MEEN 401-900

Design Review 3 Final Report

Embedded Valve and Actuator Sensors

December 4, 2023

Bray Engineering

Avery Haynes

Locke Lehmann

Cody Sims

Travis Carlson

Zachary Walker

Michael Hager

EXECUTIVE SUMMARY

The topic of this Design Report is the concept generation and selection for a method to determine key parameters within a Bray valve-actuator system. The senior design team working with Bray is: Zachary Walker, Cody Sims, Locke Lehmann, Avery Haynes, Michael Hager, and Travis Carlson. Bray assigned the team with developing a method to determine:

A) Valve position while in operation, independent of other parameters
B) Actuator output torque, independent of other parameters

Ball and butterfly valves play a pivotal role in a wide range of industrial applications and processes that encompass the conveyance of virtually any type of fluid medium. Failures or unanticipated performance degradation of these components can result in prolonged system shutdowns and may even pose a risk of worker exposure to hazardous gasses. Actuators, like valves, come in many different types. This project will mainly focus on rack-and-pinion style and scotch-yoke style actuators, both of which are manufactured by Bray. The torque supplied by the actuator may deteriorate over time, making it essential to obtain real-time data while the actuator is in operation. To mitigate these hazards and prevent productivity losses due to downtime, there is a need for a solution that can assess the valve or actuator condition over time.

Bray's current approach to torque measurement is the *IOT Torque Bracket*, which gauges the reaction torque exerted from the valve to the actuator. However, this method does not provide insight into the actuator's remaining operational capacity, making it unable to predict when the actuator might fail to control the valve. This issue is of great concern to Bray and their customers because an actuator malfunction can lead to valves becoming stuck in undesirable positions, potentially disrupting the functionality of the entire system to which the valves are integral.

Given the inherent non-digital nature of pneumatic actuators, like the two mentioned above, which lack built-in mechanisms for data recording and transmission, an external or integrated solution becomes imperative. Introducing an embedded sensor designed to measure actuator output torque independently of the reaction torque from the valve would empower Bray and their customers to continuously monitor actuator performance. This capability would allow them to determine precisely when an actuator requires replacement, thereby minimizing disruptions and maintaining the optimal functionality of their systems.

Through the first semester of the project, the design team has determined that indirect measurements are not desired due to their nature of being based on other parameters. The avoidance of indirect measurements will contribute to increased accuracy of data collection, although it adds difficulty to the project. Bray has placed a large focus on the accuracy of both methods they desire. Quantitatively, Bray would like the team to keep the error of the system under five percent. This requirement will drive the team to select the most accurate equipment and develop a process with the least amount of added error.

The design team has developed several possible solutions for each deliverable by utilizing different concept generation methods discussed in lecture. These methods include: brainstorming, mind-maps, TRIZ matrices, analogous designs, and bioinspired designs. A dozen concepts were created, and each were deeply analyzed using Pugh charts, IIAE matrices, and quantitatively driven team effort selection matrices.

For the valve position deliverable, the team is carrying out two separate solution concepts to be tested in the following semester. One is the potentiometer concept which is a way to determine position by connecting to the rotating ball in an electrical circuit. Potentiometers have relatively high accuracy and can be cheap to purchase. As the valve rotates, a potentiometer connected under the valve will vary in voltage depending on the position of the ball, so each voltage value will correspond with a degree of openness of the valve. This idea is very promising due to its strong performance in crucial aspects like accuracy and lack of influence on valve performance. The second solution includes magnetizing part of the ball and pointing a Hall Effect sensor to it. The sensor will be calibrated to recognize the open and closed position of the valve. As the ball rotates, the sensor will notice the change of the magnetic field and associate it with the valve's position.

Similar to the valve, the team is carrying out two separate solution concepts to be tested in the following semester. The first being a cylindrical strain gauge attached to the stop bolts in the actuator. The strain gauge will measure the deflection of the stop bolts as the spinning actuator comes into contact with them and the data acquisition unit will use material properties of the bolt to convert that strain into the applied torque, The second option for torque measurement is a motor-like device that will attach to the top of the actuator housing and slide a conducting belt around the indicator switch. This belt will pass through a magnetic field and generate a voltage in the motor whenever the valve opens or closes, and this generated energy can be correlated with the torque generated by the actuator.

These concepts were selected due to their accuracy, lack of interference with the system, and their simple embedded nature. After selecting these concepts, the team developed a risk analysis tree, a validation plan for MEEN 402, and performed some small-scale validation of the potentiometer for measuring position. Further details and products for each solution were also researched and decided upon. Moving into MEEN 402, the design team will continue to research parts for purchase and testing, refine the potentiometer designs in order to adhere to budget constraints and deliverable requirements, and compare results from each solution in order to determine the best one to present to Bray for implementation.

TABLE OF CONTENTS

GLOSSARY TABLE

Abbreviation	Definition
HOQ	House of Quality
TDD	Task Dependency Diagram
WBS	Work Breakdown Structure
IOT	Internet of Things
BOM	Bill of Materials
DAQ	Data Acquisition Unit

INTRODUCTION

Bray is one of the world's premier manufacturers of flow control and automation products and accessories. Bray's excellent reputation includes creating products of superior value and quality compared to competitors. This semester, our team was assigned to work with Bray to develop a method to internally measure valve position independent of an actuator and measure actuator output torque. Developing a solution to solve these deliverables would provide an understanding of actuator performance, thus improving service life. A sensor system that can report the output torque of an actuator and valve position in service will decrease downtime and maintenance costs. Increasing the valve's service life would allow Bray products to become more competitive in the market. Bray currently has an external solution for measuring actuator output torque from the stem's reaction forces, but finding an internal solution would be more beneficial for Bray so they wouldn't have to sell a separate product for this issue. Solving these problems would allow Bray to sell the actuator and valve without an external connection and a longer time before product maintenance, creating more value for the products.

BACKGROUND RESEARCH

Bray manufactures both valves and actuators of many different types. Bray provided the team with CAD models of the main types of valves and actuators to be used in this project. An understanding of how valves and actuators must work together is crucial for understanding the necessity of a solution to provide position and torque data.

Valves

Bray manufactures many different types of valves, but this project will focus on ball valves and butterfly valves. Bray designs these valves to remain either totally open or totally closed; that is, they are not meant to hold any positions other than 0 or 90 degrees. If a valve is not exactly opened to 90 degrees or shut to 0 degrees, unwanted leakage or disruption in the fluid flow could occur, which Bray's customers do not want since it would affect whatever process they are using the valve for. Butterfly valves consist of a thin disk that can be turned on a rod running down its center to open or close a fluid line. While butterfly valves are lightweight and easy to manufacture, they have some downsides, including an ever-present possibility of leakage [1]. Their turning ability is also affected by the pressure of the fluid being controlled, and the fact that the open disk remains in the fluid stream can cause unwanted pressure changes in the fluid. Ball valves are metal spheres with holes drilled through them to allow fluid flow depending on position. Ball valves are more secure than butterfly valves, due to the tight seal that the ball makes with the fluid vessel (with a wider margin for leakage error) and allow complete passage of the fluid with no obstructions [1]. However, they are more expensive to manufacture and are larger and heavier than butterfly valves [1]. Adding a sensor or some other method of measuring valve position will help Bray monitor if their valves are ending up at a position between open and closed, which would hurt valve performance and may be indicative of buildup on the valve. **Figures 1** and **2** show these valves. Bray's CAD ball valve models are shown in **Figures 3** and **4**.

Figure 1: Ball valve example [1].

Figure 2: Butterfly valve example [1].

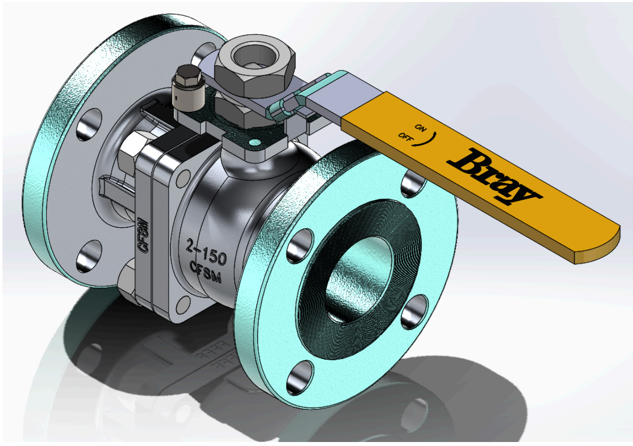


Figure 3: Bray ball valve assembly closed.

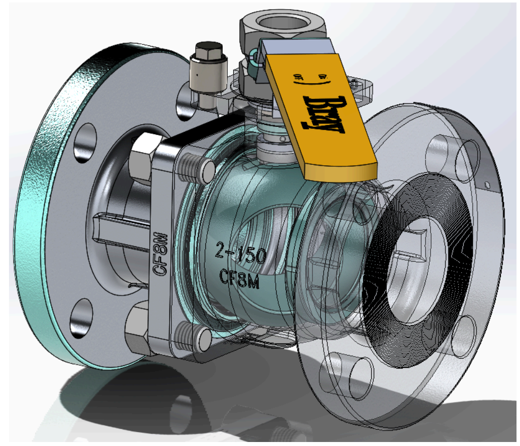


Figure 4: Bray ball valve assembly partially open.

Actuators

The actuators that Bray designated for this project are rack-and-pinion style [2] and scotch-yoke style [3] actuators, both of which are pneumatically operated. Scotch-yoke actuators transfer mechanical motion into rotation of a shaft that turns the valve open or closed [4], while rack-and-pinion actuators contain two plates that symmetrically move away from each other and teeth attached to the plates rotate the valve shaft [4]. Both of these types of actuators can be designed to be either normally open or normally closed, meaning that if there is a power failure or some other sort of disruptive event, the actuator will revert the valve to being either open or closed, depending on safety protocol [4]. The torque that the actuator provides can degrade over time, so receiving that data as the actuator is in operation can help identify issues before they become detrimental to valve operation or fluid flow. **Figures 5** and **6** show the internal workings of the rack-and-pinion and scotch-yoke actuators from Bray that this project will focus on. **Figures 7** and **8** show the CAD models, one of each type of actuator.

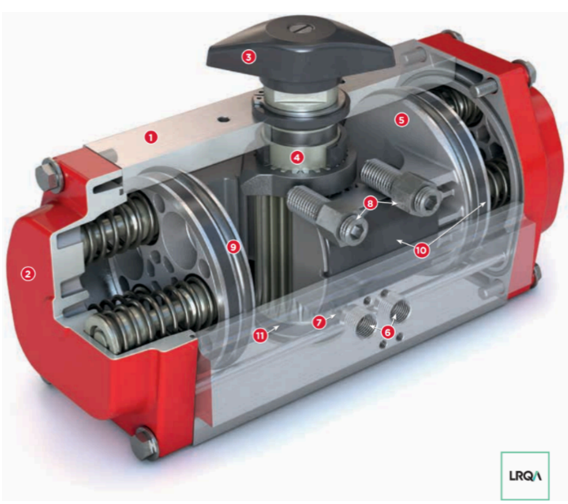


Figure 5: S92 rack-and-pinion actuator [2].

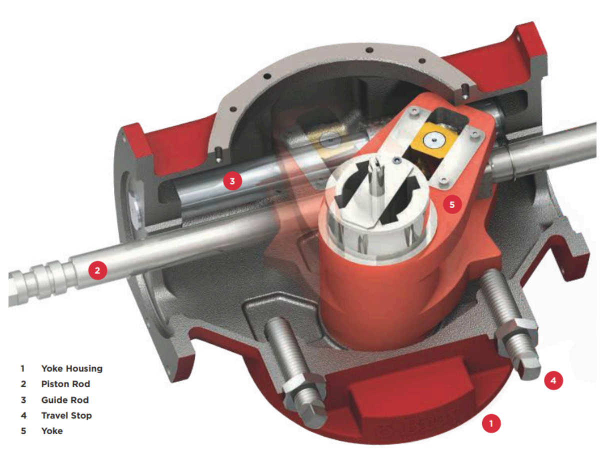


Figure 6: S98 scotch-yoke actuator [3].

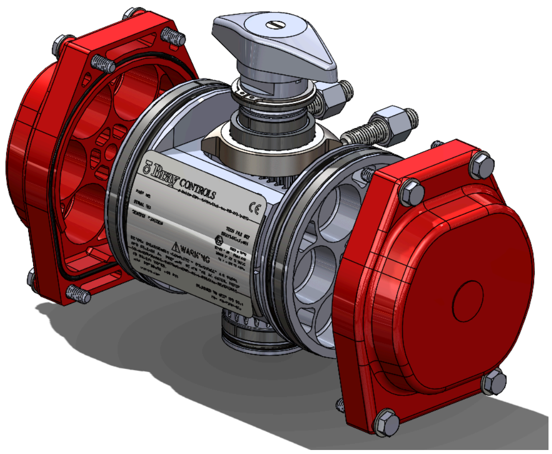


Figure 7: CAD model of S92 actuator.

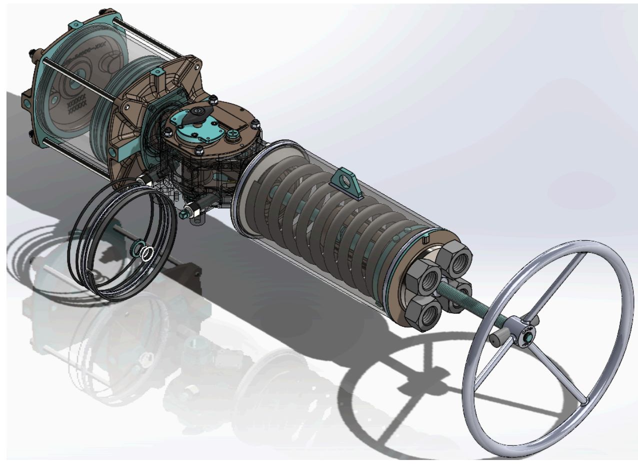


Figure 8: CAD model of S98 actuator.

Current Solution

Bray's current solution for measuring torque, the IOT Torque Bracket, measures reaction torque from the valve to the actuator. However, this does not predict when the actuator will fail to operate the valve since it does not measure the maximum capacity of the actuator. Bray and their customers care about actuator torque since a failed actuator will cause valves to be stuck in the wrong position, which could interfere with whatever system the valves are a part of. An external or embedded solution is necessary because pneumatic actuators such as the two displayed above are non-digital, meaning they have no built-in method of recording and transmitting data. An embedded sensor to measure actuator output torque, independent of reaction torque from the valve, would enable Bray and their customers to monitor actuator performance over time to determine when an actuator needs to be replaced. The IOT Torque Bracket is available as an attachable assembly to an actuator, and while it is functional, it could be improved upon by being made embedded, smaller, and more accurate.

Market Solutions

To understand the need for the embedded monitoring system proposed by Bray, alternative market solutions for external torque brackets should be considered as well as their effectiveness in accomplishing the project's mission. As a method of diagnosing the performance of an actuated valve, hand-held and attachable torque sensors do currently exist on the market. An ABQ hand-held torque meter [5] is a device that can be placed over almost any rotating cap or wheel. As the vices that grip onto the cap are rotated, the resistance torque applied by the sensor rod is read by the computer, and translates this signal into a torque measurement that can be read and recorded. While this product can be accurate and diagnose valve health, it is only an intermittent solution. This product cannot measure the torque when an actuator is placed on the valve, and must be tediously used continuously over time to track the general performance trends. Additionally, this product does not monitor the actuator's capacity.

Other solutions, such as a Futek Valve Torque Sensor [6], offer a more continuous monitoring solution. This sensor is used in place of a valve bracket that normally separates the actuator casing and valve housing. When the actuator is toggled and rotates the valve shaft to open or close the fluid system, it creates a reaction moment against the fasteners that hold it in place. The sensor then uses strain gauges placed along its casings to determine the reaction torque that acts on the valve. This system is a commonly used solution in monitoring the performance of actuated valves. The problem with this, however, is these types of sensors only measure the reaction forces of the actuator, meaning it must be acting on an object in order to be measured. This distinction makes it impossible to know the performance of the valve or actuator independently of each other, so while this product may monitor the health trends over time, it is impossible to know what part of the system is failing when it comes due for maintenance.

PROBLEM

The following solution-neutral problem statement was used to guide the project:

Develop a method to internally measure valve position independent of an actuator, measure actuator output torque, and detect fluid leakage to increase the service life of the valve.

These are three issues related to the central problem of live monitoring of valve performance. However, the first two were quickly identified by Bray as more important, so the remainder of this report will only focus on position and torque, with leakage being more of a "stretch goal".

Position Problem

The first goal of the project is to measure the position of the ball valve without relying upon the state of the actuator. The actuator and the valve can sit at different angles when they are supposed to be perfectly in line with one another. The cause of this is hysteresis error in the valve stem. Hysteresis is an error resulting from a change of direction. In this specific application, error results from the fact that there is some looseness in the stem between the actuator and the valve, so the actuator and valve may not always be in the same position, and the valve may not be completely open or closed. Since the actuator may turn a few degrees before the valve begins to turn, due to this hysteresis, the valve may open to 87 or 88 degrees when it is supposed to turn a full 90 degrees. This produces an issue when the fluid flow is interrupted and does not flow as the customer expects it to. Hence, Bray would like to know the angle at which their valves are positioned so they can quickly identify hysteresis errors and work on correcting them. Material buildup can cause the valve to become more difficult to open over time, so knowing the trends in position data can help Bray know how long it takes their valves to degrade and what timeline they must implement for preventative maintenance or cleaning.

Torque Problem

Bray would also like a method of determining the maximum output torque of an actuator, rather than simply finding the reaction torque needed to operate the valve. The actuator could fail to operate the valve due to two possible conditions. First, the actuator's capacity to provide torque can decrease over time due to mechanical wear or material buildup that contaminates its components. Second, the torque required to operate the valve can increase over time due to these same factors. As the required valve torque increases and the available actuator output torque decreases, the assembly may reach a point where the actuator is no longer sufficient to operate the valve as desired, so preventative maintenance must be performed to clean, re-calibrate, or replace the parts. Bray's goal is for the project team to develop a method for determining the maximum possible actuator output torque in real-time so that this maintenance can be predictable and planned. This way, Bray and customers can monitor the performance of their products in real-time so they can make better decisions about valve and actuator design and service life.

Possibilities and Conflicts

Bray has given clear statements of the three problems, but avenues for creativity still exist within the given boundaries. Some opportunities for innovation here are the open-endedness of the problem statement regarding the type of sensors used, the possible location of the sensors (although they must be embedded to represent a step forward from the IOT Torque Bracket), and how the data is recorded and sent to a computer. Bray has expressed interest in utilizing 3D metal printing technology to help develop a solution. Additionally, it is not required that these two parts of the problem have two separate products as solutions, but the possibility of combining two solutions into one will be determined as feasible or not further into the problem-solving process. The inherent underlying issue with these pneumatic actuators is that they are operated by compressed air, which is a physical means, not an electronic one, so they have no built-in method of recording and transmitting data. A solution for measuring torque and position would help Bray to analyze this section of their products in the same way they can see real-time data from their digitally operated valves. Some potential conflicts with this design process include differences in the data that Bray is interested in versus what data their customers are interested in from the valves and actuators, which will be explained further in the next section. Another potential conflict is lead times for parts that may need to be ordered to create the solution, which could be done in Bray's research and development facilities. Parts with shorter lead times will be preferable since the project is limited to the duration of the school year. Bray is open to a two-product solution or a one-product solution, so there is flexibility in the modularity of potential products to be developed.

