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Midterm Report

Embedded Valve and Actuator Sensors

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EXECUTIVE SUMMARY

The topic of this Final Report is the key findings, description of final product and future work for the Bray Embedded Valve and Actuator Sensors project. The senior design team working with Bray is Zachary Walker, Cody Sims, Locke Lehmann, Avery Haynes, Michael Hager, and Travis Carlson. Bray assigned the team to develop a method to determine:

A) Valve position while in operation, independent of other products such as the actuator
B) Actuator output torque, independent of other products such as the valve

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

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

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

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

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

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

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

At the conclusion of the project, the team had testing success with the potentiometer and EMF motor solutions. The potentiometer displayed acceptable accuracy and could be easily implemented into Bray's current valve fleet. However, the solution is invasive to the nature of the ball valve as it constricts the "floating" characteristic of the ball as well as comprising the seal of the valve itself. The team recommends that further testing and research be conducted on the Hall Effect sensor solution as it is both less invasive and simple in nature. Laboratory testing of the EMF motor concept provided the team with reason to believe it would be a viable solution for Bray due to its high accuracy and easy implementation although it is technically an external solution because it is not in the actuator casing. The team had difficulty conducting trials on the cylindrical strain gauge solution due to the brittle sensitivity of the gauges as well as the extensive time it takes to order, cure, and set the sensors. While the potentiometer and EMF motor showed success, the team and Bray do not think these are the "best" solutions. In the future, the team believes Bray should investigate purchasing higher quality sensors and researching better methods for implementation into both the valve and actuator.

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GLOSSARY TABLE

Abbreviation	**Definition**
IOT	Internet of Things
FEDC	Fischer Engineering Design Center
R&D	Research and Development
FMECA	Failure Modes, Effects, and Criticality Analysis
RPN	Risk Priority Number
FTA	Fault Tree Analysis
DAQ	Data Acquisition Unit

INTRODUCTION AND PROBLEM DEFINITION

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

Background Research

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

Valves

Bray manufactures many different types of valves, but this project will focus on ball valves and butterfly valves. Bray designs these valves to remain either totally open or 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 a possibility of leakage [1]. Their turning ability is also affected by the pressure of the fluid being controlled, and the fact that the open disk remains in the fluid stream can cause unwanted changes in the flow. Ball valves are metal spheres with holes drilled through them to allow fluid flow depending on position. Ball valves are more secure than butterfly valves, due to the tight seal that the ball makes with the fluid vessel (with a wider margin for leakage error) and allow complete passage of the fluid with no obstructions [1]. However, they are more expensive to manufacture and are larger and heavier than butterfly valves [1]. Adding a sensor or some other method of measuring valve position will help Bray monitor if their valves are ending up at a position between open and closed, which would hurt valve performance and may be indicative of buildup on the valve. **Figures 1** and **2** show these valves. Bray's CAD ball valve models are shown in **Figures 3** and **4**.

Figure 1: Ball valve example [1].

Figure 2: Butterfly valve example [1].

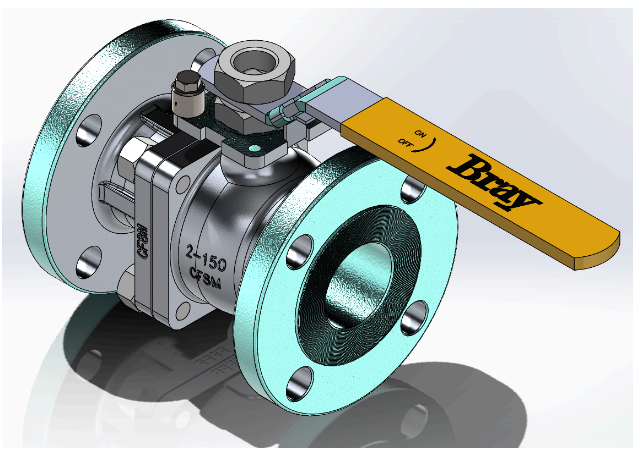

Figure 3: Bray ball valve assembly closed.

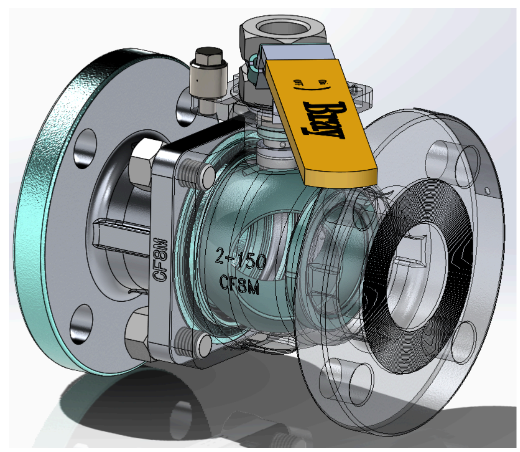

Figure 4: Bray ball valve assembly partially open.

Actuators

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

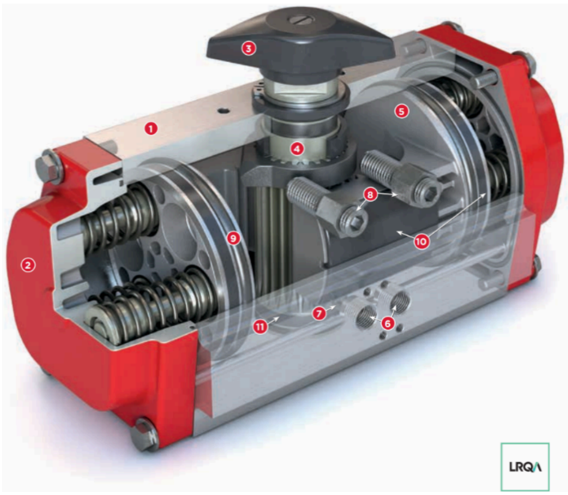

Figure 5: S92 rack-and-pinion actuator [2].

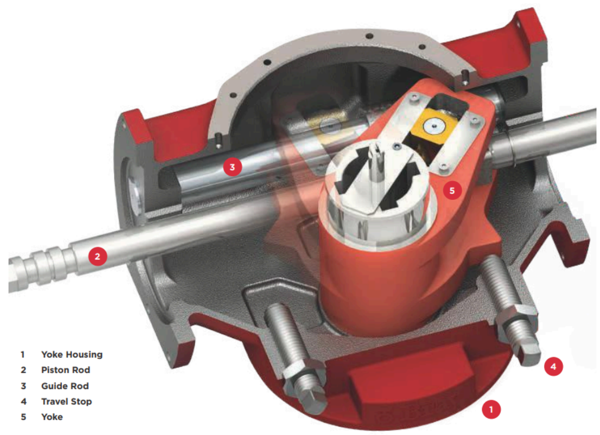

Figure 6: S98 scotch-yoke actuator [3].

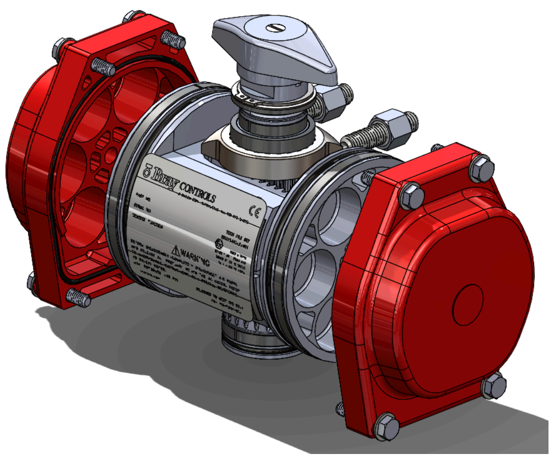

Figure 7: CAD model of S92 actuator.

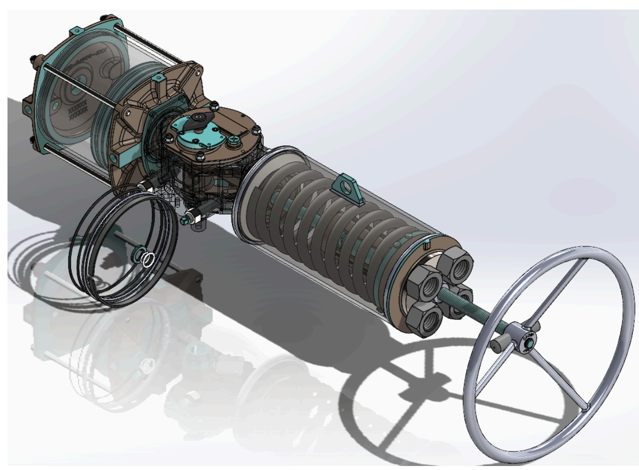

Figure 8: CAD model of S98 actuator.

Current Solution

Bray's current solution for measuring torque, the IOT Torque Bracket, measures reaction torque from the valve to the actuator. However, this does not predict when the actuator will fail to operate the valve since it does not measure the maximum capacity of the actuator. Bray and their customers care about actuator torque since a failed actuator will cause valves to be stuck in the wrong position, which could interfere with whatever system the valves are a part of. An external or embedded solution is necessary because pneumatic actuators such as the two displayed above are non-digital, or non-“smart”, 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 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 the valve shaft opens or closes 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 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.

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	Short time for calibrating the sensor	3

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

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

2. It should possess the capability to accurately determine the true valve position, independent of the actuator, within 2 degrees, as specified by Bray.

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

4. Ensuring accurate measurement of actuator torque, independent of the valve and with an error margin below 5%, as specified by Bray, is of paramount importance.

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

1. It must be scalable to accommodate valves and actuators 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. 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.

The product must be scalable to different sizes of valves and actuators, so Bray can apply it across their product lineup and create ease for their customers in a “one size fits all” solution. The temperature and pressure needs arise from the fact that Bray products are used in many industries, from manufacturing to energy production, and Bray wants the solution to be applicable in the same varied conditions that their valves and actuators are rated for. It would inconvenience their customers to change out an otherwise acceptable product due to a new addition (the sensing solution) that cannot handle a certain environment. Lastly, the embedded nature of the solution is important as it will allow Bray to sell their existing products pre-packaged as before to their customers, with new functionality but without added size requirements or assembly needed. This will make the transition from non-smart products to smart ones quicker and easier for their customers.

Codes and Standards

The valve in which the design is placed is heavily regulated due to safety concerns associated with high pressures, temperatures, and hazardous fluids. Below, 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 hydrostatic shell tested and hydrostatically seat tested without leakage to at least the requirements outlined in section 11 of API Standard 6D (incorporated by reference, see §195.3).

The code for transporting hazardous liquids was chosen because the 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 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].

Relating to Item a, if the team's concepts negatively alter the valve's functionality, then the design is not feasible. This will likely not arise as an issue, since the valves and actuators have already been designed and approved for production by Bray. The flange part of Item b in the code is something that the 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. While there are not any likely scenarios in which the sensor systems will contact the fluid, these items caused the team to consider the extreme temperatures and pressure that the fluid was placed under and how to make a design to withstand those conditions. Due to the difficulties of implementing sensors in potentially hazardous material, the team decided that the concepts must not interact with the fluid. Finally, Item d in the code states that all valves must be tested to see if there is leakage in the shell or seat. This code corresponds to the first deliverable of finding a position, and the sensor system must be evaluated to ensure it does not compromise the valve integrity in any way, as was previously discussed for Item a.

The codes and standards review helped generate a new design criterion: keeping the sensors out of contact with the fluid due to the complications with hazardous material and high temperatures and pressures.

Design Requirements

After most of the needs and metrics were understood, the team analyzed how they applied to the specification checklist categories. These categories were chosen as they applied the most to the problem of determining the position and torque of the valve. The compiled checklist, seen below in **Table 2,** shows the requirements the 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 the 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 the 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.

Using the requirements checklist also provided insight into quantifying the 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 helped separate feasible and infeasible designs for the concept selection phase and provided a way to connect design requirements with specific product functions. The checklist was useful for verifying that every design aspect had an assigned requirement.

Requirements Document

The following requirements document was made by compiling the results from the customer needs, the codes and standards, and finally, the requirements checklist. Some metrics were combined, like torque accuracy and position accuracy, due to their same accuracy requirement. **Table 3** is shown below, with a higher importance a five and a lower importance a one.

