ELECTROMAGNETIC ACTUATOR FOR CAMLESS ENGINES

FINAL DESIGN REVIEW

PROJECT MEMBERS

Darya Darvish

ddarvish@calpoly.edu

Charlie Glenwright

cglenwri@calpoly.edu

Nicholas Olesh

nolesh@calpoly.edu

Tim Wills-DeTone

Twillsde@calpoly.edu

Mechanical Engineering Department

California Polytechnic State University

San Luis Obispo

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SPONSOR

Dr. Eltahry Elghandour

Dr. Ashraf Elbarbary

Mechanical Engineering Department

California Polytechnic State University

San Luis Obispo

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Abstract

This document summarizes the research, objectives, project plan, and design for developing an electromagnetic actuator valve for use in a camless internal combustion engine. While electromagnetic valve actuators have not been implemented into a working product to date, there have been many attempts to research and develop working prototypes. Similar products have been developed, but they do not use purely electromagnetic actuation. This research is significant because it shows the challenge that must be overcome and outlines potential design solutions to the problem. The objectives section highlights the problem statement and what is aimed to be achieved in this project. The concept design section outlines the chosen design direction and the methods used to arrive at this design. The final design section describes the finalized design decisions and details the analysis used to justify the design. The manufacturing section details the process for building the finalized design of the actuator and establishes the cost and timeline of development and testing as well as the required equipment and tools. The design verification section explains the testing required to verify if the design meets the intended specifications. The accomplished testing section provides the results of tests that we were able to perform under the circumstances of the COVID-19 crisis. The new project scope section highlights the revised goals of the project while under quarantine restrictions. Finally, the project management section outlines how the goals and project milestones will be achieved.

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1.0 Introduction

Internal combustion engines rely on the precise cycling of intake and exhaust valves to control the flow of gasses during the combustion process. In standard engines, the valves are controlled by a lobed camshaft that is mechanically connected to the rotation of the engine and does not allow for variation in valve opening or valve timing.

Two research professors at California Polytechnic State University San Luis Obispo (Cal Poly), Dr. Elghandour and Dr. Elbarbary, have proposed to develop an electromagnetic actuator for a camless engine with the help of Dr. Majid Poshtan, a professor of electrical engineering and expert on electromagnetism. Actuating the intake and exhaust valves of an internal combustion engine with independently controllable actuators can improve engine performance by allowing an engine management system to vary valve displacement, duration, and timing based on driving conditions, performance requirements, and fuel efficiency goals. The electromagnetic actuator and accompanying control system could potentially be adapted for use in a wide variety of internal combustion engines. Involved in this project are Dr. Elghandour, Dr. Elbarbary, Dr. Poshtan, and our team of senior mechanical engineering students at Cal Poly: Darya Darvish, Charlie Glenwright, Tim Wills-DeTone, and Nicholas Olesh.

The goal of this report is to present a finalized design which consists of preliminary research, design ideation processes, final design decisions, analysis for justification, and project management. This report will be divided up into the following sections. The Background section will outline relevant research that we conducted in order to learn more about electromagnetic actuators, as well as summaries of meetings with the sponsors and knowledgeable professors. In the Objectives section, we will define the scope of our project. The scope describes what we aim to achieve with this project and outlines our main goals, evaluation criteria, and deliverables. A main component of our scope will be the Engineering Specifications Table, which defines all our specifications and how we will evaluate the given criteria. The Concept Design section presents the ideation methods used and the initial designs generated. The selection procedures are detailed, and a single design path is presented. The Final Design section will describe the final design decisions and provide justification through analysis. The Manufacturing Plan section contains the cost of each component, the manufacturing processes used, and the Design Verification Plan section details a testing plan to verify the design. The Accomplished Testing section provides the results from tests that we were able to complete during the COVID-19 crisis and the New Project Scope and Results section explains how the goals of the project were reshaped due to the closure of the Cal Poly campus. The Project Management section will show our process and the resources we will use in order to complete this project.

2.0 Background

Camless engines have been implemented by a few companies to date, but they do not use purely electromagnetic actuation to control their valves. Freevalve, by Koenigsegg, uses a technology that involves electro-hydraulic pneumatic actuators combined with patented advanced sensor techniques [1]. The only other product that has been commercialized is Fiat's Multi-Air System. This system uses an Electro-Hydraulic Variable Valvetrain System which allows the system to achieve variable valve timing for intake valves [2]. Variable valve timing (VVT) is the name given to any system designed to alter the timing of a valve lift event. It is often used to improve performance, fuel economy or emissions. Traditional VVT systems use electromagnetic actuation along with a hydraulic or pneumatic system to control valve timing and valve travel. These products all use electromagnetic actuators but maintain the need for a camshaft to provide the force and base timing. To date, there is no camless engine on the market that uses only electromagnetic valve actuation, all actuation systems on the market use some form of fluid actuation. Even though there are few commercial solutions to electromagnetic valve actuators, there are many patents and research papers on the subject.

2.1 Research Papers

In a paper titled "A Study on the Design of Electromagnetic Valve Actuator for VVT Engine", a design for a purely electromagnetic actuator was proposed. The valve is actuated by the motion of an armature between two torus-shaped magnetic cores, where the two valve springs fix the neutral position of the armature at the center of the air gap. Two solenoids are used to provide the electromagnetic force to the system. The schematic of the design is highlighted in Figure 1.
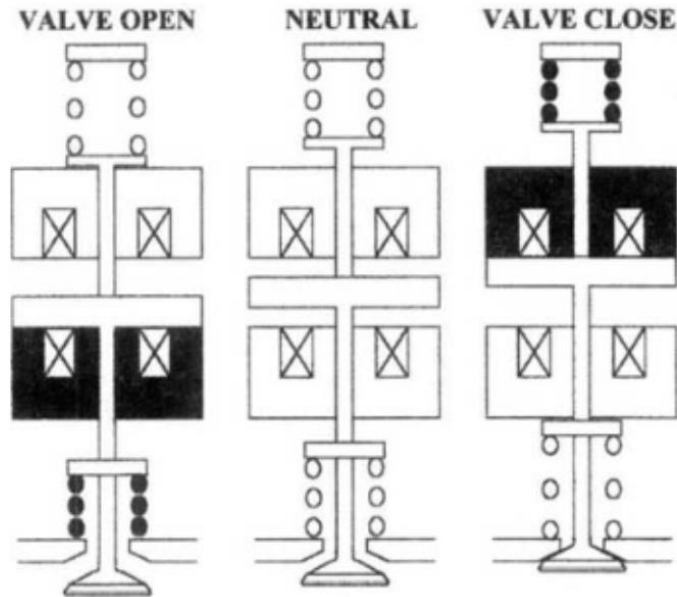
Figure 1. Electromagnetic Valve Actuator Design [3]

The key takeaways from this analysis are that the maximum size of the actuator is limited by the engine geometry, namely the valve cover height. The force output that was found in this study by using the Finite Element Method was between 200 and 800 Newtons, depending on the air gap and the current.

