Accumulator Volume Sensor
Final Project Report

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1. Disclaimer

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2. Abstract

Accumulator Volume Sensing Team has developed two sensor designs aimed at detecting the position of the piston within a 4024 accumulator. The two designs include the use of a Renishaw LMA10 magnetic encoder and a SpectraSymbol HotPot linear potentiometer. The magnetic encoder solution drastically increases the accuracy of sensing the piston position compared to the current solutions of both a string-pot and linear variable differential transformer while costing slightly less. The linear potentiometer seeks to provide a solution that drastically decreases the cost compared to the present sensing methods. Both designs call for a modification to one half of the piston guide part on the 4024 piston accumulator. The purpose of this report is to outline the design process we went through in selecting our two final solutions, as well as explain how we propose the sensors be implemented in an accumulator. Also included is the testing process and resulting accuracy uncertainty. This project covers both the mechanical design of the sensor mounting, as well as the electrical signal processing or adjustment.

3. Introduction

This senior project is a joint collaboration between Accumulator Volume Sensing Team (AVST), project sponsor Mike Brown of Pacific Design Technologies (PDT), and project advisor Professor Eileen Rossman of California Polytechnic State University, San Luis Obispo, Mechanical Engineering. AVST is composed of members Michael George, Chris Naughton, and Kinwei Yu. The team is dedicated to the completion of this senior project in partial fulfillment of a Bachelors of Science in Mechanical Engineering at California Polytechnic State University, San Luis Obispo.

During the project, AVST (Michael George, Chris Naughton, and Kinwei Yu) shall engineer a sensing solution to measure the fluid volume within an accumulator by detecting the position of the piston. Knowledge of the accumulator's volume is vital information with regard to the functionality or failure of a hydraulic system. The team created a sensing device that is less expensive than PDT's current solutions of using a string potentiometer (string-pot) or linear variable differential transformer (LVDT). The sensing device aimed to capture the entire piston stroke length while being as accurate as existing solutions. The sensor was used as proof of concept that is aimed to be implemented and tested on the current 4024 accumulator model. This project included the complete process of research, design, manufacture, test, and report.

4. Background

A thorough background investigation was conducted in order for AVST to have a complete understanding of the problem presented by PDT.

4.1. Accumulators and Volume Sensing

One of the products that PDT develops are fluid accumulators for the aerospace industry. A fluid accumulator acts as a reservoir for the coolant used in aircrafts. The fluid must be stored under high pressure in order to prevent cavitation when it enters a pump. As the coolant is cycled through, the volume of fluid within the accumulator is gradually changing. This volume must be measurable and readily available for the operator to check.

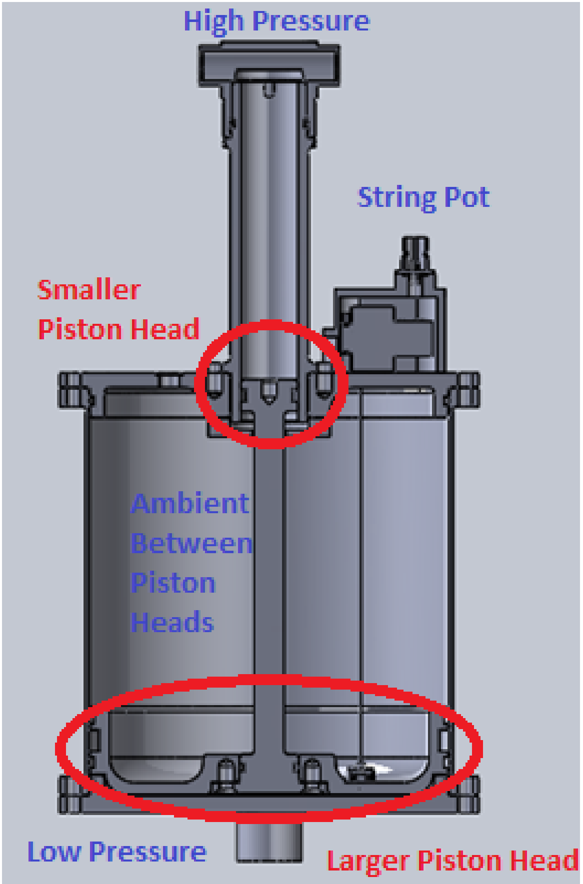


Figure 4.1. – Bootstrap 4024 Fluid Accumulator (Source: *Pacific Design Technologies* [8])

PDT designs several different types of accumulators including piston/spring, bellows, and bootstrap. AVST aimed to develop a sensor using a bootstrap accumulator as reference due to the availability and ease of implementation. A bootstrap accumulator utilizes two cylindrical chambers of different cross-sectional areas connected by a piston as seen in Figure 4.1. A high pressure source sits in the smaller chamber while the low pressure coolant resides in the bigger chamber. The piston has two ends with a surface area ratio designed for a specific pressure ratio between the two sides. As the coolant is cycled through the aircraft, the larger reservoir within the accumulator

changes, causing the piston to move up and down to balance the force exerted by the high pressure source. The volume of the coolant chamber is obtained indirectly by measuring the displacement of the piston while knowing the exact dimensions of the accumulator. Measurement of the piston's position is the preferred method in finding the fluid volume, as it takes into account system leaks.

4.2. Currently Implemented Sensors

Currently, PDT employs transducers in the form of either a string potentiometer (string-pot) or Linear Variable Differential Transformer (LVDT) to measure the piston's displacement.

A string potentiometer consists of a cable wound around a spool. The spool is attached to both a torsion spring and a rotational sensor. As the end of the cable is pulled, the spool spins along with the sensor, translating linear motion into rotary motion which effects an electrical output. The torsion spring keeps the cable in tension allowing the spool to spin the other direction as the cable retracts and winds back up. Figure 4.2 shows the components of a string-pot. In an accumulator, the string-pot is mounted outside on top of the housing, with the end of the cable attaching to the piston.

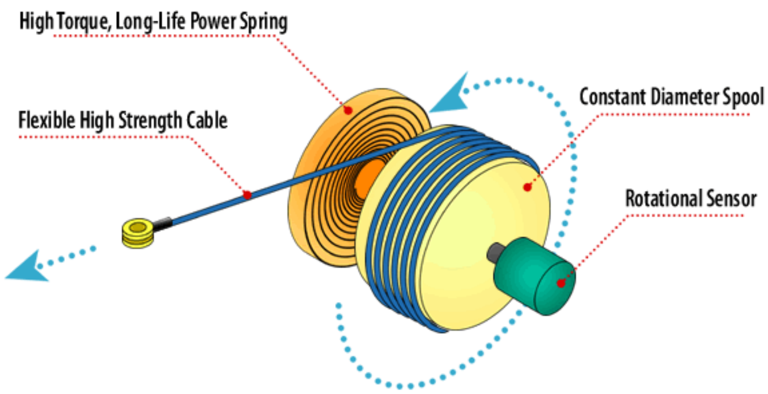


Figure 4.2. – Components of a String Potentiometer (Source: *Celesco* [3])

The rotational sensor of the string-pot is a potentiometer. A potentiometer acts as a variable resistance resistor, with a wiper that slides across a strip of a resistive element

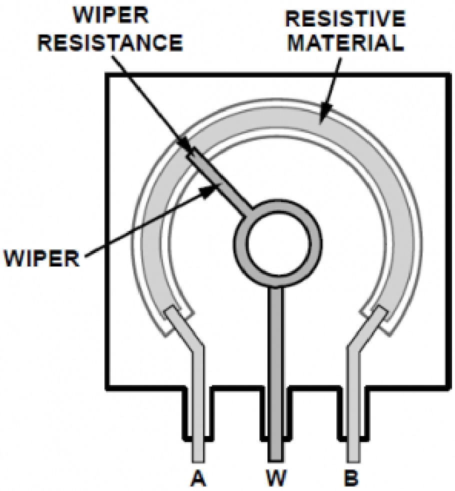
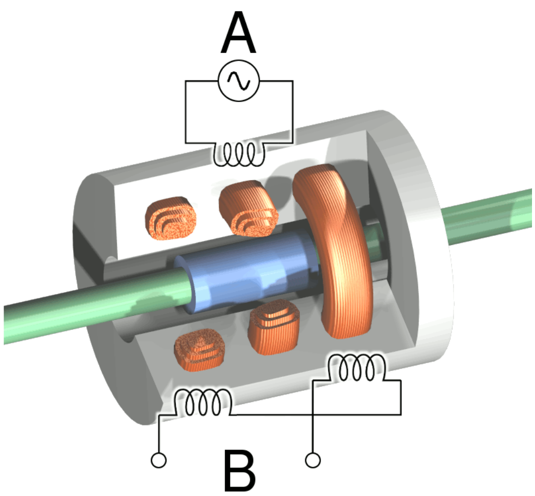
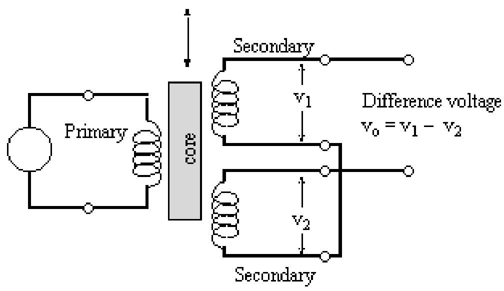


Figure 4.3. – Basics of a Potentiometer (Source: *EEWeb* [5])

as seen in Figure 4.3. As the wiper moves, the voltage drop across another fixed value resistor varies, causing the output voltage to change. In a string-pot, the cable is coupled to the wiper, causing resistance to change as the cable is pulled.



(a) Internal Structure of a LVDT (Source: *University of Jordan* [6])



(b) Circuit of a LVDT (Source: *Instrumentation and Control Engineering* [7])

Figure 4.4. – Structure and Circuit of a LVDT

A linear variable differential transformer consists of a magnetically permeable core within a hollow cylindrical rod. Between the rod and core are a pair of secondary windings on either side of a primary winding. The basic structure is shown in Figure 4.4(a). The primary winding is supplied with an AC current. When the core is in the neutral position

(same distance from both secondary windings), the induced voltages on the secondary windings (caused by the primary winding) are equal. Once the magnetic core moves, more flux is coupled to one secondary winding than the other. This causes a difference in induced voltage between the secondary windings. The transformer circuit is shown in Figure 4.4(b) The voltage difference is measured, calibrated, and output as the linear displacement of the core. In the case of an accumulator, the core is attached to the piston while the hollow rod is attached to the housing. Unlike the string-pot which has a self-contained chamber for its cable, the LVDT resides within the fluid itself and is subject to the environmental pressures of the accumulator.

Currently, the string-pot used by PDT has an accuracy of ±2% full scale and costs $800. The LVDT has an accuracy of ±1% full scale and costs $1800. The weight limit for each design is set at 2 lbs. Both designs are used in accumulators with a piston stroke length of up to 10 inches. The team aimed to design a sensor with comparable accuracy to the LVDT while costing no more than the string pot. It fit the weight and displacement requirement, while using the same input voltages of 10-28V as commonly found on air crafts.

4.3. Other Applicable Sensors

Because sensors are commonly used in multiple fields of engineering, the team quickly realized that there are many alternative solutions to the string-pot or LVDT. One method that AVST came across is a magnetic level gauge. As seen in Figure 4.5, a magnetic follower is coupled to a float or piston. The magnetic follower can then be used as a visual indicator in conjunction with a linear reference. This method would be helpful in finding the piston's position an auxilary fluid column was incorporated onto the accumulators design.

A capacitance transmitter is a method of liquid level sensing in which the capacitance between two plates changes depending on the amount of fluid between them. The change in capacitance is proportional to the amount of fluid in contact with the capacitor plates. Capacitance transmitters are limited in the application to accumulators as they would

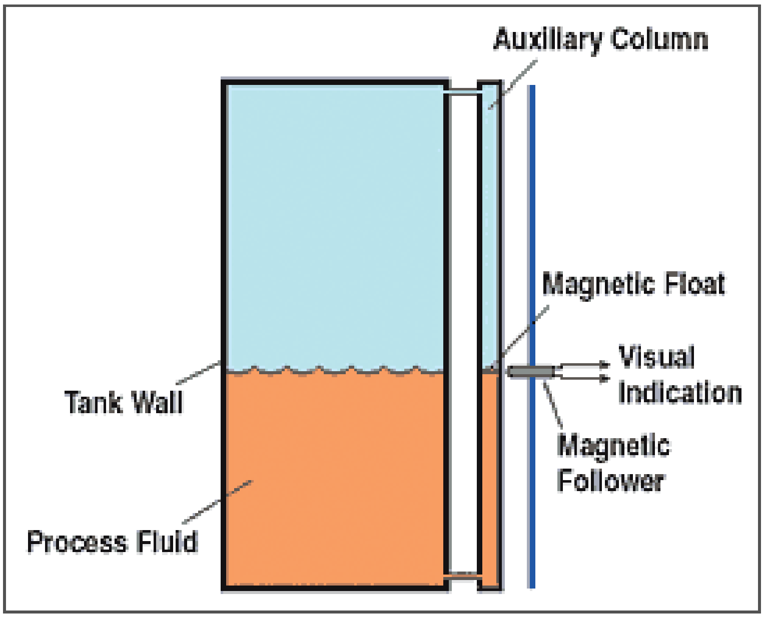


Figure 4.5. – Magnetic Level Sensor Basics (Source: *Sensors Online* [1])

require contact with the sealed portion of the accumulator. The basic ideology of a capacitance transmitter can be viewed in Figure 4.6.

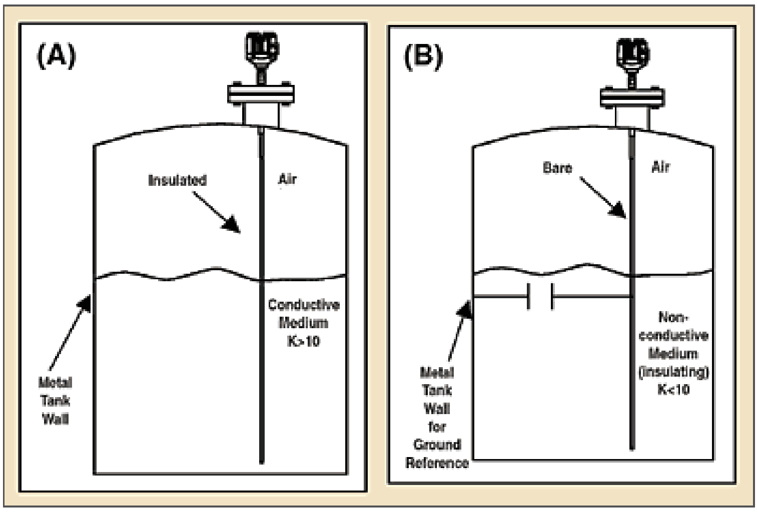


Figure 4.6. – Capacitance Transmitter Basics (Source: *Sensors Online* [1])

Another common method for determining the volume within a vessel are laser transmitters. They provide fast response times, work for a large multitude of fluids, and are precise. Laser level transmitters use the speed of light or refraction to determine the linear position of the object it reflects off of. An example of how a laser transmitter operates can be viewed in Figure 4.7.

As stated before, these are not proposed solutions for the project. These methods are

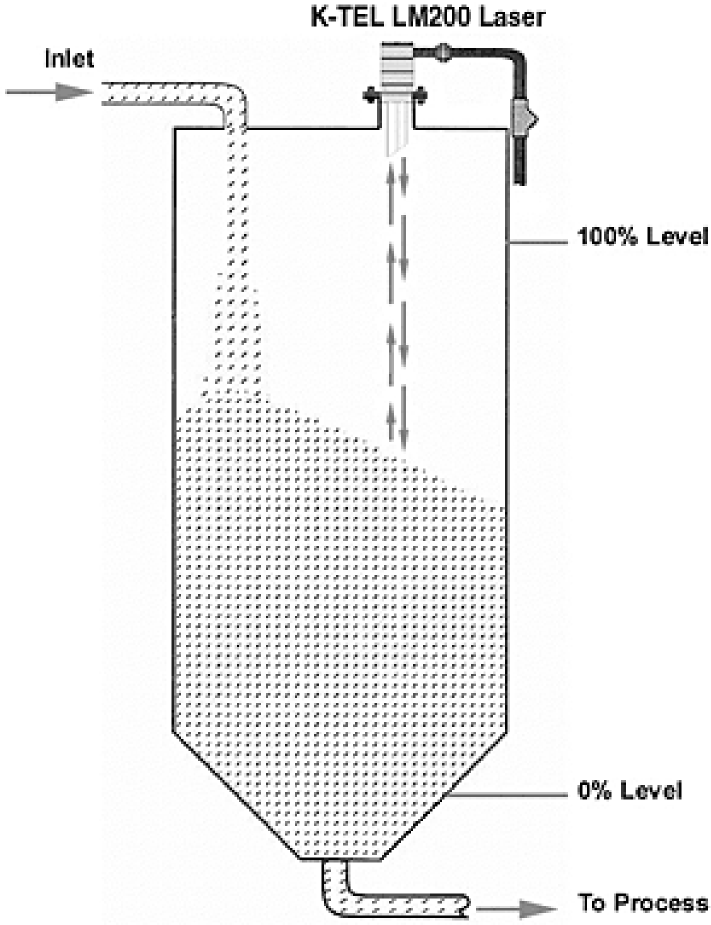


Figure 4.7. – Laser Transmitter Basics (Source: *Sensors Online* [1])

merely representative of the many existing ideas that are used for different volume sensing applications.

4.4. Patent Search

In addition to background research on accumulators and sensors, AVST also conducted a patent search. We found various patents regarding accumulators with one specifically focusing on the idea of using a sensor to determine the amount of fluid within the accumulator. This patent can be viewed by going to the website in reference [2].

5. Requirements

The goals of this project include the design, development, testing, and report of a new accumulator volume sensor which satisfy the specifications discussed in this section.

5.1. Specifications and Quality Function Deployment

The design objective of this project is to consider numerous technologies available in detail, and down-select from them based upon our QFD specifications and requirements. In short, QFD means Quality Function Deployment. QFD is a technique used to identify the needs in a market for a product. This is done using a diagram called House of Quality, where customer needs are prioritized and related to the generated engineering specifications. The House of Quality diagram will hereafter be referred to as a QFD diagram.

To summarize the QFD diagram found in Appendix A.1, our design attempts to improve upon the desirable characteristics of currently implemented solutions. More specifically, we attempted to improve upon the specifications found below in Table 5.1.

Table 5.1. – Engineering Specifications for Accumulator Volume Sensor. Table 5.2 contains a key for the abbreviations used.

Spec. #	Parameter Description	Target	Risk	Compliance
1	Accuracy	$\pm 1\%$	H	A,T
2	Cost	$<$ \$800	H	A
3	Empty Voltage	1-2 V	L	A,T
4	Malfunctioning Voltage	0 V	L	T
5	Max Extension Length	10"	L	A,T
6	Startup Time for Sensor	2 Seconds	M	T
7	Weight	<1.5 lbs	M	A,T
8	Input Voltage Range	10-28 V	L	A,T
9	Output Voltage Range	1-5 or 1-10 V	L	I,T
10	Environment Temperature (vessel)	-40° F to +185° F	H	A
11	# of Sensor Output Channels	1-3	M	A

Areas for improvement of the existing technology include improvement of the accuracy of the sensor, while attempting to keep cost low. Our solution was lower in price to the

Table 5.2. – Key for Table 5.1

Risk		Compliance	
High	H	Analysis	A
Medium	M	Test	T
Low	L	Inspection	I

string potentiometer, while maintaining an accuracy that is comparable to the LVDT (numbers available in Table 5.1). The team would like to note that these two design goals may correlate negatively with each other, so achieving the solution as desired may not be completely possible.

Another improveable characteristic that the QFD highlights in Appendix A.1 is redundancy. Currently, the LVDT incorporates redundancy through the utilization of two sensor channels. This means the same physical measurement is obtained twice by the sensor. The team would like to implement redundancy due to the high safety priority associated with aerospace applications. We have specificied a redundancy specification of 1-3 channels in Table 5.1. Two channels would be most desired if possible due to the conflicting interest of space and redundancy.

The sensor was required to have an adjustable output voltage range according to the specification found in Table 5.1. This range needed to have a calibrated minimum as well as a calibrated maximum. This allowed for a certain variance for the full scale range.

6. Design Development

The design approach used by AVST roughly follows the flow chart found in Appendix A.2. An organized process of brainstorming and concept selection is used to determine the top concept.

6.1. Concept Selection

Over the course of several weeks, the team held numerous brainstorming sessions in order to generate an extensive list of solutions. The favored approach during this time was the brain-writing method. This is a method where team members brainstorm a few ideas, then elaborate on each other's to discover different aspects of a potential design. A complete list of ideas has been compiled into a table shown in Appendix C.3. The ideas in Appendix C.3 have been categorized based on their general underlying principal, listed in the left column with each variation of that concept listed and described separately. Figure 6.1 helps to visualize our concept selection process.

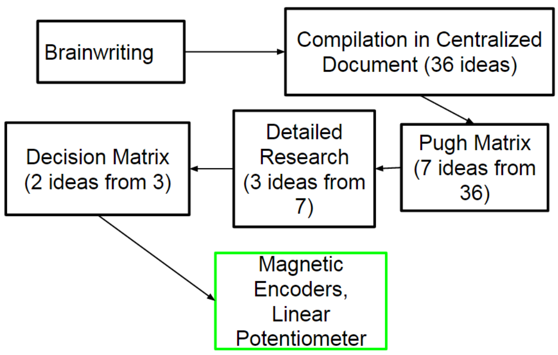


Figure 6.1. – Concept Design Process

With so many ideas to consider, another method was required to narrow down the results. A Pugh matrix was utilized to rank each idea on their ability to satisfy the specifications found in Table 5.1 and the QFD. The Pugh matrix shown in Appendix A.3 has the ideas that were deemed impractical marked orange. Ideas that were plausible and deserved more research were left unmarked. Lastly, ideas that could be combined as a component of other concepts were marked yellow. Note that in this matrix, the specifications were not weighted and thus are evaluated as being equally important. Although that isn't

necessarily true, at this stage the primary objective is to eliminate ideas that are out of reach and provide a starting point on the selection of a top concept.

Ideally, the next step in this process is to use a decision matrix with weighted specifications to once again narrow our list of ideas further. However, with the given nature of this project, more research was required to investigate the feasibility of each choice.

One of the team's more favored idea of using a sonar sensor had to be eliminated due to the spacial constraints of the accumulator. It was found that the minimum distance required for sonar sensing was greater than what the accumulator can accommodate, as seen in Figure 6.2. The detection width of the sonar wave was also too wide to be reliable given the edges and curves within the accumulator.

Portrayed in Figure 6.3, the spring gauge idea was quickly dismissed due to the unreliable prediction on the fatigue of the spring. With insufficient information on the movement and cycles of the piston strokes, too much testing would be required before the design of the spring could be validated. Additionally, the huge range of temperatures would cause the accuracy of the spring to be dubious.

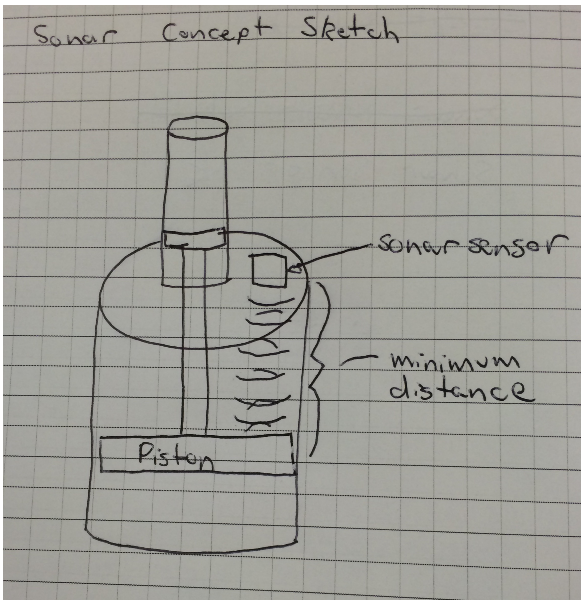


Figure 6.2. – Conceptual Sketch of implementing a sonar sensor in an accumulator.

A simple magnet and magnetometer couple also appeared simple and easily implemented initially, but a magnetometer with the accuracy and resolution fit for use in an accumulator could not be found. Most common magnetometers are intended for either small measurements of minuscule changes in magnetic fields or for large scale changes in the geological magnetic fields of the earth. This solution is depicted in Figure 6.4.

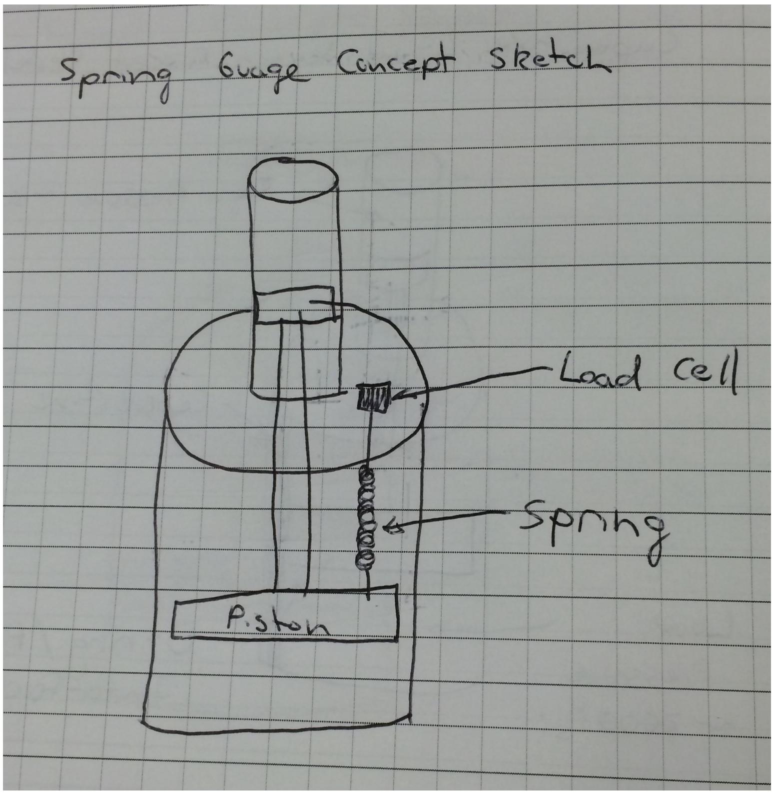


Figure 6.3. – Conceptual Sketch of implementing a Spring Guage

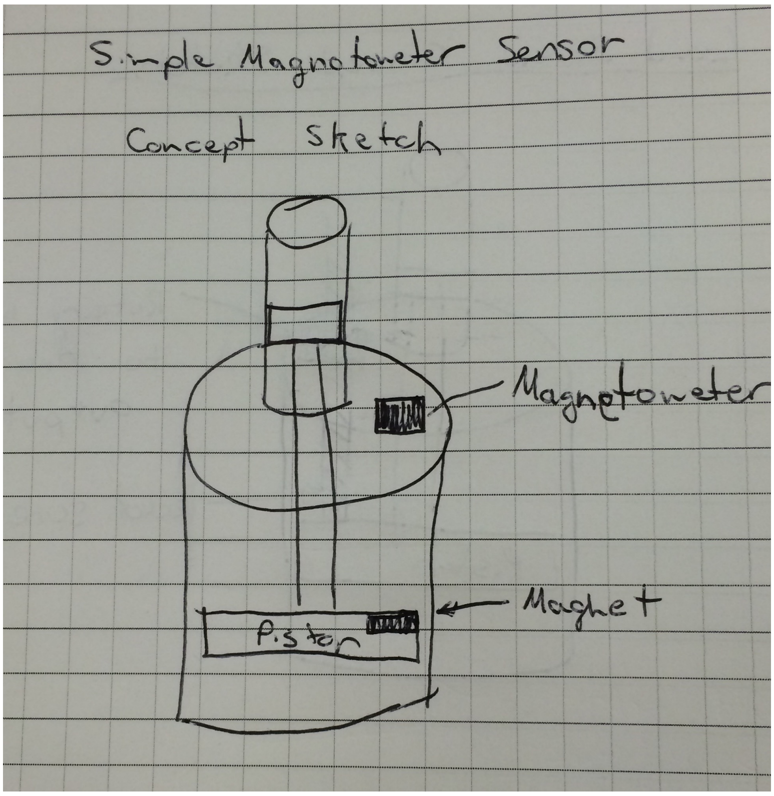


Figure 6.4. – Conceptual Sketch of implementing a Magnet and Magnetometer couple

Capacitive liquid sensors were also researched. AVST found that capacitive liquid sensors can not be implemented easily due to the requirement of contacting the fluid itself. In addition to complications of routing the sensor's wires through the sealed fluid chamber, additional considerations for the high pressures would be needed. This solution is depicted in Figure 6.5

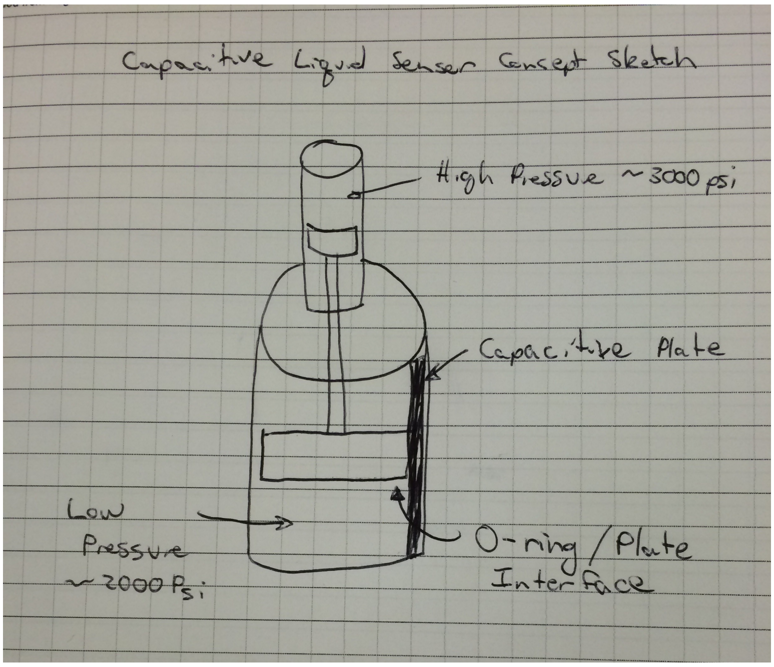


Figure 6.5. – Conceptual Sketch of implementing a Capacitive Liquid Sensor

Another idea that would not be able to be implemented is a lead screw. A lead screw could not be used as it would change the geometry of the accumulator too drastically. A general profile of the accumulator must be maintained to allow for the current transportation and use of the accumulator. This solution is depicted in Figure 6.6

Although some of the choices considered here could be designed and built from their bare components instead of bought as a whole product, the process and cost for the qualification of custom electronics is out of this project's reach. The choices examined here are packaged products with custom mounting/assembly design by AVST.

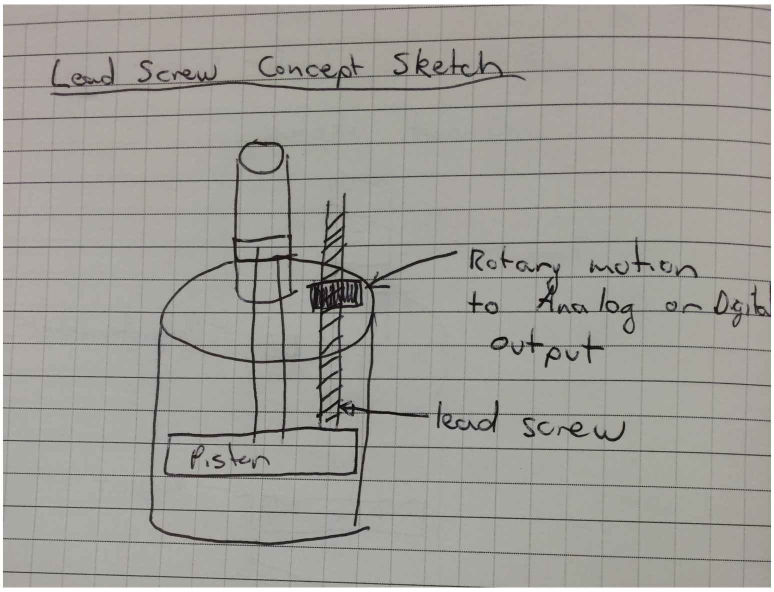


Figure 6.6. – Conceptual Sketch of implementing a Lead Screw

6.2. Decision Matrix

Following the course of the feasibility research, four choices were chosen as top potential designs. These include a refracted laser sensor, magnetic encoder, optical encoder, and linear potentiometer. The decision matrix presented in Appendix A.4 is used to see how each solution fares against each other with weights applied to our previous specifications.

Weights were applied to each specification subjectively, with the values of our sponsor in mind. Cost was weighted the highest as the primary goal of the project is to design a sensor cheaper than PDT's current solutions. Essential to the primary function of any sensor, accuracy was decided as the second most important parameter. Although being a part of our design specifications, the start-up time as well as weight are not vital to the sensor's function and were rated lowest. The remaining criteria were assigned weights based on their importance relative to each other.

While a refractive laser like the one depicted in Figure 6.7 would have outstanding matches to most of our design specifications, its cost was outside of our design parameters. As seen in Appendix C.4, the price of a suitable refractive laser system would cost about $1,900. Despite it's amazing characteristics, being so far out of range for the most important criteria, cost, served its immediate rejection as a potential solution.

Both encoders had similar ratings for each specification, with the exception of the magnetic encoder being much less expensive. From market research into existing encoder products, Table 6.1 provides some quotes for a few encoders along with some notes on their dimensions. The optical encoder was much more expensive than anticipated, almost matching the laser sensor at $1700. On the other hand, some of the magnetic encoders were much cheaper with the LMA10 ($500) and SMAZ ($300) falling within our cost requirement.

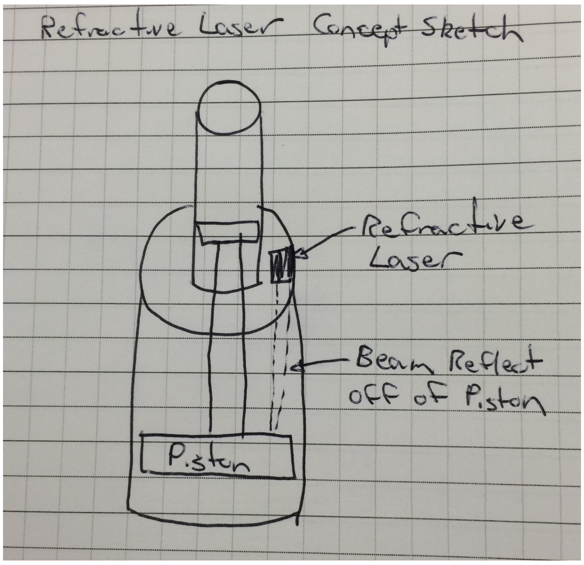


Figure 6.7. – Conceptual Sketch of implementing a Refractive Laser

Table 6.1. – Table of Commerical Encoder Products

Company	Model #	Encoder Readhead + Stripping = Price ($)	Temp Range (F)	Notes
Renishaw	LMA10	521+25 = 546	-4 to 185	Lenth 52mm, scale width 10mm, thickness 1.6mm, gap 0.1-0.6mm
Renishaw (Optical)	Resolute RELA	982 + 780 = 1762	32 to 158	Readhead Length 36mm, no cable interferance
Lika	SMAZ	248+29 = 277	-13 to 185	Readhead Length 82mm
Siko	MSA111C	1318 + 115 = 1433	-22 to 185	readhead lenth 70mm
Siko	MSA501	1123 + 71 = 1194		readhead length 82.6mm

The linear potentiometers were the cheapest option out of all the options, with typical prices ranging from $10 to $100. However, the accuracy is dependent entirely on the wiper size contacting the resistive strip, requiring further dimensional consideration. In order for this design to be sucessful, we had to consider tolerances on the total resistance of the strip as well as the presence of hysteresis in some of the linear potentiometers.

Overall, the conclusions drawn from the decision matrix is largely driven by the cost of each product. The refractive laser as well as optical encoder were far too expensive leaving the linear-pot and magnetic encoder as the final options. After additional discussions and input from PDT, the team has decided to pursue the prototyping of both the magnetic encoder and linear potentiometer.