Markets and Stakeholders

The primary market for a position and torque solution will be manufacturers, utility companies, or other corporations who purchase valves and actuators from Bray. These companies will be the ones interested most in the position and torque data, as it will affect their final product or service so they will be looking for ways to ensure high quality. Secondary markets are individuals or companies who purchase goods or utilize services provided by the primary corporations. For example, a power plant relying on a utility service to provide water for steam to run turbines would be a secondary market for the position and torque solutions. The utility plant would be the primary customer using Bray's valves, actuators, and accessories to regulate the flow of water towards its clients. The utility plant would be most interested in accurate valve torque and position data as it directly affects their output, and they are the ones purchasing the valves, actuators, and solutions, but the power plant that consumes the water provided is still a secondary market because they are impacted by the performance of those Bray parts as well. The main stakeholders of this project are: Bray, who wish to provide valves and actuators with data processing capability; Bray's clients, who care that the products they purchase have built-in troubleshooting ability and a long lifespan; and the project team in MEEN 401, who want to successfully complete the project for a good grade and for valuable real-world engineering experience.

CUSTOMER NEEDS

Table 1: Customer needs table.

#	Need	Importance
1	Final product is embedded into the actuator casing	1
2	Product is scalable for different-sized valves	2
3	Product records and transmits sensor data	1
4	Works in a wide temperature range (-40℉-300℉)	4
5	Works under various pressures (100 psi - 740 psi)	3

6	Works for various fluid mediums	4
7	Measures actuator torque to < 5% error	1
8	Relatively short lead times for parts (3-4 weeks)	2
9	Determines true valve position independent of actuator	1
10	Works for both pneumatic and hydraulic actuators	3
11	Short time for calibrating the sensor	3

Throughout our discussions with Bray, we have consistently prioritized meeting the exact needs of their customers. **Table 1** displays these needs, assessed on a scale of 1-4, where a rating of 1 indicates the highest importance, and a rating of 4 signifies the least importance. The most critical requirements identified are as follows:

1. The final product must function as an embedded sensor within the actuator/valve casing.

2. It should possess the capability to autonomously determine the true valve position, independent of the actuator.

3. Efficient recording and transmission of sensor data are essential.

4. Ensuring accurate measurement of actuator torque, with an error margin below 5%, is of paramount importance.

These requirements are considered non-negotiable by Bray and are integral to our product development process. In addition, there are other important yet slightly less critical needs.

1. It must be scalable to accommodate valves of different sizes.

2. It should operate effectively within a wide temperature range (-40°F to 300°F).

3. It must be compatible with a range of pressures (from 100 psi to 740 psi).

4. The product should be adaptable to various fluid mediums.

5. It should be designed to work with both pneumatic and hydraulic actuators.

6. The product should be user-friendly and reliable.

It is crucial to recognize the distinctions between Bray's requirements and those of the end customers. Ultimately, the primary purpose of this product is to serve as a data acquisition tool, providing Bray with a deeper insight into valve performance. On the other hand, customers simply seek a dependable and user-friendly flow control system. The data obtained through this product will empower Bray with valuable insights into the longevity and condition of their products, enabling early diagnosis of potential issues and failures.

Furthermore, during our conversations with Bray, it was concluded that the task of identifying valve leakage was currently unnecessary. Instead, our efforts should be purely focussed on determining valve position and actuator torque.

Achieving a successful design for this product entails fulfilling all essential criteria: embedding sensors within the system to facilitate data collection on valve position and torque output for Bray, while also delivering a reliable and user-friendly product to meet the customer's needs. In theory, this product has the potential to be a unique offering in the market, poised to bring significant advantages to Bray's customers. It promises to elevate the level of reliability and control within flow systems significantly, leading to increased production and efficiency for those who adopt this innovative solution.

DESIGN REQUIREMENTS AND HOQ

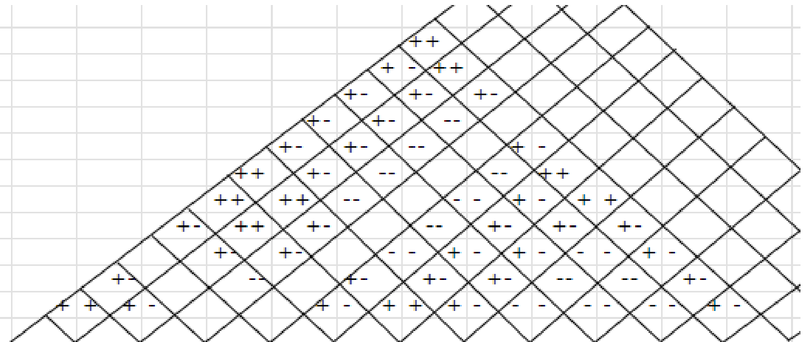
Customer Needs

The results of the customer needs in **Table 1** were used as a base for the design requirements for our project. The most critical customer needs were the deliverables of measuring valve position and actual actuator torque. These deliverables were necessary design requirements because if the team failed to design a solution to solve those deliverables, then the product would fail due to not collecting the data.

Moving forward and analyzing the customer needs table with the overall design in mind, the requirements of embedding the sensors, the ability to scale the design to different sizes, and the accuracy of the measurements were determined to impact the overall design. Embedding the sensors is necessary for the valve to be a smart device and was chosen as a design requirement by measuring the location of the data collection. Scaling the different designs is crucial as they have to be able to work at every size of the valve, or else the market will be too small to sell the valve effectively. Lastly, one of the most essential design requirements is the accuracy of the measurement. Bray stated a hard limit that anything over 5% uncertainty is unusable data. Combining all of this information from the customer needs our team began constructing what the required performance of our design was.

House of Quality

Using the customer needs identified above and input from Bray, the team began formulating the needs and metrics for the House of Quality (HOQ), seen in **Figure 9** below.



Bray: Embedded sensors and actuators	Importance	true vlave Accuracy <5%	Torque Accuracy <5%	size of sensors	location of sensors	power consumption	max temperature rating of sensor	max pressure rating of sensor	number of wires	Impact on performance of valve and actuator	weight of sensors	number of sensors	Ease of Implementation
min (-), max(+), nom(*)		+	+	-	*	-	+	+	-	-	-	-	+
Measure true valve position	5	9		1	3		3	3		3		1	3
Measure Actuator output torque	5		9	3	3		1	1	1	3		1	3
Gas leakage measurement	4			1	3		1	1				3	
embedded	3	3	3	9	3		1	1	3	3	1	3	3
Scalable	3	3	3	3	3				1	1		3	3
work under high and low pressure	1	1			3			9					
work for both pneumatic and hydraulic actuators	2		9		1					1			
work under high and low temps	1	1			3		9						
Data transmission and power	2	3	3			9			3			3	1
Units		%	%	in^3	vlave parts	Watts	F	Psi	umerical	%	lbs	umerical	me (min)
Absolute importance		20	27	17	22	9	15	15	8	11	1	14	13
Relative importance		71.0	87.0	60.0	68.0	18.0	36.0	36.0	23.0	44.0	3.0	46.0	50.0
Technical difficulty		9	9	1	3	3	1	1	1	3	1	1	3
IOT Torque bracket		N/A	5%	8	Stem	20	73	14.7	3	0%	0.50	1	1 hr
Targets		5%	5%	6	Body & stem & Actuator	10	340	720	7	0%	1.50	3	10 min

Figure 9: House of Quality for embedded sensors and actuators project.

The highest-importance customer needs were chosen as the needs for the HOQ. The Bray team suggested data transmission and power as a need to think about how the generated designs will be powered and how much power they will consume while running. After formulating the needs for the HOQ, the team collectively agreed on the importance of each need, using five as essential and one as optional. Then Bray reviewed the needs and importance scale to provide feedback to the team. The feedback was positive, with the only adjustment being that the embedded need should be lowered from our initial score of a four to a three as they had decided that it wasn't as hard of a requirement as they initially thought. After the needs were finalized, two or three metrics were generated that effectively measured each need. The selected metrics can be seen in the top row of **Figure 9** shown above.

After the needs and the metrics were identified, the correlation between the metrics and needs was identified using input from our team members and then later from Bray. A nine represents a strong correlation, a three represents partially correlated, and a one is semi-correlated. The absence of a number means the metric is not related to the need in any way. The best way to analyze these results is to look at each metric's absolute and relative importance, with a higher number correlating to a higher importance.

Importance of HOQ Metrics

The first thing to look at is absolute importance, which is the sum of every number in the metric column but does not account for the importance of each need. This is useful to determine which metric correlates to the most needs. The highest-scoring metric on the absolute scale was torque accuracy, with a score of 27, followed by the location of sensors, with a score of 22, then valve position accuracy, with a score of 20, which can all be seen in **Figure 9**. A higher score indicates that it is more impactful on meeting all of our customer needs. The top three metrics correlate to the most customer needs, meaning that they should be the focus of our design and be used in concept selection and refinement. The torque accuracy was higher than the valve position due to having to design for two different types of actuators, making the torque accuracy related to more customer needs. The other metrics were considerably lower than the ones mentioned above, showing that these metrics were not strong measurements for meeting customer needs.

The next criterion to analyze is the relative importance, which factors in the importance of the customer needs and the strength of the correlation between metrics and customer needs. The results can be seen in **Figure 9,** demonstrating that the same three metrics are still the highest. However, the order changed to torque accuracy as the highest still, then valve position accuracy, then the location of sensors. The relative scores provided values closer to what was desired, with both of the accuracy scores being the highest, as requested by Bray. This verified that the main focus when designing should be lowering the uncertainty of the collected data. It also showed that the location of the sensors was a more critical metric than was initially thought, with the location sensors having some correlation to almost all the customer needs. Also, the ease of implementation and the size of sensor metrics had more importance on the relative scale, showing that they are metrics that our team should keep in mind when deciding which ideas are feasible and selecting our final concept.

Finally, the roof of the house was analyzed in **Figure 9** to see how the different metrics interacted with one another to see if any complications would arise when minimizing and maximizing values. The most straightforward interaction was comparing ease of implementation and the sensor weight, size, and number. The product is easier to implement when the size, weight, and number of sensors are decreased. This identified that a design requirement should be compact and have few parts to be easy to implement. Our team also noticed a similar interaction with the accuracy metrics, as the fewer moving parts in the system, the less error there will be. Another interesting interaction is how the power consumption and accuracy metrics work against each other. For most sensors, more power will be consumed to achieve more precise measurements. Our team wants to minimize the power consumption, so it is necessary to balance the accuracy to be under 5% while not consuming too much power.

Overall, the House of Quality was beneficial by analyzing every customer need that had been identified and quantifying each need with at least one measurable metric. This helped the team identify what will be focused on when making design selections as it evaluates what is truly important, ensuring that the selected design prioritizes accuracy and the positioning of the sensors. It was also found that the size, weight, and number of sensors must be reduced for the design to be easily implemented. The HOQ was good at organizing all the metrics and customer needs in one place so that our team could better see how each need should be weighted for importance and measured in relation to our project.

Codes and Standards

The scope of our project is the research and development of a system of sensors to be embedded into a valve, so since there is no market product, our problem does not have specific codes or standards. However, the valve in which the design is placed is heavily regulated due to safety concerns associated with high pressures, temperatures, and hazardous fluids. In **Figure 10,** a bulleted list of the standards that valves are held to can be seen.

a. The valve must be of a sound engineering design.

b. Materials subject to the internal pressure of the pipeline system, including welded and flanged ends, must be compatible with the pipe or fittings to which the valve is attached.

c. Each part of the valve that will be in contact with the carbon dioxide or hazardous liquid stream must be made of materials that are compatible with carbon dioxide or each hazardous liquid that it is anticipated will flow through the pipeline system.

d. Each valve must be both hydrostatically shell tested and hydrostatically seat tested without leakage to at least the requirements set forth in section 11 of API Standard 6D (incorporated by reference, see §195.3).

Figure 10: US federal code for transporting hazardous liquids through a pipeline. [7]

The code for transporting hazardous liquids was chosen because our team assumed that if the selected design meets the conditions to be used in the hazardous liquids pipeline, then it will also meet the conditions to be used in a normal pipeline. These codes are important to keep in mind for our project because the team has to ensure that the design does not compromise valve integrity such that these conditions are not met. Also, if the design is in contact with a hazardous fluid, it must abide by these codes. The technical specification of the federal code is Transportation of Natural and Other Gas by Pipeline, section 49, CFR 192.145 [7].

For item a of the code, making sure the valve is of sound engineering is something that was always planned on. The project is to improve the valve so that preventative maintenance can be done. If our team's concepts negatively alter the valve's functionality, then the design is not feasible. Also, Bray valves are of very sound engineering, being what they pride themselves on, so it is difficult for our team to make such a drastic change to the valve that this will become an issue. The flange part of Item b in the code is something that our team also will not have to consider as the solutions will be located around the ball of the valve and the actuator and will not be dealing with how the flange of the valve is connected to a pipe.

Items b and c in the code state that all the valve parts in contact with the hazardous fluid must be compatible and withstand the internal pressure. This correlates with our project because some concepts could be in contact with the fluid when determining the true valve solution. This means that if a concept is generated in contact with fluid, it must be designed not to dissolve when in contact. This gets complicated when multiple hazardous chemicals run through the same valve. This also caused our team to think about the extreme temperatures and pressure that the fluid is placed under and how hard it would be to make a design that could withstand those conditions. Due to the difficulties of implementing sensors in toxic material and extreme conditions, our team developed a requirement that the concepts do not interact with the fluid.

Finally, evaluating item d in the code, which states that all valves must be tested to see if there is leakage in the shell or seat. This code corresponds to the third deliverable of valve leakage, helping determine where our team should be monitoring for the leaks. However, this item no longer applies to our team's project as Bray recommended focusing on valve position and torque, as those were the two deliverables they cared more about. However, If our team decides to revisit the leakage problem, looking into this standard more will provide useful data on where the most leaks occur.

Overall, this method of determining design requirements was not very useful because the project is developing new technology applications. Hence, there are no codes in place that regulate our design. This meant that codes and standards for the body of the ball valve were examined, ensuring that the designs generated did not interfere with the valve staying up to code. Still, this method did generate new design criteria for keeping the sensors out of contact with the fluid due to the complications with hazardous material and high temperatures and pressures.

Requirements Checklist

After most of the needs and metrics were understood, our team analyzed how they applied to the specification checklist categories. The categories discussed are geometry, kinematics, forces, energy, material, signals, safety, production, quality control, operation, maintenance, and costs. These categories were chosen as they applied the most to the problem of determining the position and torque of the valve. The compiled checklist can be seen below in **Table 2,** and it shows the requirements our team associated with each category.

Table 2: Requirements checklist for embedded sensors and actuators.

Category	**Requirements**
Geometry	Sensor must be smaller than 5 in^2 to be embedded; one solution for each deliverable; location inside the valve casing, stem, or actuator casing
Kinematics	Measure rotational motion, find velocity and acceleration of the actuator
Forces	Withstand maximum actuator force, about 150 lbs; if using dynamics, must find moment of inertia for the valve system; account for deformation
Energy	Store enough energy for sensors for at least a year; input electrical energy
Material	If a sensor is in contact with the fluid, it must withstand pressure, temperature, and hazardous fluids; high strength, and low deformation to

	withstand millions of cycles of use.
Signal	Transmit easy-to-read data collected from sensors, user-friendly display
Production	Limited to size of valve casing, preferred production is metal 3D printing, low tolerance between ball and the valve casing
Quality control	Measurement accuracy below 5% error
Operation	Have a sensor life of a minimum of 20 years, market area: smart valve
Maintenance	Access point to service the sensor, Low inspection interval
Costs	Balance cost and accuracy of the sensor with upper sensor limit = $300

The requirements checklist was extremely useful to look at the full scale of the project and not just the sensor aspect. It got our team thinking about the requirements of power that would be used, selecting electrical energy as the best way to power the sensors. It also was used to think about what was needed to transmit the data and how the display of data has to be user-friendly. However, when this information was presented to Bray, they emphasized that the power and transmission could be worked out after the team came up with a concept that had been tested and proven to work. Due to this reason, the team decided to lower the importance of the power requirement, and our team plans to revisit this issue in MEEN 402.

Using the requirements checklist also provided insight into quantifying our design requirements. These numbers were picked on some preliminary research and input from Bray so that the generated designs would be feasible. Examples of this include the size of the sensor being limited to 5 in^2 and the less than 5% error for the sensor itself. Setting these quantitative limits helps separate feasible and infeasible designs for the concept selection phase.

The requirements checklist was not very useful for our project because most of the items that related to our project had already been covered in the customer needs, HOQ, and codes and standards methods. However, it was a good method to think about what quantities each design requirement was limited to so that concept selection could go smoother. Our team does see a use for this method when the project has a huge scope and a lot of parts to make sure that everything is accounted for, but for a smaller scope, it just verifies that every aspect of the project has an assigned requirement.

Requirements Document

Compiling the results from the customer needs, the HOQ, the codes and standards, and finally, the requirements checklist, the following requirements document table was made. If requirements were too specific, meaning that they only affected certain solutions, they were left off to not limit ourselves during concept generation. Some metrics were combined, like torque accuracy and position accuracy, due to them needing the same accuracy percentage. **Table 3** is shown below, with the higher importance being a five and the lower importance being a one.

Table 3: Embedded valves and sensors design requirements document table.

Req,t #	Need #	Metric	Imp	Required Values	Units
1	7, 9, 10	Measurement Accuracy	5	< 5	%
2	1, 2, 4, 5, 6	Location of sensors	4	Valve casing, Stem, Actuator casing	N/A
3	3	Lifetime of sensors	3	> 20	years
4	8	Ease of maintenance	2	< 4	# parts
5	2, 11	Ease of implementation	3	< 2	hours
6	11	Calibration Time	3	< 2	hours
7	1, 2	Volume of apparatus	1	< 5	in^2
8	3	Power consumption	1	< 100	Watt hours

The most important takeaway from **Table 3** is the determined required values for each metric. These values determine if the design is feasible and fits within these constraints or fails them and will not be a viable design option. The market life for the valves, the desired accuracy provided by Bray, and research done by our team were used to determine the required values.

For the measurement accuracy, the less than 5% error was determined by the existing IOT toque bracket had an uncertainty of 5% therefore, Bray said the minimal viable product should be able to achieve that value or better. It was also determined that if the sensor was not accurate enough, then the data would be unusable because it would be hard to tell if the collected data was from actual valve movement or if it was just error from the sensor. Direct measurements are preferable, because there would be less opportunity for the propagation of any measurement error through a series of calculations.

Next, the team determined the exact locations where it would be viable to embed a sensor into the valve and the maximum size of the sensors. To find these locations, the solid works files of the ball valves that Bray sent to our team were examined to find the locations where there was enough room to add a sensory system to the design. From this process, our team decided the case of the valve, the stem, and the case of the actuator were the areas with the most room to make modifications. The other areas were ruled out due to insufficient space or that they would be in contact with the fluid medium, which was decided to be avoided in the codes and ethics analysis.

Moving onto the lifetime of the sensor metric, this was based on doubling the average life of a ball valve, which was determined to be ten years. The thought process was that the sensor should be able to last longer than the ball valve because in order to gather data on how the system is performing and if it's about to fail, that system has to have a lifetime longer than the valve. The doubling of ten to twenty was just to ensure that if a ball valve is used past its average life, the sensor will still be able to collect the appropriate data.

