 3 - Schematic of Ceiling Structure

The hoist mounting plate is made from 1/2" aluminum plate. It is attached to the ceiling with 1/2-13 bolts which go through the ceiling to the floor above. The hoist is attached to the plate with 3/8-16 bolts and should be tightened periodically to 33 ft-lbs. The vertical members are 1/2-13 threaded steel rods. The cross braces are zinc plated steel flats, 1/8" thick and 3/4" wide. They attach to the threaded rod with custom made nuts. The bottom plate is the powder hopper docking plate, which is made from 1/4" aluminum plate.

The hoist is a Columbia Hoist model H1000. It runs on 115 Volts AC power, and is controlled with low voltage hand-held remote. The hoist is rated to lift 1000 lbs.

However, the company has already added a safety factor of two, so the hoist can pull upwards of 2000 lbs. When the system is implemented for stainless steel powder, a full hopper will weigh approximately 500 lbs.

To prevent the destruction of the ceiling structure by the hoist due to operator error, the docking plate has a limit switch. When the hopper joins with a rubber seal on the plate, the limit switch cuts power to the hoist, ensuring a good seal from the outside environment. A safety line can be attached to the powder hopper in case the hoist creeps or possibly fails.

3.2. Powder Hopper Unit

The cutaway of the powder hopper unit is shown in Figure 4. The hopper itself is fabricated from 1/6" Stainless Steel. The stainless steel grating is driven by a 24 volt Pittman D-C brush gearmotor which requires 0.4 Amps. At 24 V, the motor originally ran at 23 rpm with 175 oz-in of torque. However, to increase the speed of the motor a 3:1 gear was removed. The motor now runs at approximately 70 rpm and 60 oz-in. Overheating was not an issue because the motor was being run extremely periodically; a layer can typically take anywhere from 30 seconds to 5 minutes.

A calculation of the power required to turn the grating in a full hopper was made to ensure the motor was large enough. The shear stress on the grating was estimated as the pressure of a column of powder the height of the hopper, with a cross-sectional area equal to that of the grating. Assuming a coefficient of friction of 1, the power required was 6.5 watts. However, the estimate of shear stress on the grating was high because the column of powder would be supported by the surrounding powder. Also, a coefficient of friction of 1 was a worst case scenario. Therefore, the power required would be less than 6.5 watts.

The motor is powered by a variable DC power supply controlled by Lab View, the printer's controller software. The speed of the motor can be slowed by raising and

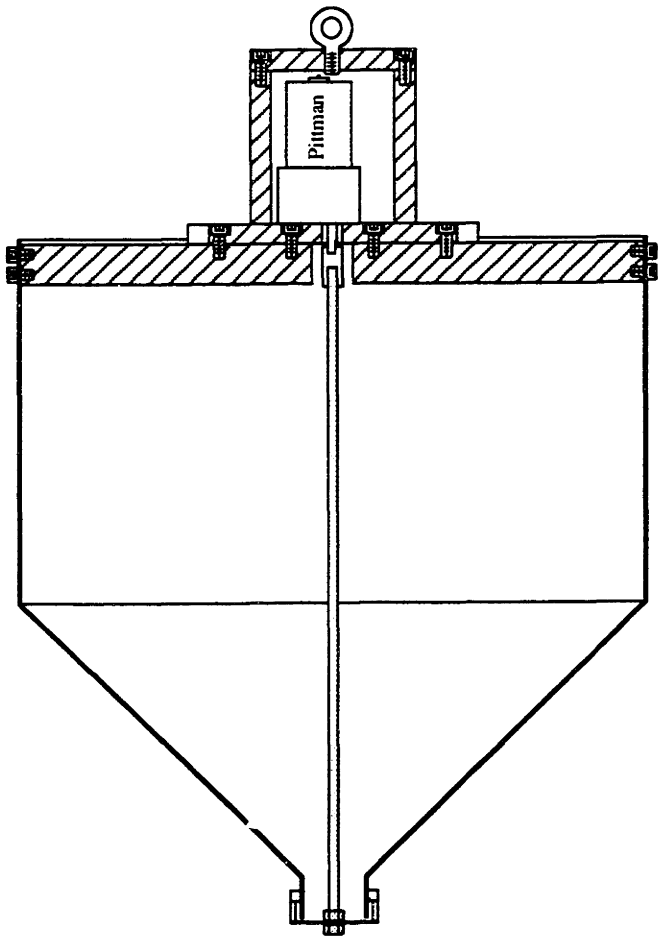


Figure 4 - Powder Hopper Assembly

lowering the voltage of the power supply. Since the motor and controller is an open loop system, the speed of the motor will be affected by the load on the grating, i.e. the quantity of powder in the hopper. The motor will speed up as the hopper empties, and the bead of powder will get larger. This prevents a failure mode of a deposited bead not having enough powder for a layer.

The motor is housed in a 1/2" thick aluminum cylinder, which is covered with a 1/2" thick plate. An eyebolt is attached to the housing cover to connect the hopper to the hoist. The motor housing is attached to the hopper by an aluminum spider made from 1" thick aluminum plate. The spider suspends the motor and housing over the center of the hopper opening while allowing areas for refilling the powder hopper. It is attached to the powder hopper with 8 1/4-20 bolts.

The shaft of the motor is extended to the bottom of the hopper with a steel rod. The motor shaft and the rod are connected with a universal joint. Attached to the shaft extension with two 1/4-20 nuts is a mesh/bearing assembly, which constrains the motion that the universal joint would allow. This bearing setup allows low accuracy in centering the motor shaft at the top of hopper. A more typical bearing setup was considered with two bearings and a bearing casing attached to the motor mounting plate inside the hopper. However, this would have required accurately centering the motor with respect to the hopper. Also, sealing the bearings from the powder would have been difficult.

The mesh is 0.018" thick stainless steel with 0.045" perforations. This perforation size stops the powder from filtering through while the grating is at rest and even when jarred. However, when the mesh is rotated, powder is grated from the powder hopper causing a light shower to empty from the powder hopper. For use with powder other than the alumina, another size mesh might be necessary.

3.3. Funnel/Tube System

The shower of powder emitted from the powder hopper is channeled to the powder bed via a funnel and tube. The funnel attached to the powder hopper catches the shower of powder, directing the flow into a plastic tube which snakes around an aluminum tube down to the powder bed. The aluminum tube is a vacuum tube, starting at the powder bed and connecting to an air evacuation line. The two tubes are attached to the cable drive system via a rubber coupling and a quick release buckle.

3.4. Cable Drive System

The powder flowing out of the tube is formed into a bead on the powder bed with a cable drive system. The cable drive is a continuous cable wrapped around a drive pulley and an idler pulley. The two pulley mounts are attached to the printer table with the cable in the direction of the fast axis. The pulleys are about 6.5" above the table which makes the cable run about 3" above the powder bed.

The drive pulley is driven by an American Precision Industries Stepper Motor, which runs at 4.7 volts and 1.8 amps and has 200 steps per revolution. The motor is powered by a nuBus Power Amplifier and Interface and is controlled by Lab View. The nuBus Amplifier allows the motor to be microstepped, running at 10 microsteps/step for a total of 2000 steps/revolution. Although the cable drive system is open loop, the cable has a limit switch which can be used as a home position. This will allow the cable's position to be reset to a desired location after each layer.

The connection between the cable drive and the powder tube is a rubber coupling with a quick release belt. The rubber coupling allows the path of the tube to maneuver around various components on the 3D Printer. Also, the powder tube retracts to the front of the printer at the end of the path avoiding a possible collision with the fast axis of the printer. The path of the powder tube is shown in Figure 5.