6.3. Magnetic Encoder

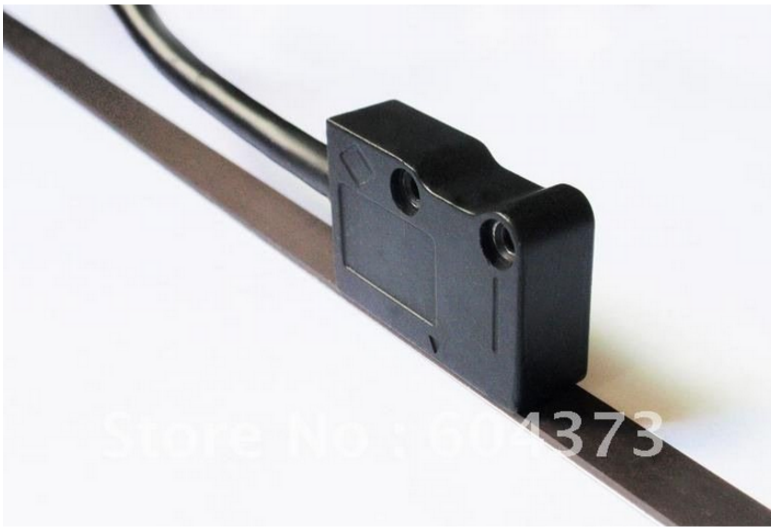


Figure 6.8. – Example of a Magnetic Encoder (Source: *AliExpress* [9])

A linear magnetic encoder (as seen in Figure 6.8) utilizes a magnetic strip with a line of alternating poles attached along the length of the piston. A magnetic sensor called a "readhead" would be mounted stationary next to the piston (within a few millimeters). As the piston moves upwards or downwards, the alternating poles would be detected by the readhead and be output most commonly as a digital signal, although some direct analog solutions exist with programming of the sensor. A readhead is usually a Hall-effect sensor or magnetoresistive sensor. In essence, the presence of a magnetic field generates a change in the voltage across the sensor. This constant reversal of the voltage as the north and south dipoles pass through the sensor generates a sine wave. In order to detect the absolute position of the piston, multiple lines of these alternating poles and sensors would be used in conjunction as seen in Figure 6.9. By overlapping the sine waves, a unique output for each position of the piston is generated. The sensor would be calibrated for accuracy by the manufacturer. The magnetic strip placement would be the most vital portion of the assembly for PDT. Most magnetic encoders would also need a bus analyzer or a digital to analog conversion micro-controller to then obtain the output as an analog voltage.

Current magnetic encoders on the market can reach resolutions of a few microns, well surpassing our accuracy specification. Their usual operating temperature ranges are very

Figure 6.9. – Absolute Magnetic Strip (Source: *Lift-Report* [10])

similar to the range required for the accumulators. The readhead and stripping are commonly sold separately with the stripping priced per length.

While researching the current absolute magnetic encoder systems being sold, the team began to notice a constraint where purchasable solutions are slightly too large to be implemented on PDT's 4024 Bootstrap Accumulator. As seen in Figure 6.10 , there is a size conflict of approximately 0.5 to 1" for most purchasable systems. A partial fix suggested by PDT is to modify the piston guide piece which interferes with the top of the encoder by removing a small section to accommodate the readhead. This allows for approximately an additional 0.5" of space. The design modification of the guide piece is discussed in more detail within Section 7. The remaining interference was left as is, preventing testing of the complete stroke length. Although out of the scope of AVST, PDT has discussed a possible solution of placing additional stoppers between the circumference of the piston and upper half.

6.4. Linear Potentiometer

Multiple forms of linear potentiometers (lin-pot) exist with most functioning on a similar basis to string-pot (discussed in section 4.2). The major difference is instead of a rotational wiper pulled by a string, a linear resistive element is used along with a wiper which slides along a straight path. The particular lin-pots considered for this project are the ones developed by *SpectraSymbol*. These linear pots have a wiper layer, which must be pressed down onto the resistive strip. Much like the magnetic strip, the linear-pot is attached to the piston, with a stationary ball plunger used to press down on the wiper layer. The ball plunger would be in constant contact with the strip as the piston slides along. There is a

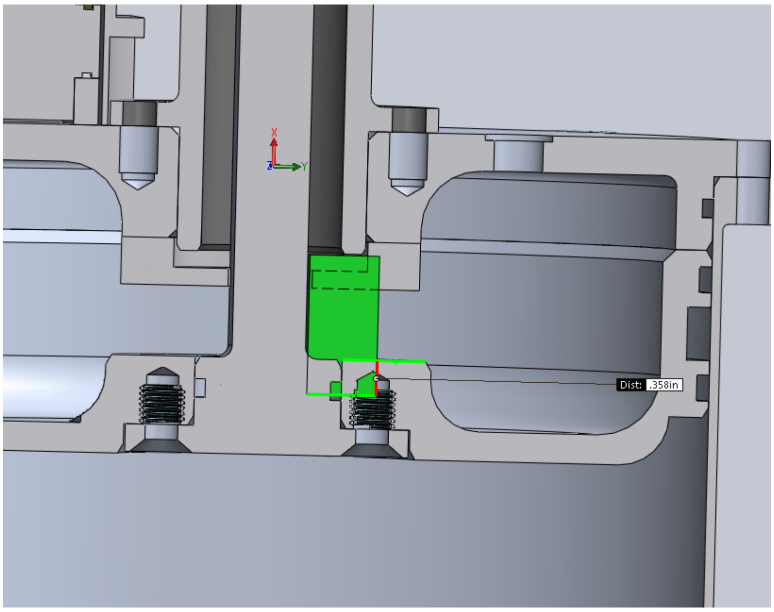


Figure 6.10. – Purchaseable Absolute Magnetic Encoder envelope (green) implemented on PDT's Bootstrap Accumulator 4024 (gray). Note the current interference of dimensions.

rectangular active region that is slightly smaller than the entire physical strip. The ball plunger must be contacting within the active region and not the edge of the strip. The active region can be seen as the inner rectangular shape in Figure 6.11. The force of the plunger connects the wiper layer and the resistive strip together. Depending on where the strip is pressed, the effective resistance the current has flown through changes, allowing the wiper to probe the continuous voltage drop anywhere along the strip. In this configuration of a potentiometer, the output voltage varies based on the location of contact with the plunger. The underlying principle of a linear potentiometer is shown in Fig 6.12.

SpectraSymbol currently offers four different lin-pot designs: HotPot, SoftPot, ThinPot, and MagnetoPot. The first three function on the same basis as described above, requiring a physical ball plunger to push down on the strip. The MagnetoPot uses "internal magnetic attractors" behind the resistive strip to act as the physical wiper. A non-contacting external magnet is used to pull the resistive layer to the wiper layer. Depending on where the external magnet is, the location of where the circuit closes follows and thus varies the resistance and voltage being output. Although this is an attractive concept, the MagnetoPot has a built in hysteresis of over 0.118 inches (over the accuracy specification required). We interpret this hysteresis to mean that a minimum movement of

Figure 6.11. – A Linear Potentiometer Strip (Source: *Trossen Robotics* [17])

0.118 inches must occur before a valid reading can be guaranteed. For applications where 0.118 inches of hysteresis is acceptable, we encourage PDT to consider the MagnetoPot. The MagnetoPot has the promising potential to be mounted external to the accumulator with a strong magnet mounted on the low pressure or high pressure piston circumference, making visual maintenance and interaction with the sensor possible.

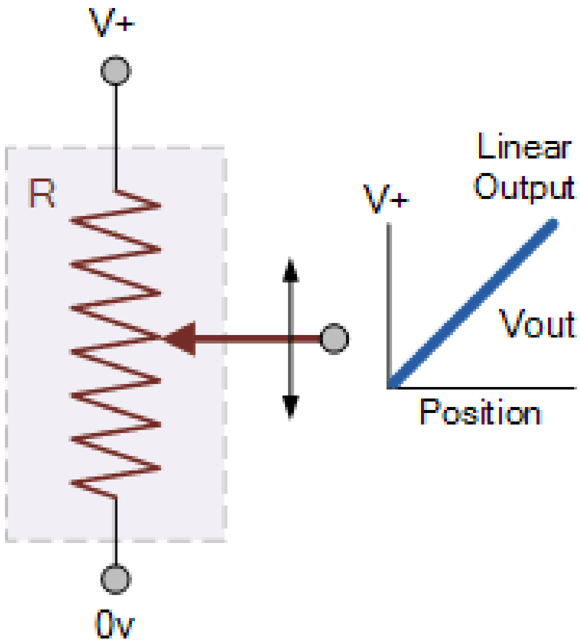


Figure 6.12. – Electrical Diagram of a Linear Potentiometer (Source: *electronics-tutorials* [16])

7. Description of Final Design

As stated in the previous section, AVST pursued the prototyping of both a magnetic encoder and linear potentiometer design. Both solutions involved the purchase of a commercial sensor product in conjunction with the custom design of components utilized to mount each sensor into the 4024 accumulator. In addition to the physical implementation of the solutions, an electronic configuration was created to read and interpret the outputs of each sensor. For the magnetic encoder, this consists of using a micro-controller and integrated circuit to read the digital BiSS-C output. For the linear potentiometer, the same micro-controller was used to read the analog voltage output.

7.1. Renishaw LMA10 Magnetic Encoder

From the magnetic encoders listed in Table 6.1, the team decided to purchase and implement the Renishaw LMA10 due to its balance between size and cost. The corresponding magnetic strip is the AS10 scale which includes a cover foil and adhesive backing. Two different sizes of the AS10 were purchased: 8.3 inches and 10 inches long. The 8.3" strip was implemented into the 4024 accumulator while the 10" strip was used during bench top testing. Table 7.1 summarizes some of the specifications of the LMA10. For more detail, please reference the LMA10 user's manual in Appendix C.5 .

The current 4024 accumulator utilizes a piston guide made out of PEEK plastic in which the square piston slides through the center. The guide is made out of two symmetrical semi-circular halves. The mechanical assembly of the LMA10 includes a custom bracket attaching the LMA10 readhead onto one modified half of the piston guide. The assembly of these three components can be seen in Figure 7.2 and in Appendix B.1. The right half of the guide is the default piece currently used by PDT. The left half, part number 64209-4, is a modified design to allow more room for the encoder. The bracket, part number 64209-5, is also a custom component designed to provide additional structural and stability between the guide and encoder. These three pieces are fastened together using four M3x12 screws. Two screws attach the underside of the bracket (64209-5) to

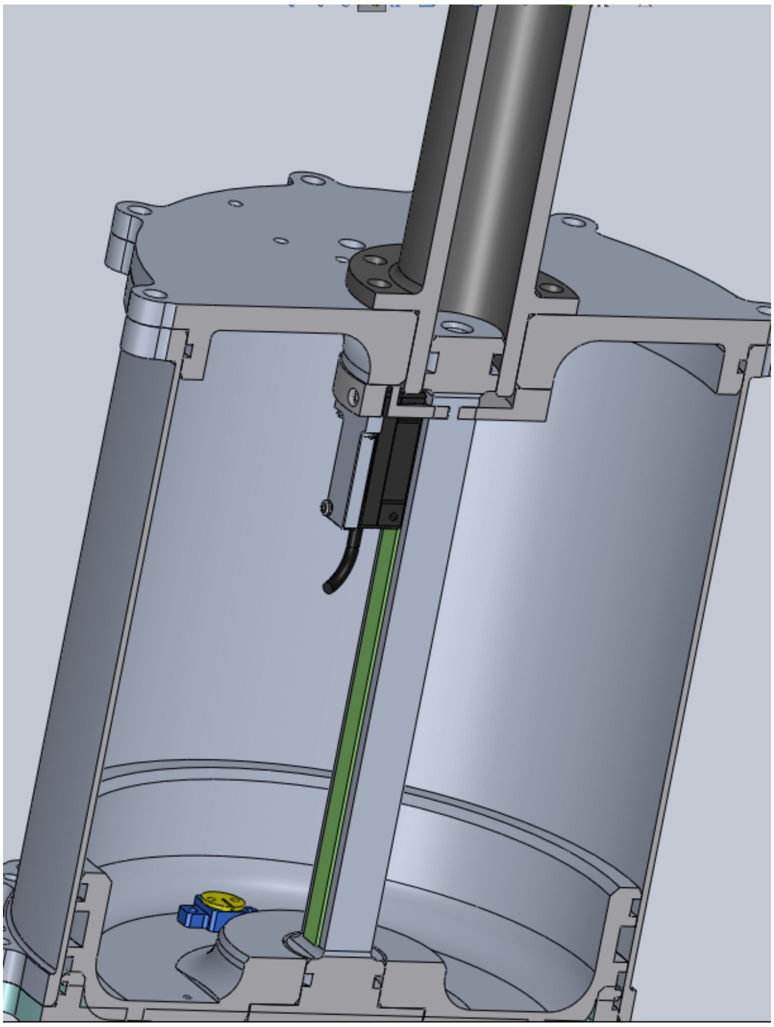


Figure 7.1. – Magnetic Encoder System Implemented into 4024 Accumulator

the guide piece (64209-4), while there are two screws attaching the encoder to the bracket and guide respectively.

The modified half of the piston guide can be seen in more detail in the right of Figure 7.3. Detailed drawings for both the 64209-4 guide and 64209-5 bracket can be found in Appendix B.1.

In Figure 7.4, the inclusion of the piston shaft into the assembly can be seen. The green strip along the shaft is the AS10 magnetic stripping which was attached to the shaft using the adhesive provided by Renishaw. Although end clamps are provided by Renishaw, it would require tapped holes on the piston shaft. Avoiding modification to the shaft itself is preferred as any changes to such a vital component of the accumulator is out of AVST's scope. Instead, the default adhesive backing provided by Renishaw was be used.

Table 7.1. – Specifications for LMA10 Magnetic Encoder (Taken from manufacturer datasheet, Appendix C.5)

Dimensions	2.05 x 0.63 x 0.66 inches
Resolution	0.0003 inches
Output Type	BISS-C
Connector	9 pin D type
Magnetic Scale Dimensions	8.3 x 0.39 x 0.06 inches
Magnetic Scale Accessories	cover foil, back adhesion tape, end clamps
Temperature Range	32 to 131 °F
Weight (readhead+scale)	0.12 lbs
Power Supply	5 V
Setup time after power on	0.250 s
Cable Length	39.4 in
Fastener Holes	M3 Tapped
Gap between readhead and scale	0.0039 to 0.0236 inches

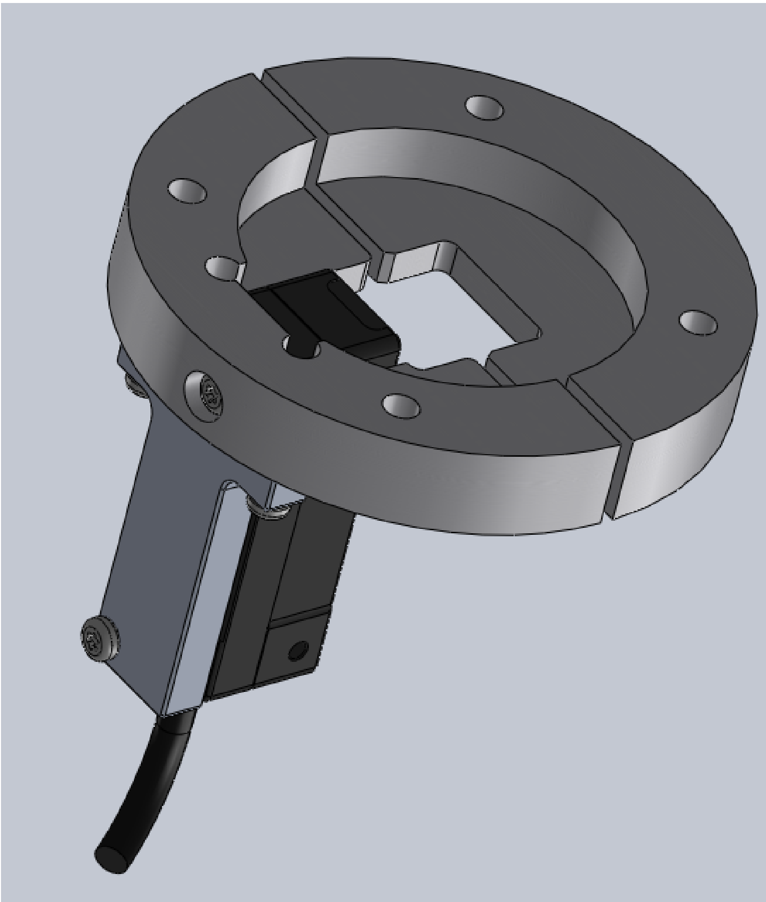


Figure 7.2. – Attachment of the Magnetic readhead onto the piston guide using a custom bracket

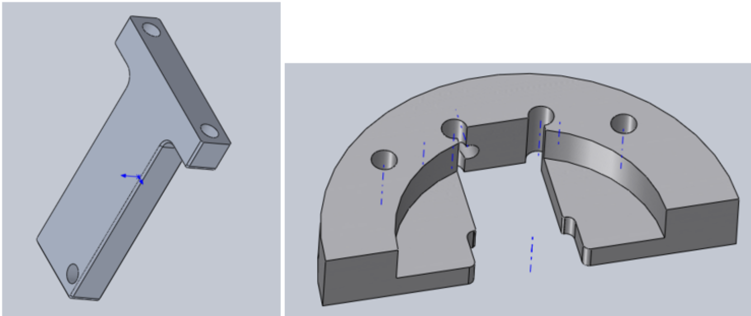


Figure 7.3. – Left: Custom bracket Right: Re-designed half of piston guide

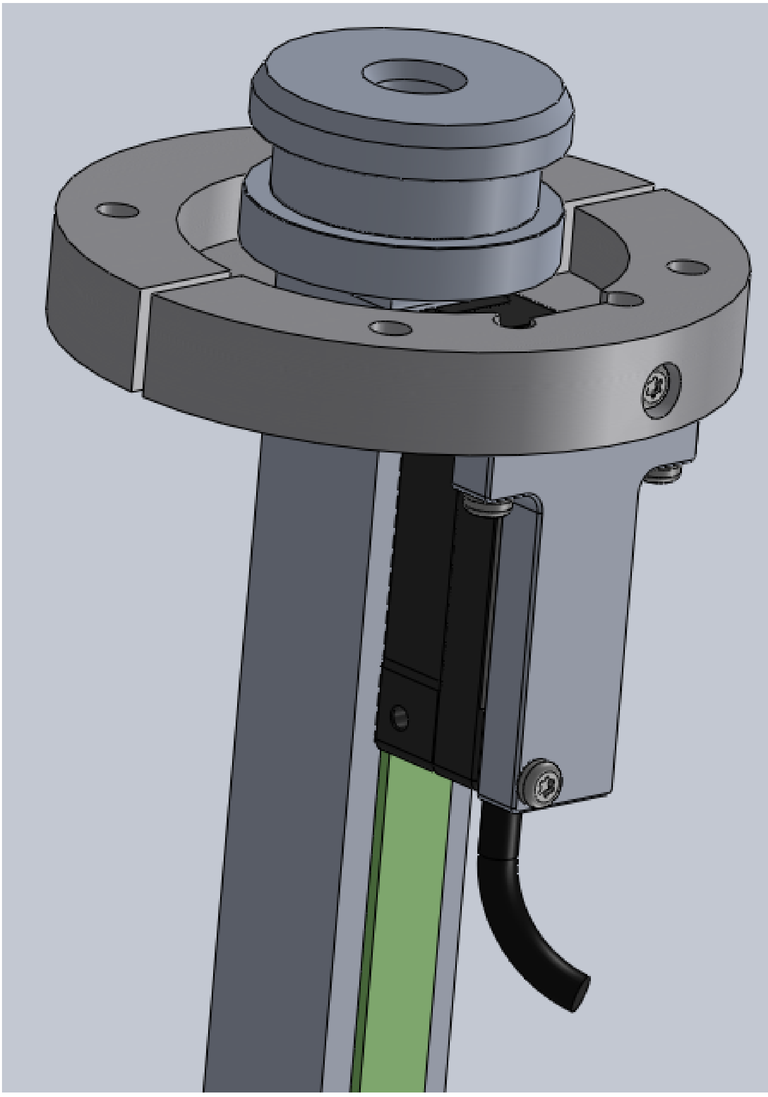


Figure 7.4. – Magnetic Encoder system attached to the piston.

7.2. SpectraSymbol SoftPot Linear Potentiometer

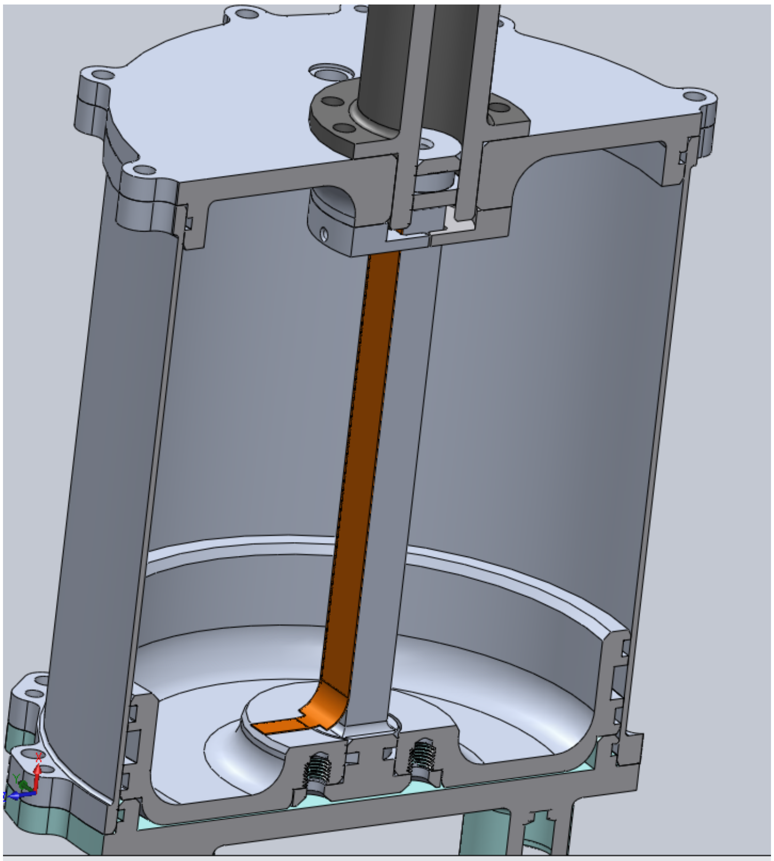


Figure 7.5. – Linear Potentiometer attached to the piston.

The linear potentiometer (lin-pot) implemented into the 4024 accumulator was the HotPot developed by SpectraSymbol. A standard length of 7.87 inches (200 mm) was purchased along with a 0.07" diameter ball plunger. The picture shown depicts a bend at the end of the linear potentiometer due to an excess in length. We inquired the manufacturer about a non-standard length to avoid the bend, but found it would cost upwards of $3000 to customize a lin-pot. (See Appendix C.9). In addition to the HotPot, the alternate SoftPot was purchased for a length of 11.8 inches (300 mm). The SoftPot is not able to withstand as large a temperature range as the HotPot and was only used during the bench top testing phase (see Section 8.1) to validate the accuracy range. Besides the temperature specification, and a slight difference in wiper force required by the ball plunger, the SoftPot is identical to the HotPot. Some specifications for the HotPot design are listed in Table 7.2 with more detail found in Appendix C.6. Note that the range of force required to guarantee wiper contact is dependent on the temperature of operation. The corresponding ball plunger used was a 8-32 thread steel spring plunger with a 0.07"

diameter plastic nose from McMcaster-Carr. The end force of the plunger ranges from 0.5 to 4 N which spans the entire range required by the HotPot.

Table 7.2. – Table of Specifications for the HotPot (taken from the manufacturer's datasheet in Appendix C.6).

Base Dimensions	8.5 x 0.8 x 0.018 inches
Tail Dimensions	0.5 x 0.4 x 0.018 inches
Active Region	7.87 x 0.28 inches
Nominal Total Resistance	10 KOhm +/- 20%
Ind. Linearity	1%
Connectors	Female Receptacles w/ plain housing
Temperature Range	-40 to 185 °F
Accuracy	Theoretically infinite. Dependent on wiper contact area.
Power rating	1 W max. (recommended < 0.5 W)
Wiper Force Required	-40 °F 3.0 to 5.0 N
	-25 °F 2.0 to 5.0 N
	23 °F 0.8 to 2.0 N
	85 °F 0.7 to 1.8 N

As seen in Figure 7.5, the HotPot fits into the accumulator much like the magnetic encoder strip, using adhesive to join the strip to the piston. The major difference is that no readhead is required. Instead, a ball plunger was be placed into the piston guide piece. This can be seen in Figure 7.6.

One half of piston guide piece was be modified again to accommodate the ball plunger. The modified half can be seen in Figure 7.7 with detailed drawings available in Appendix B.2

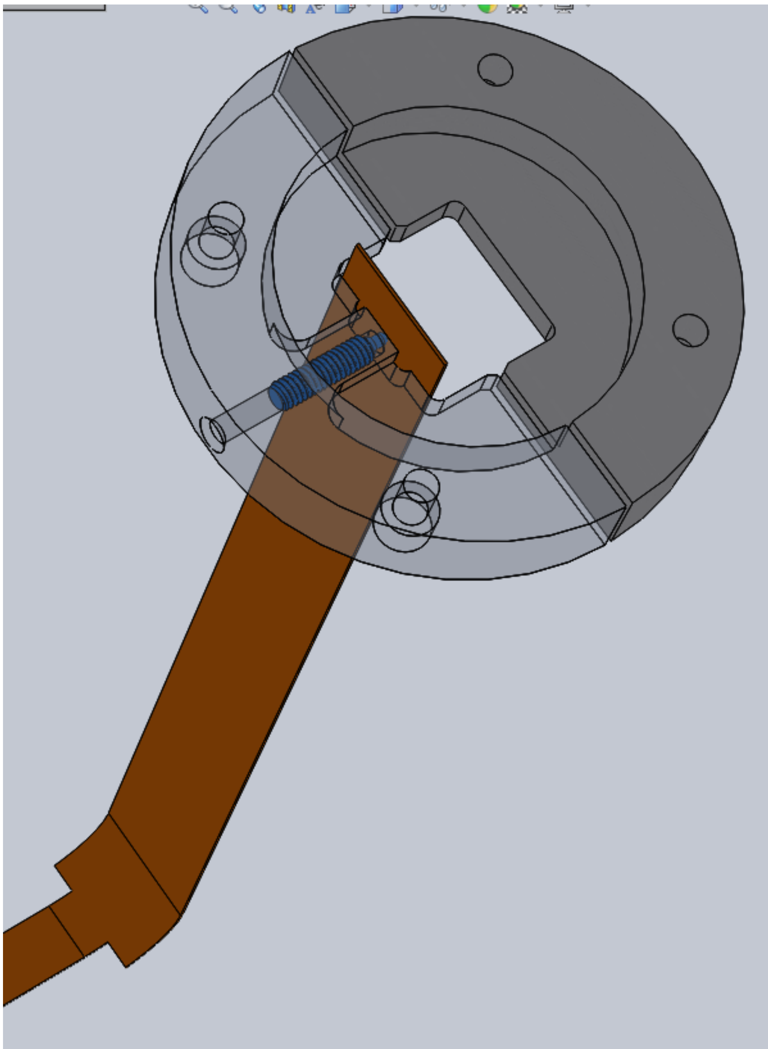


Figure 7.6. – Assembly of the ball plunger within the piston guide piece while in contact with the HotPot.

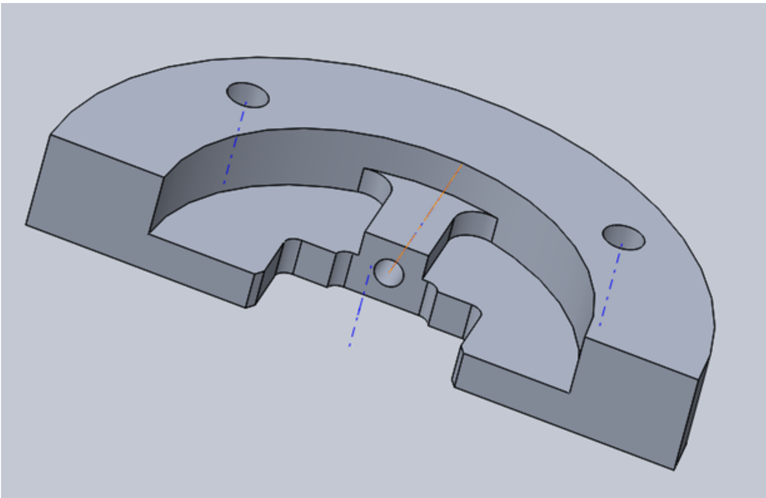


Figure 7.7. – Modified half of piston guide to allow for attachment of ball plunger.

7.3. Design Analysis

7.3.1. Tolerancing

To ensure that our design operated within the desired specifications and to address topics presented in the Failure Mode Effects Analysis (Appendix D.1 and Appendix D.2) we conducted a few case studies. For the magnetic encoder, case studies regarding tolerance of our custom part design were performed (see Appendix D.5). We observed assembly CAD models to ensure that the assembly would fit within the mounting parameters presented in the encoder installation guide (see Appendix C.5). A similar strategy was taken for the linear potentiometer. Information regarding the tolerance case studies for the linear potentiometer can be found in Appendix D.6 and Appendix C.6.

7.3.2. Encoder Deflection

Initially both the sponsor and the team expressed concern that the beam-like encoder support (part number 64209-5 see in Appendix B.1) would need additional support as to avoid deflection that results in the encoder falling outside of the tolerance presented in the installation guide. However upon rudimentary FEA using solid works (shown in Figure 7.8), we determined that this should not be an issue within the accumulator. We also did a simple beam deflection calculation, as seen in Appendix D.4, to back up the FEA analysis.

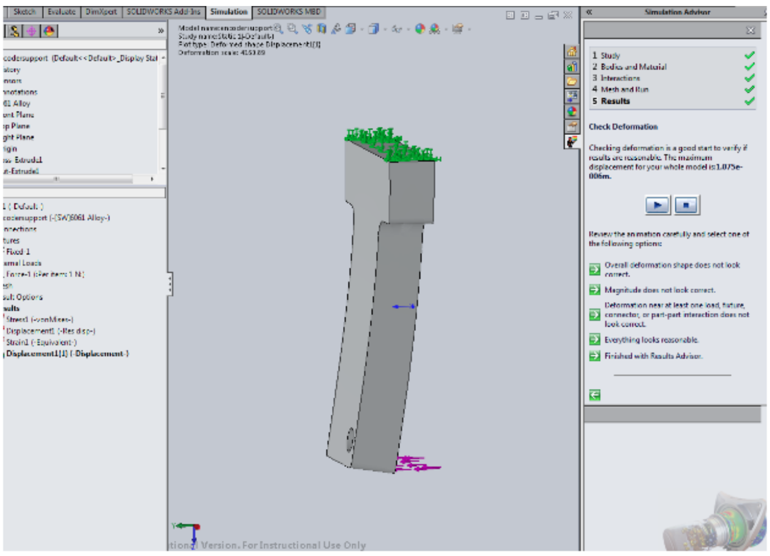


Figure 7.8. – Rudimentary Encoder Support (64209-5) Deflection FEA using Solidworks FEA

7.3.3. Signal Processing

Both the encoder and the linear potentiometer designs require forethought into how the signal from each can be obtained and processed. For the encoder, the datasheet (Appendix C.5) specifies that a digital communication protocol called BiSS-C is used. For the the linear potentiometer, the signal is purely analog. For the scope of this project, time was spent considering how the signal can be taken from the sensors, and processed/adjusted to be output within specifications laid out in Table 5.1.

7.3.4. Encoder output

For the LMA10 encoder, the open source protocol called BiSS-C is used in a unidirectional configuration. BiSS-C stands for Bidirectional Synchronous Serial - Continuous. This output consists of a serial clock (MA(+/-)) and a serial data line (SLO(+/-)). Specifications for receiving the signal from the encoder can be found in the datasheet (Appendix C.5) as well as on the BiSS-C protocol website. Depending on the option chosen, this output type may need to be investigated more thoroughly.

It is important to note that PDT had stated that they are not concerned with how the output of the encoder is obtained, and that it should function mostly as a proof of concept. Thus, the two options shown in Table 7.3 consist of either a bus analyzer or a micro-controller. Figure 7.9 shows the proposed scheme for either option. Preparing the chosen option for the output of the encoder was done during the manufacturing stage, and was further iterated to faultlessness during the testing stage.

Table 7.3. – The two options available for obtaining the encoder output.

Option	**Cost**	**Analog Output**
Arduino Micro-controller	$\approx$ \$30	Yes
Saleae Logic 8 Bus analyzer	$\approx$ \$225	No

An Arduino micro-controller allows the chance to output a 1-5v signal as originally specified in Table 5.1. However, the downfall of the micro-controller approach is that it required custom code to be written to take the BiSS-C output and translate it to an analog output. PDT has expressed concern about any code written for the project, due

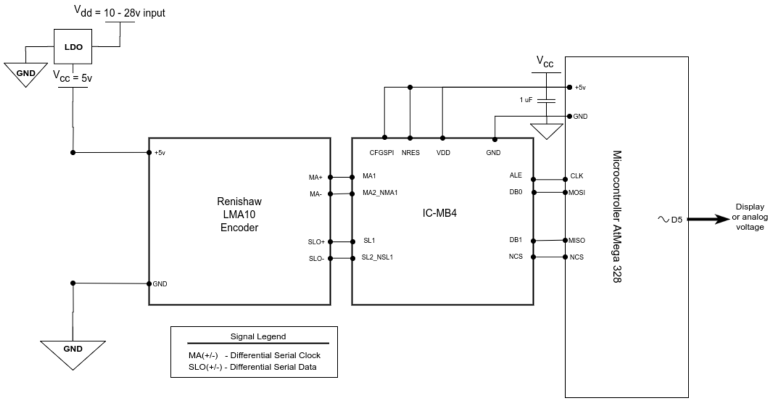


Figure 7.9. – Proposed scheme for obtaining the output of the encoder signal (Enlarge version shown in Appendix D.8)

to certification requirements for the aerospace application. It is worth noting that the design findings and code written in this report and project serve only as a proof of concept, and that perhaps a certified company should be subcontracted to write micro-controller code should the encoder be implemented in the production of the 4024 accumulator.

The alternative to programming a micro-controller is using a bus logic analyzer. This is the equivalent of using a multimeter to get the output of an analog signal's voltage, but in a digital context. The bus logic analyzer suggested by the BiSS-C website is the product made by Saleae. This bus analyzer is a tool for determining what the output of the encoder is during testing, and should not be a permanent solution. If PDT chooses this as the preferred method, then no code will be written and the solution will only be suitable as a proof of concept. The logic analyzer cannot output an analog voltage similar to a micro-controller, and will only display the data that is on the serial data line (or the position reading from the encoder). In this regard, it is similar to a multimeter, and is not remotely close to a production solution for PDT. This solution should only be pursued if a quick method of getting the output of the encoder is needed, and proof of concept is the only concern.

The ideal solution that an engineer would choose for this project would be to use the logic analyzer to obtain an output from the encoder that is known to be correct, and validate the output of micro-controller code against it. This is the approach AVST pursued. We ultimately used the micro-controller as our primary reading (see Appendix D.9 and D.10

for design details) with the logic analyzer used during development for debugging and as a backup check against the readings interpreted by the micro-controller.

7.3.5. Linear Potentiometer Output

The output of the linear potentiometer can be obtained through the use of a voltage divider circuit. This circuit is shown in Figure 7.10. The calculations justifying the choice of resistance values and usage of op-amps are shown and explained in detail in Appendix D.7. The resistance values were tuned by math and plotting the output voltage in MATLAB. From there, numerous resistance values were varied methodically until a trend was seen in how the adjustment of a resistance value effected the output voltage of the circuit. With the tuned resistance values, this circuit ensures the output of 1-10v specified in Table 5.1 is achieved.

