Magnetostrictive Torque Motor

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Team 15

Midpoint Progress Report
Document

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1. Introduction

This report details the progress made by the Magnetostrictive Actuator capstone team from Northern Arizona University. To recap, the project was initiated by Michael McCollum, a Chief Engineer of Pneumatic Controls Technology for Honeywell Incorporated. Mitchell Thune, a recent NAU graduate, is also working with Michael McCollum on this project. Honeywell Aerospace designs valves for airplane air conditioning systems. The client wants to replace an electromagnetic transducer with a magnetostrictive material in the pneumatic control systems used on commercial airliners. The magnetostrictive material for this project is Terfenol-D.

A design solution has been designed utilizing a Terfenol-D core with a piston cylinder style lever. This type of lever amplifies the stroke length via a change in fluid volume as opposed to linear motion translation. The design has been designated the Hydraulic Electromagnetic Magnetostrictive (HEM) Actuator.

The second iteration of this design uses many of the same components, but the positioning, dimensions, and materials have been altered. Additional designs have been conceptualized and will be pursued, given the time and resources are available to continue research and development.

2. Original Design

Figure 1 shows the Solidworks CAD model for the original design. The device utilizes the Terfenol-D rod in the center, with a sleeve of insulation surrounding it. The sleeve is then wrapped with magnetic copper wire and enclosed in an iron casing in order to redirect the magnetic field to the center (where the Terfenol-D rod is located). The center Terfenol-D rod is connected to a piston that will experience the stroke when the electromagnetic field is applied. This stroke will then move the hydraulic lever from the large hydraulic chamber to the smaller chamber where the actuator piston is located. As the length of the Terfenol-D rod increases and decreases, the smaller piston creates actuation. There are 4 steel bolts that span the length between the aluminum end cap and the large piston in order to keep the Terfenol-D rod in a constant state of compression.

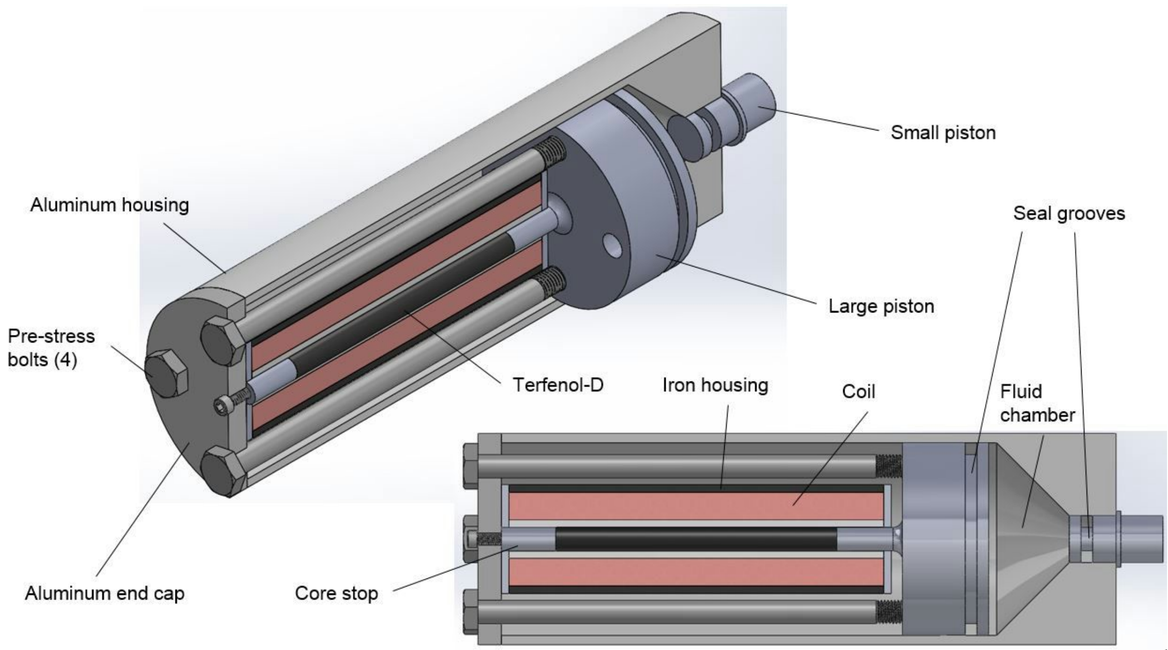


Figure 1: Original design with component markers

2.1 Issues with the Original Design

There are several problems with the original design that have been identified through the manufacturing process. Some of the parts as designed are not able to be manufactured by the NAU fabrication shop, there are a few redundant features, attaching the center components together is not feasible using only compression, and an issue with the stress ratio between the core and the bolts has been overlooked.

