

Mechanical Design of a Contra-Rotating Propeller Assembly for a Small Underwater ROV

by

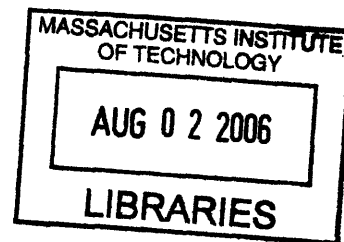
Thaddeus Stefanov-Wagner

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Signature of Author: _____ *[Handwritten Signature]* — 5/12/2006
Department of Mechanical Engineering
Date

Certified by: _____ *[Handwritten Signature]*
Franz Hover
Principal Research Engineer
Thesis Supervisor

Accepted by: _____ *[Handwritten Signature]*
John H. Lienhard V
Professor of Mechanical Engineering
Chairman, Undergraduate Thesis Committee

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MECHANICAL DESIGN OF A CONTRA-ROTATING
PROPELLER ASSEMBLY FOR A SMALL
UNDERWATER ROV

by

THADDEUS STEFANOV-WAGNER

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ABSTRACT

A project was undertaken to design and build a contra-rotating propeller assembly for a small underwater remotely operated vehicle (ROV), with the intent of commissioning a production run at a later time. The desired production rate was greater than one assembly per seven hour day with one machinist, at a material cost of less than \$600 per assembly. Lastly, the design had to be compatible with the propeller design work being done concurrently by J. Stanway.

The specified goals were met. The material cost of each assembly was \$496.02 at the time of manufacture. In the production run, the incremental time for making each assembly was under 5 hours, giving a large margin for overhead and work interruptions.

Thesis Supervisor: Franz Hover

Title: Principal Research Engineer

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1. Introduction

There is a rapidly expanding market for small underwater vehicles, both autonomous and remotely controlled. Used as equipment platforms, these vehicles have military, commercial and research uses. Military applications include mine detection and shallow-water surveys.¹ Commercial applications include oil prospecting and ship hull inspection.^{2,3} Research applications include archeology and gathering benthic contours.^{4,5} Despite the variety of uses these vehicles are applied to, one significant design constraint is the need to conserve power.

While some vehicles can run using shore based power transmitted through a tether, this creates a significant range constraint and also limits their utility in confined spaces or near snag hazards. Additionally, the cable adds a significant drag component to the vehicle movement. For these reasons, the preference is to use a sacrificial fiber optic line for data transmission and to rely on onboard power. However, this just removes one limit on performance. Relying on onboard power creates a significant range or endurance limit and reduces the maximum potential utilization of the vehicle. This limit can be breached through research into energy storage methods or by increasing the efficiency of the onboard systems.

For most vehicles, the primary power consumer is the propulsion system. Advances in CFD and fabrication have increased the efficiency of the single propeller significantly. However, further increases in efficiency can sometimes be obtained from having two propellers in a contra-rotating configuration. However, there is a significant complexity and cost increase that this increase in efficiency must be balanced against.

This configuration has several advantages over a conventional propeller. The most significant is the approximately 10-15% gain in efficiency.⁶ Another significant advantage of a

counter-rotating propeller design can be that there is no net torque applied to the vessel being propelled if designed properly. Depending on the vehicle configuration, this can be a critical advantage over a single propeller thruster. However, there are significant disadvantages as well. The additional gearing required to generate the contra-rotating motion adds more mechanical loss to the system, as well as another point of failure.

The goal of this project is to design a novel small counter-rotating thruster for use on small underwater remotely operated vehicles or autonomous vehicles. Due to the complexity of this work, the project was split into two parts. This paper will deal with the mechanical design and fabrication of the duct, motor housing and counter-rotating action. The primary focus will therefore be on machinability and robustness of design, versus hydrodynamics and computational fluid dynamics.

2. Objectives

The primary goal of this project was to design and build all but the propellers for a contra-rotating thruster assembly. The propellers would be designed and manufactured by another student, J. Stanway, and then combined with this work. Once proven, the thruster would then be placed in production for use by the MIT ROV team on their remotely operated vehicle. The team would then compete in late June in the MATE national ROV competition. This tie-in to the MIT ROV team gave the project its initial direction and basic specifications, as well as a target to design towards.

Designing for the ROV team also gave two additional quantifiable goals apart from basic functionality. Due to the limited funding available to the team, the total parts cost had to be under \$600.00 per thruster. Additionally, due to the tight schedule between finals and the

competition, it would be desirable for the manufacturing work to be completed by one person working in the MIT Edgerton Center Student Shop for less than a week. Since the Edgerton Center Student shop would be open only for a guaranteed seven hours each day, this provided a hard constraint on the total machining time.

a. Engineering Constraints

Since the thruster inherently operates in water, various components had to be sealed and corrosion resistance was a critical factor in material choice. The second major constraint was that the motor housing and associated structures had to be hydrodynamically compatible with the propellers and associated fluid flows. The third constraint was that the system needed to be robust enough to withstand rough handling and the expected wear and tear associated with operations in an underwater environment. The fourth and final constraint was that machining should be automated and simple as possible. This meant reducing parts count as much as possible, and minimizing the number of custom machined parts.

3. Design

The entire design process was carried out on computer using Solidworks™, a three dimensional computer aided design program. The use of CAD proved to be an asset in several ways. It allowed for quick modeling and verification of ideas, as well as ensuring compatibility between all parts throughout the design process. It allowed verification that the propellers being designed for the project would indeed integrate successfully to the current design. Additionally, the use of Solidworks allowed the MIT ROV team to use the model of the thruster into their own CAD models, ensuring that the mounts were in the right place and that there would be no

interference between the thrusters and other components. Drawings for all components developed are included in Appendix A.

A. Motor Housing

i. Basic Objective

To meet the primary objectives, the motor housing had to be made out of non-corrosive materials and completely seal the motor while allowing a shaft to pass through.

Additionally, the motor housing had to be able to conduct heat from the motor to the surrounding water.

Lastly, the motor housing had to be able to maintain this seal at a water depth of at least 40 feet.

ii. Design

The final design is based around an aluminum body with Acetal Copolymer end caps (figure 1). Aluminum was chosen for its strength, light weight, and high thermal conductivity. Acetal Copolymer is roughly similar to Delrin, and is a high strength easy to machine rigid

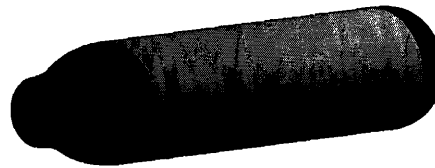


Figure 1: CAD model of motor housing, showing aluminum tube and plastic endcaps

plastic. The forward endcap contains the spring loaded PTFE spring seal and is faired between the motor diameter and the propeller hub diameter. The aft endcap has a passthrough for the motor electric power.

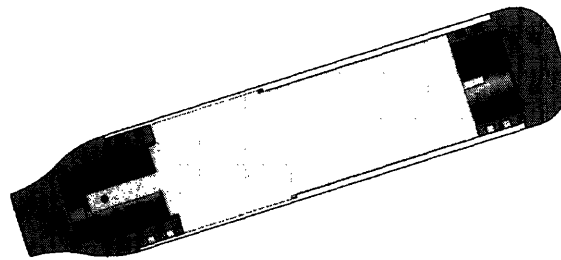


Figure 2: CAD model showing how the aluminum tube follows the motor contours. This also shows how the motor is constrained within the housing.

The aluminum tube which encloses the motor was bored out to match the contour of the motor and its attached gearbox (figure 2). This served multiple purposes. It ensured that the motor was constrained and would not move around. It reduced the air gap between the aluminum and the motor to the minimum possible amount, ensuring maximum thermal conductivity between the motor and the outside water. This was critical as the motor is being run at close to its maximum thermally sustainable power output. The motor specs are for 150w continuous when aircooled. If more cooling is provided, the motor can be run at higher power levels. Since the water surrounding the motor is an effective heat sink, by efficiently coupling the waste heat from the motor to the water the motor will run cooler and allow for potentially higher power outputs.