For ease of maintenance, this was based on the concept that the more moving parts, the more maintenance that would be required. It also was considered that the sensor systems should not have very many moving parts, so it was decided that around four would be the maximum. This number was chosen such that mechanical failure could be easily identified due to having to test a maximum of four locations. Also, maintenance difficulty depends on possible low accessibility of embedded sensors, giving another reason to limit the number of moving parts.

Ease of implementation was a requested metric by Bray, as they wanted to be able to build the design concept in a timely manner so that fast learning cycles can be achieved. The reasoning is to minimize the time to test the concepts and tweak them instead of spending a lot of time on the build for it not to work. Two hours was determined as the limit because that was the amount of time our team had available to meet consistently so that the iterations of the build could happen in one meeting. Calibration time also follows this same principle of wanting to finish the calibration of the design in one meeting, which was determined to be two hours. This will allow us to test the accuracy faster and allow for more iterations and observations to be made for the designs.

Lastly, the power consumption of the sensor systems was accounted for. The value of 100 watt-hours was the average supply of a lithium-ion battery. Maintaining a value below that number allows the system to be powered by readily available batteries. If the power consumption number is too high, then the team will have to start making custom rigs that use large and expensive batteries that will result in the system not being embedded and going over budget.

FUNCTIONAL MODELING

Before generating concepts and ideas that meet the deliverables of the design problem, it is necessary to understand the tasks the final product must accomplish to be considered successful. Functional model diagrams were developed to illustrate the product requirements of both deliverables. The creation process involved generating a black box model, correlating the customer needs to function flows, creating and aggregating function chains, and validation.

Black Box Model

A 'black box' model, a thought exercise that reduces the actions of the final product into its essential tasks and identifies the flows of matter or energy, will ensure that all requirements from Bray and their customers are met by matching each customer need to its set of functions.

For measuring the ball valve position, the essential function of this deliverable is to simply Detect Motion in the valve system. Similarly, the actuator output torque measurement deliverable has a single overall function to Detect Mechanical Energy that is applied by the gas-solenoid onto the valve stem. For both systems, electrical energy should enter the product to power the sensor or detection methods. Additionally, mechanical energy will interact with both systems in the form of the rotating valve ball for detecting position, and through the rotating actuator head for determining output torque. These systems will both then produce a single carrying data via electrical energy to a processing unit, then transmit this information to the customer. These energy flows will be mapped to illustrate the minimum functions of the product solution. **Figure 11** shows the Black Box model for both the position and torque problems.

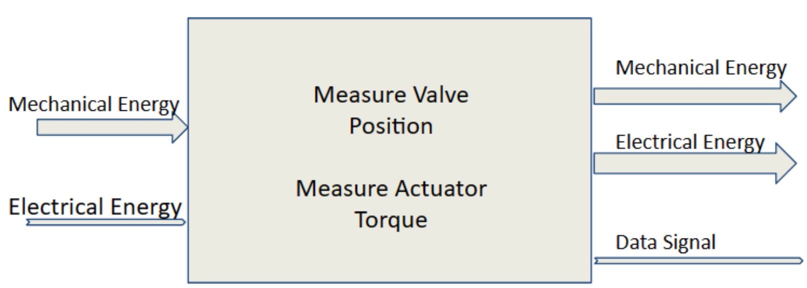


Figure 11. Black Box model for Position and Torque deliverables

Correlating Customer Needs

The customer needs and user requirements are then each assigned an energy flow to ensure that each requirement is accounted for by the function model, and thus our product design that will be derived from it. **Table 4** below lists each of the customer needs that were found during preliminary meetings with Bray, along with associated energy and matter flows.

Table 4. Customer Needs and Energy Flow Correlation Table.

Customer Needs	**Associated Flows**
Final product is embedded into the actuator casing	
Product is scalable for different-sized valves	
Product records and transmits sensor data	Signal, Electrical
Works in a wide temperature range (-40℉-300℉)	
Works under various pressures (100 psi - 740 psi)	
Works for various fluid mediums	Mechanical
Measures actuator torque to < 5% error	Electrical
Relatively short lead times for parts (3-4 weeks)	
Determines true valve position independent of actuator	Electrical, Signal
Works for both pneumatic and hydraulic actuators	Mechanical
Short time for calibrating the sensor	Electrical, Signal

Customer needs without associated flows are system specifications and constraints, rather than operational requirements. From the table, it is clear that mechanical, electrical, and signal energy flows all occur during the operation of the final product to meet each customer requirement. Because both deliverables of the project will measure some physical quantity of the system, mechanical energy must pass in and out of the product: the act of rotating the valve ball for Position, and the act of toggling the actuator for Torque. Electrical Energy (EE) will be used to power sensors and data processing technology. While the design of the final product may alter the exact type of sensor used for either deliverable, the operating principle will remain the same: Mechanical Energy (ME) entering the 'black box' system will cause some measurable change in the voltage of the supplied electrical energy. From this action, a signal or data will be generated, and the remainder of electrical energy will leave the system. These flows will then be considered with the specific tasks each deliverable will accomplish during its operation.

Function Chains

After understanding the operational requirements and ensuring they satisfy the customer needs, a function chain can be created that illustrates the entire product working as intended. To create this, the "Zen Approach" was utilized, in which every operation of the sensor system was listed as a sub-function within the final product. Following the logical operation of the Torque and Position Measurement deliverables, both systems must take in and store electrical energy, detect a chance in mechanical energy, use the resultant signal and leftover electrical energy to process data, and finally transmit this information to an interface that can be understood by the user. This operation is illustrated in **Figure 12** and **13** below, showing function chains for determining the True Valve Position and Measuring Actuator Torque.

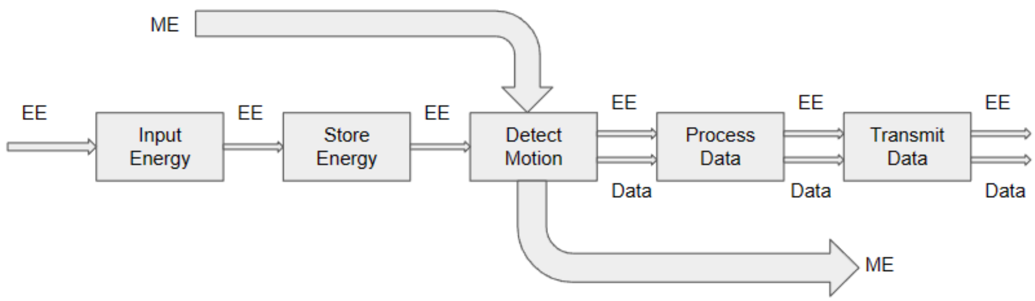


Figure 12. True Valve Position Function Chain.

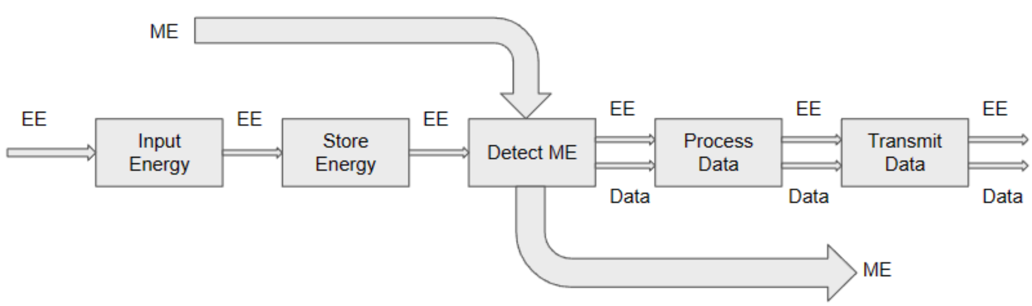


Figure 13. Measuring Actuator Torque Function Chain.

The function chains for the two deliverables are very similar in principle, but have a few key differences in actual operation. For the Position chain, the main operation is to use the input mechanical energy to detect the ball's motion and determine its location, whereas for the Torque chain, the main operation is to measure the input mechanical energy itself in the form of torque.

Validation

Validation of the function chains ensures each customer need is met by at least one sub-function of the final product. Because the two deliverables of the design problem require different sets of sensors and placed in different locations and sense two different mechanical energies, it is better to list them as two separate function chains, rather than aggregate them together. In any case, the customer needs are met from the two chains: use the motion of the valve ball to determine its true position, and use the energy applied to the actuator to determine its output torque. Other customer needs that are not explicitly met by the chains are system specifications such as accuracy tolerance and system placement that will become properties of sub-functions, rather than act as one. These systems will be used to guide the concepts of sensor products that meet the project deliverables.

IDEA GENERATION

Several different methods were utilized for idea generation for the position and torque problems. Some proved more useful than others, but a variety of methods were undertaken in order to ensure that no possible solutions were neglected or missed.

Brainstorming

Brainstorming is a very simple idea generation method consisting of writing down whatever ideas are in the minds of the design team. There is a "no bad ideas" rule, meaning that no matter how outlandish or unreasonable an idea may sound, every thought is written down in a quick manner to be sorted through later. The purpose of brainstorming is to leave no stone unturned in the search for solutions, with the refinement of ideas to be completed later on. After every idea is out on paper, they then can be sorted through, grouped, or refined and the less feasible possibilities thrown out.

Our team had to come up with two sets of ideas: one for the position problem and the other for the torque problem. A photo of the map generated from brainstorming is shown in **Figure 14**. Many ideas involved measuring or introducing various forms of energy into the valve and inferring position based on an energy measurement.

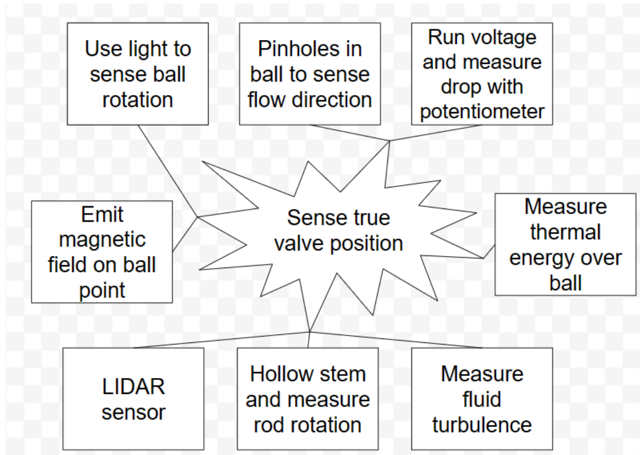


Figure 14: Position problem brainstorming map.

The most promising results for the position problem brainstorming set revolved around using some form of electrical or magnetic measurement to measure the position of the valve. One idea involved using a magnetic compass needle to indicate which direction the opening of the ball was facing, a concept that also arose in some other idea generation methods as described later on in this report. Another involved making the ball of the valve part of an electrical circuit that would only be closed if the ball was fully open or fully closed. That way, Bray would be able to spot if the ball was not reaching all the way to the correct position. However, this output of this design would give an output that was not detailed enough. The ball would essentially function as a switch in a circuit. This idea was then considered further and changed to reflect the accuracy requirement, which is detailed in the Concept Refinement section later in this report. This voltage method seemed to be the most promising from this brainstorming session, but all ideas were kept on the table for further refinement under the “no bad ideas” policy.

A separate brainstorming session was held for the torque problem. There were two schools of thought on the process of measuring torque: the solutions could either use the dynamics of the system, i.e. angular acceleration, and multiply by the moment of inertia of the valve to get torque, or use the force on the valve, multiply it by radius from the valve, and end up with the torque. The torque equation with the two possibilities is shown in **Equation 1**. The brainstorming map is shown in **Figure 15**.

$$\tau = I\alpha = Fr$$

Equation 1: Torque equation.

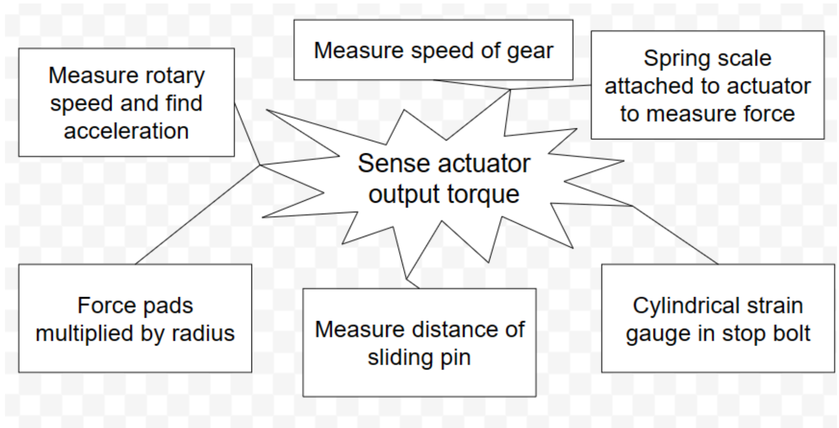


Figure 15: Torque problem brainstorming map.

The dynamics approach would be used in the ideas of measuring rotational speed of the shaft, rotational speed of the actuator gear, or motion of the sliding pin. Both of these solutions would function in a similar manner: some sort of rotational speed sensor, perhaps a potentiometer, would be used to measure the angular velocity of the rotating component, and then that could be multiplied by the known moment of inertia of the valve to find the applied torque. The force approach would be used in the ideas of a spring scale or a force sensor on the actuator stop bolts. In the former, a spring scale would be attached to the horizontally moving plate of the actuator, either scotch-yoke or rack-and-pinion, both of which use lateral motion connected to a gear to produce rotation. The scale would measure instantaneous force, which could produce applied torque when multiplied with the known radius between the motion arms and the rotating valve shaft. The latter idea would have pad force sensors placed on the stop bolts of the actuator, which are bolts in the actuator housing that prevent the device from turning too far. The force required to stop the motion, again multiplied by the known radius, should give the torque at the end of the stroke. These methods were considered further in the Concept Refinement section later in this report.

TRIZ

The TIPS/TRIZ concept generation method presents a highly structured and systematic approach to the creative concept development process. Originating in the 1940s, this innovative methodology was crafted by Genrikh Altshuller, a notable Soviet engineer. Its foundation lies in the systematic analysis of patent patterns and a strong emphasis on resolving conflicts inherent in a product's design.

Even today, TRIZ remains a critical tool utilized by industry giants such as Samsung, Rolls-Royce, GE, and NASA. The initial phase of employing the TRIZ approach involves the identification of conflicts within the specific project in question. These conflicts are then translated into generalized engineering parameters. When coupled with the powerful 40x40 contradictions matrix, this enables the identification of key design principles that can pave the way for the generation of novel and ingenious solutions.

To get started, it was important first to identify the main conflicts with our product design. Going back to the House of Quality, the main conflicts were identified as being:

1. Solution needs to be embedded within the current casing design
2. Sensors must be accurate, within 5% ideally
3. Size of the sensors will be limited
4. Power consumption must be reasonable
5. Ease of implementation

The following generalized parameters were then identified:

a. Volume of stationary object
b. Energy consumed by stationary object
c. Accuracy of measurement
d. User-friendliness
e. Level of automation

When analyzing the contradictions matrix, the highest recurring design principles were:

a. Mechanics substitution (use of sensors)
b. Parameter changes (change of physical state, change of concentration, change of flexibility)
c. Phase transitions (volume changes, absorption of heat, etc.)
d. Merging (merge similar objects or parts to perform parallel operations)

As a result of the TRIZ concept generation procedure, the following concept, shown in **Figure 16**, was generated. This concept utilizes a combination of sensor technology and phase transition properties of a material. The core of the ball is filled with a special material that undergoes a phase transition due to a change in temperature as the ball valve is opened and closed. A sensor located in the stem is then able to detect that phase and temperature change, send that data to a control unit, and assign it a corresponding value for position.

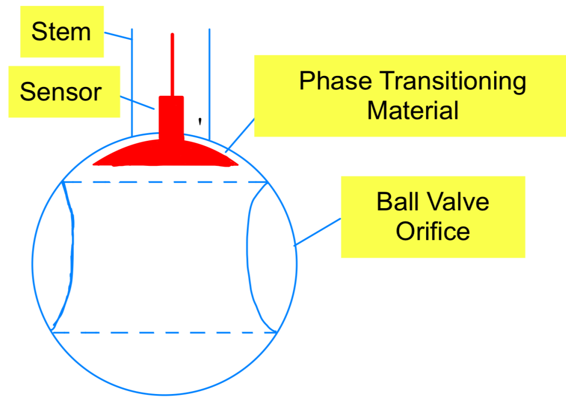


Figure 16: Ball valve position concept via TRIZ.

However, while the TRIZ concept generation method spurred creative thinking regarding the measurement of valve position and actuator torque through the use of the contradictions matrix and design principles, it primarily led us toward indirect measurement methods. The concept described above is a testament to this, as it involves a series of data conversions to determine position. It's worth noting that Bray's primary objective is to directly measure valve position and actuator torque, which necessitates further exploration to align with their needs.

Design by Analogy

Design by analogy is a method of idea generation that first makes the engineer think of existing solutions for the problem in alternative fields. The way this design generation method works is to start by coming up with synonyms for the wording of the problem. This allows the user to think about the problem differently when there is different wording used. Then, for each synonym, look for how that problem is solved in other fields using research tools, and relate the found idea to the problem that is to be solved.

Our team began this method by selecting the deliverable of true valve position to be the focus of this method. This decision was made because Bray provided solid work models for the valves but not the actuators, so the team had a better grasp on the valve position deliverables. Once valve position was identified as focus, the word position was chosen, and using a thesaurus, the team found three synonyms: location, orientation, and rotation. Using these synonyms as new angles to view the project, research was done to find how different industries find location, orientation, and rotation.

The first solution that was found for location was echolocation. This works by an animal emitting a sound wave, then the sound wave hits an object and bounces the sound wave back towards the animal. This sparked the idea of using a sound wave emitter in the shell of the valve that will emit a constant sound and have a sound wave receiver that analyzes the properties of the returned waves. Then, piggybacking off that idea of using waves, radar was considered as another concept. This works the same way as echolocation, but instead of emitting sound waves, electromagnetic waves are emitted. This seemed more promising than echolocation because the sensors can better measure electromagnetic waves. This concept would have an electromagnetic emitted and receiver embedded into the case to generate and analyze the electromagnetic waves.

Continuing with this idea of determining location, our team started to think about specific locations that involve fluids. Through this, dams were considered, which measure fluid flow through an orifice and regulate it. This generated the concept of attaching a flow meter to the orifice of the ball valve and measuring the flow rate through this hole. The idea is that when the ball is turned to where it is partially opened, then it will have different flows. Then, using calibration, the flow rates can be correlated to position. All three designs for determining location can be seen in **Appendix E**.

The next synonym that was focused on was orientation. Using the process of looking into how people and animals orient themselves. The first idea that stuck with the team was using a compass to tell people which way is north, utilizing the earth's magnetic fields. Using this, our team came up with the idea that if a point on the ball valve is magnetized, then a hyper-sensitive compass can measure where the magnetic field is generated, indicating the ball valve's position.

Another idea for determining orientation came from mosquitos orienting themselves towards blood by detecting heat. The way this can be applied to our project is to heat the ball of the ball valve non-uniformly across the surface of the ball. Thermocouples would be placed around the case of the ball valve to measure different points on the ball's surface. Then, applying heat transfer concepts to calculate the predicted temperature distribution of the ball. Matching the measured temperature to the predicted temperature on the ball of the valve, the position can be determined. The compass and the heated ball concept sketches can be seen in **Appendix E**.

The last synonym to analyze is rotation, which is applicable due to the ball's rotational motion. The first field that utilized the measurement of ration is the car industry, specifically the wheels and suspension. This got the group to think about how a spring responds to rotation. The idea for finding rotation is attaching a spring inside a hollowed-out stem to the top of the ball. This rotated spring would have different forces depending on how much the spring is rotated. Measuring and calibrating this force would allow us to find how much the ball has spun.