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

Req,t #	**Need #**	**Metric**	**Imp**	**Required Values**	**Units**
1	7, 9, 10	Measurement Accuracy	5	< 5	%
2	1, 2, 4, 5, 6	Location of sensors	4	Valve casing, Stem, Actuator casing	N/A
3	3	Lifetime of sensors	3	> 20	years

4	8	Ease of maintenance	2	< 4	# parts
5	2, 11	Ease of implementation	3	< 2	hours
6	11	Calibration Time	3	< 2	hours
7	1, 2	Volume of apparatus	1	< 5	in^2
8	3	Power consumption	1	< 100	W-hrs

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

The accuracy requirement was based on the fact that the existing IOT torque bracket has an uncertainty of 5%, so therefore Bray said the minimal viable product should be able to achieve that value or better. Data from an inaccurate sensor would be unusable because it would be hard to tell if the collected data was from actual valve movement or sensor error. Direct measurements are preferable and hold less opportunity for any measurement error propagation.

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 SolidWorks files of the ball valves that Bray sent were examined to find the locations where there was enough room to add a sensor system to the design. From this process, the 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, which was decided to be avoided in the codes and standards analysis.

The lifetime requirement was based on doubling the average life of a ball valve, which was determined to be ten years. Bray stated that this requirement could be handled at their facility after the team developed some initial concepts, and wanted the team to focus more on proof-of-concept than lifetime testing.

The ease of maintenance requirement was based on the concept that more maintenance would be required for more moving parts. This number of four was chosen such that mechanical failure could be easily identified due to having to test a maximum of four locations. Also, maintenance difficulty depends on the possible low accessibility of embedded sensors, giving another reason to limit the number of moving parts.

The ease of implementation requirement was a requested metric by Bray, as they wanted to be able to build the design concept promptly so that fast learning cycles could 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.

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 which will result in the system not being embedded and going over budget.

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. While the previous **Tables 1**, **2**, and **3** showed the needs for the entire system (that must be applied to both deliverables), the subsections below add further definitions to the specific requirements of the product for each deliverable that has not yet been addressed in this report.

As the project progressed, the team realized that it would be difficult to develop one comprehensive method to measure both actuator torque and valve position, due to the requirement that the measurement system on the actuator be independent of the valve, and vice versa. Therefore the design was broken down into two subsystems: the solution for the actuator torque, and the solution for the valve position. Additionally, given the relatively simple physical nature of the problem - placing sensors onto a product rather than designing an entirely new product - the team decided to take two possible solutions for each deliverable into the spring semester, test and compare both, and deliver to Bray one final design for each deliverable. A sample calculation matrix to demonstrate how the team selected the final four concepts can be seen in **Appendix A**. This experimental approach was approved by Bray, as this project is led by their R&D department and they encouraged the team to test multiple ideas to guide a more informed decision. A more detailed description of each design possibility for each subsystem is explored in its respective section below.

POSITION DELIVERABLE

The first deliverable is detecting the true valve position using a direct measurement without interfering with the function of the valve. Bray's current solution of detecting position has its flaws as it is an indirect measurement and will start to decay in accuracy over time due to hysteresis of the stem with the actuator, where the current measurement is being taken. The objective is to determine a solution to detect the valve position directly using sensors.

Function Structure

The function of the position sensor is to record and transmit real-time data on the position of the valve at all times, using the parameter of angular position. The true position of a ball valve or a butterfly valve can be different from the position of the actuator switch, which indicates “open” or “closed”, with 90 degrees of rotation in between the two options. This is because the valve stem can deform slightly between the actuation point and the connection to the valve, so when the valve should be fully open or closed, it may be three or four degrees away from its intended position. A difference this small would not be noticed by visual observation but could affect the fluid flow and disrupt whatever kind of piping system the valve is attached to. Over time, through thousands of on/off cycles, the valve stem could deform permanently or could experience hysteresis if the stem wore asymmetrically. Additionally, particles in the fluid, dirt, dust, mechanical wear and tear, or rust could resist the motion of the valve components and create friction, affecting the position of the ball or butterfly even further.

All of these factors indicate that the valve position can only be accurately measured at the ball or butterfly itself, and not at the top of the stem or the actuator indicator switch. Therefore, the sensor must be placed on the valve mechanism itself to get accurate data, corresponding to the customer's need to determine position independent of the actuator. It also must not rely on the stem in any way, as the stem is in an unknown condition at any time and can not be assumed to be rigid or in line with the valve. These requirements are related to the customer's need to accurately measure position within 2 degrees. **Figure 9** shows how this deformation could cause a difference in two sensor readings theoretically placed at either end of the stem.

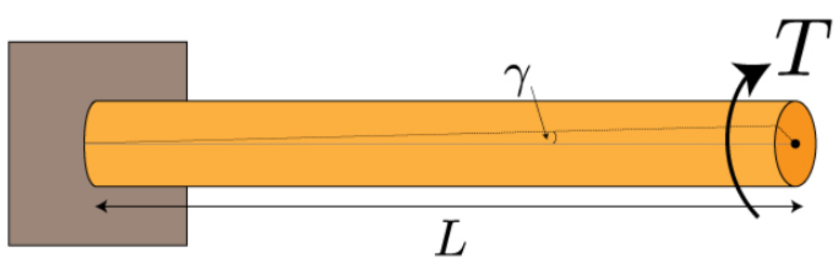

Figure 9: Depiction of valve stem deformation along the length.

The angle ɣ demonstrates that those readings could differ, and that difference could grow unpredictably over time due to the factors previously mentioned. Additionally, the sensor system must not interfere in any way with the flow of fluid through the valve or restrict the motion of the valve. Any restriction could change the flow rate or turbulence of the fluid, or change the torque required to operate the valve, and Bray is not interested in making further modifications beyond the installation of the sensor. This corresponds to the customer's need to be adaptable to various fluids, as a product physically separated from the fluid will not interfere with its flow or properties and therefore not impact the functionality of the valve.

Final Design Concept Descriptions

The two designs to measure the true valve position will be referred to as the "potentiometer" design and the "Hall effect sensor" design. Both address Bray's need for a method of determining valve position while in operation, independent of other parameters.

Potentiometer Design

This design concept consists of a potentiometer placed on the bottom of the valve, connected to a data acquisition system that records the position of the ball or butterfly at all times. The team is testing this concept on a ball valve acquired from Bray, so from here forward that will be reflected in the system description. **Figure 10** shows a CAD sketch of this concept.

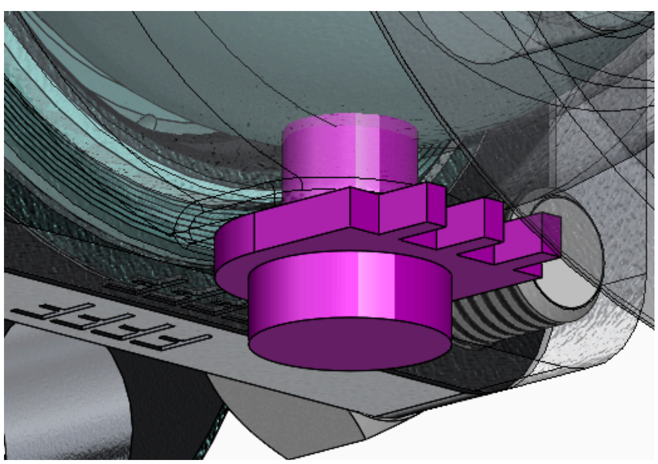

Figure 10: Potentiometer (pink for visibility) attached to the bottom of the ball valve.

This potentiometer will fulfill its intended function of providing an output voltage value that is directly proportional to its angular position. The DAQ connected will read the voltage values and be able to determine the position of the valve at any time. The location of the potentiometer was determined from the fact that the ball position must be measured directly, due to the hysteresis stem error, and placing the sensor at the top of the ball would require more valve deconstruction than the bottom. A potentiometer was selected due to its stem that could reach up to connect with the rotating ball, while its base could remain stationary and attached to the valve casing. This location also made manufacturing very simple; a hole would need to be drilled through the valve casing and ball, and as long as it was aligned with the ball's axis of rotation, which could easily be found on the SolidWorks model of the valve, the potentiometer and stem would follow the same axis of rotation. **Figure 11** shows the location for the center of the hole that must be drilled to be in line with the rotation axis.

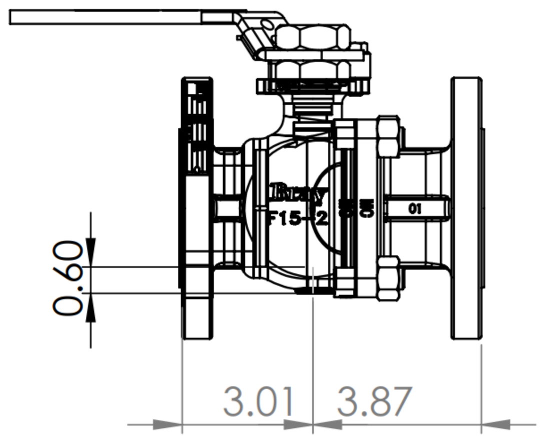

Figure 11: CAD dimensions for the location of the potentiometer hole.

The team selected a 10 kΩ rotary potentiometer for its high accuracy value of 0.5% over its full range of motion. This was determined in MEEN 401 when the team tested the accuracy of the potentiometer. This experiment used the Zachry Common Labs' resources and space and was done with a multimeter, a 10 kΩ rotary potentiometer, and a breadboard as shown in **Figure 12**.

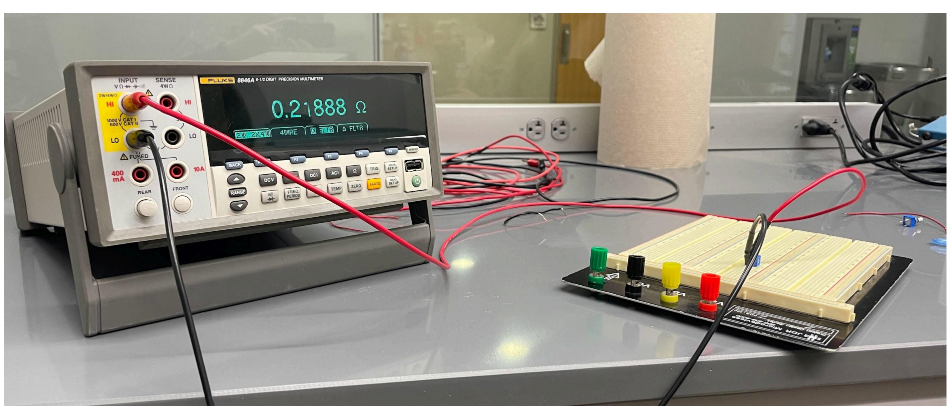

Figure 12: Experimental setup for the rotary potentiometer accuracy testing.

This potentiometer has a 270-degree range, and while only 90 degrees are needed for the rotation of the ball, it performed with accuracy that met the requirements. The team took six values for each position, and a linear slope trendline was made so that a predicted value was obtained. Then the predicted position and the expected position were compared to find the error associated with each measurement. The collected and predicted data can be seen below in **Table 4,** and the sample calculations for data can be seen in **Appendix E**.

Table 4: Collected and calculated data for the rotary potentiometer experiment.

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

The last two rows within **Table 4** have misconstrued data due to accidental physical interference with the potentiometer during data recording. The team did not remove the data from the experiment but chose to not include it when determining the maximum allowable error of the rotary potentiometer, which was 0.5%. This accuracy value translates to an uncertainty of 1.35 degrees, less than the 2% desired by Bray (as 2% of 90 degrees is 1.8 degrees).

The output voltage from the rotary potentiometer is recorded by a DAQ using an ADS1115 16-bit ADC chip. The ADC chip allows the DAQ to read the analog output from the rotary potentiometer with an accuracy of 1.5E-8%, which combined with the error from the rotary potentiometer still allows the team to meet the 2% error requirement from Bray. The team is utilizing a Raspberry Pi 4 Model B as the DAQ system, which can read analog input from the ADC chip in real time while calculating the degrees of rotation from the output voltage. While the Raspberry Pi has only been tested with the potentiometer solution thus far, its large number of pins and high accuracy suggests that it will be useful in recording data from the other design concepts as well, as all will have to transmit data of some form. **Figure 13** shows the Raspberry Pi soldered to the proper wires and to the potentiometer to read data.