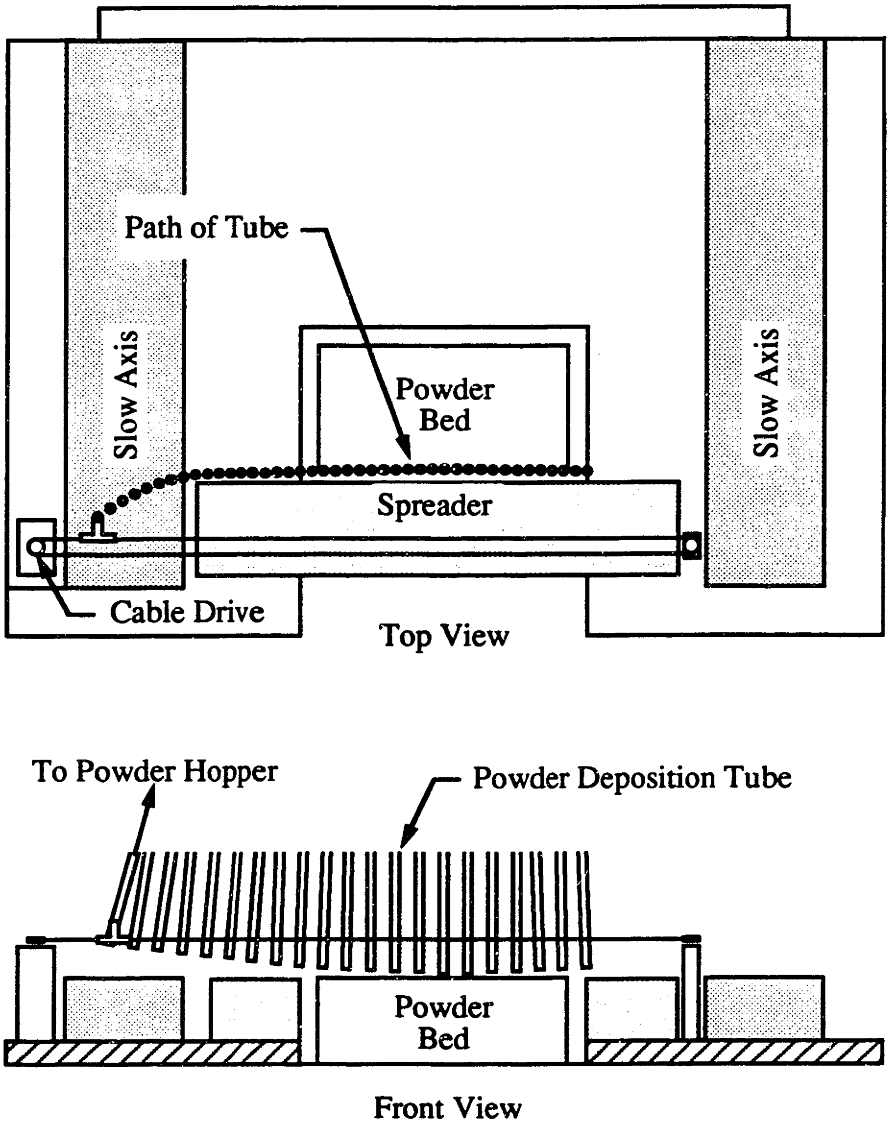


Figure 5 - The Path of the Powder Tube

4. Evaluation of Powder Deposition System Design

The new powder deposition system was first tested in February 1993. Since then, the system has been used in the production of various parts. Initially, the design had two major problems. The following sections describes these problems, the solutions implemented on the printer, and some design changes made to make the system more convenient in everyday use.

4.1. Initial Design Problems and Solutions

The first major design problem resulted from the powder exiting the tube too quickly causing a cloud of powder. To slow down the powder flow, the powder tube was snaked around another tube. This added to the friction on the powder, and lowered the effect of gravity on the powder. This solution reduced the clouding some, but was still not acceptable. A suction tube was added to vacuum the cloud of the powder, virtually eliminating the clouding problem.

The second major design problem resulted from the low flowability of the powder inside the hopper. When running the mesh, a worm hole tended to form inside the powder hopper. The powder would not collapse in on itself, and therefore the powder hopper would not empty fully. In an attempt to eliminate this problem, a vibrator was attached to the powder hopper to increase powder flow. However, the vibrator only compacted the powder more, worsening the situation.

One solution to the worm hole problem involved the use of a rubber air bladder inside the powder hopper. The bladder is periodically filled with air causing the powder to collapse into the worm hole. Then the air is vacuumed out of the bladder, returning the bladder to the edge of the hopper wall.

4.2. Convenience Features

After printing with the new powder deposition system several times, a few feature were added to facilitate smooth operation. The first feature was a quick release buckle connecting the cable drive with the powder tube. This buckle allowed the ceiling system (ceiling structure and powder hopper) and the cable drive to be separated quickly, facilitating the refill of the hopper and allowing the printer operator to experiment with the powder flow tube.

To make the entire system more visible from the outside, two windows were added, one each to the hopper and to the funnel. The window added to the funnel was mostly for demonstration purposes, showing the mesh creating the shower of powder. However, the window added to the docking plate was primarily for diagnostic purposes. This window allowed the printer operator to look inside the powder hopper without lowering it. The operator could check the quantity of powder left in the hopper and verify that the air bladder was working properly.

5. Conclusions

The new powder deposition system works well, accomplishing all of the goals intended for the system. The new design could function well in an industrial environment, even incorporating several manufacturing practices currently used in industry (e.g. separating materials from the process). With the addition of the air bladder, the system should operate without failure. The new design will work well with a variety of powder types, and a new hopper could be built for each powder used. Also, the design is low profile, maintaining ample visual access to the print head.

The new design provides accurate control over the quantity of powder deposited. By altering the speed of the grating or changing the traverse speed of the tube, the amount of powder that is deposited can be controlled. Lab View allows these parameters to be easily changed for different layer thicknesses. Also, when the powder hopper is almost empty and the DC motor speeds up due to a lighter load, the speed can be slightly reduced by lowering the motor voltage.

In the future, the demand for the production of large parts will require the 3D Printer to expand. With a print volume of a cubic meter, it would be possible to directly print an engine block. The basic principles of this new powder deposition system could be used on an expanded 3D Printer. In a scaled-up version, the powder hopper could be moved, instead of the tube, by mounting it to a motorized railing on the ceiling. To refill, the hopper would dock below a powder storage room on the floor above, and the powder would flow through a large chute in the ceiling. This would allow almost any quantity of powder to be stored in a controlled environment.

References

Lee, Sang-Joon John, "Powder Layer Generation for Three Dimensional Printing", MIT M.S. Thesis, 1992.

Pruitt, Beth L., "The Design of a Powder Deposition System for a Three Dimensional Printing Machine", MIT B.S. Thesis, 1991.

Shigley, J.E. & Mischke, C.R., *Mechanical Engineering Design* (5^{th} ed.), McGraw-Hill Publishing Co., NY, 1989.

