Magnetostrictive Torque Motor

By
Randall Bateman, Aaron Bolyen, Chris Cleland,
Alex Lerma, Xavier Petty, and Michael Roper
Team 15

Concept Generation and Selection
Document

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Submitted towards partial fulfillment of the requirements for
Mechanical Engineering Design I – Fall 2015

Department of Mechanical Engineering
Northern Arizona University

Contents

1 Introduction

This report details the concept generation and selection for the Magnetostrictive Torque Motor capstone team, from Northern Arizona University.

The project has been proposed 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 (shown in *Figure 1* below) a material that elongates and produces a force when placed in a magnetic field [1].

Figure 1: Terfenol-D Rod

In the "Problem Definition and Project Planning" report an explanation of the problem presented by Honeywell and planning for the upcoming tasks and goals of the project was presented. For the actuator, objectives and constraints have been identified along with their respective units or values. After collecting the customer needs and associating them with engineering requirements, a Quality Function Deployment and a House of Quality are used to compare and contrast different aspects of the design. The team has created a Gantt chart to generate a timeline for tasks and deadlines that must be completed. State-of-the-art research is continually being conducted to gain an understanding of the theory behind the features of the design.

2 Functional Diagram

As shown in *Figure 2* below, the functional diagram for the magnetostrictive torque motor outlines the methods in which different components of the design interact with one another as well as the type of information being transferred with each interaction. Multiple concepts can be used to fulfill each component so there are numerous usable design paths. The team has used a red line to signify a mechanical relationship between components and blue line to signify an electrical relationship. The relationship between the hysteresis control component and the power control component is labeled as a mechanical relationship, but could also be considered electrical, depending on the type hysteresis control that is chosen for implementation.

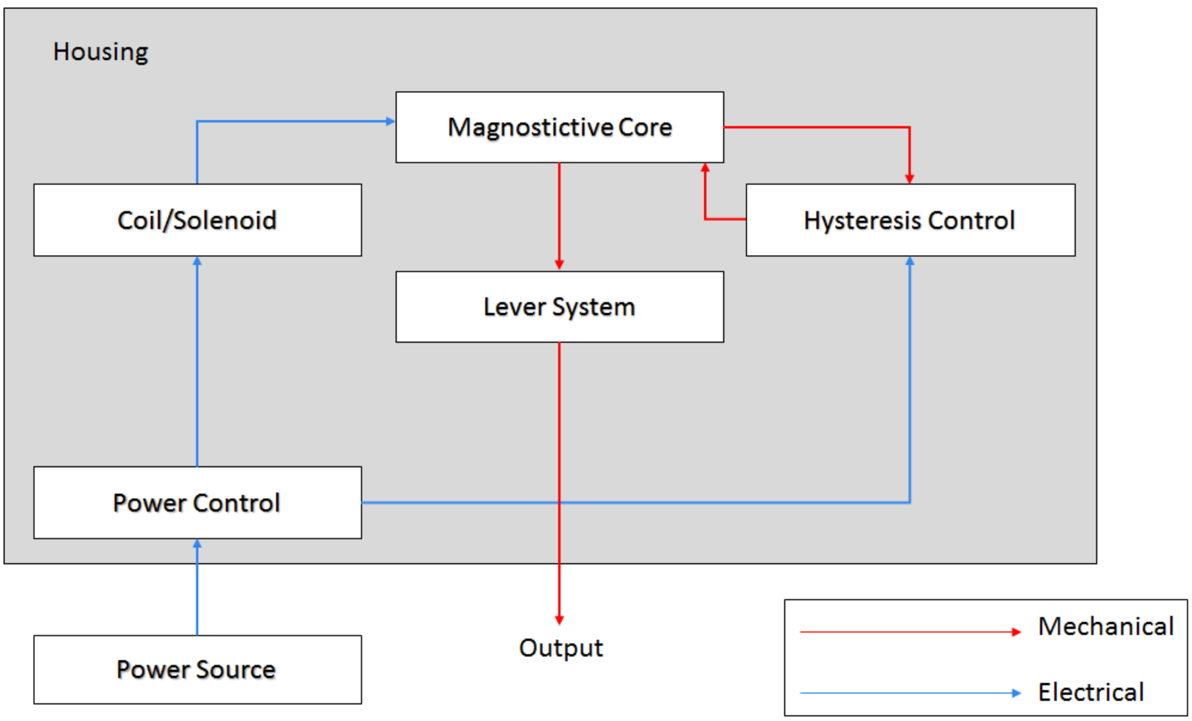


Figure 2: Functional Diagram

3 Criteria

Each section of the functional diagram has several criteria that are relevant to that particular component. However, these criteria do not all have the same level of importance. For example, a particularly costly component of the design has a greater weighting for the cost criteria than the cost criteria of a very inexpensive component. Criteria weight values are voted for by every member of the Honeywell capstone team and the resulting average weighted values can be used to rate potential design concepts.

3.1 Relevant Criteria for Functional Components

Power Source

- Capacity: Amount of power storage of the component.
- Voltage: Output voltage supplied by the power source.
- Cost: Potential price of the component.
- Weight: Potential weight of the component.
- Dimensions: Amount of space that the component will use.
- Current: Output current supplied by the power source.

Magnetostrictive Core

- Strain: The total length that the magnetostrictive core increases.
- Cost: Potential price of the component.
- Dimensions: Amount of space that the component will use.
- Output Force: Total force the core will produce on expansion.
- Hysteresis: The delayed effect between stroke value and the magnetic field strength.
- Thermal Expansion: The coefficient by which a material expands at a given temperature

Housing

- Compact: The amount (or lack thereof) free space between the housing wall and the components of the device.
- Weight: Potential weight of the component.
- Strength: The resistance to plastic deformation.
- Heat Control: How well a material is able to hold or release heat in the system.
- Safety: Whether or not the housing has sharp edges or gets very hot.
- Non-Magnetic: Potential of the component to be affected by magnetics.

Hysteresis Control

- Durability: Capability of the component to withstand cyclic loading [2].
- Force Output: Force the component applies to the core.
- Non-magnetic: Potential of the component to be affected by magnetics.

- Thermal Effects: Additional heat generated by hysteresis control system.
- Dimensions: Amount of space that the component will use.
- Cost: Potential price of the component.

Lever System

- Deformation: Internal bending of the lever.
- Output Stroke: The total movement generated after lever system.
- Fatigue Strength: Ability to withstand cyclic loading.
- Coefficient of Friction: Potential of the component to be affected by magnetics.
- Non-magnetic: Potential effect magnetics will have on the component.
- Dimensions: Amount of space that the component will use.