The endcaps are designed to be watertight and held on by water pressure and the static friction of the o-rings. Each end cap has two eighth inch o-ring grooves, both for redundancy and also to ensure that the endcaps do not loosen during normal use. The aft endcap contains the spring loaded PTFE, also known as Teflon(TM), shaft seal. This shaft seal acts like a traditional

o-ring, however with very low coefficient of friction. This is critical for the high speed propeller shaft to reduce losses and ensure high mechanical efficiency. The spring acts to ensure that the PTFE surface is always pressed against the shaft and to allow for some variation in the shaft surface. The forward end cap contains a waterproof Impulse™ connector to provide power to the motor.

The motor itself is fully constrained by the enclosure. As mentioned before, the aluminum enclosure conforms to the surface contour of the motor and gearbox assembly. This constrains the motor from moving forwards, towards the wire leads. The aft endcap is flush with the gearbox head, preventing the motor from moving forwards. Additionally, the motor is keyed to the aft endcap by a setscrew in the head of the gearbox which engages with a slot in the aft endcap. This fully constrains the motor within its housing.

B. Gearbox

i. Basic Objectives

The primary goal of the gearbox is to provide the contra-rotating action required for the propellers. It has to fit within the size constraints dictated by hydrodynamics and the design of the other components. It has to function at a high efficiency so as to not negate the increased efficiency from the contra-rotating propellers. Lastly, the gearbox has to be reliable enough to withstand high torque loading from rapid maneuvering.

ii. First Iteration

The initial layout for the system had the motor mounted perpendicular to the propeller axis. Power would be delivered from a bevel gear to the rims of the propellers (figure 3). This had the advantage of acting as a significant reduction stage, matching the motor's optimal rotational velocity with the propellers optimal rotational velocity. However, this configuration was abandoned early

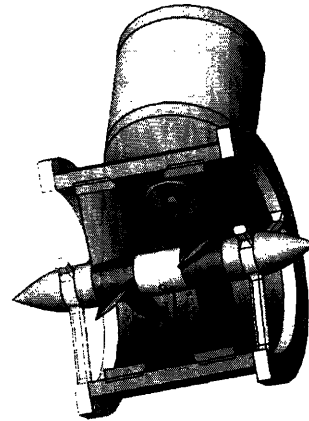


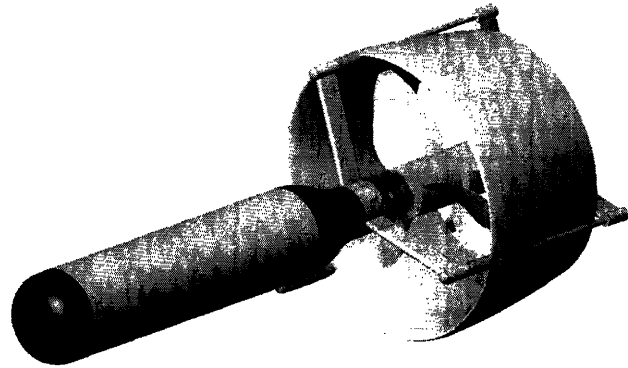
Figure 3: Early cad model showing bevel gear driving propeller rims.

on, due to an inability to find appropriately sized bevel gears from a commercial supplier. Additionally, concerns were raised about the losses from a high speed gear meshing in water. Since the power to the propellers was being delivered from the rims, the tangential velocity of the gear mating was very high, raising the losses. Lastly, the configuration would have been difficult to integrate into the final MIT ROV team vehicle, so it was abandoned in favor of a coaxial arrangement.

iii. Second Iteration

The second iteration moved the motor from the side of the propeller duct to the front of the duct. This move was made possible by the change to a motor with an integrated gearbox which would output the optimal RPM without needing additional reduction stages. This had several advantages. By switching from a rim drive to a center drive system, the rotational

velocity of the gears was significantly reduced, reducing the mechanical losses from the gearbox. The gearbox would then reside between the two propellers, and provide the reversal between the two propeller shafts. However, this design was not feasible for hydrodynamic reasons. The gearbox and shaft ends would need to be supported, and placing obstructions in the flow between the two propellers would have significantly reduced the efficiency of the propeller system.



iv. Final Iteration

The final iteration moved the gearbox from between the

Figure 4: Final CAD model with gearbox location highlighted

propellers to the front of the propeller assembly (figure 4). It also changed the shaft arrangement so that there was one common shaft running the length of the propellers, with the forward, reversed propeller running on Rulon™ bearings while the shaft turned the other way. A common stainless steel shaft ran the length of the assembly, from the motor to the aft support, reducing the part count and increasing the rigidity of propeller mounting.

The primary difficulty in designing the gearbox was ensuring that it would fit within the specified volume. Due to its placement, the gearbox had to match the hub diameter of the propellers. That provided a volume constraint that was initially very difficult to work in. The final design is a one inch cylinder of Acetal Copolymer that is seven tenths of an inch long



Figure 5: CAD model of final gearbox, showing gears meshed and dowel pins that hold the two perpendicular gears.

(figure 5). It uses nylon miter gears with a pitch diameter of half an inch. The power shaft passes through the gearbox and the pickup gear is set screwed to a flat on the shaft. Two gears are arranged symmetrically around the pickup gear and run on three sixteenth inch stainless steel dowel pins. The nylon-stainless steel interface has very little friction, eliminating the need for separate bearing surfaces for these gears. The dowel pins are made from 316 stainless steel for maximum corrosion resistance, since any corrosion on the dowel pins would result in significant losses. These gears then engage with a matching gear in the propeller hub, driving that propeller in the opposite direction from the power shaft.

C. Shroud

i. Basic Objectives

The shroud guides and funnels the flow of water through the two propellers and acts to increase the system efficiency.⁷ The shroud also prevents objects coming into contact with the

propeller blades. This protects the blades from damage and protects the users from inadvertent contact and injury.

ii. Final Design

The shroud design was dictated completely by hydrodynamic optimization, and therefore was not a significant concern during mechanical design. The final design was a rotated foil shape.

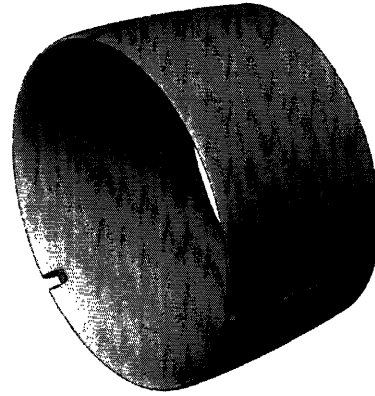


Figure 6: Final CAD model of shroud. The linear feature on the side of the shroud is a clearance hole for a mounting rod. The matching notches are where the shroud seats into its supports.

Once the shroud profile had been designed transferred to Solidworks, it was modified with additional features required to mount the shroud (figure 6). The shroud is mounted by two sets of struts, one at the front of the shroud that connects to the motor housing and one at the back which supports the shaft. Threaded stainless steel rods run between the two sets of struts, through holes in the shroud. Additionally flats were placed around each hole to allow the use of standoffs so that the shroud could be moved relative to the motor housing. Once these modifications had been verified with J. Stanway as having only minor effects on his propeller model, the shroud design was complete.

D. Shroud Supports

i. Initial Design

The initial shroud support design called for a three leg design with a hub and rim. It would be made out of half inch thick Polycarbonate. The legs would be an eighth of an inch thick with rounded edges to reduce hydrodynamic drag (figure

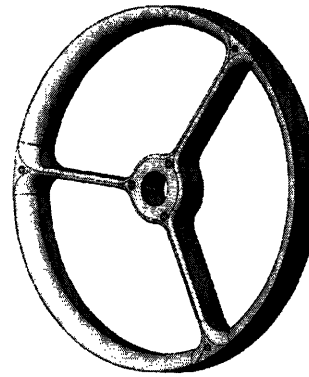


Figure 7: Initial shroud support design, showing rim, hub, and thin struts.

7). Other leg profiles, such as a standard NACA foil would be more hydrodynamic, but the large increase in machining complexity would not justify the slight decrease in drag.