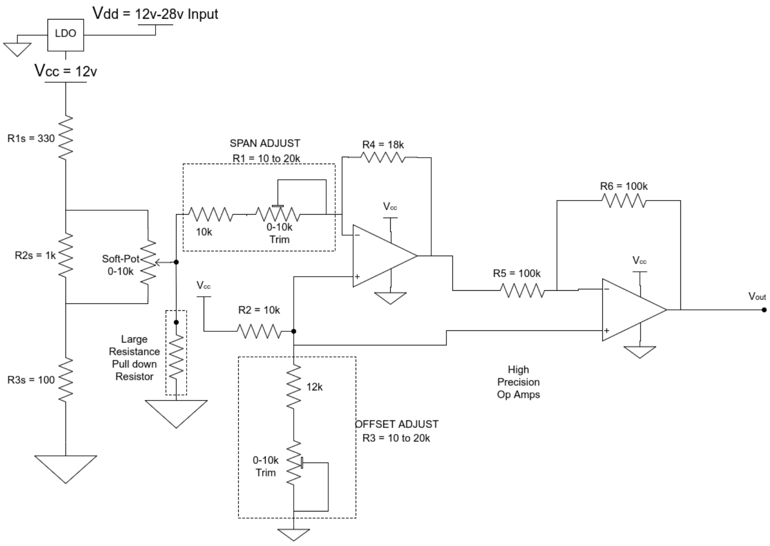


Figure 7.10. – Proposed circuit for obtaining the position output of the linear potentiometer, as well as perform adjustments for offset and span on it.

The voltage divider circuit was constructed such that a 0.89V to 9.04V output range is obtained from the linear potentiometer's wiper. Directly after the wiper voltage is a signal adjustment op-amp circuit that provides an offset and a span adjustment for the signal so that it can be tuned into the 1-10 V range. Figure 7.11 and 7.12 show how the output of the signal varies as the trim pots for span and offset are varied. Much of the design effort in this portion of the project went to making these curves as linear as possible. The voltage output function derived in Appendix D.7 shows that these adjust-

ments are hyperbolic in nature, but R_2 and R_4 were chosen in order for the curves to flatten out. Also note that in Figure 7.11 the span adjustment on the 1 V output line is relatively flat. This is preferable because it minimizes the repeating cycle of tuning offset, then tuning span, then returning to tune offset again etc.

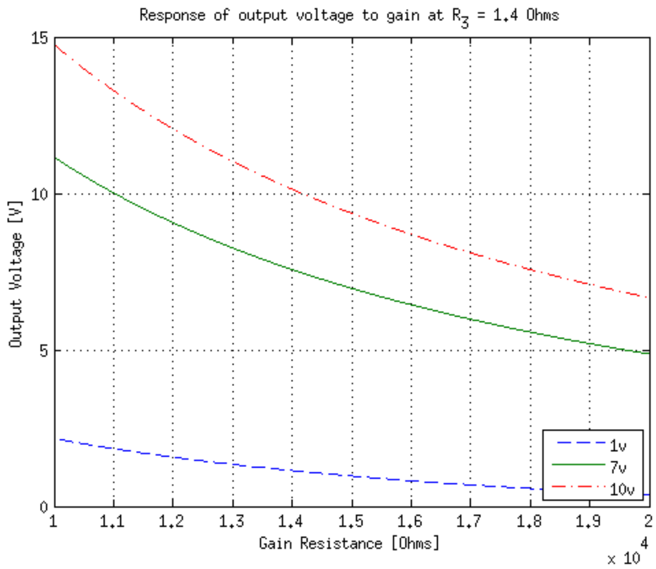


Figure 7.11. – Result of the span adjustment for voltage inputs of 1V, 7V, and 10V.

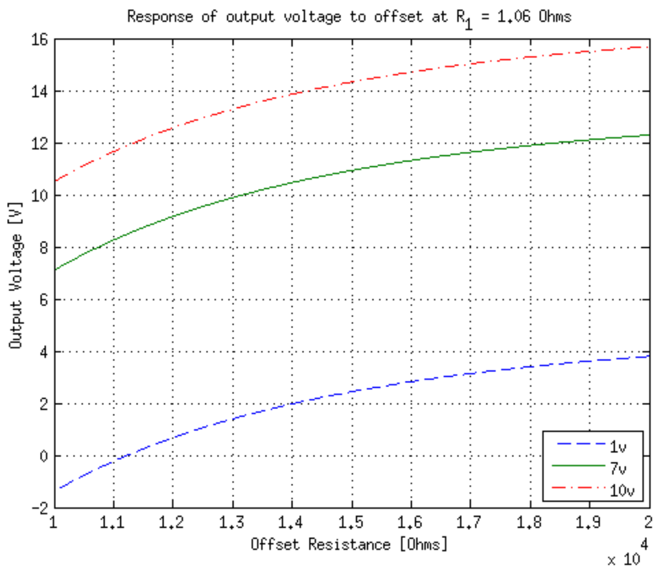


Figure 7.12. – Result of the offset adjustment for voltage inputs of 1V, 7V, and 10V.

If the span adjustment and the offset adjustments do not allow a satisfactory range of adjustment, then R_4 or the fixed resistor in R_3 can be swapped out for a different resis-

tance value, supplying a larger or smaller range of offset and span. The most practical resistor to change would be to the fixed resistor (not the trim pot) in R_3, making it a slightly lower value than 10k.

Also worth noting is that the circuit was designed so that 0V is not a valid output (as specified in Table 5.1). However, a 0V output does occur when the ball plunger loses contact with the linear potentiometer, indicating that the sensor has been compromised and a fault exists. If the plunger strays outside of the active area on the linear potentiometer, this 0V output may also occur. Care was taken in the mechanical design to ensure the tolerances do not allow this to happen.

Although the entirely analog circuit/output of the linear potentiometer is preferable as the ultimate solution for PDT, due to time constraints, AVST used a micro-controller to read the analog signal and output it in digital format (see Appendix D.9 and D.10 for design details). An added convenience is the possibility of handling both the encoder and potentiometer output simultaneously using the same micro-controller. If digital circuitry is an issue for future implementation, we recommend that PDT pursue the analog circuit shown in Figure 7.10 which provides the adjustments desired for this sensor to be implemented into the production of the 4024 accumulator.

7.3.6. Prototype Read Out Box

To gain the readouts of both sensors during testing, a final circuit was designed to allow the linear potentiometer and encoder readings to quickly be switched between and referenced. This design is shown in Appendix D.9. A black project enclosure box was used to encapsulate this circuit, and hold the 7 segment display seen in Figure 7.13.

A significant amount of code was also written for the prototype read out box. This code translated the encoder binary readings into inch equivalents. It also performed a conversion to inches for the voltage obtained from the linear potentiometer. A large amount of the code written is original and included in Appendix D.10. Explanation and documentation for the use of the code is included within it as comments.

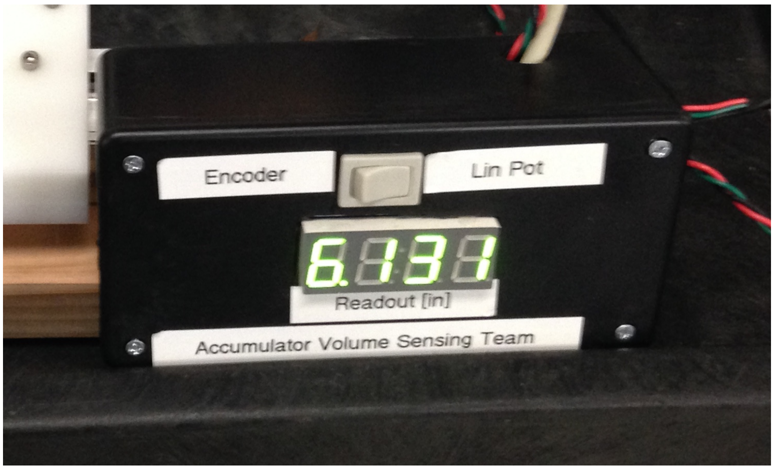


Figure 7.13. – Position Sensor Readout used for testing.

7.4. Cost

Table 7.4 summarizes the monetary cost of the entire project. Refer to Appendix C.7, C.8, C.10, and C.11 for details on quotes and order information.

Table 7.4. – Total cost of AVST's final designs

Renishaw Encoder Package	Please see Order Sheet	629.52
Digikey Linear Potentiometers	Please see Order Sheet	42.85
Adruino Microcontroller	Arduino Uno Rev3	34
Salae Logic Analyzer	Saleae Logic 8	230
Velmex Linear Slider	A1512A-S15	141
McMaster-Carr Material and Mechanical Components	Please See Order Sheet	247.43
Mouser Schmart Boards	204-0025-011 (1) 204-0017-01 (1)	17.95
Symmetry Integrated Circuit Chips	iC-MB4 TSSOP24 (1) iC-MB4 QFN28-5x5 (2) iC-HF QFN32-5x5 (2)	38.23
Amazon LED Display	Adafruit 0.56" 4-digit 7-segment display w/I2C Backpack-Green	13.49
Travel (two trips)	-	216
	Total	1610.47

7.5. Safety

During the design process, AVST has been mindful of potential safety concerns, concluding that there have not been any aspects of our design requiring special safety considerations. To ensure that we did not overlook any potential hazards, we completed a safety check list (shown in Appendix C.2). Additionally, we consulted with our advisor, Professor Rossman, to get an unbiased hardware review further confirming the absence of potential hazards.

7.6. Operation and Maintenance

7.6.1. Magnetic Encoder

Due to the non-contact nature of the magnetic encoder, there should not be a need for any heavy inspection or maintenance throughout its use. The most significant concern is the position of the encoder's cable. As currently oriented and designed, the low pressure piston of the 4024 accumulator may push into the encoder cable. This can cause wear on it over many repetitive collisions.

Although the current design leaves the cable hanging freely within the vented chamber, for future development, adjustments might include placing ring shaped bumpers attached to the circumference of the low pressure piston to avoid collision with the cable. If there was functionality failure of the magnetic encoder system, the accumulator would need to be disassembled for realignment, replacement, or any other action requiring access to the readhead.

7.6.2. Linear Potentiometer

Unlike the magnetic encoder, the linear potentiometer requires direct contact for operation. This may cause wear on the potentiometer strip or plunger which would require a periodic inspection. The manufacturer states a life cycle specification of over 10 million drags across the surface (See Appendix C.6). For the purposes of this project, AVST does not plan to encapsulate additional lifetime analysis due to time and resource constraints. Further information regarding the typical motion history of an accumulator would be required for any life-time estimates of the proposed sensors. For future implementation on an accumulator, analysis on the fatigue and wear of a linear potentiometer should be conducted to determine the level of maintenance and inspection necessary.

8. Design Verification

Once the manufacturing and assembly of the project was finished, AVST tested our sensors to the design specifications listed in Table 5.1. The testing was done according to our Design Verification Plan and Report (DVPR) as seen in Appendix D.3. The DVPR describes each specification and how they were verified according to an applicable acceptance criteria. We have split our testing into two different phases, accuracy testing on the benchtop assembly and implementation testing into the 4024 accumulator at PDT.

8.1. Bench Top Testing

In order to verify the functionality as well as electronically calibrate both sensors, the bench top testing fixture seen in Figure 8.2 was be used. The main component of this fixture is a purchased Velmex A15 Unislide. The linear slider is manually driven with a 10.5" travel distance. In order to test both sensors, the custom bracket seen in Figure 8.1 was manufactured as described in Chapter 9.

The Velmex slider provides precise, rigid and linear movement of the test subjects. Alternatives to this function would be extremely expensive machinery such as a motorized positioning stage, or a graduated adjustment slider that is on the price order of $300-$700. We decided to cut cost by using a free slider and verifying distance measurements of the test subjects by using calipers. After verifying the magnetic encoder with calipers, we proceeded to use the magnetic encoder as a baseline for the remainder of testing. The Velmex free slider was quoted at $141 as seen in Appendix C.10. However, we have found the same model on eBay for much less and have accounted for that in the development of our cost analysis in Table 7.4.

The bracket is fastened to the slider component with two #6-32 0.75" long screws. Attached to the bracket was both the LMA10 encoder and ball plunger. The encoder is fastened using two M3x30 stainless steel socket head cap screws and the ball plunger was threaded a desired distance to apply a force to the linear potentiometer. A more detailed

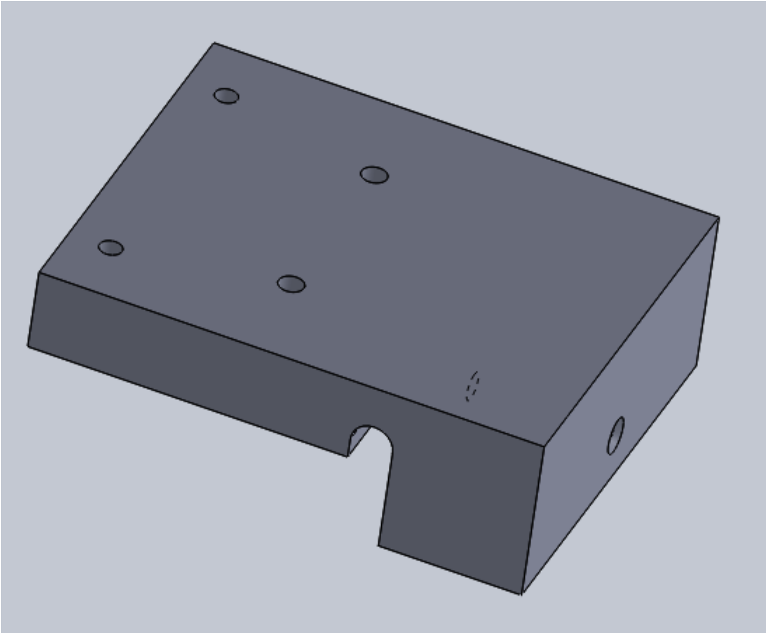


Figure 8.1. – Bracket used in bench top testing fixture.

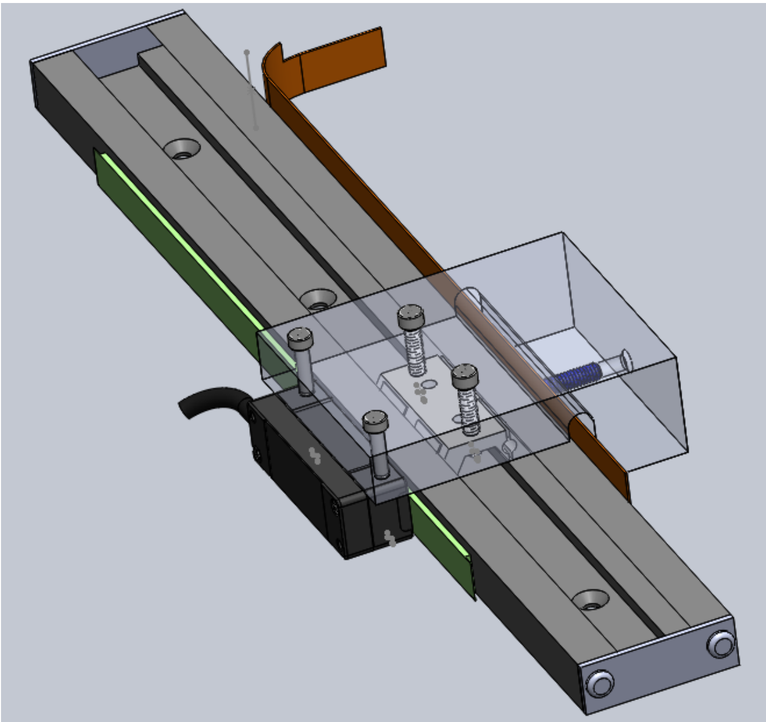


Figure 8.2. – Benchtop Test Fixture Assembly CAD

layout with part numbers, dimensions, etc can be found in Appendix B.3.

8.2. Encoder Alignment Tolerances

Using the bench top test rig, a majority of the tests described in our DVPR (found in Appendix D.3) was conducted. One of these include alignment testing of the magnetic

encoder. The data sheet claims sensitive tolerances to changes in pitch, yaw, and roll (Appendix C.5) of the encoder with respect to the magnetic strip. However, through our benchtop assembly we found that the magnetic encoder was still functional even past the tolerances shown in Figure 8.3. This is verified by the encoder's LED remaining green, signaling a valid sensor reading. Furthermore, we found the rough approximate limits of the angle tolerances highlighted red in Figure 8.3. These tests were done using feeler gauges to offset the encoder by a certain angle on one side until the encoder's LED toggled from green to red signaling an invalid reading. Although the test setup did not allow for a lot of precision, the order of our determined angle tolerances imply a much more forgiving misalignment than specified in the data sheet.

It should be noted that although the reading was still valid when slightly misaligned, the accuracy might have suffered. In order to gain a full understanding of the accuracy vs misalignment, further testing with a more precise setup is recommended. However, AVST believes that the reduced accuracy due to slight misalignment is negligible in this application due to the fact that the encoder is much more accurate than necessary.

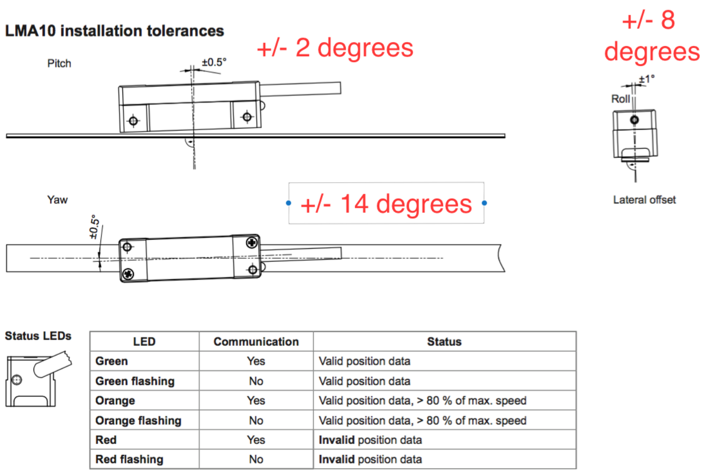


Figure 8.3. – Re-established Magnetic Encoder Installation Tolerances

8.3. Accumulator Testing at PDT

Aside from testing our linear potentiometer and magnetic encoder on the bench top assembly described in Section 8.1, the second phase of testing included taking the hardware to PDT's facility to verify their implementation within the 4024 accumulator as previously displayed in Figure 7.1. The on-site testing was conducted in a single day on November 1, 2016, as seen in 8.4.

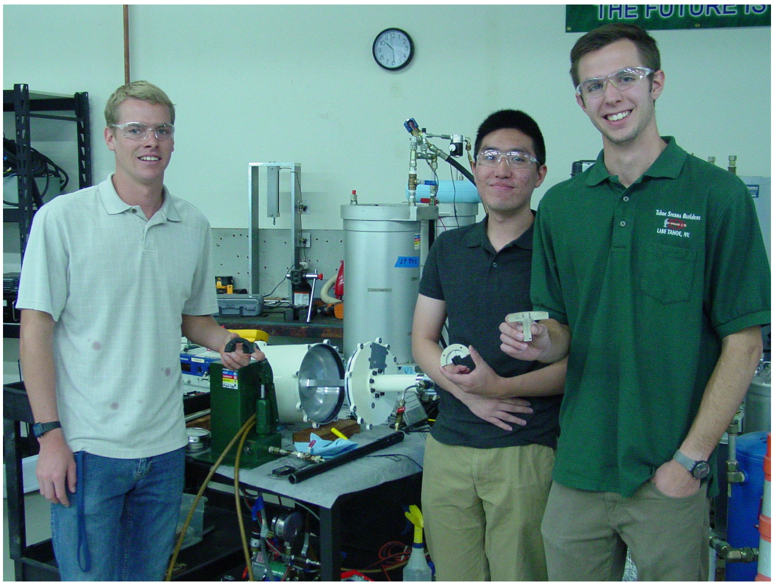


Figure 8.4. – AVST with testing Equipment at PDT.

The assembly of the accumulator and sensor parts proceeded without any anomalies. The mounting of the sensors into the accumulator went smoothly in accordance with the drawings in Appendix B.2, Appendix B.1, Figure 7.1, and Figure 7.5. Figure 8.5 shows the final assembly of the sensors within the 4024 accumulator.

Once the sensors were implemented into 4024 accumulator, we ran a one direction test by increasing pressure on the high pressure side of the accumulator. As the piston moved, we took position measurements of both sensors and compared them against caliper measurements. Results of this test can be viewed in Figure 8.6. The results verify that the sensors are mechanically functional within the accumulator. As expected, we were unable to push the low pressure piston head to the the top of the accumulator without it colliding into the encoder readhead. This limited our testing to only one direction with the piston going from the high pressure to low pressure side. Reviewing the results shown in Figure 8.6, AVST concluded that tests on the benchtop tester would be more appropriate for

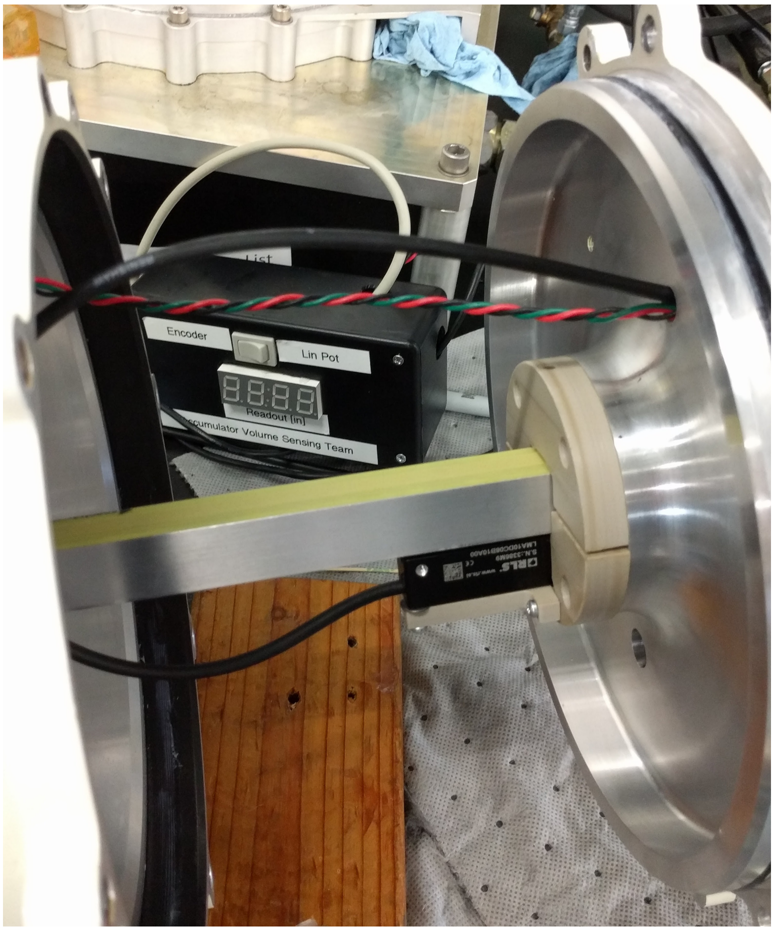


Figure 8.5. – Posistion Sensors Integrated onto the 4024 accumulater at PDT

determining the percent uncertainty of the sensors.

Unfortunately, we were unable to perform life-cycle fatigue test or temperature tests on each sensor. The linear potentiometer has the potential to change resistance at varying temperatures, so further testing should be conducted to determine temperature effects on the accuracy of the sensor. Temperature testing would also be helpful in the verification of the adhesive used to attach both strips to the piston. The ball plunger of the linear potentiometer design also has the possibility of failure over large cycles of piston movements. Due to a lack of time, we can only use the data sheet's specifications as our verification of whether these design requirements are met.

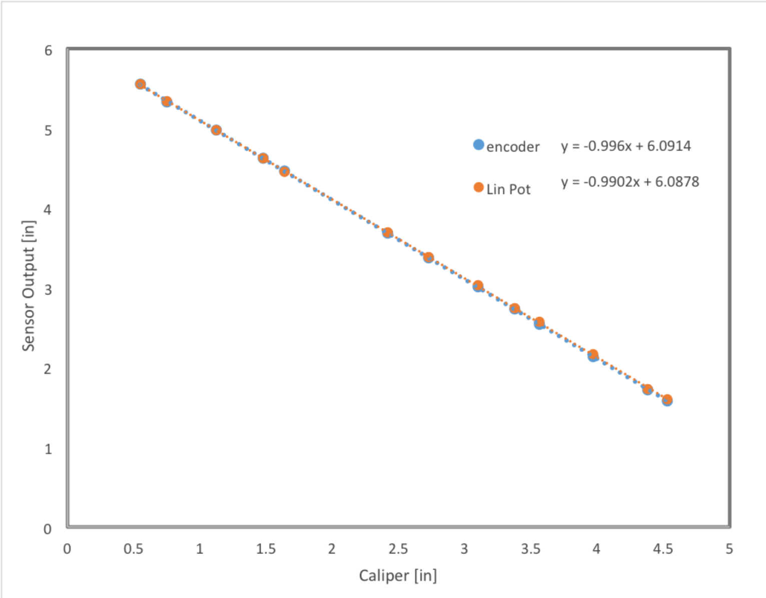


Figure 8.6. – Testing data collected at PDT on November 1, 2016

8.4. Uncertainty Testing

In order to obtain a better understanding of the actual percent full-scale uncertainty of the sensors, test data from the bench top test unit were used. Through the collection of 100 data points, a relatively large population, we were able to conclude a percent uncertainty of +/- 0.65% full-scale for the linear potentiometer. Since the Magnetic Encoder was more accurate than the calipers we were attempting to use as a base line, we decided to stick with the manufacturers claim of +/-.0000011% full scale. The encoder uncertainty is derived from the 40 micrometers stated in the datasheet (Appendix C.5).

After gathering the data seen in Appendix C.12 and in Figure 8.7, uncertainty analysis was performed using equation 7.11 of the ME 236 Course pack (see Reference [18]). The position data is graphed in Figure 8.7, in conjunction with the ideal linear curve fit. Processing further, we determined the residuals (error from ideal case) seen in Figure 8.8. Looking at Figure 8.8 we can conclude that the largest error is about .060 which corresponds to +/- 0.65% of full scale stroke length.

Due to the occurrence of a trend in the residuals plot, we decided that a first order curve fit (of Fig 8.7) was was not appropriate for our testing apparatus (since the population is not randomly dispersed). The plot of the residuals with a third order curve fit instead is shown in Figure 8.9 showing a much more even (random) distribution of data as desired.

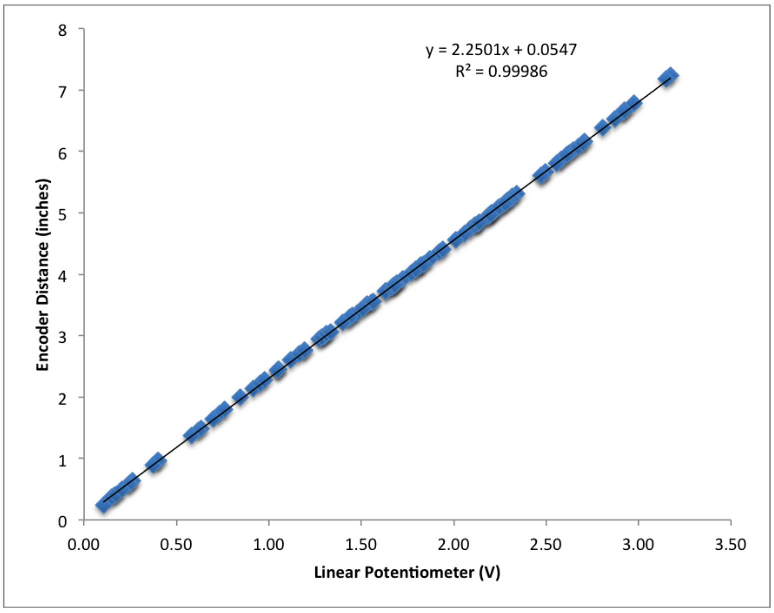


Figure 8.7. – Plot of the linear potentiometer and magnetic encoder response on the benchtop tester used to determine linear potentiometer percent uncertainty.

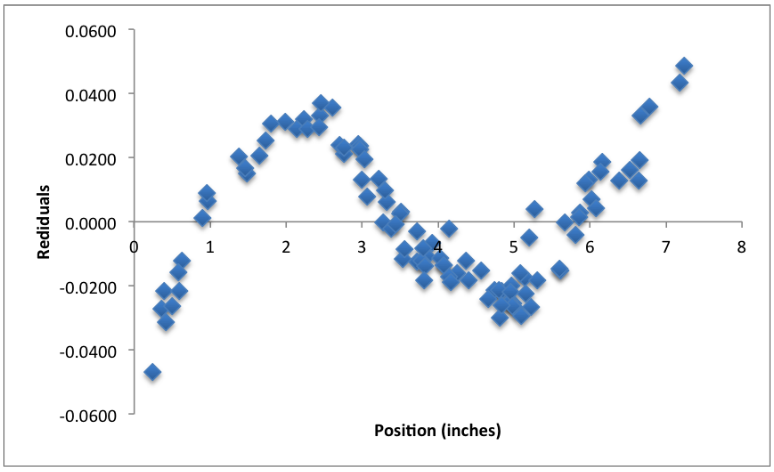


Figure 8.8. – Plot of the residuals for the linear curve fit of the linear potentiometer using the magnetic encoder as a base line.

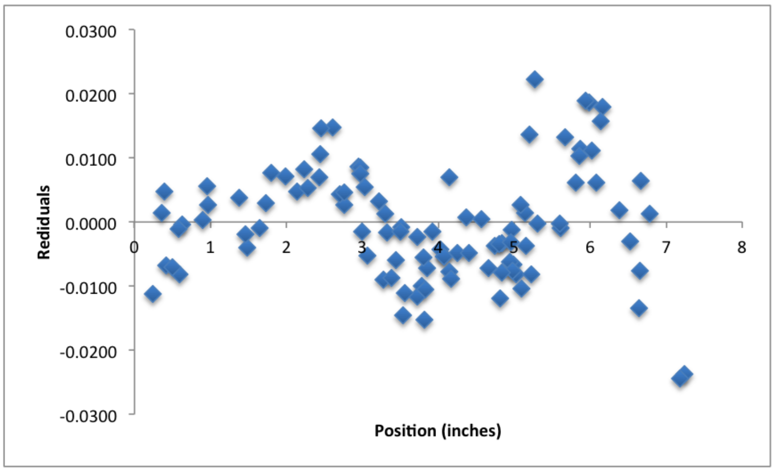


Figure 8.9. – Plot of the residuals for the linear curve fit of the linear potentiometer using the magnetic encoder as a base line.

9. Product Realization

In order to implement our design in an accumulator and perform benchtop testing, several components were fabricated. As described in Chapter 7, the components that were fabricated for the prototype and testing include four parts, 64209-3, 64209-4, 64209-5, and 64209-TAB. Detailed drawings for these parts may be found in Appendix B. The guide pieces for testing in the 4024 accumulator were made out of PEEK plastic, and the benchtop guide part was made from Delrin plastic. The manufacturing material costs can be found in Table 7.4. Shown in Figure 9.1 is a picture taken during the manufacturing of the encoder guide on a CNC mill in the Cal Poly ME machine shops. Figure 9.4 shows all finished guide pieces after they were CNC machined.

Figure 9.1. – The manufacturing of the guide pieces on a CNC mill.

Electrical circuitry was also manufactured at this stage, and a prototype board was soldered together. The prototype board includes all the necessary connections to connect the encoder and linear potentiometer. During the manufacturing and testing phase, several changes were made to the final electrical design.

9.1. Manufacturing Processes Employed

The prototype parts for the project were machined using a CNC (Computer Numerical Control) Mill. Tolerances of +/- 0.005 inches resulted on the dimensions measurable.

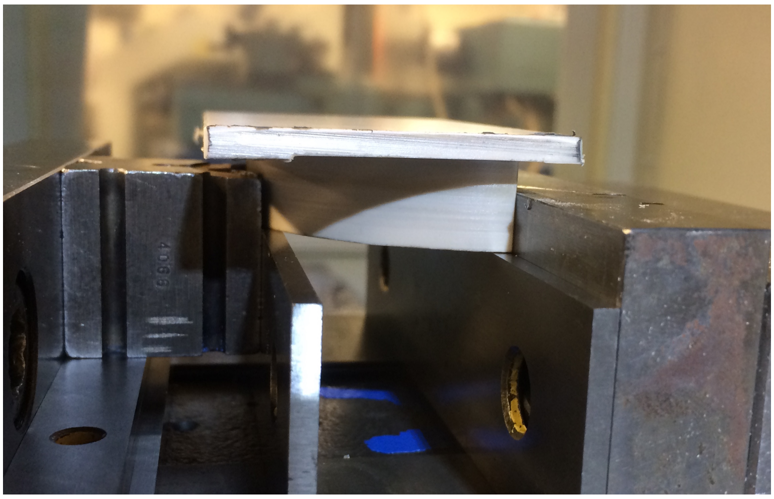


Figure 9.2. – Manufacturing method for guide pieces. Image shows last operation for manufacturing the guide piece during which the guide is held with a V-block and the rectangular holding material is removed.

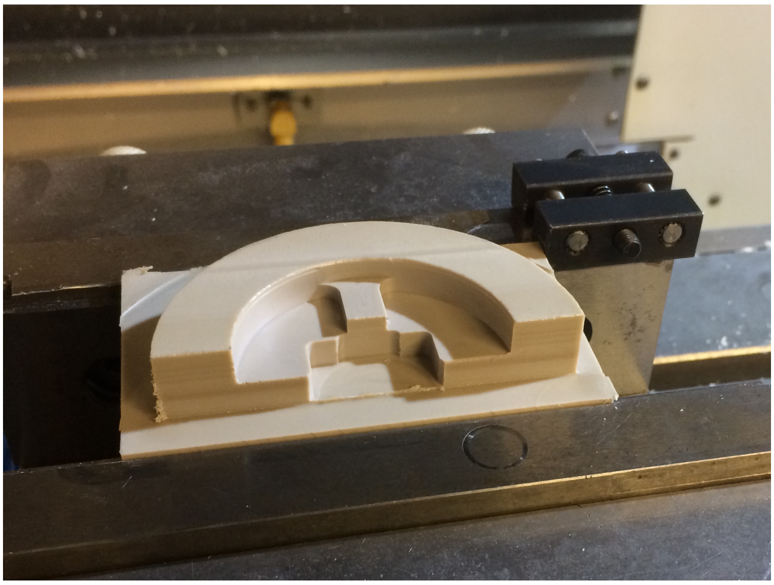


Figure 9.3. – Linear Potentiometer Guide mid-manufacturing.

As shown originally in Appendix D.5 and Appendix D.6, a tight tolerance of +/- 0.0025 inches was placed on the encoder guide piece (part 64209-4 in Appendix B). However, a minor redesign occurred after discussing the tight tolerances with PDT. A conclusion was reached that adjust-ability should be incorporated into the guide design so that the part could be guaranteed to fit without interference into the testing accumulator.

All parts made on the CNC mill were held using standard vise jaws. The holding technique used for all of the parts uses rectangular holding material where the vises grip. As

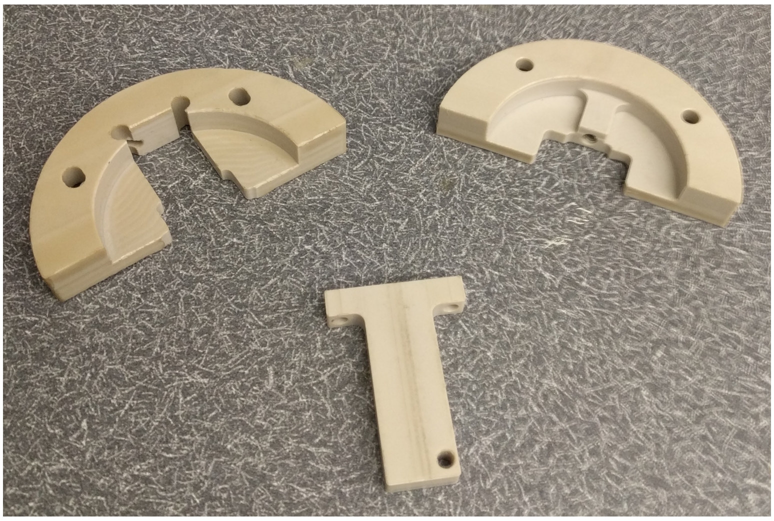


Figure 9.4. – The finished guide pieces for use in the testing accumulator.