Power Control

- Response Time: Speed at which the component reacts.
- Cost: Potential price of the component.
- Accuracy: Desired activation with reference to a given target value (be it time or some other value).
- Precision: Desired activation repeated about the same value.
- Voltage: The amount of voltage the component can withstand.
- Current: The amount of current that the component can withstand.

Solenoid

- Conductive Material: Capability of the material to transfer electric current.
- Usable Magnetic Field: Amount of magnetic field accessible or useful to core expansion.
- Size: Physical dimensions (particularly volume).
- Thermal Coefficient: The coefficient by which the material will expand at a given temperature.
- Heat Dissipation: Ability of the component to release heat.
- Weight: Potential weight of the component.
- Cost: Potential price of the component.

3.2 Relative Weight: Power Supply

In order to display the calculations and thought process for criteria values and weightings, an example component of the design is reviewed in detail, shown in *Table 1* and *Table 2*.

Table 1: Raw Criteria Values Example

Power Supply	Capacity	Voltage	Cost	Weight	Dimensions	Current
Capacity	1	5	3	1/3	1/3	3
Voltage	1/5	1	3	1/5	1/3	9
Cost	1/3	1/3	1	7	7	5
Weight	3	5	1/7	1	6	1/7
Dimensions	3	3	1/7	1/6	1	1/7
Current	1/3	1/9	1/5	7	7	1

Scale	
Extremely Preferred	9
Very Strongly Preferred	7
Strongly Preferred	5
Moderately Preferred	3
Equally Preferred	1

Table 1 above displays the value of criteria for the power source when compared to the value of other power source criteria. For instance, the capacity row and the capacity column have a 1:1 ratio of importance to one another because they are both the same criteria. Similarly, the capacity row versus the cost column has a 3:1 ratio, meaning that capacity has 3 times the importance of cost. Alternatively, the cost row versus, the capacity column has a ⅓ value, meaning that cost has ⅓ the value of capacity. The scaling for the value comparisons is shown on the righthand side of the table.

The weighted values based off of the relation ratios are shown in *Table 2* below:

Table 2: Scaled Criteria Values Example

Power Supply	Capacity	Voltage	Cost	Weight	Dimensions	Current	Overall
Capacity	0.0776	0.1740	0.1817	0.0778	0.0267	0.1632	0.1168
Voltage	0.0723	0.0790	0.1650	0.1005	0.1138	0.1672	0.1163
Cost	0.1573	0.2036	0.2080	0.2878	0.2441	0.2384	0.2232
Weight	0.2167	0.2010	0.1275	0.1290	0.2503	0.1030	0.1713
Dimensions	0.2080	0.1473	0.0544	0.0527	0.0634	0.0719	0.0996
Current	0.2681	0.1951	0.2635	0.3521	0.3017	0.2562	0.2728
							1.0000

Each value from a column in *Table 1* is divided by the sum of the values in that respective column to create a relative importance (weighted) value for each criterion. The new weighted values are then summed in the "Overall" column in *Table 2* to add their relative values when compared to every other criterion. To ensure that these weighted values are generated correctly, a simple check is conducted to ensure that the final weighted values add up to a value of 1.

3.3 Relative Weights of all Criteria

Following the same calculation method used in *Section 3.1*, the overall weightings for the criteria of every functional component of the design are shown in *Table 3*, below:

Table 3: Scaled Criteria Totals for all Components

Power Source Criteria	Weights
Capacity	0.117
Voltage	0.116
Cost	0.223
Weight	0.171
Dimensions	0.100
Current	0.273
Total:	1.000

Housing	Weights
Compact	0.205
Weight	0.220
Strength	0.157
Heat Control	0.158
Safety	0.058
Non-Magnetic	0.202
Total:	1.000

Hysteresis Control	Weights
Durablility	0.268
Force output	0.224
Non-magnetic	0.122
Thermal Effects	0.157
Dimensions	0.124
Cost	0.105
Total:	1.000

Magnetostrictive Core	Weights
Strain	0.338
Cost	0.109
Dimensions	0.093
Output Force	0.128
Hysteresis	0.234
Thermal Expansion	0.097
Total:	1.000

Lever System	Weights
Deformation	0.194
Output Stroke	0.354
Fatigue Strength	0.146
Coefficient of Friction	0.097
Non-magnetic	0.135
Dimensions	0.074
Total:	1.000

Power Control	Weights
Response Time	0.237
Cost	0.168
Accuracy	0.161
Precision	0.171
Voltage	0.108
Current	0.156
Total:	1.000

Solenoid	Weights
Conductive material	0.227
Usable Magnetic Field	0.217
Size	0.099
Thermal Coefficient	0.158
Heat Dissipation	0.095
Weight	0.122
Cost	0.083
Total:	1.000

The list of design criteria incorporates many important aspects of the design. However, the list is subject to change as new criteria develop importance or previous criteria are found to be less important to the overall design than anticipated.

4 Concept Generation

Each function of the actuator has several concepts that could accomplish the desired criteria. The functions that are required for the actuator are a power source, solenoid, magnetostrictive core, hysteresis control, housing, lever, and power control. These functions and their corresponding concepts are shown in *Table 1* of *Chapter 3*. The purpose of *Chapter 4* is to provide a clear description of the design concepts for each component of the actuator.

4.1 Power Source

For the power source, the team considered several direct current (DC) and alternating current (AC) options including a car battery, wall outlet, fuel generator, or D-cell batteries as seen in *Figures 3, 4, 5, and 6* [3,4,5,6] respectively.

Figure 3: Car Battery

Figure 4: Wall Outlet

Figure 5: Fuel Generator

Figure 6: D-Cell Battery

Using a car battery, DC power could be supplied for extended \periods of time, or for many cycles. This type of battery offers the required voltage and amperage, and has an adequate theoretical lifespan based on their performance in automobiles. Another DC option is a D-cell battery. D-cell batteries are a more economic option, and are more widely available to average consumers, though it may only suffice for prototyping and experimenting. The AC power source options include the wall outlet and electric generator. These options would most likely be available on commercial aircraft, where the actuator is intended to be used. The wall outlet option would draw from the power supplied by the aircraft, and would ensure adequate voltage, amperage, and lifespan. If power consumption is too great but cannot be improved, the external battery or generator may be the better option. The generator could offer AC or DC power supply, and would be heavy and expensive, but it may be required because the power draw may be too great for a battery or detrimental to the aircraft's power supply.

4.2 Solenoid

The solenoid options being considered are illustrated in *Figure 7* [7, 8].