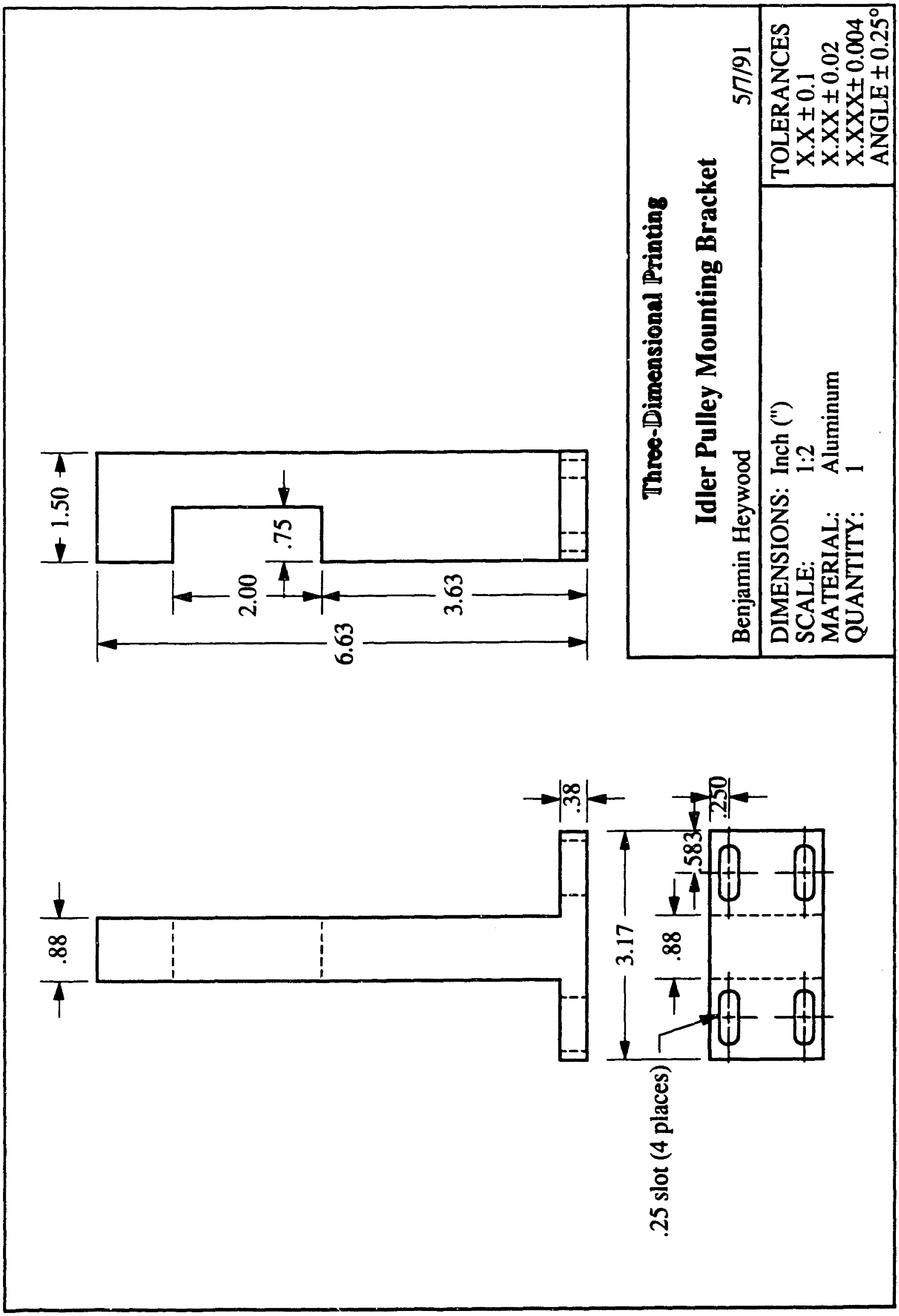
Tuerck, Harald, "Design of a Powder Cylinder with Floating Piston for Three Dimensional Printing Application", MIT M.S. Thesis, 1992.

Williams, Paul, "Three Dimensional Printing: A New Process to Fabricate Prototypes Directly from CAD Models", MIT M.S. Thesis, 1990.

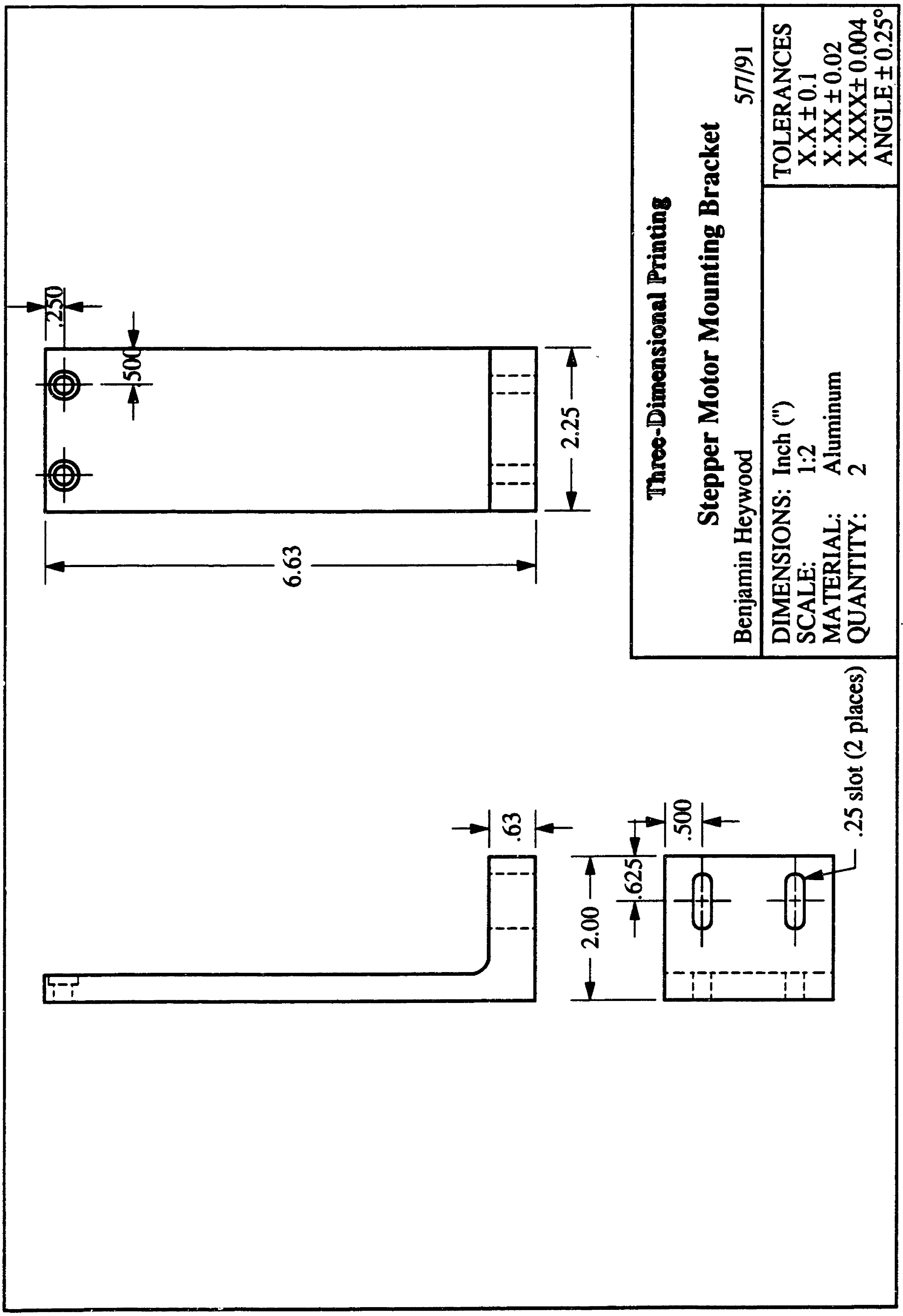
Appendix A - Parts List

Part	Vendor	Part #	#
Hoist w/ 216:1 Gearhead	Allied Power Products	H1000-A1-1	1
Shoulder Eye Bolt (3/8-16)	LMP Shop	NA	1
Motor Housing Cover	custom	see drawing	1
Motor Housing	custom	see drawing	1
24 V-DC Motor	Pittman	GM9413-4	1
Motor Mounting Plate	custom	see drawing	1
Limit Switch Plate	custom	see drawing	1
Hopper Spider	custom	see drawing	1
Powder Hopper	Advent Design Corp.	see drawing	1
Universal Joint	Small Parts, Inc.	J-UJD-13 4/4	1
Shaft Extension	custom	see drawing	1
Sleeve Bearing	custom	see drawing	1
Bearing Spacers	Nordex	BCS-A4-8	6
Grating	custom	see drawing	1
Funnel Large HDPE	Lab Supplies	152840	1
Funnel Placement Pins	3DP Lab	NA	2
Funnel Attachment Nut	custom		1
Air Vent Tube	custom		1
Powder Flow Tube	custom	NA	1
Rubber Coupling	custom	see drawing	1
Quick Release Buckle	EMS	NA	1
Cable Attaching Plate	custom	see drawing	1
Nylon Coated S.S. Cable	McMaster-Carr	8930T31	~6'
Ball End Plug	Sava Industries	405B3	2
Threaded Plug	Sava Industries	467B	1
Turnbuckle	Sava Industries	803	1
Spring (~10-20 lbs.)	LMP Shop	NA	1
Cable Spring Adapter	custom	see drawing	1
Idler Pulley	Sava Industries	SP-487	1
Drive Pulley	Allied Devices	DAE-33	1
Stepper Motor	Servo Systems	23D-6204	1
Stepper Mounting Plate	custom	see drawing	1
Stepper Mounting Bracket	custom	see drawing	2
Idler Mounting Bracket	custom	see drawing	1