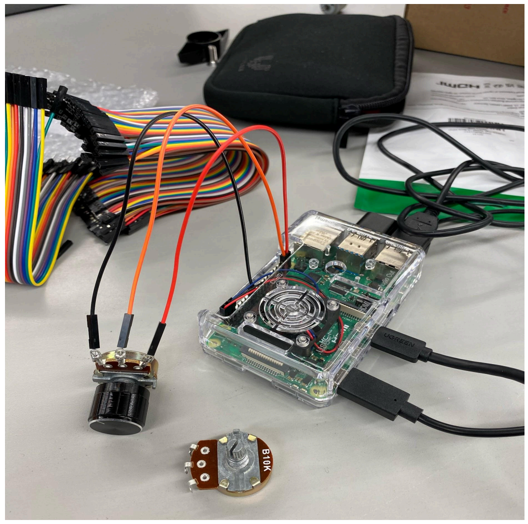

Figure 13: Data collection system for potentiometer.

The team has been able to successfully drill into the ball valve casing and the ball itself to place the potentiometer inside, shown in **Figures 14** and **15**, using a manual mill in the Zachry building's Fischer Engineering Design Center.

Figure 14: Manual mill creating the hole.

Figure 15: Aligned holes in the valve and casing.

First, a small hole of diameter 0.234 inches, roughly the diameter of the potentiometer, was drilled through both the casing and 0.2 inches into the ball valve. This left 0.3 inches of the ball valve undisturbed so as not to undermine the integrity of the flow passage, and to ensure that the flat surface of the potentiometer could rest against the raised semicircular portion on the casing. Then, a wider hole of diameter 0.33 inches was drilled only through the casing, concentric with the other, to accommodate for the wider portion of the potentiometer shaft passing through that section. There is a rough compression fit between the thin top part of the shaft and the ball, but adhesive will be used to ensure it does not slip. The flat top of the potentiometer's base will also be glued to the casing to ensure that the shaft (connected to the ball) rotates relative to the base for accurate angular position measurement. The glue's integrity will be monitored when the team subjects the valve to temperature testing, which will perhaps be done at Bray's facility as they have adjustable temperature cabinets available. The team verified that the ball still rotates on the correct axis, confirming that the potentiometer shaft is perfectly in line with the axis of rotation, as intended. In this configuration, the data channels of the potentiometer are still exposed, meaning they can easily be connected to the Raspberry Pi for data analysis. **Figure 16** shows the potentiometer installed in the valve.

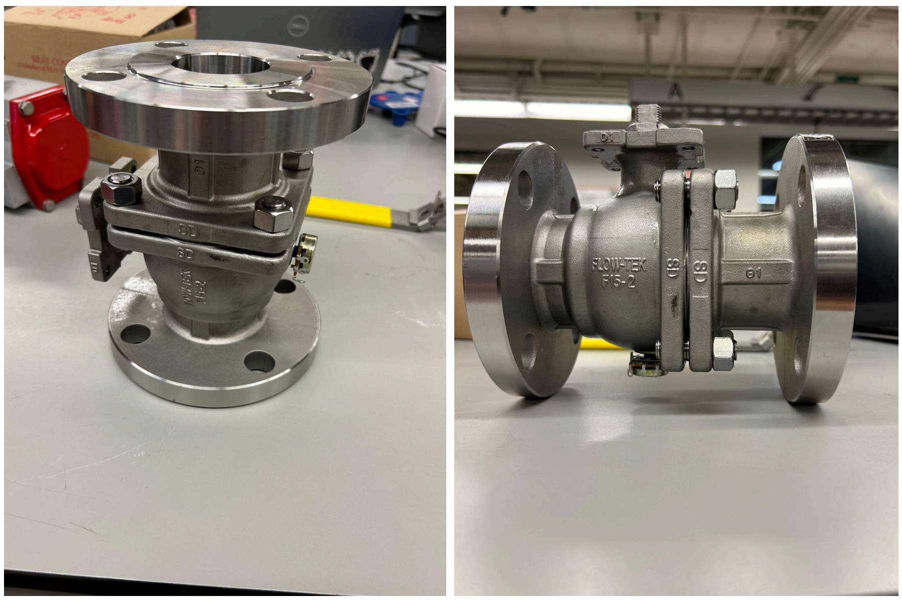

Figure 16: Potentiometer on the bottom of the ball valve.

The potentiometer has been proven to be accurate enough to meet Bray's specifications, it fits snugly in the hole drilled in the valve, and it can communicate data with the Raspberry Pi. It has been properly embedded into the valve as requested by Bray as well. The next steps are to verify that the system will function properly when all components are connected at once, which will be possible when another actuator arrives from Bray that will allow the team to toggle the actuator and open and close the valve automatically using pressurized air from the FEDC. Additionally, the temperature requirements will be verified at Bray's Houston facility to ensure the sensor operates between the proper temperature extremes.

Hall Effect Sensor Design

This design concept consists of a neodymium magnet attached at the bottom of the rotating ball with a Hall effect sensor placed directly underneath it that is attached to the Raspberry Pi DAQ. The overall principle of this design can be seen in **Figure 17**, where the large cylindrical device is the Hall effect sensor and the flat spinning piece is the magnet.

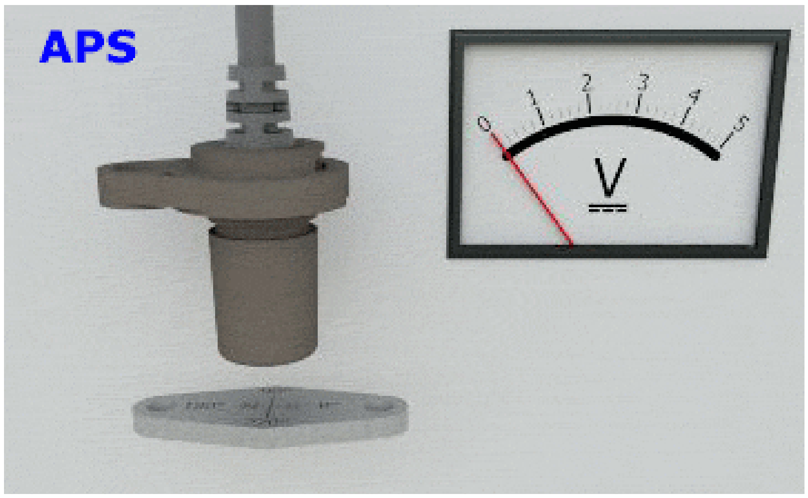

Figure 17: Operating principle of the Hall Effect sensor system

The Hall Effect sensor is able to read the position of the ball valve due to the fact that the magnet is attached to the rotating ball and will rotate 0 to 90 degrees. This rotation of the magnet alters the vector in the magnetic field which is detected by the hall effects sensor element. Depending on the direction of the magnetic field the Hall Effect sensor will output different voltages that the Raspberry Pi will read and correlate to an angle reading.

The Hall Effect sensor design was selected due to the fact that it is contactless with the ball of the valve allowing the ball valve to still be a floating ball. This was a large point of interest for Bray as the floating ball is essential to the efficient operation of the ball and is something that the potentiometer deliverable infringes upon.

Before the team installs the magnet and hall effect sensor into the valve testing will be conducted to determine the proper air gap between the hall effect sensor and the magnet. This will be done on a 3D-printed test rig where the magnet can be positioned different distances away from the hall effect sensor element and rotated between 0 and 90 degrees then calculating the error. Another element of this preliminary testing is to insert a cast iron piece in between the Hall effect sensor and magnet to gauge the impact of the ferromagnetic metal on the accuracy of the Hall effect sensor. This testing apparatus can be seen below in **Figure 18** where the square cavity at the bottom is the housing for the hall effect sensor and the rotating cylinder represents the magnet.

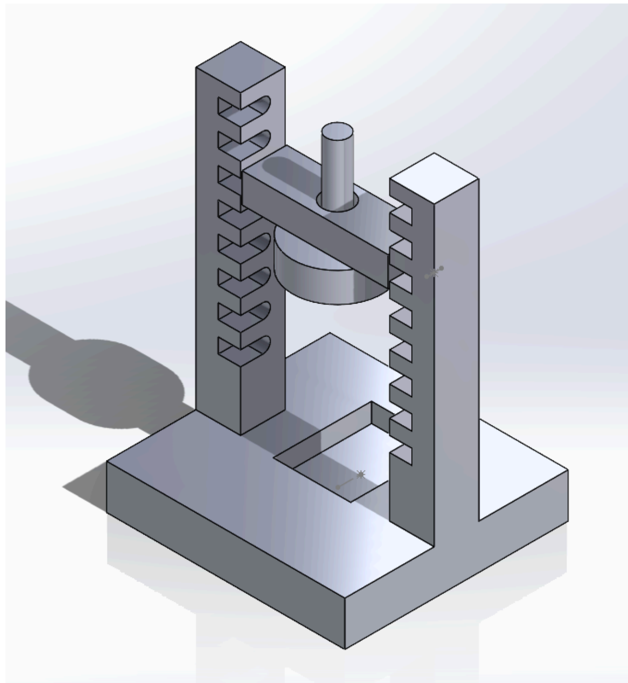

Figure 18: Preliminary testing apparatus for the Hall Effect sensor.

After the preliminary testing has been finished and the optimal air gap has been established the team will implement the Hall Effect sensor and the magnet into the actual ball valve system in the same way as the potentiometer, with a hole being drilled into the ball. Another important thing is that the sensor element must be directly aligned with the center of the magnet to get the strongest reading possible. Careful measurements will be used from CAD models of the ball valve, so that the sensor will be properly aligned to measure slight changes..

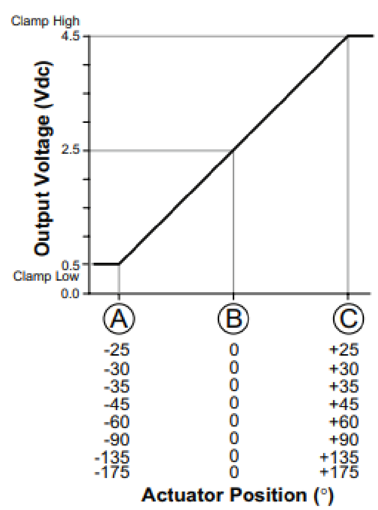

Figure 19: Correlation between angular position and voltage for RTY Hall effect sensor [10].

The main technical analysis for the Hall effect sensor that had to be done was correlating the rotational motion to the output voltage and finding that slope for 90 degrees of rotation. Luckily, the people at Honeywell have completed this already, and using the sensor specifications and data provided, **Figure 19** was made.

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

This deliverable has been delayed due to slow shipping from Digikey. The part did arrive Friday, February 23rd, but due to flooding in the JCAIN building, the part could not be picked up. After this, the team went to find the part but was unable to locate it, so if it is lost, a re-order at a local store could ensure a quick arrival even if the first order was misplaced. Once the part has arrived, the team will use calipers to make sure that the preliminary testing dimensions line up and will 3D print the setup of 3 different parts. Using personal machines, this process should take about a day to print. Once it is printed then the team can begin testing to determine what air gap is needed to implement the Hall effect sensor into the ball valve.

TORQUE DELIVERABLE

This deliverable includes determining the actuator output torque using a direct measurement without interfering with the function of the actuator when in use. Bray's current solution of determining actuator output torque is only used in the facilities, is not embedded, and is still in development. Finding a solution that can be a part of the product will allow customers to accurately determine when a change of actuator is necessary. The objective is to determine a proper solution to determine actuator output torque directly using sensors.

Function Structure

The function of the torque sensor is to measure and transmit real-time data on the maximum possible output torque of the actuator for every actuation cycle, using the parameter of applied torque. Bray's current solution, the IOT Torque Bracket, detailed earlier in this report, measures the valve reaction torque and does not measure the true output torque of the actuator. Therefore, the new design must measure only the true output torque to be an improvement over the existing prototype. As the wear and tear factors listed previously cause more system degradation over time, the reaction torque required to operate the valve at the proper speed increases, while simultaneously, wear and tear or buildup on the actuator itself can cause the maximum output torque to decrease. At some point, these curves will cross, as shown conceptually in **Figure 20**, and the actuator cannot operate the valve. The resulting stoppage and maintenance or replacement process could greatly impact the overall piping system.