Polycarbonate was chosen for its high strength and low weight.

ii. Final Design

The hub and rim design was abandoned when the final shroud

profile was developed. The machining required to make the rim match the required profile would have been complex and time consuming. As a result, the rim was discarded and the

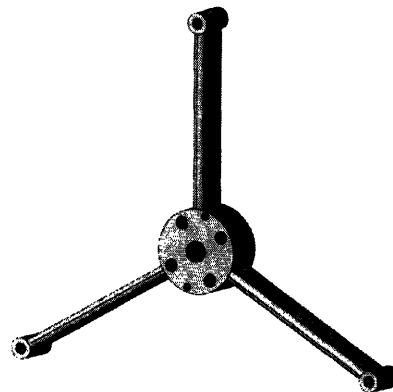


Figure 8: Final shroud support design. The four large holes in the hub are for mounting the support to the back of the motor case, and the two smaller holes are for mounting the gearbox to the support. The three holes at the end of the arms fit into the rods that pass through the three matching holes in the shroud (figure 6)

support reduced to a hub with eighth inch thick spokes which terminate in screw clearance holes. The shroud is then positioned using unthreaded spacers which fit over the threaded rod and sit between the shroud and the support.

4. Fabrication

One of the key goals of this work was to automate as much of the fabrication process as possible. This turned out to be convenient, because from the beginning parts could be designed with features that only a computer controlled machine could create. This project had access to two computer controlled machines, a HASS TL-1

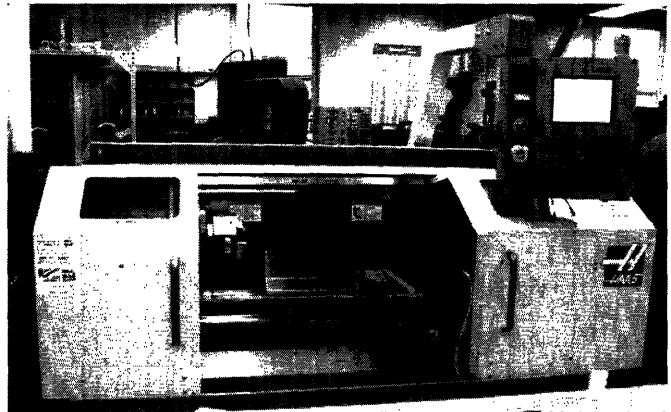


Figure 9: HASS TL-1 CNC lathe. Normally during operation the doors are closed. Visible in this picture is the boring tool used for cutting the inner profile of the shroud.

computer controlled lathe (figure 9) and a Bridgeport EZ-Trak hybrid manual and

three axis computer controlled milling machine (figure 10). These machines were programmed using a combination of the built in programming interface and Mastercam. Both machines allowed for a high level of control from their operator interface panel. The built-in interface on the Bridgeport EZ-Trak was used for the simpler operations, such as simple hole patterns and

simple shapes. However this interface was not sufficient for more complex work, such as the shroud or the shroud supports. Mastercam was used to convert Solidworks models into control code for the machine tools for the more complex operations. Additionally, a Monarch manual lathe was also used for hand controlled lathe work and some preparatory work for parts (figure 11).

The one key limitation in the production facility was that the tooling was not indexed. As a result, tool changes and recalibrating the machines to find the tool coordinates added a significant premium to the machine time as well as reduced the utility of having fully computer controlled machines. The optimal solution in this case would be to have automated tool switching on both lathe and mill. However significant time could be saved with quick change tooling that would not need to be rezeroed each time.

A. Motor housing

Motor housing machining was simple and straightforward. Since aluminum tubing was



Figure 10: Bridgeport Ez-Trak CNC milling machine. This was the machine that the majority of the machining time was spent on.



Figure 11: Monarch hand lathe with electronic readout. This machine was mostly used for stock preparation and machining the motor casing.

available in close to the appropriate size, only a few passes with a boring bar tool were required to complete the part. The primary challenge this part posed were ensuring that concentricity was maintained through the entire tube. This was accomplished by completing all internal features without moving the piece in the lathe chuck. After the boring operation had been completed, the edges were deburred and rounded, and the outside surface was sanded with a fine grit sandpaper to remove factory markings and clean up the surface. While this step was not needed for function, it was done for aesthetic reasons.

B. End Caps

Due to the high number of tool changes required for the aft end cap, most of the machining was done on the manual lathe. The initial steps were to turn down the part that would fit into the tube and to create the O-ring grooves. Afterwards, the interior was drilled out to provide clearance for the motor shaft and coupling. Next, the end cap was switched rotated in the lathe to provide access to the back face. At this point, the lathe chuck gripped the turned face with the O-ring grooves, instead of the unfinished outer surface. At this point, the clearance hole for the shaft was drilled through, and the groove for the shaft seal was cut. The operations were done in this order to ensure that the hole for the shaft was centered exactly within the shaft seal groove, but still as close as possible to the centerline of the endcap and by extension the motor housing. The next step was to add the four mounting holes that connect the endcap to the shroud support and gearbox. This was done on the Bridgeport EZ-Trak using the bolt circle command. The final step was to fair the endcap from the motor housing diameter to the hub diameter. This was done in the HASS CNC lathe to obtain a smooth curve between the two diameters. The

fairing profile was first generated in Solidworks, then exported to Mastercam. Mastercam then generated the tooling paths and exported the paths in machine-ready G code.

C. Shroud

The complexity of the shroud profile required that the final machining be done on the HASS CNC lathe, even if automation were not a priority. Additional challenges were posed by the material used and the difficulty in holding the shroud for machining. As a result, the shroud was the most complex and difficult piece to machine.

The shroud has two sets of features. The first is the contour which defines its basic shape. The second feature is the three through holes that are used for mounting and the flats on the leading edge of the shroud that the standoffs fit into. Since it would be near impossible to hold the shroud for machining after the contour had been cut, the through holes and flats were added first. To ensure that the two different sets of features lined up correctly, the blank was first placed on the manual lathe to have a center hole drilled. The blank was then transferred to the Bridgeport EZ-Trak CNC milling machine and a feeler used to align the machine to the center of the blank. The clearance holes were then drilled, following by the flats. Due to length and clearance issues, the holes drilled by the milling machine did not go the full required depth. To reach the full depth, the blank was then taken off the mill and transferred to a drill press which had the required clearance to use a longer drill bit. Since the holes had already been started, no precision was required to finish the holes.

Once the holes and flats had been completed, the part was returned to the manual lathe. At this point, the blank was drilled through with a large bore drill. A boring bar was then used to

open the hole up further to a four inch diameter, while leaving a one inch lip on the back of the blank. This lip was left so that the blank would be more rigid where the lathe chuck gripped it. This boring was done manually since the

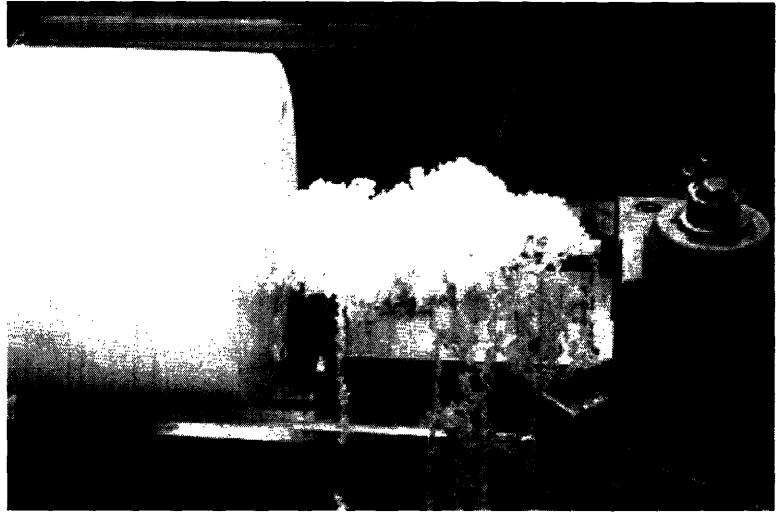


Figure 12: Boring bar with buildup of HDPE plastic. This shows how the removed material formed long strings and did not exit the bored hole. This buildup occurred in approximately a third of a full pass down the center of the part. Any further buildup would have risked pushing the part out of the lathe chuck.

polyethylene used for the shroud did not chip. Instead, when cut it came off in a long string that did not break. Instead, the process had

to be halted occasionally to remove the built up material before it began to push on the boring bar or stock (figure 12). If the material was not removed, there was the potential to either push the boring bar out of line or to eject the piece from the lathe chuck. Either situation could potentially result human injury and or loss of the part being machined. Once the inner diameter reached four inches, the internal space was sufficient for the cut material to build up without interfering with a full depth cut. However, the material still needed to be cleared after every cut.