The original design holds the iron casing and everything inside of it out on a cantilever before it is put in compression. Though, this idea should work in theory, it is difficult to hold in place without shifting while inside of the aluminum housing. This design also does not reliably hold the iron components in contact with each other because the washers and cylinder are free to slide. Production of the magnetic field will be impacted if these iron components move. These components were originally going to be welded together, but the NAU fabrication shop is unable to weld iron to iron.

Another issue comes from the compression of the core stops. Due to the strength of the 4 steel bolts the core stops will compress such that most of the Terfenol-D's elongation is lost before the bolts stretch.

The team also realized while searching for new core stop materials, that the rightmost core stop does not need to be attached to the large piston. The small bolt that holds the other core stop is also not serving a purpose because the cores are held in compression.

3. First Iteration of The Design

A new iteration of the design has been created that addresses the issues presented in *Section 2.1*. The new design is shown in Figure 2. The components of the new design still serve the same functions but their appearance and positioning has been altered.

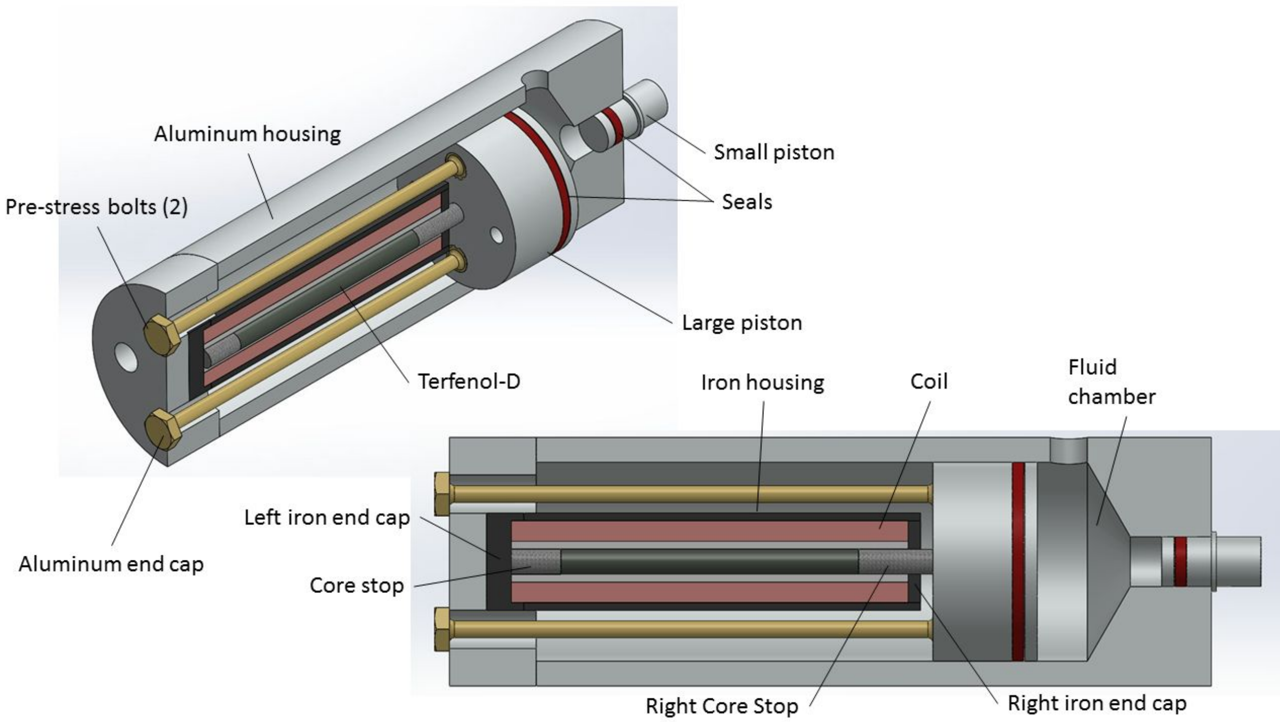


Figure 2: First iteration of the design with component markers

3.1 Design Changes

3.1.1 Aluminum End Cap

To resolve the placement issues of the center components alterations are made to the aluminum end cap. The aluminum end cap has been increased in length so that the iron components are able to sit inside on a shelf to ensure alignment.