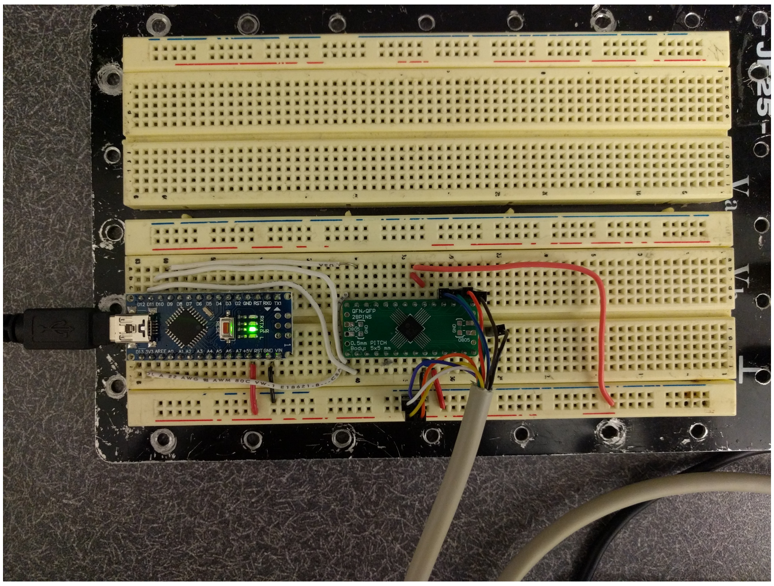


Figure 9.5. – The breadboard stage of the electronics manufacturing.

many features were made as possible during the first operation (or part orientation) in order to minimize the loss of tolerances associated with re-orienting the part. After the first operation, the part is left on a rectangular pedestal where the vises are gripping. The part is then re-oriented as needed to drill holes, and add additional features. Finally, the parts are flipped over, the holding material is machined off, and the final dimension of the part achieved. Figure 9.2 shows the holding orientation for this last operation. During the final operation, V-blocks were used to hold the hemispherical guide parts. The machine's z-axis was zeroed on the bottom of the part so that the final dimension was not reliant upon the tolerances of the stock material.

The manufacturing of the electrical components initially utilized a breadboard that was later transferred onto a soldered prototype board. The breadboarded components are shown in Figure 9.5. During this stage the components were verified to work as intended together. A minor difficulty arose due to the need of soldering a small IC onto a Schmart board so that all the pins can be exposed. The IC on the Schmart Board is on the left in Figure 9.5. It took a third try of soldering this IC (a QFN-28 pin) to the board before it worked. The design was first verified on the breadboard, then transferred to a proto-board. The proto-board is shown in Figure 9.6 where the same circuitry as the breadboard can be seen on the proto-board, as well as the additions of a display and switch. This was added to the design to make the final product a uniform interface between the linear potentiometer readings and the encoder readings.

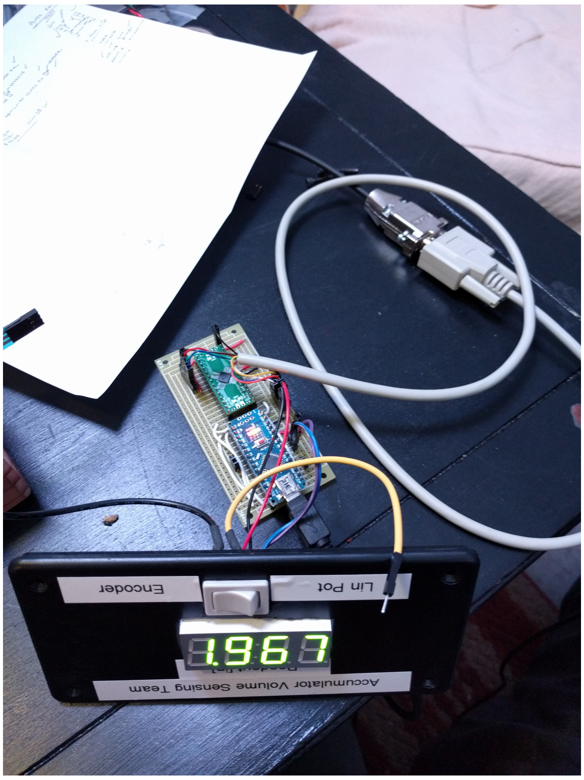


Figure 9.6. – The final product of the electronics manufacturing, the proto-board.

9.2. Changes Made During Manufacturing

9.2.1. Manufacturing Change to Part 64209-4

The change made to incorporate adjust-ability into the encoder guide piece was a 0.060 inch slotting of the 0.188 inch holes which mount the guide to the rest of the accumulator assembly. The slotting of the holes ensured that during on-site testing at PDT, the guide piece could be guaranteed to fit without interference in the 4024 testing accumulator. The slotting allowed us to mount the encoder to within the tolerances required in the

datasheet (Appendix C.5).

9.2.2. Changes to Designed Circuits

For the electrical circuitry, the changes made aimed at simplifying the test process so that a single device was used as a reference during testing. First, an integrated circuit referred to as the IC-MB4 (from iC Haus) was added and used to manage the connection with the encoder. Second, the linear potentiometer was meshed into the encoder circuit so that just one device could be referenced during testing. Third, a switch was added to select which measurement device to reference. And finally, a digital read out display was added so that the readings could be displayed. All of this was mounted in a black plastic project enclosure box. The display and resulting circuitry can be seen in Figure 9.6. The resulting circuit diagram and changes are documented in Appendix D.9.

9.3. Recommendations for Future Manufacturing

A few minor recommendations were discovered after manufacturing the prototype parts. AVST recommends that if an encoder design is to be implemented by PDT, a similar slotted feature described in Section 9.2.1 should be used to reduce the tolerances and cost of the guide part. Furthermore, AVST recommends the creation of custom vise jaws for the hemispherical guide pieces (sometimes referred to as custom "soft-jaws") so that when they are re-oriented to remove the holding material, they are held tightly and securely without the fiddling required to arrange the V-blocks. With the incorporation of these minor recommendations, AVST hopes that PDT may reduce their manufacturing costs as well as time required for each part.

For the manufacturing of the electronics, we recommend that consideration be given to developing a Printed Circuit Board (PCB) design. Also, a significant amount of trouble could be saved by utilizing an automated soldering process such as Printed Circuit Assembly (PCA) which uses pick-and-place machines along with a solder mask and re-flow oven to manufacture the finished product.

10. Conclusions and Recommendations

To conclude this design report, AVST hopes that our solutions will save PDT money, and improve their current accumulator designs. Although this design report focused on the 4024 accumulator for testing, we hope that PDT might be able to implement our solutions in other accumulators as well.

For the encoder, we recommend that PDT utilize a micro-controller solution so that the digital output may be processed and sent where it is needed. The driver code written for the IC-MB4 took a substantial amount of time, and we encourage PDT to make use of the IC-MB4 driver library written by us. This will save a significant amount of development effort. Furthermore, we would like to note that the encoder provided resolution that far exceeds the requirements of PDT. As a result, we encourage PDT to question whether the encoder solution would be cost-effective for their application. We also suggest that the encoder solution be used to improve the calibration process for their existing position measurement solutions or for calibrating the linear potentiometer. The encoder serves as an exceptional baseline measurement device.

We believe that the linear potentiometer holds the most potential for PDT due to its extremely low cost. The sensor achieved a +/- 0.06 inch accuracy using a linear calibration, and a +/- 0.03 inch accuracy using a cubic calibration. The drastic reduction in cost per sensor is appealing and would be a welcomed change during assembly into the accumulator due to it's simplicity. The linear potentiometer design has simple mechanical constraints that only require the ball plunger be in contact with the active area of the potentiometer. The linear potentiometer design could possibly be a "drop-in" replacement for the current string potentiometer. The processing circuitry should be almost identical, and the circuitry recommended in our design report might suffice. However, we ultimately recommend that an Electrical Engineer be the final authority in creating the

analog circuitry for adjusting the linear potentiometer design.

Our final recommendation for the linear potentiometer design is that further testing be performed for cyclic lifetime failure as well as temperature effects on the device calibration. If this solution is further pursued, it may be worthwhile to incorporate a temperature sensor into the design so that the calibration curve may be adjusted for any changes in temperature. As mentioned before, calibrations for the linear potentiometer might best be done by using an encoder as a baseline. AVST found the encoder to be very helpful in this regard.

In total, we would like to thank PDT for their support and sponsorship of our project, as well as our project advisor, Dr. Rossman, for her valuable advice.

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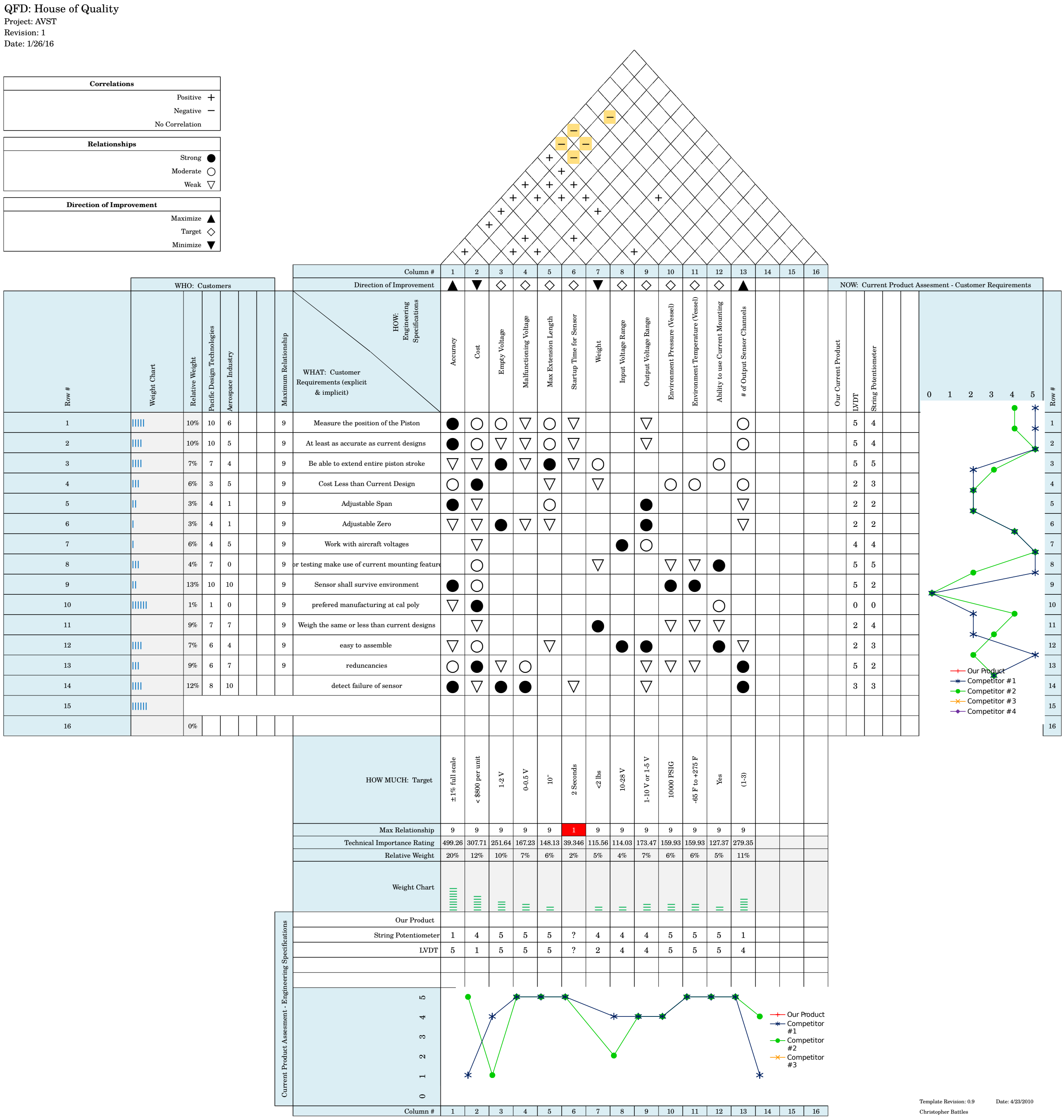
Appendix

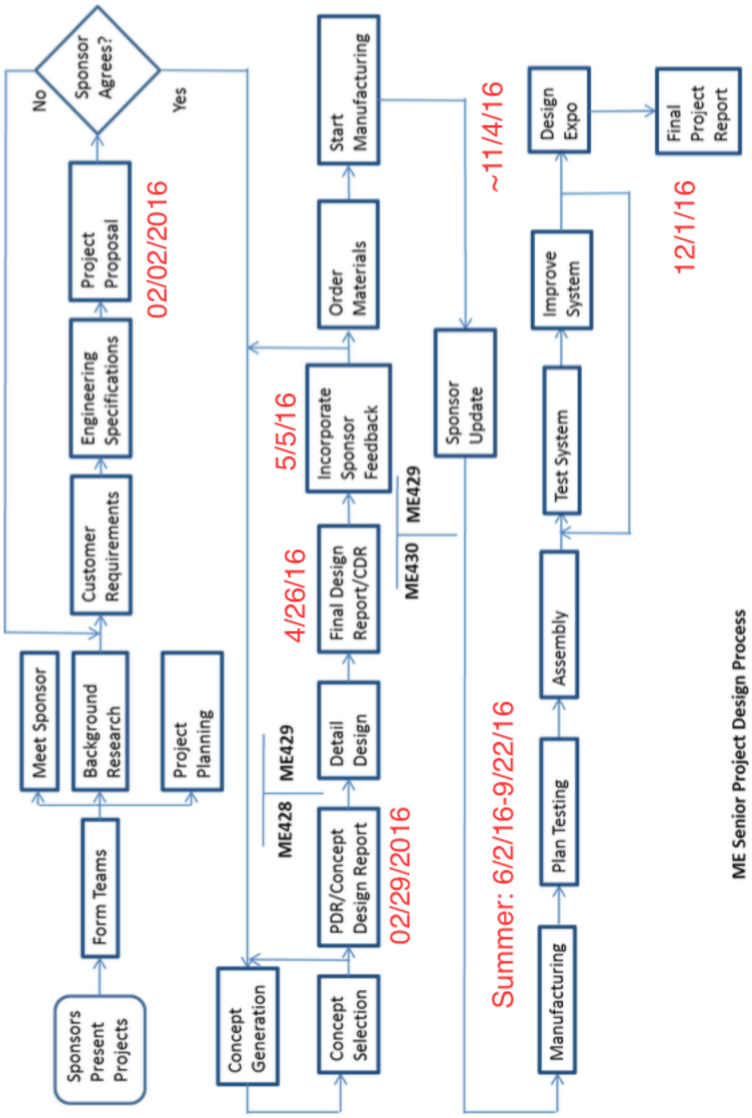
A. Diagrams

A.1. Quality Function Deployment



A.2. General Design Flowchart

Senior Project Design Process with Important Dates (Image taken from [4])



A.3. Pugh Matrix

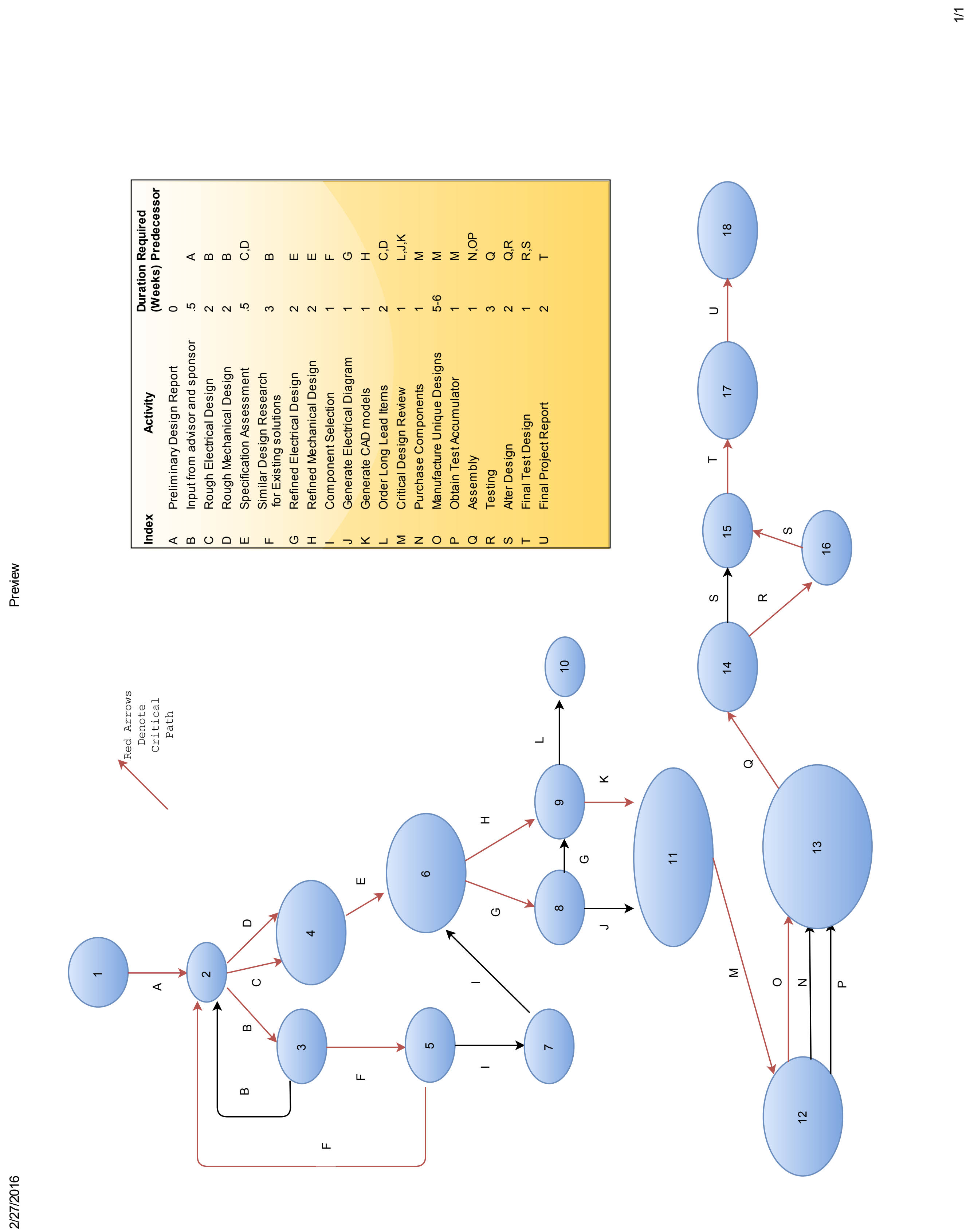
Concept/project/idea etc	String Pot	spool and string	external magnetic follower w/ camera	external magnetic follower w/ string pot	external magnetic follower w/ string encoder	internal magnetic follower	external magnetic follower w/ range strip pickup	crack finder	sonar sensor at top	sonar sensor at bottom	sonar sensor on both sides	sonar tapper w/ range strip pickup	optical encoder	magnetic encoder	capicatance encoder	laser emitter/receiver same side	refraction	angled light beam	pulley system
CTSs/Features	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**
accuracy		w	w	s	-	s	w	w	w	w	w	w	b	b	b	b	w	w	b
cost	**D**	b	w	w	w	w	w	w	b	b	b	b	b	b	b	w	w	w	b
empty voltage	**A**	s	b	s	s	s	s	s	s	s	s	w	w	w	w	s	s	s	s
malfunction voltage	**T**	s	b	s	s	s	s	w	s	s	s	w	w	w	w	s	s	s	s
maximum extension length	**U**	s	w	s	s	s	b	b	b	b	b	b	s	s	s	b	s	s	w
startup time	**M**	s	w	s	s	s	s	w	s	s	s	w	s	s	s	b	s	s	s
weight		s	w	w	w	w	s	w	s	s	s	b	s	s	s	b	b	b	w
input voltage range		s	b	s	s	s	s	s	s	s	s	s	s	s	s	s	w	q	w
output voltage range		s	b	s	s	s	s	s	s	s	s	s	s	s	s	s	s	a	w
environmental pressure		s	s	b	b	s	s	s	s	s	s	w	s	s	s	s	s	a	s
environmental temperature		s	s	b	b	s	s	s	s	s	s	w	w	s	s	s	w	w	w
ability to use current mounting		s	w	w	w	w	w	w	s	s	s	w	s	s	s	s	w	w	w
number of output channels		w	b	s	s	s	b	s	s	s	b	w	w	w	w	s	w	w	w
SB's		1	5	2	2	0	2	1	2	2	3	3	2	2	2	4	1	1	2
SW's		2	6	3	3	3	3	6	1	1	1	8	4	3	3	1	6	5	7
SS's		10	2	8	7	10	8	6	10	10	9	2	7	8	8	8	6	4	4

Concept/project/idea etc	retractable string	metallic rod with magnetics similar, fashion to LVDT	lead screw	telescoping pole	ruler	heated piston	strong magnet on piston	strong magnet on top of accumulator	magnetometes along outside of piston	spring gauge	capacitor plates immersed inside fluid chamber	capacitor plates immersed inside divided reservoir	gears to encoder	gray code strip and optical encoder	continuous bar codes w/ scanner	wheel that runs on piston	spool and string	Linear Potentiometer
CTSs/Features	**20**	**21**	**22**	**23**	**24**	**25**	**26**	**27**	**28**	**29**	**30**	**31**	**32**	**33**	**34**	**35**	**36**	**37**
accuracy	s	b	b	-	w	w	w	w	w	w	w	w	b	b	b	s	w	s
cost	s	w	w	w	w	w	w	w	w	b	b	b	w	b	w	b	b	b
empty voltage	s	s	s	s	w	-	s	s	s	s	s	s	s	s	s	w	w	s
malfunction voltage	s	s	s	s	w	-	s	s	s	s	s	s	s	s	s	w	w	w
maximum extension length	s	s	s	w	w	b	s	s	w	s	w	w	w	s	s	b	s	w
startup time	s	s	s	s	w	w	s	w	w	w	w	w	s	s	w	s	b	s
weight	s	w	w	w	-	w	s	s	s	s	s	s	s	b	w	w	b	b
input voltage range	s	s	s	s	w	w	s	s	s	s	s	s	s	s	s	s	w	s
output voltage range	s	s	s	s	w	-	s	s	s	s	s	s	s	s	s	s	w	b
environmental pressure	s	w	s	s	s	-	s	s	s	s	s	s	s	s	s	s	s	s
environmental temperature	s	w	s	s	s	w	s	w	s	s	w	w	s	s	s	w	s	w
ability to use current mounting	s	w	w	w	w	w	w	w	w	s	s	s	w	w	w	w	w	s
number of output channels	s	s	s	w	w	w	s	w	b	w	w	s	s	s	s	s	w	w
SB's	0	1	1	0	0	1	0	0	1	1	1	1	1	3	1	2	3	3
SW's	0	5	3	5	10	8	3	6	5	3	5	4	3	1	4	5	7	4
SS's	13	7	9	7	2	0	10	7	7	9	7	8	9	9	8	6	3	6

A.4. Decision Matrix

	Criteria								
	Accuracy	Cost	Assembly & Manufacturability	Calibration	Start-up Time	Weight	Reliability	Able to withstand Temperature	Sum
Weighting	20	30	8	12.5	5	5	14.5	5	100
Refractive Laser	10	1	8	5	9	7	8	4	57.25
Magnetic Encoder	10	8	6	8	8	9	9	7	83.85
Optical Code Encoder	10	6	6	8	8	9	9	8	78.35
Linear Potentiometer	7	10	10	6	9	9	6	6	80.2

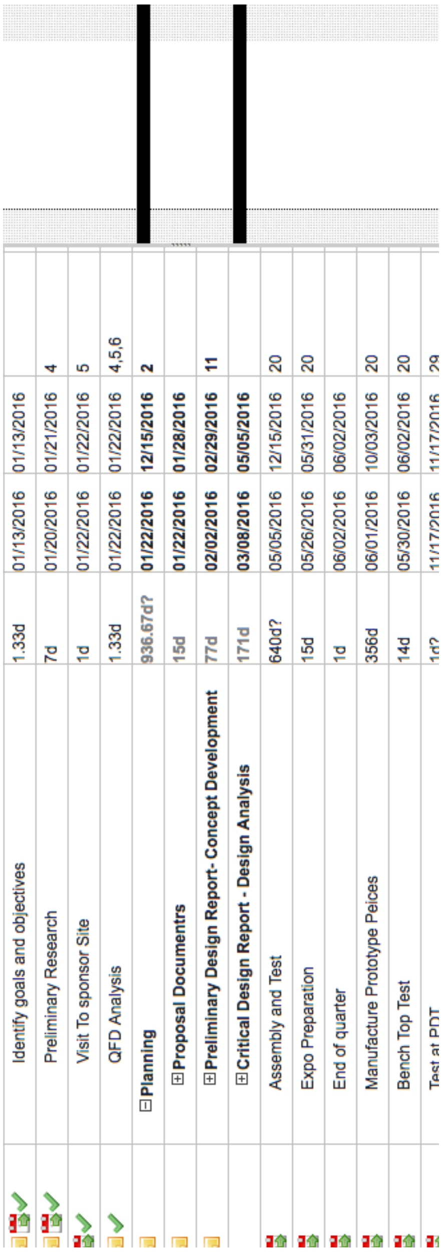
A.5. PERT Chart



Index	Activity	Duration (Weeks)	Required Predecessor
A	Preliminary Design Report	0	
B	Input from advisor and sponsor	.5	A
C	Rough Electrical Design	2	B
D	Rough Mechanical Design	2	B
E	Specification Assessment	.5	C,D
F	Similar Design Research for Existing solutions	3	B
G	Refined Electrical Design	2	E
H	Refined Mechanical Design	2	E
I	Component Selection	1	F
J	Generate Electrical Diagram	1	G
K	Generate CAD models	1	H
L	Order Long Lead Items	2	C,D
M	Critical Design Review	1	L,J,K
N	Purchase Components	1	M
O	Manufacture Unique Designs	5-6	M
P	Obtain Test Accumulator	1	M
Q	Assembly	1	N,OP
R	Testing	3	Q
S	Alter Design	2	Q,R
T	Final Test Design	1	R,S
U	Final Project Report	2	T

A.6. Gantt Chart

Unfortunately there is not an easy way to input our Gantt Chart into our report. For a more cohesive format please view with Gantter App at `https://www.smartapp.com/gantterforgoogledrive/index.html?fileID=0B9Lqw0A6VLsYVXFiQVhv0EQ5MU0#`



B. Technical Drawings

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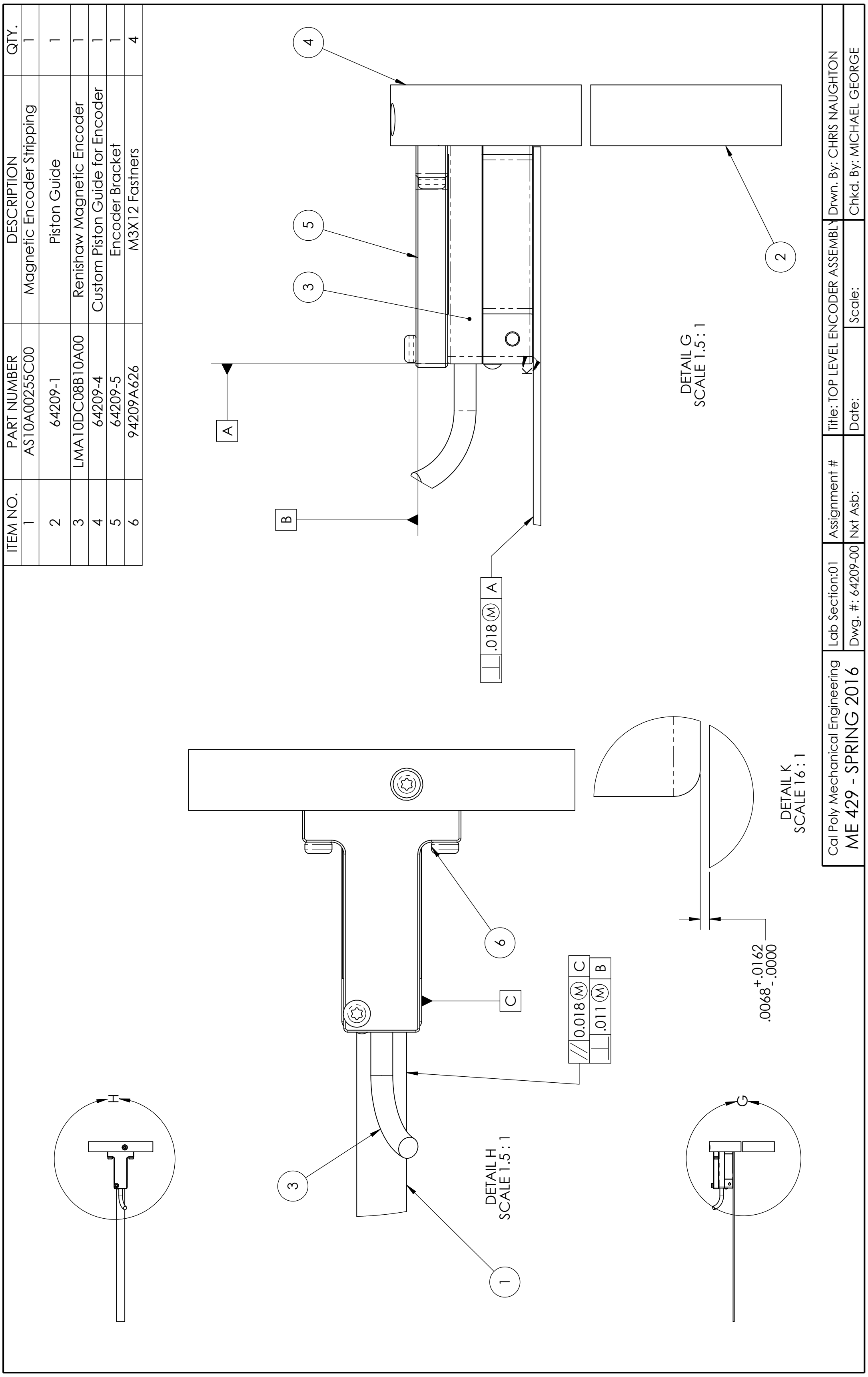
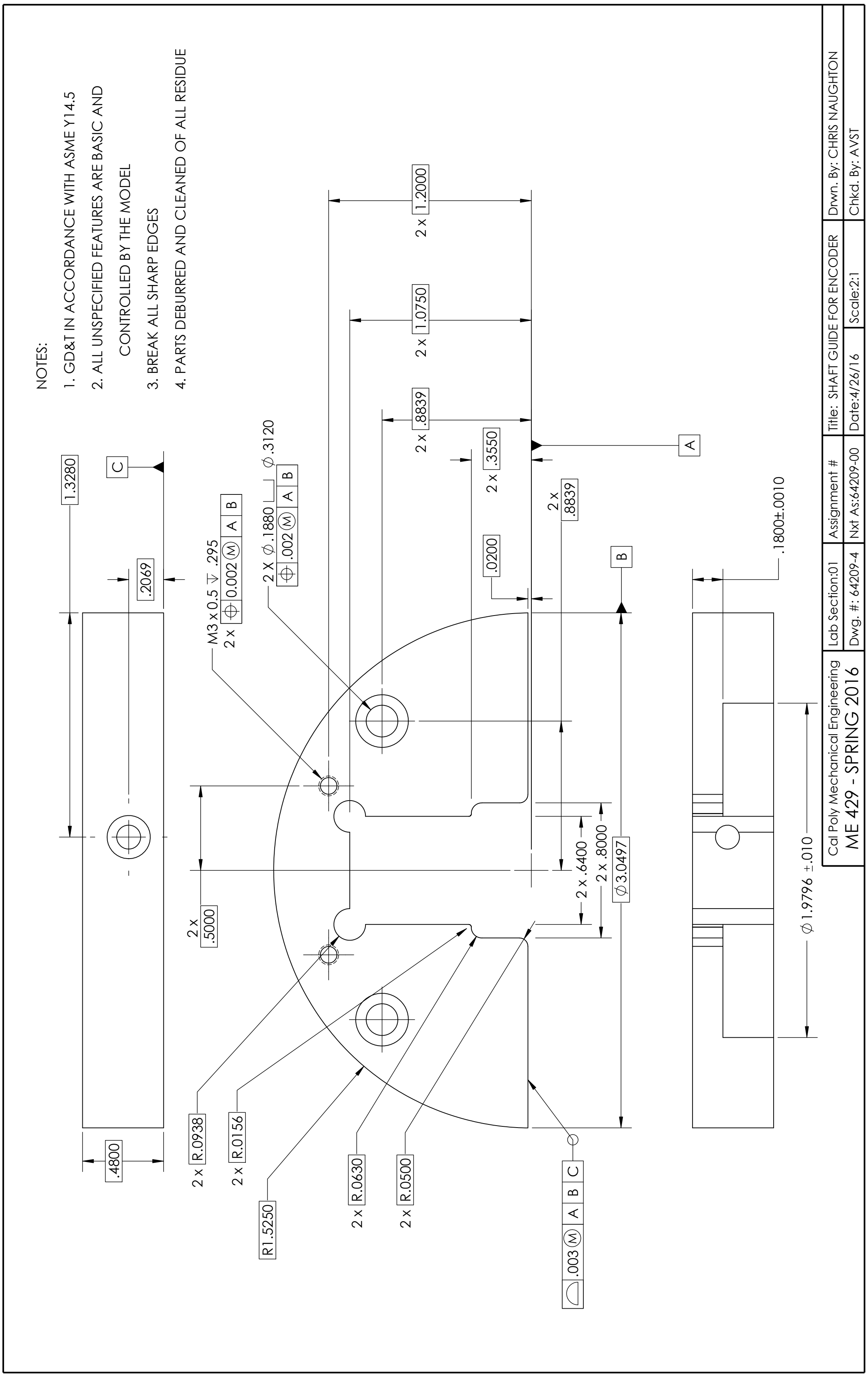
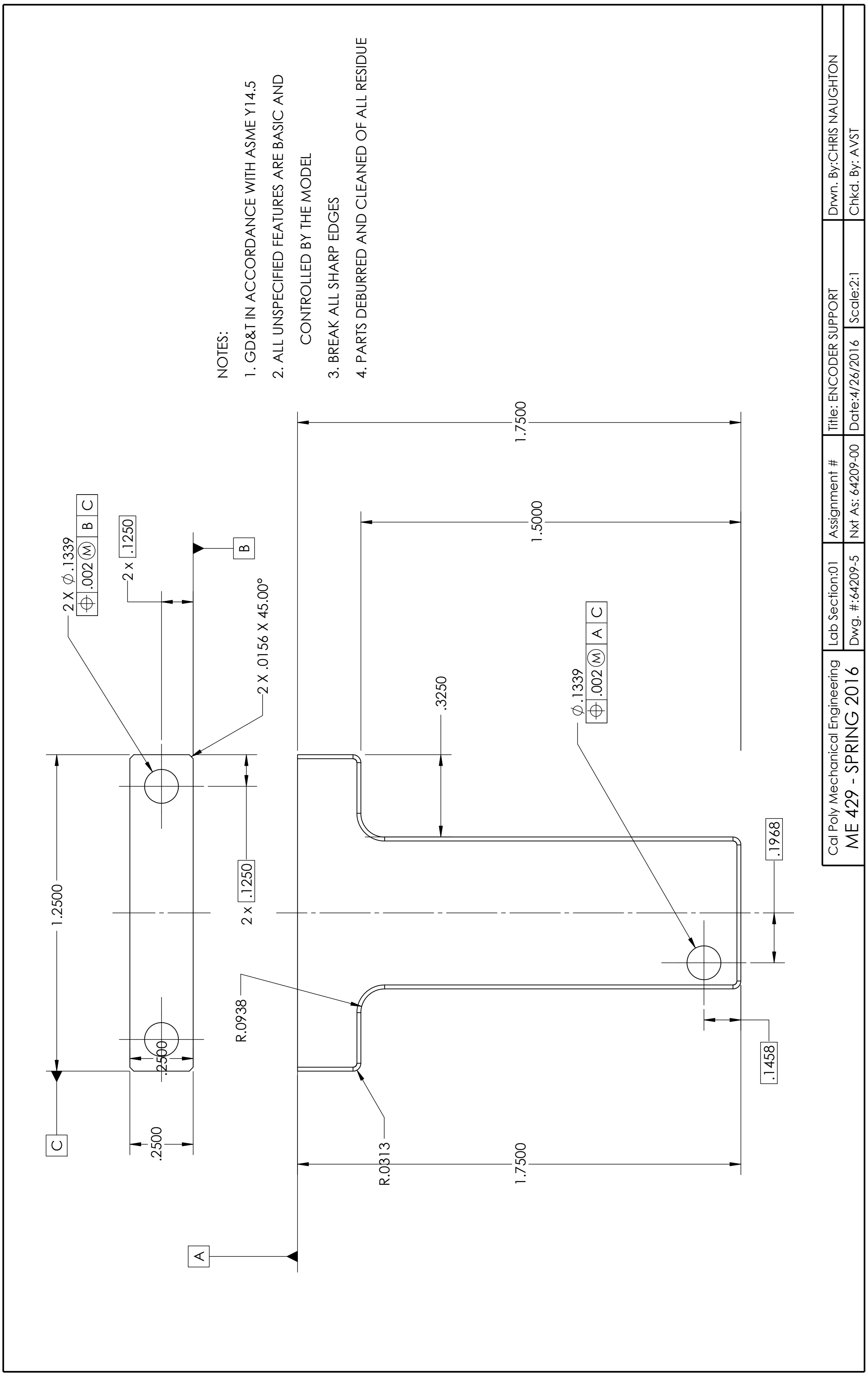
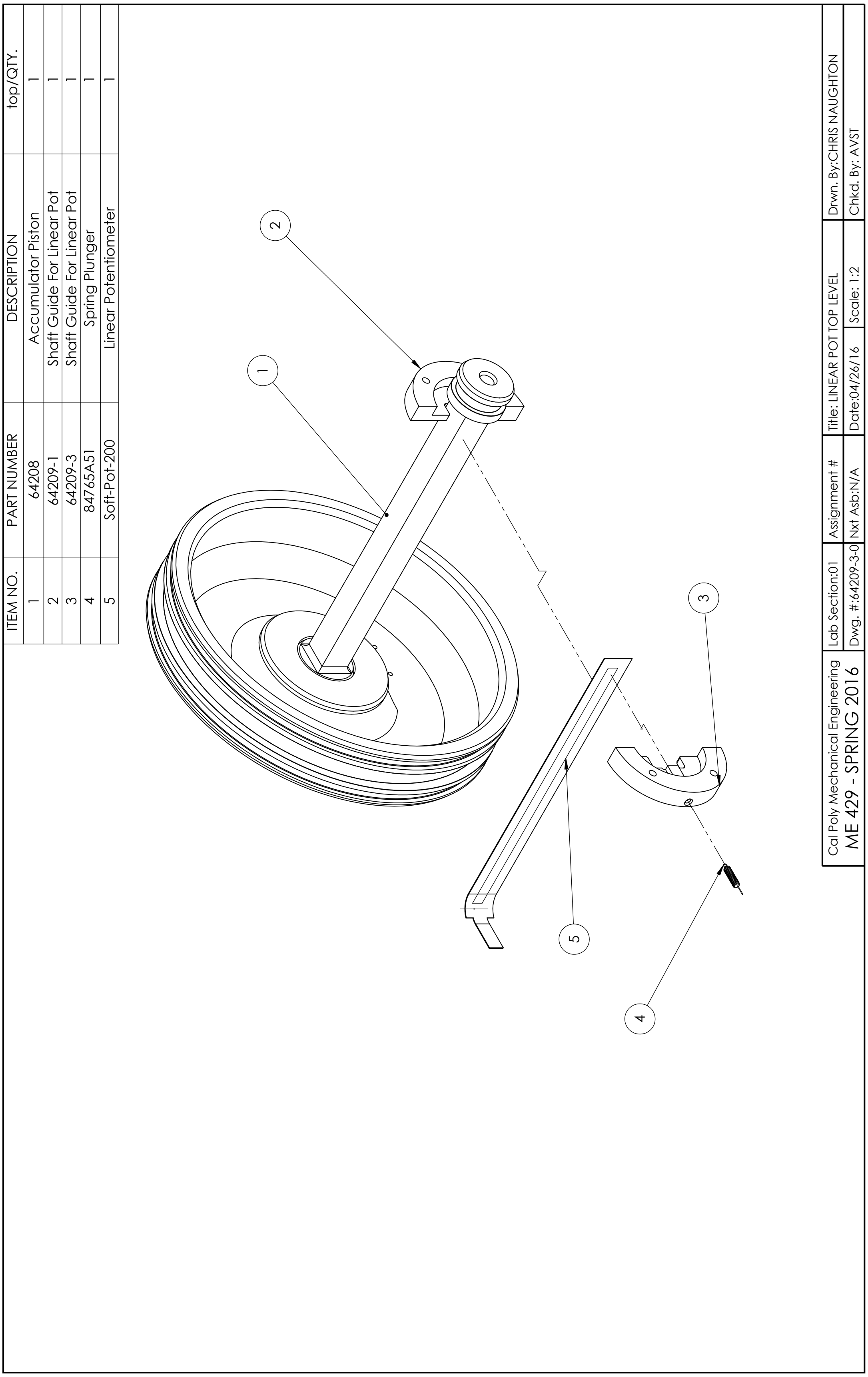
B.1. Magnetic Encoder Drawings