At this point, the blank was transferred to the CNC lathe. The boring operation was done first so that the blank was more rigid in case the removed material began to build up again and press against the blank. After each pass of the boring bar, the machine was halted and the waste cleared before the lathe was started again. Once the internal boring operations where complete, the tool was switched out for the turning tool. Since this tool discharged the removed material

on the outside of the part, the risks were different but still present. Without intervention, the built up waste would become wrapped around the blank and the chuck, creating in effect a flail which made it dangerous to approach the machine. This had the potential to get caught on the tool and pull the blank towards the tool and out of the chuck. To prevent this from happening, a vacuum cleaner hose was placed near the tool so that the plastic coming off the tool would be sucked away and prevented from building up. This was an effective though noisy solution. Once the outer surface of the duct had been completed, a parting tool was installed and manually brought in to part the duct from the remains of the blank.

Once the duct had been cut free, all that remained were finishing operations. The parted end of the duct was cleaned up with a sharp razor blade to remove the last thin layer of plastic the parting tool was unable to cut before the part separated. The razor was then used to clean up the edges of the flats and the area where the clearance holes broke through to the surface of the duct. Since the final finishing pass was done at a very low feed rate, the surface finish was smooth enough that no other finishing was required.

D. Shroud Supports

Much like the shroud itself, the primary challenge with the shroud support was figuring out how to hold it during the machining process. The solution was to use the holes already designed into the shroud support

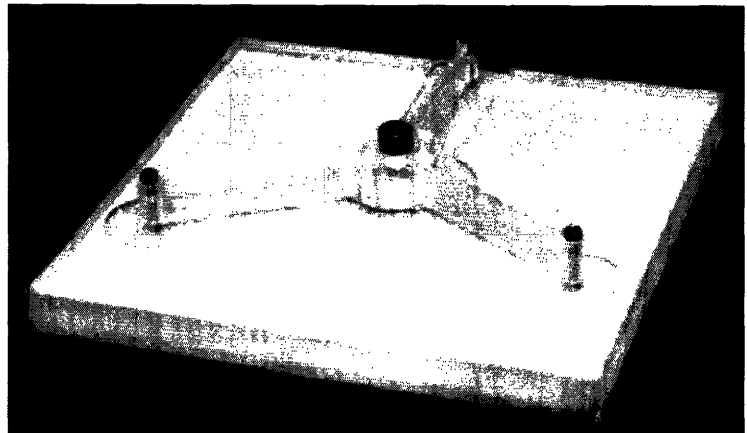


Figure 13: Backing plate shown after completing a production run. The last part completed is shown still held in the backing plate. Note that the part is completely constrained to the backing plate.

to hold the shroud to a backing plate (figure 13). The backing plate could then be clamped normally in a vice for machining. This solution solved two issues. First, it restrained the center of the support as well as the ends of the arms independent of any material other than the support itself. Secondly, since the backing plate remained clamped as parts were swapped in and out, each successive part was placed in exactly the same spot as the one before it. This way the lengthy realignment procedure was not needed for each successive part during the production run.

The first step in producing the shroud support was to cut approximately six inch square blanks from a piece of stock half inch Polycarbonate. These pieces were then placed in the mill vice and aligned by eye to the machine zero. For this stage, accuracy relative to the position of the holes on the plastic was not required so each successive blank was simply centered within the vice. Once the piece was clamped securely, a series of programs was run. The first program placed pilot holes at the positions of all the required holes. The next series of programs took different sized drill bits and made the various holes required in each size. Since a drill chuck was used, each time the bit was changed the machine had to be rezeroed to the length of the new drill bit. This recalibration added significantly to the time the drilling step took. Once all the programs had completed, the piece was removed and another inserted.

Once all the blanks had been drilled, the backing plate was placed in the mill and the mill carefully aligned to the center of the backing plate using a feeler. This alignment was critical because any errors would result in the holes not being lined up correctly with the eventual shape of the support. Once the alignment was complete, the appropriate end mill was swapped in and zeroed. The next program was then run, and cut out the basic shape of the support from its

blank. After removing the finished piece, the next drilled blank was screwed down and the program run again. Once all the blanks had been cycled through, one final step had to be done. Leaving the mounting plate in, the milling cutter was changed out for a corner rounding cutter, one that would add a one-sixteenth inch fillet to the edges of the arms. After rezeroing the mill to this new cutter, all the parts were again cycled through, relying on the alignment of the backing plate to ensure that everything lined up correctly. The very last step was to tap the two holes which the gearbox mounted to. This was done manually using a tapping press.

E. Gearbox

Next to the shroud support the gearbox was the most challenging part to manufacture. The complexity arose not because any one part was particularly hard, but rather from the number of operations that needed to be performed and ensuring that various different operations were aligned correctly to each other. Except for the initial cutting and facing of the stock, all operations were conducted on the Bridgeport EZ-Trak CNC mill. This was done to prevent potential alignment issues between the lathe and the mill.

The first step was to cut the blank gearbox from the stock and then face it to the needed dimensions. This was done using a manual lathe with a digital readout. Once the blank was ready, it was placed in a V-block in the mill vice and clamped down. Since the V-block precisely located the blank, the mill could be aligned to the blank by touching off the V-block and the clamp face which directly contacted the blank. Once the mill had been aligned, the two 4-40 clearance holes that were used to mount the gearbox to the shroud support were drilled, followed by the power shaft clearance hole. After the holes were drilled, the drill bit was replaced with a milling bit and the interior of the blank was removed.

The next step was to add the slots for the two perpendicular miter gears. However, since much of the plastic had been removed from the inside of the blank, the piece was no longer rigid enough to clamp correctly. The solution to this problem was to turn down a piece of plastic to a loose pressfit into the cavity. This insert then allowed the piece to be treated as a solid block, and clamped normally. Once this was done, and the piece realigned to the milling machine the two slots were cut. The piece was rotated by eye so that the two mounting holes were roughly parallel to the direction of the cut, but no particular care was given to the alignment. Once the slots were cut, the piece was pulled from the mill and the edges of the two slots were cleaned.

The final task was to drill the holes for the dowel pins that hold the two gears in place. The alignment for this operation was critical because the gears had to be correctly oriented

towards the power shaft and centered in the slot. This alignment was accomplished by relying on the top of the vice jaws being flat and level. By placing a parallel in one of the slots, placing the parallel flat on the jaws of the vice, and ensuring that the piece was pressed firmly into the parallel



Figure 14: This shows how the vertical holes were made perpendicular to the slots previously milled in the gearbox. The gearbox is pressed into the steel parallel to ensure that the side of the cut is parallel to the top of the vice jaws and thus perpendicular to the vertical axis of the milling machine.

before clamping down, the slots were aligned to be horizontal. Once this was done, and the mill

aligned to the new piece location, the hole for the dowel pins was drilled as well as the access hole for the internal miter gear setscrew. At this point, the piece was done except for deburring and cleaning out waste material.

F. Gears

The gears as ordered came with hubs. However, these hubs were not needed for the two perpendicular gears and had to be removed. Given the small size of the gear it was impossible to grip the gear directly in the lathe chuck. Instead, a steel rod was turned with a slight taper and then a gear hammered onto it. The rod was then inserted into the lathe chuck, and the hub of the gear was turned off. Once the turning was complete, the gear was hammered back off and deburred.

