Magnetostrictive Torque Motor

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Problem Definition and Project Planning
Document

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1 Introduction

This report details the problem definition and project planning 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, a material that elongates and produces a force when placed in a magnetic field. Terfenol-D is generally manufactured in round bars, as shown in Figure 1 [1].

Figure 1: Picture of Terfenol-D Rod Section

2 Need Statement

Currently, there are no feasible actuators for aircraft valve systems using the magnetostrictive material Terfenol-D.

3 Project Definition

The definition of the project is broken into three sections: Project Goal, Objectives, and Constraints. The goal is written as a direct answer to the need statement. The objectives list the features to be included in the design. The constraints are the limitations that we must work with in designing this product.

3.1 Project Goal

The goal of this project is to develop a viable actuator that incorporates the magnetostrictive properties of Terfenol-D.

3.2 Objectives

After meeting with the client and learning more about the project, our capstone team was able to generate a list of features that the design will include. Table 1 shows each objective the team has defined, and how each objective is measured (primarily in English customary units).

Table 1: Project Objectives

Objective	Measurables	Units
Decrease Hysteresis Effect	Magnetic Field Strength	A/m*
Increase Strain	Percent Elongation	in/in
Measure Output Force	Force	lbf
Reduce Operation Time	Time	milliseconds
Maximize Work Per Unit Weight	Work, Weight	ft^2/s^2

* English units for magnetic field are not well-defined.

3.3 Constraints

Along with the objectives and features that the design will include, the capstone team was also given a list of criteria that the design must follow.

- At least 25lb of force exerted
- Need at least 0.03in stroke (based off of 3in length rod)
- Must cost less than $5000
- Must be smaller than 3x5x12in
- Coefficients of thermal expansion must be constant throughout device
- System must be cooler than 500°F

- Greater than 1:10 ratio of input to output distances

Among these criteria, the most complex constraints to achieve are maintaining the input/output ratio with a limited stroke, and keeping the coefficients of thermal expansion constant. For this reason, these constraints should be the starting basis for a design.

4 Quality Function Deployment

The following subsections detail the customer and engineering requirements identified. Relationships between the requirements are shown in Figure 2 with the correlations between engineering requirements alone represented in Figure 3.

4.1 Customer Requirements:

- Inexpensive - Cost of the actuator should not surpass the budget given
- Durable - The system must be able to withstand the applied forces
- Efficient - Actuator needs to maintain highest possible work/weight ratio
- Quick - Movement in the actuator must be comparable to current actuators on the market
- Small - The actuator size must be within the constraints already identified
- Reliable - The actuator has to perform consistently during output and input strokes
- Feasible - An actuator using Terfenol-D must be able to replace conventional actuators
- Simple - The device should fulfill its purpose while being as simple to construct as possible
- High Stroke - The stroke of the actuator must reach the constraint given
- Heat Tolerant - The device must withstand internal or external temperature changes

4.2 Engineering Requirements:

- Weight - Total measure of the weight of the device, in lb
- Size - The measure of the dimensions of the actuator, in “in”

- Strain - The measure of the amount that the device will move, in % elongation
- Temperature - The measurement of heat in the system, in °F
- Thermal Coefficient - The constant by which a system expands or contracts at a given temperature, in $°F^{-1}$
- Hysteresis - (specifically magnetic hysteresis) the difference between expansion and contraction of a material at certain magnetic field strengths
- Force - The force measurable from the output of the actuator, in lbf
- Cost - The dollar amount of all materials used in the project, in $
- Input/Output Ratio - The multiply by which the device amplifies the stroke
- Manufacturability - The level of difficulty of producing the system

Customer Requirements / **Engineering Requirements**	Weight	Size	Strain	Temperature	Thermal Coefficient	Hysteresis	Force	Cost	Input/Output Ratio	Manufacturability
Inexpensive	◊	◊						◊		◊
Durable	◊			◊	◊			◊		◊
Efficient	◊	◊				◊	◊			
Quick			◊			◊	◊			
Small	◊	◊						◊	◊	◊
Reliable					◊	◊	◊	◊	◊	
Feasible	◊	◊	◊	◊		◊	◊	◊	◊	◊
Simple						◊		◊	◊	◊
High Stroke		◊	◊			◊		◊	◊	
Heat Tolerant				◊	◊			◊		◊

Figure 2: Quality Function Deployment

After analyzing the Quality Function Deployment, the most important engineering requirements are cost, hysteresis, and manufacturability because modifying these specific aspects has an effect on many other features of the design.

4.3 House of Quality

The House of Quality shown in Figure 3 is a tool used to identify relationships between the engineering requirements present in the design. Relationships denoted with plus signs are positive relationships, and those with negative signs are negative relationships. Double signs mean very strong positive or negative correlations.