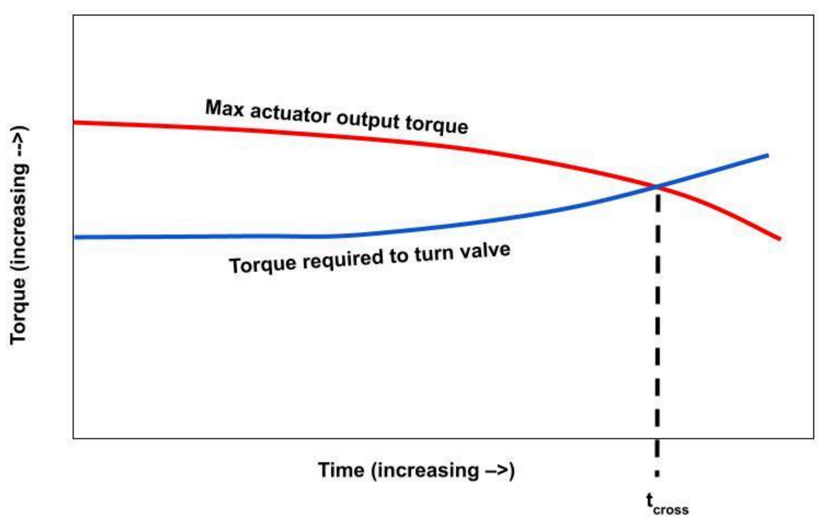

Figure 20: Torque curves for the valve-actuator assembly.

Knowing when this failure is imminent will allow companies to schedule preventive maintenance, anticipate downtime, and develop safe replacement procedures to avoid unexpected damages from part failures. Given this torque relationship, the actuator must not rely on the valve for data, corresponding to the customer's need to measure torque data independent of the actuator, as the torque solution must produce the red curve, not the blue one, in **Figure 20**. The torque solution also must not rely on any inertia values or other data from the connected valve, as this would make the torque solution interconnected with the valve, which would violate the customer's need for the torque solution to be independent of the valve.

Final Design Concept Descriptions

The two designs to measure the true actuator output torque will be referred to as the "bolt strain gauge" design and the "electric motor" design. Both address Bray's need for a method of determining true actuator output torque, independent of other parameters.

Bolt Strain Gauge Design

This concept consists of strain gauges placed in the stop bolts of the actuator to measure the force required to bring the actuator collar to a stop. A view of the S92 actuator (which this concept will be tested on), with the relevant portion highlighted, is shown in **Figure 21**.

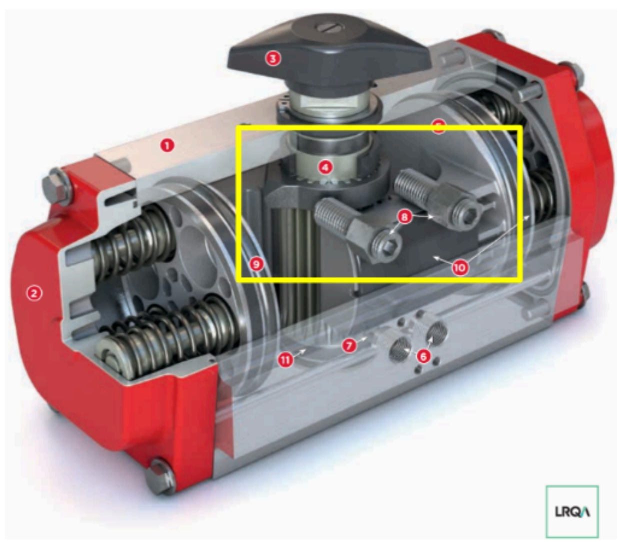

Figure 21: Stop bolts and collar of the S92 actuator [2].

Measuring the torque at the actuation point, rather than at the bottom of the valve (as the IOT Torque Bracket does), will satisfy the requirement that the torque sensor be independent of the valve and be embedded into the actuator. Cylindrical strain gauges for bolts, sold by HBK, will be placed inside the stop bolts to measure the longitudinal strain applied when the collar collides with the bolts to stop rotating [11]. This strain can be converted into a torque, using known bolt properties of Young's modulus and cross-sectional area for the actuator in question, by following the procedure in **Figure 22**. One bolt will experience a force for each actuator turn.

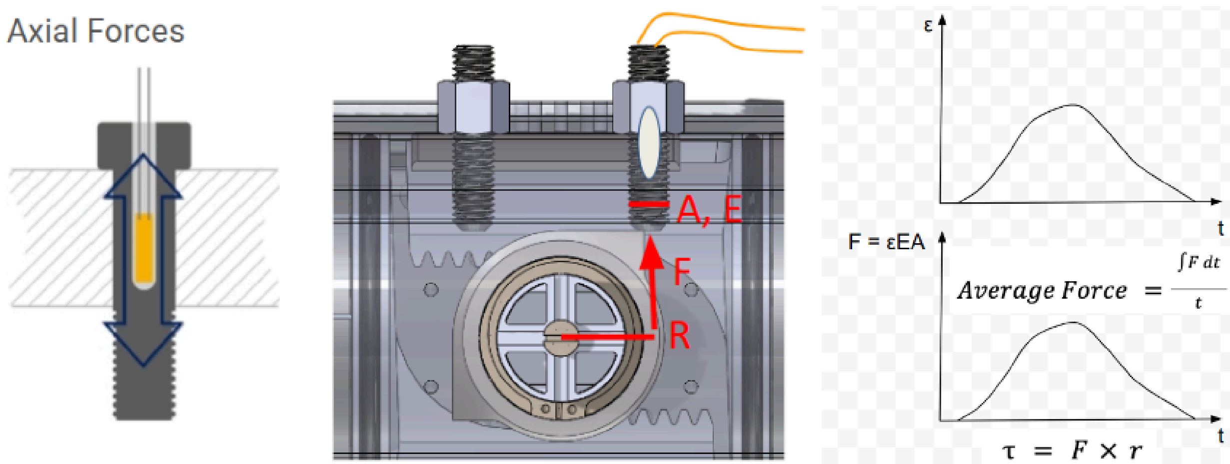

Figure 22: Method for turning force-vs-time data into applied torque.

The strain gauges inside the stop bolts will fulfill their intended function of measuring strain values over time. Then, since strain is directly proportional to force, the DAQ will construct a force versus time curve, find the average force, and multiply it by the radius of the collar (which will depend on actuator size) to obtain the torque. This should be equal to the torque output of the actuator, which can then be plotted over time to observe the red curve in **Figure 20**. Another design, such as the IOT Torque Bracket or a similar device, could be used in conjunction with the strain gauges to provide the full picture and predict actuator failure.

These strain gauges were selected because they only require a hole diameter of 2 mm for insertion, and the bolt diameter for the actuator given to the team by Bray (which is one of their smallest ones) is about 9.5 mm, so the hole should not compromise the integrity of the bolt [11]. HBK also claims a manufacturer's accuracy of 1%, better than the current IOT Torque Bracket uncertainty of 5%. Additionally, many strain gauges of this type come in the form of collars that fit around bolts, and those would possibly take up too much space inside the actuator or risk being non-embedded, so they were ruled out. Two long wires extend from the strain gauges, so they can easily be connected to the DAQ, like the potentiometer wires for the position deliverable. This strain gauge method was selected over its main opponent concept, which included placing a rotational torque sensor around the valve shaft, because it is completely independent of the valve, unlike the IOT Torque Bracket.

Unlike the potentiometer concept, the implementation of this concept has been delayed due to difficulties relating to sourcing strain gauges from overseas suppliers. However, both the strain gauges themselves and the epoxy required to set them in the bolts have been ordered and the size verifications for the bolts have been made, as mentioned previously. While waiting for the gauges to ship, the team plans to drill the 2 mm holes in the stop bolts, so the actuator can be ready for immediate strain gauge insertion as soon as the parts arrive. This will make the strain gauge solution embedded in the actuator, and the Raspberry Pi will likely be able to read the strain gauge data, similarly to the other concepts. Testing will take place very shortly after the components arrive as the most time-consuming and physically intensive process step, drilling, will be completed before they do.

Electric Motor Design

This concept involves performing calculations using the dynamics of the actuator while it is being toggled. The implementation of this system will be done on the overhead indicator of the actuator, as illustrated in **Figure 23** below.

Figure 23: Overhead indicator of the S92 Actuator [2]

When the actuator is toggled via a shop air supply and solenoid valve, the overhead indicator will rotate as it is directly connected to the actuator stem. The working concept to measure the output torque is assuming the radius of rotation is known and constant for a rack and pinion actuator, this can be combined with the power generated from the actuator rotation to meet the design deliverables. The derived equation to describe this relationship is shown below.

$$\tau = \frac{P \cdot \Delta t}{0.5 \cdot \pi}$$

Where P is the power output from toggling the actuator. The design concept generated from this idea is to use a DC brushless motor to measure the dynamics of the system with a Raspberry Pi. The microprocessor will be used to measure the back-emf generated by the motor, multiplied by the amount of time the actuator takes to completely rotate the valve $\frac{\pi}{2}$ radians or 90 degrees.

The progress of developing the concept shows promising results in meeting project deliverables. Initial validation testing involved connecting the selected 5V motor shown below to a multimeter set to measure the output voltages as the motor is rotated. Rotating the motor by hand approximately 90 degrees at a speed similar to the toggle speed of the actuator showed a measurable spike in the measured voltage, showing this concept could be implemented into the final system. Turning this idea into a working prototype that meets the customer's needs includes fitting the motor onto the actuator. This will be accomplished by 3D printing a casing (**Figure 24**) designed to hold the motor directly over the actuator indicator and the motor stem attached using a resin epoxy. This design will ensure the motor will freely spin with the actuator while its outer casing is held in place, thus minimizing any hysteresis.

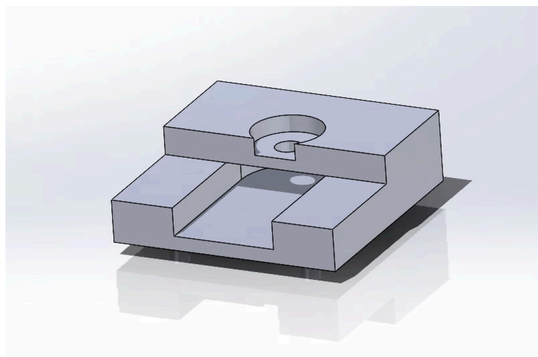

Figure 24: 3D-printed model of the bracket for the electric motor.

The back-emf produced by the motor will be measured by attaching its leads to a 12-bit analog-digital converter chip connected to the Raspberry Pi. When the actuator is toggled, the Pi will detect the sudden increase in live measurement of the voltage and then return the measured torque. This value will be compared to the expected torque output as a function of input air pressure to the actuator to verify the concept measurements are accurate. For later-stage validation testing, this torque measurement will be compared to the readings of the external IOT torque bracket developed previously by Bray.

Progress on this deliverable has been delayed due to mistakenly using Digital-Analog converter chips instead of Analog-Digital converters, as well as the delay in the arrival of the corrected chips. Once this part arrives, it is expected to take two days to implement the motor into the actuator as the casing and fixture will be ready to set up.

FULL SYSTEM PLAN

The final goal of this capstone project is to provide at least two working solutions that complete the deliverables and can work in unison. Providing this would allow Bray to sell products in the future that will have much more value than currently available solutions. This section of the report is dedicated to a top-down view of the embodiment design of the project deliverables, risk assessments, and budget constraints.

Challenges and Significant Changes

Throughout the project, the core of the design plan has remained relatively unchanged. The team remains confident that the current approach will satisfy Bray's aspirations. The most significant change from the initial design pertains to the electric motor torque deliverable. Following the presentation of our preliminary design concept to Bray, the team discovered that the plastic indicator on top of the S92 actuator was removable and merely served a cosmetic purpose. Consequently, the team concluded that the motor bracket depicted in **Figure 24** was redundant. As a result, the team will pursue an alternative method where the electric motor will be mounted in line with the actuator shaft, eliminating the need for gears and belts.

The main challenges faced so far have revolved around delays in material acquisition from both suppliers and Bray, and have delayed the manufacturing of the Hall effect sensor and cylindrical strain gauge deliverables. These shipping challenges are described in further detail in the "Project Concerns" section later in this report, as well as a Gantt chart for timeline analysis.