G. Final Assembly

Final assembly was straightforward compared to the machining required to produce the parts. Once all the parts were gathered together, assembly began with the motor. The shaft was inserted into the end of the motor output, and the

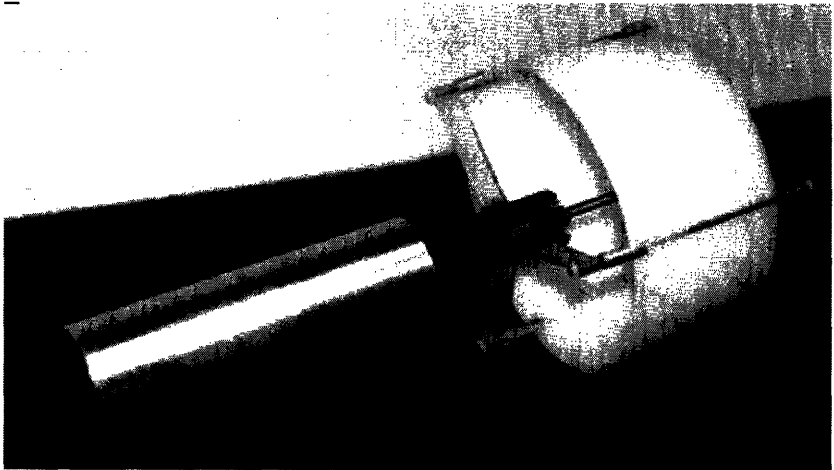


Figure 15: The assembled thruster, minus the propellers.

springpin holes aligned. After placing the springpin in, the motor was then slipped into the motor housing and the locking setscrew inserted into the end of the gearbox. Next, the O-rings

were placed on the endcaps and lubricated with a silicone based O-ring lubricant. Each endcap was then inserted and pushed down completely, making sure to line up the aft endcap with the locking setscrew in the motor. Next, the shaft seal was run down the shaft after being similarly lubricated. The shroud support then went over the shaft seal and tightened down, locking the shaft seal in place. Next the gearbox was assembled by forcing the two dowel pins through their respective holes with the hubless gears correctly aligned. Next, the miter gear with setscrew was placed on the shaft and the setscrew tightened down. The gearbox was then placed on and screwed down. Finally, the shroud was aligned with the support and the threaded rods were installed. Finally, the Rulon bushing was inserted into the aft shroud support, and the support was aligned over the shaft and the three threaded rods. Once everything was aligned and pushed together, nuts were placed on the ends of the threaded rods to lock the assembly.

5. Production Costs

The end goal of this project was a production run of at least 5 complete units. As a result, an emphasis was placed on shifting as much work as possible to computer controlled machine tools and reduce to a minimum the amount of direct human interaction. Unfortunately, the facility available for the production, the MIT Edgerton Center Student Shop, was configured mostly for hand work and not for high speed automated production. As a result, the machining time for some of the pieces could be significantly optimized beyond what was possible with a facility that had machine tools configured with quick change collets or automatic tool changing.

A. Machine Time

The machining time for each listed part (Table 1) represent the incremental time per part, which includes the tool changes required to switch from each step. However, these times do not

include the initial machine setup time, nor cleanup time afterwards. Additionally, these times were recorded with the machines set to fairly conservative feed speeds, due to worries over the strength of various part mounting and potential for part breakage.

Table 1: Machining time for each component of the thruster assembly. A breakdown of the time for each operation required to complete the part is in Appendix B.

Part	total time
Gearbox	25
Shroud	94
Shroud Support	33 x2
Motor Housing	19
Forward Endcap	22
Aft Endcap	38
Shaft	4
Motor	9
gear	1 x2
Threaded rod	3
Total Machine Time	279 minutes, or ~4 2/3 hours

B. Material Cost

These costs (table 2) represent the cost to the project from McMaster industrial supply and Maxxon Motors. The total price represents the pro-rated cost for each component rather than the cost of the minimum quantity purchasable from McMaster. The motor is the primary expense in the construction of the thruster assembly, responsible for 88% of the total material cost.

Table 2: This table shows the price breakdown for one thruster assembly. Also shown is the package cost from McMaster which is then pro-rated for the quantity used on one assembly.

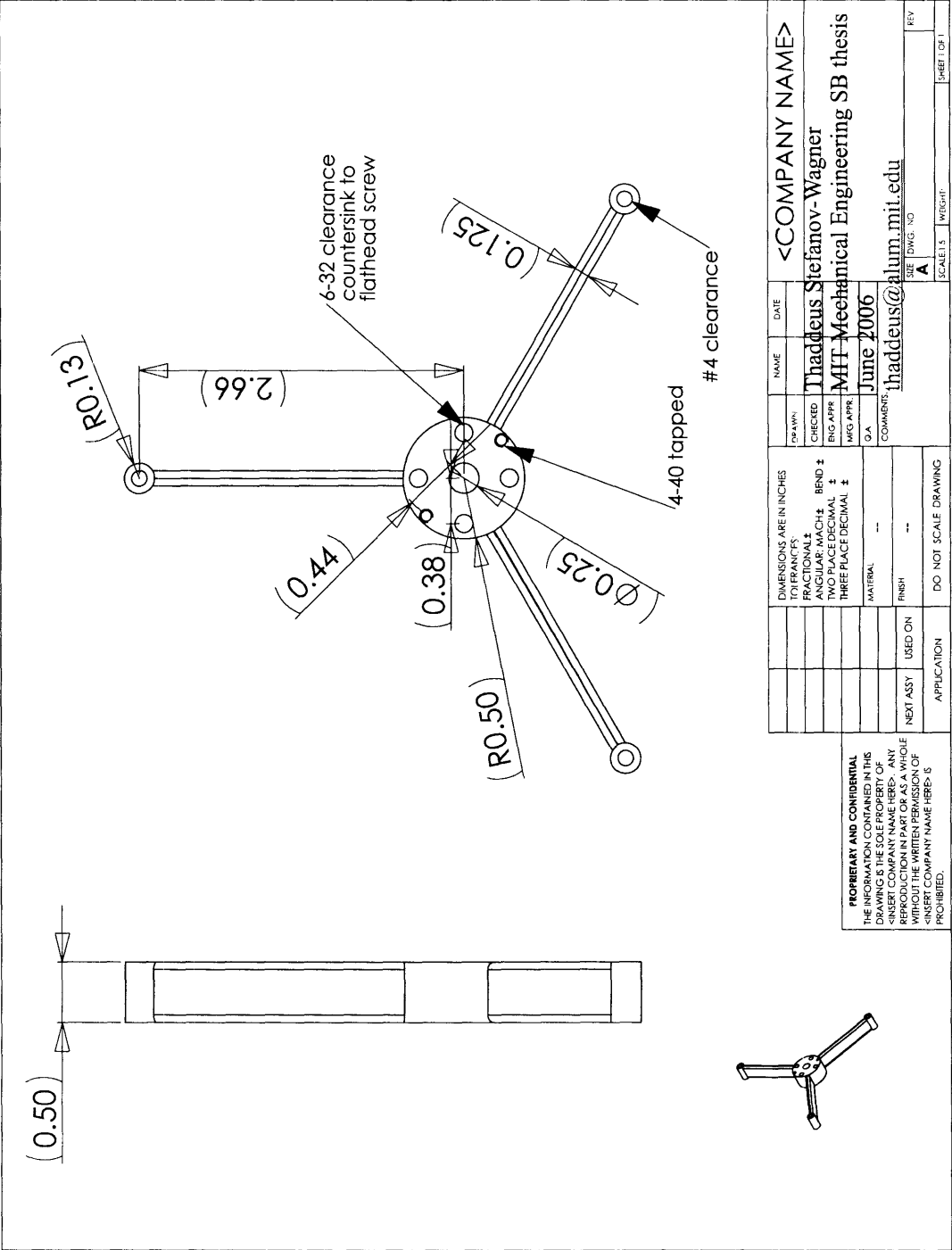
Item	Cost	quantity used	cost per thruster
SS 4-40 1" pan head screw	3.77/100	2	0.08
SS 12mm M4 setscrew	5.83/25	1	0.23
SS 4-40 1/8" setscrew	4.83/25	1	0.19
SS 4-40 threaded rod	1.38/2'	15"	0.86
SS 6-32 3/4" flat head screw	7.87/50	4	0.63
nylon miter gear, .5" P.D	2.13	4	8.52
SS 3/16" ground rod	17.33/6'	7"	1.68
3/16" PTFE shaft seal	7.40	1	7.40
1" dia. Acetal Copolymer rod	4.13/12"	1"	0.34
3/4" #4 Aluminum spacer	0.35	3	1.05
9x6" UHMW polyethylene disk	39.65	4.5"	19.83
3/16" Rulon flange bearing	8.53	1	8.53
SS 3/16x3/8" dowel pin	6.67/10	2	1.33
SS 1/16x1" spring pin	3.16/100	1	0.03
0.5x12x24 Polycarbonate sheet	12.66	6x12"	3.04
1 3/4" dia. Acetal Copolymer rod	11.94/12"	4"	3.98
1/8x1 3/8" id Buna-N O-ring	8.86/100	4	0.35
Maxxon 40mm 150w motor	437.95	1	437.95
Total:			496.03