Another paper published by SAE International goes into more detail about the design and implementation of electromagnetic actuators. This paper, titled "Electromagnetic Fully Flexible Valve Actuator" [4], states that potential barriers to the electromagnetic actuator adoption are "increased electrical power consumption, too great a valve seating velocity, unacceptable actuator failure modes, cost, and actuator packaging difficulties". It also states that current cam valvetrain technology is extremely well-developed and sets a high standard for replacement technologies. This paper also states that a common issue for actuator design is which components move relative to the external body [4]. The two possibilities that that are highlighted in this paper are as follows: moving magnets and stationary coils or moving coils and stationary magnets. Other design options include a moving plunger with stationary coil and magnets. The design selected in this study is shown in Figure 2.
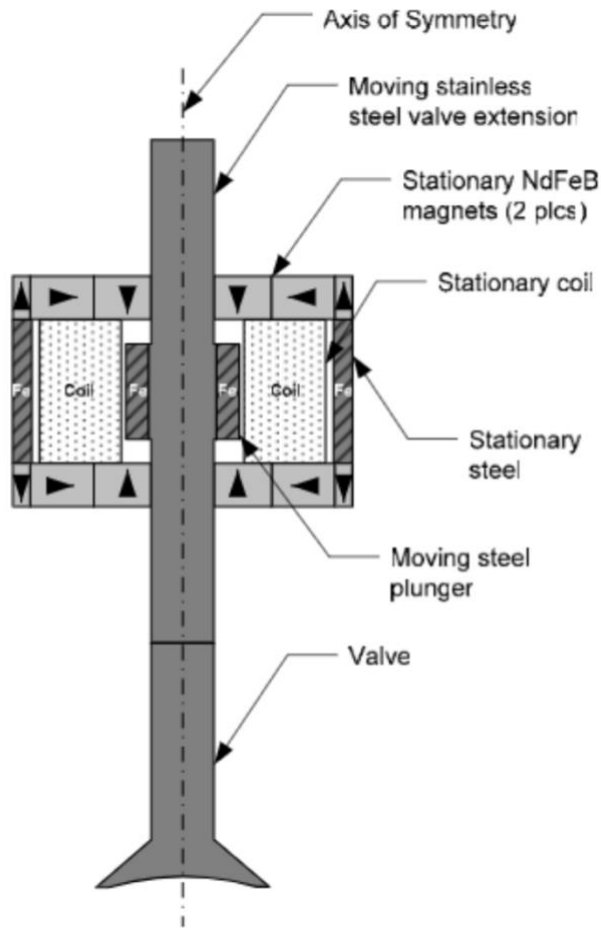
Figure 2: Selected Actuator Design [4]

The actuator was analyzed by using MFEA (Magnetic Finite Element Analysis). The average power consumed at 6000 rpm for a constant acceleration was found to be 188 Watts, and the maximum force for these conditions was found to be 180 Newtons. This paper concluded that it was possible to achieve benefits such as variable timing, variable lift, and low valve-landing speed with this type of design.

Other control methodologies that have been researched include adaptive control [10]. This paper used a permanent magnet, a coil, inner core, and an outer core in order to actuate the valve. The prototype of their design is shown in Figure 3.
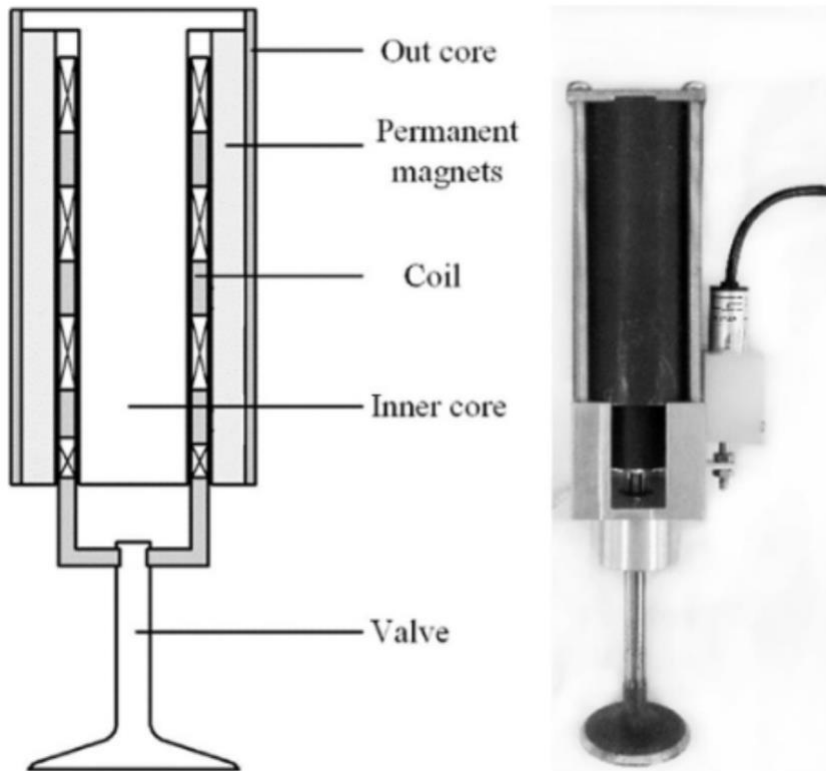
Figure 3. Proposed Prototype for EMVA (Electromagnetic Valve Actuator) [10]

One aspect that this paper accounts for is the actuation force required to overcome the combustion force. Since there will be a high pressure in the cylinder, it will take more actuation force to open the exhaust valve after combustion. In order to control this system, a basic feedback control system (shown in Figure 4) is first implemented.
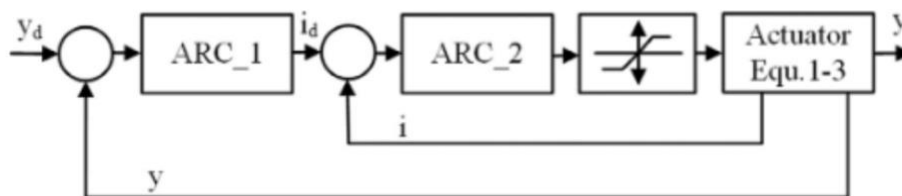
Figure 4. Block Diagram of Basic Control of EMVA [10]

This paper takes the control a step further to adapt to increases in combustion force. Two feedback loops are introduced, one where the current feedback (i) is incorporated and one were position feedback (y) is incorporated. This paper compares a theoretical model to experimental results, and the results show that a pressure of 5 bar can be overcome by applying a force of 160 N. This causes a valve lift of 8 mm after a time of 5ms.

2.2 Patents

To gain a better understanding of what unique aspects of designs have already been explored, we found patents pertaining to electromagnetic actuators and actuator implementation in engines.

US Patent 3178151 presents the original design of a linear electromagnetic actuator from 1965 [5]. The information in this patent provides a starting point for actuator design and the required functional components.

US Patent 5868108 presents a double-acting solenoid design for electromagnetic actuation of a valve similar to the design presented in Figure 1 [6]. This design has never been feasibly implemented for functional use and requires the control of an additional electromagnet for every valve.