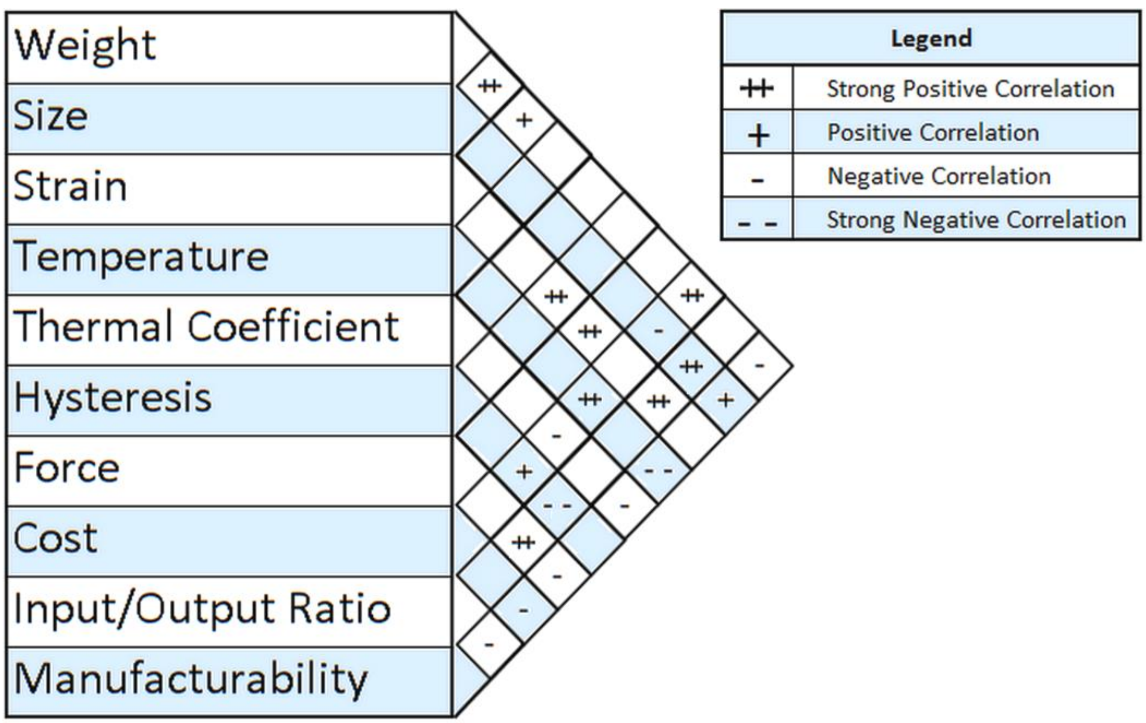

Figure 3: House of Quality with Relation Legend

Upon analysis of the House of Quality, it is determined that most of the engineering requirements have a direct effect on how easy the system will be to manufacture or how much it will cost. The actuator will be used in commercial airplanes, so weight and the other factors that affect weight are also of great importance. Requirements with hard limit values that have been given by the client such as input/output ratio, force, and strain must be kept within the limitations at the cost of more expendable features.

5 Project Plan

The capstone team has identified several tasks that must be complete by the end of the semester. The Gantt chart shown in Figure 4, shows the tentative schedule for the project. The major tasks that will need to be completed are designing and testing the system. Some tasks, such as design and redesign continue as other tasks are being assigned. There are also several milestones scheduled, such as progress presentations and meetings with the clients.