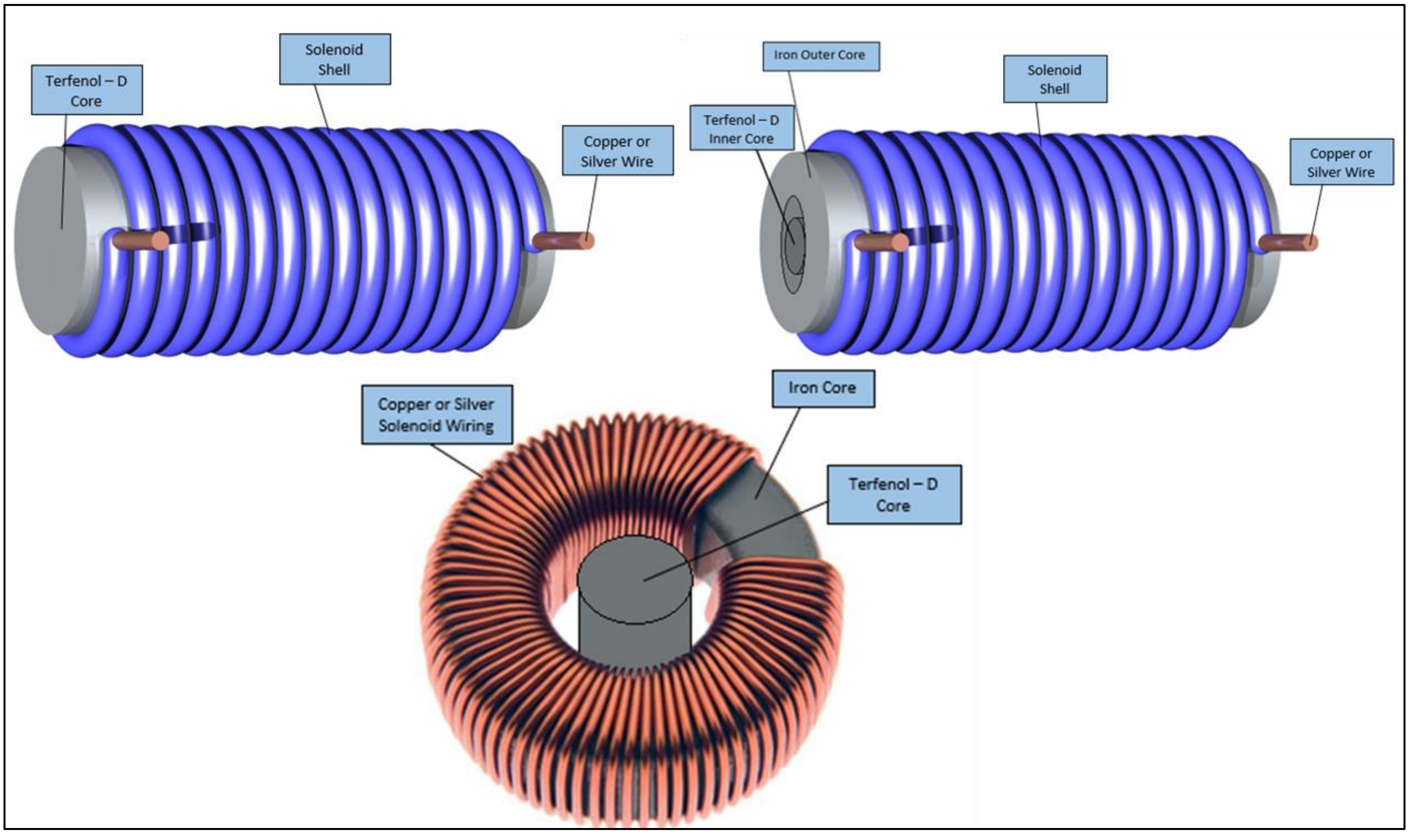


Figure 7: Solenoid and Core Positioning

The coil could be composed of a copper or silver wire coil, a tube coil with or without a core, or a ring coil. The copper coil would be the most economical due to availability of copper, and its widespread use has offered a proof of concept from similar applications. The silver wire coil would offer less electrical resistance than the copper, and therefore a stronger magnetic field. It would be used in an identical manner to the copper wire, validating it for this application. A tube coil with a core is a solenoid that contains iron within the coil windings and without a core excludes iron but still applies the magnetic field. These options are economical and easily obtained, but may not provide any additional methods to decrease effects from hysteresis.

4.3 Magnetostrictive Core

The magnetostrictive core has one binding requirement; it must be made of Terfenol-D. This core could, however, be a rod with a cylindrical cross- section, square or rectangular cross-section, or could be powdered, as can be seen in *Figure 8* [1]. These three forms are the only options from Etrema, the supplier and sole patent owner of Terfenol-D.

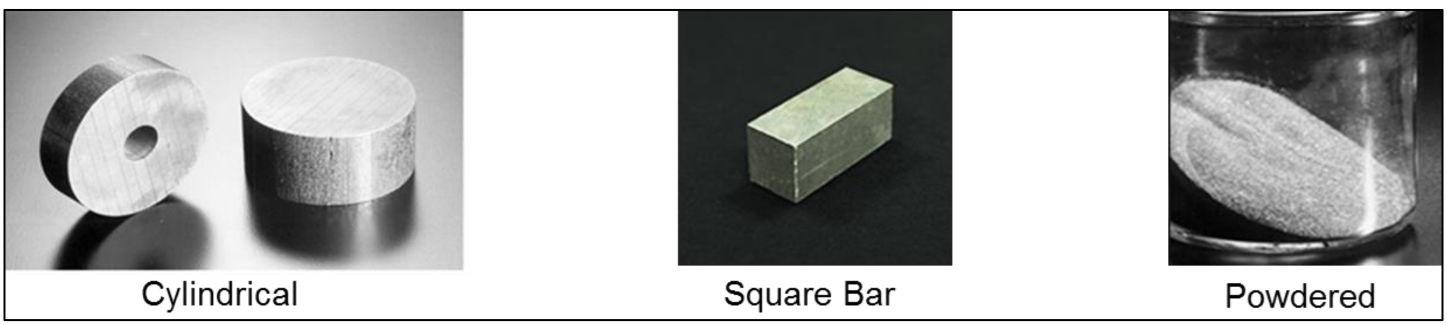


Figure 8: Magnetostrictive Cores

A rod with a cylindrical or rectangular cross- section would be simple to implement, as they already are in the proper shape and form to be used in the actuator, but they do not offer the elongation required to be applied in the actuator, and the effects of hysteresis are detrimental. If powdered Terfenol-D is used, it could be mixed with oil to make a ferrofluid, or added to a pre-existing ferrofluid in order to offer the required elongation, while maintaining a percentage of the output force adequate for the application. Hysteresis may also be more easily controlled using a ferrofluid.

