MEEN 401-900
Design Review 2 Report
October 30, 2023
Bray Engineering

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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. All six are senior mechanical engineering majors working on this project through their capstone design course. 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
C) Leakage of the valve-actuator system

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. To mitigate these hazards and prevent productivity losses due to downtime, there is a need for a solution that can assess the condition of a valve over time. The solution requested by Bray is a way to place real-time sensors into the valve itself in order to determine the ball/plate position.

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. This data can be instrumental in detecting potential issues before they negatively impact the valve's performance or disrupt the flow of fluids. Similar to the valve solution, Bray requested a method to embed sensors in the actuator in order to determine the performance of the actuator.

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 two months of the project, the design team has determined that indirect measurements are not desired due to their nature of being based on other parameters. For example, the team will not be using reaction forces felt by the actuator casing in order to determine the output torque because this is not a direct torque reading. 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. Bray and the design team have decided to place the focus of the project on determining valve position and actuator output torque, meaning less emphasis on the detection of fluid leakage through the valve. Narrowing the scope of the project will allow the design team to focus on the quality of the solution for valve position and actuator output torque.

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. Each concept generated went through a vigorous selection process described above. The design team selected a potentiometer-like sensor for measuring both the valve position and torque outputted by the actuator.

For the valve, the potentiometer concept was chosen as 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 was most promising due to its strong performance in crucial aspects like accuracy and lack of influence on valve performance.

For the actuator, like the approach used for identifying the valve ball's position, the concept's operational principle is to utilize the actuator stem as a source of variable voltage. A rotary slip-ring potentiometer will be used at the top of the actuator shaft to measure the angular acceleration. When paired with a known moment of inertia of the stem, these values can be multiplied to find the instantaneous torque output by the actuator. These concepts were selected due to their accuracy, lack of interference with the system, and their simple embedded nature.

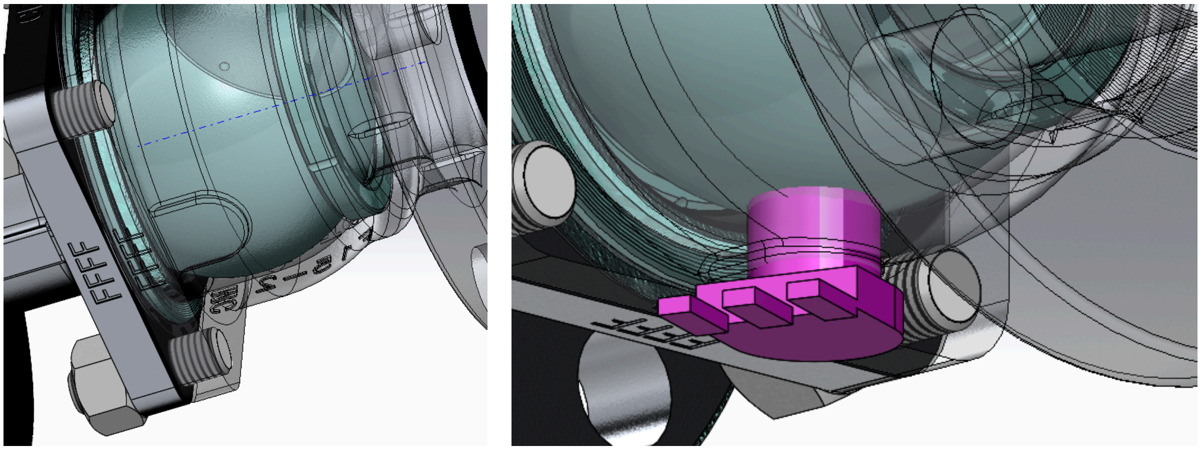

Figure 1: Example of position potentiometer solution installed on valve.

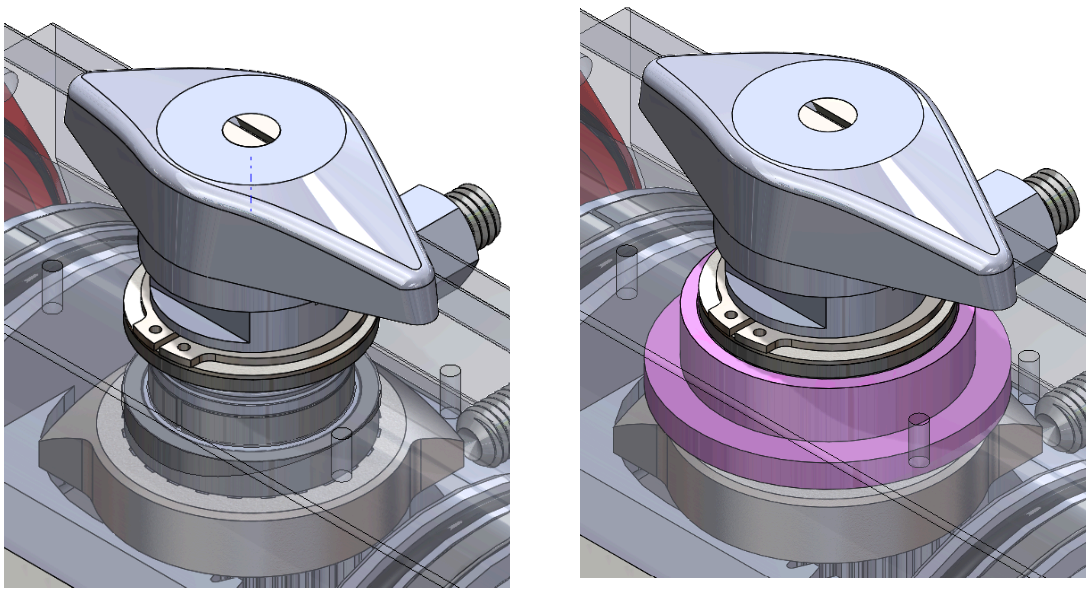

Figure 2: Example of torque potentiometer solution installed on actuator.

Figures 1 and **2** show the solutions. Future work for Bray and the design team include steps to finalize each of the designs, discuss product architecture, define a layout for each potentiometer sensor, perform a technical analysis, and develop a preliminary product risk analysis. The design team will continue to refine the potentiometer designs in order to adhere to budget constraints and deliverable requirements.

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GLOSSARY TABLE

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

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, measure actuator output torque, and detect fluid leakage to increase the valve's service life. Achieving the design goal of detecting fluid leakage can increase the valve’s service life by recognizing where fluid is leaking from which allows our team to offer a well-suited solution to prevent further leakage, or it can allow Bray to notify its customers more accurately when it is needed for a valve to be replaced. Doing this can prevent customers from prematurely replacing valves. 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

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]. Due to their thin design, just a small accidental turn can cause a valve to open when it is not supposed to. 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 3** and **4** show these valves.

Figure 3: Ball valve example [1].

Figure 4: Butterfly valve example [1].

Actuators

Actuators, like valves, come in many different types. 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.

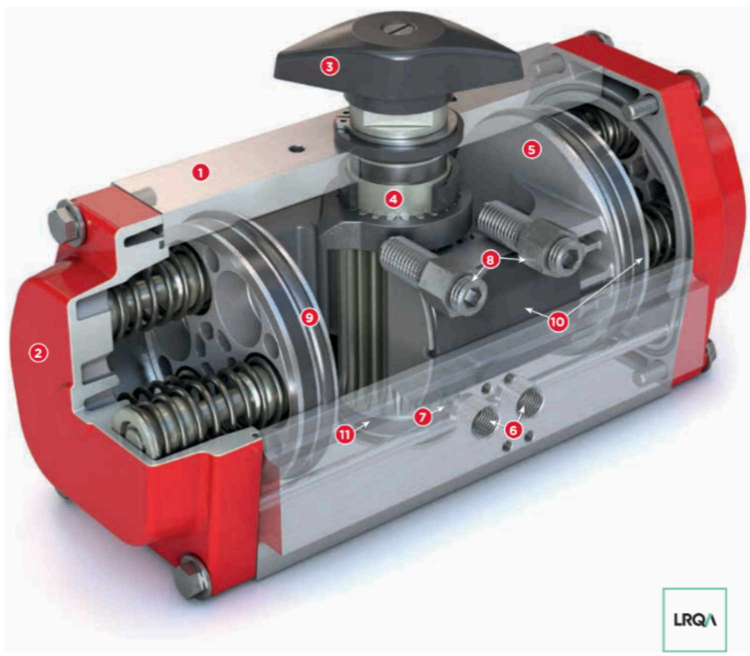


Figure 5: S92 model rack-and-pinion actuator [2].