US Patent 5991143 provides response curves for the force generated by an electromagnetic actuator for various inputs [7]. The patent is specific to controlling an actuator for an engine valve, so the control system design that is presented will be a useful starting point for our model and is shown in Figure 5. One of the design requirements stated in the patent is a metric for the valve closing velocity that is required for low noise operation.
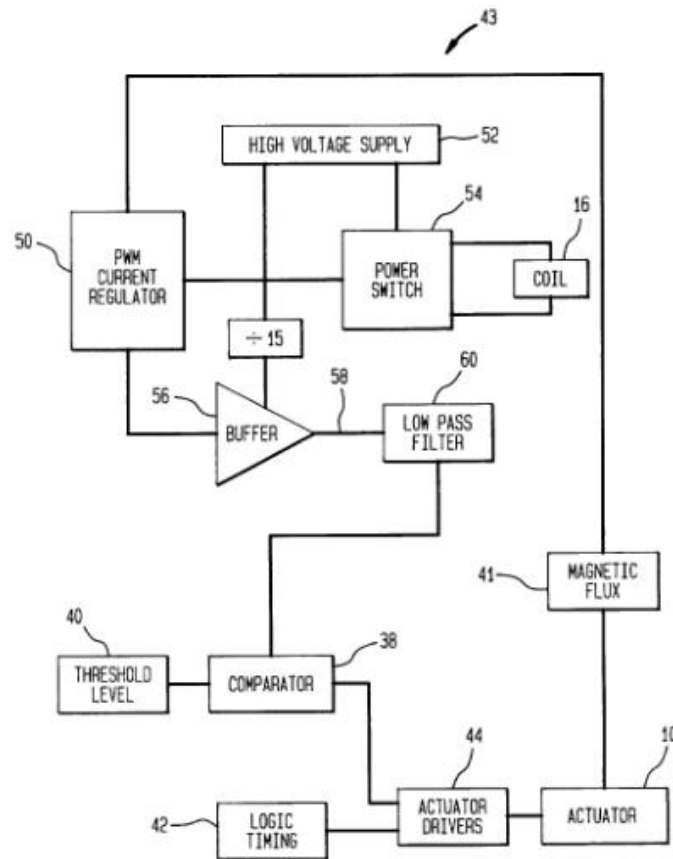
Figure 5. US5991143 Claimed Control System [7]

US Patent 7476990 details an improved linear actuator design and provides a design that is claimed to be easily adjusted for force and reliability requirements [8].

US Patent 9647466 is held by Freevalve and provides an idea of how this problem has been approached previously but does not provide any useful technical information that would benefit our design [9].

2.3 Interviews

We met with several professors in order to learn more about this project and the challenges that we may face. Dr. John Ridgley, professor of mechanical engineering. Dr. Ridgley is an expert in mechatronic systems design and software engineering for mechanical system control; his advice was to conduct as much research as possible on past designs and projects. He also provided information on different software solutions to control our system. Python will give us the ability to execute our control every 1 millisecond, while using C++ will allow us to execute our control every 0.1 millisecond.

Professor Patrick Lemieux, an expert on internal combustion engines, provided us with an idea of what engine speed we should design our system to withstand and the general force profile that an exhaust valve must overcome in the combustion cycle. He was unable to provide exact values for valve forces but suggested a design goal for engine speed of 6000 rpm.

3.0 Objectives

Engine manufacturers need individual programmable actuators that can apply enough force to open engine valves with precise timing. Programmable electromagnetic actuators would allow engine manufacturers to improve fuel efficiency without sacrificing performance. Because most combustion engines use a cam driven valve actuation system, the valve timing, duration, and lift cannot all be varied continuously and independently of each other. Programmable actuators would allow the manufacturers to optimize valve timing, duration, and lift for all operating conditions, thus improving efficiency without sacrificing power.

3.1 Boundary Diagram

The boundary diagram shown in Figure 6 provides a visual representation of our responsibilities regarding this project. We are tasked with designing and building the EM actuator, and thus are only concerned with the engine so far as the valve and spring, as well as the mounting points on the cylinder head. We are also responsible for programming the controller that will control the timing of the actuator, and the power source that will supply both systems with electricity. As seen in the diagram, we are not tasked with integrating this system into an automobile.
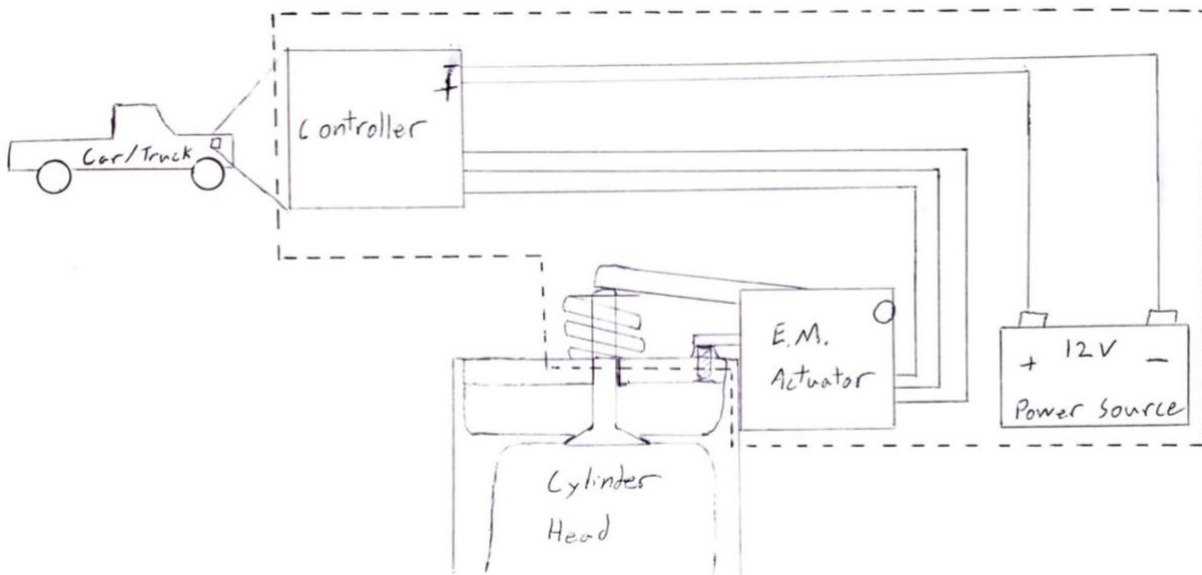
Figure 6: Boundary Diagram

3.2 Wants and Needs Table

Table 1 outlines the sponsors' wants and needs for this project. These requirements and design considerations were developed over the course of several conversations with Dr. Elghandour and Dr. Elbarbary. The requirements that we must meet are under "Needs" and the design considerations that are not strictly required are under "Wants". The items in the "Wants" column are things that we've discussed as necessary to integrate the actuators into a real production engine, but are not critical for our prototype. We can meet the space and weight considerations in our final design given the time and resources we are allowed.

Table 1: Customer Wants and Needs

Needs	Wants
Overcomes spring force to open valve	Weight below 5 lbs.
Controlled with a programmable interface	Fits within a 6 in. cube
50 Hz actuation speed	Power consumption below 140W
No more than 3 moving parts	Less than $500

3.3 The Quality Function Deployment (QFD) Process

The wants and needs discussed are part of the QFD process, which involves filling out the House of Quality (listed in Appendix A). Our QFD process started with identifying the customers, who in this case were our sponsors. We then conducted a meeting with our customers to determine their needs in order to fill out the "what" section of the House of Quality. The customers' requirements were then weighed in the "who vs. what" section, where each requirement is assigned a level of importance. This process helped determine which requirements were the most important overall, with critical requirements getting an asterisk next to their title. The next step involved filling out the columns to the far right of the chart where the benchmarks are located. The names of the competition were listed at the top of each column, and how well they each satisfy the customer requirements was recorded below them. We then established specifications that are measurable and verifiable. These specs correspond to the customer's wants and needs list that had already been filled out on the left side. Once the specifications were defined, they were related to the wants and needs list in the central area of the chart, called the "hows vs. whats" section. Each combination of specification and want/need was given a relation value, ranging from a strong relation to no relation. Once that section was completed, engineering targets were set based on the benchmarks and the requirements defined by the "hows vs. whats" section. This process helped us make sure that we are solving the problem that our customer came to us with, and from it we have set our engineering targets as shown in Table 2. The specifications are not listed in any particular order, but all of our most important specs are listed as high risk (H) in table 2. The QFD process allowed us to narrow down our critical wants and needs. It also helped us ensure that all our engineering specifications will be measurable.