3.1.2 Iron End Caps

With the removal of the small bolt the left iron end cap is changed to a solid cylinder with a hollowed section. This hollowed section is made to allow space for the solenoid to be moved inside of it. The right iron washer will be heat-fit inside the iron cylinder to force constant contact between the components.

3.1.3 Core Stops

The core stops material is changed to iron so that it has a much higher modulus of elasticity. This will ensure that both core stops will experience less compression when the Terfenol-D core is activated. Another cheap and viable option is to use neodymium magnets for the core stops. Neodymium core stops will compress more than the iron, but they also have the potential to create a bias magnetic field around the Terfenol-D.

3.1.4 Bolts

To ensure that the core stops compress less than the bolts elongate, the dimensions, quantity, and material of the bolts has been altered. The new bolts must have a small diameter, a low modulus of elasticity, a low quantity, and their lengths must be maximized. All of these qualities will increase the deformation in the bolts.

3.2 Calculations for New Components

Two of the new components required a new calculation to determine their dimensions and what material to construct them from.

One of the iron end caps will slide over the top of the solenoid, so its inner diameter must simply be larger than the outer diameter of the solenoid. The iron washer however, is going to be heat fit inside of the iron cylinder. This end caps outer diameter will be slightly larger than the inner diameter of the iron tube so that when the tube is heated, the end cap can be inserted and allowed to cool. The tube will contract as it cools, holding the iron washer in place. The approximate calculations for this heat fitting are shown in Table 1.

Table 1: Press-fit calculation

α	6.7E-06
Room (°F)	70
Diameter (in)	0.829
$Area_0$ (in^2)	0.5398
$Diameter_{big}$ (in)	0.834
$Area_{big}$ (in^2)	0.5463
ΔA (in^2)	0.00653
Desired Temp. (°F)	973

In order for the heat-fit to be successful, the iron tube must be heated to a temperature of 973°F or greater.

The next calculation that is required for the first iteration of the design is for the bolts. Originally there were 4 steel bolts. However, the team has found that when the Terfenol-D core elongates, the core stops will compress more than the bolts will elongate, resulting in a loss of stroke distance from the Terfenol-D core. For this reason fewer bolts will be used, their diameters will be decreased, and they will be made from brass instead of steel. Using brass bolts with a lower yield strength means that the threading is more likely to shear, so the diameter of the threaded portion of the bolts is also increased to compensate. Using the calculation shown in Table 2, Table 3, and Table 4, a suitable bolt design is selected that can also be manufactured by the NAU fabrication shop on campus.

Table 2: Bolt Data

Force per bolt: (lb)	275
Bolt Diameter (in)	0.17
Thread Diameter (in)	0.375
Threads per inch (1/in)	24
Bolt material	Brass
Yield Strength (psi)	10007.6
Bolt Modulus of Elasticity (ksi)	14793.85
Potential Deformation:	0.0030578

Shank Length (in)	4.875
Thread Length (in)	0.625
Thread Minimum Length (in)	0.3214
Stress on Threads (psi)	3131.11
Tensile Stress Threads (psi)	3437.5
Tensile Stress on Shank (psi)	2059.65
Factor of Safety:	2.91

Table 3: Core Stop Data

Material	Neodymium
Modulus of Elasticity (ksi)	14503.77
Total Length (in)	1.25
Diameter (in)	0.25
Potential Deformation (in)	0.000966

Table 4: Lever Ratio from Bolts

Original Lever Ratio	16
Actual Lever Ratio	12.13

There will be 2 new brass bolts. These bolts will have a 0.17” shaft diameter, are 5.5” in length, and have a ⅜” threaded section. This will result in a 1:12 lever ratio for the output of the actuator if the core stops are neodymium. With iron core stops the resulting lever ratio becomes 1:14.