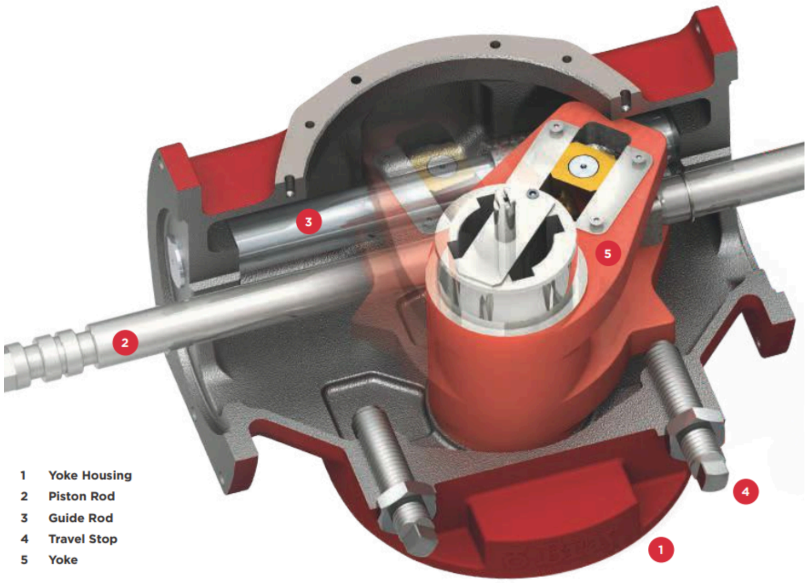


Figure 6: S98 model scotch-yoke actuator [3].

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. **Figures 7-10** show more images of Bray's ball valve and actuators.

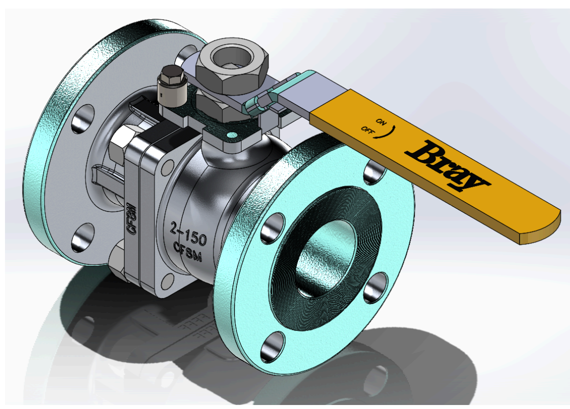


Figure 7: Bray ball valve assembly closed.

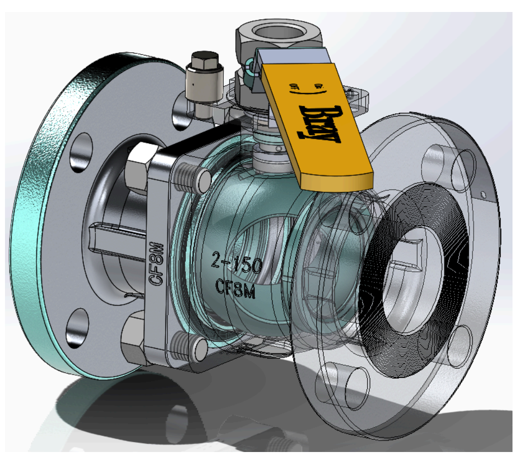


Figure 8: Bray ball valve assembly partially open (transparent for visibility).

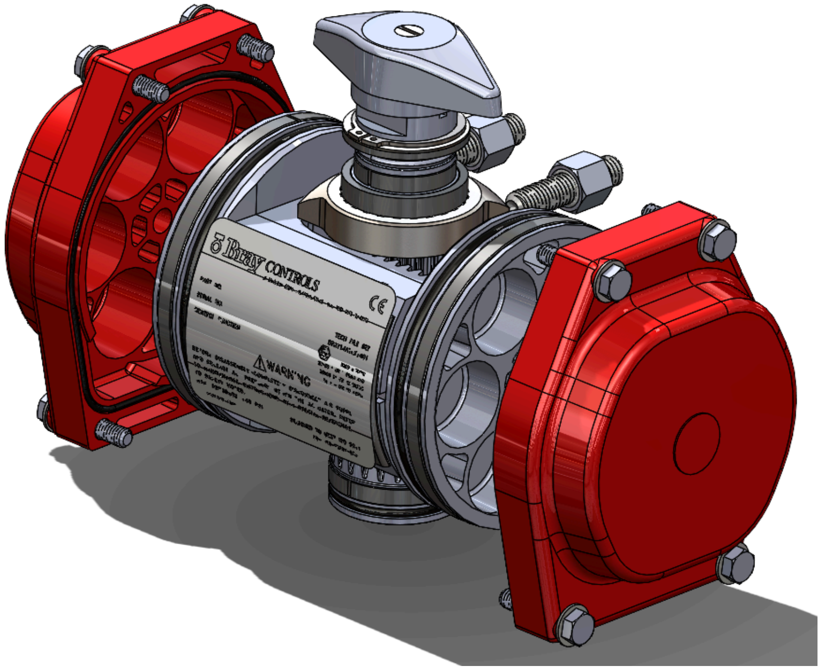


Figure 9: Bray rack-and-pinion actuator assembly (cover missing for visibility).

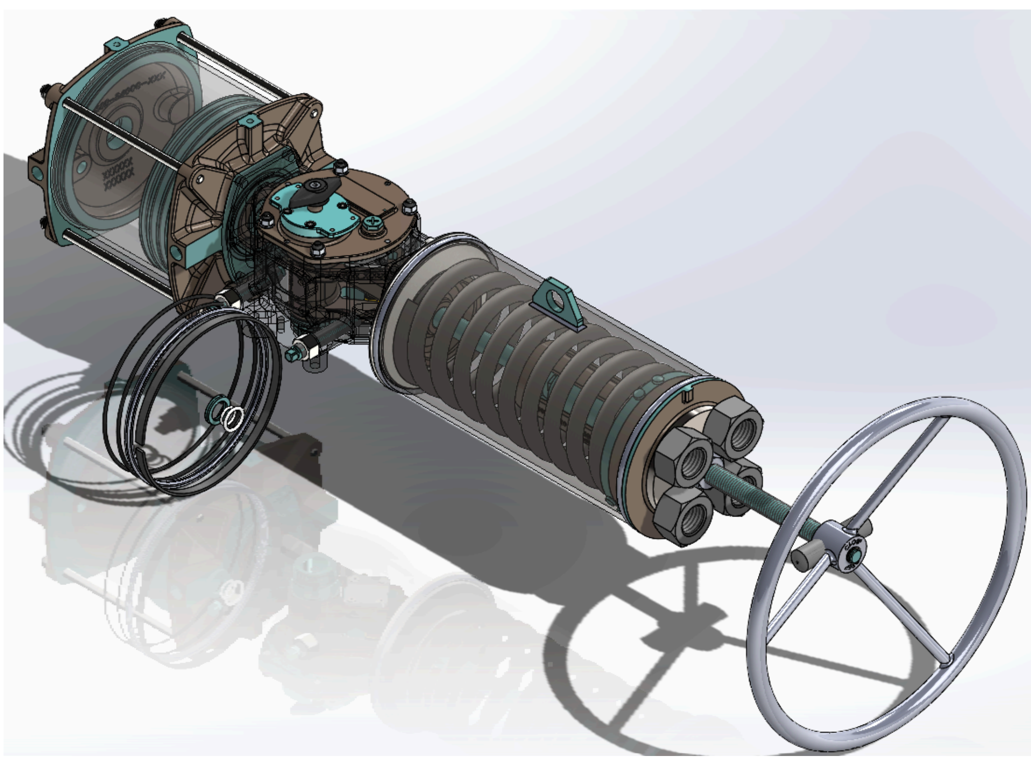


Figure 10: Bray scotch-yoke actuator assembly (transparent for visibility). Note the similar shape of the shaft-turning mechanism and indicator.

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.

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.

Leakage Problem

While these first two issues are the most critical for Bray to solve (due to their direct impact on valve and actuator function), there is a third issue of valve leakage that is a separate issue from the first two. There are several points on the valve that fluid may leak from, and this will be discussed further in the next section. Bray would like a method for determining the location of valve leakage so that they don't need to wait for a problem to occur down the line after the leak has already been going on for some time. The valve leakage portion of the problem statement was more vaguely defined by Bray than the other two and could be considered a "stretch goal" for this project. The team will focus its resources more heavily on the first two goals. The main constraint on the problem is that the leakage sensor or measurement method must be embedded into the actuator or the valve itself, separate from the other parts of the assembly so that the components can still be sold separately. Thus far, the team has not addressed this leakage issue and likely will continue to put it to the side in favor of prioritizing the position and torque problems, as these are most important to Bray.

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 three parts of the problem have three 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.