3.4 Project Specifications

Table 2: Preliminary Project Spec Sheet

Spec #	Specification Description	Requirement or Target (Units)	Tolerance	Risk	Compliance
1	Weight	5 (lb)	Max	M	A, T, S
2	Size	6 (in3)	Max	L	I, A
3	Actuation Speed	0.003 (s)	Min	H	A, T
4	Mechanical Complexity	3 moving parts	Max	L	I, A
5	Actuation Force	250 (lbf)	Min	H	A, T
6	Production Cost	500 ($)	Max	M	A
7	Power	140 (W)	Max	H	T, A

The weight specification was set on the high end but allows us room to use larger stator coils in order to achieve our target actuation force. This value may need to be adjusted as we learn more about the rules of designing systems that use electromagnetics.

Size was set by the engine, since we want the actuator to fit underneath the stock valve cover and thus within the same footprint as the original valvetrain. The minimum actuation frequency was calculated based on an assumed maximum engine rpm of 6,000 rpm in a four-stroke engine, which comes out to 50 valve actuations per second.

Mechanical complexity was determined based on the customer's desire to reduce the number of moving parts when compared to a traditional engine.

Actuation force was set by our measurement of the spring stiffness of an engine valve spring out of a 1965 Ford Mustang, and as such is subject to change depending on the stiffness of our development engine's valve springs.

Production cost was set at $500 in order to minimize the temptation to use exotic materials that would not be viable for use in production vehicles.

The power specification was set at 140 watts under the assumption that the system would be operated with 10 amps max at 14 volts, a reasonable power consumption for the electrical systems of modern cars. Each specification will be met using the following methods:

- Weight: Analysis will be performed during the design phase in CAD to make sure that the design meets our weight goal.
- Size: Inspection and analysis of the actuator in the design phase will be performed in CAD to make sure proposed designs stay within the size constraints.
- Actuation Frequency: Analysis will be conducted using hand calculations and magnetic field Finite Element Analysis (FEA) to determine the potential for a powerful stator coil to cycle fast enough. Testing of the actuator will then be performed to validate the spec.
- Mechanical Complexity: Visual inspection of proposed designs will be performed in order to make sure moving parts stay below the limit.

- Actuation Force: Analysis will be performed to calculate the theoretical max force, which will then be verified with a loadcell based test rig
- Production Coast: A budgeting spreadsheet will track expenditures.
- Power: Power consumption will be measured by a multimeter o.1r an equivalent electrical diagnostic instrument.

We have several high-risk specifications, which are the actuation force, power, and actuation frequency. These goals will be the hardest to meet given what we have learned about the history of electromagnetic actuators and their known weaknesses. Many of the available electromagnetic actuators that we were able to find had either a high force output, long travel, or high actuation speed, but virtually none had all three, which is sign for us that such a goal may in fact be very hard to achieve, and we can expect to put most of our resources into maximizing these values.

4.0 Concept Design

Once our preliminary research was completed, we began working towards our concept design. The process of arriving at our current design played out in several distinct stages starting with ideation, then concept modeling, and finally decision matrices and sponsor feedback.

4 .1 Ideation

During our ideation phase, we took inspiration from research papers and designs proposed by our sponsor in order to come up with multiple solutions for our problem. In order to come up with more creative ways to implement certain functions of our design, our group used sticky note ideation. The ideas from our sticky note ideation are highlighted in Appendix B. We then kept brainstorming ideas in our notebooks and continued to learn more about electromagnetic actuator design. During the concept model ideation day, we took the existing ideas and sketches and turned them into prototype concept models. We also developed new concepts during this time and tried to be as creative as possible while doing so. The models created during our concept model ideation are shown in Appendix C. After all of this ideation we narrowed our ideas down in order to create concept models.

4.2 Concept Modeling

The concept modelling phase involved building simple representations of many of the ideas explored in the ideation phase. We used simple arts and crafts type materials to build semi-functional models in order to begin validating design concepts. The models helped us understand some of the benefits and drawbacks of many of our design ideas. Our project is fairly limited in scope. Since we are constrained to designing an electromagnetic actuator to operate our engine valves, our concept models primarily explored various ways to use multiple coils or mechanical advantage to increase useable force. Notable ideas included arranging three coils in an array on a rocker arm that actuates the valve, using a coil on the top and bottom of the rocker arm, and using a design like a film clap board, with the coil on the same side of the rocker pivot as the valve. Our final concept designs are shown in Figures 7 through 12.

Figure 7 shows a rotating arm design that uses three coils acting in unison. This design will use three electromagnets that will be driven by an alternating current. This will create an oscillating force back and forth that will open and close the valve. A spring could also be used in order to return the arm back to its original position and pulses could provide the actuation force.
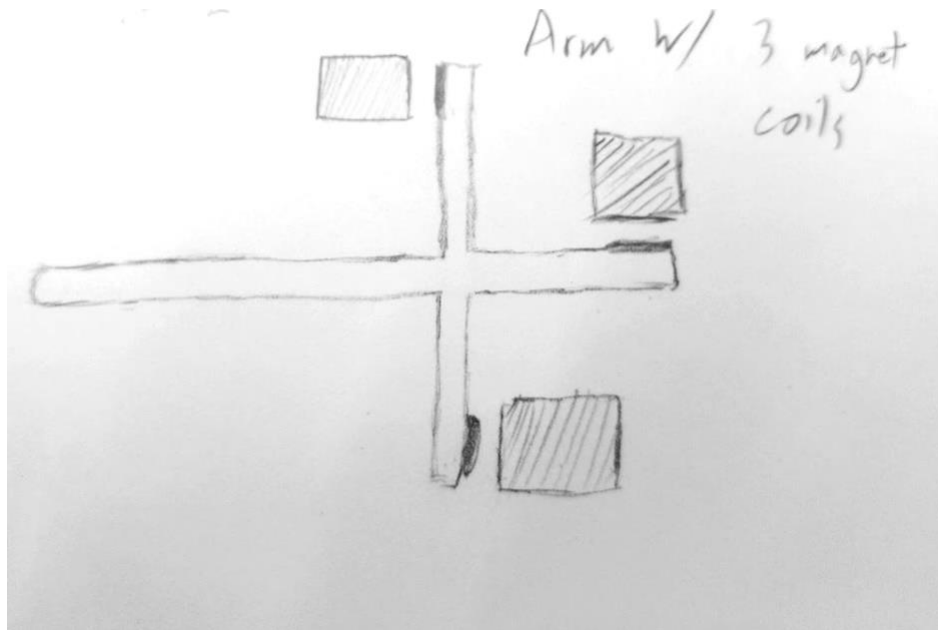
Figure 7. Three Coil Rotating Arm