3.3 Problems with the New Design

The new iteration has corrected many issues, but there are still some unresolved problems with this design. The new design still uses brake fluid as the median for motion transfer in the lever. There could be a significant amount of thermal expansion in this type of fluid if the system temperature increases. The design also works with the assumption that the left iron end cap is in direct contact with the iron cylinder. Iron is difficult to machine, so the faces do not have a good surface finish, this may result in a poor magnetic circuit around the solenoid. Although the new design implements a bleeder valve to remove excess air, there is still a possibility for very small bubbles to remain and for leakage to occur from the piston seals as they slide. These imperfections could damage the overall stroke distance. The fluid chamber is also difficult to refill so any changes to the future design require that the chamber be cleaned thoroughly and resealed. Which are both very time consuming processes.

4. Current Progress

Every component of the assembly has been manufactured or has been ordered. Once these parts have all been acquired, then the design can be finalized and tested.

4.1 Manufactured Components

Most of the components have been manufactured, but they can not be fully tested until all components are acquired.

4.1.1 Fluid Chamber

The fluid chamber shown in Figure 3 and Figure 4 is the most time consuming part to manufacture, it consumed more aluminum stock than all the other parts combined and required that most of the interior be removed. A chamfer is added at the very bottom of the tube where the fluid will reside.

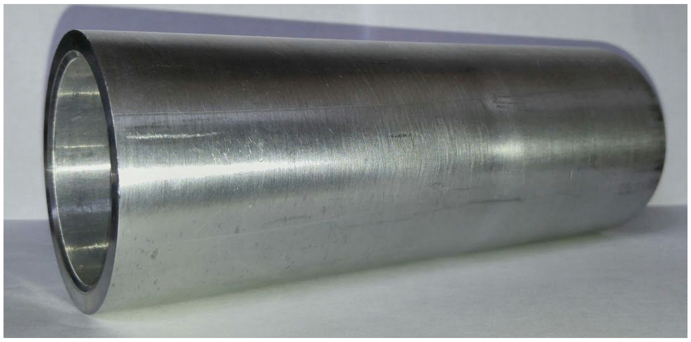


Figure 3: Fluid chamber side view **Figure 4: Inner View**

4.1.2 Pistons

The large piston shown in Figure 5 fits into the fluid chamber at one end and the small piston from Figure 6 fits into it at the other end. Both pistons were turned town from the original aluminum stock using a lathe and grooves for the seals have been added. Threaded holes for the bolts on the large piston are also drilled. The pistons have been tested and verified that they can still move freely with the seals installed.

Figure 5: Large Piston **Figure 6: Small Piston**

4.1.3 Iron Components

This grade of iron is particularly difficult to machine, and some of the parts have not yet finished manufacturing. However, two of the iron components are completed. The first, shown in Figure 7, is the left iron end cap which was cut from a solid iron rod. While the second is the 4in cut iron cylinder that will house the solenoid, shown in Figure 8. The iron core stops and the right iron washer are not yet produced.

Figure 7: Iron cylinder

Figure 8: Left iron endcap

4.1.4 Aluminum End Cap

The aluminum end cap, shown in Figure 9, is made from the leftover stock. While there are overlapping holes they will not be a problem because the bolts are a slightly smaller diameter, leaving clearance between the core and the bolts.

Figure 9: Aluminum end cap

4.1.5 Bolts

The new bolts, discussed in *Section 3*, are displayed in Figure 10. However, these bolts have not been manufactured correctly and require a 3/8in threaded section instead of a 1/4in threaded section. The work order has been submitted and the new bolts are being manufactured. All bolts are cut from hex stock and enough stock remains to create the new bolts.

Figure 10: 1/4in bolts

4.1.6 Combined Parts

All of the components that precede the small piston will be combined together before being inserted into the fluid chamber. The partially complete assembly of these inner components is shown in Figure 11, with the total assembly shown in Figure 12.

Figure 11: Core assembly

Figure 12: Assembly

4.2 Collected Components

Several other components are pre-made and have already been acquired while others are currently being shipped. Figure 13 shows the bleeder valve usable in filling the fluid chamber. The Terfenol-D rod has also been acquired but remains in its packaging to protect it until all other components are assembled. Additionally, the solenoid has been ordered from Custom Coils, Inc.

Figure 13: Bleeder valve

4.3 Currently Working On

Several components are near completion, but still require being combined with parts that are unfinished.
The bleeder valve must be installed into the fluid chamber, but the hole for the chamber is not yet drilled and threaded. So this hole must be machined to finish the fluid chamber.