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. 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, which should be kept in mind:

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

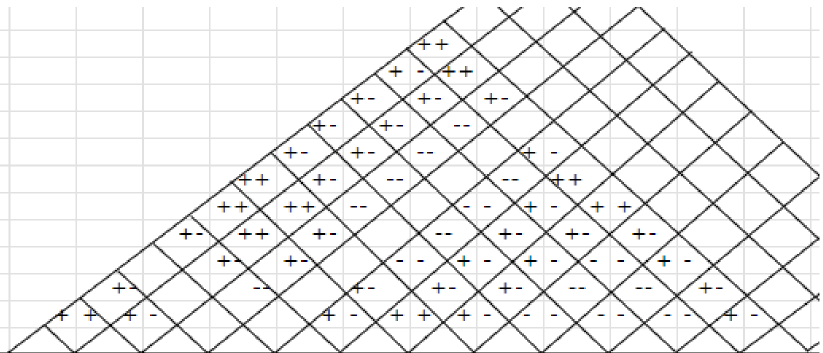
The results of the customer needs in **Table 1** were used as a base for the design requirements for our project. The most critical customer needs were the deliverables of measuring valve position and actual actuator torque. These deliverables were necessary design requirements because if the team failed 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 11** 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 11: 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 11** 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 11**. 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 11,** 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 11** 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 12,** 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 12: 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 design 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 either MEEN 402 or the end of MEEN 401.

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	Moving 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 specific 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 is difficult, depending on how embedded the sensors are due to low accessibility, giving our team 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 is a thought exercise that reduces the actions of the final product into its essential tasks and identifies the flows of matter or energy into/ out of the product system. This will later 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 13** shows the Black Box model for both the position and torque problems.

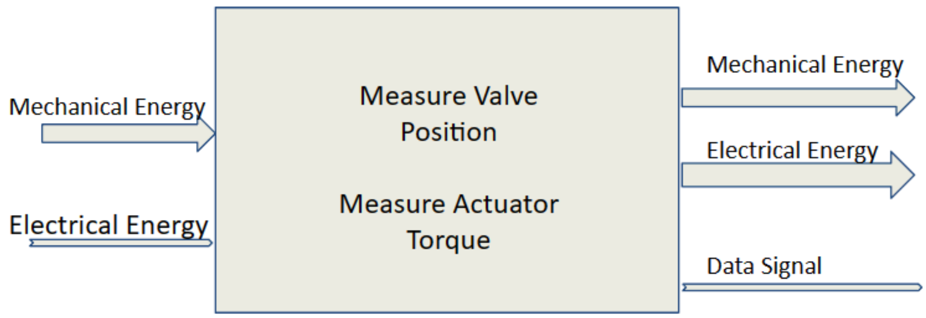


Figure 13. Black Box model for Position and Torque deliverables

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 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 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 14** and **15** below, showing function chains for determining the True Valve Position and Measuring Actuator Torque.

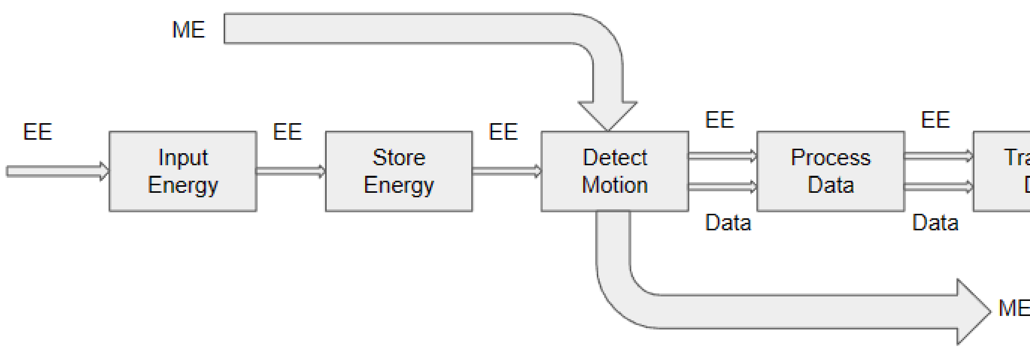


Figure 14. True Valve Position Function Chain.

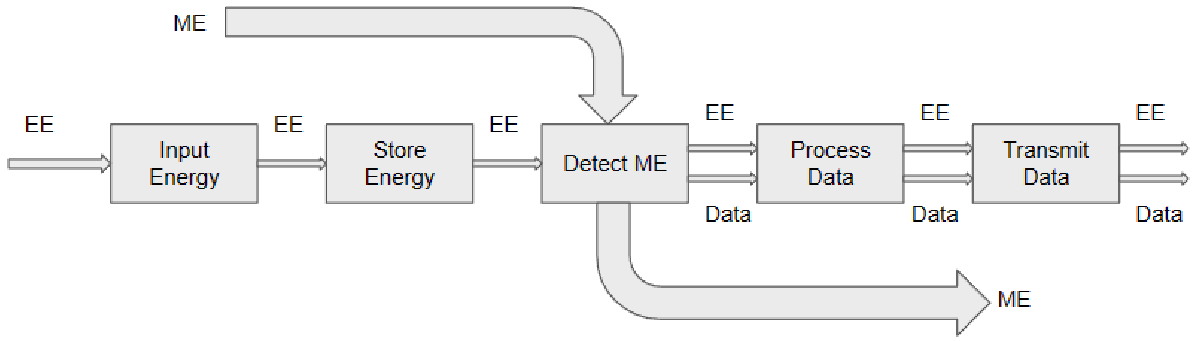


Figure 15. Measuring Actuator Torque Function Chain.

The function chains for the two deliverables are very similar in principle, but have a few key differences in actual operation. Namely for the Position chain, the main operation is to use the input mechanical energy to detect motion of the valve ball and determine its new 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 conception of sensor products that meet the project deliverables.

IDEA GENERATION

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 16**. Many ideas involved measuring or introducing various forms of energy into the valve and inferring position based on an energy measurement.

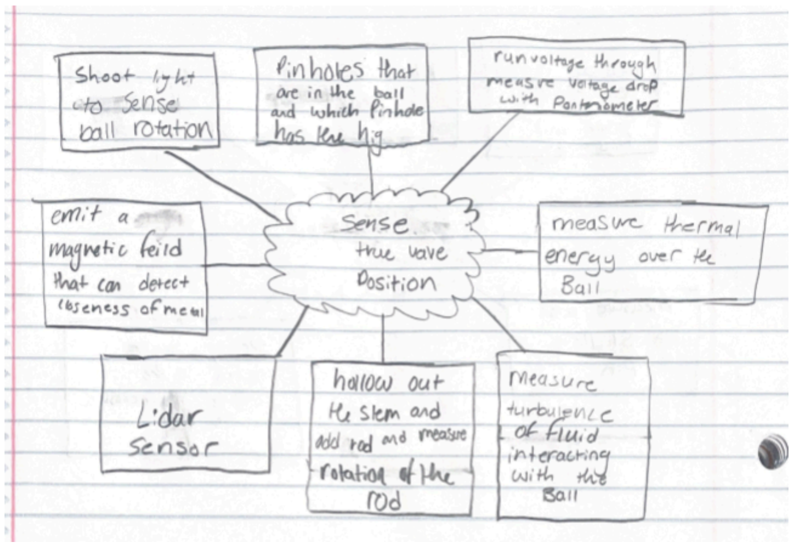


Figure 16: Position problem brainstorming map.

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 17**.

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

Equation 1: Torque equation.

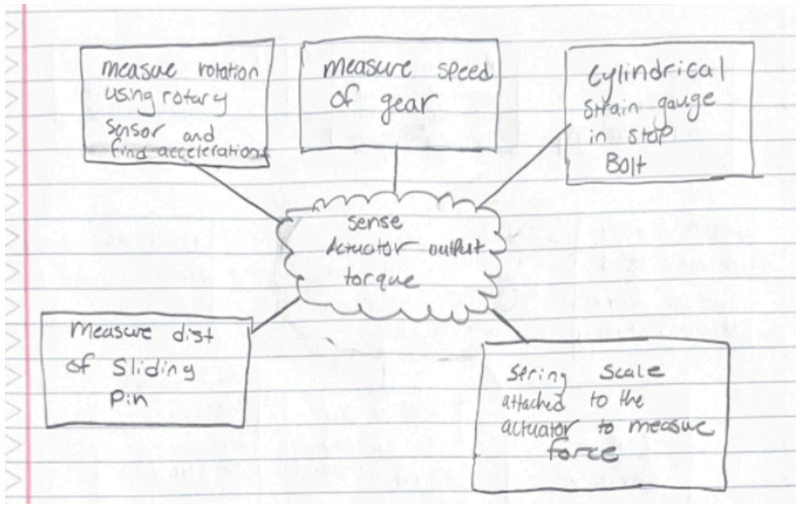


Figure 17: Torque problem brainstorming map.

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 18**, 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.