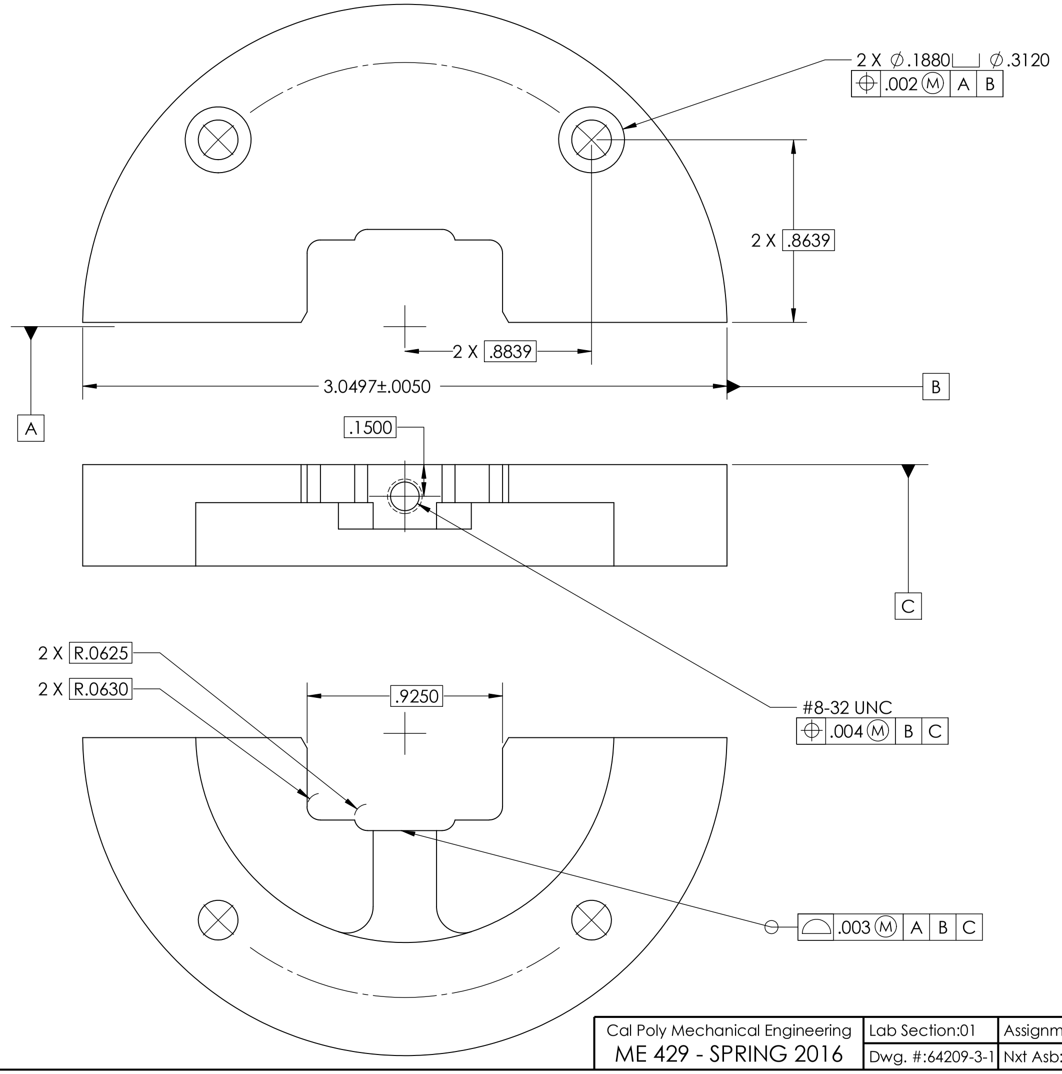



NOTES:
1. GD&T IN ACCORDANCE WITH ASME Y14.5
2. ALL UNSPECIFIED FEATURES ARE BASIC AND CONTROLLED BY THE MODEL
3. BREAK ALL SHARP EDGES
4. PARTS DEBURRED AND CLEANED OF ALL RESIDUE
1.3280
.2069
.4800
C
A
B
2 x 1.2000
2 x 1.0750
2 x .8839
2 x .3550
2 x .8839
.0200
M3 x 0.5 ↧ .295
2 x ⊕ 0.002 Ⓜ A B
2 X ∅.1880 ⌴ ∅.3120
⊕ .002 Ⓜ A B
2 x .5000
2 x .6400
2 x .8000
∅3.0497
.1800±.0010
∅1.9796 ±.010
2 x R.0938
2 x R.0156
R1.5250
2 x R.0630
2 x R.0500
.003 Ⓜ A B C
Cal Poly Mechanical Engineering
ME 429 - SPRING 2016
Lab Section:01
Dwg. #: 64209-4
Assignment #
Nxt As:64209-00
Title: SHAFT GUIDE FOR ENCODER
Date:4/26/16
Scale:2:1
Drwn. By: CHRIS NAUGHTON
Chkd. By: AVST


NOTES:
1. GD&T IN ACCORDANCE WITH ASME Y14.5
2. ALL UNSPECIFIED FEATURES ARE BASIC AND CONTROLLED BY THE MODEL
3. BREAK ALL SHARP EDGES
4. PARTS DEBURRED AND CLEANED OF ALL RESIDUE
2 X ⌀.1339
⌖ .002 Ⓜ B C
2 x .1250
2 X .0156 X 45.00°
B
C
A
1.2500
.2500
.2500
2 x .1250
R.0938
R.0313
1.7500
1.5000
1.7500
.3250
⌀.1339
⌖ .002 Ⓜ A C
.1968
.1458
Cal Poly Mechanical Engineering
ME 429 - SPRING 2016
Lab Section:01
Dwg. #:64209-5
Assignment #
Nxt As: 64209-00
Title: ENCODER SUPPORT
Date:4/26/2016
Scale:2:1
Drwn. By:CHRIS NAUGHTON
Chkd. By: AVST

B.2. Linear Potentiometer Drawings

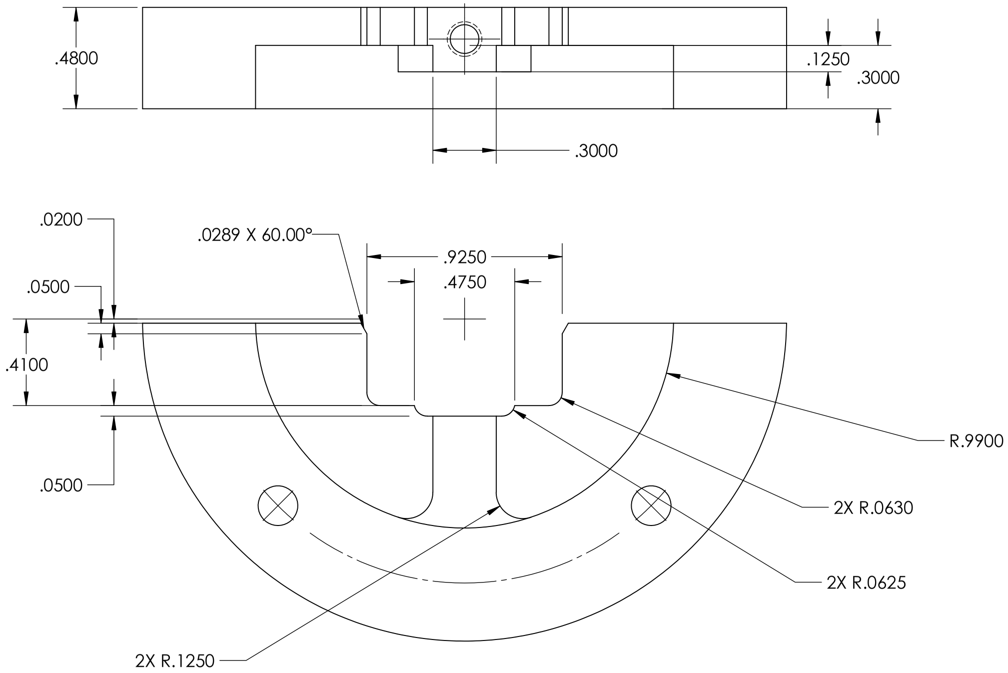




NOTES:

1. GD&T IN ACCORDANCE WITH ASME Y14.5
2. ALL UNSPECIFIED FEATURES ARE BASIC AND CONTROLLED BY THE MODEL
3. BREAK ALL SHARP EDGES
4. PARTS DEBURRED AND CLEANED OF ALL RESIDUE

Cal Poly Mechanical Engineering	Lab Section:01	Assignment #	Title:SHAFT GUIDE LINEAR POT GDT		Drwn. By: CHRIS NAUGHTON
ME 429 - SPRING 2016	Dwg. #:64209-3-1	Nxt Asb:64209-3-0	Date:4/26/16	Scale:2:1	Chkd. By: AVST



NOTES:

1. UNLESS OTHERWISE SPECIFIED, ALL DIMENSION ARE ±.005

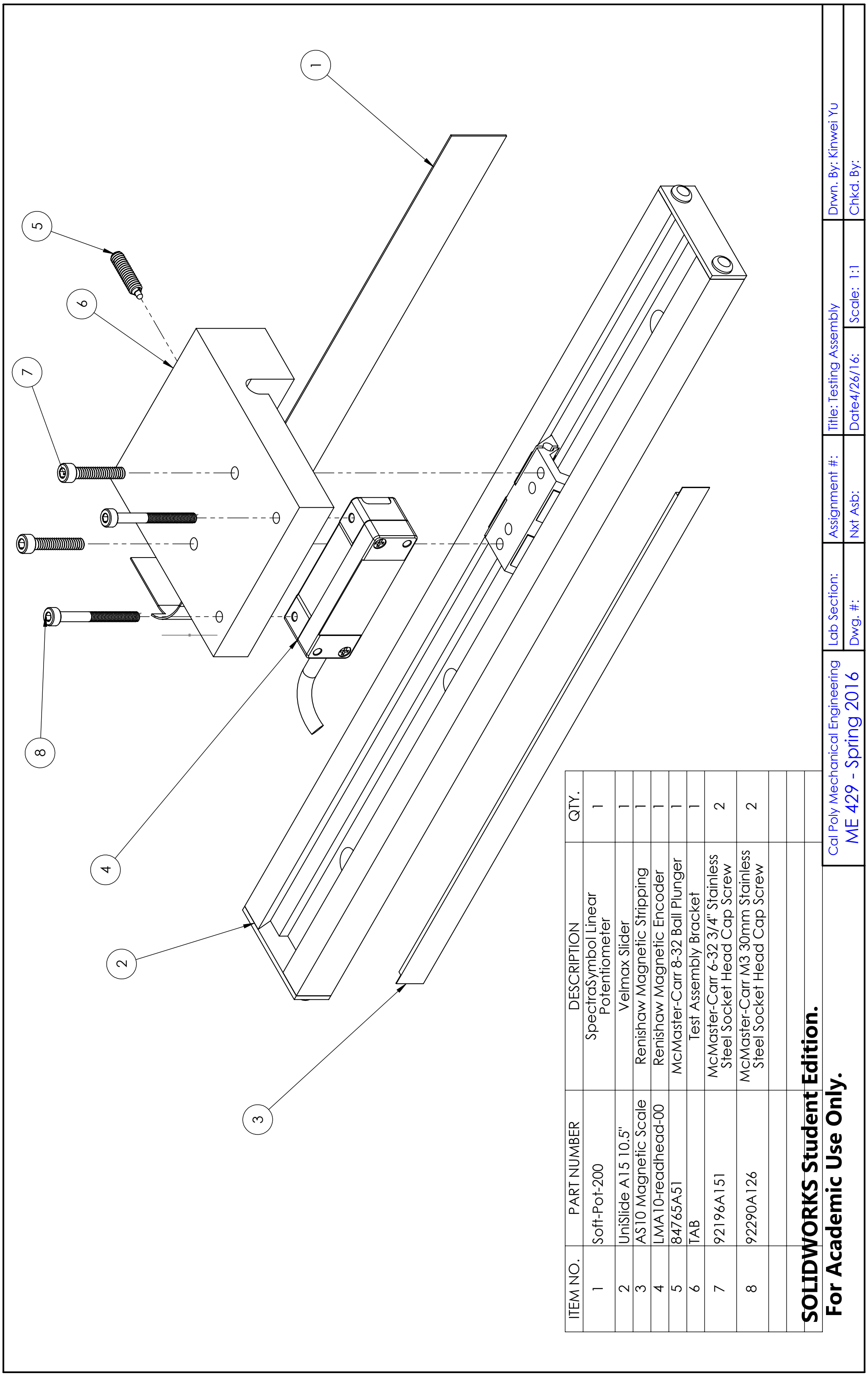
2. FOR TOLERANCES AND DIMENSIONS NOT SEEN ON THE SHEET PLEASE CONTINUE TO DRAWING 64209-3-1

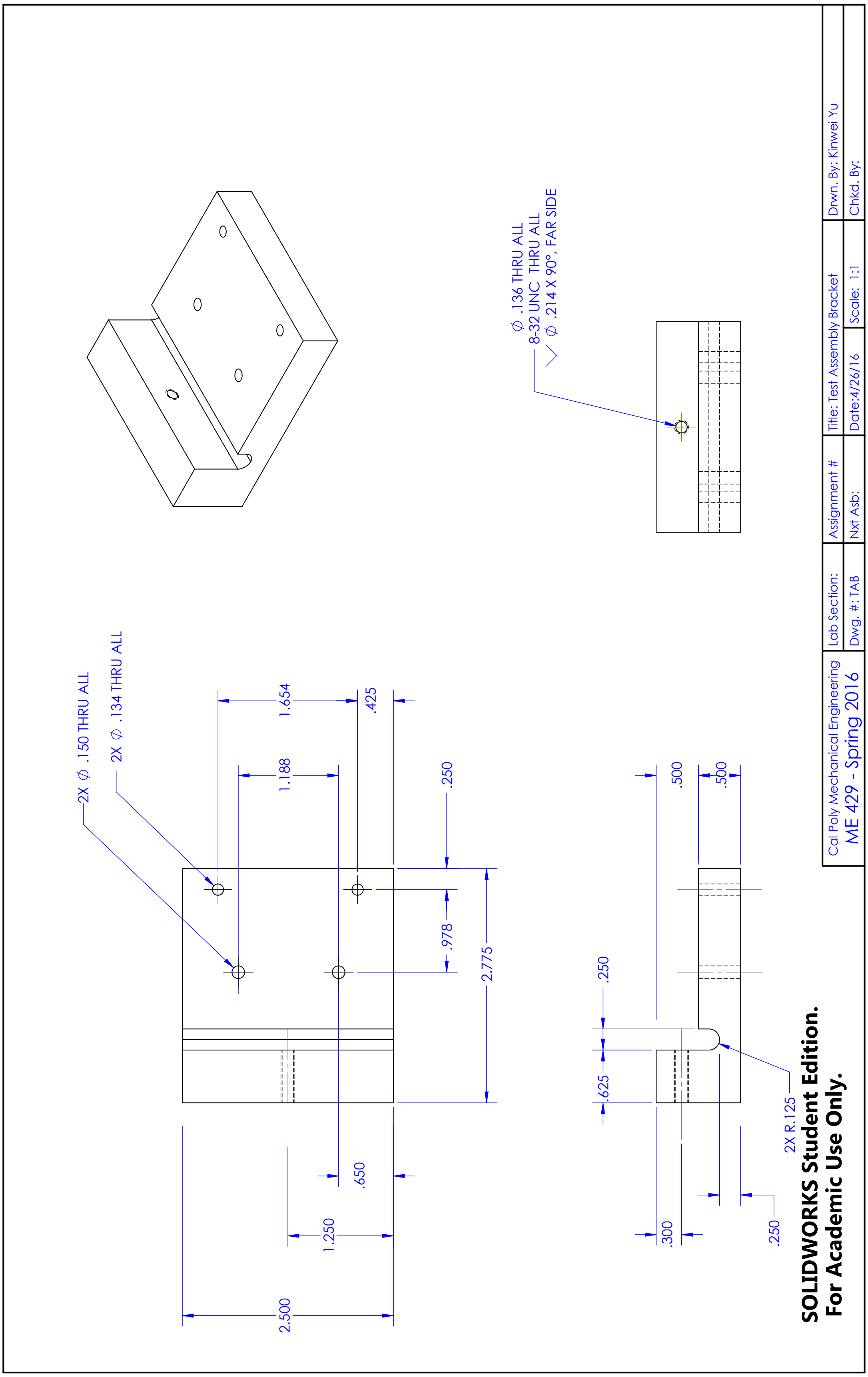
3. BREAK ALL SHARP EDGES

4. PARTS DEBURRED AND CLEANED OF ALL RESIDUE

Cal Poly Mechanical Engineering	Lab Section:01	Assignment #	Title: SHAFT GUIDE LINEAR POT DIM		Drwn. By:CHRIS NAUGHTON
ME 429 - SPRING 2016	Dwg. #:64209-3-2	Nxt Asb:64209-3-0	Date:04/28/16	Scale:	Chkd. By: AVST

B.3. Benchtop Test Drawings





2X ⌀ .150 THRU ALL
2X ⌀ .134 THRU ALL
1.654
.425
1.188
.250
.978
2.775
.650
1.250
2.500
.500
.500
.250
.625
.300
.250
2X R.125
⌀ .136 THRU ALL
8-32 UNC THRU ALL
⌀ .214 X 90°, FAR SIDE
SOLIDWORKS Student Edition.
For Academic Use Only.
Cal Poly Mechanical Engineering
ME 429 - Spring 2016
Lab Section:
Dwg. #: TAB
Assignment #
Nxt Asb:
Title: Test Assembly Bracket
Date:4/26/16
Scale: 1:1
Drwn. By: Kinwei Yu
Chkd. By:

C. Referenced Documents

C.1. Team Contract

Mission:

The purpose of the mission definition is to provide an explanation of the team functions.
The mission of the Accumulator Volume Sensing Team is to provide a robust means to measure and report the volume of a fluid accumulator, at a significantly lower cost than the current practice.

Section 1—Name

A. This organization shall be known as the Accumulator Volume Sensing Team.
B.

Section 2—Membership

The purpose of this section is to define who is part of the team and the specific roles needed to manage team business.

A. Members of the team include: Chris Naughton, Michael George, Kinwei Yu
B. No member shall purport to represent the team unless so authorized by the team.
C. Each member shall be provided a copy of the team contract.
D. Officers of the team shall include those listed below with their designated responsibilities. (spell out specific responsibilities of each officer position, some suggestions below).

1. Communications Officer- Chris Naughton
   a. Be main point of communication with sponsor
   b. Facilitate meetings with Sponsor
   c. If applicable manage contact with manufacturers
   d. Maintain group email
   e. Any other communication task that may arise.

2. Team Treasurer – Michael George
   a. Maintain team's travel budget
   b. Maintain team's materials budget (in 2nd quarter
   c. Maintain budget information in spreadsheet.

3. Secretary/Recorder – Kinwei Yu
   a. Maintain information repository for team (e.g. team binder, google docs site, etc..)
   b. Maintain record of meeting agendas
   c. Maintain group calendar

Adapted from the IDEALS Teamwork Planning module

Section 3—Decision Making

The purpose of this section is to explain how decisions will be made by the team. The following suggestions are offered.

A. By Consensus

Discussion will take place until all team members understand each other's views and ideas. Agreement will be deemed as an event where everyone is able to say they approve of the decision made, without any single member left in extreme disproval of th choice made.

Section 4—Team Interactions

The purpose of this section is to define how the team will interact including rules for meetings, basic project room civility) including food,drink, cleanup, security, etc. along with a description of generally accepted forms of ethical behavior (e.g. treat everyone with respect, language, etc.).. The following suggestions are offered.

A. All affairs of the team shall be governed by Golden Rule, unless otherwise specified. Golden Rule meaning treat others as you wish to be treated.
B. Meetings shall be held as needed and on lab days.
C. Unless otherwise noticed, all meetings will be held at an agreed location beforehand via groupme.
D. Special meetings of the team may be called by an agreement by all members via groupme.
E. Attendance is mandatory for all important decision making.
F. Meeting discussions will be conducted in a conversational format with special regard for a dialogue th is respectful and considerate of all members in attendance.
G. A meeting agenda, distributed 12 hours in advance, will guide meeting topics and timing.
H. The length of meetings shall be stated in advance.
I. All team members are expected to be punctual.
J. All meetings will be publicized to members using: phone calls, team websites, e-mail, and texting.
K. Repeated violation of team rules will result in consulting advisor after problem has been discussed in group and attempted to be resolved.

Section 5—Conflict Resolution

The purpose of this section is to discuss the procedure you will follow when inevitable conflicts arise wi possible escalation to a meeting with you lab advisor. This takes some serious thought about what process the team would like to follow

Conflicts will be resolved in the following manner:
A. Informal discussion and attempted agreement.
B. Formal discussion and equal time for team members to express their view
C. Formal discussion mediated by team advisor (Professor Rossman).

Section 6—Amendments

The purpose of this section is to define the process by which this contract can be amended. This contrac is considered a living document and will be updated throughout the project. List the conditions when th should occur and a procedure for doing so.

A. Consensus
B. If locked with consensus have Professor Rossman assist in amending contract.

Adapted from the IDEALS Teamwork Planning module

Section 7—Effective Date (Required)

The purpose of this section is to state the date of the initial adoption of this contract. Statement of an effective date is required.

A. This contract of the Accumulator Volume Sensing Team shall become effective on1/12/16.

B. Dates of amendment must be recorded in minutes of meetings at which amendments were approved, together with a revised set of bylaws.

Section —Signatures

The contract must be signed and dated by each team member.

Chris Naughton 1/12/16

Kinwei Yu 1/12/16

MICHAEL GEORGE 1/12/16

C.2. Safety Checklist

- ☐ ☑ Would it be possible for the system to fall under gravity creating injury?
- ☐ ☑ Will a user be exposed to overhanging weights as part of the design?
- ☐ ☑ Will the system have any sharp edges?
- ☐ ☑ Will any part of the electrical systems not be grounded?
- ☐ ☑ Will there be any large batteries or electrical voltage in the system above 40 V either AC or DC?
- ☐ ☑ Will there be any stored energy in the system such as batteries, flywheels, hang weights or pressurized fluids?
- ☐ ☑ Will there be any explosive or flammable liquids, gases, or dust fuel as part of th system?
- ☐ ☑ Will the user of the design be required to exert any abnormal effort or physical posture during the use of the design?
- ☐ ☑ Will there be any materials known to be hazardous to humans involved in either design or the manufacturing of the design?
- ☐ ☑ Can the system generate high levels of noise?
- ☐ ☑ Will the device/system be exposed to extreme environmental conditions such as fog, humidity, cold, high temperatures, etc?
- ☐ ☑ Is it possible for the system to be used in an unsafe manner?
- ☐ ☐ Will there be any other potential hazards not listed above? If yes, please explain reverse.

For any “Y” responses, add a complete description, list of corrective actions to be taken, and dates to be completed on the reverse side.

C.3. Centralized Ideas Document

Table 1. Solution Ideas

Idea	Variation	Short Description	Location (Name Page#)
Magnetic Follower	External Magnetic Follower with camera	magnetic follower follows the piston outside of the accumulator and then the follower is measure using a camera that uses a “red dot tracker” to find referance	C 33
	External Magnetic Follower with string potentiometer	magnetic follower follows the piston outside of the accumulator and then the follower is measure using a string potentiometer	C 33
	External Magnetic Follower with string encoder	magnetic follower follows the piston outside of the accumulator and then the follower is measure using a retractable string and encoder	C 33
	Internal Magnetic Follower	Magnetic follower on a rail inside the accumulator that is detecting the time for a torsional wave to go down and back up.	M 24
	External Magnetic Follower with Range strip pickup	Have a magnet mounted on piston inside accumulator and have an electric strip on the outside of piston that is sensing the location of the strongest magnetic field along the strip. Put on both sides?	M 29
Acoustics	Crack Finder	Acoustics, method that is used to find cracks within a pipeline.	C 33
	Sonar sensor at Top	Use a sonar sensor mounted to the top of the accumulator casing which points down to the piston to gain a distance reading.	C34 M 29
	Sonar sensor at bottom	Use a sonar sensor mounted on the piston side to gain a distance reading from the piston side up to the top.	M 29
	Sonar Sensor from both sides	Use sonar sensors mounted on top and bottom to gain a distance reading from both ends for redundancy.	M 29
	Sonar Tapper with range strip pickup	Mount a “tapper” that is on the piston and constantly tapping the side wall of the cylinder. On the outside of the casing, mount acoustic pickups and determine location based upon the relative strength of the tapping to each pickup. Put on both sides?	M 29

Encoders	Optical	similar to string pot but with optical encoder instead of potentiometer	K35
	Magnetic	similar to string pot but with magnetic encoder instead of potentiometer	
	Capacitance	similar to string pot but with capacitance encoder instead of potentiometer	
Photoelectric	Laser Emitter/ Receiver same side	A laser design that emits light to a reflective spot mounted on the piston, and measures the time for it to reflect back to the receiver mounted next to the emitter.	M 25 M 26
	Refraction	Shine a light through fluid, a more full chamber will cause the light to bend for a longer distance, hitting a different spot depending on fluid level. have a series of receivers.	K 37
	Angled light beam	Shine a light from bottom of piston to top of accumulator. As the piston moves, the light will hit a different spot cause of the angle. have a series of receivers	K
Connection to piston	Pulley System	Using a string navigated through a pulley system to decrease or increase revolutions on sensor	C 36
	Retractable String	Currently used on PDT’s String pot accumulators	n/a
	Metallic Rod	Similar to LVDT. Using reference of rod engagement to determine linear placement	C 43
	Lead Screw	Having a lead screw rigidly attached to the piston and driving a gear train on top of the accumulator to potentiometer/rotary encoder	C 43
	Telescoping Pole	Using a telescoping pole attached to piston and accumulator end to drive some sort of sensor	C24
	Ruler	Attach a ruler to piston that sticks out through the vents. Have a camera detecting the location of the ruler sticking out of the vent.	K 34 C35
Cameras	Heated Piston	Heat up a part of the piston, detect where the location with an infrared camera	K 34
Magnometer	Strong magnet on piston	measuring magnetic field from top of accumulator	C34
	Strong magnet on top of accumulator	reverse of above	C34

	Magnetometers along outside of piston	(see idea in magnetic follower) Have magnometers be the pickups that are detecting the location of the strong magnets mounted on the piston.	
Force Transducer	Spring Gauge	Attach a spring to piston, as the spring stretches, measure the force of the spring and find the distance	K 34
Capacitance level gauge	Capacitor plates immersed inside chamber fluid	Putting Capacitor plates within the chamber	C 43
	Capacitor plates immersed inside divided reservoir	Putting the capacitor plates in a separate reservoir outside of change	C43
Piston Connector Rod Measurement	Gears to encoder	Attach a line of teeth to piston, those teeth turn a gear as the piston moves up and down, gear connects to rotary encoder or any other rotary sensor	K 44
	Gray code strip and optical encoder	Have a gray code strip that has shaded in boxes, with an optical sensor reading the boxes and correlating the binary number to a position on the piston	M 33
	Continuous bar codes with scanner	Similar to the gray code idea, except use a laser scanner to read many rows or unique bar codes corresponding to a position.	M 33
	Wheel that runs on piston	wheel base rigidly attached to top of accumulator, and wheel runs on piston. Wheel rotates some sort of encoder or potentiometer	C 43
Optical signals	spool and string	Attach string to piston. count the # of coils around the spool. As the piston moves down, there will be less coils due to the string extending/stretching out	K 43
Potentiometer	Linear Potentiometer	Linear potentiometer strip attached to piston, with a stationary wiper pressing on it	

C.4. Refractive Laser Quote

Christopher Naughton <chrisnaughton06@gmail.com>

Acuity laser sensor information

1 message

Joe Miller <jmiller@acuitylaser.com> Mon, Feb 22, 2016 at 7:12 PM
To: Chris Naughton <cmnaught@calpoly.edu>
Cc: RB SYSTEMS <bobbohle@cox.net>

Greetings Chris Naughton,

Our least expensive triangulation sensor that meets your requirement of a 10" measurement span would be the AR500-250 with 9.8" of range or the next larger model is the AR500-500. Both will meet your accuracy requirements. Price of $1,900 each. If you would like a written quote just let me know. For an educational facility we also offer a 5% discount from that price.

Please feel free to contact me at the address and numbers below.

Thank you,

Joe Miller

Schmitt Industries / Acuity laser products
10624 South Eastern Ave., Suite A-271
Henderson, NV 89052
702-616-6070
702-616-6071 Fax

Company: California Polytechnic San Luis Obispo
Person: Chris Naughton
Country: United States
State: CALIFORNIA
Telephone: 8057576837
E-mail: cmnaught@calpoly.edu
Source: Web
Product:
Inquiry: What is the price range of your short distance laser sensors? Our senior project design is heavily influenced by cost. We have to fit a criteria of +/- .05 " on a 10" scale.

ar500-data-sheet.pdf
700K

C.5. LMA10 Magnetic Encoder Datasheet

Data sheet
LMA10D01_02
Issue 2, 22nd April 2014

RLS®

LMA10 absolute magnetic encoder system

LMA10 is an absolute magnetic linear encoder system which has been designed for motion control applications as a position and velocity control loop feedback element.

The encoder system is highly reliable due to contactless absolute measuring principle, built-in safety algorithms and high quality materials/components used.

The measuring standard is a magnetic scale which consists of a stainless steel substrate with an elasto-ferrite layer.

The elasto-ferrite layer is magnetised with two tracks. The incremental track is magnetised with 2 mm long (alternating south and north) poles and the absolute track is magnetised by a pseudo random binary sequence (PRBS) absolute code with 13 bit length. The elasto-ferrite layer is immune to chemicals commonly found in industry.

The readhead includes Hall sensor arrays for PRBS track reading, an AMR sensor for incremental track reading, interpolation electronics and custom logic circuitry. The data from the Hall arrays and interpolator are processed in the logic circuitry using special algorithms to determine the absolute position.

The electronic design provides extremely short response and recovery times, which consequently make it ideal for applications with highly dynamic control loops.

Diagnostic information is available through a serial communication channel and status LED.

If a failure is diagnosed, the encoder needs to be switched off and then switched on again in order to resume functionality.