Figure 8 shows a design that uses two coils to provide actuating force. A design like this in nonlinear and has a significant air gap which will decrease the actuation force. Also, this design is very bulky and would be difficult to fit on an existing engine.
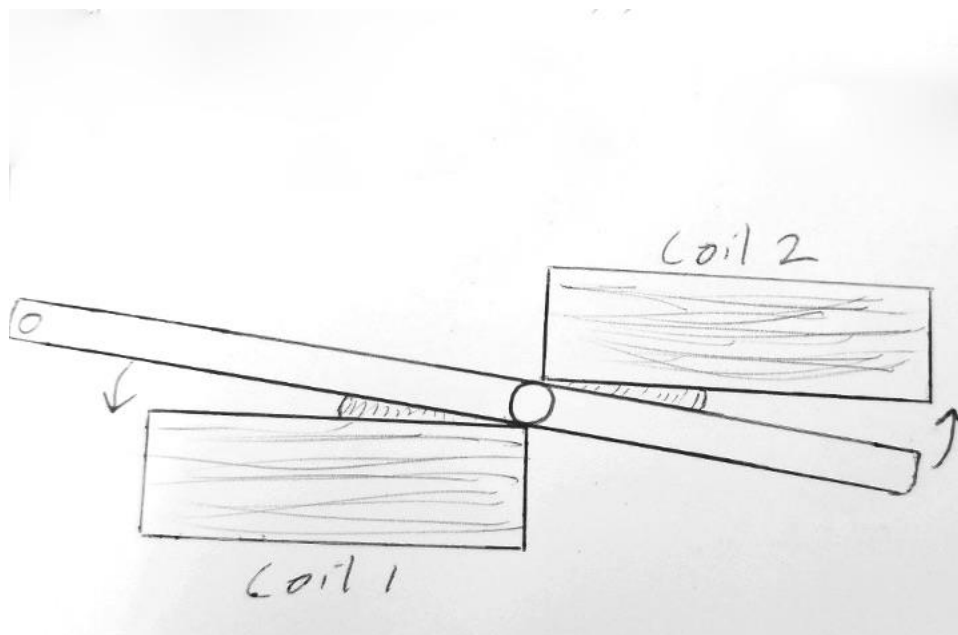
Figure 8. Two-Sided Coil Design

Figure 9 shows a design like the previous design, but instead it uses a single large coil and has the hinge at one end of the electromagnet. The issues with this design are that it is still nonlinear and creates an air gap which has a high permeability (resistance to magnetic field propogation).
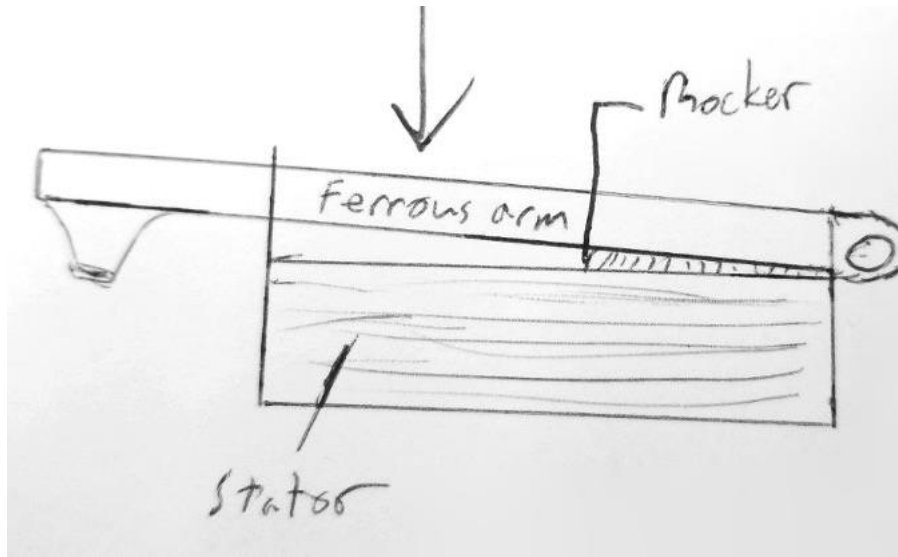
Figure 9. Torque Arm Design

Figure 10 shows a design that uses three linkages in order to create additional force along with two electromagnets. This idea is very bulky and has many components which will lead to increased weight and complexity. This is also nonlinear, and it would be difficult to develop a control system.
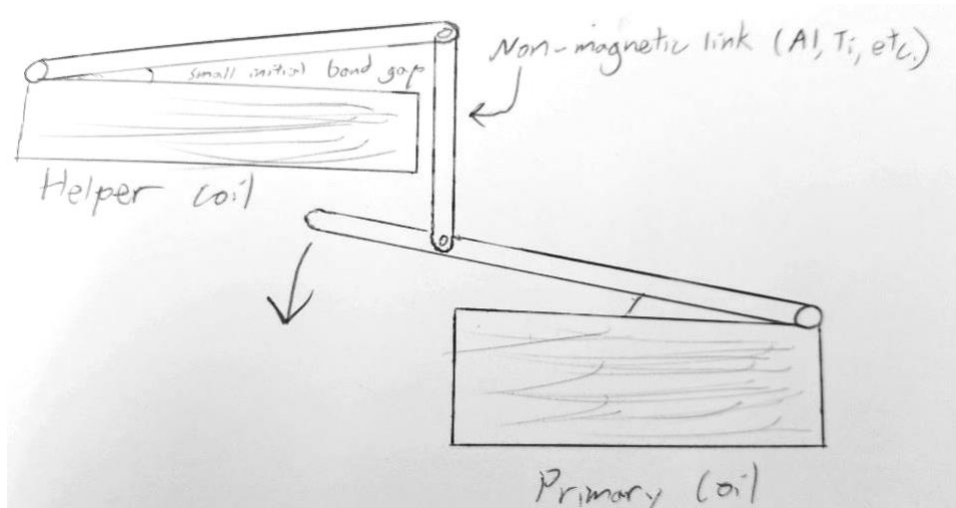
Figure 10. Multi-Link Design

Figure 11 shows a design that utilizes a permanent magnet and coils that are charged so that one attracts the magnet and one repels the magnet in order to provide extra force. This idea requires the control of two solenoids and space for two fixed coils.
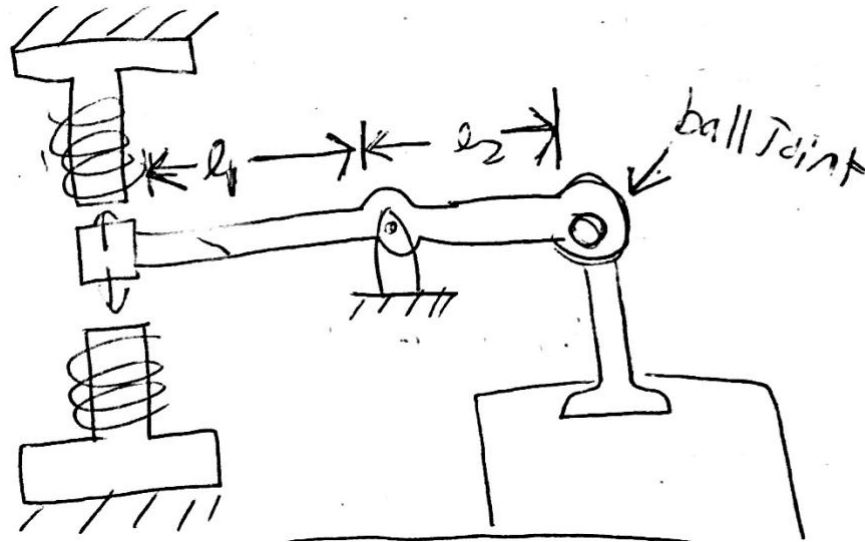
Figure 11. Double Acting Solenoid Design

Figure 12 shows a moving core design where the metal core of the actuator is fixed to a lever arm and moves within the coil. This design removes the air gap that is present in other designs, providing a linear response which will be easier to control.
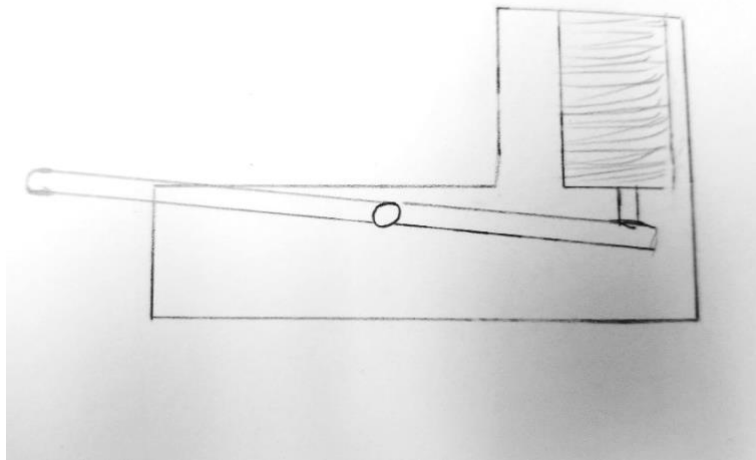
Figure 12. Moving Core Design