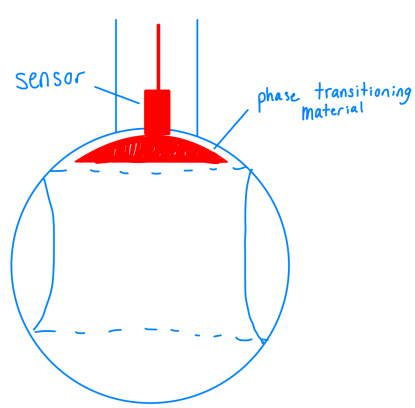


Figure 18: Ball valve position concept via TRIZ.

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 **Figure 19** below, which shows the concept sketch for each idea.

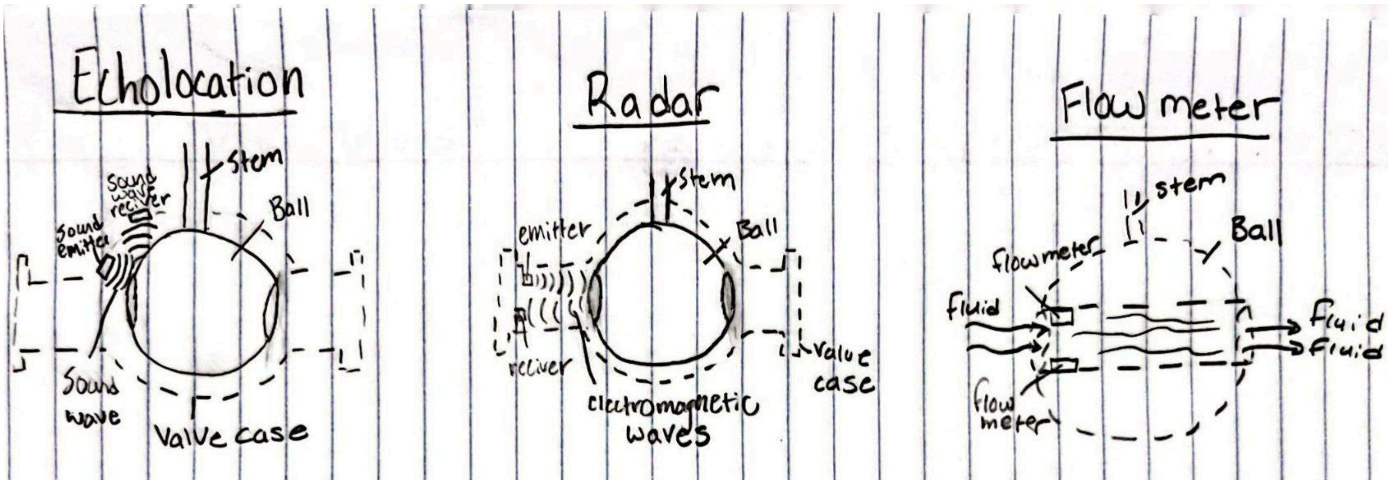


Figure 19: Concept sketches for echolocation, radar, and flow meter.

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 position of the ball valve.

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 **Figure 20**.

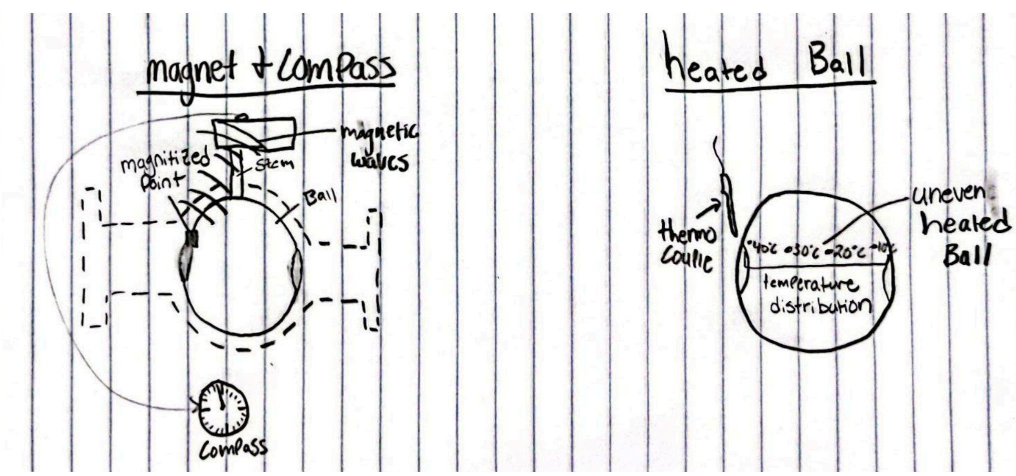


Figure 20: Concept sketches for magnet and compass and heated ball.

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 **Figure 21**.

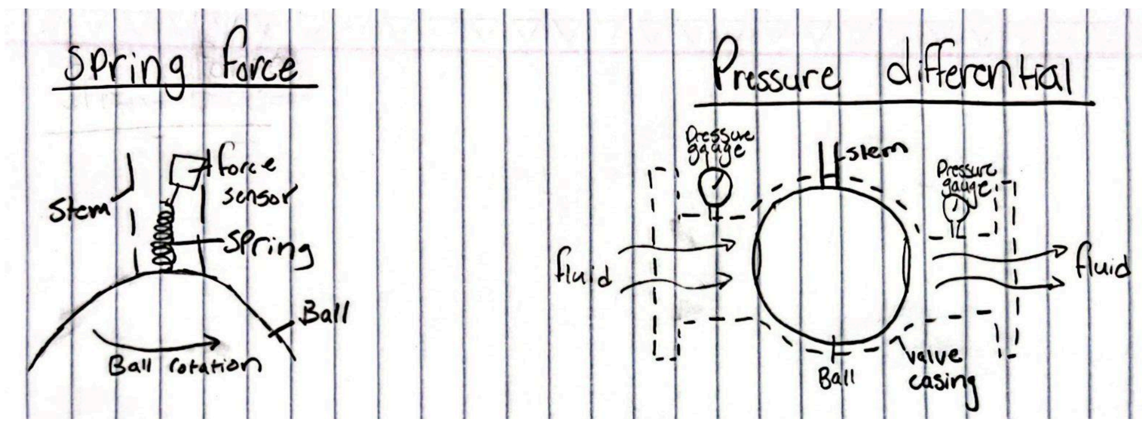


Figure 21: Concept sketches for spring force and pressure differential.

Overall, our 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 into the existing system and inexpensive. Sensor choice is further explored in the Concept Refinement and Selection sections.

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 three different subsystems: measuring true valve position, actuator torque, and gas leakage from the valve. However, during our needs analysis, Bray stated to focus on just the position and the torque and to leave leakage until the team has developed a product that measures the valve position and actuator torque. Also, the subfunctions do not interact, so ideas between each subsystem cannot be combined. To refine our ideas, a Pugh Chart was used for the two deliverables to select which seemed to have the most promise for the metrics determined in the design requirements section.

Position Concept Refinement

First, the team analyzed all the position ideas utilizing a Pugh chart. The results of this analysis can be seen in **Table 6** below for the position deliverable. The metrics were pulled from our identified design requirement table in **Table 3** and turbulence at the interface was set as the datum to use for comparison between ideas.

Table 6: 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 like accuracy, impact on performance, lifetime of sensor, and cost 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. The reason for indirect measurements not being usable is that too many factors can affect the readings and the conversions causing a lot of error. Examples of indirect measurement were the measured flow rate, heated ball, and pressure differential ideas. Our team decided to not move forward with the pressure differential idea as it is a form of indirect measurement. This left the team with two ideas to turn into actual functioning concepts: the magnet and compass and the potentiometer.

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 22,** showing how the Hall effect sensor will collect data from the vectors in the magnetic field to find where the magnetized point is.