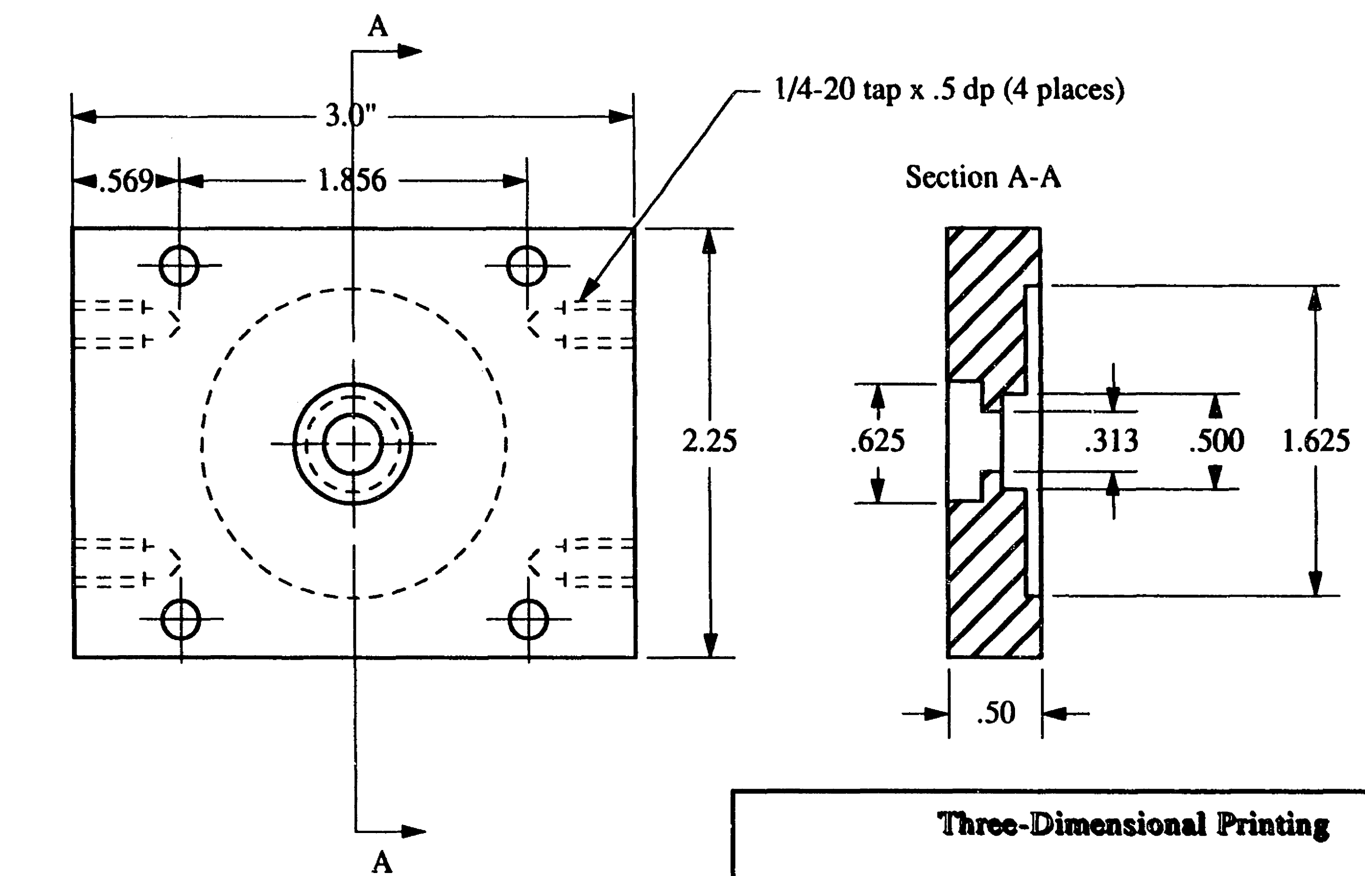
Appendix B - Parts Drawings



Three-Dimensional Printing
Idler Pulley Mounting Bracket
Benjamin Heywood
5/7/91
DIMENSIONS: Inch (")
SCALE: 1:2
MATERIAL: Aluminum
QUANTITY: 1
TOLERANCES
X.X ± 0.1
X.XX ± 0.02
X.XXX± 0.004
ANGLE ± 0.25°
1.50
.75
2.00
3.63
6.63
.88
.38
.250
.583
3.17
.88
.25 slot (4 places)



Three-Dimensional Printing
Stepper Motor Mounting Bracket
Benjamin Heywood
5/7/91
DIMENSIONS: Inch (")
SCALE: 1:2
MATERIAL: Aluminum
QUANTITY: 2
TOLERANCES
X.X ± 0.1
X.XX ± 0.02
X.XXX± 0.0004
ANGLE ± 0.25°
.250
.500
2.25
6.63
.63
.500
.625
2.00
.25 slot (2 places)

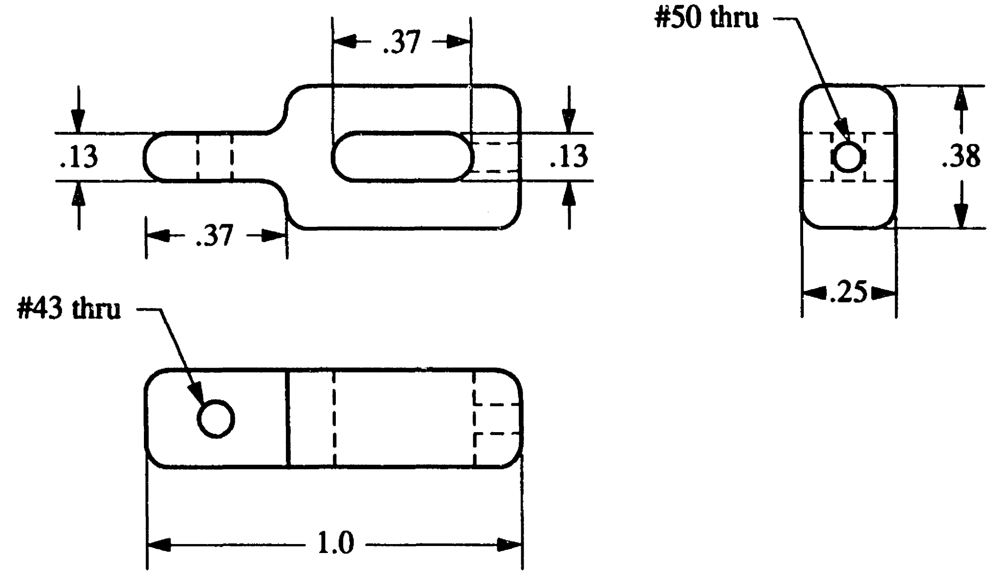


Three-Dimensional Printing

Stepper Motor Mounting Plate

Benjamin Heywood 5/7/91

DIMENSIONS:	Inch (")	TOLERANCES
SCALE:	1:1	X.X ± 0.1
MATERIAL:	Aluminum	X.XX ± 0.02
QUANTITY:	1	X.XXX± 0.004
		ANGLE ± 0.25°