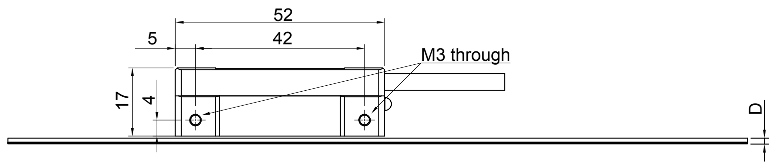
- **True absolute system**
- **Suitable for highly dynamic control loops**
- **Small footprint**
- **High accuracy**
- **Resolution to 0.244 µm**
- **Lengths up to 16.2 m**
- **Speeds up to 7 m/s at 0.977 µm resolution**
- **Integral status LED**
- **BiSS-C unidirectional communication protocol**
- **Simple and fast installation**
- **Robust measuring principle**
- **Excellent degree of protection to IP68**

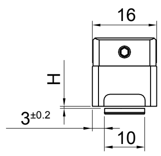
A RENISHAW associate company

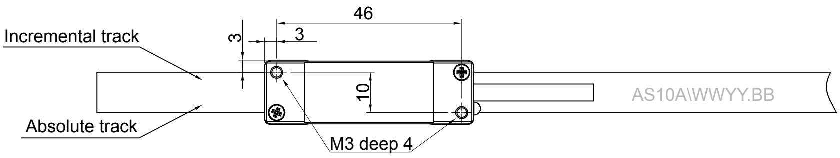
Data sheet
LMA10D01_02

LMA10 dimensions

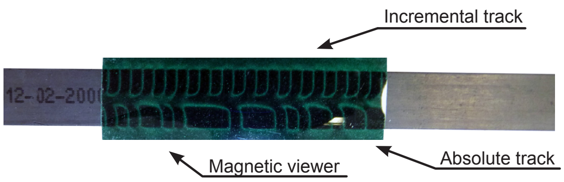
Dimensions and tolerance in mm.







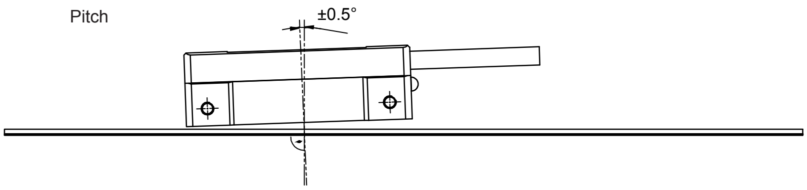
NOTE: Orientation of readhead relative to AS10 magnetic tape should be according to drawing. As reference use surface print on AS10 tape or use magnetic viewer (see image below).

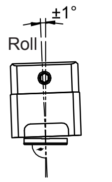


	Magnetic scale thickness (D)	Ride height (H)
With back-adhesion tape (option A)	$1.5^{\pm0.15}$	0.1 - 0.6
With back-adhesion tape, with cover foil (option B)	$1.6^{\pm0.15}$	0.1 - 0.5
No back-adhesion tape (option I)	$1.3^{\pm0.15}$	0.1 - 0.6
No back-adhesion tape, with cover foil (option N)	$1.4^{\pm0.15}$	0.1 - 0.5

LMA10 installation tolerances

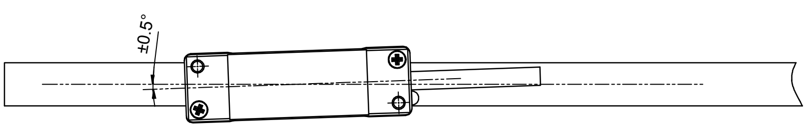
Pitch



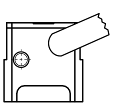


Yaw

Lateral offset



Status LEDs



LED	Communication	Status
Green	Yes	Valid position data
Green flashing	No	Valid position data
Orange	Yes	Valid position data, > 80 % of max. speed
Orange flashing	No	Valid position data, > 80 % of max. speed
Red	Yes	**Invalid** position data
Red flashing	No	**Invalid** position data

LMA10 technical specifications

System data	
Incremental pole length	2 mm
Maximum scale measuring length	16.332 m
System accuracy	±40 μm/m
Short range accuracy	< ±10 μm/10 mm (see diagram 3)
Hysteresis	< 2 μm (0.1 mm ride height) (see diagram 1)
Repeatability	Unit of resolution
Available resolutions	0.244 μm · 0.488 μm · 0.976 μm · 1.953 μm
Maximum traverse velocity	1.75 m/s · 3.5 m/s · 7 m/s · 14 m/s
Maximum velocity during power on	0.5 m/s
Electrical data	
Power supply	5 V ± 5 % (voltage on readhead) Consider voltage drop over cable (see diagram 2)
Set-up time after switch-on	< 250 ms
Power consumption (without load)	< 150 mA
Mechanical data	
Mass	Readhead (with 1 m cable, no connector) 41 g, magnetic scale 60 g/m
Cable	PUR high flexible cable, drag-chain compatible, double-shielded 8 × 0.05 mm²; durability: 20 million cycles at 20 mm bend radius at whole temperature range
Environmental data	
Temperature	Operating 0 °C to +55 °C
	Storage -20 °C to +85 °C
Vibrations (55 Hz to 2000 Hz)	300 m/s² (IEC 60068-2-6)
Shocks (11 ms)	300 m/s² (IEC 60068-2-27)
Humidity	100 % (condensation permitted)
EMC Immunity	IEC 61000-6-2 (particularly: ESD: IEC 61000-4-2; EM fields: IEC 61000-4-3; Burst: IEC 61000-4-4; Surge: IEC 61000-4-5; Conducted disturbances: IEC 61000-4-6; Power frequency magnetic fields: IEC 61000-4-8; Pulse magnetic fields: IEC 61000-4-9)
EMC Emission	IEC 61000-6-4 (for industrial, scientific and medical equipment: IEC 55011)
Environmental sealing	IP68 (according to IEC 60529)

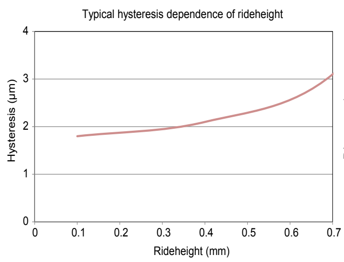


Diagram 1

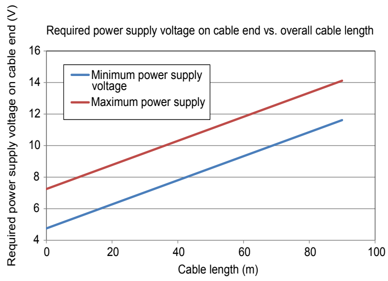


Diagram 2

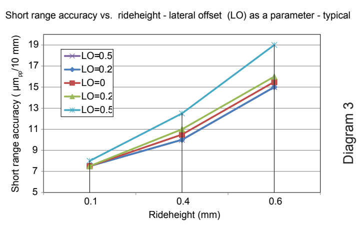
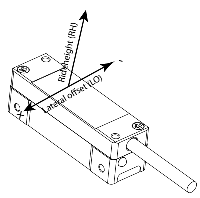


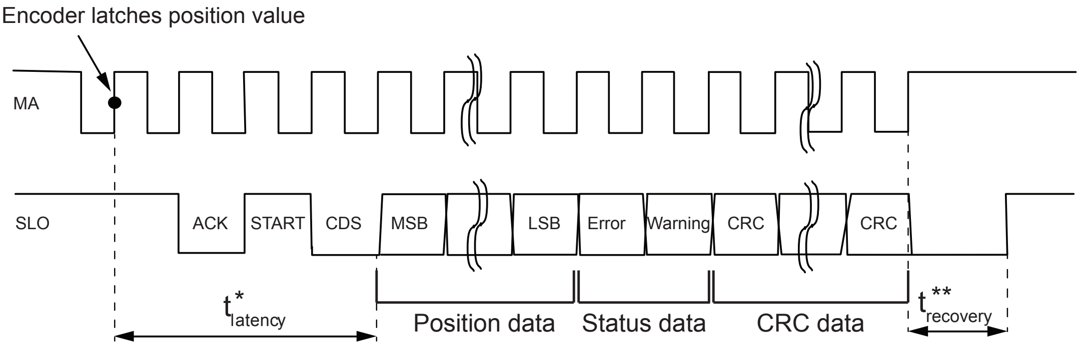
Diagram 3



LMA10 communication protocol – BiSS-C unidirectional

Type of interface	BiSS-C unidirectional (point to point)
Signal level	RS422
Maximum MA frequency	5 MHz
Length of position data	26 bit LSB= (2000 µm)/2^13 ≈ 0.244 µm
Length of status data	2 bit
Length of CRC	6 bit (inverted bit output – polynomial 0×43)
Position data encoding	Pure binary
Latency time *	0.8 µs at 5 MHz MA frequency; otherwise 4 MA clock periods
Recovery time **	≥5 µs

Timing diagram

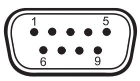


Status data

bit	Type	"H" ("L" at special option 03)	"L"("H" at special option 03)	Possible reason for failure
E	Alarm	Invalid position data	OK	Movement too fast, demagnetisation, sensing distance too high, orientation of readhead and scale
W	Warning	Valid position data, close to overspeed	OK	Current velocity is >80 % of maximum traverse velocity

Connections

9 pin D type plug



Pin	Colour	Signal
1	Internal shield	
2	Pink	MA+
3	Blue	MA-
4	Green	n.c.
5	Brown	+5 V
6	Grey	SLO+
7	Red	SLO-
8	Yellow	n.c.
9	White	0 V
Case	Outer shield	

LMA10 readhead part numbering

LMA10 DC 13B 10 A 00

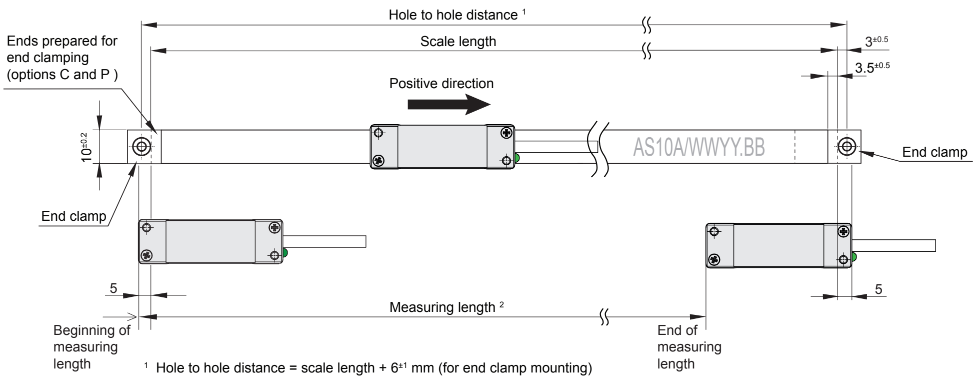
Output type
DC - BiSS-C communication protocol

Resolution
13B - 2/2[13] mm (~ 0.244 µm)
12B - 2/2[12] mm (~ 0.488 µm)
11B - 2/2[11] mm (~ 0.977 µm)
10B - 2/2[10] mm (~ 1.953 µm)

Cable length
10 - 1.0 m (standard)

Connector option
A - 9 pin D type plug
F - Flying lead (no connector)

Special requirements
00 - No special requirements (standard)
03 - LOW active status bits



[1] Hole to hole distance = scale length + $6^{\pm 1}$ mm (for end clamp mounting)
[2] Measuring length = scale length - 42 mm

AS10 magnetic scale part numbering

AS 10 A 01000 A 00

Scale width
10 - 10 mm width

Scale length
xxxxx - Where xxxxx equals scale length in mm

Options
A - No cover foil
B - Cover foil supplied (separately - 5 cm longer than tape)
C - No cover foil, ends prepared for end clamping
I - No back-adhesion tape
N - No back-adhesion tape, with cover foil
P - No back-adhesion tape, ends prepared for end clamping
G - Track system; sides prepared for insertion into track system
H - Track system; sides prepared for insertion into track system, with cover foil

Special requirements
00 - No special requirements (standard)

Accessories part numbering

Cover foil **CF 10 1000**

Foil width
10 - 10 mm width
08 - 08 mm width (CF for track system option **G**)

Foil length
xxxx - Where xxxx equals foil length in cm

Applicator tool for magnetic scale and cover foil	**LMA10ASC00**
End clamp kit (2 clamps + 2 screws)	**LM10ECL00**
Magnetic viewer	**MM0001**

A RENISHAW associate company

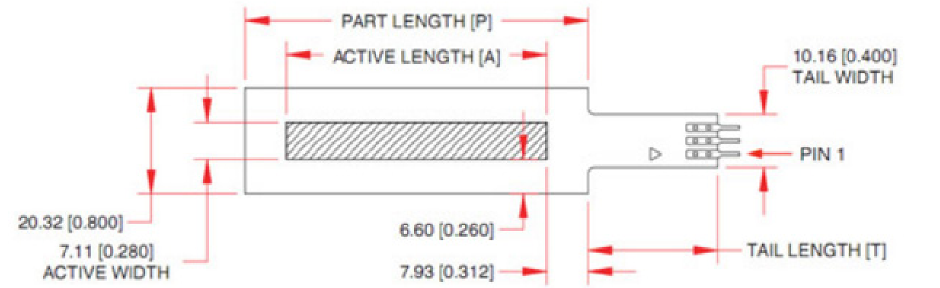
C.6. HotPot Data Sheet

Mechanical Specifications	
Life Cycle:	>10 million
Height:	≤0.51mm (0.020")
Actuation Force (with a 10mm wide active cavity):	-40°C 3.0 to 5.0 N -25°C 2.0 to 5.0 N +23°C 0.8 to 2.0 N +85°C 0.7 to 1.8 N

Electrical Specifications	
Resistance – Standard:	10k Ohms(lengths >300mm = 20k Ohms)
Resistance – Custom:	5k to 100k Ohms
Resistance Tolerance:	±20%
Effective Electrical Travel:	10 to 1200mm
Linearity (Independent):	Linear ±1% or ±3% Rotary ±3% or ±5%
Repeatability:	No hysteresis, but with any wiper looseness some hysteresis will occur
Power Rating (depending on size, varies with length and temperature):	1 Watt max. @ 25°C, ≤0.5 Watt recommended
Resolution:	Analog output theoretically infinite; affected by variation of contact wiper surface area.
Dielectric Value:	No affect @ 500VAC for 1 minute

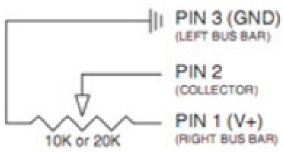
Environmental Specifications	
Operating Temperature:	-40°C to +85°C
Humidity:	No affect @ 95% RH, 24hrs 60°C
IP Rating of Active Area:	IP65

Dimensional Diagram - Stock Linear HotPots

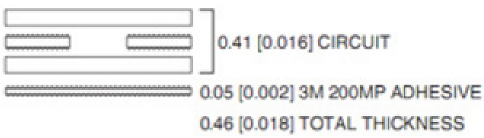


A	12.50mm 0.492"	25.00mm 0.984"	50.00mm 1.969"	100.00mm 3.937"	150.00mm 5.906"	170.00mm 6.693"	200.00mm 7.874"	300.00mm 11.811"	400.00mm 15.748"	500.00mm 19.685"	750.00mm 29.528"	1000.00mm 39.370"
P	28.36mm 1.117"	40.86mm 1.609"	65.86mm 2.593"	115.86mm 4.562"	165.86mm 6.531"	185.86mm 7.318"	215.86mm 8.499"	315.86mm 12.436"	415.86mm 16.373"	515.86mm 20.310"	765.86mm 30.153"	1015.86mm 39.995"
T	12.70mm 0.500"		24.89mm 0.980"									

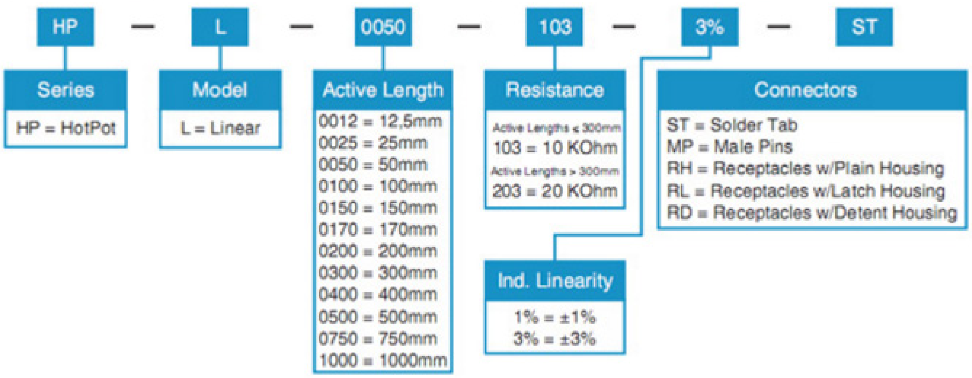
Electrical Schematic



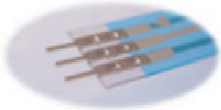
Material Cross-Section



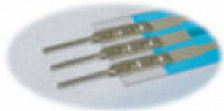
How to Order - Linear HotPots



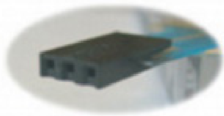
Standard Connector Options



Crimpflex Solder Tab (ST)



Crimpflex Short Male Pins (MP)



Crimpflex Female Receptacles with a Plain Housing (RH)

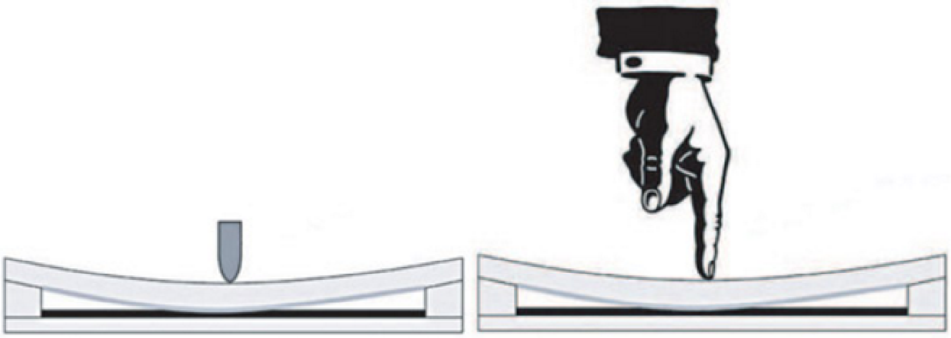
Crimpflex Female Receptacles with a Latch Housing (RL)

Crimpflex Female Receptacles with a Detent Housing (RD)

What is a HotPot
In simple terms, the HotPot membrane potentiometer is a resistive element, which comprises a conductive resistor, a sealed encasement and a simple wiper assembly. A membrane potentiometer can also function as a voltage divider.

The HotPot is a three-wire system with two resistive output channels and an electrical collector channel.

By pressing a wiper down onto the top circuit the HotPot produces the desired electrical output. The "wiper" is a non-conductive mechanism that depresses the top circuit actuating the potentiometer from the outside of the element. The top and bottom circuits are separated by 0.15mm (0.006") of spacer adhesive build-up and contact between the circuit occurs by pressure (usually 1-3 Newtons) from the wiper on the top circuit, pushing down until the top circuit connects with the bottom circuit to create a potentiometric output.



The construction of the wiper design can adapt to any application because most materials can serve as the wiper: plastics, metals, sliders, rollers, wheels, etc. Also, the HotPot can also be manually (hand) actuated.

C.7. LMA10 Magnetic Encoder Order Confirmation

5277 Trillium Boulevard
Hoffman Estates,IL 60192
United States

Fax: +1 847 286 9974

Email: usa@renishaw.com
Web: www.renishaw.com

RENISHAW
apply innovation™

ORDER ACKNOWLEDGEMENT

Order #: 550035

Ship To:
CALIFORNIA STATE POLYTECHNIC
CHRIS NAUGHTON
590 FELTON WAY
SAN LUIS OBISPO CA 93407

Bill To:
RENISHAW CALIFORNIA VISA
5277 TRILLIUM

SANTA FE SPRINGS CA 90670

Attention:

Order #:	550035
Customer #:	9004-CA
Customer PO:	CALIFSTPOLYTECHNIC
Order Date:	4/07/2016
Date Scheduled:	4/07/2016
Payment Terms:	**CREDIT CARDS**
Sales Contact:	KIM KRENZ
Tax Exempt?:	YES/NO
Certificate #:	
Tax Exemption:	

If exempt, please fax certificate to the Fax # shown above

YOUR ORDER HAS A 3-4 WK LEAD-TIME

Line	Product / Service Code	Qtv	List Price	Discount	Net Price	Total Price
	LMA10DC08B10A00 LMA10 7.713UM RES 1M CBL 9D SUB CONN	1	665.00	144.00	521.00	521.00
	LM10ECL00 END CLAMP KIT (2 CLAMPS + 2 SCREWS)	2	14.00	8.00	6.00	12.00
	CF100025 MS10 COVER FOIL 0.25M	1	2.00	0.00	2.00	2.00
	AS10A00255C00 AS10A SCALE 255MM FOR END CLAMPS	1	30.00	14.00	16.00	16.00
	AS10A00211C00 AS10A SCALE 211MM FOR END CLAMPS	1	26.00	10.00	16.00	16.00
	CF100021 MS10 COVER FOIL 0.21M	1	2.00	0.00	2.00	2.00
	FRT SHIPPING & HANDLING	1	15.00	0.00	15.00	15.00
	Subtotal Sales Tax:					584.00 45.52

Shipping Terms:	ENTERED	Grand Total: USD	**629.52**
Carrier:	UPS GROUND		

!! VERIFY ADDRESS OF CREDIT CARD HOLDER !!
THANK YOU FOR YOUR ORDER - IT HAS BEEN BILLED TO YOUR VISA

Continued...

C.8. Linear Potentiometer Order Confirmation

www.digikey.com
Orders 1-800-344-4539
Fax 218-681-3380

701 Brooks Ave. South, Thief River Falls, MN 56701-0677 USA

Invoice # **53052908**
U.S. $

Sold To:
CUSTOMER 8998429
MONCERRATT PERALTA
CA POLYTECHNIC STATE UNIVERSITY/
MECHANICAL ENGINEERING
1 GRAND AVE
SAN LUIS OBISPO CA 93407-0000

Bill To:
MONCERRATT PERALTA
CAL POLY STATE UNIVERSITY
13-263
1 GRAND AVENUE
SAN LUIS OBISPO CA 93407-0000

Terms	Invoice Date	Page
Visa	7-APR-2016	1

Customer Purchase Order	Sales Order
CNAUGHTON	46185794

Back Orders	Account
Accepts to 7-MAY-2016	31216

Entered By / Date	Shipped Via	Ship Date
ZUNI/ 7-APR-2016	XGT	7-APR-2016

Easy to Remember:
1-800-DIGI-KEY

For Office Use Only	Received	VAT/Tax ID	Billing	Pack List No.	Printing Date	Currency Type:	MSC #
	INTERNET		BILL SHIP	1	7-APR-2016	U.S. $	0

Idx	Box	Ordered	Cancelled	Shipped	Item Number/Description	Back Order	Unit Price US $	Amount US $
1	1	1	0	1	905-1012-ND SENSOR HOTPOT 10K OHM 200MM HTSUS: 8533.40.8070 ECCN: EAR99 LEAD: LEAD FREE ROHS: ROHS COMP REACH: REACH UNAFFECTED DEC-2015 Mercury: Cert on File. For more information contact RoHS@DigiKey.com COUNTRY/ORIGIN: USA CAGE: 4UC81		17.58000	17.58 T
2	1	1	0	1	905-1055-ND SENSOR SOFTPOT 10K OHM 300MM HTSUS: 8533.40.8070 ECCN: EAR99 LEAD: LEAD FREE ROHS: ROHS COMP REACH: REACH UNAFFECTED DEC-2015 Mercury: Cert on File. For more information contact RoHS@DigiKey.com COUNTRY/ORIGIN: USA CAGE: 4UC81		13.98000	13.98 T
					BOX 1 SHIPPED XGT WEIGHT 0 LBS 8 OZS (0.23 KG) BOX ID 012606072425960			
					TOTAL INVOICED			31.56
					SHIPPING CHARGES APPLIED			8.77
					** CHARGES SUBTOTAL **			40.33
					SALES TAX			2.52
					(T INDICATES TAXABLE AMOUNTS)			
					TOTAL CHARGED TO CREDIT CARD			42.85 U.S. $$
					YOUR CREDIT CARD HAS BEEN CHARGED THE ABOVE INDICATED AMOUNT THE ORDER IS COMPLETE			
					REF #: CNAUGHTON			
				Ship To:	CHRIS NAUGHTON CA POLYTECHNIC STATE UNIVERSITY/ MECHANICAL ENGINEERING 1 GRAND AVE MUSTANG 60 MACHINE SHOP SAN LUIS OBISPO CA 93407-0000			

Claims for pricing errors, shortages, and defective product must be reported within 30 days of invoice date.

Contact Customer Service at 1-800-858-3616

All transactions with Digi-Key, including its subsidiaries and/or affiliates, are subject to Digi-Key's Terms of Use and Conditions of Order, available at www.digikey.com.

DUNS No: 05 760 2120 FEI No: 41-1234968 Any applicable sales tax not collected on this invoice is the responsibility of the customer

C.9. Linear Potentiometer Custom Quote

To 'kinwei yu'
CC 'Shannon Mills'

Kinwei,

Thank you for your interest in our Hotpot and Magnetopot products for your application. Sorry it took me a few extra days to respond, I was out of the office all last week.

Would you be able to give me a quote on both a HotPot and MagnetoPot of length 250mm (~10 inches)? Are these directly purchasable from SpectraSymbol, or would we need to find them through a secondary seller like DigiKey?

Since 250mm isn't a standard off the shelf length that we offer this would be considered a custom product. We offer a prototype fee for new designs at a reasonable price.
Hotpot 250mm would be $3000.00 and that includes the custom tooling/nre and 10 pcs of your custom length.
Lead time is 5 weeks from order placed and paid for in advance.

Magnetopot 250mm would be $4000.00 and that includes the custom tooling/nre and 10 pcs of your custom length.
Lead time is 7 weeks from order placed and paid for in advance.

Lastly, could you provide some insight on the accuracy and resolution of these devices? Is it almost entirely dependent on the size of the actuator (at least for the HotPot), and is the hysteresis a property that is similar to resolution?
Ultimately the resolution is infinite but you are correct in understanding that it is entirely dependent on the size of the actuator for the hotpot and the hysteresis for the Mangetopot. It is recommended to have a strong drive magnet on your piston not necessarily a large magnet. Large diameter magnet will increase you hysteresis.

Shannon Mills
Business Development Engineer
Spectra Symbol Corp www.spectrasymbol.com
Tel: 801-972-6995 ext. 20 | Fax: 801-972-8012
SMills@spectrasymbol.com
3101 West 2100 South Salt Lake City, UT 84119

spectrasymbol

C.10. Velmex Slider Pricing

Velmex, Inc. 2014 Pricing

"Positioning Systems for Science and Industry"

Effective 2/1/2014

Prices subject to change without notice.

UniSlide® Manual Series A15

UniSlide® Manual Series A15 with standard 1.5" length slider

Read down for travel, across for desired lead screw and price. Call Velmex for longer units.

A15 Free Sliding Models — **Price with Std. Length Slider**

Travel Inches	Item Number	Base Length	Weight lbs.	Weight kg	2014 Price
1.5ò	A1503A-S1.5	3ò	0.31	0.14	$89
4.5ò	A1506A-S1.5	6ò	0.44	0.2	$103
7.5ò	A1509A-S1.5	9ò	0.63	0.28	$121
10.5ò	A1512A-S1.5	12ò	0.81	0.37	$141
13.5ò	A1515A-S1.5	15ò	1	0.45	$160
16.5ò	A1518A-S1.5	18ò	1.2	0.54	$178
19.5ò	A1521A-S1.5	21ò	1.44	0.65	$199
22.5ò	A1524A-S1.5	24ò	1.63	0.74	$221
25.5ò	A1527A-S1.5	27ò	1.82	0.83	$250

A15 Screw Drive Models

Travel Inches	Lead Screw Pitch 40 turns inch	20 turns inch	10 turns cm.	5 turns cm.	Base Length	Weight lbs.	Weight kg	2014 Price
1.5"	A1503C-S1.5	A1503B-S1.5	A1503K1-S1.5	A1503K2-S1.5	3"	0.5	0.23	$176
4.5"	A1506C-S1.5	A1506B-S1.5	A1506K1-S1.5	A1506K2-S1.5	6"	0.5	0.23	$197
7.5"	A1509C-S1.5	A1509B-S1.5	A1509K1-S1.5	A1509K2-S1.5	9"	0.75	0.34	$220
10.5"	A1512C-S1.5	A1512B-S1.5	A1512K1-S1.5	A1512K2-S1.5	12"	1	0.45	$241
13.5"	A1515C-S1.5	A1515B-S1.5	A1515K1-S1.5	A1515K2-S1.5	15"	1.25	0.57	$264

A15 Graduated Knob Models

Travel Inches	40 turns inch	20 turns inch	10 turns cm.	5 turns cm.	Base Length	Weight lbs.	Weight kg	2014 Price
1.5"	A1503P40-S1.5	A1503P20-S1.5	A1503Q1-S1.5	A1503Q2-S1.5	3"	0.5	0.23	$300
4.5"	A1506P40-S1.5	A1506P20-S1.5	A1506Q1-S1.5	A1506Q2-S1.5	6"	0.5	0.23	$319
7.5"	A1509P40-S1.5	A1509P20-S1.5	A1509Q1-S1.5	A1509Q2-S1.5	9"	0.75	0.34	$347
10.5"	A1512P40-S1.5	A1512P20-S1.5	A1512Q1-S1.5	A1512Q2-S1.5	12"	1	0.45	$367

A15 Scale and Vernier Screw Drive Models

Travel Inches	40 turns inch	20 turns inch	10 turns cm.	5 turns cm.	Base Length	Weight lbs.	Weight kg	2014 Price
1.5"	A1503CE-S1.5	A1503BE-S1.5	A1503K1M-S1.5	A1503K2M-S1.5	3"	0.5	0.23	$260
4.5"	A1506CE-S1.5	A1506BE-S1.5	A1506K1M-S1.5	A1506K2M-S1.5	6"	0.5	0.23	$295
7.5"	A1509CE-S1.5	A1509BE-S1.5	A1509K1M-S1.5	A1509K2M-S1.5	9"	0.75	0.34	$332
10.5"	A1512CE-S1.5	A1512BE-S1.5	A1512K1M-S1.5	A1512K2M-S1.5	12"	1	0.45	$371

A15 Rapid Advance Model D, DE/DM with Scale and Vernier and GE/GM with Micrometer, all with limited fine adjust

Travel Inches	Model D	Base Length	Weight lbs.	Weight kg	2014 Price
1.5"	A1503D-S1.5	3"	0.5	0.23	$248
4.5"	A1506D-S1.5	6"	0.5	0.23	$270
7.5"	A1509D-S1.5	9"	0.75	0.34	$295
10.5"	A1512D-S1.5	12"	1	0.45	$322

with Scale and Vernier

Travel Inches	Model DE	Model DM		Base Length	Weight lbs.	Weight kg	2014 Price
1.5"	A1503DE-S1.5	A1503DM-S1.5		3"	0.5	0.23	$330
4.5"	A1506DE-S1.5	A1506DM-S1.5		6"	0.5	0.23	$366
7.5"	A1509DE-S1.5	A1509DM-S1.5		9"	0.75	0.34	$407
10.5"	A1512DE-S1.5	A1512DM-S1.5		12"	1	0.45	$449

TF: 800-642-6446
P: +1-585-657-6151
P: +1-585-624-1080
F: +1-585-657-6153

info@velmex.com
www.unislide.com
www.velmex.com

C.11. McMaster-Carr Materials and Mechanical Components Order Confirmation

McMASTER-CARR

Receipt

562-692-5911
562-695-2323 (fax)
la.sales@mcmaster.com

Purchase Order	**AVST**
Paid	**$247.43**
Invoice	**59697087**
Invoice Date	**5/13/16**

Billed to

ATTENTION: MONCERRATT PERALTA
CALIFORNIA POLYTECHNIC STATE UNIVERSITY
1 GRAND AVE
SAN LUIS OBISPO CA 93407-9000

Shipped to

Attention: Kinwie Yu
Mustang 60 Machine Shop
Mustang 60 Machine Shop
California Polytechnic State University
1 Grand Ave
San Luis Obispo CA 93407-9000

Information About Your Payment

Credit Card	Visa Ending- 6364
Date	5/16/16
Name on Card	Moncerratt Peralta
Your Account	171690100

Moncerratt Peralta placed this order.