4.3 Decision Matrices

The next step involved setting up a Pugh Matrix to test our design ideas against the one that we thought would be the best initially. Generally, a Pugh Matrix would be created for each function, and a morph chart would then be used to generate combinations of ideas. However, since we are limited to using electromagnets for force application, and their qualities require specific conditions for optimal performance, we did not have enough options to form a proper morph chart. Instead, our Pugh Matrix covered different ideas for magnetic coil positioning relative to a rocker arm. The datum design is represented as concept 1 in Table 3. Each concept model after that was compared to the datum and listed as either better (+), worse
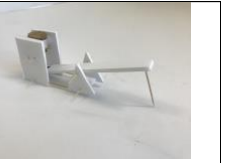
(-), or the same (S) in each of the design criteria. Concept 5 uses an electromagnetic actuator with a moving core. These actuators are called voice coils and are commonly found as the actuators used to drive speaker cones. This design beat all the other designs in the Pugh Matrix, so we moved on to a weighted decision matrix to check the results.

Table 3: Pugh Matrix

Concept / Criteria	1	2	3	4	5
Low Weight		-	-	-	-
Low Inertia		+	-	+	+
High Force		+	+	+	+
High Speed		-	-	+	-
Reliable	Datum	+	-	-	+
Programmable		+	-	-	+
Easily Manufacturable		-	-	-	-
Low Noise		-	-	-	+
Small Footprint		+	-	-	+
Low Mechanical Complexity		-	-	-	-

In Table 4, each design criterion was given a weight from one to five according to the importance of each requirement. Each design was then given a raw score from 0 to 5 in each category before the weights were multiplied by the raw scores to give the actual score in each category as shown in the table. After finding the total score for each concept, the moving core design came out as the clear winner. It beat the other designs primarily with its ability to apply more force, largely due to the lack of an air gap between the core and the rocker arm.

Table 4: Weighted Decision Matrix

Factors	Weights	Torque Motor	Double Coil	Coils in an array	Coil w/ Moving Core
Inertia	3	15	6	3	9
Weight	1	3	2	0	3
Force	5	10	15	20	25
Speed	4	12	8	12	12
Reliability	1	4	4	4	4
Noise	1	1	1	0	3
Size	2	6	4	0	4
Mechanical Complexity	2	10	8	4	6
Total:		**61**	**48**	**43**	**66**

Since the moving core actuator received the highest score in the decision matrix, we brought it to one of our sponsors, Dr. Poshtan, to check the feasibility and receive feedback.

4.4 Sponsor Feedback

After consulting with Dr. Poshtan, he confirmed that a moving core design would best suit our needs in this application. By using a moving core connected to the lever, the air gap would be made constant and internal to the solenoid. This concentrates the magnetic field by preventing magnetic flux leakage. Having a metal core also strengthens the magnetic field. Air has a relatively low permeability, which leads to a

decrease in the strength of the magnetic field. By replacing the air between the core and the lever with metal, the permeability is increased, therefore the magnetic field is strengthened. Another section that will require analysis is vibration. In our design, we intend to include a mechanism to dampen the vibrations seen by the electromagnet.

4.5 Concept Prototype and CAD

We chose the moving core design based on the feedback from Dr. Poshtan and the results of the matrix analysis. The moving core design provides the most force of any design and is the easiest to control due to the linear nature of the force profile. The opening of an exhaust valve requires a large amount of actuation force at the beginning of travel due to the pressure inside the cylinder. All other designs considered produce minimal force at the beginning of travel due to the presence of an air gap, making the moving core design superior. Figure 13 shows a basic 3D model of the chosen design created to verify feasibility and develop a starting point for prototyping. An accurate model of the cylinder head with which initial testing will be performed was used to provide a reference for size and spacing constraints. The generation of the model resulted in a new challenge for the design. The need for lateral movement of the solenoid core within the rocker arm was not previously considered and was initially addressed by the addition of a slotted hole. Further ideation and testing will be performed to analyze potential options to overcome this challenge.
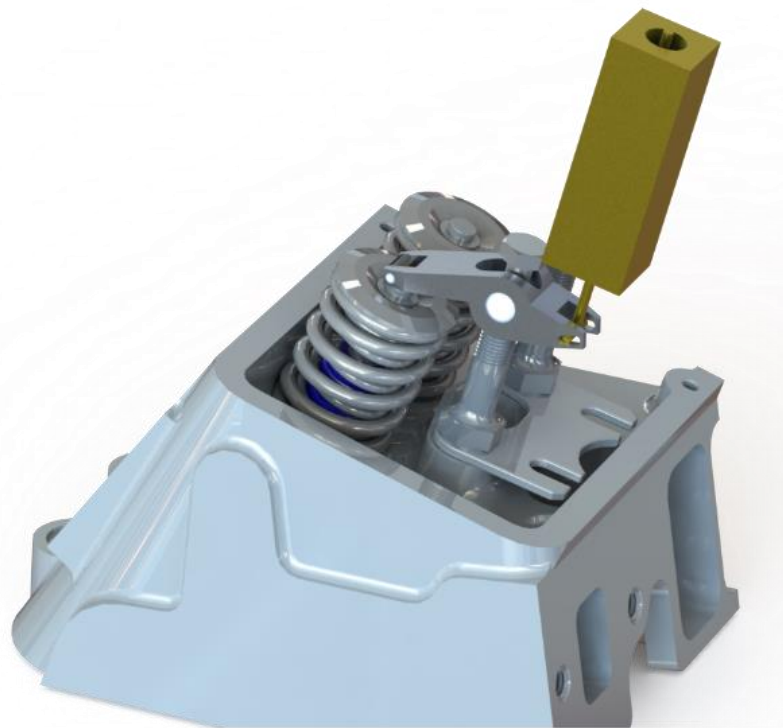
Figure 13: Concept CAD Model

As seen in Figure 14, we also built a simple concept prototype out of PVC pipe and wood to improve our understanding of the hinge mechanism and the relationship between the rocker and the moving core actuator. This prototype provides a physical example of the movement demonstrated by the CAD model in Figure 13 and proves that we must carefully consider the relationship between linear and rotational motion at the joint between the moving core of the electromagnet and the rocker arm.
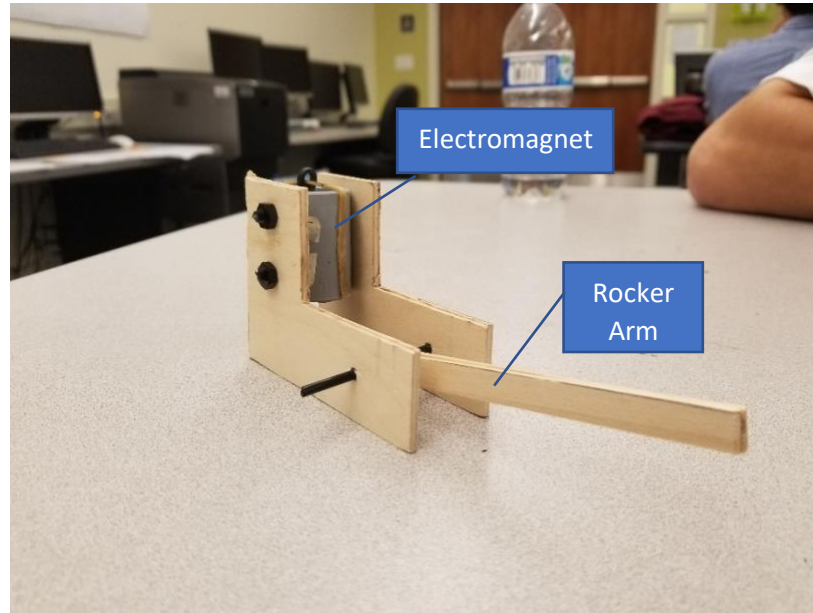
Figure 14: Concept Prototype