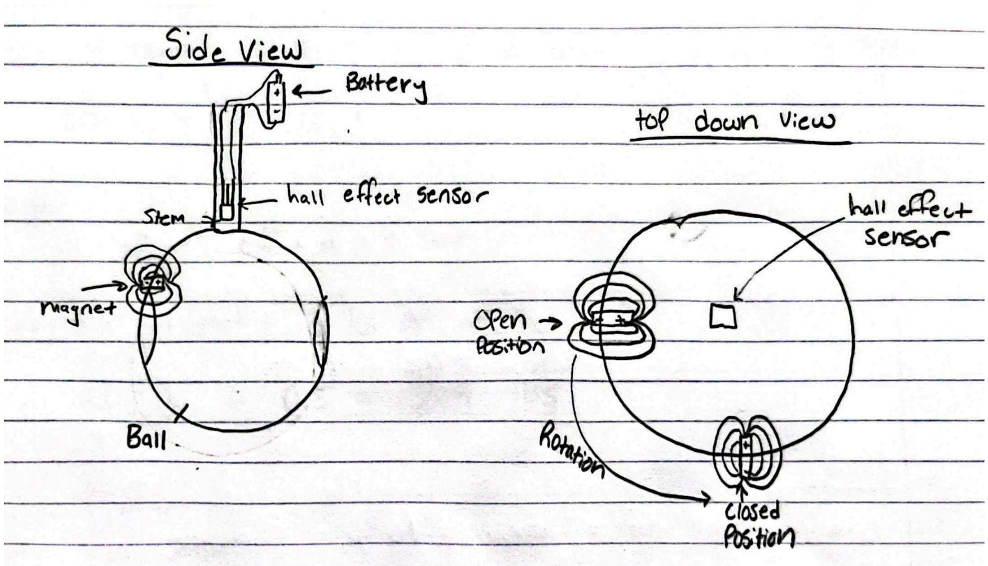
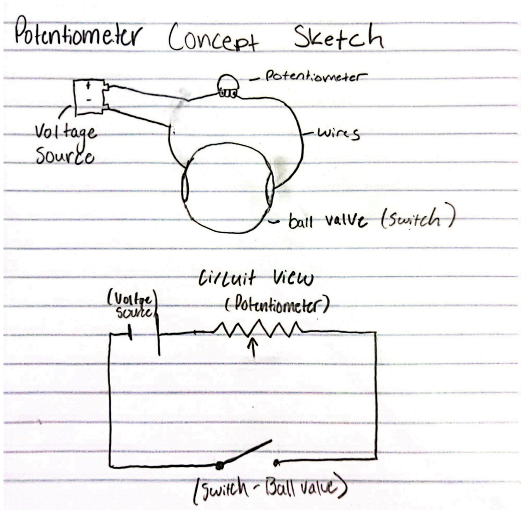


Figure 22: Hall effect sensor concept sketch.

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 23** and **24**. 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 essential categories of accuracy and impact on valve performance.



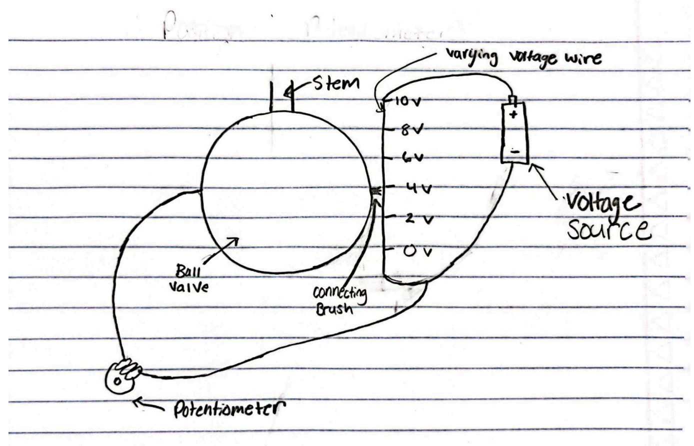


Figure 23: First iteration of potentiometer concept sketch.
Figure 24: Second iteration of potentiometer concept sketch.

Torque Concept Refinement

The concept ideas for determining the true output torque of the valve actuator were then compared using a Pugh Chart, setting the existing solution used by Bray, cylindrical strain gauges on the valve bracket, as the datum. The populated chart and weighted importance scores are demonstrated in **Table 7** below.

Table 7: 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

From the total sums of each concept compared with the datum, the only idea that is comparatively better than the existing solution is to use a potentiometer to measure the dynamics of the actuator and use it to approximate the torque output. 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. Ultimately, the ideas that were chosen to be explored and refined were using a potentiometer and improving the existing cylindrical strain gauge design.

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 25**. .

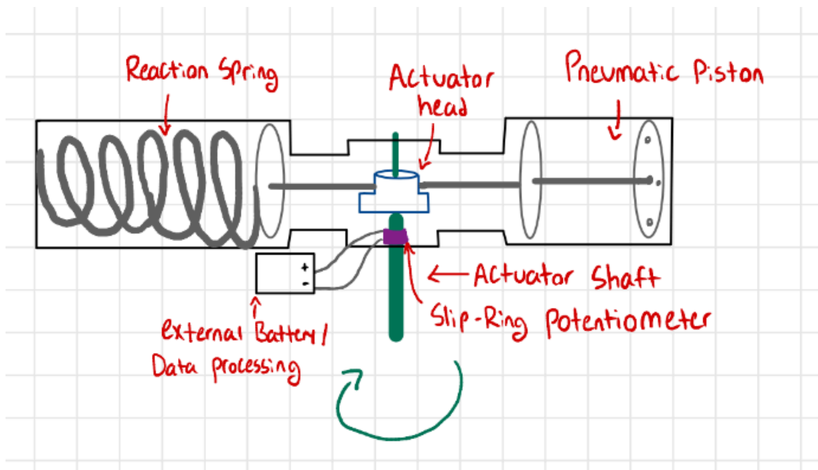


Figure 25: Potentiometer to measure torque concept sketch.

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 26** below.

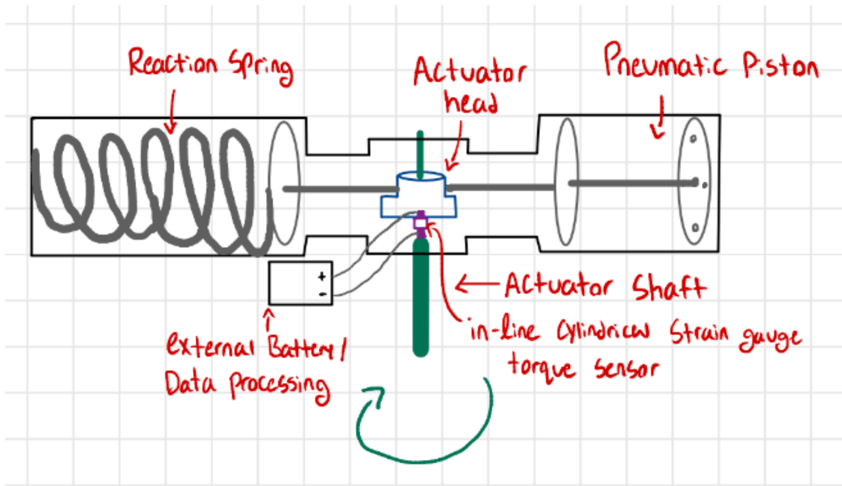


Figure 26: Modified strain gauge to measure torque concept sketch.

CONCEPT SELECTION

The team selected the potentiometer ideas for both the actuator torque problem and the valve position problem. We created CAD models of the various potentiometer types and inserted them into CAD models of the valve and actuators that were given to us by Bray. The solutions for torque can be seen in **Figures 27** and **28** with the potentiometers in pink.

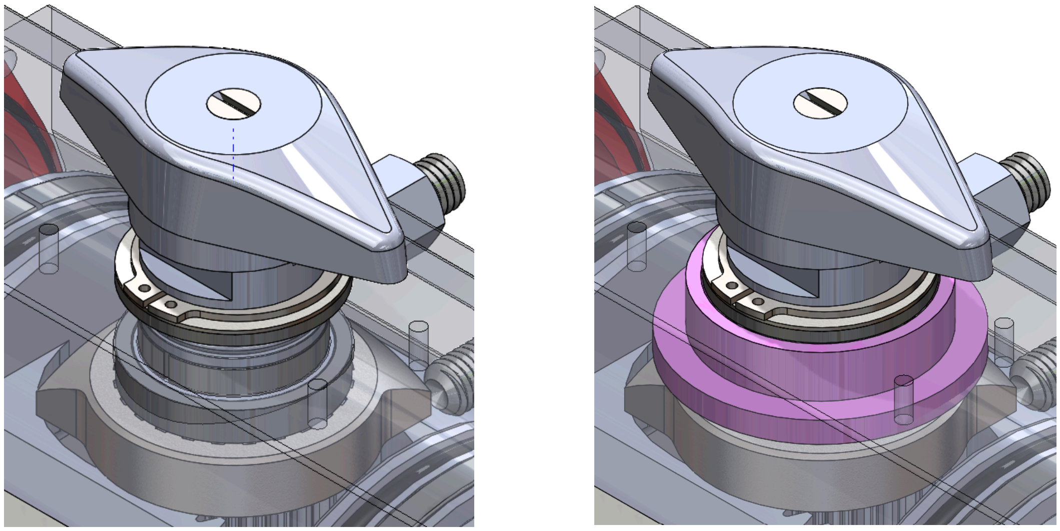


Figure 27: Before-and-after-potentiometer CAD models of rack-and-pinion actuator.