4.4 Hysteresis Control

Hysteresis control is one of the most complex functions to conceptualize because it is the most ambiguous and has the least supporting research and development. The current hysteresis control systems involve springs, bolts, and combinations of a spring and bolt. The team also theorized the use of dual magnetic fields to elongate and compress the Terfenol-D, randomizing the magnetic field, and mixing Terfenol-D to create a ferrofluid, or mix with a pre-existing ferrofluid. Hysteresis control via springs and bolts is not ideal because it has a constant compression on the core, and therefore does not offer the full potential elongation Terfenol-D could offer. It also utilizes some of the force that could be exerted by the Terfenol-D. The use of dual magnetic fields is illustrated in *Figure 9*, and allows the application of the magnetic field both parallel and perpendicular to the rod.

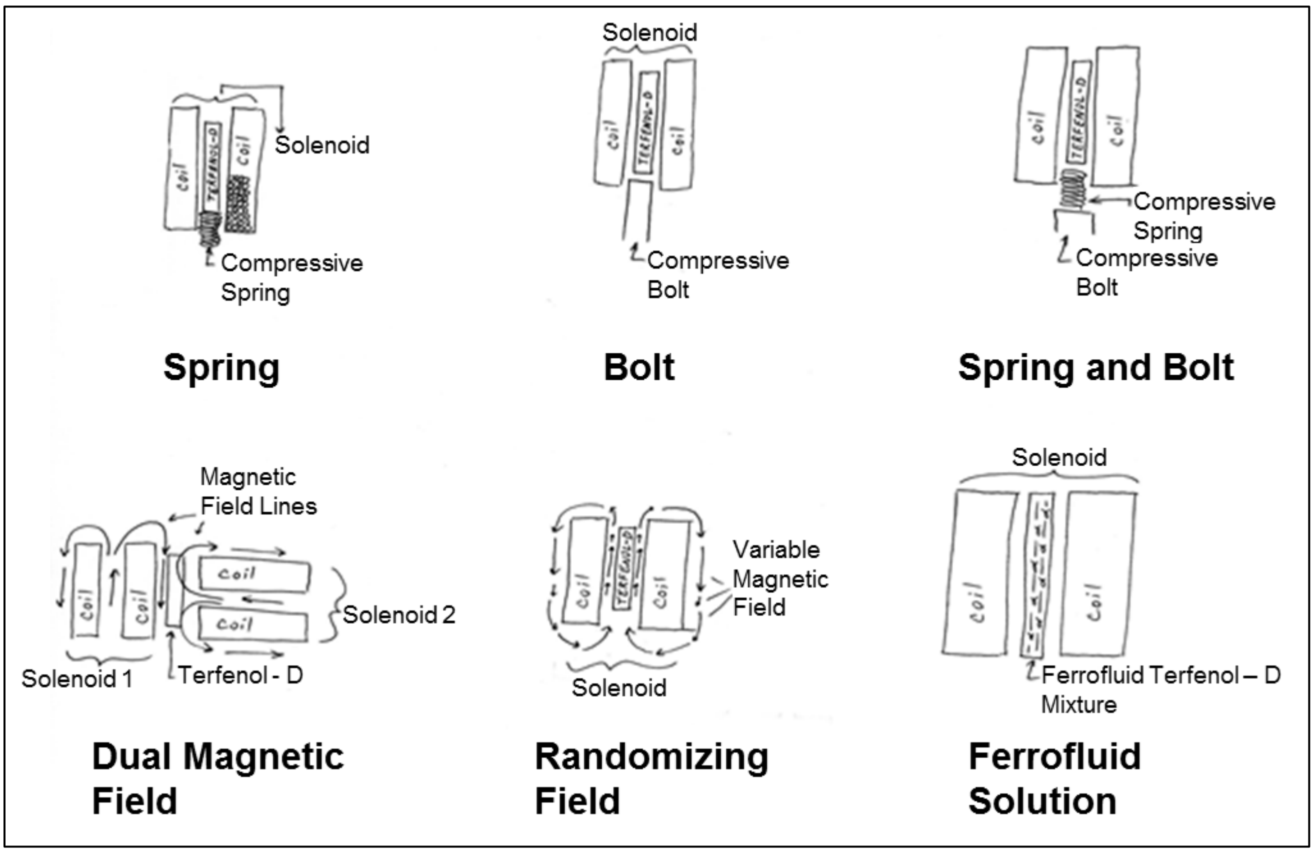


Figure 9: Hysteresis Control Options

This causes the molecules to become aligned parallel to the length of the rod when the parallel coil is activated, elongating the core, and aligning the molecules perpendicular to the length when the perpendicular coil is activated, compressing the core. A randomized magnetic field could be used to control hysteresis because, in theory, by randomizing the strength of the magnetic field, the molecules will align randomly, and allow slip between the molecules to allow the material to compress with greater ease than a single, constant strength magnetic field. The final hysteresis control concept involves a ferrofluid with Terfenol-D powder, adding space between the Terfenol-D molecules along with lubricative effects. This allows the molecules to align freely with little to no friction between them, decreasing force output and increasing elongation. If the elongation and force output remain within the set parameters for the project, this option could be the most viable and cheapest.

4.5 Housing

The housing for the actuator could be made of wood, non- ferrous metal, or plastic, and can take the form of a box, flat plate- mounted parts, or a compact casing, where the parts are aligned and casing is thermoformed around them. The different cases being considered can be seen in *Figure 10*.