Further examination of how to determine rotation led the team to think about how a sink determines how much water to let through based on how much the handle has been rotated. This resulted in the idea that the two sides of the valve have different pressures. Attaching a pressure gauge to both ends of the valve and finding the pressure difference will indicate how much the valve has been rotated. Concept sketches for the rotation ideas can be seen in **Appendix E**.

Overall, the team found that this method was advantageous in generating new ideas. This method of generating ideas allows you to identify your needs and start thinking about how other industries and nature accomplish this task. This helped innovation because, after our team's brainstorming session, it was difficult to develop substantially different ideas. However, with design by analogy, it was easy to develop unique solutions and new ideas to consider. Design by analogy proved to be the most productive idea-generation method used for this project.

Morphological Analysis

Morphological analysis is a method of concept selection that requires an analysis of the form of the final product, rather than its operation. The deliverables are broken down into their subfunction, and ideas are generated for each one independently, then combined at the end to create a concept. This method allows complex problems to be simplified and forces the design to meet the needs of every subfunction. Looking at the system requirements for both deliverables in the function chain, the products must have a way to accept an input electrical energy, store the energy, use it to measure torque, measure valve ball position, transmit this signal as usable data, and be embedded into the current valve-actuator system. The ideas generated for each sub function are listed in **Table 5**, where the ideas highlighted are contenders for each category.

Table 5: Morphological Analysis Table.

Input Electricity	Measure Torque	Read Position	Embed System	Transmit Data
Outlet Power	Torque Bracket	Potentiometer	Casing for Valve	Ethernet
Battery Powered	Rotational Torque Sensor	Hall Effect Probe	Independent Casing	Internet
Solar/ Renewably powered	Washer Strain Gages	Flow meters	Casing for actuator	Light Indicator
	Force Sensors	Magnetic Fields		Sound Indicator

To input electrical power, a battery pack was selected as the optimal choice due to the unknown deployment conditions of the valves. While there may be access to power in closed factory settings, the valves could be deployed to outdoor chemical plants or hard to reach areas. It is better that the product has its own power source and not rely on outlet power or wind or solar sources. For measuring torque, a rotational torque sensor was the best option due to their high accuracy and low procurement cost. Similarly, a potentiometer was an ideal choice for reading valve ball position because it is easy to implement and is inexpensive.

The options for embedding the final sensor product included fitting the device inside the actuator casing, valve casing, or developing an independent case. Ultimately, it is the most feasible option to fit the sensor system into the actuator casing due to its higher tolerances for space compared to the ball and butterfly valve casings. The external power source, however, will need to be fitted outside the casing for ease of access. This option was also preferred over developing an independent case due to manufacturing costs and it may create unnecessary space constraints for valve customers. Juxtaposed to the inlet power, an ethernet connection was preferred when figuring out how to transmit data from the valve to a user interface. Although wireless options such as IOT devices exist, they are often unreliable and difficult to maintain. An ethernet connection can be buried or discretely run along a valve piping system to the nearest interface system for an operator to observe the life of the valve-actuator system.

Using the Morphological Analysis method, the concept generated was very similar to other ideas generated to meet our deliverables, including embedding a rotational torque sensor and data acquisition unit inside an actuator casing, with leads attached to a potentiometer connected to the valve ball. This entire system is battery-powered, with data transmitted by the sensors running through an ethernet connection to the final user interface.

CONCEPT REFINEMENT

For this project's scope, our main sub-functions were the measurement systems for each deliverable provided by Bray. This resulted in two different subsystems: measuring true valve position and measuring actuator torque. Also, the subfunctions do not interact, so ideas between each subsystem cannot be combined. In this section, two concepts for each deliverable will be described in detail, as they showed the most promise during initial discussions and brainstorming.

Position Concept Refinement

The two concepts that showed the most promise for position sensing were a magnetic field sensor and a potentiometer. These ideas are direct measurements of position, a good trait given that Bray stated that direct measurements are preferred to indirect methods such as pressure differences or a volumetric flowmeter.

- **Magnetic Field Sensor for Position**

The magnet and compass was considered a reasonable design because it did not contact the ball or have contact with the fluid. The main benefit of this idea is that it utilizes magnetic fields, so there are no moving parts of the system. It also does not alter the ball valve in any way except for the need to magnetize a point on the front of the ball. Another benefit is that the magnetized point would be in a sealed location. It is not in contact with the fluid and doesn't have to be a material designed for high temperatures and pressures. What made the idea truly feasible is that the magnetic waves generate themselves needing no power and, given a strong enough magnet, can be measured with any compass. The main concern with this concept is that the metal parts of the ball valve and casing will interfere with the magnetic waves, making it hard to get accurate with a compass device, and that the compass itself is not very accurate.

The issue with the accuracy of the compass led our team to ask how else a magnetic field could be measured. This is when our team found the Hall effect sensor, which could do everything the compass can but is more accurate. Another benefit is that the Hall effect sensor is much smaller than the compass. Hence, it can be embedded into the valve's stem, allowing less disruption between the origin of the magnetic field and the sensor. The Hall effect sensor was a much better idea than the compass in terms of accuracy, so a new name was decided for the concept: the Hall effect sensor. The only issue with the new Hall effect sensor is that a lot of energy is required to make it sensitive enough to get good accuracy. This means a substantial power source is needed to get the desired accuracy. A sketch of this new concept iteration can be seen in **Figure 17,** showing how the Hall effect sensor will collect data from the vectors in the magnetic field to find where the magnetized point is.

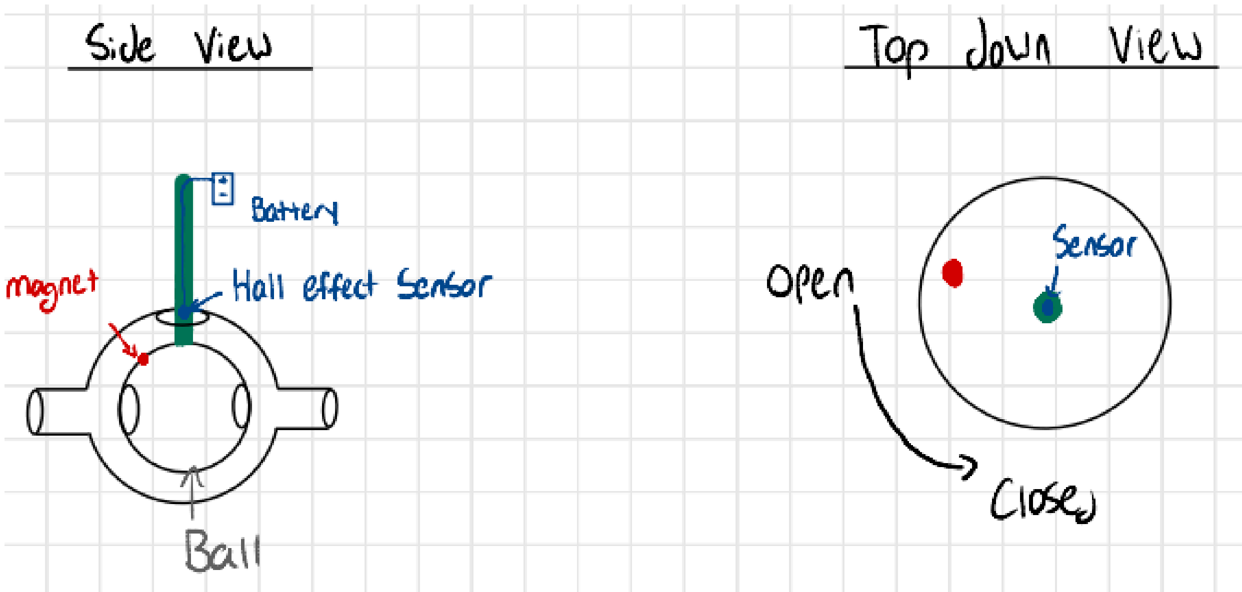


Figure 17: Hall effect sensor concept sketch.

- **Potentiometer for Detecting Position**

The potentiometer idea was the other idea selected to be a concept to determine the position. This idea was to try and rig the ball in a manner that the ball would act like a switch in a circuit. The reason this concept is believed to be feasible is the fact that the ball of the valve is a conductor, so it can be made into a circuit, and the accuracy of a standard potentiometer is 1%, meaning that it is already within our design requirement for accuracy. This concept was also good because it would be relatively inexpensive compared to other solutions (see **Table 6)**. The main concern with this design was it didn't measure the exact position. The idea would only measure if the valve was in the closed or open position, but not any of the in-between positions. This was a major concern as the exact position is needed to measure the hysteresis of the stem. The reason this idea was selected for refinement was that the team believed there was a configuration that would measure the full rotational movement of the ball.

The refinement of the idea into an actual functional concept was to add a wire apparatus that varies the voltage along the length of the valve case. This works because the ball will have a metal brush that connects the ball to the edge of the case. Then, at this point of contact, a wire will be installed that has a maximum voltage at the position of the valve being turned off and the minimum voltage at the point with the valve being turned on. The valve rotates up and down the wire, supplying different voltages to the valve's ball that will connect to a potentiometer to read that voltage. A sketch of the original and improved concepts can be seen below in **Figures 18** and **19**. This was a considerable improvement over the old design because the team now had an accurate way of measuring the entire range of motion for the ball with good accuracy. The only downside to this improved concept is that it added more moving parts with the connecting brush. This brush will break down over time due to the friction from moving along the wire. This will cause an increase in maintenance which increases costs and calibration time due to it being done every time a part is switched in and out. This is still a promising idea as it performs well in the essential category of accuracy and has a negligible impact on valve performance.

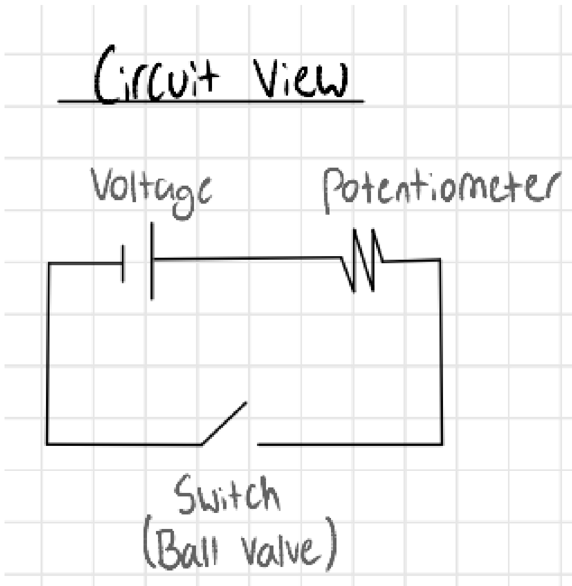


Figure 18

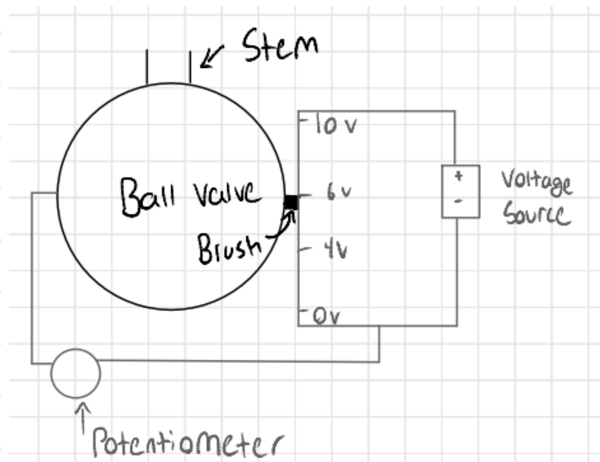


Figure 19

First (Fig. 18) and second (Fig. 19) iteration of potentiometer concept sketch for position.

Torque Concept Refinement

Two concepts that were most promising for torque measurement were a potentiometer and a strain gauge on the actuator stop bolts. Like the position deliverable, these two concepts were chosen for further analysis and refinement in this section because they are direct measurements of torque, thought to be more accurate than indirect measurement methods.

- **Potentiometer for Measuring Torque**

Similar to the concept applied to determining valve ball position, the operating principle behind this concept is to let the actuator stem act as a switch in a circuit. As the actuator was toggled, the dynamics of the system could be measured and combined with known properties to determine the instantaneous torque on the system. The advantages of using this method is the high accuracy available from using existing potentiometer sensors, the low cost, low space constraints, ease of measurement and calibration, and the well-established lifetime of the sensor. The largest concern with this concept is using dynamics to determine an applied ‘force’ from the actuator, as this may be another form of using an ‘indirect measurement’ technique depending on the method used to determine torque from sensor measurements. Additionally, the sensor location placement along the actuator stem could have an impact on the quality of reading provided by the sensor. If the potentiometer were to measure the dynamics at the point of contact between the actuator and valve stem, it may only calculate the "reaction torque" between the two components. This is inadequate because the data will only indicate the performance of the entire valve-actuator system and will not indicate if the system is failing due to a stiff valve or weakened actuator. Regardless, this concept was refined due to its ease of implementation if an optimal design was found that met all deliverables of the project.

Refinement of this idea into a functional idea centered around the potentiometer placement. If the exact dynamics of the actuator shaft were measured as close to the torque source as possible, the resultant measurement would be a more direct result of the applied torque, rather than the reaction forces at the valve stem. This idea justifies the use of a rotary slip-ring potentiometer, attached to the top of the actuator shaft. This sensor is inexpensive, widely available in a large range of sizes, and retains the accuracies of traditional potentiometers (up to 1% of the full value). After calibrating the sensor to determine the change in voltage over change in time and corresponding this to a change in angular position, the angular acceleration of the actuator shaft can be directly determined. Using the idea that $T = I\alpha$, the moment of inertia of the actuator shaft could be used to determine the instantaneous torque applied. A challenge presented with this concept is the moment of inertia of the shaft would be very difficult to theoretically determine due to the numerous fasteners, connection to the valve ball, and other irregularities in the part shape. To counteract this, the value for I could be found experimentally, then scaled for different sizes and types of valves used by Bray. These measurements would only have to be found in lab settings then could be applied to perform calculations upon product deployment. This concept assumes the shaft dimensions are perfectly known and the machining tolerances are small enough as to not impact the needed measurement accuracies for torque. A sketch of this concept and a potential configuration in an actuator casing is shown in **Figure 20**.

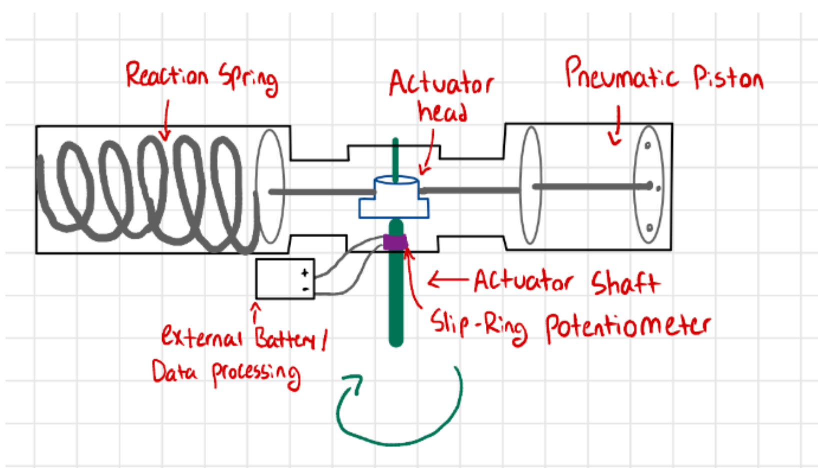


Figure 20: Potentiometer to measure torque concept sketch.

- **Strain Gauge for Measuring Torque**

Rather than generating a new idea for measuring the actuator torque, alternatively the existing solution used by Bray could be modified to better fit the project deliverables and customer needs. The current operating principle used is a set of strain gauges attached to a bracket that sits between the valve body and actuator casing. When the actuator rotates, the 'reaction torque' applied against the stationary bracket is measured and returned as a torque value. This method is inadequate for similar downfalls from the potentiometer concept where the reaction forces do not reveal any useful information about the life of either the actuator or valve, rather just the entire system itself. However, this concept has potential to also be an inexpensive and relatively easy solution to implement, so there is merit in exploring ways to improve it. The contending concept refinement idea is to change the strain gauge type currently used and change its placement within the actuator system.

Rather than an external bracket with attached strain gauges, the sensor selection could be changed for a rotational torque sensor that uses a cylindrical strain gauge in its casing to measure torque, and the entire system could be modified to fit inside the actuator casing. This solution offers a few advantages, namely protecting the sensors and conveniently packaging the system inside the existing actuator casing while retaining the use of inexpensive yet highly accurate strain gauges. An in-line rotating torque sensor is fixed between the torque source and actuator shaft. When the actuator is toggled, the shaft rotates and the maximum torque output is recorded and returned. While this method would be potentially difficult to implement into the valve system, it solves the problem of recording reaction forces by measuring torque values at the source itself. This idea would allow the actuator life to be accurately diagnosed and its lifetime tracked. A sketch of this modified system is shown in **Figure 21** below.

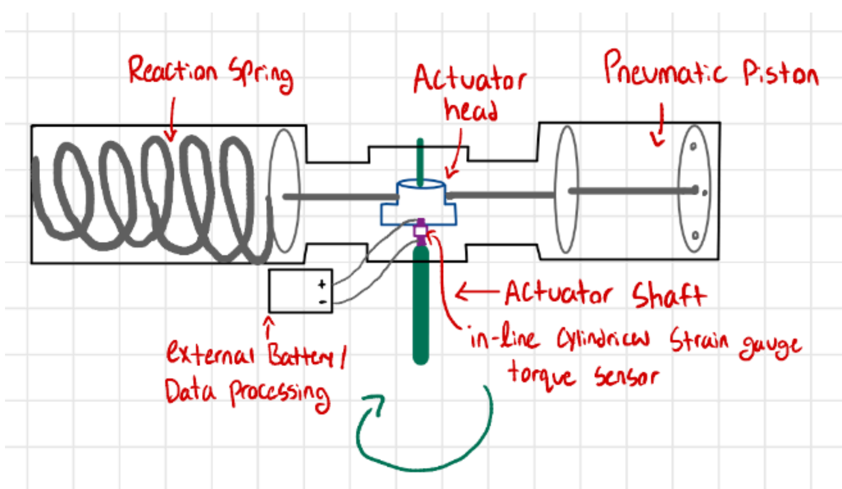


Figure 21: Modified strain gauge to measure torque concept sketch.

CONCEPT SELECTION

This section of the report will discuss concept comparison and selection in two parts; one for the position deliverable and one for the torque deliverable. Since the last report, the team's approach has changed. The main design problem statement centers around finding a method to collect data, rather than designing a product, so after conversations with Bray, the team decided on testing two different solutions for each deliverable and comparing to see which gave more accurate data. This will allow for better method selection next semester to implement. The experimental approach will allow the solution possibilities to be tested against one another for determination of which is the best to select.

Torque Concept Selection

All five generated concepts for torque were compared using a Pugh chart, seen below in **Table 6**. The concept of strain gauges was set as the datum and design metrics were pulled from **Table 3**, seen earlier in this report.

Table 6: Pugh Chart for the Torque deliverable.