Another incomplete component is the iron casing. Once the iron washer has been manufactured, the next step is to use a 1500W heat gun to increase the temperature of the iron cylinder until the washer can fit inside. The calculations for the heat-fit are discussed extensively in *Section 3.2*.

After the threaded portion of the bolts has been increased, 2 of the holes in the large piston must also be redrilled to accommodate the 2 new brass bolts.

4.4 Setbacks

During the manufacturing process, there have been many issues with acquiring all of the necessary components. Some of the setbacks are from physical defects or parts not fitting together properly, also lead times have cost the team construction and testing time.

4.4.1 Physical Problems

During assembly of the pistons there were several problems related to the seals. The first occurred when applying the seal to the small piston. Because of the dimensions of the seal it was not able to stretch over the face of the seal. This was resolved by turning the face down half the height of the seal. The second issue was caused by the seals extending past the grooves and interfering with the small clearance between the pistons and the fluid chamber, restricting piston movement.

The bolts have also been a source of problems due to their dimensions. A miscommunication during size changing to increase manufacturability resulted in the bolts mentioned in *Section 4.1.6*.

4.4.2 Lead Times

When ordering parts for the design, there is a balance between shipping cost and when the product is required. Lead times increase depending on the complexity of the component, and can multiply from small miscommunications or slow responses from the seller. The result of these extensive lead times is that much of the needed testing has yet to be conducted.

Some components such as the custom-made solenoid take additional lead time that is spent contacting the seller, setting up a quote, confirming the price/dimensions, purchasing the product, manufacturing the product, and shipping it to the team. The bleeder valve also had to be reordered and more aluminium stock was required than expected. Once the stock or parts arrive, there is additional waiting time to set up a work order and have the parts to go through the manufacturing process.

5. Bill of Materials

Table 5 contains the type and cost of all purchased materials. Shipping has not been included in the listed prices for each purchase.

Table 5: Bill of Materials

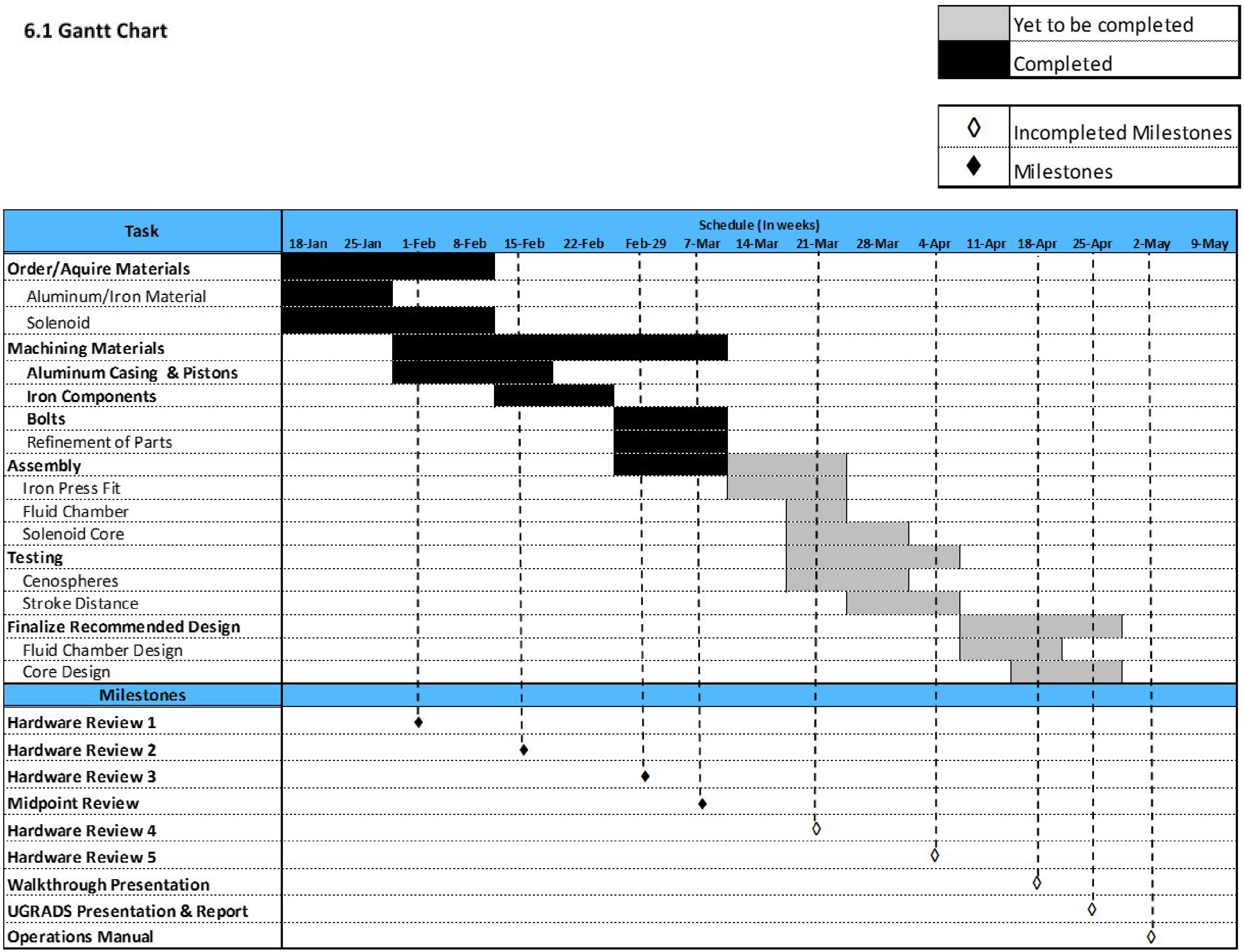
Item	Individual Cost ($)	Quantity	Total Cost ($)
2.5"Aluminum 2011-T3	41.52	2	83.04
Iron Tube	138.00	1	138.00
Iron Rod	171.00	1	171.00
Solenoid	790.00	1	790.00
0.4375" Brass Hex	9.32	1	10.97
Terfenol-D	447.00	1	447.00
Large Seal	5.56	1	5.56
Small Seal	3.94	1	3.94
Brake Fluid	9.95	1	9.95
Cenospheres	12.55	1	12.55
¼"x⅛" N42SH Magnet	0.50	1	0.50
¼"x¼" N42SH Magnet	0.86	4	3.44
Total Cost			1675.95