Line		Product	Ordered	Shipped	Balance	Price	Total
1	84765A71	Stainless Steel Spring Plunger with Long Plastic Nose, without Lock Element, 8-32, .7-2.3 lb Nose Force	1 Each	1	0	5.57 Each	5.57
2	92290A126	Type 316 Stainless Steel Socket Head Cap Screw, M3 Thread, 30MM Length, .5MM Pitch, Packs of 25	1 Pack	1	0	6.80 Per Pack	6.80
3	92196A151	18-8 Stainless Steel Socket Head Cap Screw, 6-32 Thread, 3/4" Length, Packs of 100	1 Pack	1	0	5.83 Per Pack	5.83
4	94209A626	Thread-Forming Screw for Soft Metal, Zinc-Plated Steel, M3 X 0.5 Thread, 12MM Length, Packs of 25	1 Pack	1	0	7.64 Per Pack	7.64
5	8739K61	White Delrin Acetal Resin Rectangular Bar 1-1/4" Thick X 3" Width, 1 ft. Length	1 Each	1	0	32.89 Each	32.89
6	9089K139	PEEK Rectangular Bar, 3/4" Thick, 2" Width, 1' Length	1 Each	1	0	165.78 Each	165.78

Merchandise	224.51
Sales Tax	16.84
Shipping	6.08
Total	$247.43
Payment Received 5/16/16	(247.43)
Balance Due	$0.00

Packing List	Shipped	Weight	Carrier	Tracking
3330243-01	5/13/16	5 lb	UPS Ground	1Z9293810365358161

Federal ID 36-1458720 McMaster-Carr Supply Company Page 1 of 1

C.12. Benchtop Testing Data

Data Point	Encoder			LinPot			inches to V	Theoretical Slope	Experimental Slope	Y Intercept	t	Max Uncertainty (in)	Max Residual (in)	
							0.423333333	2.362204724	2.2501	0.0547	1.984	0.04257343	0.0488	
	Initail Position [in]	position [in]	distance [in]	Initial Postion [in]	position [in]	distance [in]	Linpot voltage from Distance	Yc	Y-Yc	(Y-Yc)^2	U	XI-XBAR	SUM	
1	2.527	3.16	0.633	1.87	2.49	0.62	0.262	0.645	-0.012	0.00015	0.0424	2.025	64.19	
2	2.527	7.266	4.739	1.87	6.81	4.94	2.091	4.760	-0.021	0.00045	0.0418	0.165	AVERAGE	
3	2.527	5.801	3.274	1.87	5.25	3.38	1.431	3.274	0.000	0.00000	0.0418	0.065	1.685	
4	2.527	4.518	1.991	1.87	3.87	2	0.847	1.960	0.031	0.00097	0.0420	0.703	Sum	
5	2.527	3.493	0.966	1.87	2.82	0.95	0.402	0.960	0.006	0.00004	0.0423	1.647	0.04391	
6	2.527	5.473	2.946	1.87	4.88	3.01	1.274	2.922	0.024	0.00058	0.0418	0.169	Syx	
7	2.527	6.246	3.719	1.87	5.73	3.86	1.634	3.732	-0.013	0.00016	0.0418	0.003	0.0210	
8	2.527	6.666	4.139	1.87	6.16	4.29	1.816	4.141	-0.002	0.00000	0.0418	0.017	Percent Uncertainty From Residual (%)	
9	2.527	4.977	2.45	1.87	4.35	2.48	1.050	2.417	0.033	0.00109	0.0419	0.404	0.650	
10	2.527	4.016	1.489	1.87	3.36	1.49	0.631	1.474	0.015	0.00023	0.0421	1.112		
11	2.527	2.922	0.395	1.87	2.25	0.38	0.161	0.417	-0.022	0.00047	0.0425	2.324		
12	2.527	7.361	4.834	1.87	6.91	5.04	2.134	4.856	-0.022	0.00046	0.0418	0.201		
13	2.527	7.67	5.143	1.87	7.23	5.36	2.269	5.160	-0.017	0.00030	0.0419	0.341		
14	2.527	4.668	2.141	1.87	4.03	2.16	0.914	2.112	0.029	0.00083	0.0420	0.594		
15	2.527	5.855	3.328	1.87	5.3	3.43	1.452	3.322	0.006	0.00004	0.0418	0.054		
16	2.527	4.255	1.728	1.87	3.6	1.73	0.732	1.703	0.025	0.00065	0.0421	0.908		
17	2.527	6.894	4.367	1.87	6.41	4.54	1.922	4.379	-0.012	0.00015	0.0418	0.056		
18	2.527	2.888	0.361	1.87	2.22	0.35	0.148	0.388	-0.027	0.00073	0.0425	2.363		
19	2.527	3.486	0.959	1.87	2.81	0.94	0.398	0.950	0.009	0.00008	0.0423	1.657		
20	2.527	5.289	2.762	1.87	4.69	2.82	1.194	2.741	0.021	0.00045	0.0419	0.242		
21	2.527	5.519	2.992	1.87	4.94	3.07	1.300	2.979	0.013	0.00017	0.0418	0.149		
22	2.527	6.246	3.719	1.87	5.72	3.85	1.630	3.722	-0.003	0.00001	0.0418	0.003		
23	2.527	6.776	4.249	1.87	6.29	4.42	1.871	4.265	-0.016	0.00025	0.0418	0.035		
24	2.527	3.122	0.595	1.87	2.46	0.59	0.250	0.617	-0.022	0.00047	0.0424	2.061		
25	2.527	7.519	4.992	1.87	7.08	5.21	2.206	5.017	-0.025	0.00065	0.0419	0.271		
26	2.527	5.904	3.377	1.87	5.36	3.49	1.477	3.379	-0.002	0.00000	0.0418	0.043		
27	2.527	3.989	1.462	1.87	3.33	1.46	0.618	1.445	0.017	0.00028	0.0421	1.139		
28	2.527	6.67	4.143	1.87	6.18	4.31	1.825	4.160	-0.017	0.00029	0.0418	0.019		
29	2.527	3.109	0.582	1.87	2.44	0.57	0.241	0.598	-0.016	0.00024	0.0424	2.085		
30	2.527	5.132	2.605	1.87	4.51	2.64	1.118	2.569	0.036	0.00127	0.0419	0.322		
31	2.527	5.501	2.974	1.87	4.91	3.04	1.287	2.950	0.024	0.00056	0.0418	0.159		
32	2.527	6.033	3.506	1.87	5.49	3.62	1.532	3.503	0.003	0.00001	0.0418	0.023		
33	2.527	6.452	3.925	1.87	5.94	4.07	1.723	3.932	-0.007	0.00004	0.0418	0.001		
34	2.527	4.174	1.647	1.87	3.52	1.65	0.699	1.626	0.021	0.00042	0.0421	0.974		
35	2.527	2.941	0.414	1.87	2.28	0.41	0.174	0.445	-0.031	0.00098	0.0425	2.286		
36	2.527	4.757	2.23	1.87	4.12	2.25	0.953	2.198	0.032	0.00103	0.0419	0.537		
37	2.527	7.472	4.945	1.87	7.03	5.16	2.184	4.970	-0.025	0.00062	0.0419	0.249		
38	2.527	7.187	4.66	1.87	6.73	4.86	2.057	4.684	-0.024	0.00058	0.0418	0.138		
39	2.527	3.907	1.38	1.87	3.24	1.37	0.580	1.360	0.020	0.00041	0.0422	1.222		
40	2.527	4.981	2.454	1.87	4.35	2.48	1.050	2.417	0.037	0.00137	0.0419	0.404		
41	2.527	6.023	3.496	1.87	5.48	3.61	1.528	3.493	0.003	0.00001	0.0418	0.025		
42	2.527	6.381	3.854	1.87	5.87	4	1.693	3.865	-0.011	0.00012	0.0418	0.000		
43	2.527	3.421	0.894	1.87	2.75	0.88	0.373	0.893	0.001	0.00000	0.0423	1.724		
44	2.527	3.022	0.495	1.87	2.36	0.49	0.207	0.521	-0.026	0.00070	0.0425	2.184		
45	2.527	4.327	1.8	1.87	3.67	1.8	0.762	1.769	0.031	0.00094	0.0421	0.853		
46	2.527	4.811	2.284	1.87	4.18	2.31	0.978	2.255	0.029	0.00084	0.0419	0.501		
47	2.527	5.83	3.303	1.87	5.27	3.4	1.439	3.293	0.010	0.00009	0.0418	0.061		
48	2.527	7.496	4.969	1.87	7.05	5.18	2.193	4.989	-0.020	0.00039	0.0419	0.258		
49	2.527	6.926	4.399	1.87	6.45	4.58	1.939	4.417	-0.018	0.00034	0.0418	0.064		
50	2.527	6.313	3.786	1.87	5.8	3.93	1.664	3.798	-0.012	0.00015	0.0418	0.000		
51	2.527	2.773	0.246	1.87	2.12	0.25	0.106	0.293	-0.047	0.00219	0.0426	2.495		
52	2.527	7.831	5.304	1.87	7.4	5.53	2.341	5.322	-0.018	0.00033	0.0419	0.430		
53	2.527	6.066	3.539	1.87	5.54	3.67	1.554	3.551	-0.012	0.00013	0.0418	0.017		
54	2.527	8.192	5.665	1.87	7.76	5.89	2.493	5.665	0.000	0.00000	0.0420	0.653		
55	2.527	7.323	4.796	1.87	6.87	5	2.117	4.817	-0.021	0.00046	0.0418	0.186		
56	2.527	8.51	5.983	1.87	8.08	6.21	2.629	5.970	0.013	0.00017	0.0421	0.890		
57	2.527	7.546	5.019	1.87	7.11	5.24	2.218	5.046	-0.027	0.00073	0.0419	0.284		
58	2.527	6.336	3.809	1.87	5.82	3.95	1.672	3.817	-0.008	0.00007	0.0418	0.000		
59	2.527	5.5	2.973	1.87	4.91	3.04	1.287	2.950	0.023	0.00051	0.0418	0.159		
60	2.527	6.359	3.832	1.87	5.85	3.98	1.685	3.846	-0.014	0.00019	0.0418	0.000		
61	2.527	8.395	5.868	1.87	7.97	6.1	2.582	5.865	0.003	0.00001	0.0420	0.805		
62	2.527	7.62	5.093	1.87	7.19	5.32	2.252	5.122	-0.029	0.00085	0.0419	0.321		
63	2.527	9.765	7.238	1.87	9.36	7.49	3.171	7.189	0.049	0.00238	0.0425	2.206		
64	2.527	8.139	5.612	1.87	7.72	5.85	2.477	5.627	-0.015	0.00023	0.0420	0.626		
65	2.527	7.343	4.816	1.87	6.9	5.03	2.129	4.846	-0.030	0.00090	0.0418	0.197		
66	2.527	9.056	6.529	1.87	8.65	6.78	2.870	6.513	0.016	0.00026	0.0422	1.404		
67	2.527	7.475	4.948	1.87	7.03	5.16	2.184	4.970	-0.022	0.00048	0.0419	0.249		
68	2.527	5.972	3.445	1.87	5.43	3.56	1.507	3.446	-0.001	0.00000	0.0418	0.032		
69	2.527	4.964	2.437	1.87	4.34	2.47	1.046	2.407	0.030	0.00087	0.0419	0.409		
70	2.527	8.384	5.857	1.87	7.96	6.09	2.578	5.856	0.001	0.00000	0.0420	0.797		
71	2.527	7.091	4.564	1.87	6.62	4.75	2.011	4.579	-0.015	0.00023	0.0418	0.106		
72	2.527	6.607	4.08	1.87	6.11	4.24	1.795	4.093	-0.013	0.00018	0.0418	0.012		
73	2.527	9.167	6.64	1.87	8.77	6.9	2.921	6.627	0.013	0.00016	0.0423	1.527		
74	2.527	7.614	5.087	1.87	7.17	5.3	2.244	5.103	-0.016	0.00026	0.0419	0.312		
75	2.527	8.542	6.015	1.87	8.12	6.25	2.646	6.008	0.007	0.00005	0.0421	0.922		
76	2.527	6.345	3.818	1.87	5.84	3.97	1.681	3.836	-0.018	0.00033	0.0418	0.000		
77	2.527	7.796	5.269	1.87	7.34	5.47	2.316	5.265	0.004	0.00002	0.0419	0.397		
78	2.527	5.554	3.027	1.87	4.97	3.1	1.312	3.008	0.019	0.00038	0.0418	0.139		
79	2.527	7.756	5.229	1.87	7.33	5.46	2.311	5.256	-0.027	0.00071	0.0419	0.392		
80	2.527	8.91	6.383	1.87	8.5	6.63	2.807	6.370	0.013	0.00017	0.0422	1.257		
81	2.527	6.552	4.025	1.87	6.05	4.18	1.770	4.036	-0.011	0.00013	0.0418	0.007		
82	2.527	7.73	5.203	1.87	7.28	5.41	2.290	5.208	-0.005	0.00002	0.0419	0.366		
83	2.527	5.59	3.063	1.87	5.02	3.15	1.334	3.055	0.008	0.00006	0.0418	0.124		
84	2.527	5.225	2.698	1.87	4.62	2.75	1.164	2.674	0.024	0.00057	0.0419	0.272		
85	2.527	8.331	5.804	1.87	7.91	6.04	2.557	5.808	-0.004	0.00002	0.0420	0.760		
86	2.527	7.499	4.972	1.87	7.06	5.19	2.197	4.998	-0.026	0.00070	0.0419	0.262		
87	2.527	8.687	6.16	1.87	8.26	6.39	2.705	6.141	0.019	0.00034	0.0421	1.040		
88	2.527	9.197	6.67	1.87	8.78	6.91	2.925	6.637	0.033	0.00110	0.0423	1.537		
89	2.527	6.607	4.08	1.87	6.11	4.24	1.795	4.093	-0.013	0.00018	0.0418	0.012		
90	2.527	5.291	2.764	1.87	4.69	2.82	1.194	2.741	0.023	0.00054	0.0419	0.242		
91	2.527	7.685	5.158	1.87	7.251	5.381	2.278	5.180	-0.022	0.00050	0.0419	0.351		
92	2.527	9.712	7.185	1.87	9.31	7.44	3.150	7.142	0.043	0.00188	0.0425	2.144		
93	2.527	8.606	6.079	1.87	8.19	6.32	2.675	6.075	0.004	0.00002	0.0421	0.980		
94	2.527	6.697	4.17	1.87	6.21	4.34	1.837	4.189	-0.019	0.00035	0.0418	0.023		
95	2.527	9.314	6.787	1.87	8.9	7.03	2.976	6.751	0.036	0.00129	0.0423	1.666		
96	2.527	5.748	3.221	1.87	5.18	3.31	1.401	3.208	0.013	0.00018	0.0418	0.081		
97	2.527	8.665	6.138	1.87	8.24	6.37	2.697	6.122	0.016	0.00024	0.0421	1.023		
98	2.527	6.088	3.561	1.87	5.56	3.69	1.562	3.570	-0.009	0.00007	0.0418	0.015		
99	2.527	8.471	5.944	1.87	8.04	6.17	2.612	5.932	0.012	0.00015	0.0421	0.859		
100	2.527	7.366	4.839	1.87	6.92	5.05	2.138	4.865	-0.026	0.00068	0.0418	0.205		
101	2.527	9.183	6.656	1.87	8.78	6.91	2.925	6.637	0.019	0.00037	0.0423	1.537		
102	2.527	8.13	5.603	1.87	7.71	5.84	2.472	5.618	-0.015	0.00021	0.0420	0.619		

D. Design Analysis Appendix

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D.1. Failure Mode Effects Analysis Magnetic Encoder

(Design FMEA)

___ System
___ Subsystem
___ Component

Design Responsibility:

Model: LMA10 Magnetic Encoder

Key Date:4/30/16

Core Team: AVST

FMEA Number:

Page 1 of 1

Prepared By:AVST

FMEA Date (Orig.) (Rev.)

Item / Function	Potential Failure Mode	Potential Effect(s) of Failure	Sev	Potential Cause(s) / Mechanism(s) of Failure	Occur	Crit	Recommended Action(s)	Responsibility & Target Completion Date	Action Results: Actions Taken	Action Results: Sev	Action Results: Occur	Action Results: Crit
bracket/guide to hold encoder	loose bracket, broken bracket,	misalignment of encoder and inaccurate readings, damage to encoder, damage to piston	8	vibration, contact with piston	4	32	stiffen bracket, add fasteners to design	4/26/2016	Beam Calculation, None action needed	5	1	5
Accurate reading of piston's position	misaligned encoder	inaccurate reading or no reading at all	9	vibration, shaft twisting	5	45	tighten tolerances	4/26/2016	Guide re-designed so it will stop piston from moving too much.	7	2	14
Wires to transmit data between encoder and	damage to wires	fatigue,	7	wires moving with piston, entanglement,	4	28	investigate harness routing techniques to minimized friction	4/26/2016	Plastic Sleeving and strain reliefs to protect wiring	6	2	12
magnetic stripping to be read encoder	peeling off piston, adhesive melting	inaccurate reading or no reading at all	9	high temperatures, unknown sources of damage	2	18	ensure adhesive is rated for high temperature range	4/26/2016	verify not an issue with temperature testing	9	2	18

D.2. Failure Modes Effects Analysis Lin Pot

__ System (Design FMEA) FMEA Number:
___ Subsystem
___ Component Design Responsibility: AVST Page 1 of 1

Model: Linear Potentiometer **Key Date: 4/30/16** **Prepared By: AVST**

Core Team: **FMEA Date (Orig.)** **(Rev.)**

Item / Function	Potential Failure Mode	Potential Effect(s) of Failure	Sev	Potential Cause(s) / Mechanism(s) of Failure	Occur	Crit	Recommended Action(s)	Responsibility & Target Completion Date	Action Results: Actions Taken	Action Results: Sev	Action Results: Occur	Action Results: Crit
ball plunger to act as wiper	misalignment, too little or too much force, losing contact with lin-pot	inaccurate or no reading at all	8	screw becomes loose, vibration, thermal strain, piston moving	3	24	ensure design of ball plunger fixture allows for appropriate force applied	4/26/2016	loctite	7	2	14
adhesive sticking lin-pot to piston	adhseive melts off	inaccurate or no reading at all	8	high temperatures, foreign liquid dissolving adhesive, wear from plunger	5	40	choose an adhesive with high temperature range	4/26/2016	high temp adhesive selected	6	3	18
wires providing output	damage to wires	inaccurate or no reading at all	8	movement of wires due to piston moving	6	48	route the wires to prevent contact with piston and apply Scuff tape, Haylar, and other	4/26/2016	protective sleeving and strain reliefs	8	4	32

D.3. Design Verification Plan and Report

Linear Potentiometer

ME428 DVP&R Format

Report Date:4/14/2016 | Sponsor:Mike Brown | Component/Assembly | REPORTING ENGINEER: AVST

TEST PLAN: Linear Potentiometer / **TEST REPORT**

Item No	Specification or Clause Reference [1]	Test Description [2]	Acceptance Criteria [3]	Test Responsibility [4]	Test Stage [5]	SAMPLES TESTED		TIMING		TEST RESULTS			NOTES
						Quantity	ype [6	Start date	Finish date	est Result [7	Quantity Pass	Quantity Fail	
1	Accuracy	Verified in Bench Top Testing at Cal Poly. Use calipers as a reference	is +/- 0.100 "	AVST	DV	1	B	5/1/2016	12/6/2016	PASS	"+/- 0.65%	NA	
2	Empty Voltage	Verified in Bench Top Testing at Cal Poly. Visual inspection.	not 0 V	AVST	DV	1	B	5/1/2016	12/6/2016	PASS	not 0	NA	
3	Malfunction Voltage	Verified in Bench Top Testing at Cal Poly. Visual inspection.	display 0 V	AVST	DV	1	B	5/1/2016	12/6/2016	PASS	0 V	NA	
4	Max Extension Length	Verified in Bench Top Testing at Cal Poly. Visual inspection.	Read 10"	AVST	DV	1	B	5/1/2016	12/6/2016	PASS	11.26"	NA	
5	Start Up Time	Verified in Bench Top Testing at Cal Poly. Use stopwatch for verification	2 sec	AVST	DV	1	B	5/1/2016	12/6/2016	PASS	< 2 sec	NA	
6	Input Voltage Range	Verified in Bench Top Testing at Cal Poly. Verified with voltmeter	10-28V	AVST	DV	1	B	5/1/2016	12/6/2016	PASS	adjustable	NA	w/ voltage regulator
7	Output Voltage Range	Verified in Bench Top Testing at Cal Poly. Verified with voltmeter	1-5V or 1-10V	AVST	DV	1	B	5/1/2016	12/6/2016	PASS	adjustable	NA	w/ voltage regulator
8	Environmental Temp.	Oven Temperature Testing in Accumulator at PDT	survive -45 to180 F	AVST	DV	1	B	5/1/2016	12/6/2016	PASS	-40 - 185 F	NA	FROM DATASHEET
9													

ME428 DVP&R Format

Report Date:4/14/2016 | Sponsor:Mike Brown | Component/Assembly | REPORTING ENGINEER: AVST

TEST PLAN: Magnetic Encoder										TEST REPORT			
Item No	Specification or Clause Reference [8]	Test Description [9]	Acceptance Criteria [10]	Test Responsibility	Test Stage [12]	SAMPLES TESTED		TIMING		TEST RESULTS			NOTES
						Quantity	ype [1	Start date	Finish date	est Result [1	Quantity Pass	Quantity Fail	
1	Accuracy	Verified in Bench Top Testing at Cal Poly. Use calipers as a reference	is +/- 0.100 "	AVST	DV	1	B	5/1/2016	12/6/2016	PASS	"+/- 0.0000011%	NA	
2	Empty Voltage	Verified in Bench Top Testing at Cal Poly. Visual inspection.	not 0 V	AVST	DV	1	B	5/1/2016	12/6/2016	NA	NA	NA	DIGITAL
3	Malfunction Voltage	Verified in Bench Top Testing at Cal Poly. Visual inspection.	display 0 V	AVST	DV	1	B	5/1/2016	12/6/2016	NA	NA	NA	DIGITAL
4	Max Extension Length	Verified in Bench Top Testing at Cal Poly. Visual inspection.	Read 10"	AVST	DV	1	B	5/1/2016	12/6/2016	PASS	10"	NA	
5	Start Up Time	Verified in Bench Top Testing at Cal Poly. Use stopwatch for verification	2 sec	AVST	DV	1	B	5/1/2016	12/6/2016	PASS	< 2 sec	NA	
6	Input Voltage Range	Verified in Bench Top Testing at Cal Poly. Verified with voltmeter	10-28V	AVST	DV	1	B	5/1/2016	12/6/2016	PASS	adjustable	NA	w/ VOLTAGE REGULATOR
7	Output Voltage Range	Verified in Bench Top Testing at Cal Poly. Verified with voltmeter	1-5V or 1-10V	AVST	DV	1	B	5/1/2016	12/6/2016	NA	NA	NA	DIGITAL
8	Environmental Temp.	Oven Temperature Testing in Accumulator at PDT	survive -45 to180 F	AVST	DV	1	B	5/1/2016	12/6/2016	FAIL	NA	32 TO 131 F	FROM DATASHEET
9													

D.4. Encoder Support Deflection

Deflection of the Encoder Support was determined to be negligible in our design.

______ - 12

BOOK PAGE

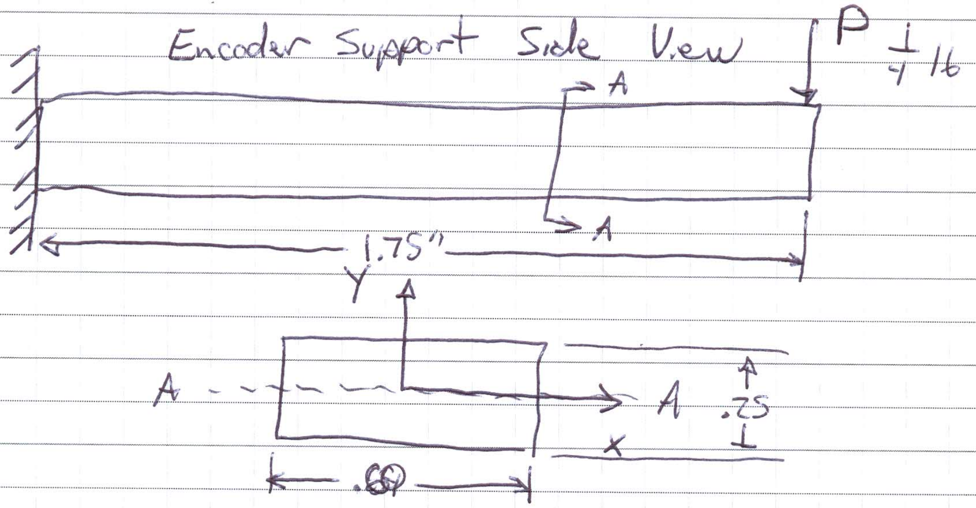
TITLE Deflection Calculation **PROJECT**

Continued from Page

Given: Dimensions, mass, material properties

Find: Deflection From a certain Force or Force From certain deflection

Schematic



$$I_x = \frac{1}{12}(.60)(.25)^3 = 7.8125 \times 10^{-4}\ in^4$$

$$\Delta y = \frac{PL^3}{3EI} = \frac{.25\,(1.75)^3\ in^4}{3\left(2.9 \times 10^7 \frac{lb_f}{in^2}\right) 7.8 \times 10^{-4}\ in^4}$$

$$\Delta y = 2 \times 10^{-5}\ in$$

0.001" Deflection with 12.6 lb_f

Continued to Page

SIGNATURE

DATE 4/30/16

DISCLOSED TO AND UNDERSTOOD BY

DATE

PROPRIETARY INFORMATION

D.5. Encoder Tolerance Analysis

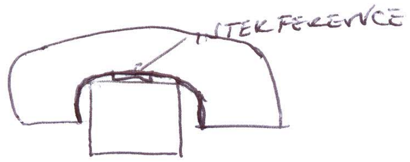
The tolerances in our technical drawings were derived from these three case studies.

4/18/16: TOLERANCING ENCODER DESIGN

CASES OF CONCERN:

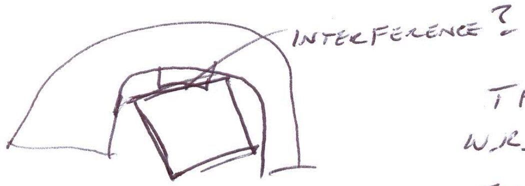
TOP VIEWS

1



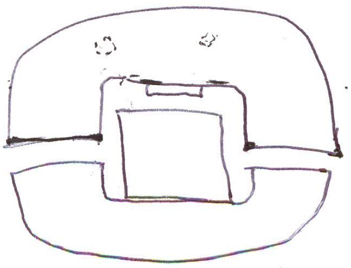
THE SHAFT EDGES PRESSED UP AGAINST GUIDE RADII

2



THE SHAFT TWISTED W.R.T. GUIDE AT AN EXTREME
↳ ANGLE OUT OF TOLERANCE FOR ENCODER?

3



SHAFT AGAINST FAR SIDE
↳ FALL OUT OF RANGE?

CASE:	RESOLUTION:
1	DESIGNED SO ~~0.007"~~ 0.004" CLEARANCE (> 0.003" NEEDED FOR ENCODER READINGS)
2	SHORTENED WIGGLE ROOM TO ABOUT ~~0.010~~ 0.01"
3	DESIGNED SO ~~0.018"~~ 0.019" IS FURTHEST (< 0.023" NEEDED FOR ENCODER READING)

PISTON WIGGLE ROOM IS ± 0.0025", THE NOMINAL DISTANCE IS 0.006".

ALL CRITICAL DIMS MUST BE ±0.0025"

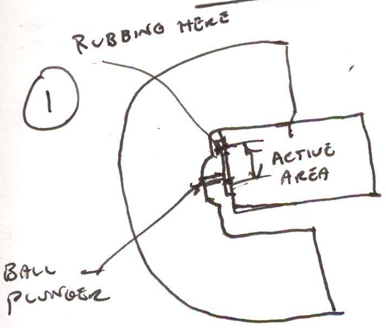
D.6. Linear Potentiometer Tolerance Analysis

The tolerances in our technical drawings were derived from these three case studies.

CASES OF CONCERN:

TOP VIEWS:

(1)



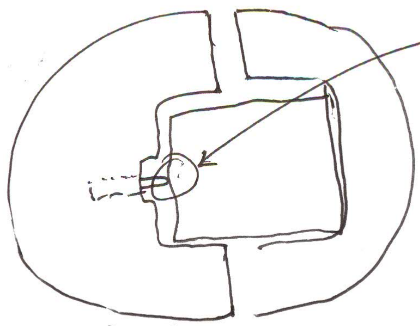
THE SHAFT FAVORS ONE SIDE AND THE POT'S ACTIVE AREA RUBS ON THE CORNER OF THE RECESS.

CURRENT AMOUNT OF ACTIVE AREA RUBBING: 0.0715"

RESOLVED CLEARANCE: 0.016" → MAX: 0.021" / MIN: 0.011" CLEARANCE

THIS DIM CAN BE ±.005

(2)



BALL PLUNGER LOSES CONTACT W/ THE STRIP.

NEED: TRAVEL AND ENGAGEMENT OF BALL PLUNGER TO BE MORE THAN PISTON MOVEMENT

CONFIRMATION: PISTON MAX MOVEMENT IS 0.078" AND BALL PLUNGER HAS 0.300" MOVEMENT

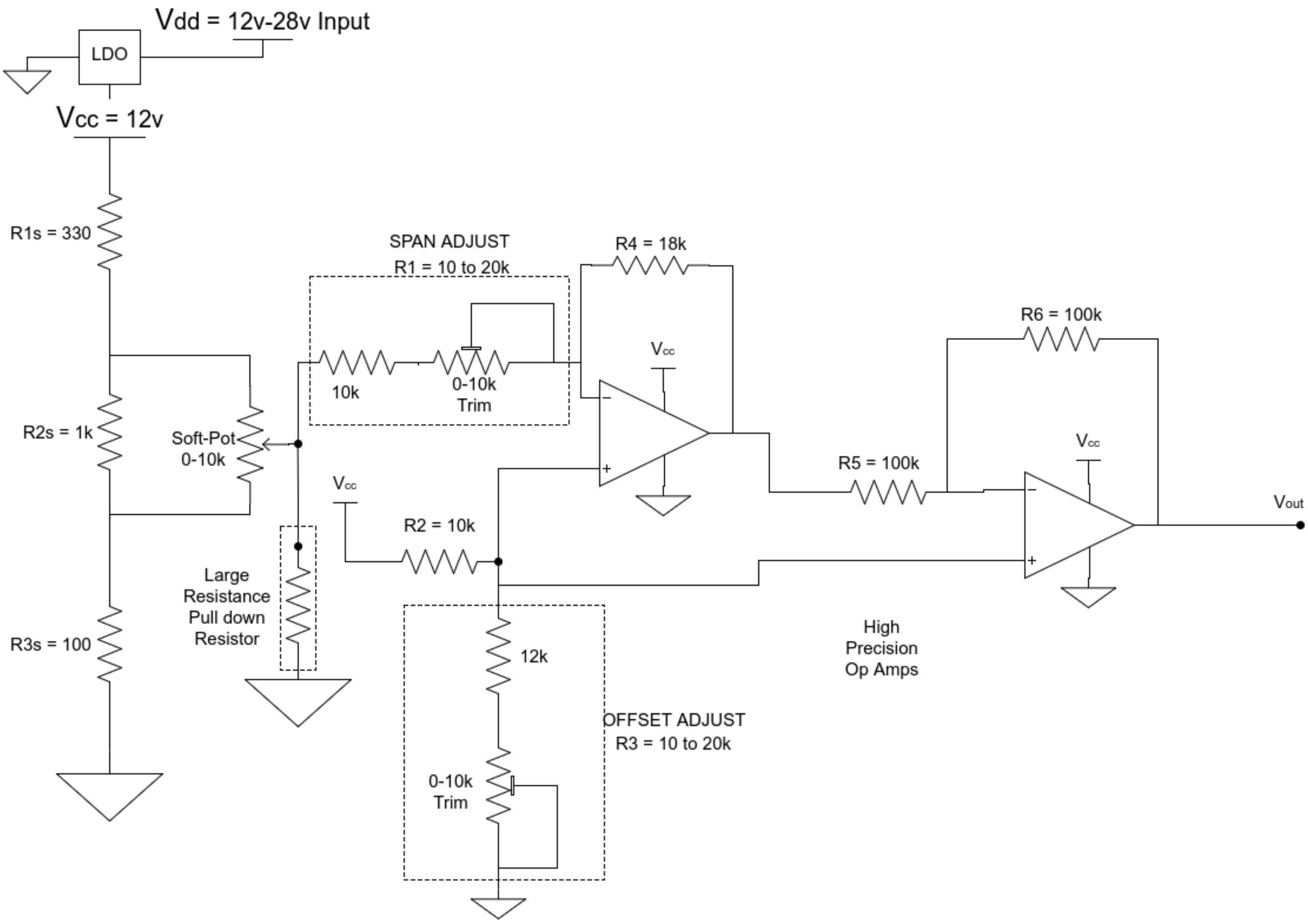
(3) NEED A BALL PLUNGER W/ ALLEN SOCKET ON OPPOSITE SIDE BUT STILL SATISFYING THE SPECS OF (2)

OR

BUY BALL PLUNGER WRENCH FROM MCMASTER AND INSTALL TIP SO THAT THE BODY TIP OF THE PLUGER IS VISIBLE ON SHAFT SIDE

D.7. Linear Potentiometer Signal Circuit

The following circuit was designed in order to obtain an adjustable analog output from the linear potentiometer (Soft-Pot or Hot-Pot).



Analysis was performed on this circuit in order to justify it.

Analysis begins with the potentiometer circuit on the left hand side consisting of R_{1s}, R_{2s}, and R_{3s}.

$$R_{eq} = R_{1s} + R_{3s} + \frac{1}{\frac{1}{R_{2s}} + \frac{1}{10k\Omega}}$$

The resistance values were picked such that $(R_{1s}, R_{2s}, R_{3s}) << 10k\Omega$ so that most current flow is through the resistors, and not the linear pot. This is to avoid conflicts with the loose tolerance of the soft-pot of $\pm 20\%$. With the chosen resistances above, the

equivalent resistance is:

$$
\begin{aligned}
R_{eq} &= \left(330 + 100 + \frac{1}{\frac{1}{1k} + \frac{1}{10k}}\right)\Omega \\
&= 1339\Omega
\end{aligned}
$$

The current through the circuit assuming $V_{cc} = 12v$ is then:

$$
\begin{aligned}
i_s &= \frac{12v}{1339\Omega} \\
&\approx 9\,mA
\end{aligned}
$$

The current can then be used to calculate the maximum and minimum voltage output of the linear potentiometer's wiper in this configuration:

$$
\begin{aligned}
V_{max} &= 12v - \frac{12v}{1339\Omega} \times 330\Omega \\
&= 9.04v \\
V_{min} &= \frac{12v}{1339\Omega} \times 100\Omega \\
&= 0.89v
\end{aligned}
$$

This is close to the 1v to 10v output specified in our table. 0.89v to 9.04v is a result of working with the existing resistance values available for low volume purchases, the specified temperature range, and a $\pm 1\%$ tolerance on the resistance. The signal adjustment circuit consisting of the op-amps and the trim-pots can adjust the signal into the desired spec. The output signal voltage is designated as V_s. The analysis for this portion is uses the convention that i_1 is the current across R_1 and V_1 is the voltage **after** R_1 from left to right. This section utilizes the reasonable assumption of ideal

op-amp performance. This was validated in testing.

$$
\begin{aligned}
i_2 &= \frac{V_{cc}}{R_2 + R_3} \\
V_2 &= i_2 \times R_2 \\
&= \frac{V_{cc} \times R_2}{R_2 + R_3} \\
i_1 &= \frac{V_s - V_2}{R_1} \\
i_4 &= \frac{V_4 - V_2}{R_4} \\
0 &= i_1 + i_4 \\
&= \frac{V_s - V_2}{R_1} + \frac{V_4 - V_2}{R_4}
\end{aligned}
$$

$$
\boxed{V_4 = \frac{V_{cc} \times R_2}{R_2 + R_3}\left(1 + \frac{R_4}{R_3}\right) - \frac{R_4}{R_1}V_s}
$$

$$
\begin{aligned}
i_5 &= \frac{V_4 - V_2}{R_5} \\
i_6 &= \frac{V_{out} - V_2}{R_6} \\
0 &= i_5 + i_6 \\
&= \frac{V_4 - V_2}{R_5} + \frac{V_{out} - V_2}{R_6}
\end{aligned}
$$

$$
\boxed{V_{out} = \frac{V_{cc} \times R_2}{R_2 + R_3}\left(1 - \frac{R_6 \times R_4}{R_5 \times R_3}\right) + \frac{R_6 \times R_4}{R_5 \times R_1}V_s}
$$

Here it can then be see that the first term is the offset, and the second term is the span. In order to make these adjustable, we need to narrow down which ones exist only in one or the other.

$$
\begin{aligned}
&\text{Offset:} \quad R_2, R_3 \\
&\text{Span:} \quad R_1
\end{aligned}
$$

For offset, R_3 is chosen because it has the potential to make the offset both (+) & (-).
For span, R_1 is the only choice.
After analyzing the transfer function of this circuit in MATLAB, the following

resistance values were found:

$$10k \leq R_1 \leq 20k\Omega$$

$$R_2 = 10k\Omega$$

$$10k \leq R_3 \leq 20k\Omega$$

$$R_4 = 18k\Omega$$

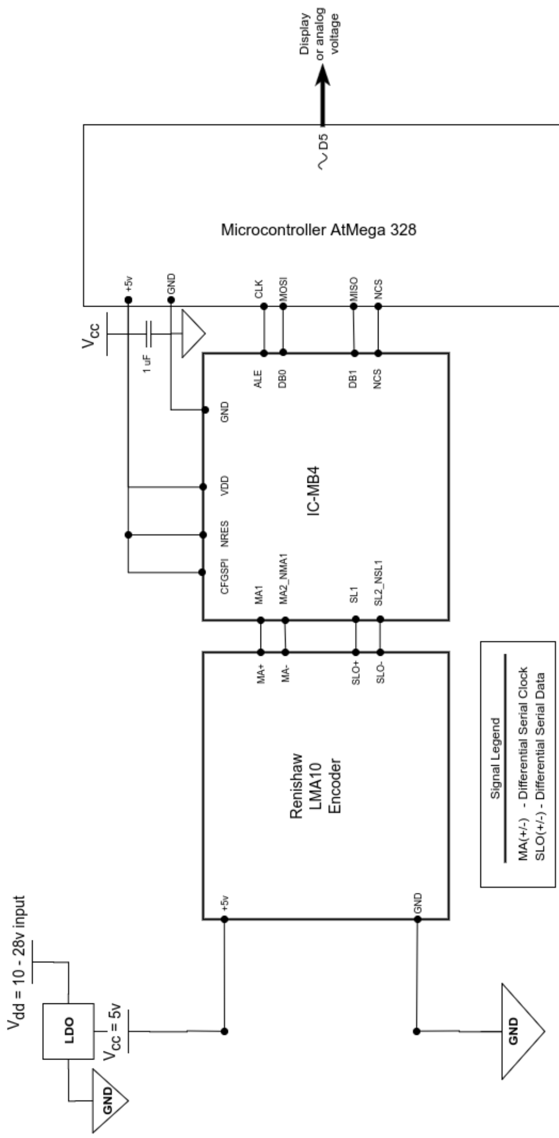
$$R_5 = 100k\Omega$$

$$R_6 = 100k\Omega$$

Upon testing the circuit, if the range of both the span and the offset are incorrect, a small adjustment in the value of R_4 or the fixed resistor in R_3 can be made. However, with the present R_4 value, this circuit had adjustment curves that were relatively flattened out and linear, making the calibration adjustments easier. Practical adjustments will most likely occur in the resistor that is fixed in the R_3 series.