TORQUE	Importance	Cylindrical Strain Gauge	Encoder connected to gear	Spring Scale	Lidar to measure distance of sliding pin	Potentiometer
Measurement Accuracy	0.2	Datum	1	-3	2	0
Embedded	0.1	Datum	-1	0	-2	1
Scalable	0.1	Datum	0	0	-1	-1
Impact on performance	0.15	Datum	0	-1	2	-1
Ease of implementation	0.1	Datum	-2	2	-1	0
Calibration time	0.05	Datum	-1	-1	0	-1
Cost	0.15	Datum	-2	2	-2	0
Lifetime of sensor	0.15	Datum	2	-2	0	1
	SUM	Datum	-3	-3	-2	-1

None of the other solutions scored better than strain gauges. This has changed since the last report, after conversations with Bray made it clear that measuring the moment of inertia of each valve would be too cumbersome and would make the torque measurement dependent on the valve, which is not desired. While measurement accuracy is the most important metric for our product design, concepts that may have been more accurate were considered not feasible due to cost, ease of implementation, or ability to embed the product in the actuator casing.

Since the last report, a new concept was thought of which will be referred to as the electric motor design. In this design, a conducting belt will be passed around the turning switch indicator on top of the actuator and will also pass through a magnetic field inside of a motor. The movement of the switch, which turns 90 degrees back and forth as the actuator opens and closes, will generate a voltage, the energy of which can be measured for each actuator cycle, and divided by $\frac{\pi}{2}$ radians to obtain torque, since energy and torque have the same units of measurement. This equivalence gave rise to this electric motor design idea. The team and Bray are not entirely sure if the energy generated by the motor will equal the energy input into the valve, but the idea merits testing to compare with the strain gauge concept.

Position Concept Selection

Table 7 below shows similar Pugh chart concept analysis as for the torque deliverable.

Table 7: Pugh Chart for the Position deliverable.

VALVE POSITION	Imp	turbulence at interface	Potentiometer	Pinholes in the Ball valve	Inductive proximity sensor	Echolocation	Radar	Flow meter	Magnet and Compass	Thermal detection of non-uniformly heated sphere	Spring Force	Pressure difference
Measurement Accuracy	0.2	Datum	1	-1	2	-2	-2	0	0	-2	-1	-1
Location of sensors	0.1	Datum	0	2	0	1	1	0	1	0	1	-1
Scalable	0.1	Datum	-1	1	-1	0	0	0	2	0	1	2
Contact with fluid	0.05	Datum	2	-2	2	0	0	0	1	-2	1	0
Impact on performance	0.15	Datum	2	-2	1	1	1	1	-1	0	-1	1
Ease of implementation	0.1	Datum	-1	-1	-2	-2	-2	1	-1	-2	-1	1
Calibration time	0.05	Datum	-1	-1	-1	-1	0	0	2	-2	0	-1
Cost	0.125	Datum	0	0	-1	-2	-2	0	0	-1	2	1
Lifetime of the sensor	0.125	Datum	2	-1	1	0	0	0	0	-1	-1	1
	SUM	Datum	4	-5	1	-5	-4	2	4	-10	1	3

After analyzing the total sums for each idea and weighing the importance of each idea, our team narrowed eleven ideas for determining position down to three. The best ideas were the potentiometer, magnet and compass, and pressure differential. These three ideas were picked because they had the highest total sum, meaning they satisfied all of the metrics and were weighed to ensure the most important metrics were satisfied. Our team then presented our findings to Bray and was told to avoid means of indirect measurement. This meant that methods that measured data and then converted the data into position or torque through a calculation were not usable, such as measuring flow rate and the heated ball and pressure differential ideas. This left the team with two ideas: the compass and the potentiometer, which were detailed previously.

Previously, the team had identified the potentiometer as the solution to move forward with. With the new experimental approach described above, the team will now move forward with both the Hall effect magnetic field sensor and the potentiometer for sensing position. The results from both will be compared for final selection in the spring. Both of these solutions scored equally high on the Pugh chart so it is logical to move forward with both over the rest. Below in **Table 8** is the quantitative matrix for concept selection, utilized in the initial concept selection. It was not updated with the newest concepts, but is a visualization of the initial concept selection process, and its calculations are shown in **Appendix A**.

Table 8: Quantitative matrix for concept selection.

Metrics	Importance	Hall effect sensor	Potentiometer (position)	Rotational Torque Bracket	Potentiometer (torque)	Force sensor
Measurement Accuracy (% uncertainty)	0.5	3% to 1%	0.01%	0.5 %	2.00%	3%
Calibration Time (sec/min)	0.1	110 min	80 min	90 min	30 min	15 min
Cost ($)	0.05	$549.00	$136.00	$2,900.00	$125.00	$150.00 (need 2)
Lifetime of sensor (years or cycles)	0.1	10 million cycles	1-20 million cycles	100 million cycles	1-20 million cycles	1-10 million cycles
Volume of apparatus (in^3)	0.05	12	4.825	5.88	8	5
Weight of apparatus (lbs)	0.03	2.9 lbs	.5 lbs	1.1 lbs	2.5lb	1
Ease of manufacturing (# of parts)	0.1	4	2	5	2	3
Ease of maintenance (# of moving parts)	0.07	0	2	2	1	0

To summarize, the team will be moving into next semester with two ideas for data collection to test out for each deliverable. Bray has given positive feedback about this method, as they are also interested to compare methods and get as much data as possible before implementation. The winning ideas were a potentiometer and a magnetic field sensor for position, and an electric motor design and strain gauges for torque.

EMBODIMENT DESIGN

This section of the report will describe details about the potential solutions: their layouts, working principles, shapes and sizes, and the like. While these data points are subject to change pending further physical validation and testing next semester, it is important to plan out a detailed design now to have a good base with which to begin purchasing and testing components.

Product Architecture

Measuring position and measuring torque are the two sub-functions of our problem statement, described earlier in the Functional Modeling section. This problem statement was easy to sort into subfunctions, given that the subfunctions were simply Bray's two main tasks asked of the team. **Table 9** below shows the clustering of solution options into their correct subfunctions under the new experimental method. Also listed are the physical components, both pre-existing from Bray and newly added, required for each solution with the correct subfunction.

Table 9: Subfunction grouping of solutions.

Subfunction	Possible Solution	Pre-existing Parts	New Components
Measuring true valve position	Potentiometer	Valve ball/butterfly, stem, and casing	Potentiometer, additional sealing, wired connection
	Hall effect sensor	Valve ball/butterfly and casing	Hall effect sensor, magnet, power supply, wired connection
Measuring actuator output torque	Strain gauges	Actuator stop bolts and spinning collar	Strain gauges, wired connection
	Electric motor	Actuator indicator switch and housing	Motor, conductive belt, wired connection

The solutions will not interact with each other, as torque and position are separate concepts, required to be solely dependent on the actuator and valve, respectively, and be agnostic to the other component in the assembly. This is so the actuator torque solution need not be modified if the actuator is attached to a different valve, and vice versa. It could be possible for the data readings to be monitored by the same data acquisition unit, depending on if Bray would like the DAQ component to be attached to the assembly or separate and simply be uniform for each design, attached to an external computer and connected to wires from the various sensors.

Using the CAD models of actuators and valves given by Bray, the team was able to create rough CAD models of each solution type. While somewhat crude, these sketches give a good representation of the approximate location of each component and depict how each solution could be physically implemented into the valve. The next section, Definitive Layouts, will describe in more detail the working principles and connections of the solutions, but these CAD models are meant to simply be a high-level representation for visualization purposes.

Figures 22 and **23** show the potentiometer for measuring valve position. The potentiometer has been drawn in pink for visibility and is shown attached to the bottom of the ball valve casing.

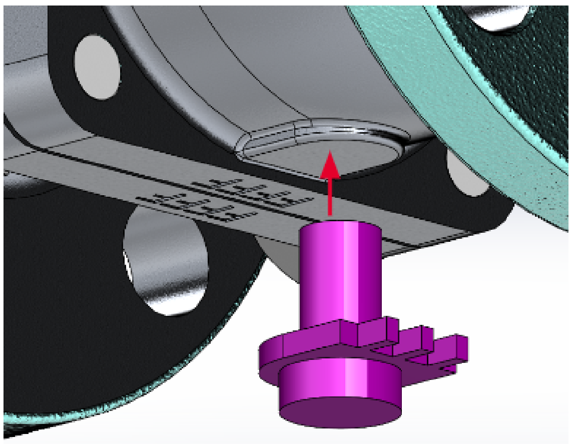


Figure 22

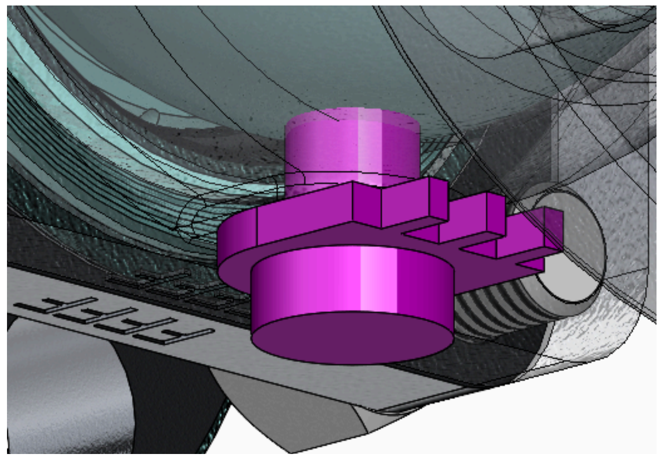


Figure 23

Potentiometer solution attached to bottom of ball valve casing.

Figure 24 shows the rough layout for the Hall effect sensor to measure position.. A point on the valve will be magnetized, and the sensor (in the valve stem) will change its readout based on orientation of the ball or butterfly of the valve.

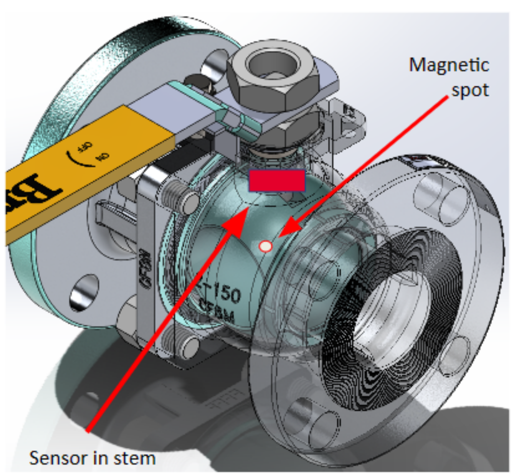


Figure 24: Hall effect sensor layout sketch.

Figures 25 and **26** show the strain gauge concept for measuring torque. The strain gauges will be embedded in the stop bolts of the actuator and will measure the force required to stop the opening or closing stroke of the valve (measured by the spinning collar) and convert to torque. More details about the calculations can be seen in the Definitive Layouts section below.

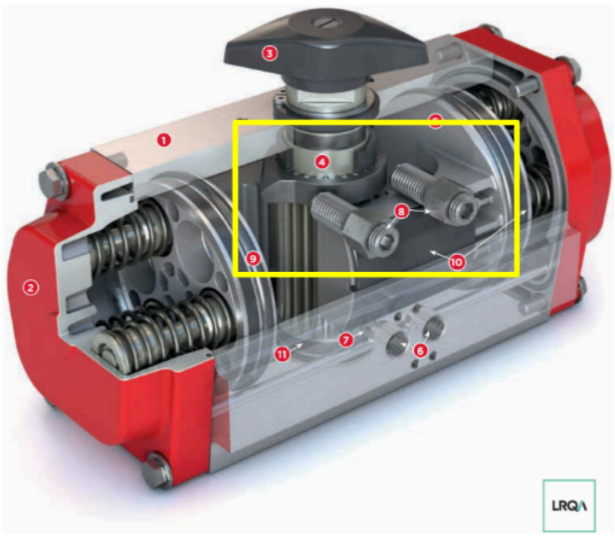


Figure 25

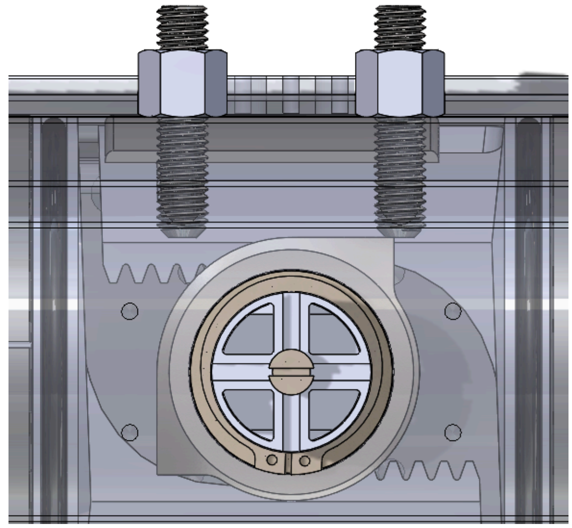


Figure 26

Full view and close view of spinning collar and stop bolts that strain gauges will be inserted into.

Figure 27 shows the concept model for the electric motor design for measuring actuator output torque. The belt will move when the switch moves, creating a voltage inside the motor that will correspond to the torque generated by the actuator.

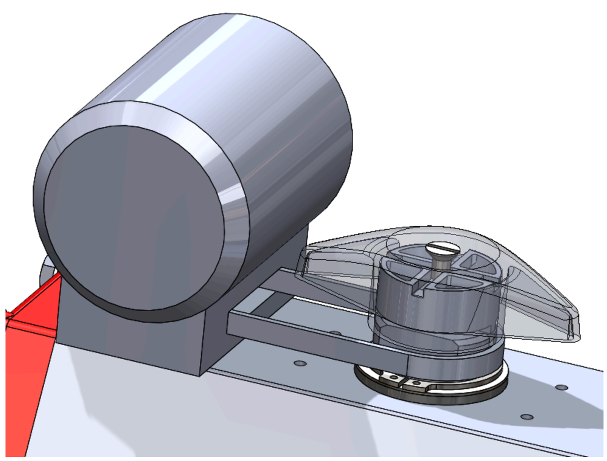


Figure 27: Electric motor design concept mounted on top of actuator.

Definitive Layouts

For each of the subfunction deliverables and potential concepts, the exact sensor location, type, size, material, and form was selected after considering the project constraints based on accuracy, cost, ease of maintenance, and optimal service life. This section describes a definitive layout that will be tested and validated by the team in the upcoming weeks for each possible solution in creating a smart valve. For all of these solutions, data from the sensors is sent to a Jessinie ADS1256 Data Acquisition Unit [8] where it is then processed and sent to a computer interface for a customer or technician to diagnose the life of the valve.

Valve Position - Potentiometer

To sense position, the P3 America STWOF30 Wire Wound Potentiometer [9] was primarily chosen for its incredibly high accuracy of 0.5% of full value. This product reads resistance values up to 10k ohms with a service life of over 200,000 turns.

In order to install it into a valve body, a hole will need to be drilled into the very bottom of the valve casing along its rotational axis. The sensor has a body width of 32mm and a shaft thickness of 5mm, so any holes made to fit the part will be minimal for most valve sizes. The shaft then must be fixed onto the valve ball or butterfly shaft along its exact rotational axis point via a pin interlocking mechanism. This will fix the sensor in place more reliably than any adhesive when in contact with the moving fluid, and can easily be switched out in the event of sensor failure.

To minimize fluid leakage, the sensor will need to be sealed into the valve casing and constantly exposed to the working fluid, so the part must be able to withstand potential shorts and a wide range of operating conditions. This is the justification for a more robust potentiometer compared to a much cheaper alternative. Lead wires connecting the sensor into a Digital Analog Converter leading to a Data Acquisition System will also need to be sealed into and along the valve casing. These wires will plug into an external casing containing the Bray 5.0V 1.4 AH battery needed to power the sensor, along with data transmission equipment.

Exact configuration and location of the sensor is shown above in **Figure 23**, not including the additional housing for supporting products and guide holes for fasteners.

Valve Position - Hall Effect Sensor

In contrast to the potentiometer solution, this method does not require direct contact between the sensor and valve body. A HoneyWell RTP Rotary Position Sensor [10] was selected for testing due to its high accuracy of 2% and large operating temperature from -40 to 257 Fahrenheit. This sensor occupies about 2 square inches of space and requires a maximum clearance of 2 mm between the sensor and rotating body to function.

To meet this space requirement, a hole will still need to be drilled into the bottom of the ball valve, with the positioning magnet fixed onto the bottom of the floating ball along its rotating axis. This sensor, however, is advantageous because it allows the ball to still freely float within the valve and correct any deformation of the valve over its service life. Once inserted into the valve, the RTP sensor will be connected to a digital analog converter through leads sealed onto the valve body, with the sensor itself being sealed into the valve to prevent any fluid leakage and retain ASME valve safety code ratings.

Holes will need to be drilled into the valve using a drill press capable of penetrating non ferrous carbon steel to secure the sensor and screw holes for the system. An additional casing will also need to be manufactured and attached to the system to hold the Bray 5.0V 1.4 AH battery needed to power the sensor, along with data transmission equipment.

Exact configuration and location of the sensor is shown above in **Figure 24**, not including the additional housing for supporting products and guide holes for fasteners.

Actuator Torque - Strain Gauges

The first method for measuring a discreet actuator output torque will be accomplished using a HBK TB21 bolt-cased strain gauge [11]. These sensors will be used in the stop bolts of the actuators and send a measurement reading after being struck from an actuator toggle. These sensors can be installed in just about any bolt, and only require a 2mm hole to be drilled into the part and fixed with an adhesive.

These sensors will ensure a very long service life and high accuracy of 1% at 10k ohm resistance. The leads for the gauges will connect from the stop bolt to the inner casing of the actuator to prevent interference of the moving parts. These leads will then need to exit the actuator body through a 1.5mm hole drilled into the front side (facing the pneumatic inputs) where it will connect to the external casing housing a power supply, DAC, and DAQ to process data and send to the user.

To prevent external elements such as sediment or ambient temperature from interfering with actuator service, the sensor wire hole will need to be sealed using a metal-safe epoxy with a large temperature tolerance. Data from the strain gauges will then be read as a force value by the computer interface, and using the known turn radius of the actuator a discreet torque measurement will be derived for each toggle. Exact location of the stop bolt strain gauges is shown above in **Figure 25** and **26.**

Actuator Torque - Electric Motor

The actuator torque output will also be measured using a motor attached to the actuator head and found using the dynamics of generated power. To accomplish this, a Transmotec brush-commutated DC motor will be mounted onto the actuator head using steel plating

[14]. A gear will be fixed onto the motor shaft connected to a belt that wraps around the actuator head. The advantage of this solution over embedded ones is there are no internal connections or product modifications required, so the entire system can be easily changed out in the event of failure.

As the motor is rotated a quarter turn at a time, the induced current as a result of the EMF from motor rotation is measured using the data acquisition system at 5V. Knowing the moment of inertia of the rotating actuator shaft and the rotational speed of the actuator, the induced torque can then be calculated in real time by the computer interface being used to relay information to the user. The accuracy of this system will depend on the error of the moment of inertia, as well as the resolution of the measured induced current.

The motor system will be connected to the external casing using soldered leads and powered using the Bray 5.0V 1.4 AH battery needed to power the sensor, along with data transmission equipment.

Exact configuration and location of the motor is shown above in **Figure 27**, not including the additional housing for supporting products and guide holes for fasteners.

Technical Analysis

The first step in our analysis was to experimentally test the rotary potentiometer to see if it could achieve less than 2% accuracy. This experiment used the Zachry Common Labs' resources and space and was done with a multimeter, a 10 kΩ rotary potentiometer, and a breadboard. The potentiometer was placed on the breadboard and wired to the multimeter, which recorded resistance. This setup can be seen in **Figure 28** below.