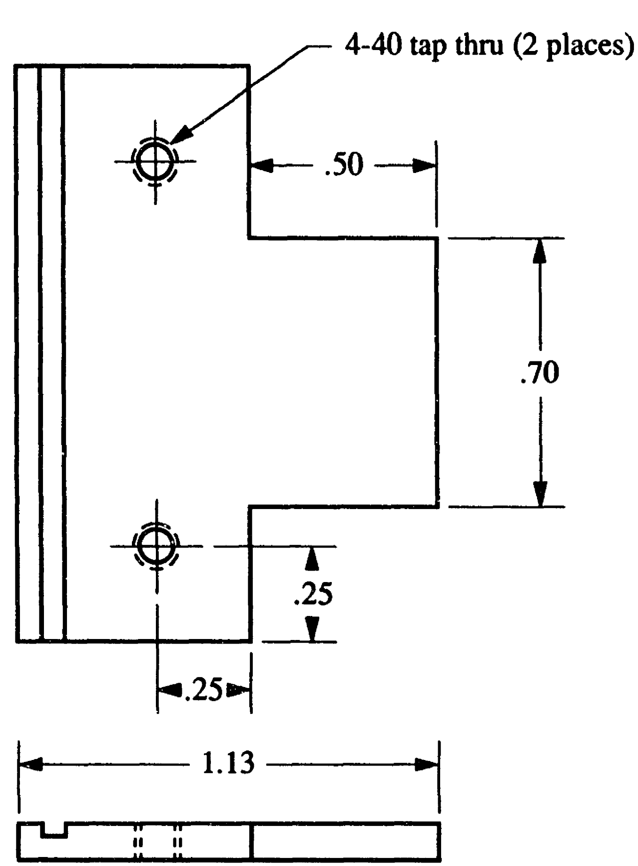


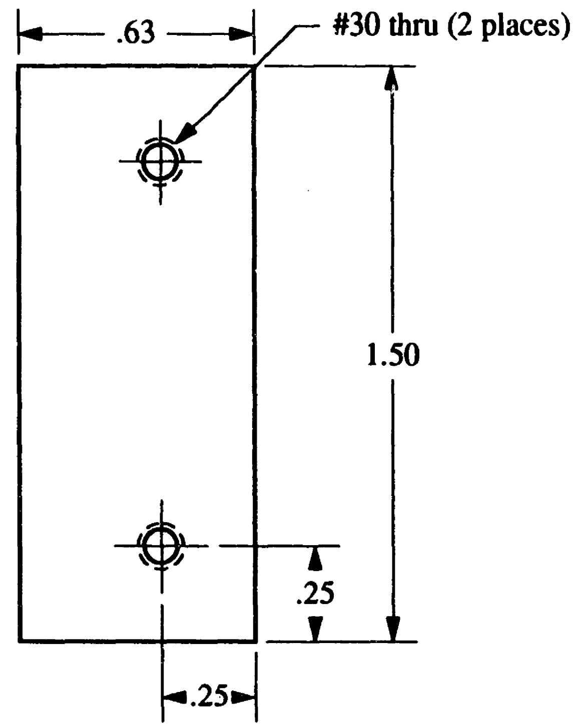
Three-Dimensional Printing

Cable Spring Adaptor

Benjamin Heywood 5/7/91

DIMENSIONS:	Inch (")	TOLERANCES
SCALE:	2:1	X.X ± 0.1
MATERIAL:	Aluminum	X.XX ± 0.02
QUANTITY:	1	X.XXX± 0.004
		ANGLE ± 0.25°



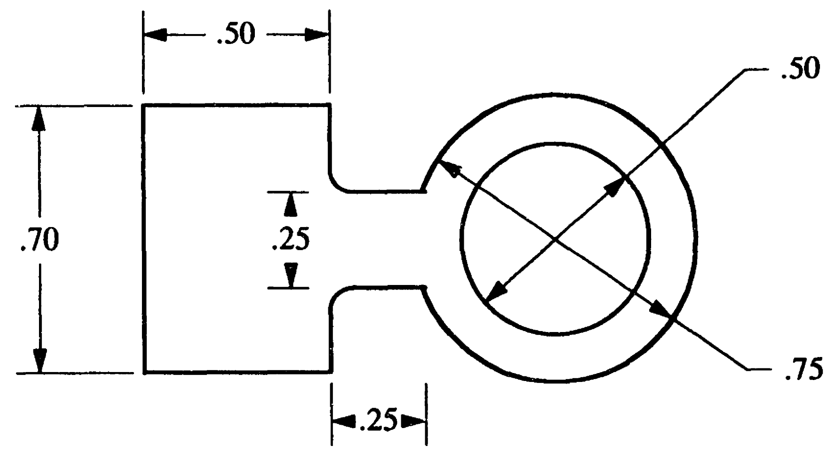


Three-Dimensional Printing

Cable Attaching Plates

Benjamin Heywood 5/7/91

DIMENSIONS:	Inch (")	TOLERANCES
SCALE:	2:1	X.X ± 0.1
MATERIAL:	3/32" thick aluminum	X.XX ± 0.02
QUANTITY:	1 of each	X.XXX± 0.004
		ANGLE ± 0.25°

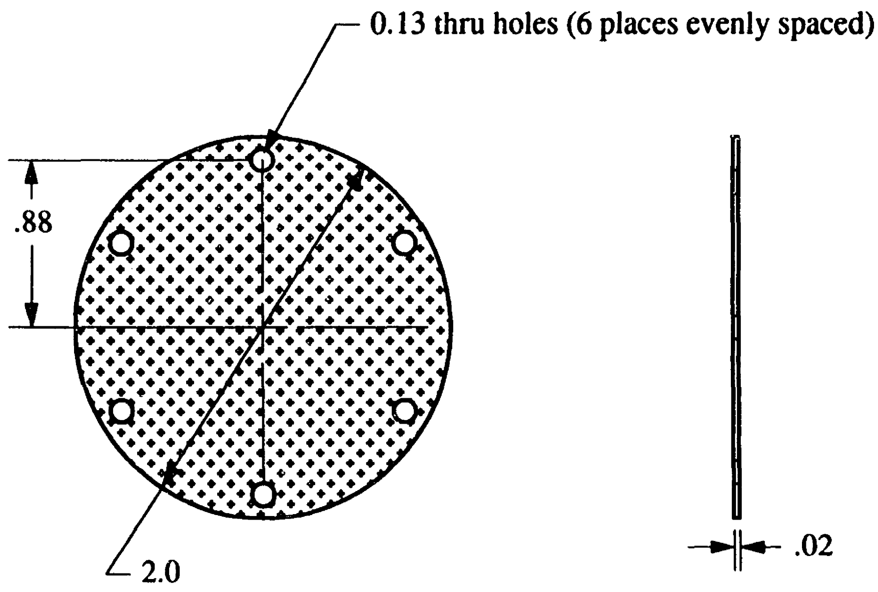


Three-Dimensional Printing

Rubber Coupling

Benjamin Heywood 5/7/91

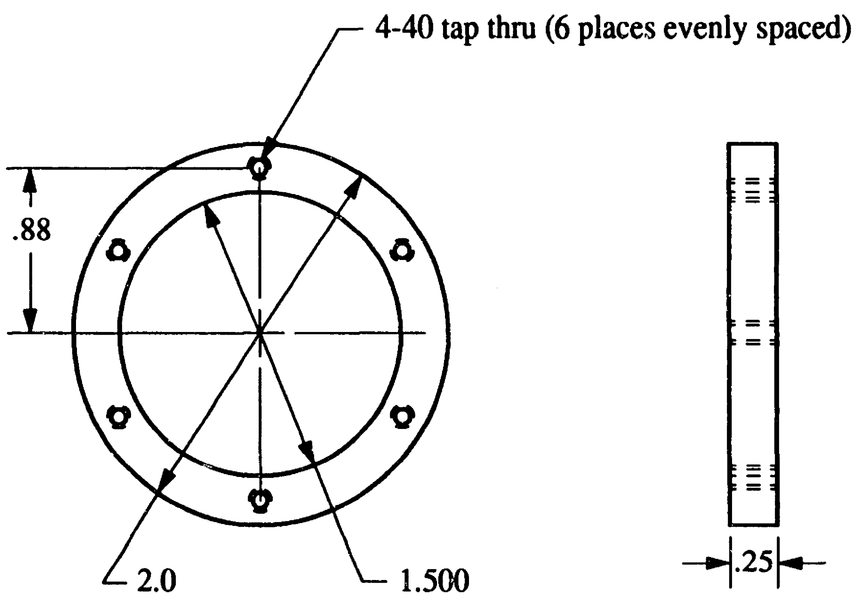
DIMENSIONS:	Inch (")	TOLERANCES
SCALE:	2:1	X.X ± 0.1
MATERIAL:	1/8" thick rubber	X.XX ± 0.02
QUANTITY:	1	X.XXX± 0.004
		ANGLE ± 0.25°



Three-Dimensional Printing

Grating

Benjamin Heywood		5/7/91
DIMENSIONS:	Inch (")	TOLERANCES
SCALE:	1:1	X.X ± 0.1
MATERIAL:	Stainless Steel Mesh	X.XX ± 0.02
	.045 Round Perforations	X.XXX± 0.004
QUANTITY:	1	ANGLE ± 0.25°