Full System Embodiment Design

Bray provided the customer needs for this project with the desired outcome of the project to be able to measure the position of the valve with less than 2% error and the torque of the actuator with less than 5% error. To satisfy this customer need, the team decided to test multiple designs for each of the deliverables so that data could be provided to Bray on the best design for each deliverable. This experimental plan that the team set up will allow for measuring the accuracy of each design so that the main customer's need for accuracy is met.

Each solution design was selected for testing because of the distinct advantages each provides for measuring their respective deliverable. The potentiometer was selected due to its advantage of being a highly accurate sensing device, with the preliminary testing showing that the error was well below the desired 2%. The advantage of the Hall effect sensor is that it preserves the floating ball aspect of the valve, making the operation of the valve less tampered with, and it also has a longer service life due to its contactless nature. The cylindrical strain gauges provide consistent data and are easily embedded without changing anything in the actuator design, but it can only measure the beginning and end torque. The motor emf is the most susceptible to noise, causing a higher error in the torque values but it reads a continuous value so it can display the entire trajectory of the actuator.

The materials were carefully selected based on the customer needs identified at the beginning of the project. Each of the specific sensors was selected from reputable brands that provided data on the service life of the sensors. Each sensor needs to withstand about 2 million cycles because that is 1.5 times the average service life of a valve or actuator, so the sensors have to last just as long. Another important material is the epoxy selected, which has to withstand high temperatures. For this reason, an epoxy was selected that needed 200 degrees Fahrenheit just to be cured which allows the team to not be concerned about higher environmental temperatures affecting sensor attachments to the valve or actuator. A Raspberry Pi was chosen for the computing power so that during lifetime testing it can keep up with the millions of data points that are being collected.

Moving to the system's layout, the team focused on making the easiest connections with the least amount of mechanical interactions to maximize the system's accuracy. The Hall effect sensor and the potentiometer are located at the bottom of the valve along the axis or rotation. This layout is the most optimal because being along the axis of rotation allows the rotation to be measured without any translational input. Also, this location is most optimal because there is a flat surface to drill into, which allows the team to manufacture the prototypes easily and precisely into the valve using a mill. Lastly, this layout is one of the smallest distances between the outside of the valve case and the inner ball, meaning that the potentiometer can make good contact and the hall effect sensor can have as minimal air gap as possible.

The layout for the torque deliverable depends on which system is being evaluated. The layout for the cylindrical strain gauges is simple because the location has to be the stop bolts, and the size of the strain gauges is 2mm so the width of the hole being drilled is 2 +-.5 millimeters. The motor had the trickiest layout because the strongest connection to the stem reduces the noise of the data collected. Originally, the actuator cap blocked the motor from being attached to the stem, so a motor mount was modeled to be attached to the edge of the actuator with a rubber belt connecting the motor and actuator shaft. Bray informed the team that the black cap is for visuals and does not serve a purpose meaning it could be removed and the motor could be mounted directly to the actuator shaft, greatly reducing the noise of the data collected.

Now that the layout has been established as the most optimal for collecting the necessary data, the team must look at how energy will be transferred to each sensor in the system. All the sensors selected require electrical energy to operate, which the Raspberry Pi supplies. The layout of these sensors was oriented so that the connecting ports of each of the sensors were accessible from outside the valve or actuator casing. This is efficient for energy transfer because all electrical energy will be transferred directly through wires, losing very little voltage as waste.

The team believes the four design concepts have considered all the safety factors for the operations and user. All of the designs are specifically located at nonintegral parts of the valve's operations so that if one of the sensors breaks, it will not stop the valve or actuator from performing its duties and lose the customer millions of dollars. This is because the project's goal is to predict failure, so the design the team came up with cannot be a reason detrimental failure can occur, which was one of the design requirements that affected the project in 401. Also, this device is supposed to measure data without human interaction, meaning that the design is very safe for the user and there is very little ergonomics.

Now that the layout of the project has been finalized, the team can do an analysis of the production methods. Starting off economically, the production is quite cheap because the main techniques are drilling and adhesives. The drilling and cutting will be done in the FEDC, meaning there are no costs. The epoxy used is about 200 dollars but will last for the entire project. Technically, the main device used to machine the valves will be a mill so the team can make precise holes into the valve casing and the actuator stop bolts. All team members have been trained on how to use this device so there should be no issues manufacturing the prototype.

After production, the system will be assembled into the valve system. This area is where the designs are very efficient, as assembly only involves inserting the sensor into the machined slot and applying the adhesive. This means it is easy to repeat as the holes are cut specifically for each sensor element and will not require much manual labor. The longest time for assembly is the epoxy, as it needs time to cure to ensure a sufficiently strong grip on the sensors. These assembly processes are easily repeatable on most valve sizes due to each actuator and valve size having the same designs just with bigger dimensions.

The sensor system is operated by the Raspberry Pi, which is a microprocessor. The actuator supplies pressure from the processing line and then turns the valve on or off depending on the side the pressure is input to. This pressure input is not designed by our team but by the process engineers installing it. Once the system actuates, the Raspberry Pi will update the computer display with the torque reading and position reading. Environmental effects have been accounted for by ensuring our sensors can operate within cold or hot temperatures. Noise is also mitigated by having the systems embedded into the devices so that if the valve is slightly vibrating, then the sensors are vibrating with it, reducing the stress on the system.

If this system breaks down in operation, the position sensors will be harder to replace due to being directly attached to the ball of the valve. If they need to be replaced, then the valve can be opened up causing the pipeline to be shut down. The upside is that both position sensors are relatively cheap, keeping the maintenance cost down for the actual parts. The torque deliverables are easier to perform maintenance on as they are more accessible. For the cylindrical strain gauges, all that would be needed is to take out the bolt with the faulty strain gauge and install a new bolt and strain gauge system. The motor can be easily accessed, and with some effort to remove the epoxy, the motor can be disconnected and then replaced.

Maintenance costs are not the only cost limits for this project. When working in an industry any minor increase in cost can result in millions of more dollars spent. This is why for the project the team attempted to limit sensor costs. Most of the sensors cost between \$3-\$10 each, which is low. Then the cylindrical strain gauges cost $200 for a set, but it is worth the investment due to easily being embedded into the system, and the data that they can provide is the most promising for the torque deliverable. Additional operating costs are not much as the only thing needed to operate the system is electrical power so it will just add a couple of cents to the monthly power bill. With a total budget of $4000 from the project the team is well within the cost margin that we set spending only $800 on parts.

Overall the team was able to account for most of the items on the embodiment design list, and it helped steer the design and initial prototyping of the project by making sure that every aspect of the project was considered. Some more details on embodiment design and analytical analysis from the first semester of this project can be seen in **Appendix F**.

Risk Analysis

FTA Fault Tree

A product risk analysis is necessary in order to determine possible causes of failure in the final product so that they can be mitigated or prevented. The tools used to perform this risk analysis were the FTA fault tree and the FMECA table. The FTA tree was the first risk analysis performed by the team during 401 and was updated later in 402. The FTA is a tree of possible failures in the system. For this project, the top-level failure was that the sensors did not achieve the desired accuracy level. Then each branch splits into different causes for this problem ending at a root cause. The FTA performed by the team can be seen below in **Figures 25** and **26**.

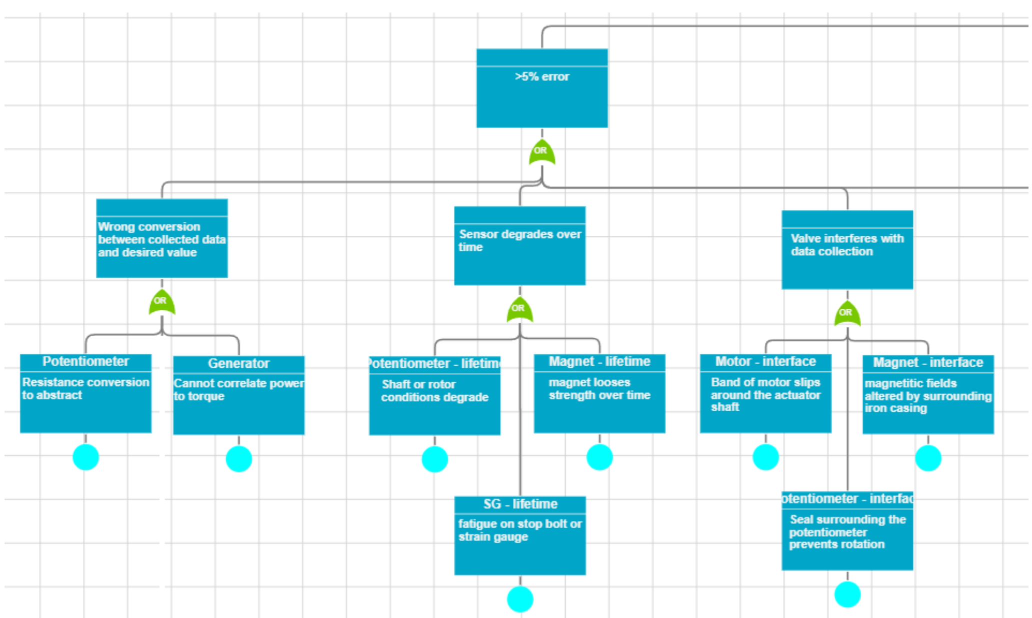

Figure 25: Left side of FTA.

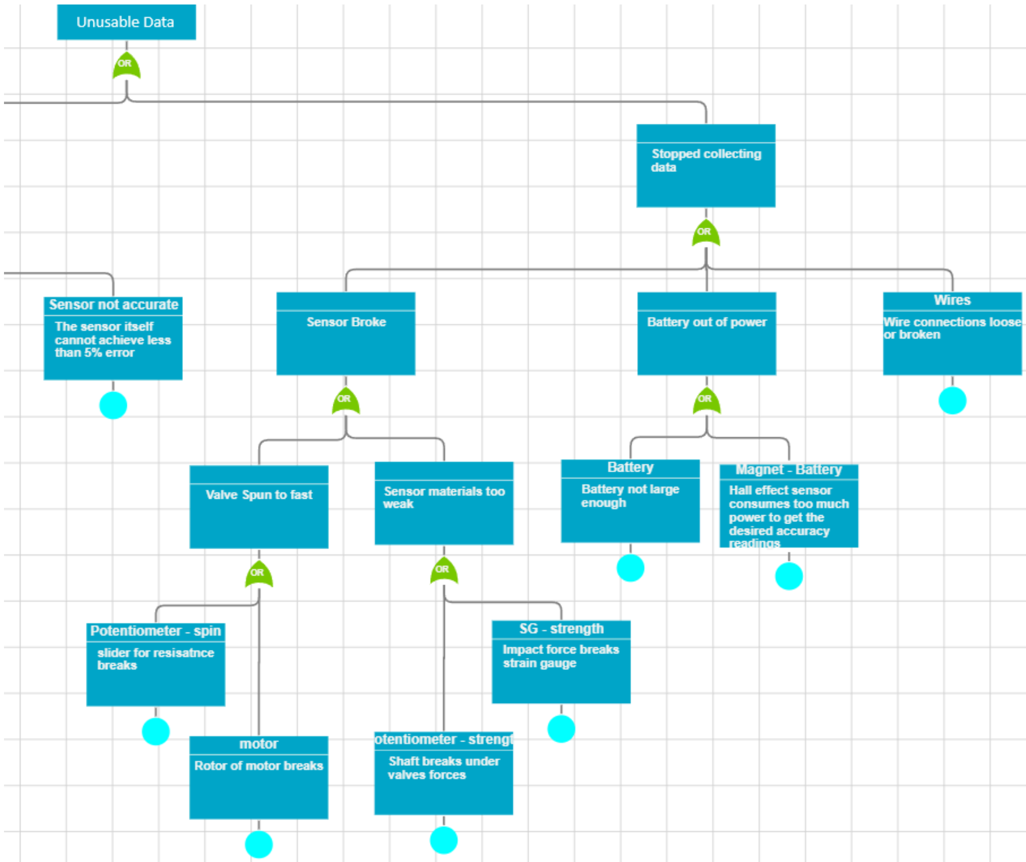

Figure 26: Right side of FTA.