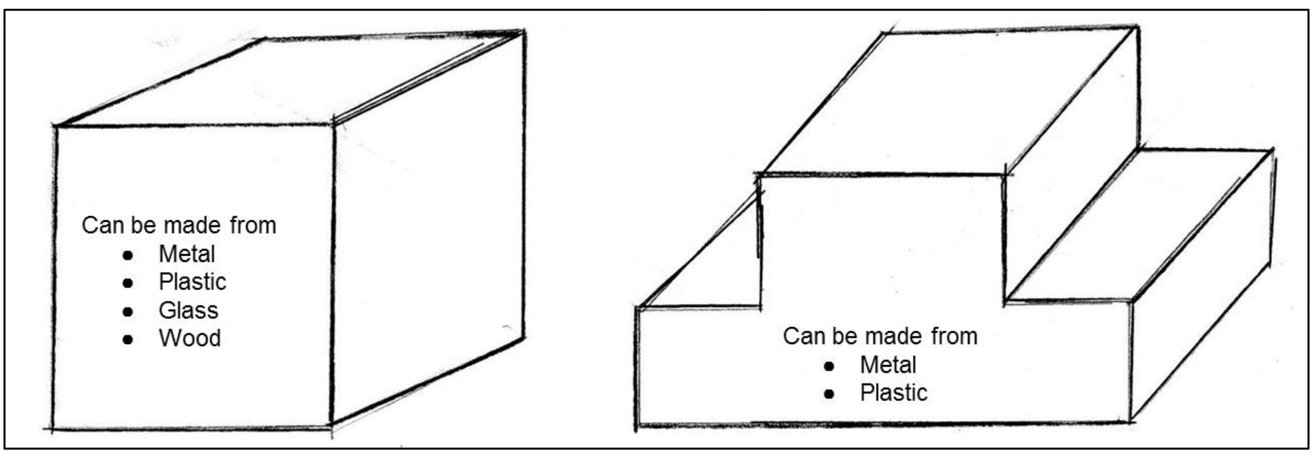


Figure 10: Housing Shapes and Materials

A wood casing is not practical because of the potential temperatures that the actuator could reach, though it would be highly economical. The metal casing could be easily constructed and would be the strongest against compressive or torsional forces, but it needs to be made of non- ferrous metal so the magnetic field does not have adverse effects to other components in or surrounding the actuator. A metal housing would also be the most expensive option due to the physical properties, but it could be used for either cylindrical or rectangular box housing, or a flat plate- mounted case. In a flat plate- mounted case, all the components could be aligned on a single plane, and the casing built around it, much like a computer chip. This would be easiest for manufacturability and assembly, but space allocation may be more practical in a cylindrical or rectangular box and may be heavier than a more practical, plastic casing. A plastic casing could be in the form of a box, or thermoformed around the components, though it would require high thermal resistivity and insulative properties [9].

4.6 Lever System

A lever system must be used to translate the elongation of the Terfenol-D into a mechanical motion that can be used to open and close a pneumatic actuating valve. The different type of lever systems in consideration can be seen in *Figure 11*.

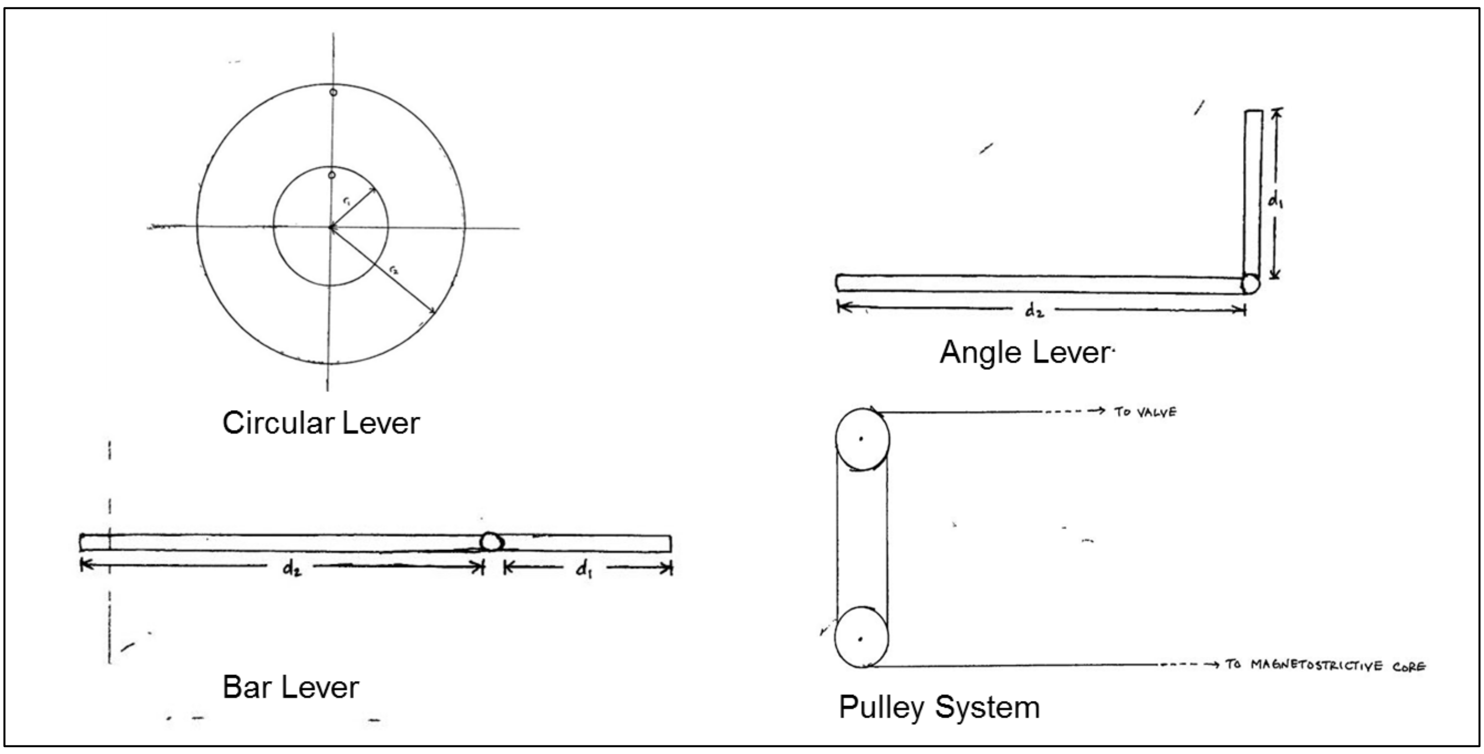


Figure 11: Lever System Designs

The first type considered by the team was a straight or angled lever with a rectangular cross- section. This is the simplest and most conventional option. It will increase the stroke through a simple mechanical swing motion and a pin offset from the center. A lever with a circular cross- section would accomplish the same task, but because of the shape, there is more material to the same cross- section size, and therefore it would not bend or deform as easily. The final option of a lever system would be a very small pulley system. The pulley would be attached to the end of the core, and offer a pulling rather than a pushing motion. The issues are that the string would need to be under tension either by gravity or some other sort of connection, it may not have enough tensile strength to withstand the forces acting on the system. It is also difficult to find very small pulley systems that are also reliable enough to perform actuation properly each time.

4.7 Power Control

Power control systems, shown in *Figure 12* [10, 11, 12, 13, 14] will be needed to regulate power to the solenoid and potential hysteresis control systems.