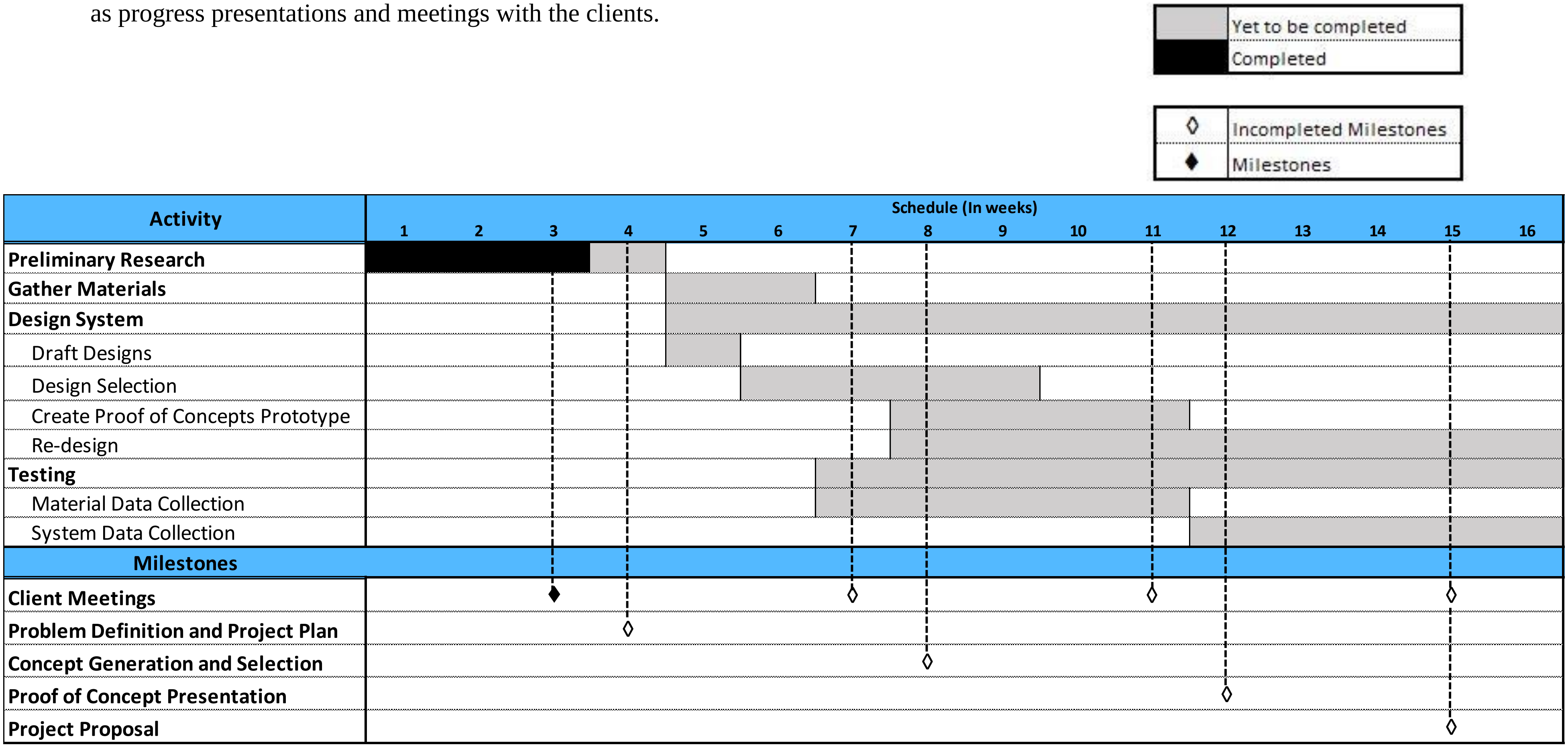

Figure 4: Gantt Chart

6 State-of-the-Art Research

Terfenol-D is the main component of the actuator design and it requires knowledge of magnetism, hysteresis effects, and material properties. Therefore a large portion of this project will be researching. The capstone team obtained a presentation on magnetic actuators and solenoids from the client, Michael McCollum, that has helped with understand of the basics for designing actuators. The team has also obtained a book titled *Electromagnetic Devices* by Herbert C. Rotors to begin researching magnetic machines [2]. Dr. Constantin Ciocanel, a faculty member in the mechanical engineering department at Northern Arizona University, has also been contacted to offer his expert advice and information on smart materials. The team will also be using various reliable informational databases such as Engineering Compendex, WorldCat, and Google Scholar to obtain relevant articles and a dissertation on magnetostrictive materials from Ohio State University.

Terfenol-D was originally developed by the U.S Navy at the Naval Surface Warfare Center in Indiana, but other magnetostrictive materials were first discovered in 1842 [3,1]. Only more recently however, during World War I, has magnetostriction been considered as a viable resource for new electromagnetic devices.

There are several devices already using both Terfenol-D and other magnetostrictive materials in different types of inventions. The Navy uses magnetostrictive materials to generate sonar for detecting submarines. The basic design of the sonar system is a Terfenol-D rod surrounded by a solenoid that rapidly oscillates a magnetic field. The field then passes through the magnetostrictive rod and causes it to elongate and push on a vibration plate, thus creating a sound wave before contracting again. The rapid movement of the vibration plate creates sonar pulse [4, 3]. The Navy also developed the magnetostrictive material intended for this project, called Terfenol-D and sold the patent to Etrema. Since then, Etrema has developed and patented several different devices including different types of sonar and actuators [1].

To begin to understand how to use Terfenol-D, an understanding of magnetic fields must be incorporated. A magnetic field can be represented similar to an electric circuit where the magnetomotive force ($\mathcal{F}$), magnetic flux (ϕ), and reluctance (R_m) represent voltage, current, and resistance respectively. There are two main components caused by a magnetic coil, the first is magnetic flux density (B), and the second is magnetic field strength (H). The flux density of an electromagnet depends on the number of turns per unit length [5]. Another term that is relevant to Terfenol-D is the piezomagnetic constant which is used to relate magnetic and mechanical properties of a material [6].