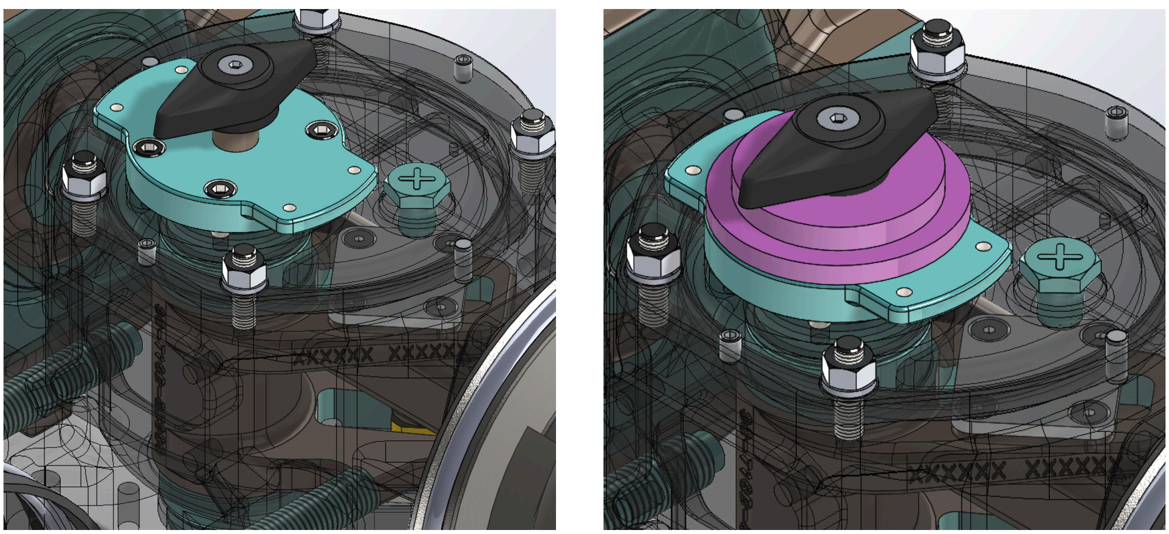


Figure 28: Before-and-after-potentiometer CAD models of scotch-yoke actuator.

Torque Concept Selection

We selected the potentiometer in-line method of measuring torque on the shaft. Placing the potentiometer in the actuator housing, close to the turning gear, will allow for a more accurate measurement of output torque than measuring the bottom of the valve stem as is currently done with the IOT Torque Bracket. The type of hollow-shaft potentiometer that will be used gets within the desired accuracy (it gives 2%, below the 5% that is needed) and is able to be embedded into the actuator casing which fulfills another requirement. Potentiometers are relatively inexpensive compared to other types of sensors and are not difficult to implement into a system due to their widespread availability and usage. The quantitative matrix in **Table 8** was utilized to compare the three most feasible torque options. Measurement accuracy was decided by Bray to be the most important attribute, and that is reflected in the table. The potentiometer was selected due to its small number of moving parts, accuracy within the range specified by Bray, and low cost. The option with force sensors on the stop bolts was deemed to ultimately be too indirect of a measurement, and it would only measure the torque at the very end of the stroke, insufficient for a non-constant-torque actuator like the scotch-yoke design [3]. Moving forward, the team will determine the best sensor to use as well as creating a reliable calculation and reporting method for determining the actuator output torque from the angular acceleration of the shaft. The potentiometers may have to be sized differently, but their working principle be the same due to the similar lateral-to-rotational motion mechanisms of both actuators.

Position Concept Selection

We also selected the potentiometer method for determining the true position of the ball valve. The position potentiometer (in pink) embedded in the valve can be seen in **Figure 29**, and a side-by-side comparison of the simple CAD model and an actual potentiometer of the type to be used is seen in **Figure 30**.

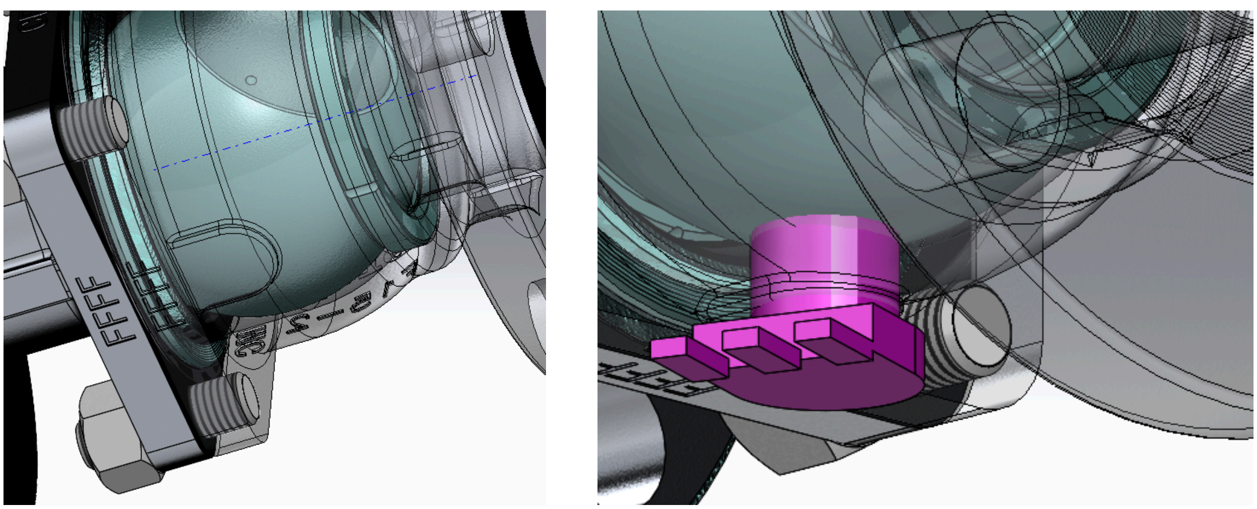


Figure 29: Before-and-after-potentiometer CAD models of the ball valve.

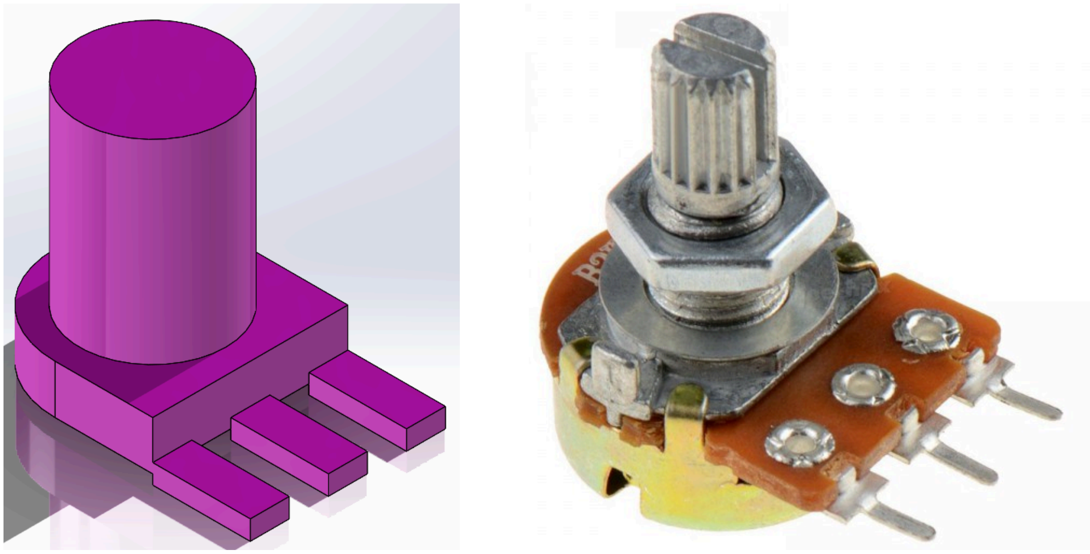


Figure 30: CAD representation and actual potentiometer of similar type [8].

The comparison between the potentiometer and the Hall effect sensor (in **Table 8**) showed that the potentiometer was less expensive, more accurate, had less moving components, and less cumbersome than the Hall effect magnetic field solution. The potentiometer was selected due to its superiority over all of these attributes. This concept differs from the one discussed in the Concept Generation section. When considering the ball-in-a-variable-circuit option for position sensing, the team realized that it may be difficult to implement the circuit in the very small space between the ball and its casing, and it additionally may pose a challenge to avoid short-circuiting due to the close proximity of many metal parts. The selected concept places the potentiometer at the bottom of the ball, which enables it to be embedded in the design (by drilling through the casing, which does not compromise the valve operation) while still having the space needed to connect to its power source and data transmitting capability [8]. The uncertainty for torque potentiometer is greater than the position potentiometer due to the fact that extrapolation is needed for torque calculations, but both are within the needed accuracy range so the increased uncertainty is not critical in the decision-making process.