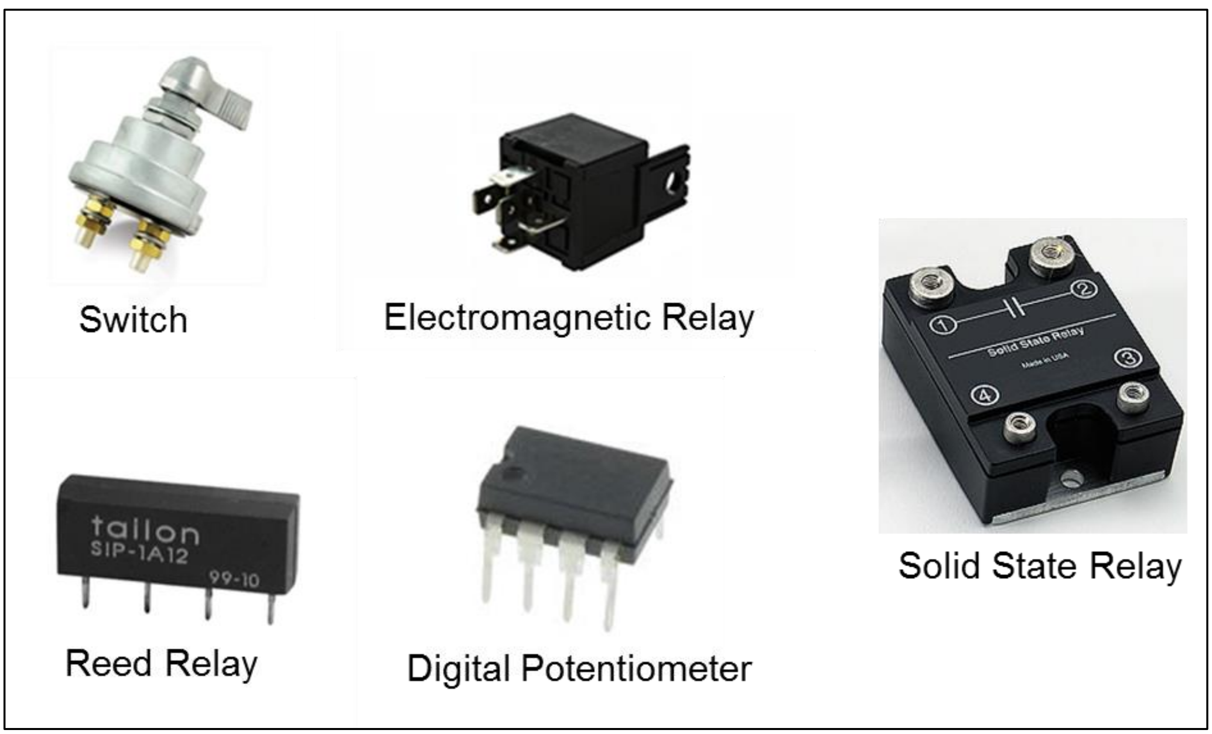


Figure 12: Power Control Systems

One type of power control is a simple switch that can be used manually to activate and deactivate the current to the solenoid, thus activating and deactivating the magnetic field to the Terfenol-D core. The switch will not require a processor or other computing element to control, but these devices are used in the other concepts. An electromagnetic relay utilizes a coil that, when current is applied, an internal switch is activated, and that bridges the electrical connection [15]. The Solid State relay has no mechanical parts uses transducers inside to open and close the circuit. A Reed relay also uses a coil, however instead of a switch there are two thin plates which upon field activation contact each other allowing current to flow through. Digital Potentiometers are able to function as variable resistors allowing current to be altered, and would be most helpful if utilized with a randomized magnetic field hysteresis control system.

As research on the potential concept generation continues, it may be realized that designs are not feasible for a magnetostrictive actuator or new design options can also be developed and tested.

5 Decision Matrices

With the relevant criteria for each component established, the weighted values produced in *Section 3* are applied to concept variants through the use of decision matrices. In each decision matrix, scores from 1-10 are provided for each criteria where 1 represents a maximum negative impact on the design and 10 represents a maximum positive impact on the design. The base values are displayed in the first section of each table, and the weighted equivalent values along with a total score row are shown in the second sections of each table. The highlighted column score represents the highest scoring concept for each section of the actuator design. However, this is only a guideline for concept choices and does not necessarily guarantee that the highlighted concept will be incorporated into the final design.

5.1 Power Supply

Table 4: Scored Power Source Designs

Power Source	Car Battery	D-Cell Batteries	Wall Outlet	Fuel Generator
Capacity	8	4	10	3
Voltage	7	2	10	10
Cost	5	10	10	1
Weight	3	8	7	1
Dimensions	4	9	7	2
Current	10	2	10	10

Power Source Criteria	Weights	Car Battery	D-Cell Batteries	Wall Outlet	Fuel Generator
Capacity	0.117	0.935	0.467	1.168	0.351
Voltage	0.116	0.814	0.233	1.163	1.163
Cost	0.223	1.116	2.232	2.232	0.223
Weight	0.171	0.514	1.370	1.199	0.171
Dimensions	0.100	0.399	0.897	0.697	0.199
Current	0.273	2.728	0.546	2.728	2.728
Total:	1.000	6.505	5.744	**9.187**	4.835

Using a basic wall outlet scored the highest in *Table 4* because it scored extremely high in two of the largest weighted categories. The team identified that a wall outlet drawing power from the grid would supply the appropriate amperage and voltage necessary to operate the device. With cost being the next largest weighted categories, the team also is considering that regardless of where this device is being presented, there will be an available wall outlet that supplements no direct cost. The next highest total score for a potential power supply belongs to a car battery. A car battery supplies adequate voltage and amperage, but in the end will likely be too large in volume, weight, and cost.

5.2 Solenoid

Table 5: Scored Solenoid Designs

Solenoid	Ring Solenoid (Silver Wire)	Ring Solenoid (Copper Wire)	Coil Solenoid (Silver Wire)	Coil Solenoid (Copper Wire)	Coil Solenoid (Silver Wire) with Iron Core	Coil Solenoid (Copper Wire) with Iron Core
Conductive material	10	8	10	8	10	8
Usable Magnetic Field	6	5	8	7	6	5
Size	4	4	6	6	3	3
Thermal Coefficient	5	6	5	6	4	5
Heat Dissipation	8	7	7	6	7	6
Weight	4	6	5	7	3	4
Cost	3	5	6	8	4	6

Solenoid	Weights	Ring Solenoid (Silver Wire)	Ring Solenoid (Copper Wire)	Coil Solenoid (Silver Wire)	Coil Solenoid (Copper Wire)	Coil Solenoid (Silver Wire) with Iron Core	Coil Solenoid (Copper Wire) with Iron Core
Conductive material	0.227	2.266	1.813	2.266	1.813	2.266	1.813
Usable Magnetic Field	0.217	1.304	1.086	1.738	1.521	1.304	1.086
Size	0.099	0.395	0.395	0.593	0.593	0.296	0.296
Thermal Coefficient	0.158	0.789	0.946	0.789	0.946	0.631	0.789
Heat Dissipation	0.095	0.759	0.664	0.664	0.569	0.664	0.569
Weight	0.122	0.487	0.730	0.608	0.852	0.365	0.487
Cost	0.083	0.249	0.415	0.498	0.665	0.332	0.498
Total:	1.000	6.248	6.050	**7.156**	6.958	5.858	5.538

The highest score, shown in *Table 5*, for this category was a horizontal solenoid using a silver coil. Silver is by far the most appropriate conventional material to use for the coil, receiving a score of 10 in the highest weighted criteria of "conductive material". [16] The next highest weighted criteria is "useable magnetic field", which directly affects both the power and stroke of the actuator. The ring solenoid idea lost most of the points off the theory that the magnetic field created in a ring solenoid would be produce in a tangential line away from the ring, which would not be feasible in this design. A horizontal solenoid using a copper coil scored relatively close to a silver coil, proving that if the team found it to be too expensive to use a silver coil, then a copper coil could be used without sacrificing much in the design [17].