Lower boxes are the cause of higher-level boxes. For example, in **Figure 26**, the rotor of the motor breaking can cause the valve to spin too fast, which can break the sensor, which can cause the sensor to stop collecting data, and so forth. This tree includes failures of the sensors, power supplies (written as batteries), DAQ units, the valves or actuators themselves, or connections between the components. Identifying all of the possible failure points allows the team to focus on potential trouble spots and easily find problems when they do occur. No design process can occur without failures at any level, and this tree will help guide the team to the correct troubleshooting method when failures occur in validation, testing, or assembly.

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

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

The higher cost will be worth it in the event that it provides the team with a sensor that can collect data over the lifetime of the valve.

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

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

FMECA table

The next risk analysis method that was used by the team was the FMECA table where quantitative values were determined for each failure mode. The failure modes were pulled from items identified in the FTA and other issues that had arisen while prototyping. Each identified failure mode was assigned a number 1-10 for severity, occurrence, and detection, with low numbers meaning low risk. The full FMECA table can be seen in **Appendix B**.

The team evaluated the highest RPN numbers, selecting the highest numbers to make design alterations to minimize or remove the failure of the issue. The highest group of RPN values occurred in the resolution of data collected by the Raspberry Pi. These high values were because of the severity of the data not being usable if the step size of the resolution was too high. After all, our team would not meet the accuracy requirements set by Bray due to this bad resolution. Another reason for the high RPN was that this bad resolution would happen with every data point collected, so its occurrence is maxed out at a 10. Fortunately, this failure is easy to detect because the user can see the different step sizes recorded and take action accordingly.

To combat this high RPN, the team started researching what could be done to increase the measuring capabilities of a Raspberry Pi, which is when the ADC chip that converts analog data to digital data was found. This would solve the issue of the Raspberry Pi measuring only 1 and 0, which gave a low resolution. Still, another design decision was to be made as the team had to decide how many bits the chip should have, with more bits increasing the resolution. Ultimately, the team decided on a 16-bit ADC chip that will provide data down to 0.004 steps, which is plenty of resolution for the outcome of this project. The team has already ordered this part, and it will be implemented into the Pi as soon as it arrives.

Another high RPN failure is that the motor emf will not be usable due to high fluctuations in the voltage reading. To find torque from the motor emf, the motor will need a consistent voltage output and if the voltage is fluctuating, the torque reading will be wrong. The RPN for this failure mode was high at 192 because of the occurrence of fluctuations due to the amount of mechanical interactions between the motor shaft and the actuation shaft. Once this system was identified as such a high risk, the team made alterations to the design. This resulted in the motor being directly attached to the actuation shaft instead of having a rubber band that connects the two shafts. This design decision was made to reduce the number of mechanical interactions to make the EMF generation more stable.

The last RPN over 150 was the Hall effect sensor apparatus with an RPN of 180, specifically the ferromagnetic casing of the valve interfering with the readings of the Hall effect sensor. This failure mode has high risk because the team has not been able to test the effects that this has on the hall effect sensor reading yet so estimates were made on the severity and occurrence numbers for the worst-case scenario. Still, this was useful because it got the team thinking about how to change the prototyping apparatus in the event that the data collected was not good enough to achieve less than 2% error. The first possible solution if needed is to cut a hole between the sensor element and the center of the magnet to remove some of the interference. The only problem with this is that the valve is no longer sealed. Another option is to increase the strength of the magnets used or move the sensor and magnets closer together in an effort to have less distortion of the magnetic field by the valve case.

The team is still in the prototyping phase of the project, but as testing begins the FMECA table will be updated with new risks that have been identified. Also if needed the 5 whys will be a very useful tool to identify the root cause of failure found during the testing phase. Overall the FMECA table was useful to identify major issues that needed to be addressed before the testing phase began so that testing could go smoothly and quickly without major problems to the systems design.

Validation

Position Deliverables

To validate that the position-measuring designs meet customer needs, the team will conduct validation testing. This validation testing will prove that the designs can achieve below 2% error in measuring the rotational position of the valve. The independent variable for this testing is the expected position reading, and the dependent variable is the measured position reading and then the calculated error. Bray will provide the team with an extra actuator and a positioner device that will allow the team to observe the difference between the true reading from the positioner and the potentiometer or Hall effect sensor's reading.

For the potentiometer, the Raspberry Pi will measure the resistance and voltage associated with the different set degrees of 0, 45, and 90 degrees. These degree steps were chosen to see if the error fluctuates depending on how far the ball is rotated along the path. The valve will be turned on and then off over and over again, getting 20 data points for each degree step, with 60 data points in total. This experimental validation plan can be seen in **Table 5** below, which will be used to collect the data.

Table 5: Experimental design plan for the potentiometer

Trial #	Set Degrees of Rotation	Resistance	Measured Degrees of Rotation	% Error
1	0			
2	45			
3	90			
4	0			
5	45			
6	90			
...	...			
60	90			

The Hall Effect sensor has a very similar validation testing process, with the valve being set to either 0, 45, or 90 degrees. The Raspberry Pi will measure the voltage reading from the sensor and display the correlating position. There is an added element with the hall effect sensor experiment of how the air gap affects the strength of the readings. The air gap is the distance between the hall effect sensor element and the surface of the magnet. This test will be repeated for 0, 2, 4, 6, …, 20 mm air gaps, using the test rig in **Figure 18**, to find the optimal distance from the hall effect sensor. Then, the team will introduce a cast iron block to simulate the ferromagnetic interference from the valve casing and determine the optimal air gap to reduce error. The experimental table for each air gap distance can be seen below in **Table 6**. This table reduced the number of trials from 60 to 18 for each air gap distance to ensure swift and still accurate validation testing.

Table 6: Experimental design plan for the hall effect sensor

Trial #	Set Degrees of Rotation	Voltage (V)	Predicted degrees of rotation	% Error
1	0			
2	45			
3	90			
4	0			
5	45			
6	90			
…	…			
18	90			

Torque Deliverables

To validate that each torque deliverable solution is able to measure actuator torque independent of the valve while reporting less than 5% error, similar experiments will be conducted on the motor and strain gauge systems.

Once installed, the torque output using strain gauges will be measured using the Raspberry Pi after firing the S92 actuator with the FEDC shop air and solenoid. Initial testing will be done between 40 and 60 psi to emulate system operation in low-intensity conditions. Error for the dataset will be found by measuring each trial's deviation from a linear regression line fitted over the data. Measurements will also be validated using the expected torque outputs listed by Bray for the provided actuator size. **Table 7** below shows the incomplete experimental design table.

Table 7: Experimental Design Plan for Cylindrical Strain Gauges

Trial #	Pressure (psia)	Expected Torque	Measured Strain	Measured Torque	% Error
1	40				
2	45				
3	50				
4	55				
5	60				
…	…				
50	60				

Measuring the torque output using the motor subsystem will undergo a similar validation testing strategy. Table 8 below shows the experimental validation plan for the motor when attached to the pneumatic actuator. After being properly fitted inside the external casing and emf measurement is verified with the Pi, the microcontroller will constantly read the induced EMF on the motor and wait for any large spikes in measured voltage. When this occurs, the Pi will measure the voltage while considering the average toggle time for each pressure input along with the actuator radius of rotation, and calculate the measured torque. This measurement will again be compared to the linear regression fit line to determine the error each data point has from the expected trend.

Table 8: Experimental Design Plan for back-EMF motor

Trial #	Pressure (psia)	Expected Torque	Toggle Time	Measured Voltage	Measured Torque	% Error
1	40					
2	45					
3	50					
4	55					
5	60					
...	...					
50	60					

Combined Deliverables

Once each of the designs has been tested separately, the best-performing designs for both position and torque will be selected to move forward in the testing stages. This will consist of seeing if the valve and actuator system together cause an error increase for either of the sensors. This validation test will also consider the extreme environmental temperatures, so testing will be conducted at 40 degrees Fahrenheit, room temperature, and 100 degrees Fahrenheit. The actuator will receive pressure inputs between 40 and 60 psi with 5 psi steps. The output of our sensors will read torque, position and then calculate percent error. This experimental design can be seen below **Table 9,** which shows the data collection table for an experiment run at one temperature condition. The table will be repeated for different temperatures, as Bray products are used in many fields that operate in varied environments, including oil and gas and subsea conditions.

Table 9: Experimental design for the combined position and torque system.

Trial #	Pressure (psia)	Measured Torque	Measured position	Error % Position	Error % Torque
1	40				
2	45				
3	50				
4	55				
5	60				
…	…				
100	60				

Overall Budget

The expenditures for the project thus far have remained well below previously detailed expectations. The majority of the cost reductions have come from high-value equipment such as valves and actuators being supplied by Bray International and not purchased through the team's senior design account. A complete updated reflection of the original budget is described in **Appendix C**. **Table 10** below shows the categorical expenditures of the project up to this point, including the total amount spent for the project.

Table 10: Categorical Expenditures through February 25, 2024.

Sensors	$ 313
Electrical Equipment	$ 107
External Casing	$ 145
Travel	$ 208
Total	**$ 775**

A complete ledger of all purchased materials organized by their purchase date and vendor is listed in **Appendix D**. The biggest expenses for the project have been the purchase of cylindrical strain gauges from HBK as part of the torque measurement deliverable, as well as reimbursement for mileage traveled to Cypress, Texas to visit the Bray facilities. A number of sensors and materials that were originally proposed in the original budget have been changed to better meet the needs of the project deliverables. However, most of these changes have lowered costs and purchase lead times, so there has been minimal impact to the project timeline.

Expected expenditures for the remainder of the project include the purchase of analog-digital converter chips to facilitate sensor measurements with the Raspberry Pi, adhesive materials to secure a solenoid valve onto the S92 actuator, and materials to build an external rig to support the valve-actuator system during final validation testing of the product. An adjusted budget reflecting the current state of the project is shown below in **Figure 27**.

Category		Component	Purchase Unit Cost	Assembly (Labor)	Number of Units	Total Unit Variable Cost	Margin	Adjusted Cost
Tooling	FEDC Access							
Materials	Sensors							
		Current Expenses						*$313.41*
	Electrical & Data							
		Current Expenses						*$109.19*
		ADC Chip (3)	$15.99		1	$15.99		$15.99
	External Casing							
		Current Expenses						*$144.98*
		Teflon Tape	$1.48		1	$1.48	25%	$1.85
		Resin Adhesive	$14.99		1	$14.99	25%	$18.74
		2 x 4 Wood (10 ft)	$5.85		1	$5.85	25%	$7.31
		1" Bolts & Nuts	$2.67		2	$5.34	25%	$6.68
Travel		*Current Expenses*						$209.32
		College Station to Cypress, TX	$104.66		2	$209.32		$209.32
				TOTAL		$252.97		$1,036.79

Figure 27: Budget for remaining project expenditures.

As shown by the budget, the total upcoming costs are estimated to be about $250 in materials to construct the validation test rig and then drive the product to Bray for lifecycle testing, bringing the new estimated total budget for the project to **$1,040.** Overall, the deliverables of the project are currently on pace to be met well below the originally expected costs. These changes are a result of more time being invested in researching sensors and materials that could minimize lead times, which often led to a decrease in costs when buying through wholesale vendors such as Amazon or DigiKey.

FUTURE WORK

This section of the report lays out a summary of what is still to come for this project. It summarizes the details that have been described in previous sections into a general outline of time and task allocation for the remainder of the semester.

Action Items for Validation

The team has thoroughly analyzed the majority of aspects regarding the embodiment design outlined above. Considerations such as the function of each deliverable, layout, life cycle, and maintenance have been carefully evaluated throughout the project timeline. However, there are still some crucial aspects that need further consideration, including the energy source and kinematics of the system. It is imperative to determine how these systems will be efficiently powered in the field—whether through battery, solar, or grid power. Given Bray's current priorities, addressing this issue will be deferred to later stages of development, while the team focuses on devising a solution compatible with readily available power sources.

Additionally, transportation risks have not been fully addressed. The expectation is that Bray can leverage existing transportation and packaging capabilities for the embedded sensors without significant adjustments. However, this aspect will be tackled by Bray's team in the later stages of development when preparing the product for shipment to customers. Furthermore, scheduling remains another aspect of the embodiment design that requires attention. This entails assessing whether delivery dates can be met within manufacturing timelines and exploring modifications to reduce cycle time and enhance delivery efficiency. This aspect will also be addressed later in development, as Bray prepares to commence manufacturing for customers.