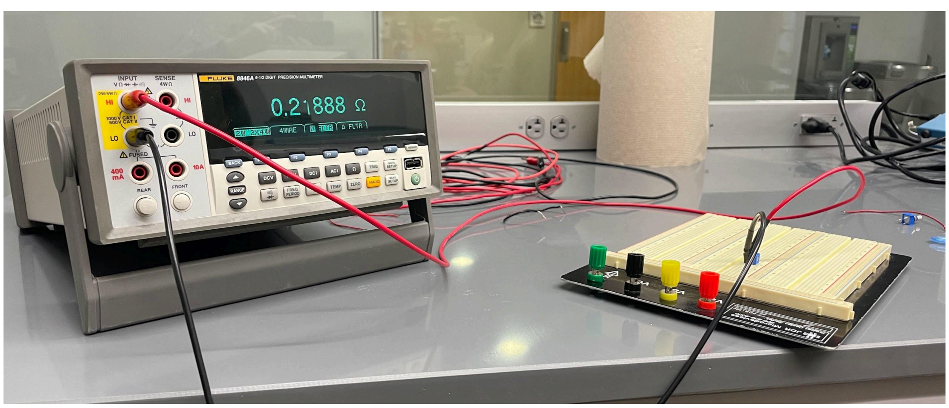


Figure 28: Experimental setup for the rotary potentiometer accuracy testing.

The rotary potentiometer was spun between its minimum of 0 degrees and its maximum of 270 degrees, and the respective resistance values were recorded. Our team took six values for each position, and a linear slope trendline was made so that a predicted value was obtained. Then the predicted position and the expected position were compared to find the error associated with each measurement. The collected and predicted data can be seen below in **Table 10,** and the sample calculations for data can be seen in **Appendix F**.

Table 10: Collected and calculated data for rotary potentiometer experiment.

Position (degrees)	Resistance (ohms)	Predicted Position (degrees)	error %
0	0.24	-0.000024	0.24
270	94732	270.1	0.029
0	0.24	-0.000024	0.24
270	94748	270.1	0.046
0	0.22	-0.000081	0.81
270	94736	270.1	0.034
0	0.25	0.0000048	0.048
270	94806	270.3	0.11
0	0.25	0.0000048	0.048
270	94616	269.7	0.093
0	0.29	0.00012	1.2
270	94587	269.7	0.12

From this it can be seen that the error for all of the measurement readings were below the 2% threshold for position accuracy. This means that this solution satisfies the accuracy requirement and is a valid solution to implement into the valve. One thing to be noted is that a jump can be seen in the error in the last test of 0 and 270. This is explained by our team accidentally knocking the potentiometer loose, and when it was put back in the breadboard, it was reading slightly different values. While still below the 2% error our team noted that when the prototype is being built a large emphasis will be placed on securing the potentiometer and its connections so that this change in values does not occur in the prototype.

For the Hall effect sensor the main analysis that had to be done was correlating the rotational motion to the output voltage and finding that slope for 90 degrees of rotation. Luckily, the people at Honeywell have completed this already, and using the sensor specifications and data provided, **Figure 29** was made.

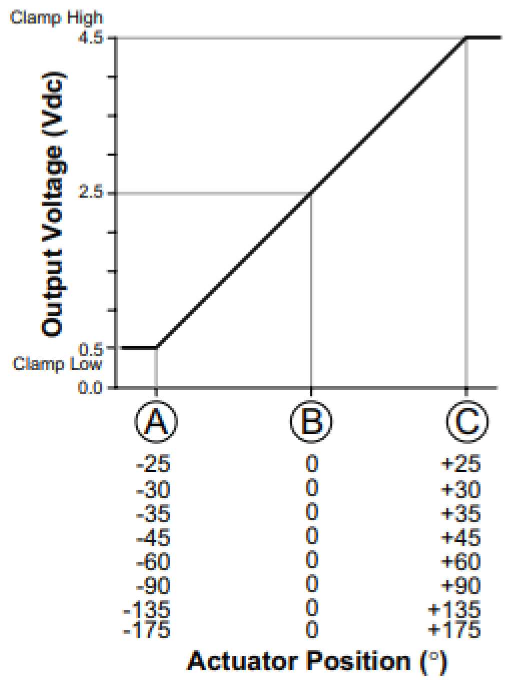


Figure 29: Correlation between angular position and voltage for RTY Hall effect sensor [10].

This analysis for the Hall effect sensor is very useful because it allows us to have an expected correlation between 0 and 90 degrees of rotation. From the graph, it can be seen that if the sensor is set to an overall rotation of 90, then the 0 degrees rotation of the ball valve will be 0.5 Volts, and the 90 degrees will be 4.5 volts. Then, the slope can be discovered to be 0.0444 volts per degree of rotation. Using this information, it will be possible to correlate every reading to a degree of rotation between 0 and 90. This information provides preliminary validation that a Hall effect sensor can measure the full range of motion and not just on-off controls.

Moving onto the cylindrical strain gauges, the main area of concern is the accuracy of the drive, so the team did an uncertainty analysis to see what measurements were going to have the largest impact on the uncertainty of the data and the predicted uncertainty percent. This uncertainty analysis process can be seen below.

<u>Governing Equations</u>

$$T = F * r \qquad \sigma = \frac{F}{A} \qquad E = \frac{\sigma}{\varepsilon}$$

Where T: Torque, F: Force, r: Radius, σ: Stress, A: Area, E: Young's modulus, ε: Strain

From these equations, the following equation to find torque using constants and strain was made.

$$T = E\varepsilon Ar = 3E7 * 0.012 * 0.5 * 1 = 180000\ lbs/in$$

Using this equation for uncertainty analysis, knowing the uncertainty for the strain to be 0.000042, and uncertainty for distance measurements to be 0.0004 in:

$$dT = \sqrt{(EAr\frac{d\varepsilon}{dT})^2 + (E\varepsilon r\frac{dA}{dT})^2 + (E\varepsilon A\frac{dr}{dT})^2}$$

$$dT = \sqrt{(3E7(0.5)(1)(0.000042))^2 + (3E7(.012)(1)(.0004))^2 + (3E7(.012)(0.5)(0.0004))^2}$$

$$dT = \sqrt{(3.9E5) + (2.1E4) + (5184)}$$

dT = 645 lbs/in

Percent uncertainty: 0.36%

The percent uncertainty of 0.36% was below the 5 % threshold using data from the specification sheet. This is good because all of the sensing uncertainty is well below the threshold. This means that when other sources of error are added to the system due to the physics of the real world, it should still be below the 5%, making this a valid design. Using this uncertainty analysis, it is beneficial to look at each variable's impact on the torque. The largest impact was the strain uncertainty with 3.9E5, while the smallest was the radius uncertainty with 5184. This means the strain gauge must be implemented correctly using the proper adhesion of 1-EP70 [11]. Other cheaper adhesions may increase this uncertainty, causing more torque calculation errors. Also, the exact type of steel must be known because Young's modulus had a major effect on the uncertainty in the torque, so knowing the exact alloy and its Young's modulus will be necessary. **Figures 30**, **31**, and **32** below show a visualization of how this calculation will be performed.

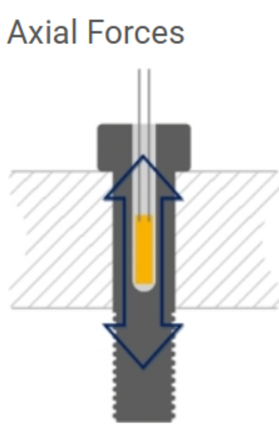


Figure 30

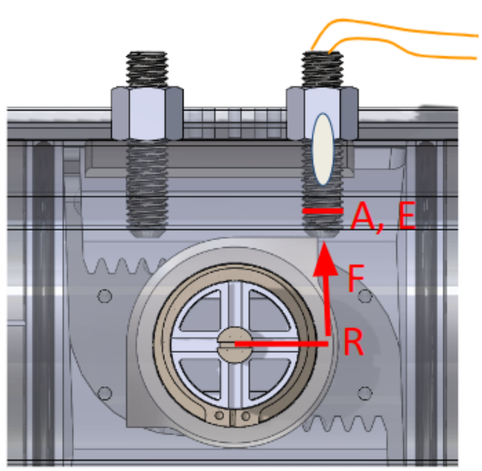


Figure 31

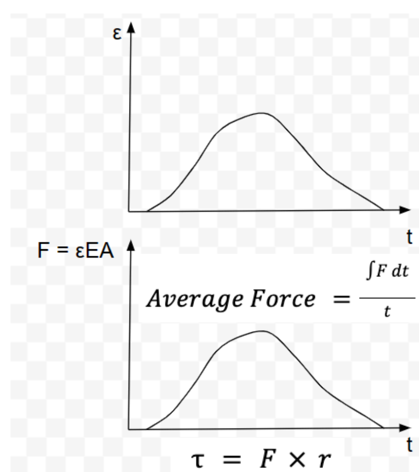


Figure 32

Depiction and graphs of how the strain gauge data will be recorded and calculated.

The last concept to verify is the EMF motor. To ensure that this concept would work properly, the team had to figure out how to convert the voltage generated by the motor to a usable torque value. The analysis below shows the team's thought process to arrive at the final equation to get torque from voltage produced by a motor.

Governing Equations

$$T = F * dist \qquad E = F * disp \qquad T = \frac{E}{\theta}$$

Where T: Torque, F: Force, dist: Distance, E: Electrical energy, disp: Displacement, Θ: Radians

Still, the motor generates voltage which is not the same as electrical energy. To use the voltage reading of the motor, the energy in the torque equation above must be converted to power.

$$E = P * \Delta t$$

$$P = \frac{V^2}{R}$$

$$T = \frac{\frac{V^2}{R} * \Delta t}{\theta}$$

Where P: Electrical power, Δt: Change in time, V: Voltage, R: Resistance

This analysis proved it is possible to measure the torque from just the electrical properties of the motor and did not need the moment of inertia. This was an important validation as every other concept that utilized rotational dynamics required this value as it would be incredibly difficult and time-consuming to experimentally find. Another important aspect of this analysis was discovering that the motor solution needs a known resistance value to find the power. The time will also need to be measured from the start of voltage generation to stopping the voltage generation, which can be measured by the DAQ. Lastly, the radians should be π/2 as the actuator shaft will rotate 90 degrees. All of this combined will allow for a torque based on the rpm of the motor and the power output of the motor.

Preliminary Product Risk Analysis

A product risk analysis is necessary in order to determine possible causes of failure in the final product so that they can be mitigated or prevented. For this project's product risk analysis, all four solutions were generalized as "a sensor connected to a data acquisition system" in order to simplify the fault tree map. If four trees had been created, they would have been nearly all the same in meaning with differences only being seen in the type of sensor. **Figures 33** and **34** below show the generalized product risk analysis for the planned sensor and data collection system, split up into two figures due to the fault tree's large size.

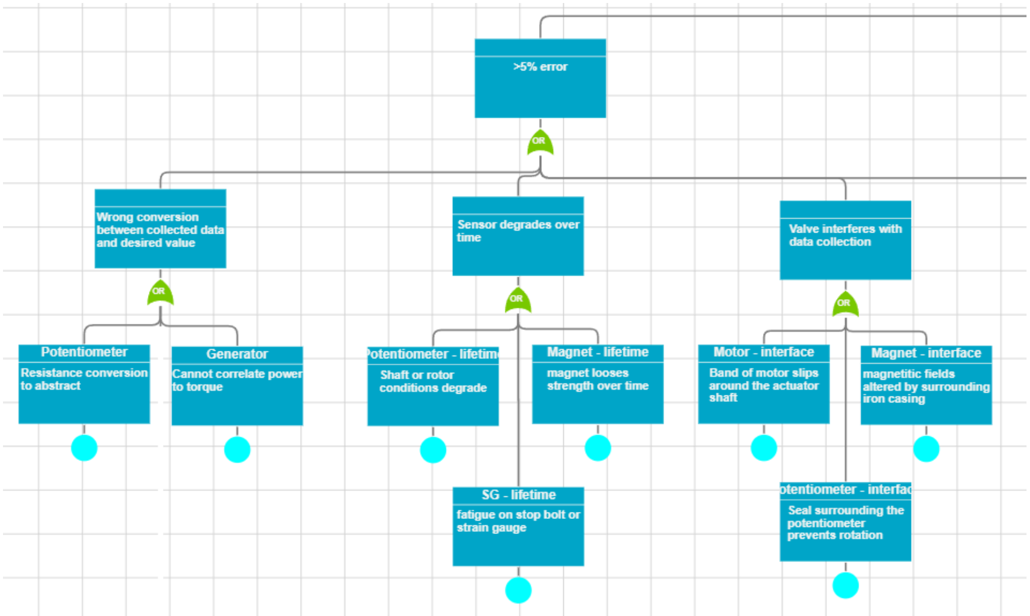


Figure 33: Left side of product risk tree.

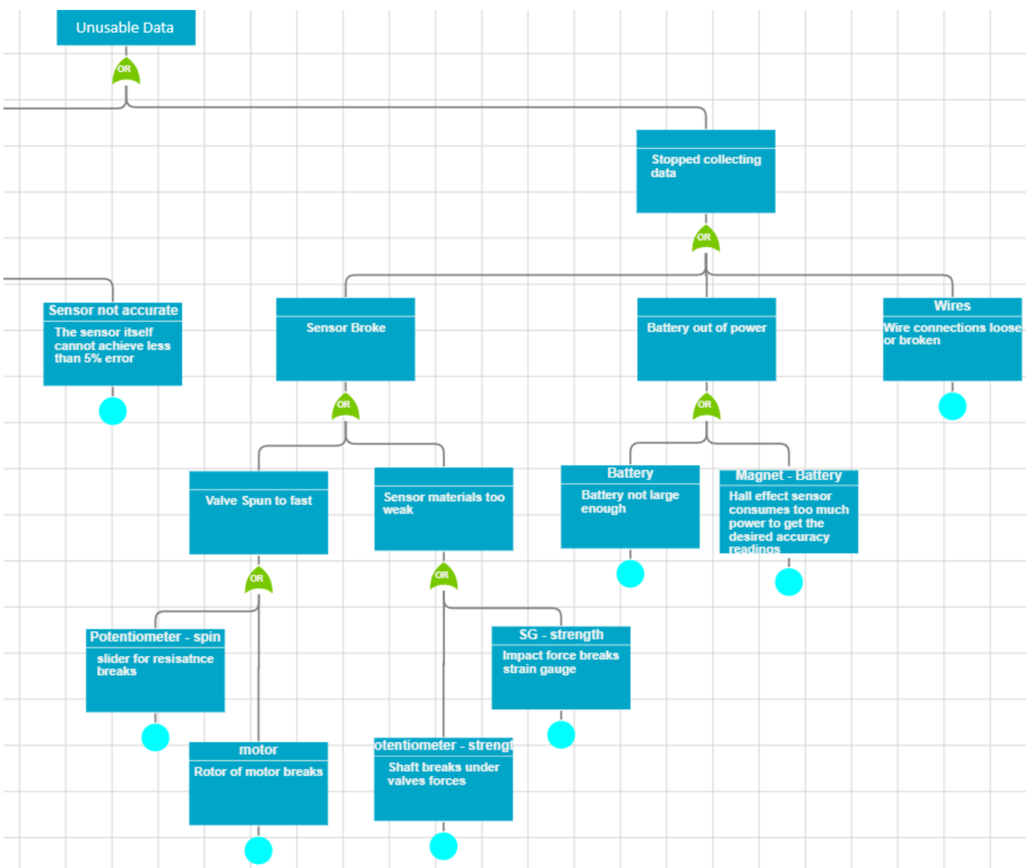


Figure 34: Right side of product risk tree.

Lower boxes are the cause of higher-level boxes. For example in **Figure 34**, the rotor of the motor breaking can cause the valve to spin too fast, which can break the sensor, which can cause the sensor to stop collecting data, and so forth. This tree includes failures of the sensors, power supplies (written as batteries), DAQ units, the valves or actuators themselves, or connections between the components. Identifying all of the possible failure points allows the team to focus on potential trouble spots and easily find problems when they do occur. No design process can occur without failures at any level, and this tree will help guide the team to the correct troubleshooting method when failures occur in validation, testing, or assembly.

This also provided insight into what can be done to solve these problems should they occur. To start with a problem that could occur is that the slider of the potentiometer could break trough repeated use. If this were to happen, the team decided that the potentiometer woulfsd be upragded to a contactless potentiometer that uses magnets. This device is more expensive and slightly less accurate but it will be used if necessary if the potentiometer does not have the proper lifetime.

Another issue for a lot of these sensors is the accuracy degrading over time as well as the sensor being too weak and breaking. A solution that can be used for all sensors is to find a higher-end version of the same sensor that was built to last longer. These higher-end sensors are built with better quality materials and, therefore, can last longer, but they do have a higher cost. The higher cost will be worth it in the event that it provides the team with a sensor that can collect data over the lifetime of the valve.

A prominent risk for the hall effect sensor is the valve's ferromagnetic properties altering the magnetic field reading by the Hall effect sensor. Should this be a problem, our team will experiment with how close the magnet needs to be in order to get accurate readings. Then based on this information, the case of the valve will have to be tweaked to ensure that the Hall effect sensor can get close enough. Another issue in the hall effect sensor is the voltage supply needed for accurate reading is too high, causing the battery to run out of power. This is because the more voltage supplied, the more sensitive the sensor is to weaker magnetic fields. The only solution for this problem is to either increase to a bigger battery or use a solution for the torque that requires less power so that it can be diverted to the hall effect sensor.

A common fault could be caused by parts of the system breaking like the motor band, potentiometer shaft, and other parts. The solution for this process is to provide extra parts for items that commonly break when shipping these smart valves out. This will allow for the client to replace these parts when they break, so things like the motor band can easily be replaced because it is accessible. This will build better customer relations and ensure that the sensors are constantly recording data.

Our team recognizes that this is not a comprehensive list of all failures that could occur and many that were not thought of will occur when in the build and testing phase. However, the fault tree analysis was useful to see what were the overarching issues and some of the root causes for these issues. It was incredibly useful for the team to start thinking ahead on possible solutions so that when the problem occurs, a procedure is already in place, and the team does not waste time trying to figure out how to resolve the failure. Overall, this was a helpful tool to begin the risk analysis process, and as the project progresses further into the 402 semester, the team will translate the faults from the FTA branches to a full FMEA analysis.

VALIDATION PLAN FOR MEEN 402

The project is split up into two deliverables: finding the position of the valve and the torque of the actuator, and validation testing must be done for both deliverables. A validation plan was made to provide an overview of what information is needed to validate each design, which can be seen in **Table 11** for the position deliverables and **Table 12** for the torque deliverables. All requirements were made using Bray's input and the valve specifications.

Table 11: Top-level validation plan for the valve position deliverable.

Functional Requirement	Quantitative Requirement	Design feature	Validation Test
Measurement Accuracy Position	< 2%	Potentiometer	Measure the reading of the position slider of the rotary potentiometer and compare to actual rotation by hand (test how ambient temperatures affect accuracy)
Surrounding metals do not interfere with accuracy	<2 %	Hall effect sensor and magnet	Attach a magnetic point to the edge of the butterfly disc and measure change in magnetic field due to rotation
Ease of implementation	<2 hr	Prototype Apparatus	Time how long it takes to set up the sensors on the prototype valve system
Calibration Time	< 1 hr	Sensor	Time how long it takes the team to get accurate readings from the sensor system from start to finish
Measurement accuracy with extended use	< 5%	Potentiometer and Hall Effect Sensor	Measure the decay of accuracy as the potentiometer cycles till failure
Lifetime of sensor	> 2 million cycles	Potentiometer and Hall Effect Sensor	Rotating ball system that open and closes to test how many cycles until the sensor fails

Total power Consumption	<100 wh	Battery	Use prototype system and measure the amount of power consumed over an hour

Table 12: Top-level validation plan for the actuator torque deliverable.