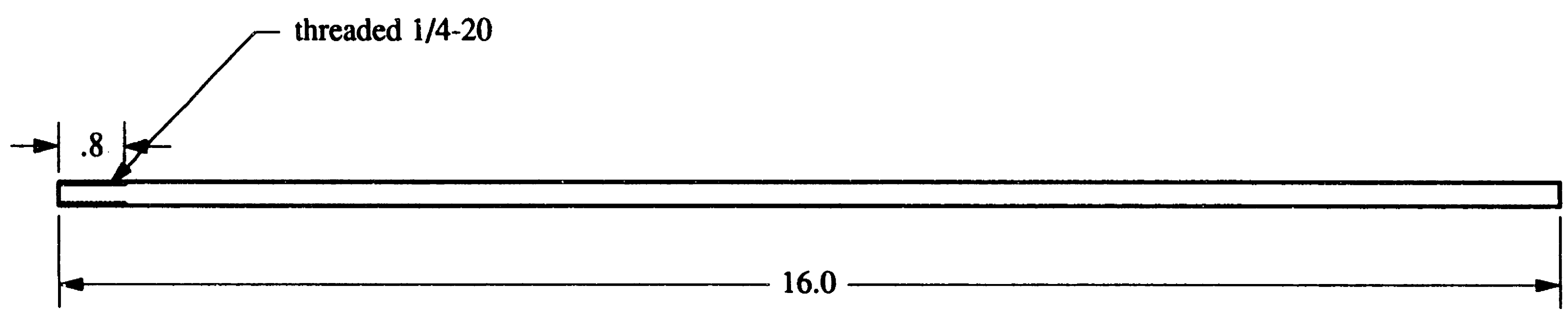


Three-Dimensional Printing

Sleeve Bearing

Benjamin Heywood 5/7/91

DIMENSIONS:	Inch (")	TOLERANCES
SCALE:	1:1	X.X ± 0.1
MATERIAL:	Ultra High Molecular Weight Plastic	X.XX ± 0.02
		X.XXX± 0.004
QUANTITY:	1	ANGLE ± 0.25°

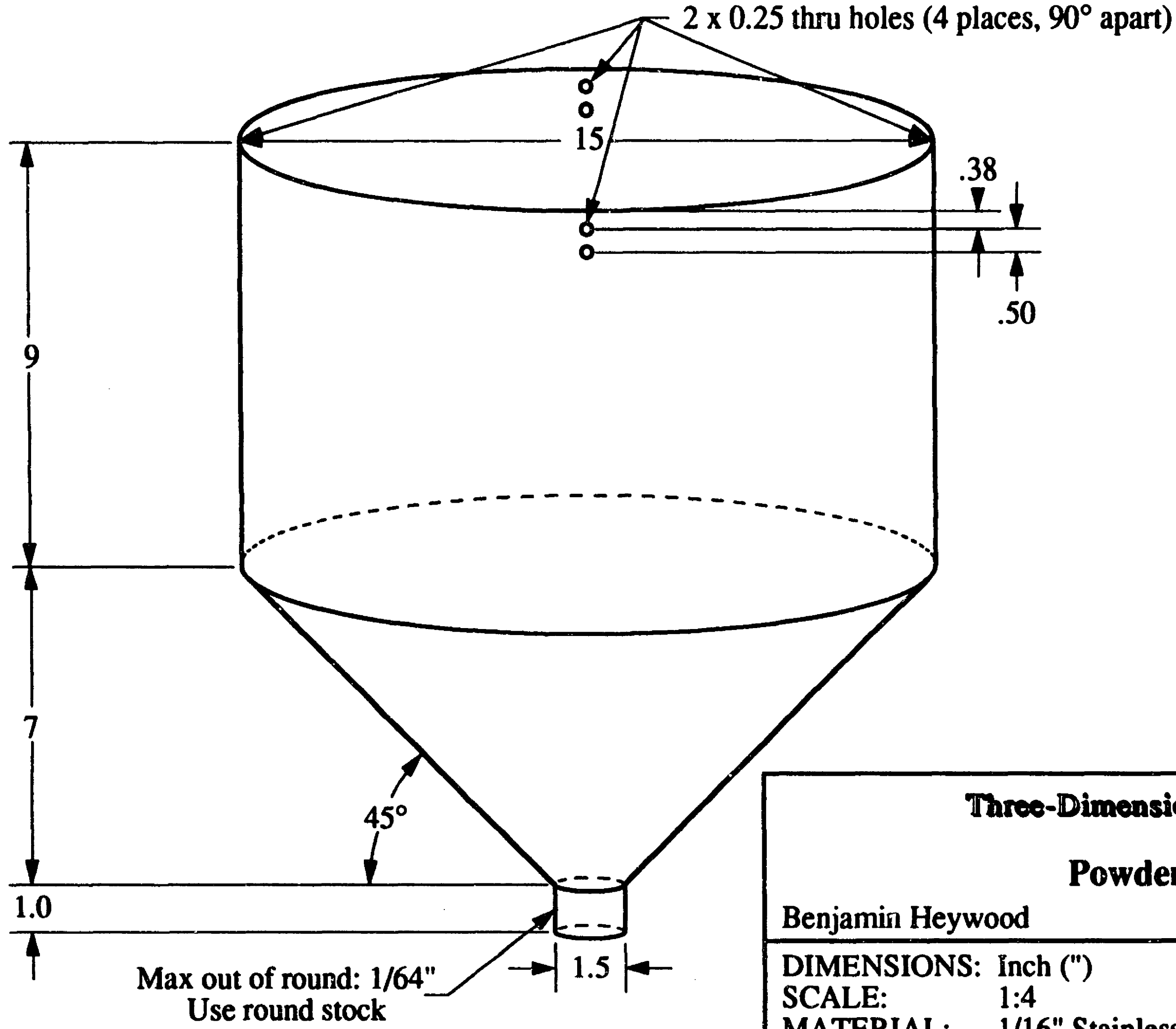


Three-Dimensional Printing

Shaft Extension

Benjamin Heywood 5/7/91

DIMENSIONS:	Inch (")	TOLERANCES
SCALE:	1:2	X.X ± 0.1
MATERIAL:	Case Hardened 1/4" Steel Rod	X.XX ± 0.02
		X.XXX± 0.004
QUANTITY:	1	ANGLE ± 0.25°