The most costly items are the Solenoid due to its custom specification, and the Terfenol-D. These two components also are the most vital and unchangeable portions of the design, so it is expected that only one of each will be purchased for the duration of the project. The iron components are also costly and difficult to machine, so there will be safety precautions taken when handling and testing them. The aluminum, magnets, bolts, and seals are all fairly inexpensive, and it is not unlikely that more of each will be purchased and machined for multiple tests. The fluids (brake fluid and cenospheres) were both inexpensive, so there is no concern for preserving them beyond testing, except to include one in the final prototype. The total cost of all the materials together is about $1700, well within our $5000 budget.

6. Project Planning

A plan has been created to complete the HEM actuator by the end of the Spring 2016 semester. The progression plan is shown in *Section 6.1*. There are also several possible design improvements that can be utilized in the next iteration of the HEM actuator.

6.1 Gantt Chart



The Gantt chart highlights important dates and deliverables throughout the Spring 2016 semester. Currently, all tasks on the timeline up to the midpoint review have been completed. The UGRADS presentation will be on April 29th, where the team must deliver a final presentation of the project. Shortly thereafter, the Operations Manual for our device is due on May 6th. Additionally, there are two more hardware reviews that will wrap up the construction of the device, assuming there are no major issues that arise.

6.2 Testing

The next step in the design process is to begin testing the individual components of the actuator to ensure they operate as predicted before they are synthesized into a whole product. The three main components that need to be tested are the cenospheres, filling of the fluid chamber, and the heat-fit iron components.

6.2.1 Cenospheres

The cenospheres are very small spheres made of silica and alumina that are intended to replace any sort of hydraulic fluid in the fluid chamber. They have a diameter roughly the same size as the width of a hair, so they appear like a fine, white powder, but they have a consistency like lotion. They have little thermal conductivity and a small coefficient of thermal expansion. This means that, in theory, they should work like a fluid in translating the stroke through the narrowing fluid chamber, while translating nearly no heat and remaining in an isotropic state. If the cenospheres have negligible or no thermal expansion and properly, efficiently translate the stroke to the small piston, and appear to operate as an incompressible fluid, they will be an appropriate fluid replacement.