Terfenol-D is composed primarily of iron and terbium, but also contains small amounts of dysprosium. Due to the fact that it is made with a large amount of iron, the tensile and compressive strengths of Terfenol-D are very similar to those of iron. However, Terfenol-D has much greater variation in the values depending on the method by which it is produced [1, 7]. Terfenol-D has a tensile strength of 28-40 MPa and a compressive strength of 300-880 MPa; the compressive strength of Terfenol-D allows it to be pre-stressed even before being subjected to a magnetic field, however tensile strength of the material drastically limits its use in many other types of engineering applications [4]. The unique properties of Terfenol-D are of more interest for the application of this material. The strain generated when Terfenol-D is placed under a magnetic field are substantial. According to the manufacturer's website, Terfenol-D can produce strains of up to 0.12% and has a piezomagnetic constant of up to 10 Nm/A [1].

Using informational slides gained from the client, Michael McCollum, the team was able to gain valuable information regarding solenoid operation and design. A common type of solenoid is composed of a magnetic wire for coiling and a ferrous type core i.e. iron core [5]. Honeywell started implementing their same solenoid design concepts to Terfenol-D to use as an actuator for airplane A/C systems. Results show that there is potential for this idea due to the fact that the material acts as predicted under the magnetic conditions [5]. For the Terfenol-D to be feasible for actuator use further testing needs to be conducted on certain aspects, such as material stroke and output force. The team will further analyze the research this year to validate whether or not Terfenol-D is an option for actuator use.

Dissertation research conducted by graduate student named Suryarghya Chakrabarti from Ohio State University includes magnetostrictive characteristics and structural features of Terfenol-D. An important conclusion from Chakrabarti’s research is that the Terfenol-D exhibits non-linear coupling and hysteresis effects in an actuator system. The dissertation also includes information on a similar magnetostrictive material called Galfenol, which is also being tested for actuator use [8]. This information will be utilized in the capstone team’s own data collection and research.

When a material such as Terfenol-D is magnetized, an unwanted phenomenon occurs called hysteresis. As shown in Figure 5 [8], the poles of the magnetic domains at the atomic level are all oriented somewhat randomly before the magnetic field is applied [8]. Once the field is applied, these domains line up and point in the direction of the field lines. During this motion of the domains, energy is dissipated and lost through friction between the molecules. When the magnetic field is removed, some of the domains will attempt to return to their original, comfortable direction. However, not all domains will return to their original position because of the lost energy. This will cause latent magnetization to remain in the material. In order to return the magnetization to zero, an external magnetic field or force must be applied in the opposite direction [8]. This hysteresis effect must be compensated for in the design of the actuator. A common method used for overcoming hysteresis is to stress the material, which forces the molecules into a specified initial orientation [8].

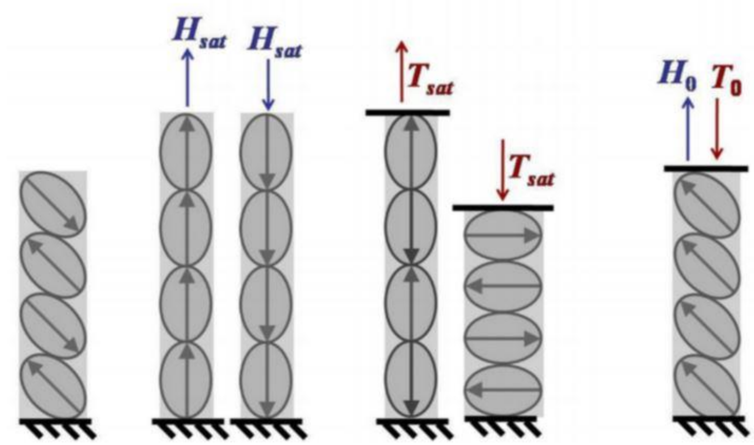

Figure 5: Diagram showing magnetostrictive expansion

State-of-the-art research is an ongoing process, and research will continue to be gathered and analyzed throughout the course of the project. This allows for new design ideas to be considered that may be more effective or efficient than ideas generated from previous research.

7 Conclusion

In summary, the report has defined the problem presented by Honeywell and planned the upcoming tasks and goals of the project. The goal of this project is to determine the feasibility of using Terfenol-D in actuators for aircraft valve systems because of its magnetostrictive properties. 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 being conducted to gain an understanding of the theory behind the features of the design. From this research a comprehensive list of references is complied. The various reports and studies will contribute to the next phase of the project. Now, the team is ready to begin developing design concepts and test their performance against each other.

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