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Apendix A: Blueprints

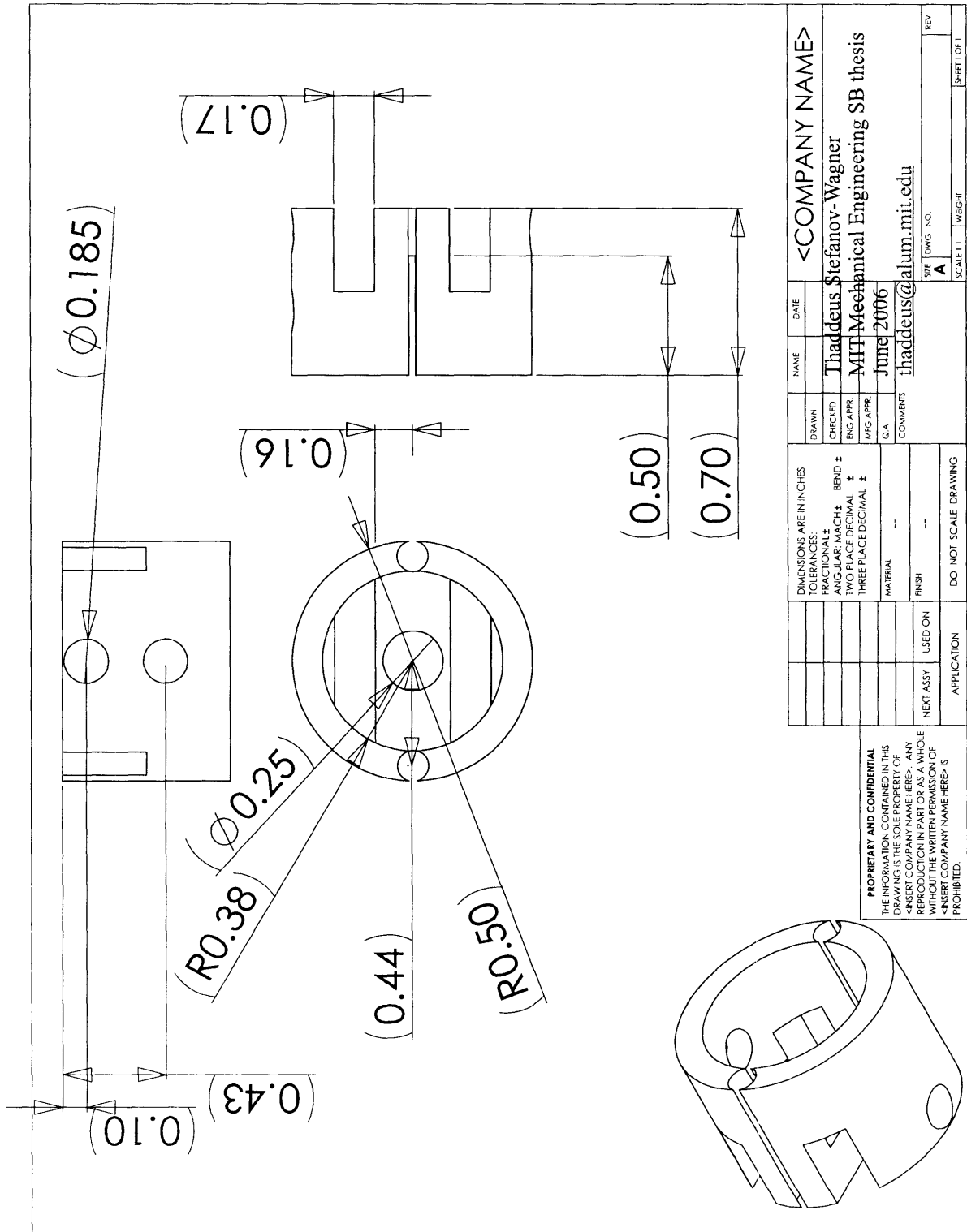
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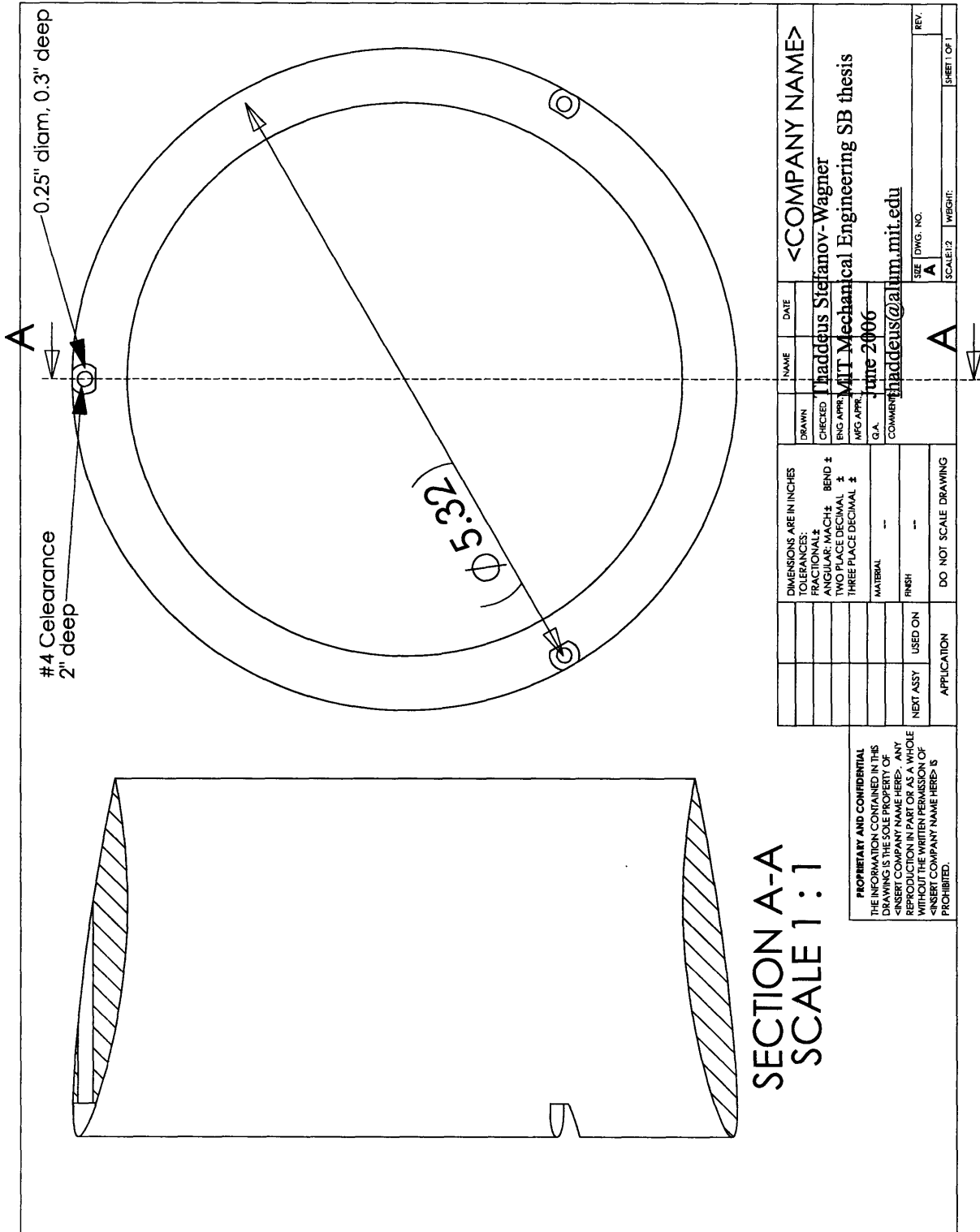
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B. Gearbox