4.6 Preliminary Analysis and Tests

Since electrical design has not been selected yet, the preliminary analysis and tests involve the mechanical requirements that our selected design will need to meet. We first tested our valve spring and found that the stiffness is about 256 lbf/in. These tests are highlighted in Appendix D. We are basing our design to meet the requirements of a stock 350 cubic inch Chevrolet V-8 engine because this engine is widely used, and we believe it to be a good benchmark. Next, we researched how much we need our valve to travel, and from this we came up with force requirements. Based on the factory parameters of the 350 cubic inch V-8 engine, the maximum valve lift will be 0.46 inches which corresponds to 0.31 inches of actuator travel. Our design will meet this specification if we can create a large enough magnetic field in our actuator. We also chose the design that will give us the highest force, and we plan to analyze different core sizes and actuator designs once we learn more about the subject. When we consider exhaust pressure during exhaust valve opening, the maximum force required to open the valve is 128.1 lbs. at the valve, which corresponds to 198.8 lbs. of actuation force on the rocker arm. Table 5 shows the stock specifications of the 350 cubic inch V-8 and calculated valve event parameters at 6000 RPM.

Table 5. Valve Event Parameters

Engine Rotational Speed (RPM)	6000
Cam Intake Lift (in)	0.45
Cam Intake Duration (deg)	222
Cam Exhaust Lift (in)	0.46
Cam Exhaust Duration (deg)	222
Intake Valve Diameter (in)	1.94
Exhaust Valve Diameter (in)	1.5
Rocker Ratio	1.5
Spring Rate (lb/in)	267
Cylinder Pressure at Opening (bar)	5
Crankshaft Speed (deg/s)	36000
Intake Valve Opening Time (s)	0.00308
Exhaust Valve Opening Time (s)	0.00308
Intake Valve Speed (in/s)	145.9459
Exhaust Valve Speed (in/s)	149.1892
Opening Force (lb)	128.1181
Max Travel Force (lb)	122.82
Maximum Actuator Force (lb)	198.8039
Maximum Actuator Force (N)	884.3239
Maximum Actuator Travel (in)	0.307
Maximum Actuator Travel (mm)	7.789

4.7 Current Risks, Challenges, and Unknowns

It is important to understand what we need to consider and what we do not know for this project. For the current risks of this design, the main risk comes with using the stock rocker arm and slot to create the linear motion. This adds mechanical complexity to the assembly and could result in different failure modes. The fiction between the slot and the actuator stem could also result in wear and failure due to fatigue. Another risk could be the size and weight of this design. Since this design has multiple components as opposed to just an actuator, the weight will be larger, and it will take up more space. The hinge could also be receiving fluctuation loads which can result in failure due to fatigue. The Design Hazard Checklist is in Appendix F.

The challenge for this design will be to create a smooth motion that minimizes friction while also providing the correct amount of force, valve travel, and timing. The main challenge will be to design the electromagnetic actuator to meet all these criteria. If we buy an actuator from the market, then this factor will be eliminated, but it will be ideal to design the actuator ourselves. Another challenge that comes with this design is the method to control the actuator. We must develop a control algorithm and use a microcontroller to implement it such that it will respond quickly while being able to control the current precisely. We must also make sure that temperature changes and vibration do not affect the electrical components of the design.

There are many unknowns for this project. We will continue finalizing an electromagnetic design. Things we still need to figure out are how much force we can get from our design, what power will be required to create this force, and how we will control the actuator. We also do not know what frequency we will achieve, and whether we may need to add springs or other components in order to get the correct response from our assembly. All these things will need to be sorted out before CDR.

5.0 Final Design

The final design of our electromagnetic actuator focuses on two main subsystems: the solenoid and the control system. These two systems work together to act as a linear actuator, which can be applied on an internal combustion engine. This actuator will be custom made for a Chevy small-block engine. To test and show the results of the actuator, a test stand will also be built. The electromagnetic actuator and test stand will allow a user to enter any engine speed up to 1500 revolutions per minute (RPM) and have the actuator run at the corresponding valve event frequency.

5.1 Solenoid

The solenoid acts to convert electrical energy to mechanical work in our system. Based on the principles of electromagnetism, it will be constructed of copper wire, an iron core, and a steel housing. Several variables of the design were determined by the constraints of the engine. These variables include the outer dimensions, air gap, and maximum current. The air gap, often referred to as the stroke, is the distance the core must travel. In our case, the air gap is determined by the maximum valve lift, which can be found from the engine specifications in Table 5 to be 0.46 in. This left us with several variables in the design that could be manipulated in order to achieve the required force.

5.1.1 Design Description

The chosen design of the solenoid features a three-piece case with a closed top, a solid moving core, and a multilayer coil. A labeled cross-section view of the actuator is shown in Figure 15. When a magnetic field is generated by the coil, the core moves towards the center of the actuator. In an engine, the core would pull on a rocker arm to open the valve. For simplicity, testing will be performed on a test stand where the actuator pulls on a valve spring directly. The function of the case is to maintain a clean environment in the solenoid and provide heat dissipation for the coil. The case additionally reduces magnetic flux leakage, making the magnetic field in the center of the actuator stronger than without a case. The top end cap of the case stops the core from travelling beyond the stroke, preventing damage in an engine. The coil produces a concentrated and controllable magnetic field when current is applied. The strength of the magnetic field is dependent on the number of turns and the current applied.
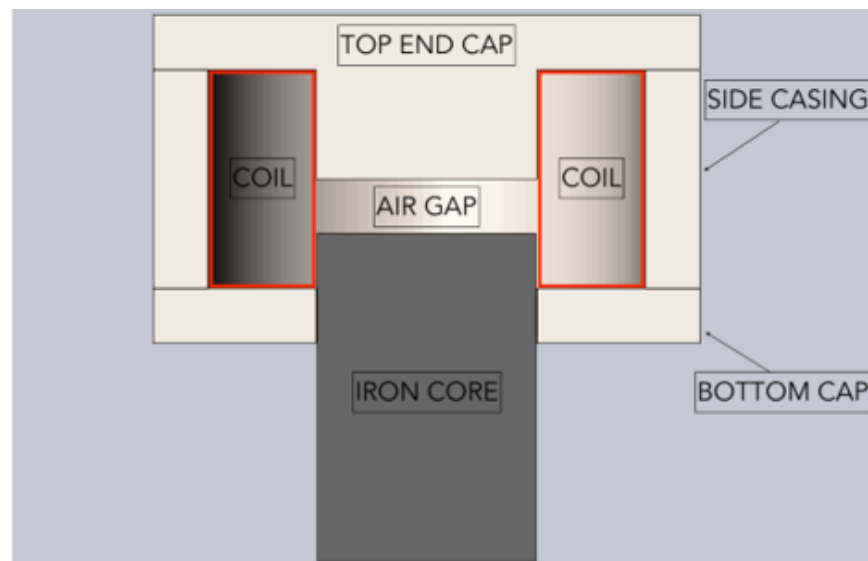
Figure 15. Cross-section of solenoid actuator