Functional Requirement	Quantitative Requirement	Design feature	Validation Test
Measurement Accuracy Torque	< 5%	Cylindrical Strain Gauge and Motor	Measure and compare the reading of the torque reading to the actual set value (test how ambient temperatures affect accuracy)
Ease of implementation	<2 hr	Prototype Apparatus	Time how long it takes to set up the sensors on the prototype valve system
Calibration Time	< 1 hr	Sensor	Time how long it takes the team to start getting accurate readings from the sensor system from start to finish
Measurement accuracy with extended use (torque)	< 5%	Cylindrical Strain Gauge and Motor	Measure the decay of accuracy as the rotational torque bracket or potentiometer cycles till failure
Lifetime of sensors	> 2 million cycles	Cylindrical Strain Gauge and Motor	Rotating Actuator system that open and closes to test how many cycles until the sensor fails
Total power Consumption	<100 wh	Battery	Use prototype system and measure the amount of power consumed over an hour

Validation Plans

The first step in the validation testing for position is to ensure that the potentiometer set up can maintain a less than 2 percent error. The plan is to bore a hole through the bottom of the ball valve, attach the stem of the 10 kΩ potentiometer to the bottom of the ball valve, and put a multimeter in line to measure the resistance. Bray is providing a gear crankshaft that will turn the valve while displaying the degree of rotation the ball is at. Then, comparing the readings obtained from the potentiometer and the degrees on the rotation of the gearbox, the percent error can be found. This plan was selected to make sure that the connection between the potentiometer and the ball valve does not add any error to the potentiometer readings. It also validates that the potentiometer can be secured to the valve, or else there will be no readings taken and, therefore, no error value obtained.

The Hall effect sensor requires a different sort of validation test due to the ferromagnetic properties of the valve casing and parts. The plan for this test is to attach a magnetic strip to the disc of the butterfly valve. Then, the Hall effect sensor will be placed around the valve, including the stem section, at the bottom of the valve, and the side portion. Using the same gear crankshaft apparatus as for the potentiometer, the actual rotation will be known then we can compare it to the voltage reading of the Hall effect sensor to see if a below 2% error is possible. This plan was selected to test how the metal properties of the valve interfere with magnetic fields in different locations of the hall effect sensor to result in better accuracy readings and to see, in general, if the 2% error can be achieved or else it will not be able to be used in industry. The butterfly valve was selected because it is easy to access the disc to magnetize as it is completely exposed compared to the ball valve, where the ball is enclosed, so it would have to be taken apart to magnetize.

The plan for the cylindrical strain gauge will be tested for the accuracy of the torque measurements. A rack and pinion actuator will be used, and cylindrical strain gauges will be installed into the stop bolts by drilling small holes. The actual torque value will be known because the actuator was previously unused, and the expected value can be calculated by monitoring the pressure supplied to the actuator. Combining the strain data collected with the actuator torque a error value can be found. For the torque data to be valid, it must remain less than 5 percent. This plan was selected because if the collected data has more than 5 percent error, then it cannot be used in industry to predict the torque. Another important aspect of the test will be to see how far into the stop bolt the cylindrical strain gauge has to be placed to get accurate readings.

For the motor apparatus, the team and Bray do not know if this design will yield usable results, so the purpose of determining the accuracy is to see if it is a viable solution before it is embedded into the actuator. To start, the motor will be mounted to the top of the actuator with a band that is around the rotating shaft. A multimeter will be hooked up to monitor the voltage produced by spinning the motor. Then, the actual and experimental data can be compared using the conversion equation made by the team and knowing the actuator torque based on the pressure supplied. If the error is high, then the assumptions for time and rotation will be revisited to see if that is the issue. If troubleshooting does not yield usable results with an error below 5 percent, then the product will have failed and will not be moved forward. This test aims to see if this apparatus can obtain accurate data while not moving too far forward with the concept and embedding the solution into the actuator.

After all sensor systems have been tested and validated to see if they meet the respective error requirements, the team plans to optimize and finalize the designs that passed the initial validation testing. The first step for this is to optimize how long it takes to implement the sensor system, which is the ease of implementation. The plan is to time how long it takes to wire all of the sensors together to start transmitting data. The slots for the sensors will be manufactured but will not have the sensors implemented. The team will see how long it takes two people to set up the sensors, and it should be under 2 hours. If it is over, the longest part of the process will be identified, and the team will focus on reducing the time until it is under the 2-hour time limit. The reason for this validation is to ensure that the process of installing this smart package of sensors is not too complicated and time-consuming, wasting Bray's manufacturing resources.

The next optimization stage is to bring the calibration time of the sensors down to under an hour. This test will be done by starting a new data collection log for all sensors, then collecting the data and correlating it to both torque and position. This process will be timed, and once again, if the sensors take too long to calibrate, the calibration process will be revisited to see what assumptions or techniques can be implemented to shorten the time. This test aims to reduce the valves' installation time because the companies will not want to install these smart valves if they shut off their facilities for too long. This plan was selected to be iterative and constantly shrink down the longest process until the entire procedure is optimized.

After optimizing the installation and calibration techniques, the sensors that passed the initial validation test for error will be lifetime tested. The first stage of this process is to test how the accuracy of the sensors changes over millions of cycles of the valve. The plan to test this is to bring the valve and actuator apparatus with the sensors installed to Bray's facilities, where automated actuators repeatedly open and close the valves. They will be set up and monitored on the Bray computer system that will constantly record the number of cycles and the error of the sensors. Then, once a sensor starts getting an error over the allotted amount of 2% or 5%, the number of cycles will be noted. While this validation test is happening, the lifetime test will be happening simultaneously to see if any of the sensors stop providing data due to breaking. If the cycles are below the 2 million cutoff for either the error or the lifetime, then the sensor will be evaluated to see if alterations can be made or cut depending on Bray's advice. The plan was selected because the error of the sensors will change over time as repeated use causes degradation, and Bray's R&D department has the technology as they do this every day. The lifetime is also important to validate because if the sensor fails before the valve starts to fail, it will provide no useful data on how to prevent valve failure. This validation test should be done at Bray as they have all the proper equipment and tools to do this, and it will not come out of the team's budget.

The final stage of validation planning will be determining each sensor's power draw to collect accurate data. The plan is to individually connect the battery to each sensor in the valve system. Then, the power consumption will be monitored using a multimeter to ensure that no sensor is drawing more power than what can be provided by a compact lithium-ion battery, which was determined to be 100 watt-hours. This validation plan will eliminate nonrealistic designs because if a sensor draws too much power, it will not be able to operate in a remote field for an extended time.

Project Plan Selection Validation

Overall, this plan was selected based on the feedback from Bray that the error of the measurements was the main concern while also trying to optimize the process of setting up the system. The initial accuracy test is to ensure that the valve is not interfacing with any of the sensors, causing the sensor's accuracy to be thrown off. This test will catch things like loose connections between mechanical parts or the valve and sensor system not acting together like the team anticipated. The next stage is to ensure the design is not overcomplicated by ensuring everything is easy to set up and can be easily calibrated, no matter the conditions. Lastly, the designed system has to be able to outlast the valve in terms of lifetime and maintain a level of accuracy, or else it will not be able to collect useful data because it will not be able to predict the failure of the valve. Power consumption will be used as a final test to see whether any concepts are not valid based on needing way more power than can be supplied by a portable battery.

To verify that this validation process is appropriate, our team will present the results to Bray every week to get input on whether it is okay to move forward to the next step or if a certain area needs to be looked at more. The most helpful thing is that the validation process is laid out in steps, so if something is not caught in the initial testing and optimizing phase, it will be caught when lifetime and power testing happens. Another useful process is that moving into the spring semester, our team plans to test multiple designs in validation testing so that if one fails, it can be dropped. The team can continue with the solution that works. Lastly, our team decided on measurable tests and set quantitative limits to what is accepted to avoid bias by just analyzing the raw data.

BUDGET PLANNING

The total expected expenditures for developing and testing the four concepts that meet the project deliverables is broken down into categories of tooling, materials, facility access, and travel. In developing a budget for the project, the valve and actuator equipment donated from Bray was first taken into consideration including butterfly and ball valves, scotch-yoke and rack & pinion actuators, and mounting equipment. Since this equipment is being donated, it will not be counted against the total expenditures. The sensors needed to validate the aforementioned concepts were then considered. For cost estimates, sensors were chosen within the same size and power rating tolerances that is expected of our final product, including rotary potentiometers, hall effect sensors, cylindrical strain gauges, and EMF motors. Finally, supporting equipment such as lead wires, power supply, multimeters, data acquisition unit, and digital analog converters were considered to process data within the valve system. A full detailed budget listing each expenditure is included in **Appendix D.** A breakdown of the budget expenditures by category is shown below in **Figure 35.**

CATEGORY	COST
Tooling	$0
Sensors	$1,290
Power & Data	$298
Product Casing	$844
Facilities	$0
Travel	$523
TOTAL	$2,955

Figure 35: Breakdown of estimated budget by category.

Notably, there are no expected costs for facility access to the FEDC or Bray's workshop, as well as no charges for necessary tooling. The largest expected costs are within the sensors section, as multiple sensors of each selection will need to be purchased for product validation and security in the event a component breaks. The next largest costs are for product casing for items such as a DAQ, metal casings, and seals to encapsulate the sensors that interact with the valve inside the fluid system. Travel is also a notable cost, with each trip from College Station to Cypress, TX costing about $105 per driver, per trip. There are an expected 3 more trips to Houston that will need to be made to complete the project. Additionally, a margin of up to 30% was added to every product to account for a possible change in brand or size, as well as unexpected shipping costs that may occur while procuring items for the project. This budget will be used as a tool to guide the team expenses throughout the project build & execution phase and properly account for travel, fabrication, assembly, testing, and analysis costs. Purchase orders made throughout the project will also be tracked and compared to the original budget.

SCHEDULING AND MANAGING A PROJECT

As a team of engineers, being able to accurately plan and schedule due dates to stay on track is essential for the success of the project. The tools our team utilized to effectively manage our project include a Work Breakdown Structure, a Gantt chart, and a Process Risk Assessment. The following sections will go into detail regarding our scheduling and management tools, as well as how they were incorporated into the project.

Work Breakdown Structure

Utilizing a Work Breakdown Structure (WBS) offers several key advantages in project management. Firstly, it provides a clear and structured framework for breaking down complex projects into manageable components, which enhances project planning and organization. Secondly, a WBS enables better resource allocation and cost estimation by focusing on specific tasks and deliverables. It also helps in assigning responsibilities and setting clear expectations for team members, fostering collaboration and accountability. Additionally, a well-defined WBS helps in tracking progress, identifying potential bottlenecks, and managing project risks more effectively. Finally, it enhances communication within the project team and with stakeholders, ensuring that everyone has a common understanding of the project's scope and objectives.

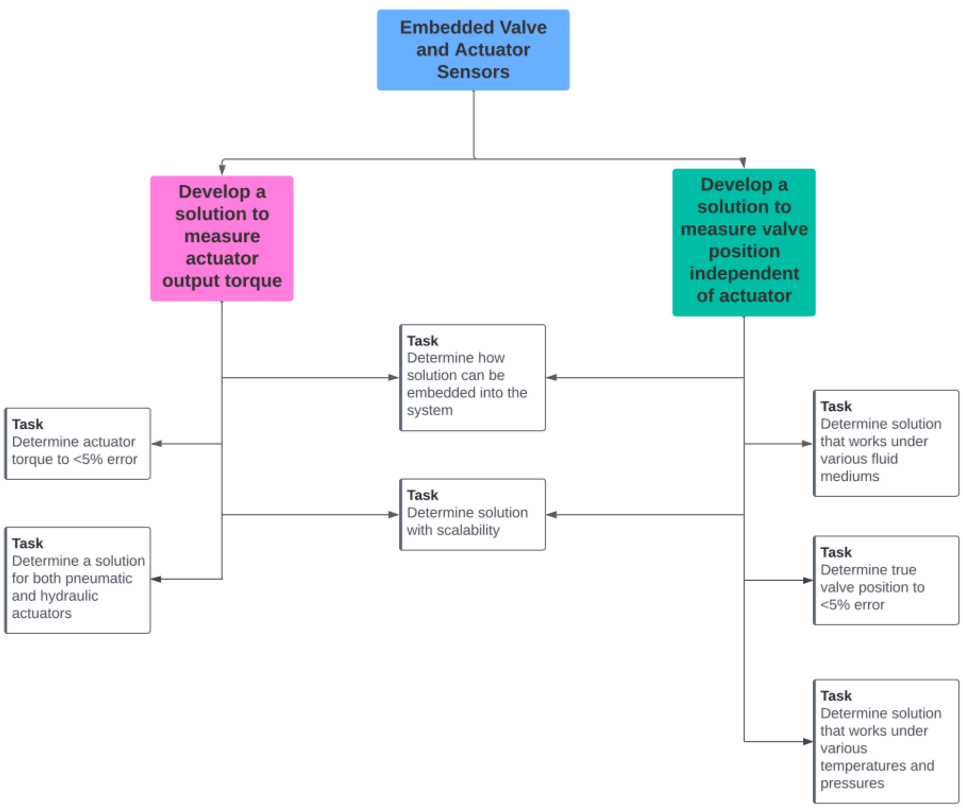


Figure 36: WBS for MEEN 401.

In **Figure 36**, we can identify the key tasks that need to be completed to make progress in completing our project deliverables. The tasks in the center of the WBS are shared tasks between the two deliverables, while the tasks on the outside are specific to each assigned deliverable.

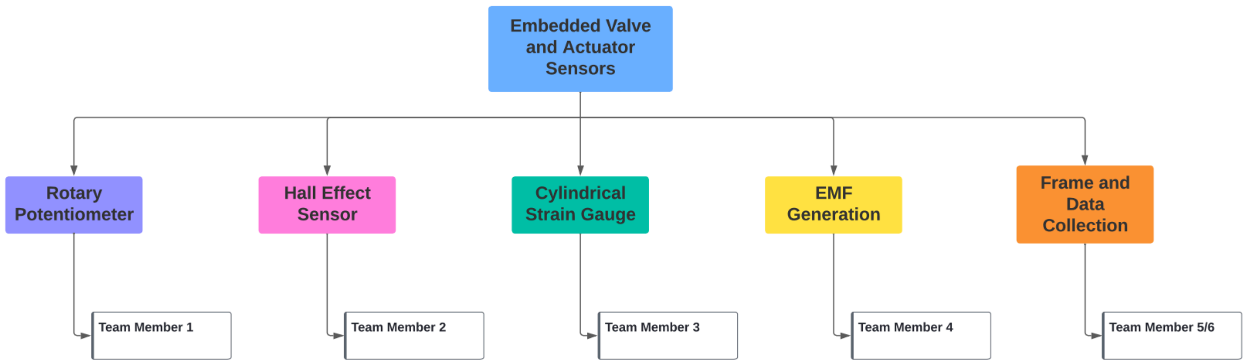


Figure 37: WBS for MEEN 402.

In **Figure 37**, we can identify the assignments of individual team members for specific solutions that will be tested in MEEN 402. The team has agreed that with everyone having general knowledge of the areas of work for our team, there is benefit in having specific persons assigned to focus on specific solutions for expertise purposes.

Gantt Chart

When it came to building a Gantt chart to visualize due dates and manage assignment deadlines, our team decided to use Trello. Trello is a website that allows sections for assignments, milestones, and notes to be stored and allows an automatic generation of a Gantt chart for selected sections. Our team utilized this tool to effectively plan out our due dates for assignments and milestones, as well as to generate the Gantt chart for visualization purposes. **Figure 38** represents the milestones from the Gantt chart. The Gantt chart also includes holiday breaks and reading days so team members know what time blocks to not work during.

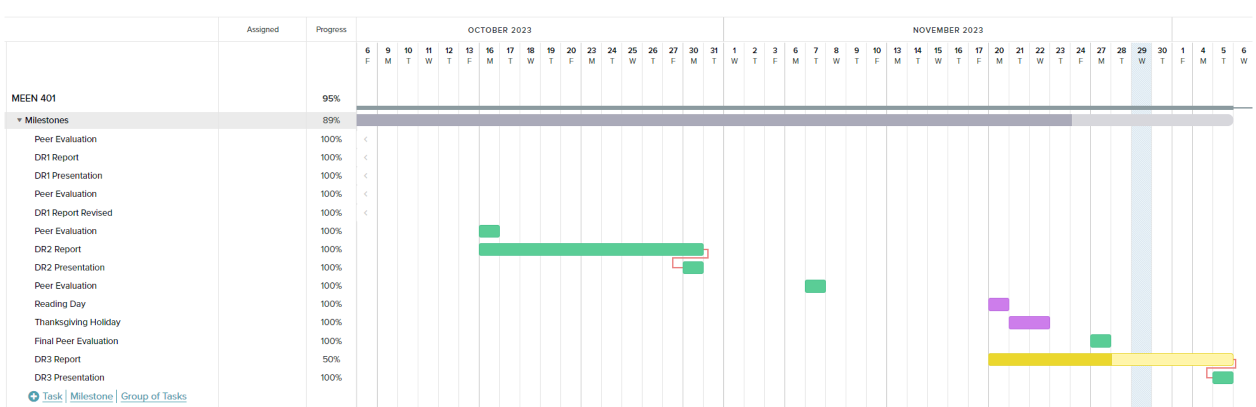


Figure 38: Gantt chart for project milestones.

A similar Gantt chart was also generated for the assignments for the lecture and studio sections in Canvas, as well as the estimated MEEN 402 planning, which is represented in **Figure 39** and **Figure 40**. Trello does not allow for the Gantt chart to show the people or person assigned to individual tasks, but the team is able to view this under the listed sections of the milestones and assignments.

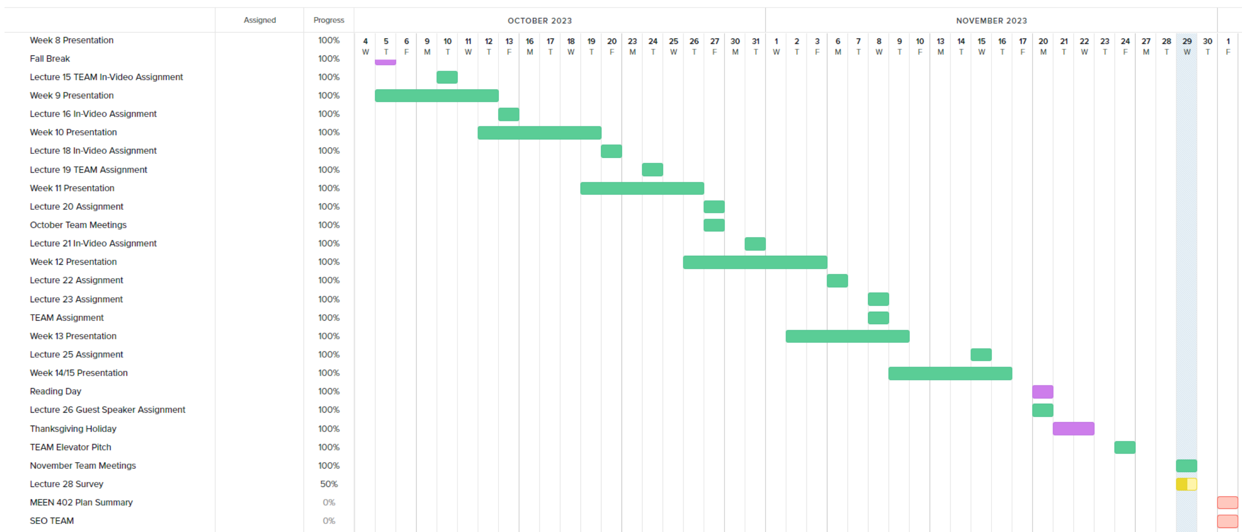


Figure 39: Gantt chart for project assignments.