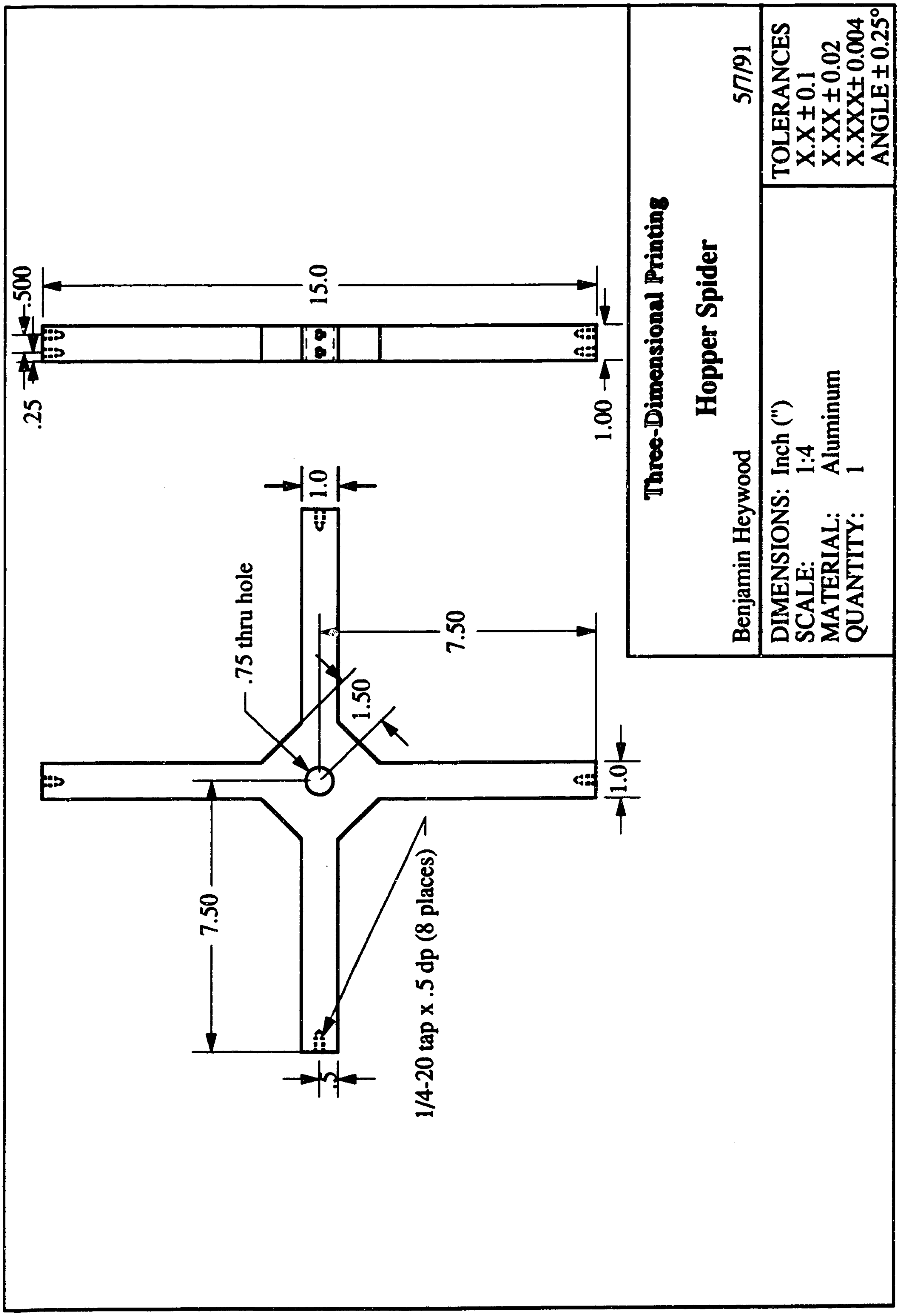
Three-Dimensional Printing

Powder Hopper

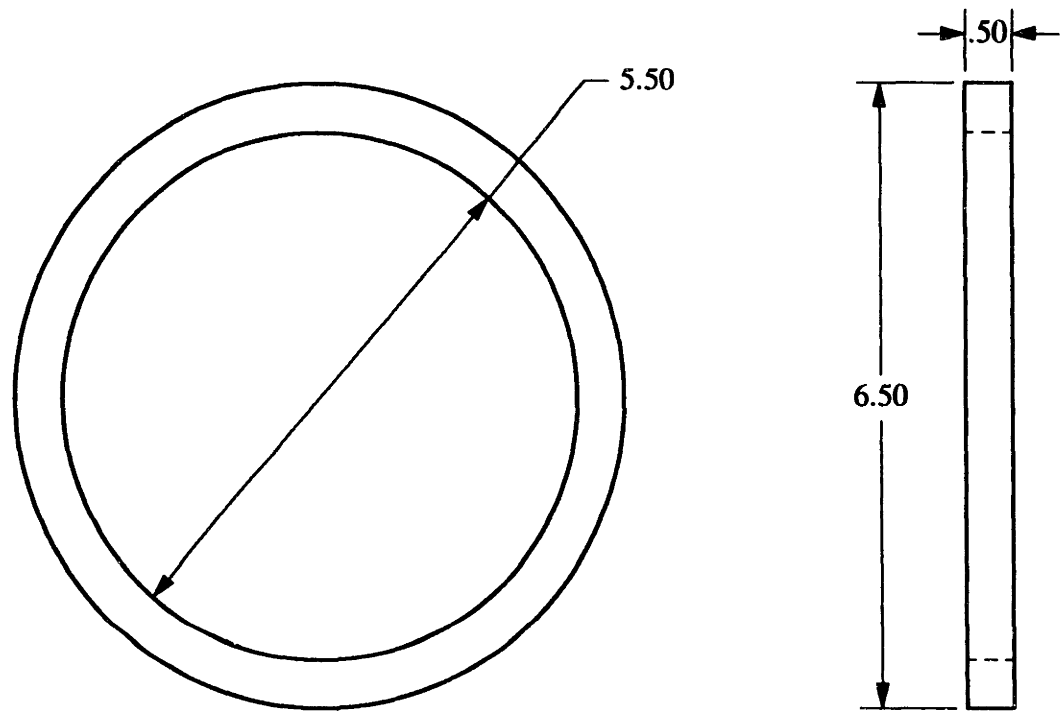
Benjamin Heywood 5/7/91

DIMENSIONS: Inch (")
SCALE: 1:4
MATERIAL: 1/16" Stainless Steel
QUANTITY: 1

TOLERANCES
X.X ± 0.1
X.XX ± 0.02
X.XXX± 0.004
ANGLE ± 0.25°



.500
15.0
.25
1.00
.75 thru hole
1.0
7.50
1.50
1.0
7.50
.5
1/4-20 tap x .5 dp (8 places)
Three-Dimensional Printing
Hopper Spider
Benjamin Heywood
5/7/91
DIMENSIONS: Inch (")
SCALE: 1:4
MATERIAL: Aluminum
QUANTITY: 1
TOLERANCES
X.X ± 0.1
X.XX ± 0.02
X.XXX± 0.004
ANGLE ± 0.25°