C. Duct

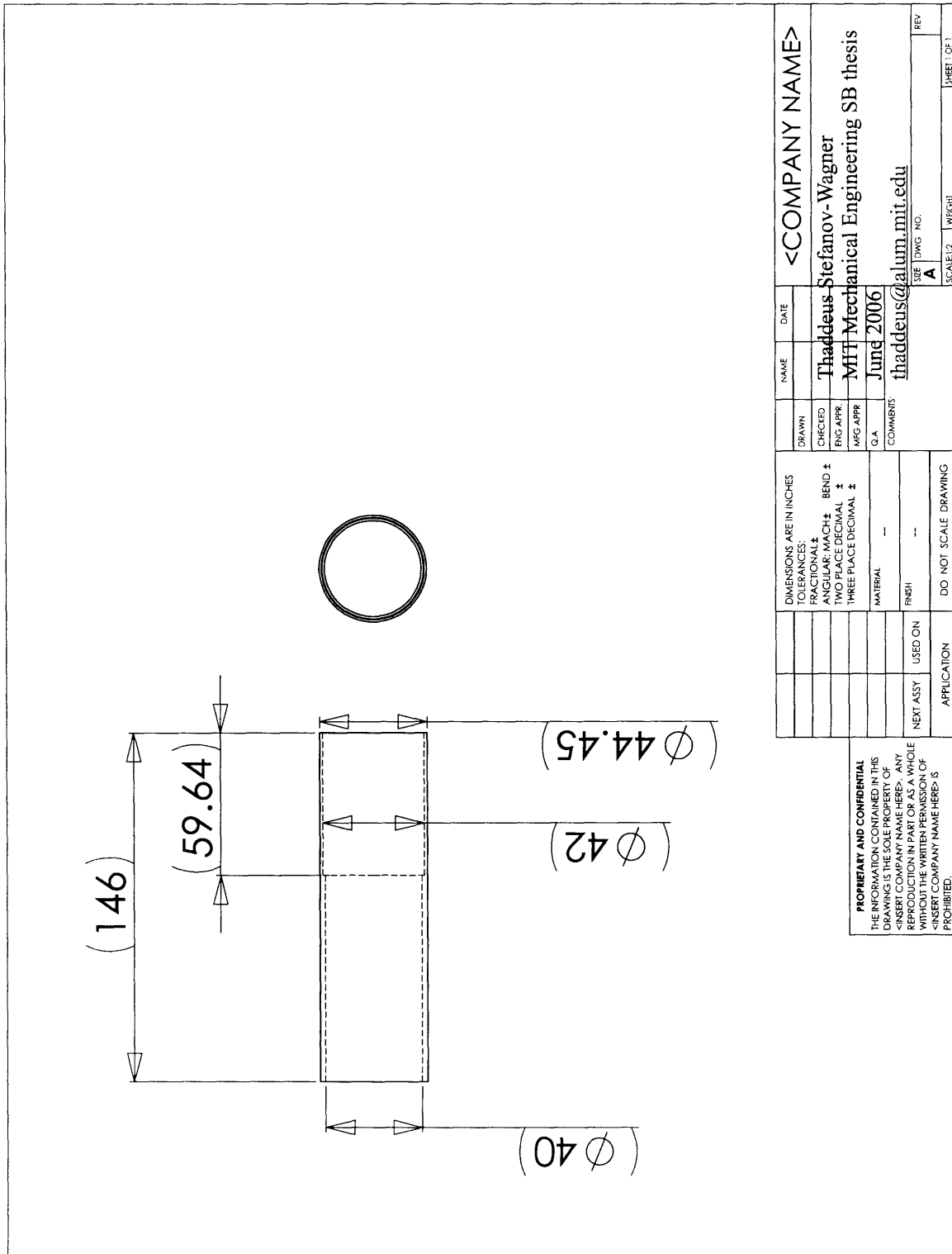


SECTION A-A
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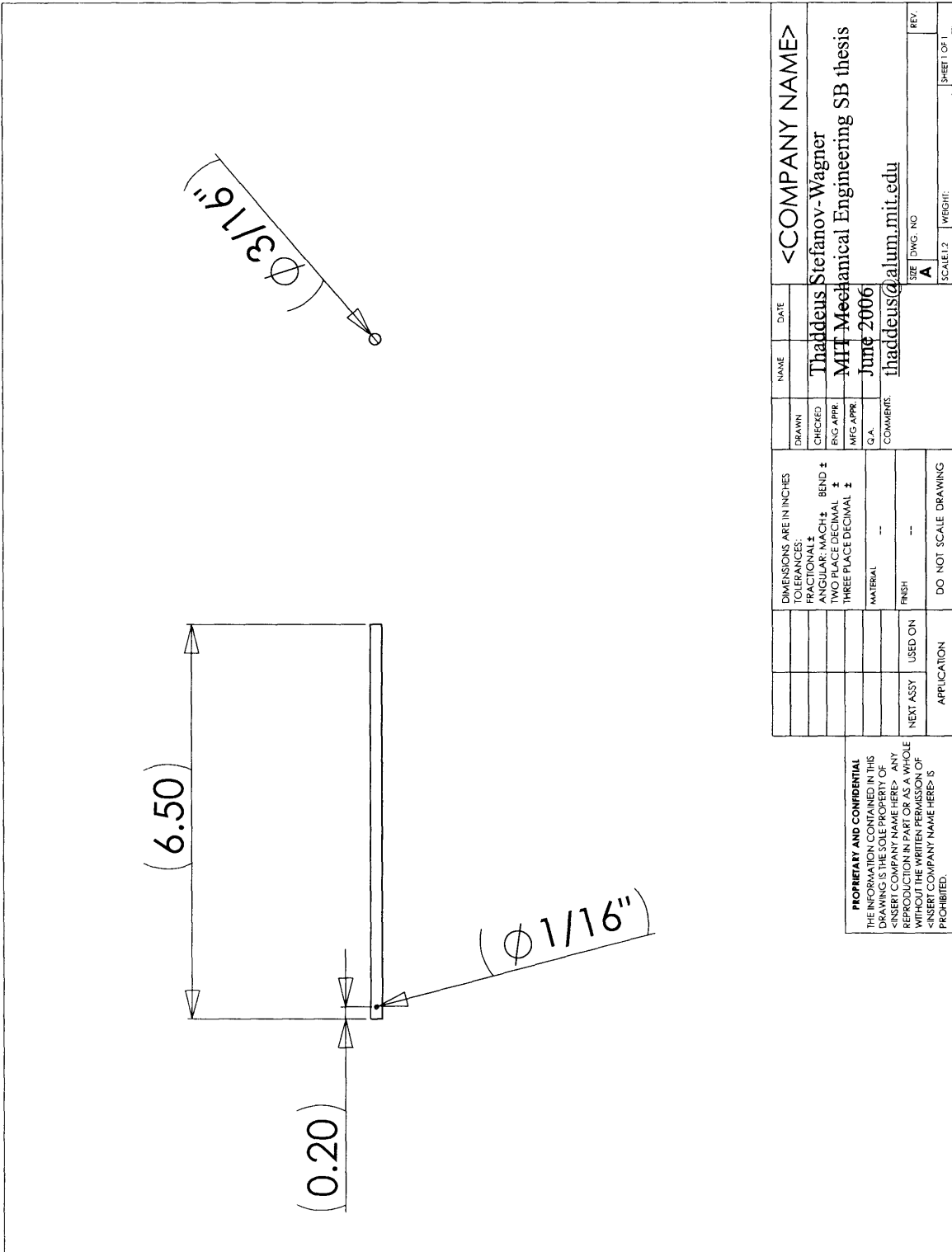
E. Motor Tube