5.3 Magnetostrictive Core

Table 6: Scored Magnetostrictive Core Designs

Magnetostrictive Core	Cylindrical	Square Bar	Powdered
Strain	7	7	1
Cost	5	5	8
Dimensions	8	6	10
Output Force	8	8	3
Hysteresis	4	5	6
Thermal Expansion	5	5	5

Magnetostrictive Core	Weights	Cylindrical	Square Bar	Powdered
Strain	0.338	2.367	2.367	0.338
Cost	0.109	0.546	0.546	0.873
Dimensions	0.093	0.745	0.559	0.931
Output Force	0.128	1.028	1.028	0.385
Hysteresis	0.234	0.936	1.170	1.404
Thermal Expansion	0.097	0.486	0.486	0.486
Total:	1.000	6.107	**6.155**	4.418

A Terfenol-D bar with a square cross-section scored the highest between the three different possible shapes, shown in *Table 6*. This shape of material scored slightly higher than a cylindrical rod because the effect of hysteresis would be less apparent on the bar with square cross-section. The powdered form of Terfenol-D scored very poorly in the weighted criteria because there is a high possibility that there is little-to-no strain when a magnetic field is applied. The matrix shown also shows that a bar with square cross-section and a cylindrical rod are nearly interchangeable in this device.

5.4 Hysteresis Control

Table 7: Scored Hysteresis Control Designs

Hysteresis Control	Spring	Bolt	Spring and Bolts	Duel Magnetic Fields	Randomizing Field	Ferrofluid Solution
Durablility	6	9	7	10	10	9
Force output	7	8	9	6	1	3
Non-magnetic	9	9	9	2	2	1
Thermal Effects	7	4	6	1	3	8
Dimensions	8	9	7	2	10	5
Cost	10	10	9	3	5	3

Hysteresis Control	Weights	Spring	Bolt	Spring and Bolts	Duel Magnetic Fields	Randomizing Field	Ferrofluid Solution
Durablility	0.268	1.610	2.416	1.879	2.684	2.684	2.416
Force output	0.224	1.570	1.794	2.018	1.345	0.224	0.673
Non-magnetic	0.122	1.095	1.095	1.095	0.243	0.243	0.122
Thermal Effects	0.157	1.099	0.628	0.942	0.157	0.471	1.256
Dimensions	0.124	0.989	1.113	0.865	0.247	1.236	0.618
Cost	0.105	1.051	1.051	0.946	0.315	0.525	0.315
Total:	1.000	7.414	**8.096**	7.745	4.992	5.384	5.399

The hysteresis control can either be a physical piece, or a way to magnetically reduce hysteresis in the magnetostrictive core. Using a bolt to pre-stress the core scored the highest in *Table 7* due to the strength and force output that is possible with a solid bolt. Using a spring or some combination (of both the spring and bolt) also scored very high, proving that if one of these concepts is not feasible, it can be replaced with something similar. The concepts with magnetic field scored less in important weighted criteria due to the lack of testing done with these ideas. Using dual magnetic fields would require creating a second solenoid to try and change the direction of strain for the magnetostrictive material, and would thus increase the weight, dimensions, and cost of the device. Using a randomizing field would require sending random amperage through the coil of the solenoid, but this could not guarantee that the core would compress back to original length with minimal hysteresis.

5.5 Housing

Table 8: Scored Housing Designs

Housing	Sheet Metal Box	Sheet Metal Compact Casing	Glass Viewing Box	Wood Box	Wood Plate Mounted Parts	Plastic Box	Plastic Compact Casing
Compact	3	8	3	3	6	3	8
Weight	3	4	2	6	8	9	10
Strength	10	9	2	5	1	4	3
Heat Control	7	8	1	3	3	5	5
Safety	2	1	2	8	8	8	8
Non-Magnetic	2	2	8	8	8	8	8

Housing	Weights	Sheet Metal Box	Sheet Metal Compact Casing	Glass Viewing Box	Wood Box	Wood Plate Mounted Parts	Plastic Box	Plastic Compact Casing
Compact	0.205	0.615	1.641	0.615	0.615	1.230	0.615	1.641
Weight	0.220	0.660	0.880	0.440	1.320	1.760	1.980	2.200
Strength	0.157	1.569	1.412	0.314	0.784	0.157	0.627	0.471
Heat Control	0.158	1.108	1.267	0.158	0.475	0.475	0.792	0.792
Safety	0.058	0.115	0.058	0.115	0.461	0.461	0.461	0.461
Non-Magnetic	0.202	0.404	0.404	1.617	1.617	1.617	1.617	1.617
Total:	1.000	4.472	5.661	3.259	5.272	5.700	6.092	**7.181**

The concept of a plastic compact casing scored the highest for the housing designs shown in *Table 8*. This concept scored high in the largest weighted categories because of the potential lightweight and non-magnetic properties of plastic. The plastic box scored the next highest. Plastic scored higher than the other concepts due to the safety and low weight. Metal scored high in the criteria of strength, but is too heavy and lacked criteria like being non-magnetic and safe.