The items that the team must validate and verify for each deliverable have been described in the sections of this report covering the concepts and validation. Below is a summarized list of what must be done for each deliverable; a simplified list of what has previously been described.

- Potentiometer concept: connect valve-potentiometer-Raspberry Pi in sequence, test position with positioner versus sensor reading, seal casing around potentiometer (only seal if time permits)
- Hall effect sensor concept: Receive Hall effect sensor and test on 3D-printed testing rig, test the sensor on a valve versus positioner data, connect valve-sensor-Raspberry Pi in sequence
- Strain gauge concept: drill into actuator stop bolts, receive strain gauges, install strain gauges in bolts, connect actuator-gauges-Raspberry Pi in sequence, implement formula for the Pi to convert the raw strain or force data into a torque value for the actuator (by comparing to the known torque value of a new actuator)
- Electric motor concept: attach motor to actuator shaft, connect actuator-motor-Raspberry Pi in sequence, implement formula for the Pi to convert raw voltage values into torque (by comparing to the known torque value of a new actuator)

While the details for each validation step are described elsewhere in this report, this list will serve as a back-of-the-hand checklist for what still needs to be accomplished for each deliverable. The team is confident that once the final part shipments arrive, testing and implementation can be accomplished fairly quickly as the plans have already been laid out.

Timeline for System Validation

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. The 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 28** represents the first half of MEEN 402, while **Figure 29** represents the second half. The Gantt chart also includes holiday breaks and reading days so team members know what time blocks to not work during.

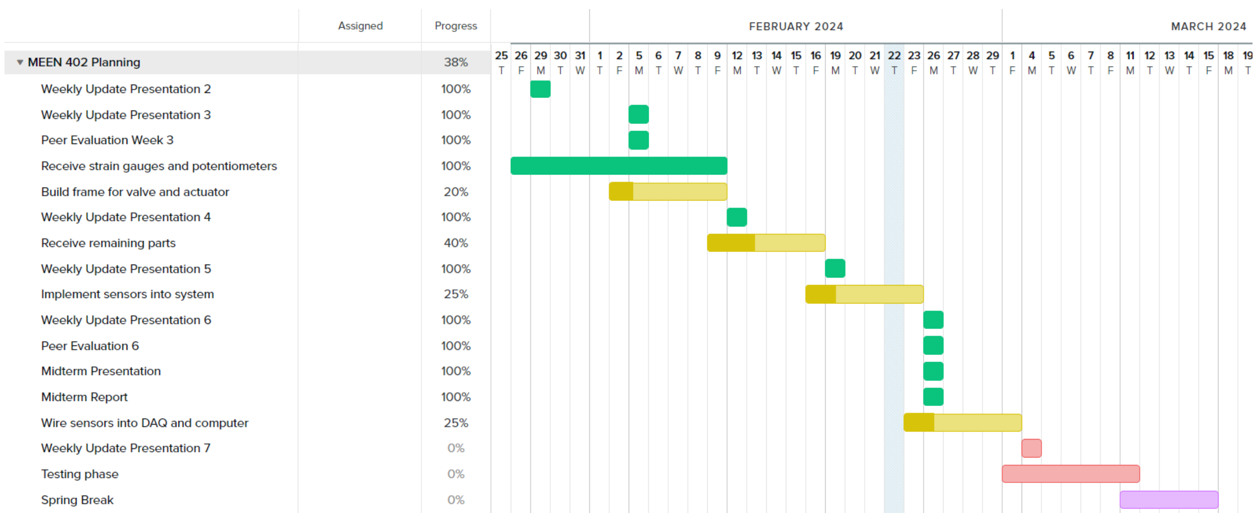

Figure 28: Gantt chart for MEEN 402 before spring break

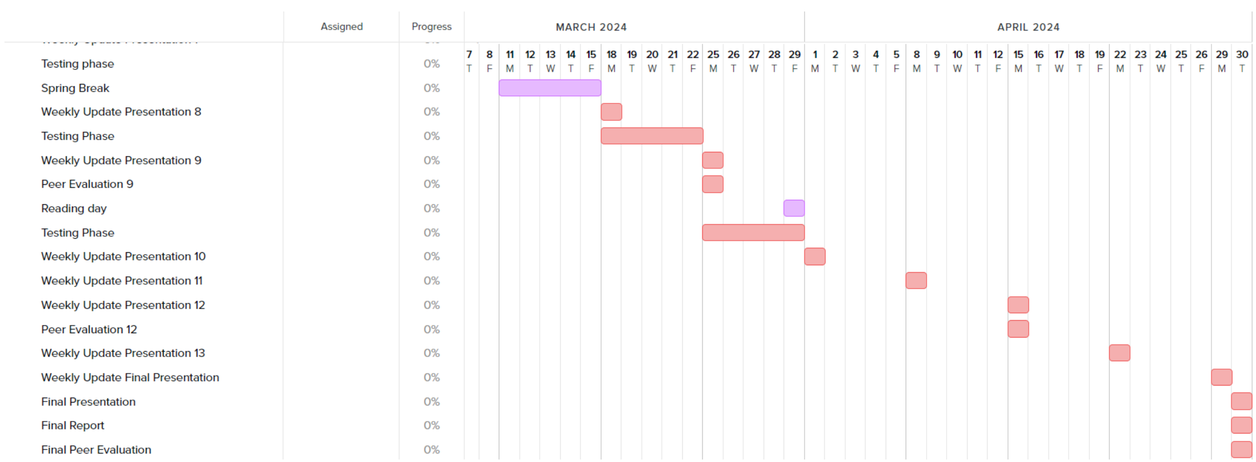

Figure 29: Gantt chart for MEEN 402 after spring break

The team is behind on phases for the capstone project due to awaiting the arrival of parts. Although the team has been temporarily roadblocked from pursuing certain solutions such as the Hall effect sensor and the bolt strain gauge design, further progress has been made in other areas of the project. The team has recently finished the drilling on the ball valve which will allow for preliminary testing to begin for the rotary potentiometer, and the Hall effect sensor once received. There is still more drilling to do for the implementation of the Hall effect sensor into the butterfly valve, but this should not be time-consuming since the same procedure with the ball valve will be followed for the butterfly valve. The rotary potentiometer has been fully set up with the DAQ and tested individually, which leads to testing with this solution arriving very soon. In **Figure 29**, the first two weeks following spring break are reserved for finalized testing. The team has roughly 2 weeks' worth of buffer in case finalized testing is not completed by the desired deadline. This buffer ensures that if extra time is needed, the quality of the solution will not have to be affected by the current deadline. Once the remaining components arrive, the team will be able to build them into the valve and actuator and test them after that. The team looks forward to presenting two finalized solutions that answer both deliverables presented by Bray.

Project Concerns

One potential cause for concern about the potentiometer design is that the necessary hole through the valve may compromise the sealed compartment that fluid flows through, as the potentiometer will be exposed to the environment unless a seal is placed around it. While it is unlikely that the fluid will ever leak into the small clearance between the ball and the casing, it is nonetheless important to secure this area so that the valve can meet all necessary standards. Bray stated to the team that their engineers could work on the sealing aspect of this design if the team can provide good data on the installation and measurements from the potentiometer, so the team will focus on the functionality of the potentiometer before raising the concern of sealing.

The other major cause for concern is the timing of parts shipments. The team has run into several issues with this, including the Hall effect sensor package potentially getting lost (this is still being determined) and the strain gauges being difficult to source. However, the team believes that all necessary parts have arrived or at least have been ordered. The team has already received the potentiometers, electric motors, Raspberry Pi with wires and assorted accessories, and magnets. Still in the mail are the strain gauges, Hall effect sensor, and epoxy for securing sensors onto the products. All parts should arrive fairly soon except for possibly the strain gauges, which had to be sourced from HBK in Germany as most vendors would not sell to individual buyers. However, even with this probable delay, the extra buffer time built into the end of the schedule (seen in **Figure 29**) should allow for the prototypes and testing to be completed even with shipping lags. The team is confident that all building and testing will be able to be accomplished and Bray will receive the prototypes and data they need to make an informed decision about how to move forward with the implementation of the team’s solutions.

Final Deliverables

At the end of this project, the team plans to be able to deliver to Bray a working prototype for each concept. By then, each concept will have been tested for accuracy and other embodiment design and validation requirements, and the team will give Bray the testing data along with the physical prototypes, which will be implemented into devices that Bray has given the team. The potentiometer concept is already embedded into the ball valve, and the Hall effect sensor concept will be implemented into the butterfly valve. Bray only gave the team one S92 [2] actuator, but both the motor concept and the strain gauge concept can be placed on the same actuator since they occupy different regions of space. Therefore, the team will give Bray their actuator back with both concepts installed on it. With these prototypes and testing data, Bray will be able to decide which solutions they would like to implement into their fleet of products and they will make an informed decision on how to put them into production. Finally, the team will hand over to Bray all plans, calculations, photographs, sensors, prototypes, and other items that were used in the Embedded Valve and Actuator Sensors project.

CONCLUSIONS

In summary, Bray would like the project team to develop embedded sensors for valve position and 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 customer's 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, and time spent on the refinement of concepts, the top two concepts were selected to be tested and compared for both deliverables. This experimental approach will allow the team and Bray to devise the best possible method of accurately measuring valve position and actuator torque. A rotary potentiometer and a Hall effect sensor will be prototyped to measure position, and an electric motor and a strain gauge on the actuator stop bolts will be compared to measure output torque. These concepts won out over their competitors due to their embedded nature (they can fit into the valve/actuator casing), their comparatively low cost, and their small number of moving parts which produces easier maintenance should it be needed. Currently, the team is prepared to begin preliminary testing with the rotary potentiometer and is currently advancing in progress with the strain gauge, Hall effect sensor, and electrical motor design. The solution of the rotary potentiometer will nearly complete one of the two assigned deliverables, leaving the team to detect true actuator torque and test the Hall effect sensor for position. Both deliverables will be tackled following spring break, including prototype building and data collection for accuracy testing. Successful design and implementation of solutions for the issues would be one more step towards real-time, complete data acquisition from these valve and actuator 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 disluption of the magnetic feild due to heat and metal Pollution

total Accuracy 3% – 1%

Callibration time

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

each Run ≈ 1 min

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

Callibration time = 110 min

Cost

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

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

life time of Sensor

Hall effect sensor = 10 million cycles

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

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

Volume of apparatus

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

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

Weight
weight of Hall effect ≈ 0.5 lbs

weight of magnet = .3 lbs per in^2

$.3(8in) + 0.5 = 2.9$ 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 [10] and [12], the rotary potentiometer specs [8] and [9], the rotational torque bracket specs [6], and the torque potentiometer specs [5].

Appendix B: Full FMECA analysis.