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F. Motor Shaft



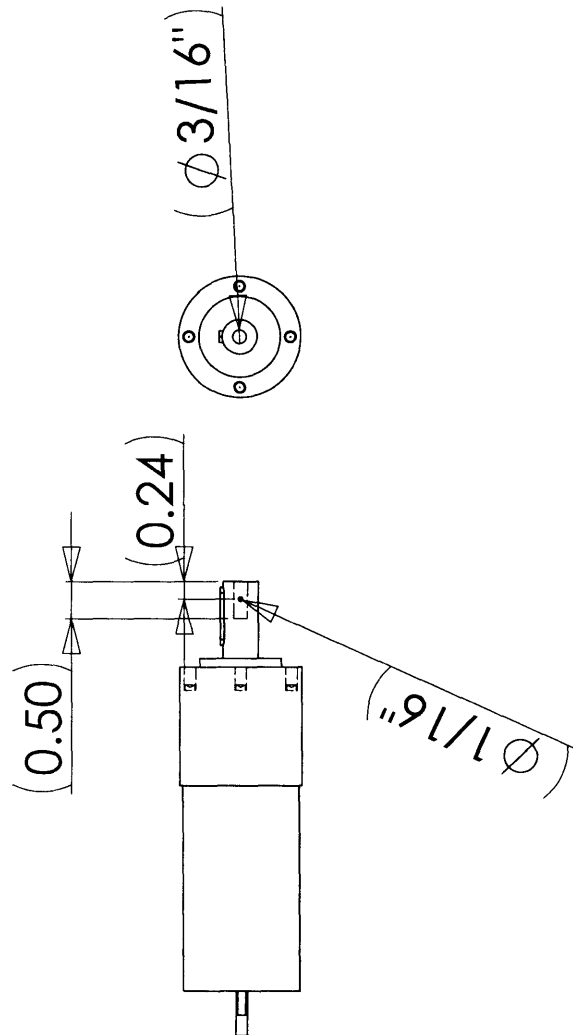
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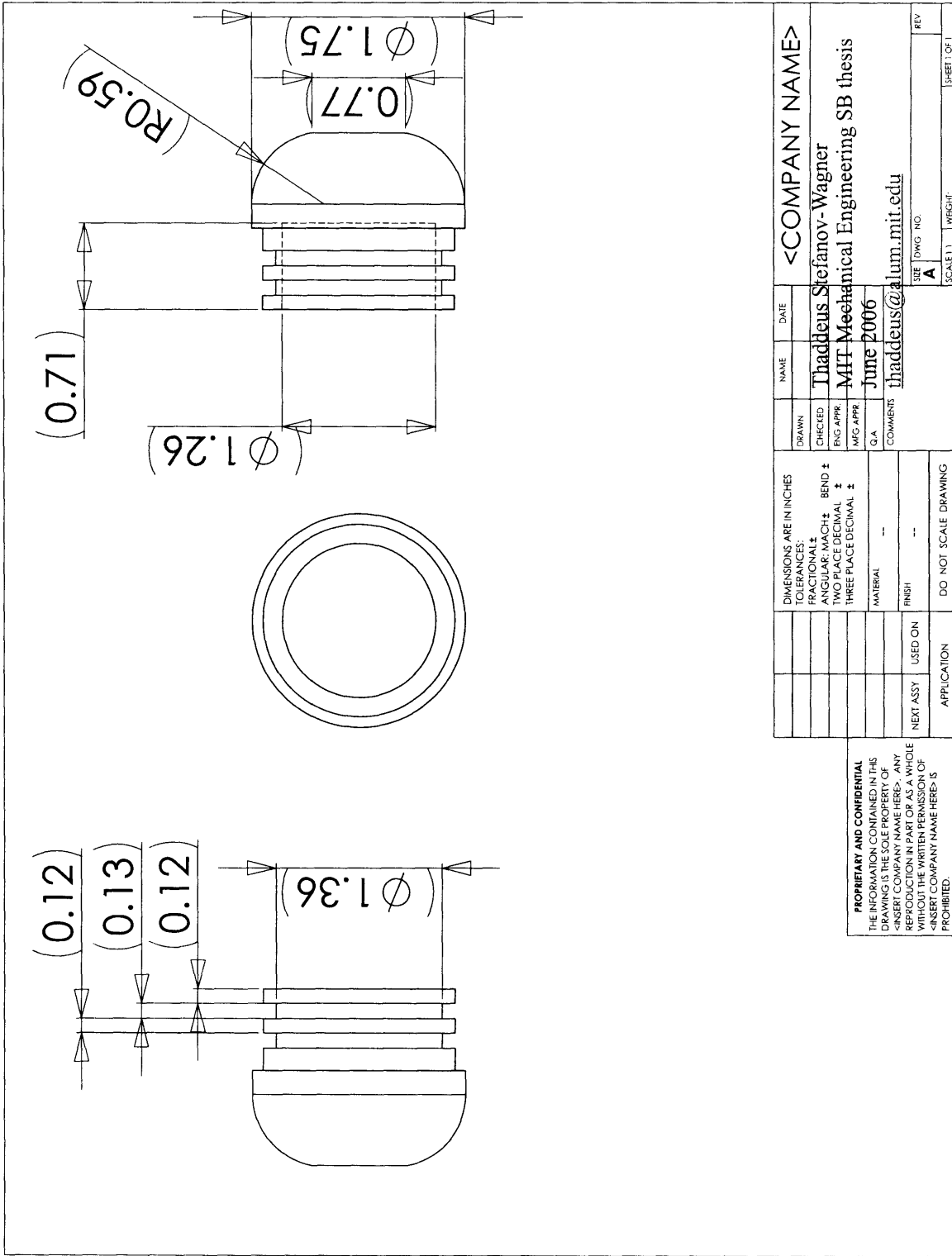
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G. Motor



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H. Forward Endcap



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Appendix B: Machining Time Breakdown

This table is an expansion of the table given in the Machine Time section of the text. This table goes into more detail about the operations required to complete each part and the time each operation took. These times are all approximate and the result of only one machining cycle. The times do not include the basic setup or breakdown time required on the machine being used, but do include the tool change time and machine configuration change time required during each machining process. For example, in the case of the gearbox, the time to drill the gear mounting holes includes the time it took to change over from a collet to a drill chuck and rezero the machine. However, these times do not include changing out a lathe chuck from what the previous user had installed. Since each part can be machined independent of each other part, the sequence of parts has no relevance to the eventual production order.

Piece	Operation	time (minutes)
Gearbox	Cut, prepare stock	5
	align, drill shaft and mount holes	5
	Bore center	3
	mill slots	10
	drill gear mounting holes	2
		25
Shroud	Cut, prepare stock	7
	clearance holes, flats	8
	Bore center manually	20
	CNC lathe inner profile	30

	CNC lathe outer profile	25
	Part from stock	2
	deburr	2
		94
Shroud Support	Drill holes	6
	mill profile	15
	round corners	6
	countersink holes	3
	tap holes	3
		33 x2
Motor Housing	cut stock	2
	bore profile	10
	round edges	2
	clean surface	5
		19
Forward Endcap	Bore center, connector hole	7
	turn diameter, o-ring grooves	8
	part from stock	2
	CNC lathe profile	5
		22

Aft endcap	Bore center	7
	turn diameter, o-ring grooves	8
	part from stock	2
	drill shaft clearance	2
	shaft seal groove	3
	CNC lathe profile	6
	drill shroud support mount holes	6
	tap shroud support mount holes	4
		38
Shaft	part from stock, round edges	2
	drill springpin hole	2
		4
Motor	drill hole for shaft	6
	drill springpin hole	3
		9
Gear	remove hub	1
		1 x2
Total Time		279 minutes