5.6 Lever

Table 9: Scored Lever System Designs

Lever System	Angle Lever	Bar Lever	Pulley System	Circular Lever
Deformation	7	4	9	6
Output Stroke	5	5	4	5
Fatigue Strength	7	7	8	9
Coefficient of Friction	8	8	5	6
Non-magnetic	8	8	9	7
Dimensions	10	7	3	4

Lever System	Weights	Angle Lever	Bar Lever	Pulley System	Circular Lever
Deformation	0.194	1.360	0.777	1.748	1.166
Output Stroke	0.354	1.771	1.771	1.417	1.771
Fatigue Strength	0.146	1.019	1.019	1.164	1.310
Coefficient of Friction	0.097	0.773	0.773	0.483	0.580
Non-magnetic	0.135	1.082	1.082	1.217	0.946
Dimensions	0.074	0.742	0.520	0.223	0.297
Total:	1.000	**6.746**	5.941	6.252	6.069

The angled lever scored the highest in the matrix shown in *Table 9*. This was due to the compact dimensions of an angle lever as opposed to other longer or bulkier designs, though most of the lever designs have the ability to accomplish nearly even amounts of stroke increase. The pulley system has the potential for very high stroke increase, but it takes up a vast amount of space. The circular lever is very strong, but would require too much volume and wasted material. Many of the lever systems scored very similarly in the design selection, so if the chosen design does not meet expectations, it can easily be substituted with another.

5.7 Power Control

Table 10: Scored Power Control Designs

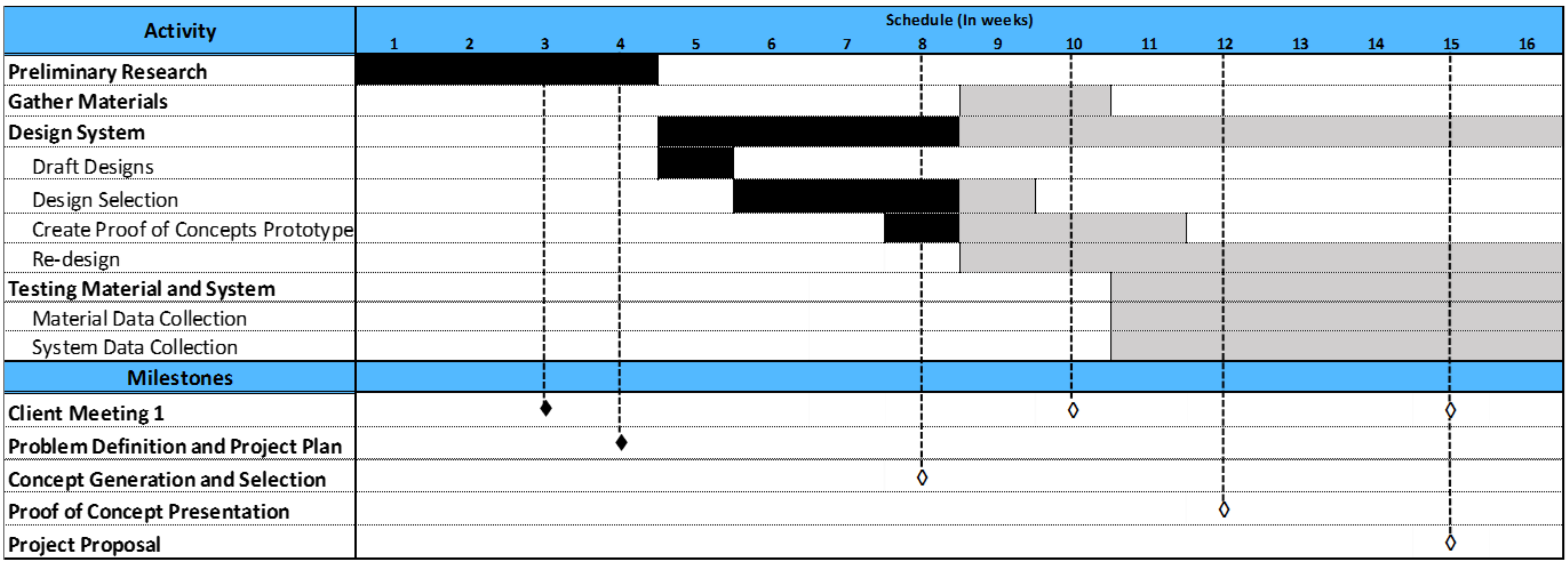
Power Control	On/Off Switch	Electromagnetic Relay	Digital Potentiometer	Solid State Relay	Reed Relay
Response Time	1	5	7	6	6
Cost	9	7	10	6	8
Accuracy	3	6	5	7	6
Precision	6	7	8	7	7
Voltage	9	8	1	9	8
Current	9	8	1	9	8

Power Control	Weights	On/Off Switch	Electromagnetic Relay	Digital Potentiometer	Solid State Relay	Reed Relay
Response Time	0.237	0.237	1.183	1.656	1.420	1.420
Cost	0.168	1.509	1.173	1.676	1.006	1.341
Accuracy	0.161	0.484	0.967	0.806	1.129	0.967
Precision	0.171	1.025	1.196	1.367	1.196	1.196
Voltage	0.108	0.969	0.861	0.108	0.969	0.861
Current	0.156	1.404	1.248	0.156	1.404	1.248
Total:	1.000	5.627	6.629	5.769	**7.123**	7.033

From *Table 10* the response time is the most important criteria with precision closely following it. The decision matrix shows that the solid state relay best fits the selected criteria with the reed relay having a very close value. This is due to both relays having high response times and the ability to support high voltages and currents. While given a good score on response times, the digital potentiometer is unable to manage high voltage and current.

6 Project Planning

In the previous report, a Gantt chart was presented that outlined the upcoming tasks and deliverables for the project. Since then, the team has progressed and therefore the Gantt chart has been updated, as shown in *Figure 13*, below:



Several updates have been made to the Gantt chart based on recent completed goals and changes in upcoming tasks. For one, the team has finished drafting concepts of each component and begun the design selection. As discussed in *Section 3*, criteria are applied to each system component in decision matrices. While the matrices determine which concept variants best fit the criteria, the team has yet to finalize these decisions. Additionally, gathering the necessary materials has been postponed because the client has not yet provided a budget. Finally, a client meeting was scheduled for Week 7; however, the team will be visiting the Honeywell campus in Tempe, Arizona in Week 10. Due to this new development, the second client meeting is now scheduled for Week 10 to take advantage of an in-person meeting with the client. All other tasks and deliverables will follow the original schedule.

7 Conclusion

In summary, this report outlines the process of generating concept variants and selecting one for each system component. The Honeywell capstone team initially constructed a functional diagram in order to visually present the relationships between components along with their methods of information transfer. Furthermore, criteria are established along with several concept variations specific to each component of the overall system. These criteria are also related to each other to quantitatively determine their effect on the final design. Both the criteria and concept variants are compiled in a decision matrix in order to determine which concepts best fit the criteria based on their weighted values in comparison to all other aspects of the actuator. This information allows the team to make educated decisions on the construction of each component.

Looking forward, the team will finalize the decisions for the concept of each component. Once the design components are established, a bill of materials will be created to assess the cost of each component of the design as well as the overall cost of construction. Using this information, a proof of concept prototype will be constructed to physically demonstrate the goals of the project.

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