An advantage of choosing similar methods for both deliverables is that it will reduce complexity in powering the sensors and translating the raw data into useful information. Given the fact that one torque potentiometer will be mounted on each actuator and one position potentiometer will be mounted on each valve, they could potentially be connected to the same power source and/or transmitting device to reduce the amount of devices needed for the full data collection system. The exact model, vendor, and so forth for the potentiometer has yet to be determined, but the selection of a primary concept for each deliverable will allow the team to work with Bray to find the best option to implement. Calculations and reasoning for the quantitative matrix (**Table 8**) can be found in the Appendix section 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

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, Task Dependency Diagram, 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 each 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.

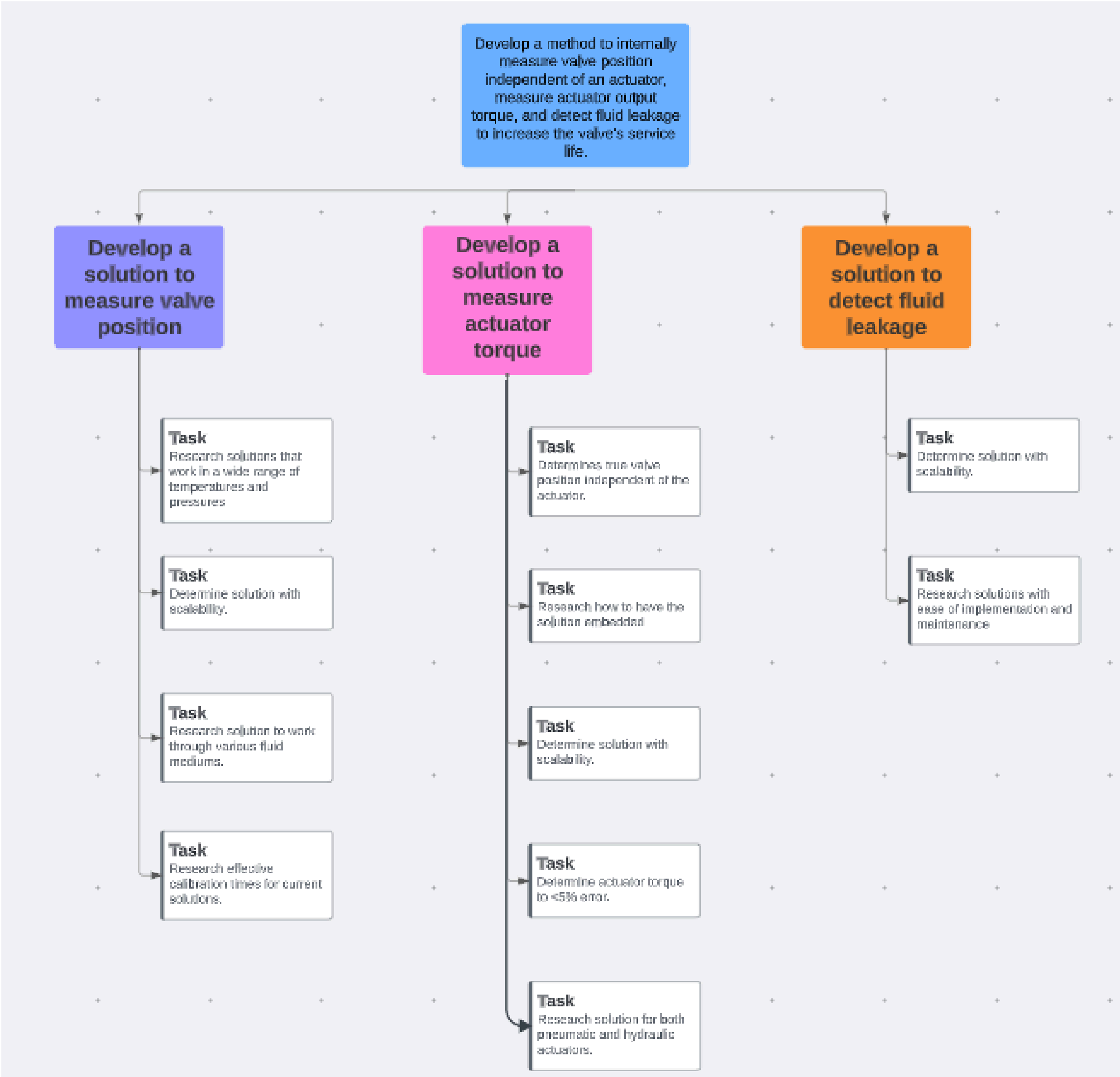


Figure 31: WBS for project deliverables.

In **Figure 31**, we can identify the key tasks that need to be completed to make progress in completing our project deliverables. After discussing with Bray, the deliverables dealing with detecting valve position and actuator torque will have more importance then detecting leakage. If our team successfully finds a solution for detecting valve position and actuator torque early in the semester, we can allocate time to potentially also find a solution for detecting valve leakage.

Task Dependency Diagram

A task dependency chart offers several advantages in project management. Firstly, it provides a clear and visual representation of task relationships and sequencing, allowing for efficient planning and scheduling. This helps our team understand the order in which tasks must be completed and identify critical paths. Additionally, it fosters better coordination among team members, as they can see how their work impacts others and adjust their timelines accordingly. Task dependency charts also facilitate effective resource allocation, as project managers can allocate resources based on the timing and requirements of specific tasks. Overall, they enhance project transparency, communication, and control, ultimately contributing to smoother project execution and successful outcomes.

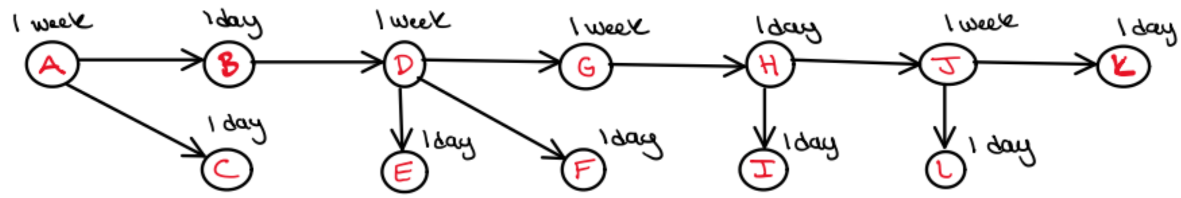


Figure 32: TDD for project milestones.

In **Figure 32**, we can identify the tasks dependencies for the milestones of MEEN 401. In this specific figure, the letters are represented by the following:

A - DR1 Report
B - DR1 Presentation
C - Peer Evaluation
D - DR1 Report Revised
E - Peer Evaluation
F - Peer Evaluation
G - DR2 Report
H - DR2 Presentation
I - Peer Evaluation
J - DR3 Report
K - DR3 Presentation
L - Final Peer Evaluation

After reviewing the TDD, the critical path would be [A, B, D, G, H, J, K]. This makes sense, as the reports and presentations are the key deadlines to focus on, with the peer evaluations being slightly less important for task dependency.

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 33** 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.

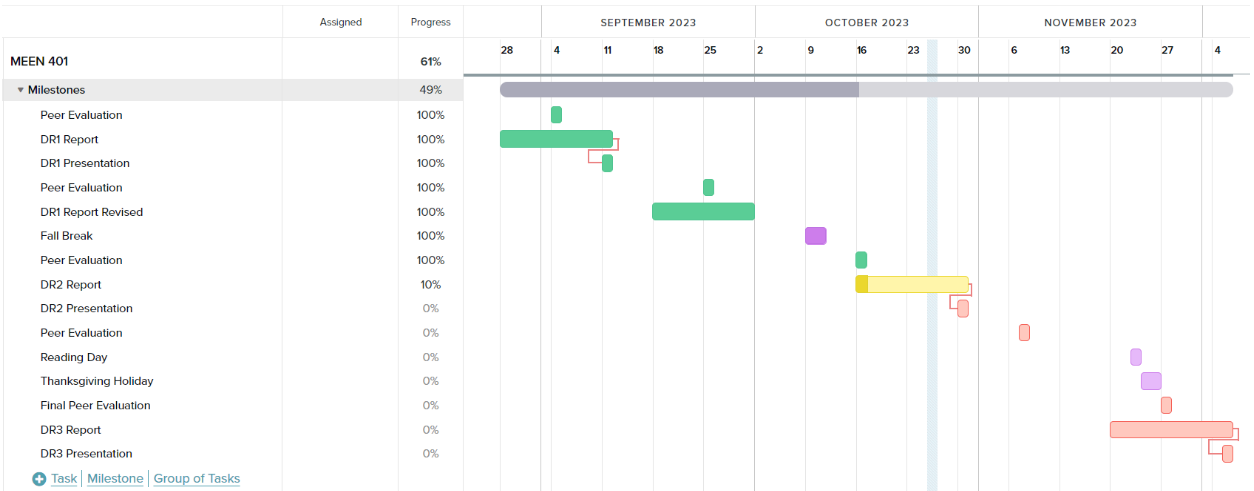
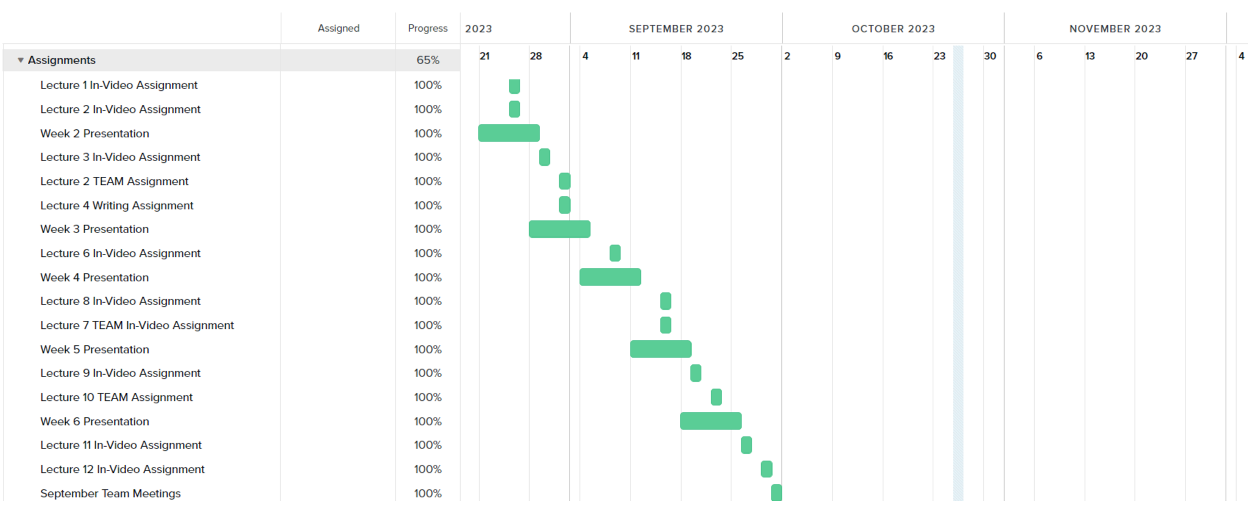