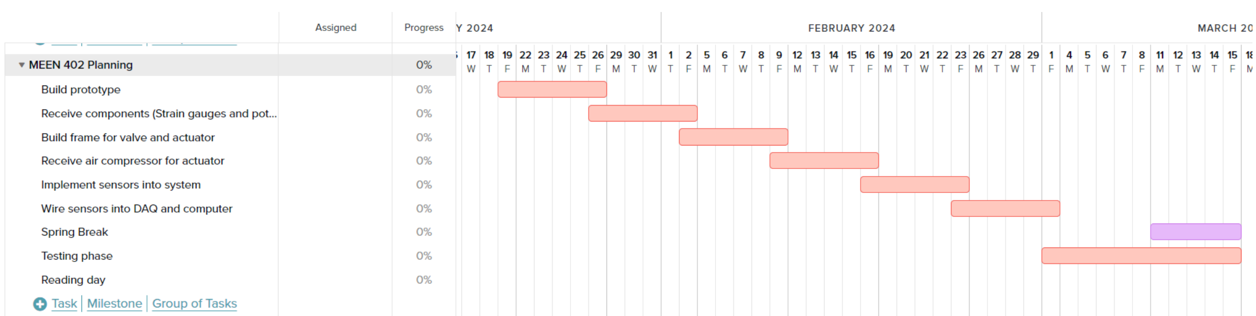


Figure 40: Gantt chart for MEEN 402 planning.

For **Figure 40**, the shown tasks and dates are estimated and will change if necessary when we approach the start and enter into MEEN 402. Each task was assigned one week to accomplish, however there are some that will take longer than one week, and some that will take less time to complete. Overall, sticking with this plan will allow our team to finish testing and have our final solution by the end of March at the latest.

Process Risk Assessment

Utilizing process risk assessment offers several key advantages for our team. Firstly, it helps identify and mitigate potential risks in the tasks, reducing the likelihood of accidents, errors, and financial losses. This proactive approach enhances safety and operational efficiency. Secondly, it enables businesses to comply with regulatory requirements, safeguarding against legal and financial penalties. Additionally, process risk assessment promotes a culture of continuous improvement, fostering innovation and adaptability.

Table 13: MEEN 402 process risk assessment.

Process Risk	Probability	Severity	Actions to Minimise Risk
Missing deadlines	Unlikely	Major	Have an updated calendar with due dates relayed to team members regularly.
Safety concerns with handling equipment	Moderate	Major	Refer to FEDC staff if any questions arise when handling equipment.
Equipment scheduling conflicts at FEDC	Unlikely	Moderate	Reserve equipment as soon as possible, plan ahead for testing.
Student schedule conflicts	Moderate	Minor	Share schedules in Google Drive so common meeting times can be established early.
Solution time allocation	Unlikely	Major	Give our team time for prototyping and testing for each solution, and avoid becoming hyperfocused on a specific solution.

When filling in the details for **Table 13**, the team first analyzed the tasks from **Figure 40** to see what contained risk for our team and/or Bray. Identifying the risks contained within the tasks, our team was able to identify the probability and severity of each risk, as well as the actions our team can take to mitigate these risks. This approach to project planning allows our team to think and act proactively.

FINAL DELIVERABLES

As our team approaches the conclusion of MEEN 402, our expected final deliverables are to provide a comprehensive solution for detecting valve positions and internal actuator torque. This solution is designed to be adaptable to valves and actuators of varying sizes, ensuring its applicability across a wide range of related products. Our objectives are to ensure the safety and cost-effectiveness of the end product for our customers. During MEEN 402, our team remains committed to adhering to milestones and deadlines, allowing us to provide effective material for our upcoming reports. Presently, our chosen solution for both project deliverables relies on the utilization of a strain gauge and potentiometer. In the upcoming semester, we plan to collaborate with Bray to 3D-print prototypes of our solution, which will undergo testing with their valves and actuators. It's worth noting that measurement accuracy is of utmost importance, and we anticipate that the potentiometer and strain gauge will provide near-perfect accuracy based on our research and analysis. Overall, based on the research and progress made by our team, we are confident that these deliverables are well within the realm of accomplishment during our senior year, aligning with the objectives and expectations of MEEN 402.

CONCLUSIONS

In summary, Bray would like the A&M project team to develop embedded sensors for valve position and real actuator output torque. These desires arise from the fact that non-digital valves have no built-in method of monitoring live valve performance. Wear and tear on the assembly over time can cause the actuator to fail to operate the valve, and knowing the trends in this data ahead of time would allow Bray and their customers to better predict valve failure and schedule more accurate preventative maintenance procedures. Bray and their customers' most important needs include the embedded nature of the solution, its ability to transmit data in real-time, and its accuracy within the decided-upon margins of error.

Through the use of functional modeling, several idea generation methods, time spent on the refinement of concepts, and the use of Pugh charts and quantitative matrices, the top two concepts were selected to be tested and compared for both deliverables. This experimental approach will allow the team and Bray to devise the best possible method of accurately measuring valve position and actuator torque. A rotary potentiometer and a Hall effect sensor will be prototyped to measure position, and an electric motor and a strain gauge on the actuator stop bolts will be compared to measure output torque. These concepts won out over their competitors due to their embedded nature (they can fit into the valve/actuator casing), their comparatively low cost, and their small number of moving parts which produces easier maintenance should it be needed. While preliminary detailed design has been performed (selection of sensors, data acquisition systems, mounts, and the like), the team will continue to work with Bray to identify the exact method to test, compare, and implement the solutions into the valves and actuators. Successful design and implementation of solutions for the issues would be one more step towards real-time, complete data acquisition from these assemblies.

REFERENCES

[1] "A Comprehensive Guide on Butterfly Valve Vs Ball Valve". *Dombor Valve*, 2021, https://www.dombor.com/ball-valve-vs-butterfly-valve/. Accessed 11 September 2023.

[2] "Pneumatic Actuator: Series 92/93 Rack & Pinion Pneumatic". *Bray International, Inc*, n.d., https://www.bray.com/valves-actuators-controls/actuators/pneumatic-actuator/series-92-93-pneumatic-actuator. Accessed 11 September 2023.

[3] "Scotch Yoke Pneumatic Actuator: Series 98". *Bray International, Inc*, n.d., https://www.bray.com/valves-actuators-controls/actuators/pneumatic-actuator/series-98-scotch-yoke-pneumatic-actuator. Accessed 11 September 2023.

[4] "Fluid Power Actuators Explained". *Rotork Fluid Systems*, May 2016, https://www.rotork.com/uploads/documents-versions/24733/1/pub010-024-00_0516.pdf. Accessed 11 September 2023.

[5] "Mark-10 MTT03C-100 Hand-held Cap Torque Meter CAP-TT03". *ABQ Industrial*, n.d., https://www.abqindustrial.net/store/mark-10-mtt03c-100-hand-held-cap-torque-meter-cap-tt03-100-100-lbf-in-capacity-p-807-op-1306_4671.html. Accessed 25 October 2023.

[6] "Torque Sensor - Valve Torque Testing". *Futek Advanced Sensor Technology*, n.d., https://www.futek.com/applications/Valve-Torque-Testing. Accessed 23 October 2023.

[7] "Piping Codes and Valve Standards". *Valve Magazine*, September 29, 2015,

https://www.valvemagazine.com/articles/piping-codes-and-valve-standards. Accessed 25 October 2023.

[8] "Jessinie ADS1256 24 Bit 8 ChannelAnalog Digital Converter". *Amazon*, n.d., https://www.amazon.com/JESSINIE-ADS1256-Converter-Converters-Acquisition/dp/B0BG2BZTT9?source=ps-sl-shoppingads-lpcontext&ref_=fplfs&psc=1&smid=ACSUDGHCXWYXE. Accessed 4 December 2023.

[9] "STWOF30 Oil Filled Single Turn Wire-Wound Potentiometer". *P3 America*, n.d., https://p3america.com/stwof30-r10k-10-l0-5/. Accessed 4 December 2023.

[10] "RTY Series and RTP Series Hall-Effect Rotary Position Sensors Datasheet". *Honeywell Advanced Sensing Technologies*, n.d., https://prod-edam.honeywell.com/content/dam/honeywell-edam/sps/siot/en-us/products/sensors/motion-position-sensors/magnetic-position-sensors/common/documents/sps-siot-rty-series-rtp-series-datasheet-32307665-b-en-ciid-154842.pdf. Accessed 4 December 2023.

[11] “LB11/TB21 Strain Gauges for Measuring in Screws and Bolts”. *HKB Sensors*, n.d., https://www.hbm.com/en/7452/cylindric-strain-gauges-for-measurements-in-bolts/?product_type_no=LB11/TB21%20Strain%20Gauges%20for%20Measuring%20in%20Screws%20&%20Bolts. Accessed 4 December 2023.

[12] “Introduction to Hall effect sensors”. *Texas Instruments,* March 2022*,* https://www.ti.com/lit/ml/slyt824a/slyt824a.pdf Accessed 20 October 2023.

[13] “Rotary Potentiometer - 10k Ohm, Linear”. *Osoyoo*, May 7, 2015, https://osoyoo.com/2017/05/07/rotary-potentiometer-10k-ohm-linear/. Accessed 29 October 2023.

[13] “Compression Force Sensor for Tight Spaces” *McMaster-Carr*, https://www.mcmaster.com/products/force-pressure-sensors/compression-force-sensors-for-tight-spaces-5/ Accessed 19 October 2023.

[14] “DC-Motors 2.4VDC 2.2A - Transmotec.” *Transmotec*, n.d., https://www.transmotec.com/product/GR-3548-CVC/?c=usd. Accessed 4 December 2023.

APPENDICES

Appendix A: Quantitative Matrix Calculations (Table 8)

Quantitative Calculation Hall effect Sensor

Accuracy

Accuracy of sensor = 1%

- can be affected by disluption of the magnetic feild due to heat and metal pollution

total Accuracy 3% – 1%

Callibration time

10 Runs measuring 0°
10 Runs measuring 90°
3 Runs for every 3° between 0+90°

each Run ≈ 1 min

$$10(1) + 10(1) + \frac{90}{3}(3)(1) = 110 \text{ min}$$

Callibration time = 110 min

Cost

High end Hall effect Sensor = 70 $
ball of Valve = 200 $
Manufacturing cost = 200 $
wiring = 10 $
lithium Ion Battery = 69 $

$\boxed{\text{Total cost} = 549\$}$

life time of Sensor

Hall effect sensor = 10 million cycles

magnet = looses 1% strength of magnetic feild every 100 years

Hall effect will give out before magnet so
life time of system is 10 million cycles

Volume of apparutus

Size of sensor $\approx 4 in^2$
Size of magnet $\approx 8 in^2$ ← large to ensure strong magnetic feild

total = $4 + 8 = 12 in^2$

Weight

weight of Hall effect ≈ 0.5 lbs

weight of magnet = .3 lbs per in^2

$.3(8 in) + 0.5 = 2.9$ lbs

# of Parts

- Hall effect sensor
- magnitized point
- wires
- Battery

\# of moving Parts

Only moving Part is the Ball of the Ball Valve but that is not part of our design system.

Hall effect Sensor is contactless so no moving Parts

Other values used in the quantitative matrix were pulled from the specification sheets for each sensor and can be found within each sensor's respective reference: the Hall effect sensor specs [12], the rotary potentiometer specs [9], the rotational torque bracket specs [6], the torque potentiometer specs [5], and the force sensor [13].

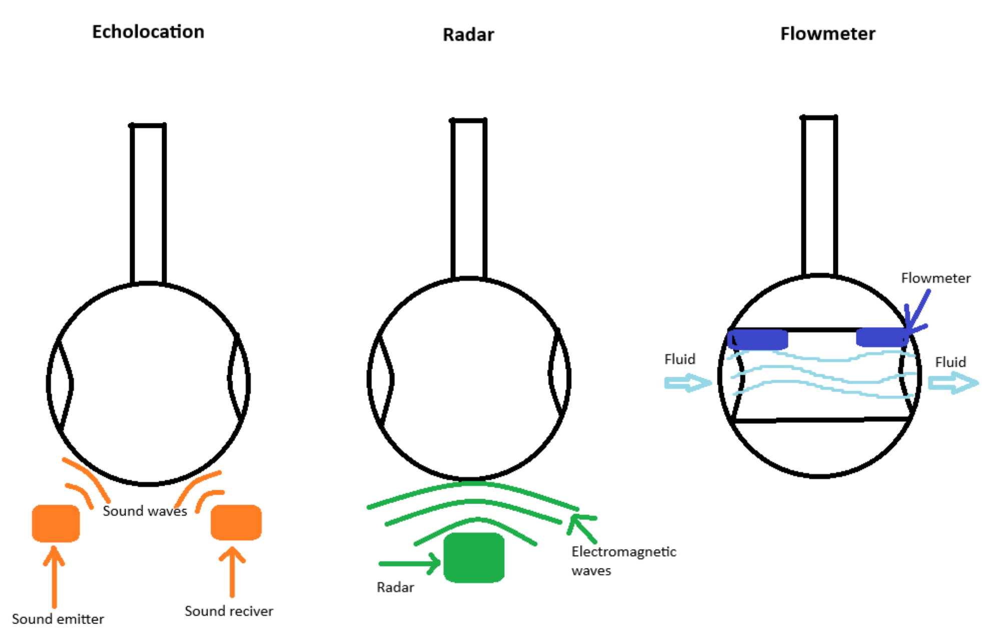
Appendix B: Locations of Figures

<u>Appendix C:</u> Locations of Tables

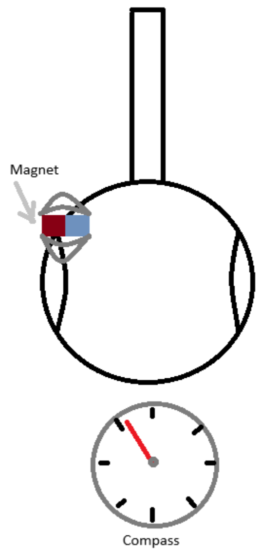
Appendix D: Complete Estimated Project Budget For Bray Smart Valve System.

Category	Component	Purchase Unit Cost	Number of Units	Total Unit Variable	Shipping Costs	Total Fixed Costs	Total Cost	Margin	Adjusted Cost
Tooling	FEDC Access								
	Voltmeter								
	3D Printing Access								
	Drill Press								
	Drill (Handheld)								
	Soldering Iron								
	Instant Weld								
Materials	Sensors								
	Potentiometer	$146.00	2	$292.00	$7.84	$7.84	$299.84	30%	$389.79
	Hall Effect Sensor	$53.12	2	$106.24			$106.24	30%	$138.11
	Rotary Torque Sensor	$1,000.78	0	$0.00			$0.00	30%	$0.00
	Rotary Potentiometer	$11.19	1	$11.19	$8.00		$11.19	30%	$14.55
	Bolt Strain Gauge (5)	$249.85	2	$499.70			$499.70	30%	$649.61
	Strain Gauge (6)	$29.99	2	$59.98			$59.98	30%	$77.97
	Neodymium Magnets	$15.00	1	$15.00			$15.00	30%	$19.50
	Power Transmission								
	Lead Wires	$0.56	20	$11.20			$11.20	30%	$14.56
	Solder	$7.48	2	$14.96			$14.96	30%	$19.45
	Battery Source	$187.80	1	$187.80	$15.00	$15.00	$202.80	30%	$263.64
	Product Casing								
	Pneumatic Rack & Pinion Actuator	$248.37	0	$0.00	$0.00	$0.00	$0.00	30%	$0.00
	Pneumatic Stotch-Yoke Actuator	$221.29	1	$221.29	$20.00	$20.00	$241.29	30%	$313.68
	Butterfly Valve	$380.89	0	$0.00	$0.00	$0.00	$0.00	25%	$0.00
	Ball Valve	$304.00	1	$304.00	$20.00	$20.00	$324.00	25%	$405.00
	Digital Analog Converter	$16.59	1	$16.59			$16.59	25%	$20.74
	Data Acquisition Unit	$79.00	1	$79.00	$5.00	$5.00	$84.00	25%	$105.00
Equipment									
	Metal 3D Printing Access								
	Valve Testing Equipment								
User Facilities									
	FEDC Shop Access								
	Bray Shop Access								
Software									
	Software Development								
Travel	College Station to Bray International	$104.66	5	$523.30			$523.30	0%	$523.30
			TOTAL	$2,342.25		$67.84	$2,410.09	27%	$2,954.90

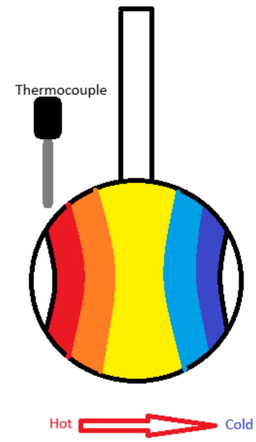
Appendix E: Concept generation sketches for Design by Analogy.



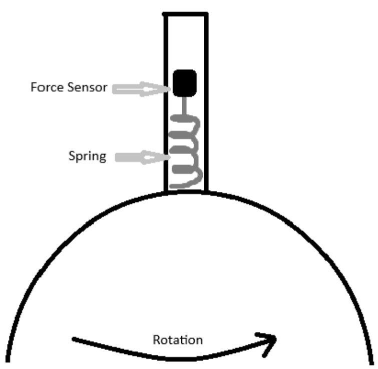
Magnet & Compass



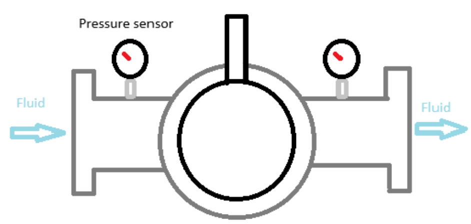
Heated Ball



Spring Force



Pressure Differntial



Appendix F: Sample calculations for potentiometer validation testing.

$$0avg \ = \ \frac{\Sigma R_0}{n} = \frac{.24+.24+.22+.25+.25+.29}{6} = 0.248333\Omega$$

$$270avg \ = \ \frac{\Sigma R_{270}}{n} = \frac{94732+94748+94736+94806+94616+94587}{6} = 94704.17\Omega$$

$$Slope \ = \ \frac{rise}{run} = \frac{94704.17-.24833}{270-0} = \ 350.75$$

$$y_{int} = \ 0avg \ =.24833\Omega$$

Using first 0 test case for rest of the calculator

$$Predicted\ Position = \frac{R_{measured} - y_{int}}{slope} = \frac{.24 - .24833}{350.75} = -\ 0.000024^{o}$$

$$\%\ error = \frac{|Act - Predicted|}{Act} * 100 = \frac{|.001 - 0.000024|}{.001} * 100 = 0.24\%$$

used 0.001 as substitute for 0 because it is impossible to divide by 0