Part # and Functions	Potential Failure Mode	Assessment							Recommended Actions	
		Potential Effect(s) of Failure	Severity (S)	Potential Causes and Mechanisms of Failure	Occurrence (O)	Current Design Controls Test	Detection (D)	RPN	Description of Action	Responsibility & Target Completion Date
Potentiometer Sensor embedded into underside of ball valve	Potentiometer head breaks off of sensor body	Sensor head causes a jam in the ball valve operation	8	Assembly error; sensor not directly in line with ball rotation axis	3	Lifetime cycle testing, verify measurements before drilling, verify drill spots before sensor insertion	2	48	Ensure high-precision mill and accurate measurements before drilling into valve casing	Cody Sims, 2/28/24
		Potentiometer stops transmitting position data to end-user	9	Part error; poorly manufactured sensor or defective	2	Research effectiveness of selected sensor, its lifetime, and operating conditions	2	36	Lifecycle test of potentiometer prior to embedding in valve	Michael Hager, 2/28/24

		Sensor head damages exterior casing of valve	3	Environmental error; operation temperature or pressure causes degradation to the part over time	4	Lifetime cycle testing in ambient conditions	2	24	Lifecycle test of potentiometer prior to embedding in valve	Michael Hager, 2/28/24
Cylindrical strain gauge embedded into the stop bolts of the actuators	Strain gauge cannot withstand force of actuator	Strain gauge falls out of stop bolt	7	adhesive used is not strong enough	4	use recommended adhesive with the strain gauge and life time test with millions of actuations	4	112	ensue proper amount of adhesive is applied by practicing on extra bolts before using the actual stop bolts	Locke Lehmann (3/10/24)
		Strain gauge breaks	8	Too Much actuation force	3	Test design between 40 psi and max of 80 psi	5	120	Use larger-sized stop bolts so that there is more metal between the sensor and the stop bolt	Locke Lehmann (3/26/24)
		stain gauge oriented improperly in stop bolt	8	incorrect implementation of strain gauge or strain gauge wrong size for stop bolt.	3	follow instructions and communicate with the company on the size needed with the dimensions of the stop bolts	3	72	Contact the supplier and provide schematics to get the best bolt size. Also, receive insertion instructions and follow them carefully	Avery Haynes (3/10/24)
Motor attached to the raspberry PI ADC converter chip and actuation stem	Bad MotorEMF data	Raspberry Pi is not able to read motor EMF data	8	ranges of voltages is measured when one consistent voltage is needed	6	Fast actuation time so little variance can happen, Attached as close to the stem to reduce mechanical noise	4	192	get a higher-quality motor that will spin more consistently over time. Use the least amount of mechanical interactions to connect to the stem.	Michael Hager (3/10/2024)

		Torque error greater than 5%	9	motor used outputs inconsistent voltages between each trial	4	record each voltage value and compare them to previous trials at the same conditions	2	72	Get higher quality motor that has better quality bushing and will output consistent voltages over multiple trials. Use the least amount of mechanical interactions to connect to the stem.	Travis Carlson (3/10/2024)
		The motor does not rotate the same amount as the actuator	7	adhesive between metal and plastic is not strong enough	3	Use eyes to see if the plastic gear is slipping. Do this by making marks and see if the gear is rotating the full 90 degrees as it should.	3	63	use a gear that screws into the hole on the actuator shaft	Zachary Walker (3/1/2024)
hall effect sensor placed under a magnetic field	Cannot sense magnet field accurately	position error greater than 2%	9	Magnetic properties of the valve casing interferes with magnetic field	4	test with magnetic interference to determine how to position sensor with relation to sensor device	5	180	cut a hole between the sensor element and magnet so there is not direct interference between them. (can use potentiometer hole)	Cody Sims (3/1/24)
		no signal outputted from the sensor	9	Magnet too far from hall effect sensor, or magnet not strong enough	4	test distances from magnet to sensor to determine the sensing range of the hall effect sensor	4	144	put magnet as close as possible but still keep the ball of the valve floating	Zachary Walker (3/1/2024)

Raspberry Pi collecting sensor data	resolution of data to imprecise	can not achieve desired accuracy due to measuring resolution	5	10 bit processor cannot provide enough resolution for measurements. 0.4 increments	10	test linear potentiometer to see steps in increasing position	3	150	Buy 16-bit processing chip that can achieve better resolution	Avery Haynes (2/21/24
		time measurement is not accurate due to low resolution	7	Pi can not keep track of time in small enough steps to be precise	10	start and stop timer in less than 1 second in small steps to see if we can get substantially different times.	4	280	Buy 16-bit processing chip that can achieve better resolution	Avery Haynes (2/21/24)

<u>Appendix C:</u> Complete Estimated Project Budget For Bray Smart Valve System. Items in red were supplied to the team from Bray International.

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

<u>Appendix D:</u> Ledger of currently purchased materials for the project.

Team Name:	402-500 BRAY		**Account #:**	02-460006-24005			
Term:	2023-2024		**Instructor:**	Dr. Suh			
Order #	**Date Ordered**	**Vendor**	**Part**	**QTY**	**Qty Cost**	**Part Cost**	**Total Cost**
1	Jan 16, 2024	Amazon	DC Motors (5)	1	$11.49	$11.49	**$128.47**
			Niodenium Magnets	1	$11.99	$11.99	
			Raspberry Pi & Starter Kit	1	$104.99	$104.99	
2	Feb 06, 2024	DigiKey	Hall Effect Sensor	2	$4.96	$9.92	**$14.12**
			Jumper Wires (20)	2	$2.10	$4.20	
3	Feb 06, 2024	Amazon	Motor Gear Kit	1	$9.99	$9.99	**$9.99**
4	Feb 13, 2024	HBK	LB11 Strain Gauge (5)	1	$259.00	$259.00	**$415.00**
			Epoxy Resin Adhesive	1	$123.00	$123.00	
			SHIPPING			$33.00	
5	Sep 08, 2024		Drive to Bray				**$104.00**
6	Dec 01, 2024		Drive to Bray				**$104.00**
					TOTAL		**$775.58**

<u>Appendix E:</u> Sample calculations for potentiometer validation testing.

$$0avg = \frac{\Sigma R_0}{n} = \frac{.24+.24+.22+.25+.25+.29}{6} = 0.24833\Omega$$

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

$$Slope = \frac{rise}{run} = \frac{94704.17-.24833}{270-0} = 350.75 \qquad y_{int} = 0avg = .24833\Omega$$

Using first 0 test case for rest of the calculator

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

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

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

Appendix F: Further In-depth Embodiment Design Details (from MEEN 401 Design Report 3)

The following paragraphs are from last semester and show the initial stages of embodiment design that have been modified and implemented as part of MEEN 402.

Product Architecture

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

Table A: Subfunction grouping of solutions.

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

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

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

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

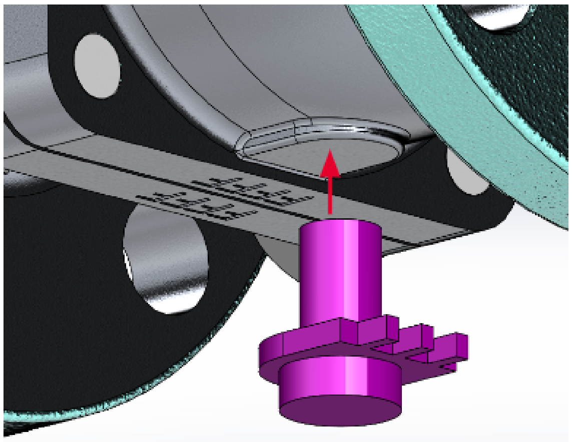


Figure A

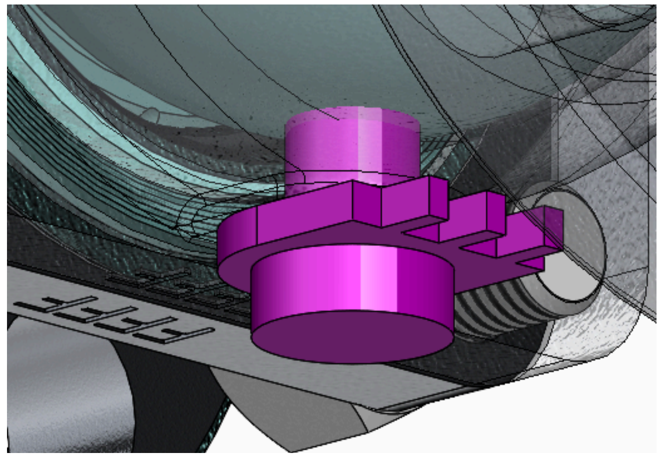


Figure B

Potentiometer solution attached to bottom of ball valve casing.

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

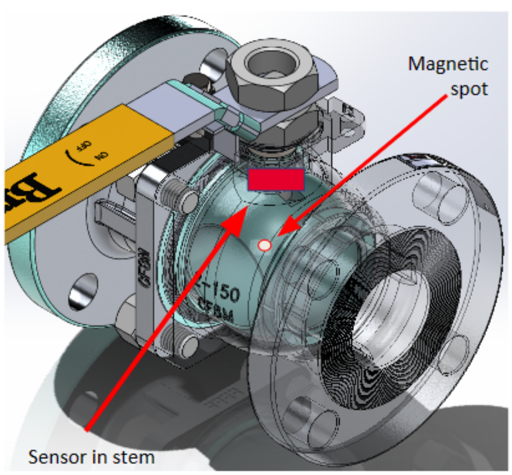
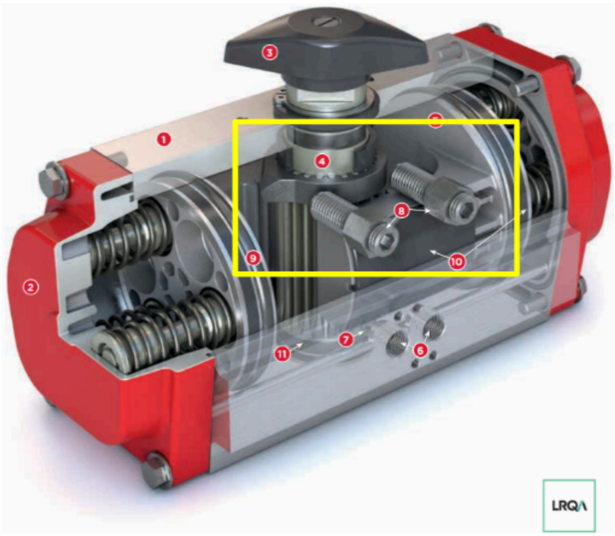


Figure C: Hall effect sensor layout sketch.

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



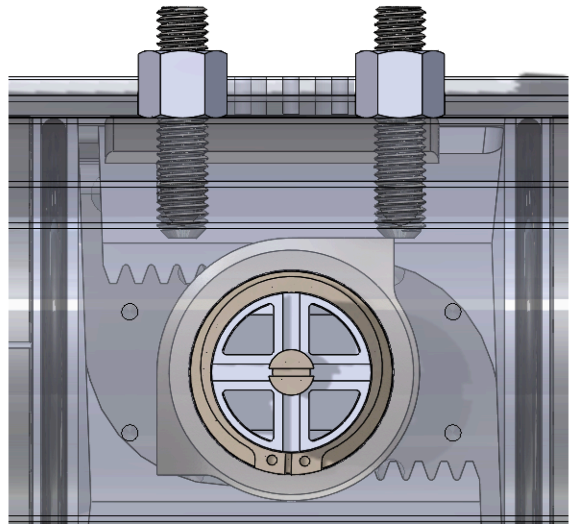


Figure D **Figure E**

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

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

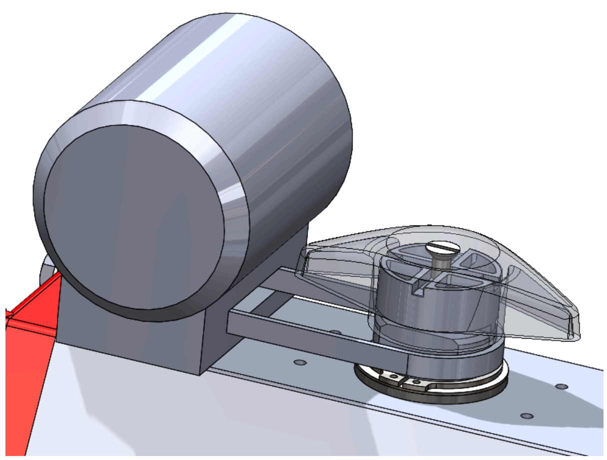


Figure F: Electric motor design concept mounted on top of actuator.

Definitive Layouts

For each of the subfunction deliverables and potential concepts, the exact sensor location, type, size, material, and form was selected after considering the project constraints based on accuracy, cost, ease of maintenance, and optimal service life. This section describes a definitive layout that will be tested and validated by the team in the upcoming weeks for each possible solution in creating a smart valve. For all of these solutions, data from the sensors is sent to a Jessinie ADS1256 Data Acquisition Unit [13] (later replaced with a Raspberry Pi) where it is then processed and sent to a computer interface for a customer or technician to diagnose the life of the valve.

Valve Position - Potentiometer

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

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

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

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

Valve Position - Hall Effect Sensor

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

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

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

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

Actuator Torque - Strain Gauges

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

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

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

Actuator Torque - Electric Motor

The actuator torque output will also be measured using a motor attached to the actuator head and found using the dynamics of generated power. To accomplish this, a Transmotec brush-commutated DC motor will be mounted onto the actuator head using steel plating [14]. A gear will be fixed onto the motor shaft connected to a belt that wraps around the actuator head. The advantage of this solution over embedded ones is there are no internal connections or product modifications required, so the entire system can be easily changed out in the event of failure.

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

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

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