Figure 33: Gantt chart for project milestones.

A similar Gantt chart was also generated for the assignments for the lecture and studio sections in Canvas, which is represented in **Figure 34**. 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.



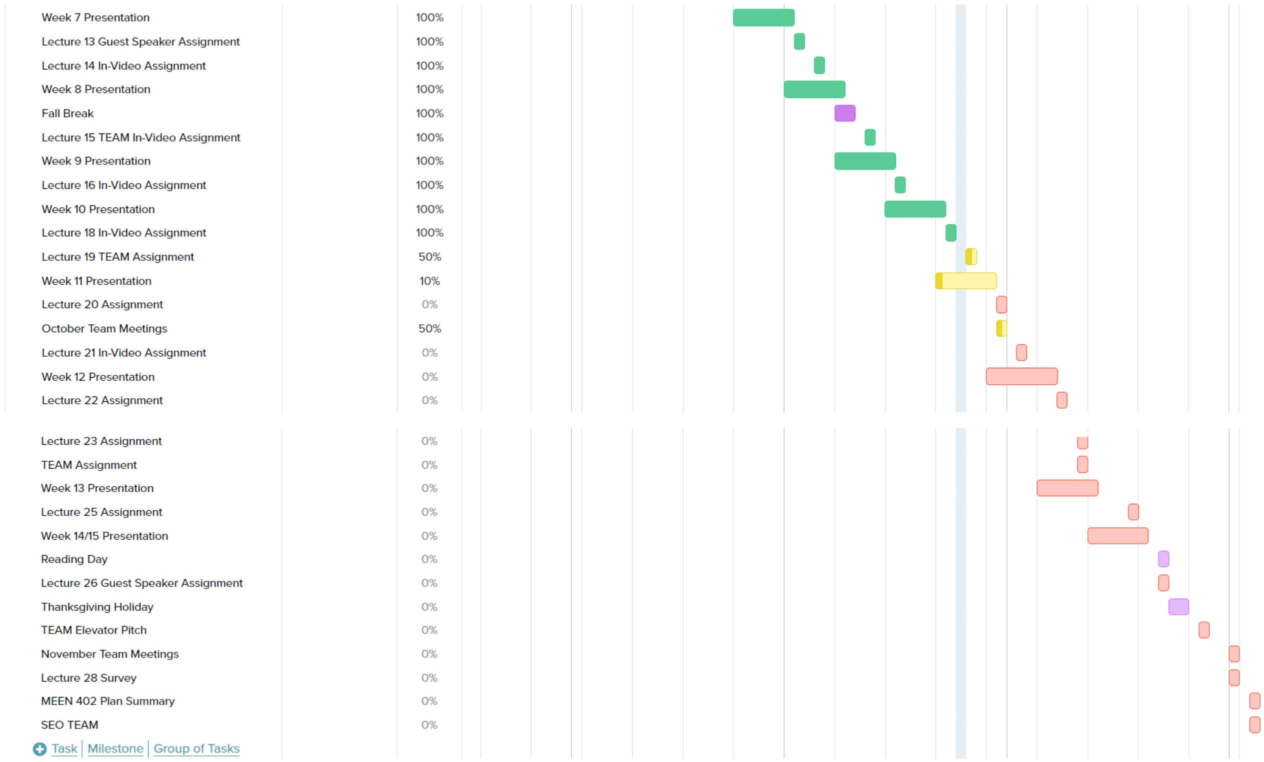


Figure 34: Gantt chart for assignments.

In the Gantt charts, the tasks were assigned colors to signify which assignments have been completed, started, or not started yet. Tasks with the color green represent tasks that have been fully completed. This can also be seen in the "progress" column where the progress is represented as a percentage. Tasks with the color yellow have been started but not yet completed, and tasks that are red have not yet been started. Holiday breaks and reading days are represented by the color purple.

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 9: Process risk assessment for project deliverable tasks.

Risk	Probability	Severity	Actions to Minimise Risk
Solution does not work for a wide range of temperatures and pressures.	Unlikely	Major	Research potential solutions utilizing materials that can work within the given range of temperatures and pressures.
The solution does not have scalability.	Moderate	Minor	When designing solution, take into account sizing up and down the resoruces being used.
The solution does not work for various fluid mediums.	Unlikely	Major	Research potential solutions utilizing materials that can work within the given fluid mediums.
Does not determine valve position independent of the actuator.	Unlikely	Major	Make sure the solution strictly excludes measuring anything from the stem of the valve.
Does not determine actuator torque to <5% error.	Moderate	Major	Give our team time for prototyping and testing to find a solution with high accuracy.
Solution does not work for both pneumatic and hydraulic actuators.	Unlikely	Moderate	Specifically research both actuators when developing a solution.

When filling in the details for **Table 9**, the team first analyzed the tasks from **Figure 31** 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 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 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.

FUTURE WORK

The upcoming project phases will center on embodiment design, budget planning, and the creation of a validation plan for MEEN 402. In the realm of embodiment design, we will be making critical decisions regarding product architecture, conducting comprehensive technical analyses, and performing preliminary assessments of potential product risks. These steps are pivotal in the ongoing development and refinement of our concepts. Furthermore, we will establish a detailed budget plan outlining all the financial requirements for the entire project, encompassing expenses such as travel, fabrication, assembly, testing, analysis, and contingency. Additionally, we will create a Bill of Materials (BOM) to accurately track all components and resources needed. Lastly, we will formulate a MEEN 402-specific validation plan, which will involve the development of prototypes and minimal viable products. This phase will also entail the discussion and planning of key milestones throughout the completion of MEEN 402, with a concurrent evaluation of process-related risks for the entire validation plan.

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, a winning concept was selected for both the position and the torque problem. A hollow-shaft potentiometer will be used to measure the angular acceleration of the shaft nearest the point it is driven, and that will be multiplied by the known moment of inertia to find output torque. A rotary potentiometer will be fixed to the valve casing and attached to the ball (or butterfly) of the valve in order to determine the true angular position of the valve. Both of 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. Moving forward, the team will work with Bray to identify the exact types of sensors, power supplies, and data transmission methods needed, as well as the method to 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.

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APPENDICES

Appendix A: Quantitative Matrix Calculations (Table 8)

Quantitative Calculation Hall effect Sensor

Accuracy

Accuracy of sensor = 1%

- can be affected by disruption 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 apparatus

Size of sensor ≈ 4in²
Size of magnet ≈ 8in² ← large to ensure strong magnetic feild

total = 4 + 8 = 12in²

Weight

weight of Hall effect ≈ 0.5 lbs

weight of magnet = .3 lbs per in²

.3(8in) + 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 [9], the rotary potentiometer specs [8], the rotational torque bracket specs [6], the torque potentiometer specs [10], and the force sensor [11].

<u>Appendix B:</u> Locations of Figures

Appendix C: Locations of Tables