6.2.2 Fluid Filling

The forces inside of the fluid chamber are expected and intended to be immense. This means that an incompressible fluid must be utilized to translate the stroke from the large piston to the small piston. This also means that any air bubbles inside the chamber containing “compressible” air pockets, as well as any leaks, must be mitigated. The intended method to achieve this is to include a bleeder valve system to eradicate the chamber of excess air, and the seals around the pistons should prevent leakage.

6.2.3 Heat-Fit Iron

The iron core that surrounds the solenoid needs to be one, cohesive piece so the magnetic circuit can be completed. If there are any gaps between the iron pieces, the small amount of air will create magnetic resistance, and the actuator will not operate efficiently. The Terfenol-D needs to have an ample amount of magnetic field running through it in order to achieve proper elongation. This magnetic field must also be predictable. The size and shape of the iron core is such that a proper magnetic circuit should be achieved. The iron core consists of two end caps: one that will remain in constant contact with the cylinder but be a physically separate piece, and one washer that will be heat-fit into the cylinder. This will be achieved by heating the iron cylinder to expansion, then the washer will be placed into the cylinder and cooled, compressing the cylinder around the washer. A test will be run beforehand on a different iron washer to ensure that there will be no cracking or crushing of the iron components.

6.3 Future Changes

There are a couple changes that the team will need or want to make to improve the design. One such change will be the addition of holes to allow the solenoid wiring to reach an external power source. Another could be the addition of thin, low heat conductive, materials between the solenoid and the fluid chamber.

In order to improve the machinability of the fluid chamber the aluminum housing can be split into two pieces. The front half will only be deep enough to allow room for piston movement, while the back half will be a much longer version of the end plate.

A major issue with the fluid chamber is that heating it will cause thermal expansion and interfere with the stroke distance generated by the Terfenol-D core. To address this issue, the team wishes to purchase some thin plastic insulation that will force the heat from the solenoid out of the encap rather than into the large piston or around the fluid chamber.

7. Risk Assessment and Contingencies

Malfunction and unpredictability are an inherent part of the engineering process, and they must be accounted for in the design plan. Although several modes of failure have been identified in order to prevent malfunction in the design, it is possible that failure may occur in other aspects of the design process. The following list outlines possible risks and contingency plans for each component of the device.

- Solenoid does not produce sufficient magnetic field strength
  - Increase number of turns of wire, and therefore overall diameter of solenoid
  - Purchase silver wire solenoid, thus increasing the cost of the device
- Terfenol-D does not produce desired stroke
  - Increase magnetic field through alternative solenoid design
  - Adjust amount of prestressing placed on Terfenol-D
  - Strengthen material to reduce deflections
- Hydraulic system does not function properly

    - Replace with mechanical lever system
- Thermal expansion of fluid is too great
    - Implement cooling system
    - Use a different fluid
    - Use heat insulation
    - Balance the thermal expansion of the chamber and the fluid
- Thermal expansion of mechanical components is too great
    - Implement heat insulation
    - Balance thermal expansions
    - Reduce length of components
- Materials fail due to stresses or temperature changes
    - Reiterate design with higher factors of safety
    - Consider different materials
    - Reuse materials that have not been damaged
- The iron components crack during heat-fitting
    - Moderate cooling and heating rates
    - Use a slightly smaller iron washer

8. Conclusion

The Northern Arizona University Magnetostrictive Actuator capstone team is partway through the completion of the proposed device. Most of the core and fluid chamber components have been produced or are currently being made. Several complications arose with the manufacturing of the original design that resulted in a new iteration of the design. The appropriate calculations have been conducted for the new components that have been altered. The project has stayed well within budget thus far, and the two most expensive items have already been covered. Testing will have to be accelerated once the solenoid component arrives to make up for time that was lost in lead times. There are several core improvements that the team aims to complete with the next iteration of the design and we have prepared a list of contingency plans for numerous scenarios to ensure that we will be able to make it to this next iteration before the end of the semester.

With a total material cost of about $1700, the HEM actuator may be a viable replacement for the current valve systems currently in use by Honeywell. We are progressing steadily through design and problem fixes on the HEM actuator and we hope to finish testing on a functioning design by the end of April, 2016.