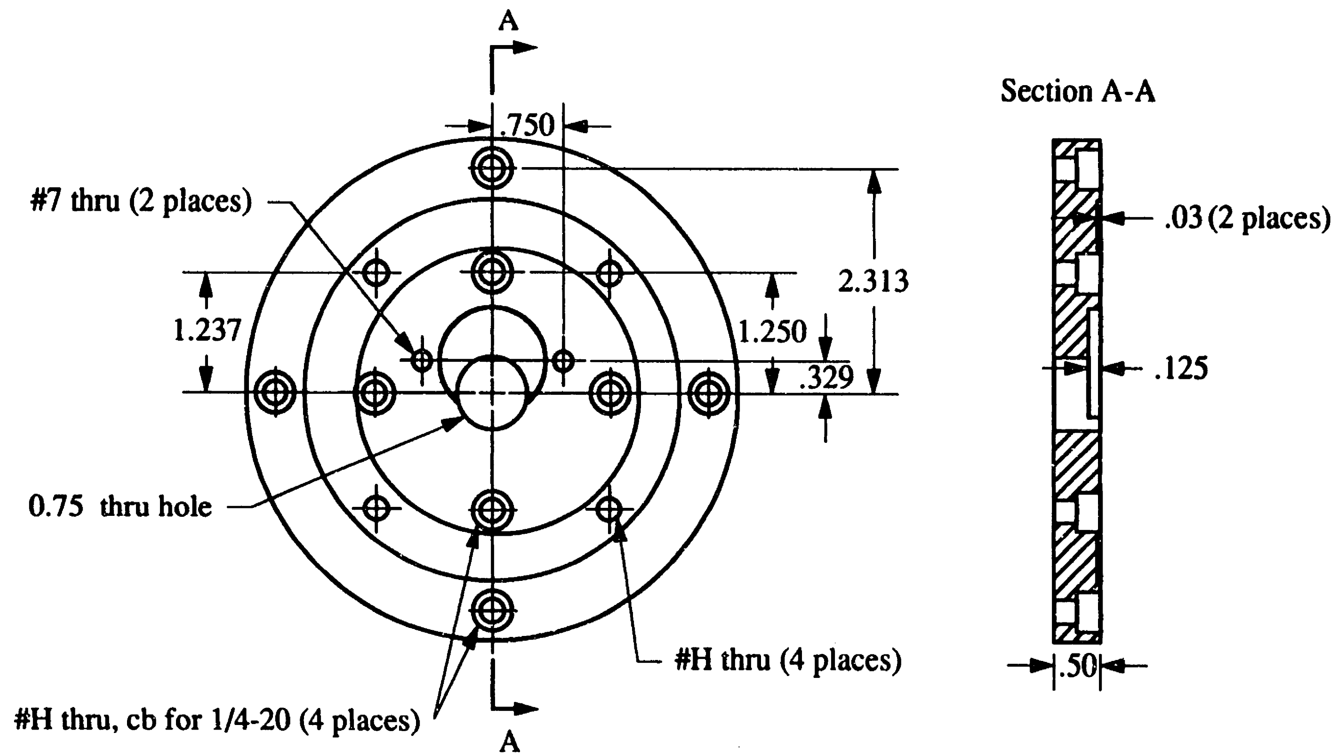
Three-Dimensional Printing

Limit Switch Plate

Benjamin Heywood 5/7/91

DIMENSIONS: Inch (")
SCALE: 1:2
MATERIAL: Plexiglass
QUANTITY: 1

TOLERANCES
X.X ± 0.1
X.XX ± 0.02
X.XXX± 0.004
ANGLE ± 0.25°

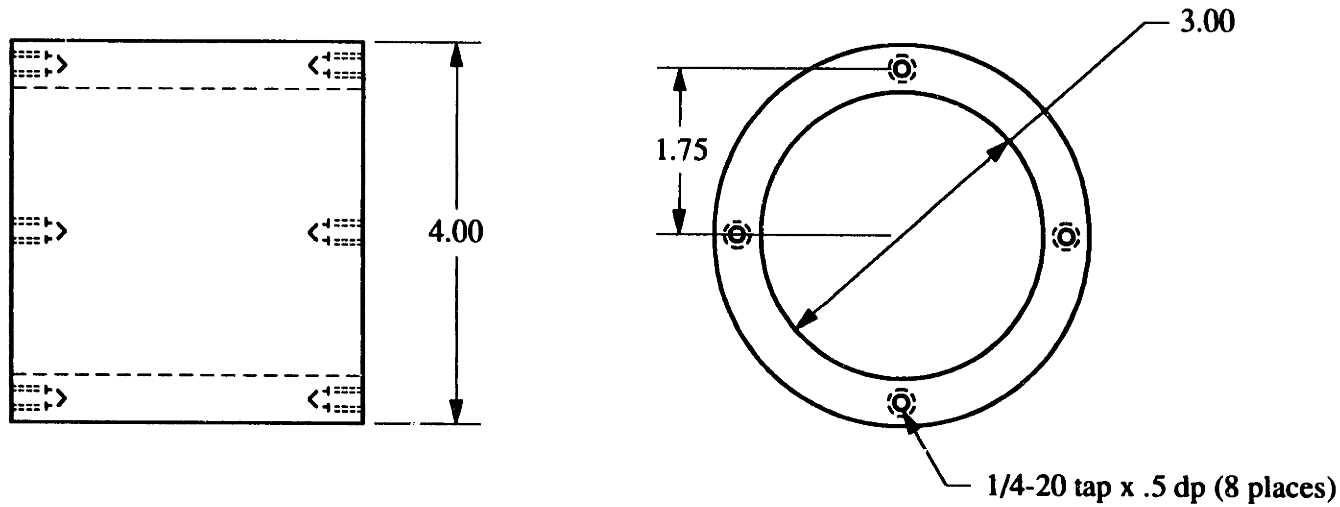


Three-Dimensional Printing

Motor Mounting Plate

Benjamin Heywood 5/7/91

DIMENSIONS: Inch (") SCALE: 1:2 MATERIAL: Aluminum QUANTITY: 1	TOLERANCES X.X ± 0.1 X.XX ± 0.02 X.XXX± 0.004 ANGLE ± 0.25°

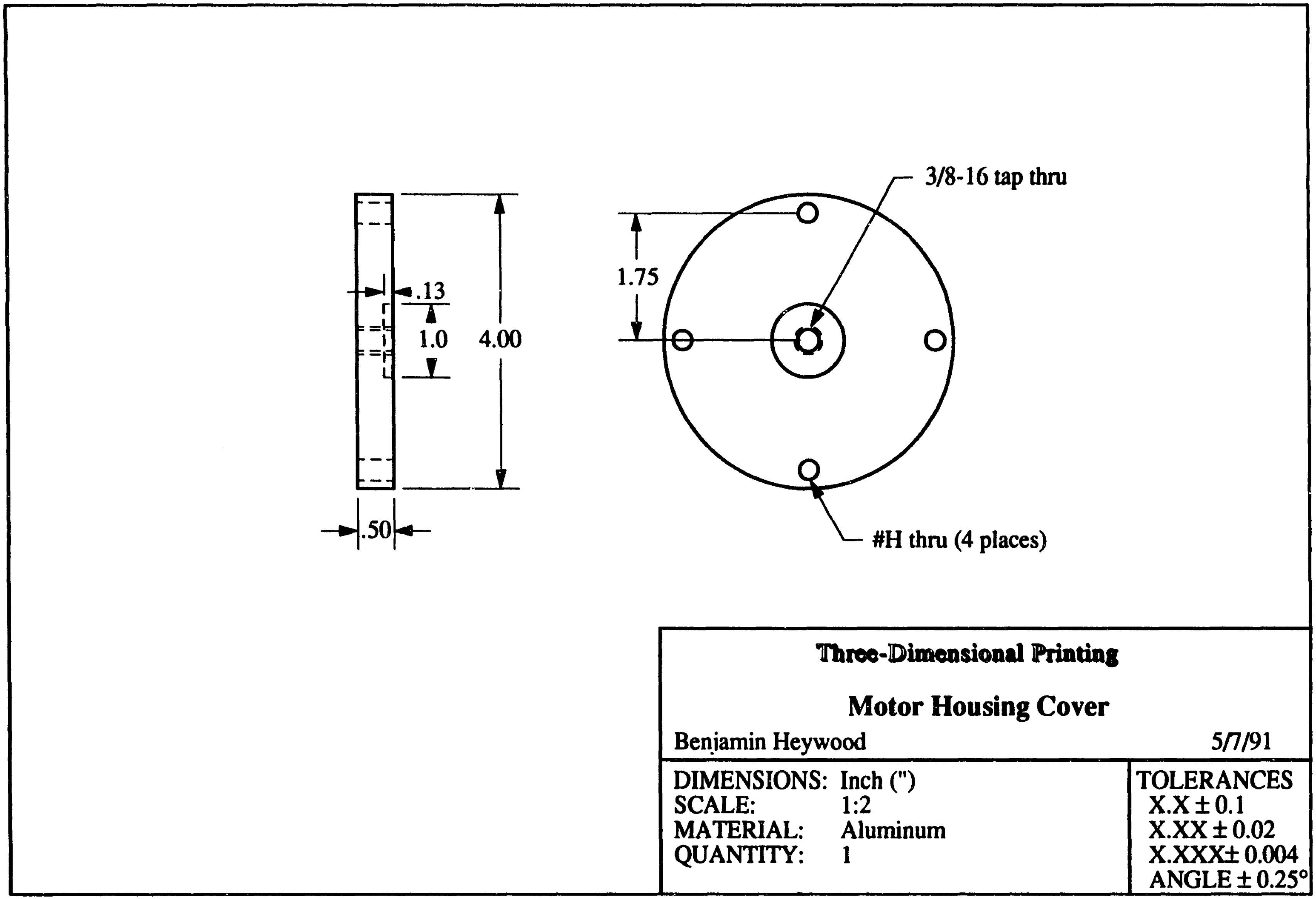


Three-Dimensional Printing

Motor Housing

Benjamin Heywood 5/7/91

DIMENSIONS:	Inch (")	TOLERANCES
SCALE:	1:2	X.X ± 0.1
MATERIAL:	Aluminum	X.XX ± 0.02
QUANTITY:	1	X.XXX± 0.004
		ANGLE ± 0.25°


3/8-16 tap thru
.13
1.0
4.00
1.75
.50
#H thru (4 places)
Three-Dimensional Printing
Motor Housing Cover
Benjamin Heywood
5/7/91
DIMENSIONS: Inch (")
SCALE: 1:2
MATERIAL: Aluminum
QUANTITY: 1
TOLERANCES
X.X ± 0.1
X.XX ± 0.02
X.XXX± 0.004
ANGLE ± 0.25°

THESIS PROCESSING SLIP

FIXED FIELD: ill. ______ name ______

index ______ biblio ______

► COPIES: (Archives) Aero Dewey Eng Hum

Lindgren Music Rotch Science

TITLE VARIES: ►☐ ______

NAME VARIES: ►☑ see deg reg book

IMPRINT: (COPYRIGHT) ______

►COLLATION: 41 l

►ADD. DEGREE: ______ ► DEPT.: ______

SUPERVISORS: ______

NOTES:

cat'r: date:

page: ► J29

►DEPT: M.E.

►YEAR: 1993 ►DEGREE: B.S.

►NAME: HEYWOOD, Benjamin