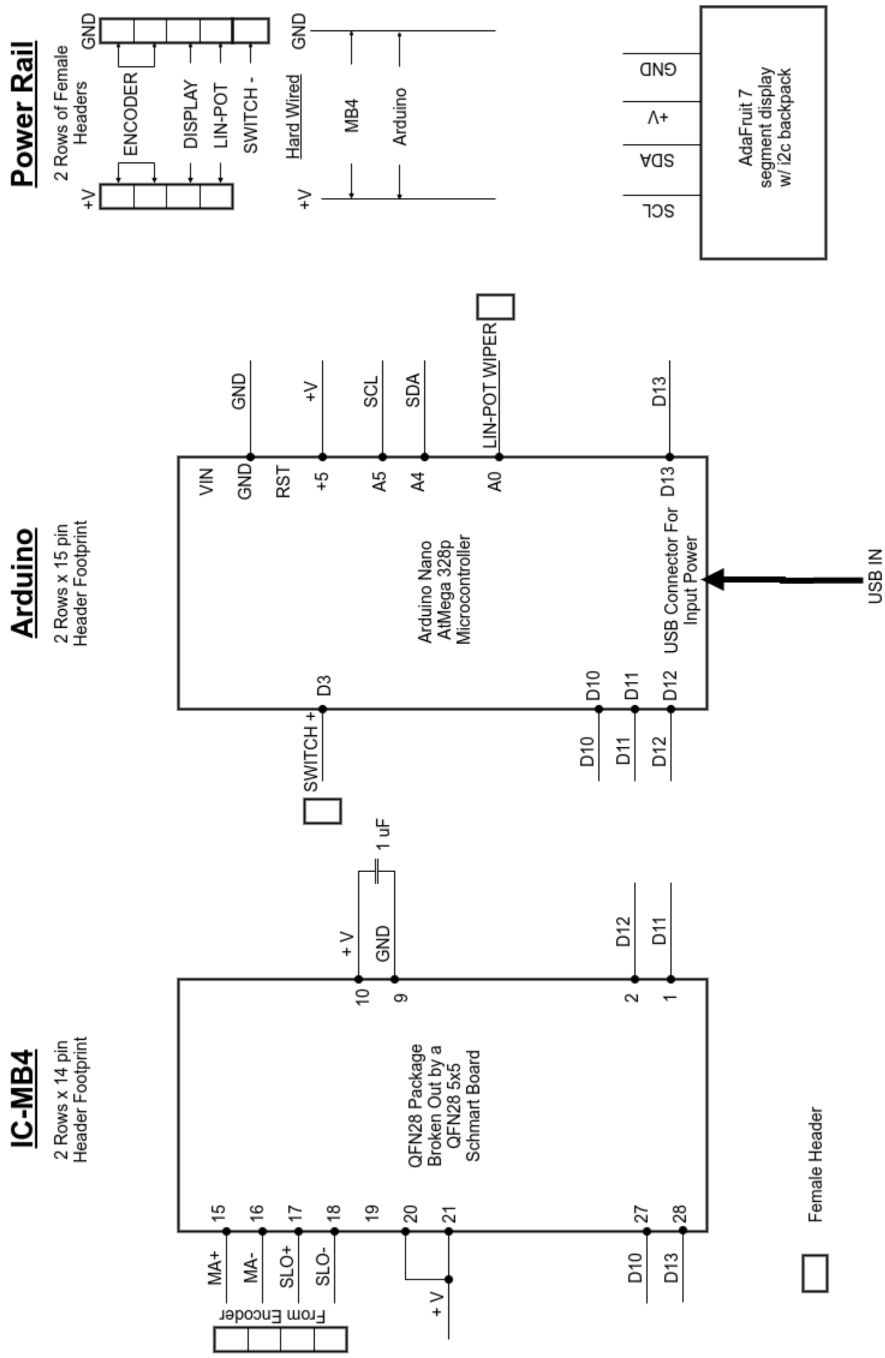
D.8. Encoder Signal Diagram

Below is the proposed method for receiving and processing the encoder signal. The configuration shown below utilizes an IC-MB4 for facilitating the BiSS-C communication. The IC-MB4 then communicates with a micro-controller using SPI communication. It is recommended that the wire length required for the SPI be kept minimum, and that any length needed be added to the BiSS line. This is because BiSS is an industrial differential signal that is less perceptible to noise.



D.9. Final Electronic Circuit Design

The circuit shown below was used in the black prototype box for obtaining the output of both the encoder and the linear potentiometer. Since a micro-controller is used, the extra analog circuitry shown in Appendix D.7 is not needed, as all the signal conditioning can be done in code. A switch was added so that the two devices could be quickly be displayed. A digital read out was added for displaying the measurements.



D.10. Final Code used in Design

Included below is the final code that was used for running the black proto-box. This code obtains readings from a linear potentiometer or encoder based upon the position of a switch, and updates readings onto a display. The original parts of the code are licensed under the Modified BSD license, and may be used by PDT for any commercial purposes they would like. Git version control was used to log the development of this code, and a log of the development may be viewed upon request (send request to Michael George). The source code is also available for download from the github repository at this url: `https://github.com/mfgeorge/senior-project`

D.10.1. Final-Code.ino

```
/*
 BiSS-Reader.ino
 The main file for a program to read a BiSS signal after it has
 been processed via an IC Haus MB4 chip.
 The communication between the two chips occurs via SPI.

  California Polytechnic State University, San Luis Obispo
  In partial fulfillment of the requirements for a bachelor's
  degree from the department of Mechanical Engineering.

  Michael George
  10/21/16

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  ON ANY THEORY OF LIABILITY, WHETHER IN CONTRACT, STRICT LIABILITY, OR TORT
  (INCLUDING NEGLIGENCE OR OTHERWISE) ARISING IN ANY WAY OUT OF THE USE OF THIS
```

```
   SOFTWARE, EVEN IF ADVISED OF THE POSSIBILITY OF SUCH DAMAGE.
*/

// Includes for all of the relevant libraries needed for this main file to run:
// Basic arduino libraries for SPI communication and i2c communication
#include <SPI.h>
#include <Wire.h>

// Adafruit libraries required for using the 7 segment display
#include "Adafruit_LEDBackpack.h"
#include "Adafruit_GFX.h"

// Filter library required to digitally filter the analog readings from the
// linear potentiometer to settle down the fluctuations on the display
#include "Filters.h"

// Library of original code written by AVST to communicate with the IC that
// manages communication with the encoder
#include "mb4-driver.h"


// Encoder Offset if reading does not start at 0 at the start of the encoder
#define ENCODER_OFFSET       124.9 // in inches

// Linear Potentiometer calibration values
#define LIN_POT_OFFSET       -1.43+.640
#define LIN_POT_SCALE        2.2501*5/1023 // in inches for 200 mm length strip

// The connections from the Arduino Uno to the IC-MB4 chip are:

// Arduino Uno       |  IC-MB4
//       10       -> 1  (slave select)
#define SELECT       10
//    11          -> 3  (Master Out Slave In)
//       12          -> 4  (Master In Slave Out)
//       13          ->    2  (Serial Clock)

// Linear Pot
#define LIN_POT   A0

// Mode Selection switch input
#define SWITCH    3 // Pin D3

// Display
// Arduino Uno   | 7 seg display
//    A5      ->    SCL
//    A4      ->    SDA

// enumeration for the different position measurement modes that
// we can be in based upon the switch
enum Position_Mode {
  linearPot,
  encoder
} mode;

// Function prototype for converting linear pot analog reading to inches
float linearPotToInches(uint16_t rawPosition, float offset);

// Function for setting the measurement mode to encoder or linear pot
uint8_t setMeasureMode();

// create a 7 segment display object for displaying the reading
Adafruit_7segment display = Adafruit_7segment();

// This setup function is required by arduino and runs once upon startup
// of the microcontroller or after a reset.
```

```
void setup() {
     // enable serial communication for debugging if a computer is connected
    Serial.begin(9600);
    // Print out a statement over serial if a computer is connected
    Serial.println("----␣Accumulator␣Position␣Testing␣Code␣Start␣Up␣----");
    // Start the 7 segment display for displaying position readings
    // at the i2c address 0x70
    display.begin(0x70);
    // Set the measurement mode based upon the position of the external
    // mode switch
    mode = setMeasureMode();
}

// This loop function is required by arduino, and basically wraps all of the code
// within it in a while (true) loop. In this case it serves as the outermost while
// loop
void loop() {

   // Variable for holding position in inches
   static float position;

   // check what mode we are in and run the appropriate mode
   if (mode == encoder) {
     // If we reach this point in the code, the switch was read to be
     // in encoder measurement mode

     // Perform all of the setup necessary for reading the encoder

     // create an MB4 master object that is connected to the encoder
     MB4Driver master = MB4Driver(SELECT, ENCODER_OFFSET);

     // Raw position in bits
     static uint32_t rawPosition;

     // Inner while loop for simply updating the encoder readings and output
     // the readings to the disply
     while (true) {
      // Get the raw encoder position
      rawPosition = master.getRawPosition();

      // Get the position in inches
      position = abs(master.getPosition());

      // Display the position
      display.println(position, 3); // Try to diplay to 3rd decimal point
      display.writeDisplay();

      // Print out position information to a serial terminal too for debugging
      Serial.print("Position␣[in]␣=␣\t");
      Serial.print(position, 4);

      // Print out the raw bit position as well for debugging
      Serial.print("\t␣Raw␣Position␣[bits]␣=␣\t");
      Serial.println(rawPosition);
      // Check for a mode change
      if (!(digitalRead(SWITCH))){
        // Set the measurement mode to the new state
        mode = setMeasureMode();
        // Break out of this inner while loop so that the other state can be reached
        break;
      }
      // Delay after breaking out of the while loop for 100ms
      delay(100);
    }
   }
   else if (mode == linearPot) {
```

```
    // If we reach this point in the cod, the switch was read to be in
    // linear potentiometer measurement mode

    // Perform all of the necessary setup for obtaining readings from the linear
    // potentiometer

    // Raw position in bits
    static uint16_t rawPosition;

    // Filter objects for filtering the linear potentiometer readings to prevent constant
    // flickering of the display
    //
    static const float testFrequency = 2;                     // test signal frequency (Hz)
    static const float windowLength = 20.0/testFrequency;     // how long to average the signal, for statistist
    static FilterOnePole filterOneLowpass( LOWPASS, testFrequency );   // create a one pole (RC) lowpass filter
    static RunningStatistics filterOneLowpassStats;                    // create running statistics to smooth these values
    filterOneLowpassStats.setWindowSecs( windowLength );

    while (true) {
      // The inner while loop for getting the linear potentiometer readings, and constantly
      // updating the display

      // Print the state of the digital pin connected to the switch
      Serial.print("Digital Pin: ");
      // Read the state of the switch and display for debugging
      Serial.println(digitalRead(SWITCH));
      // Read in the raw analog reading
      rawPosition = analogRead(LIN_POT);

      // Convert the reading to inches
      position = linearPotToInches(rawPosition, LIN_POT_OFFSET, &filterOneLowpass);

      // output the position to the buffer of the display
      display.println(position, 3); // Try to diplay to 3rd decimal point
      // refresh the display so that the new reading is seen on it
      display.writeDisplay();

      // Print out position information to a serial terminal too for debugging
      Serial.print("Position [in] = \t");
      Serial.print(position, 4);

      // Print out the raw bit position as well for debugging
      Serial.print("\t Raw Position [bits] = \t");
      Serial.println(rawPosition);

      // Check for a mode change
      if (digitalRead(SWITCH)){
        mode = setMeasureMode();
        break;
      }
      delay(100);
    }
  }
}

// Function for converting the raw position obtainted from the linear potentiometer
// to readings in inches.
// Parameters:
// rawPosition: a number from the 10-bit adc ranging from 0-1023
// offset: a number in inches representing the offset of 0 from the start of the
//          linear potentiometers active area
// filterOneLowpass: a pointer to a first order lowpass filter object
// returns: a float- the position in inches

float linearPotToInches(uint16_t rawPosition, float offset, FilterOnePole* filterOneLowpass) {
```

```

  // pass the raw position reading into the lowpass filter
  filterOneLowpass->input(rawPosition);
  // update the rawposition variable to be the output from the lowpass filter
  rawPosition = filterOneLowpass->output();
  // return the position in inches based upon a linear calibration
  return float(rawPosition)*LIN_POT_SCALE - offset;
}

// Function for setting the measurement mode based upon the position of an external
// switch.
// Parameters: none
// returns: the measurement mode that the switch has selected

uint8_t setMeasureMode(){
  // Set the pin mode before a reading occurs to be an input connected
  // to the internal pull up resistors of the arduino
  pinMode(SWITCH, INPUT_PULLUP);
  // Read the connected switch once
  if (digitalRead(SWITCH)) {
    // If the switch is open, then the encoder mode is selected.
    mode = encoder;
    // Print a debug statement
    Serial.println("Encoder Mode Selected");
  }
  else {
    // If the switch is closed, then linear potentiometer
    // mode is selected
    mode = linearPot;
    // print a debug statement
    Serial.println("Linear Pot Mode Selected");
  }
  // Return the mode based upon the position of the switch
  return mode;
}
```

D.10.2. mb4-driver.h

```
/* mb4-driver.h
   Class for interfacing with an IC-MB4 master IC.

   California Polytechnic State University, San Luis Obispo
   In partial fulfillment of the requirements for a bachelor's
   degree from the department of Mechanical Engineering.

   Michael George
   10/21/16

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   (INCLUDING NEGLIGENCE OR OTHERWISE) ARISING IN ANY WAY OUT OF THE USE OF THIS
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*/

#include <SPI.h>

// Conversion factor to go from raw position to physical
// this is 2^26 (26 bits max from encoder)
#define CONV_FAC     .000000244*39.3701 // inches

// The BREAK instruction stops all ongoing processes of the MB4
#define BREAK     0b10000000

// The INIT instruction sends out an MA pulse train on all MA clock lines
#define INIT      0b00010000

// Define Channel 1 as in use and Channel 2 as not active
#define CH1         0x01

// The correct setting for bit 4:0 of the
// FREQ register for a 20/8 MHz clock
#define CLOCK_SPEED 0x03

// Setting for the BiSS C protocol to go in bit 6 of REGVERS
// and into bit 1:0 of CFGCH1
#define BISS_C       5
```

```
// Setting for automatically restarting read cycles
// to go into the FREQAGS register (set exactly to this)
#define AGSFREQ   0x81

// Setting for RS422 line levels to be or'd into
// bit 3:2 of the CFGIF register
#define RS422     0x02

// Setting to enable Single Cycle Data (SCD) in bit 6 of ENSCD1
#define SCD_AVAIL    1

// Setting for data length of SCD (26+2 bits -1 since 0 is a length of 1)
// to go into register SCDLEN1 bit 5:0
#define DATA_LENGTH  27

// Setting for CRC Polynomial selection in SELCRCS1 bit 7
#define CRC_SELECT   0

// Setting for the CRC polynomial in SCRCLEN1 bit 6:0
#define CRC_POLY     6

// Setting for the initial start value of CRC in SCRCPOLY1 bit 15:0
#define CRC_START    0

// Setting for all slaves to be sensors
#define SLAVES    0x00

// Commands sent over SPI for the IC Haus MB4
#define WRITE_DATA   0x02
#define READ_DATA    0x03
#define READ_STATUS  0x05
#define WRITE_INSTRUCTION 0x07
#define READ_DATA0   0x09  // 0 Provides fast access to read
#define WRITE_DATA0  0x0B

// Register addresses to read from the IC Haus MB4 Chip
// Please refer to the datasheet, as the same names for the
// registers are used here that are in the datasheet
#define SCDATA1   0x00
#define SCDATA1_CRC  0x07
#define ENSCD1    0xC0
#define SCDLEN1   0xC0
#define SELCRCS1  0xC1 // bit 7
#define SCRCLEN1  0xC1 // bit 6:0
#define SCRCSTART1   0xC2 // bit 15:0
#define CHSEL     0xE4
#define REGVERS   0xE5
#define FREQ      0xE6
#define FREQAGS   0xE8
#define REVISION  0xEA
#define VERSION   0xEB
#define CFGCH1    0xED
#define ACTnSENS  0xEF
#define STATUS_REG   0xF0
#define SVALID    0xF1
#define CDMTIMEOUT   0xF3
#define INSTR     0xF4
#define CFGIF     0xF5
#define CDS_STATUS0  0xF8
#define CDS_STATUS1  0xF9

// MB4Driver class: a class for communicating with the IC-MB4 master from
//                  iC Hause over SPI. This class also implements methods for
//                  reading a Renishaw LMA10 absolute magnetic encoder that is
//                  connected to the IC-MB4 in the first slave position. However,
```

```
//                  primitive readRegister and writeRegister methods are available,
//                  allowing this code to be adapted for use in other applications.
//                  It is strongly recommended that one is familiar with the IC-MB4
//                  datasheet before attempting to interpret specific low level
//                  parts of this code, or before adapting this code to a different
//                  specific application than it was originally intended.
//
// For all functions, see the comment above each one in the source file (.cpp) for a more in
// depth explanation.
class MB4Driver {
   // Private methods are for use only within other methods in the MB4Driver
   // class.
   private:
      // The SPI chip select pin that the IC-MB4 is connected to
      uint8_t selectPin;

      // The different status states the MB4 can have. This status also contains
      // status interpretations that are specific to the Renishaw LMA10 encoder
      enum status
      {
         no_errors,         // All clear for data release
         encoder_alarm,     // Invalid position data from encoder
         encoder_warning,   // Warning from the encoder (close to overspeed?)
         invalid_crc        // Cyclic check sum reported incorrectly

      } currentStatus; // currentStatus will hold the status

      // For descriptions of these two functions please see source file
      uint8_t checkStatus_unprotected();

      uint32_t currentRawPosition;

      // Class member variable that will hold the offset for the encoder
      float offset;
   public:
      // For descriptions of these functions please see the source file,
      // however effort has been made to make the function names self
      // explanatory.
      MB4Driver(uint8_t selectPin, float offset);

      uint32_t readRegister(uint8_t registerAddress, uint8_t numBytesToRead);

      void writeRegister(uint8_t registerAddress, uint8_t* data, uint8_t numBytesToWrite);

      void writeRegister(uint8_t registerAddress, uint8_t data);

      void writeInstruction(uint8_t instruction);

      uint32_t getRawPosition();

      float convertRawPosition(uint32_t rawPos, float offset);

      float getPosition();

      void printImportantRegisters();

      void printSCDATA1Registers();

      void printVersion();
};
```

D.10.3. mb4-driver.cpp

```
/* mb4-driver.cpp
   Source code for a class for interfacing with an IC-MB4 master IC.

   California Polytechnic State University, San Luis Obispo
   In partial fulfillment of the requirements for a bachelor's
   degree from the department of Mechanical Engineering.

   Michael George
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   SOFTWARE, EVEN IF ADVISED OF THE POSSIBILITY OF SUCH DAMAGE.
*/

// Include the header file which has all of the prototypes of the functions
// contained in this source file.
#include "mb4-driver.h"

// For class description, please refer to the header file. This is the first
// place to start for a general overview of the methods available, and can
// provide a general idea of the methods available in this class.


// MB4Driver: Constructor for the MB4Driver class
// Parameters:
// selectPin: the SPI chip select pin that the mb4 is connected to
// offset: (optional parameter) the offset in inches for the encoder readings
MB4Driver::MB4Driver(uint8_t selectPin, float offset=0){
   // Begin the SPI communication protocol that will be used to
   // communicate with the IC-mb4 chip
   SPI.begin();

   // Setup the necessary serial communication for this library
   if(!Serial){
      Serial.begin(9600);
   }
```

```
this->selectPin = selectPin;

// Setup Pin 10 to be a digital output for slave select
pinMode(this->selectPin, OUTPUT);

// Set the select pin high so that communication is not yet enabled
digitalWrite(this->selectPin, 1);

// Store the offset from 0 for this encoder
this->offset = offset;

// Tell master to stop any previous processes and start fresh
this->writeInstruction(BREAK);

// Set the Channel 1 as the only active channel
this->writeRegister(CHSEL, CH1);

// Set up the channel as BiSS register configuration
this->writeRegister(REGVERS, BISS_C << 6);

// Set the FREQ register bit 4:0 to communicate with encoder
uint8_t currentFREQ = this->readRegister(FREQ, 1);
currentFREQ &= ~(0b00011111);
currentFREQ |= CLOCK_SPEED;
this->writeRegister(FREQ, currentFREQ);
Serial.print("FREQ: \t\t");
Serial.println(this->readRegister(FREQ, 1));

// Set up the communication for BiSS C protocol
uint8_t currentCFGCH1 = this->readRegister(CFGCH1, 1);
currentCFGCH1 &= ~(0b00001111);
currentCFGCH1 |= BISS_C;
this->writeRegister(CFGCH1, currentCFGCH1);
Serial.print("CFGCH1: \t");
Serial.println(this->readRegister(CFGCH1, 1));

// Set up for automatically starting read cycles
this->writeRegister(FREQAGS, AGSFREQ);
Serial.print("FREQAGS: \t");
Serial.println(this->readRegister(FREQAGS, 1));

// Set up for RS422 Line levels in CFGIF bit 3:2
uint8_t currentCFGIF = this->readRegister(CFGIF, 1);
currentCFGIF &= ~(0b00001111);
currentCFGIF |= (RS422 << 2);
// Enable the internal clock sou~rce
currentCFGIF |= (1);
this->writeRegister(CFGIF, currentCFGIF);
Serial.print("CFGIF: \t\t");
Serial.println(this->readRegister(CFGIF, 1));

   // Configure the data length of the SCD. bit 5:0 SCDLEN1
uint8_t currentSCDLEN1 = this->readRegister(SCDLEN1, 1);
currentSCDLEN1 &= ~(0b11111111);
currentSCDLEN1 |= (DATA_LENGTH);
currentSCDLEN1 |= (SCD_AVAIL << 6);
this->writeRegister(SCDLEN1, currentSCDLEN1);
Serial.print("SCDLEN1 & ENSCD1: \t");
Serial.println(this->readRegister(SCDLEN1, 1));

// Configure the CRC info
this->writeRegister(SELCRCS1, (CRC_SELECT << 7) | CRC_POLY);
Serial.print("SELCRCS1: \t");
Serial.println(this->readRegister(SELCRCS1, 1));
```

```
    // Configure the CRC start
    uint8_t crcStartToSend[2];
    crcStartToSend[0] = CRC_START;
    crcStartToSend[1] = CRC_START;
    this->writeRegister(SCRCSTART1, crcStartToSend, 2);
    Serial.print("SCRCSTART1: \t");
    Serial.println(this->readRegister(SCRCSTART1, 2));

    // Configure all slaves to be sensors
    this->writeRegister(ACTnSENS, SLAVES);
    Serial.print("ACTnSENS: \t");
    Serial.println(this->readRegister(ACTnSENS, 1));

    // Enable the AGS (Automatic Get Sensor) bit so that the MB4 now polls
    // encoder
    uint8_t currentInstruction = this->readRegister(INSTR, 1);
    currentInstruction |= 1;
    this->writeInstruction(currentInstruction);
    Serial.print("INSTR: \t ");
    Serial.println(this->readRegister(INSTR, 1), BIN);

    // Notify user that MB4Driver is instantiated
    Serial.println("MB4Driver Instantiated");

    // Notify user of version of the MB4 IC
    this->printVersion();

    // Give Time to collect the first reading
    delay(1000);

    // Print out all the initial registers for SCDATA1
    Serial.print("00:\t");
    Serial.print(this->readRegister(0x00, 1), HEX);

    Serial.print("\t01: ");
    Serial.print(this->readRegister(0x01, 1), HEX);

    Serial.print("\t02: ");
    Serial.print(this->readRegister(0x02, 1), HEX);

    Serial.print("\t03: ");
    Serial.print(this->readRegister(0x03, 1), HEX);

    Serial.print("\t04: ");
    Serial.print(this->readRegister(0x04, 1), HEX);

    Serial.print("\t05: ");
    Serial.print(this->readRegister(0x05, 1), HEX);

    Serial.print("\t06: ");
    Serial.print(this->readRegister(0x06, 1), HEX);

    Serial.print("\t07: ");
    Serial.println(this->readRegister(0x07, 1), HEX);

    // Print the first raw position reading
    this->getRawPosition();

    //this->printImportantRegisters();

}

// readRegister: Function for reading a specific register on the MB4
// Parameters:
// registerAddress: the register starting address to read from
// numBytesToRead: the number of the bytes to read
```

```
// returns: the value read from the register address assuming that the
//          first register read is the most significant byte
uint32_t MB4Driver::readRegister(uint8_t registerAddress, uint8_t numBytesToRead){
   // Drop the chip select pin low to select MB4 for output
   digitalWrite(this->selectPin, 0);

   // Configure the correct SPI settings to be used
   SPI.beginTransaction(SPISettings(1000000,MSBFIRST,SPI_MODE0));

   // Send the read command
   SPI.transfer(READ_DATA);

   // Send the register address to read from
   SPI.transfer(registerAddress);

   // Create a buffer to read bytes into
   uint8_t buffer = 0;

   // Create a value to return
   uint32_t value = 0;

   // Read the bytes in a loop
   for(int i=0; i<numBytesToRead; i++){
      buffer = SPI.transfer(0);
      // Arrage the bytes for a proper number to return
      value *= 2^8;

      value +=buffer;
   }

   // Bring chip select high to stop communication with MB4
   digitalWrite(this->selectPin, 1);

   // End the SPI transaction for nice cooperation with other
   // SPI dependent libraries
   SPI.endTransaction();

   return value;

}

// writeRegister: A function to write data to a register on the MB4
//                (array version)
// Parameters:
// registerAddress: the starting address of the register to write to
// data: an array of bytes to write
// numBytesToWrite: the number of bytes in array pointer or data to write
void MB4Driver::writeRegister(uint8_t registerAddress, uint8_t* data, uint8_t numBytesToWrite){
   // Drop the chip select pin low to select MB4 for output
   digitalWrite(this->selectPin, 0);

   // Configure the correct SPI settings to be used
   SPI.beginTransaction(SPISettings(1000000,MSBFIRST,SPI_MODE0));

   // Send the read command
   SPI.transfer(WRITE_DATA);

   // Send the register address to write to
   SPI.transfer(registerAddress);

   // Write the bytes
   SPI.transfer(data, numBytesToWrite);

   // Bring chip select high to stop communication with MB4
   digitalWrite(this->selectPin, 1);

```

```
  // End the SPI transaction for nice cooperation with other
  // SPI dependent libraries
  SPI.endTransaction();

}

// writeRegister: A function to write data to a register on the MB4
//                (byte version)
// Parameters:
// registerAddress: the starting address of the register to write to
// data: the byte of data to be written to that address
void MB4Driver::writeRegister(uint8_t registerAddress, uint8_t data){
  // Drop the chip select pin low to select MB4 for output
  digitalWrite(this->selectPin, 0);

  // Configure the correct SPI settings to be used
  SPI.beginTransaction(SPISettings(1000000,MSBFIRST,SPI_MODE0));

  // Send the read command
  SPI.transfer(WRITE_DATA);

  // Send the register address to write to
  SPI.transfer(registerAddress);

  // Write the data
  SPI.transfer(data);

  // Bring chip select high to stop communication with MB4
  digitalWrite(this->selectPin, 1);

  SPI.endTransaction();

}

// writeInstruction: A function to quickly write data to the MB4's instruction
//                register.
// Parameters:
// instruction: The instruction to write to the MB4's instruction register
// returns: nothing
void MB4Driver::writeInstruction(uint8_t instruction){
  // Drop the chip select pin low to select MB4 for output
  digitalWrite(this->selectPin, 0);

  // Configure the correct SPI settings to be used
  SPI.beginTransaction(SPISettings(1000000,MSBFIRST,SPI_MODE0));

  // Send the read command
  SPI.transfer(WRITE_INSTRUCTION);

  // Write the bytes
  SPI.transfer(instruction);

  // Bring chip select high to stop communication with MB4
  digitalWrite(this->selectPin, 1);

  SPI.endTransaction();

}

// getRawPosition:
// A function to get the raw position data from the MB4 chip. This is
// where SPI must be used to communicate with the MB4 chip.
// Parameters: none
// Returns: raw position in a 0 to 2^26 number.
uint32_t MB4Driver::getRawPosition() {

```

```
    // Lock the bank before reading SCDATA1 to prevent data corruption
    uint8_t currentInstruction = this->readRegister(INSTR, 1);
    currentInstruction |= (1 << 6);
    this->writeInstruction(currentInstruction);

    // // Check out how the instruction register responds
    // Serial.print("INSTR after lock: \t ");
    // Serial.println(this->readRegister(INSTR, 1), BIN);

    // Create an array of 4 x 8 bit numbers
    uint32_t readingBuffer;

    // Initialize a zero reading
    uint32_t reading = 0;

    // Read the data and unpack into correct order one register at a time
    for(uint8_t index = 0; index < 4; index++){
       readingBuffer = this->readRegister(SCDATA1 + index, 1);
       reading += readingBuffer << (index*8);
    }

    // Shift the status bits out of the reading
    reading = reading >> 2;

    // Check if the reading is valid
    // Can use unprotected checkStatus_unprotected() since data registers are
    // locked.
    if (this->checkStatus_unprotected() == no_errors){
       this->currentRawPosition = reading;

       // // Print out the raw encoder reading recieved
       // Serial.print("Raw Encoder Reading: \t");
       // Serial.println(reading);
    }

    // Unlock the bank after reading SCDATA1 to allow those registers to update
    currentInstruction = this->readRegister(INSTR, 1);
    currentInstruction &= ~(1 << 6);
    this->writeInstruction(currentInstruction);

    // // Check out how the instruction register responds
    // Serial.print("INSTR after unlock: \t ");
    // Serial.println(this->readRegister(INSTR, 1), BIN);

    return this->currentRawPosition;

}

// checkStatus_unprotected: a function for use after the data registers
//                          have been locked. Checks the error registers
//                          to make sure the encoder and the MB4 are not
//                          reporting any errors.
// Parameters: None
// Returns: the currentStatus of the encoder. which can be
//          no_errors, invalid_crc, encoder_warning, or encoder_alarm.
uint8_t MB4Driver::checkStatus_unprotected(){

    // The encoder status (no warnings is 00, refer to LMA10 datasheet)
    uint32_t encoderStatus = this->readRegister(SCDATA1, 1);

    // Check if CRC is correct
    bool valid = (this->readRegister(SVALID,1) == 2) ? true : false;

    // Check for errors in this order of precedence (some errors trump others)
    if ((encoderStatus == 0) && valid && this->currentStatus != encoder_alarm) {
       this->currentStatus = no_errors;
```

```
    }
    else if (!valid && this->currentStatus != encoder_alarm) {
    // Error in com between MB4 and encoder
        this->currentStatus = invalid_crc;
        Serial.println("INVALID␣CRC");
    }
    else if (encoderStatus == 1 && this->currentStatus != encoder_alarm) {
    // Close to overspeed, consult LMA10 datasheet
        this->currentStatus = encoder_warning;
        Serial.println("ENCODER␣WARNING");
    }
    else if (encoderStatus == 2 || this->currentStatus == encoder_alarm) {
    // Encoder invalid position data
        this->currentStatus = encoder_alarm;
        Serial.println("ENCODER␣ALARM");
    }

    return this->currentStatus;
}


// convertRawPosition: converts the raw position readings of the encoder (bits)
//                     into a decimal number in inches
// Parameters:
// rawPos: The raw position in bits
// offset: The offset distance in inches to acheive 0 (some encoder strips don't
//         start at 0)
// returns: a float representing the position in inches on the encoder strip
float MB4Driver::convertRawPosition(uint32_t rawPos, float offset){
    return (float)(rawPos)*CONV_FAC - offset;
}

// getPosition: gets the current position of the encoder in inches. This function
//              will automate the call of getRawPosition() and put the output into
//              convertRawPosition.
// Parameters: None
// returns: a float representing the position of the encoder in inches
float MB4Driver::getPosition(){
    // get the current position in inches from the encoder
    float position = this->convertRawPosition(this->getRawPosition(), this->offset);
    // For some reason, the position will suddenly jump to <100 if the encoder
    // goes off the strip
    if (position > 10.0 && position < 100) {
        position -= 85.60; // cover the case of barely going off the strip
    }
    else if (position > 190) {
        position -= 200; // cover the case of the 200 range
    }
    return position;
}

// printImportantRegisters: A function to print all of the important registers that
//                          must be configured in order for a single encoder sensor
//                          to be used in a polling scheme. This function is useful
//                          for designing and debugging applications with the MB4 ic
// Parameters: None
// returns: Nothing (the print to standard out is what results)
void MB4Driver::printImportantRegisters(){
    Serial.println();
    Serial.println("------␣Important␣Registers␣Print␣out␣------");

    Serial.print("C0:\t");
    Serial.println(this->readRegister(0xC0, 1), HEX);

    Serial.print("C1:\t");
    Serial.println(this->readRegister(0xC1, 1), HEX);
```

```
    Serial.print("E4:\t");
    Serial.println(this->readRegister(0xE4, 1), HEX);

    Serial.print("E5:\t");
    Serial.println(this->readRegister(0xE5, 1), HEX);

    Serial.print("E6:\t");
    Serial.println(this->readRegister(0xE6, 1), HEX);

    Serial.print("E8:\t");
    Serial.println(this->readRegister(0xE8, 1), HEX);

    Serial.print("EA:\t");
    Serial.println(this->readRegister(0xEA, 1), HEX);

    Serial.print("EB:\t");
    Serial.println(this->readRegister(0xEB, 1), HEX);

    Serial.print("EC:\t");
    Serial.println(this->readRegister(0xEC, 1), HEX);

    Serial.print("ED:\t");
    Serial.println(this->readRegister(0xED, 1), HEX);

    Serial.print("F0:\t");
    Serial.println(this->readRegister(0xF0, 1), HEX);

    Serial.print("F1:\t");
    Serial.println(this->readRegister(0xF1, 1), HEX);

    Serial.print("F3:\t");
    Serial.println(this->readRegister(0xF3, 1), HEX);

    Serial.print("F5:\t");
    Serial.println(this->readRegister(0xF5, 1), HEX);

    Serial.print("F8:\t");
    Serial.println(this->readRegister(0xF8, 1), HEX);

    Serial.print("F9:\t");
    Serial.println(this->readRegister(0xF9, 1), HEX);

    Serial.println("------ End of Important Register Print out -------");
}

// printSCDATA1Registers: prints all of the registers associated with the
//                        first slave device. This function is useful for
//                        debugging and designing code for specific applications.
// Parameters: None
// Returns: nothing
void MB4Driver::printSCDATA1Registers(){

    // Lock the bank before reading SCDATA1 to prevent data corruption
    uint8_t currentInstruction = this->readRegister(INSTR, 1);
    currentInstruction |= (1 << 6);
    this->writeInstruction(currentInstruction);

    // Print out all the SCDATA1 registers for debugging
    Serial.print("00: ");
    Serial.print(this->readRegister(0x00, 1), HEX);

    Serial.print("\t| 01: ");
    Serial.print(this->readRegister(0x01, 1), HEX);

    Serial.print("\t| 02: ");
```

```
    Serial.print(this->readRegister(0x02, 1), HEX);

    Serial.print("\t|␣03:␣");
    Serial.print(this->readRegister(0x03, 1), HEX);

    Serial.print("\t|␣04:␣");
    Serial.print(this->readRegister(0x04, 1), HEX);

    Serial.print("\t|␣05:␣");
    Serial.print(this->readRegister(0x05, 1), HEX);

    Serial.print("\t|␣06:␣");
    Serial.print(this->readRegister(0x06, 1), HEX);

    Serial.print("\t|␣07:␣");
    Serial.println(this->readRegister(0x07, 1), HEX);

    // Unlock the bank after reading SCDATA1 to allow the registers to update
    currentInstruction = this->readRegister(INSTR, 1);
    currentInstruction &= ~(1 << 6);
    this->writeInstruction(currentInstruction);

}

// printVersion: Function to use for printing the version of the MB4 ic
//               iC Haus reccomends this as the first step to see if your
//               MB4 is wired correctly and initially establishing
//               communication
// Parameters: None
// Returns: Nothing
void MB4Driver::printVersion() {

    // read the version and revision register
    uint32_t version = this->readRegister(VERSION, 1);
    uint32_t revision = this->readRegister(REVISION, 1);

    // Print them out to the user over serial
    Serial.println("Version␣data␣of␣MB4␣instantiated:");
    Serial.print("\n␣Version␣recieved␣is:␣\t");
    Serial.print(version);
    Serial.print("\t␣Revision␣recieved␣is:␣\t");
    Serial.print(revision);
    Serial.println();

}
```