Materials for each piece of the solenoid were selected based on magnetic properties. Grey cast iron was selected for the core because it features the highest magnetic permeability of any reasonable material. The high permeability allows for a stronger magnetic field as the saturation limit of the core is higher. Because the main challenge of the design is to reduce the opening time of the actuator, lighter materials were considered but the impact of the decrease in permeability was greater than the decrease in weight. The material for the case was chosen to be steel for ease of manufacturing and low cost. Steel contains the magnetic flux produced by the coil as well as any other metal, as the containment does not require high permeability. An added benefit of the steel is its ability to conduct heat away from the coil, since overheating is a concern. The coil will be made with motor winding wire which is specially designed for electromagnetic applications. The copper wire is shielded to allow for high temperature use and is highly conductive. Motor wire was chosen over other copper wire for its ability to maintain shape once wound into a coil and the precise calculation of insulation thickness to maximize conductor area. With the current being well over 10 A, the thickness of the wire became an important design consideration. For a duty cycle of about 15%, IEEE recommends 14 gage wire [10] to prevent overheating.

Due to the high current required for the solenoid there is a risk of electric shock and the potential for high temperatures. The solenoid is a self-contained unit, so the risk of injury or damage is low. The solenoid is activated by the application of a voltage across the coil. The precise control of the voltage by the controller changes the current through the coil and allows for control of the force on the core. The solenoid is maintenance free as all the parts are contained within the case, which cannot be opened. Due to the nature of the system, if the solenoid fails, it fails permanently and must be rebuilt.

5.1.2 Justification and Evidence

Analysis for the actuator was performed using MATLAB and a magnetism specific finite element analysis software called Finite Element Magnetic Method (FEMM). An optimization program was developed to find the fastest opening time attainable within the constraints of the engine. The optimization program worked by generating a random set of initial geometry and parameters, then scales the geometry unilaterally to produce the minimum force required to open an exhaust valve against the valve spring and exhaust gas pressure. Every new geometry condition is drawn in FEMM by a MATLAB function. A set of geometry conditions drawn in FEMM is shown in Figure 16.
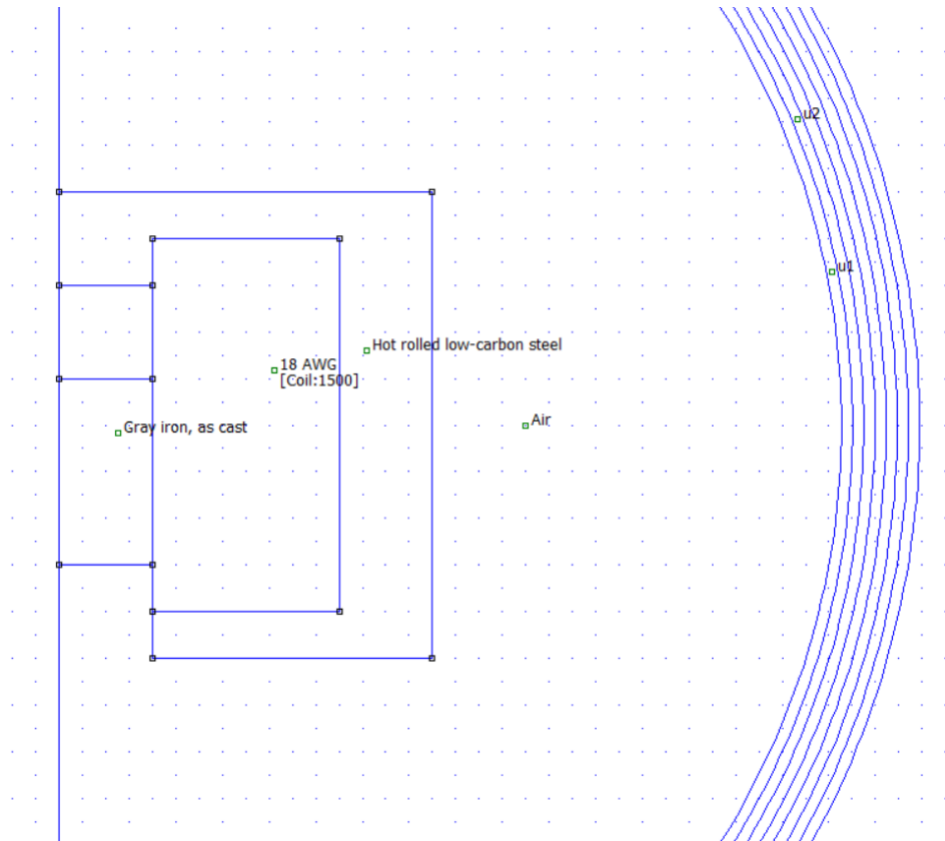
Figure 16. FEMM application window with drawn geometry

The FEMM program is able to calculate the force generated on the core by the magnetic field and does so at a specified number of intervals throughout the stroke. A snapshot of the FEMM solver that shows magnetic flux lines and the calculation of force on the core can be seen in Figure 17.
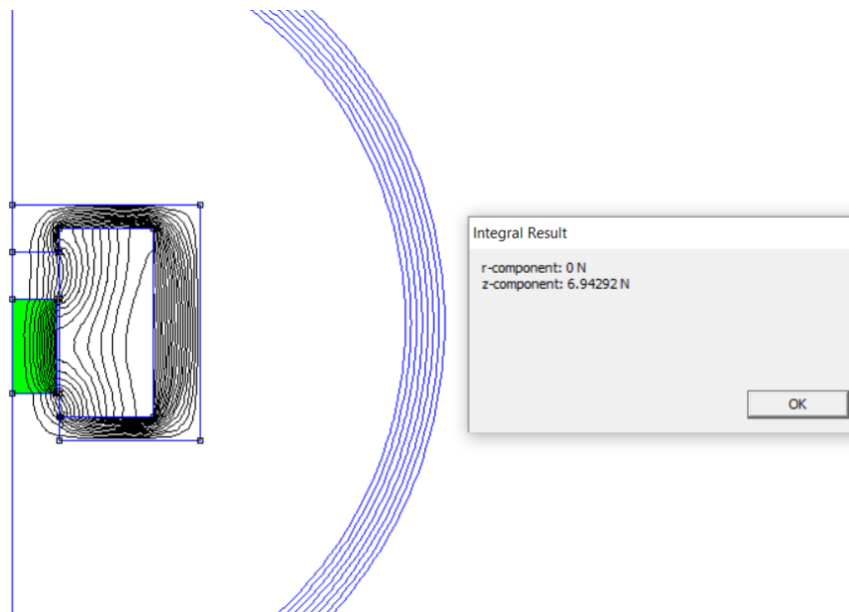
Figure 17. FEMM application window with force calculation

The force results from the FEMM solver are returned to MATLAB for analysis. The mass of the core is calculated and used along with the force values to determine the opening time using kinematic equations. The opening time is compared to the previous best value and the current geometry is saved if improvement is found. New geometry is then created based on the current best results, with slight modifications. The scale of the changes decreases when no improvement is found within a specified number of attempts. The process continues until no improvement can be found with a change scale of less than 1%.

The optimization program was run under five sets of conditions. An unbounded iteration was run as a proof of concept and to establish a baseline. This iteration produced an opening time of 8.7 milliseconds with an outer case diameter of 33.01 inches. Next, an iteration was run with the addition of a 1.5:1 ratio rocker arm. This produced an opening time of 8.3 milliseconds with a case diameter of 111.3 inches. The case diameter was then limited to a maximum of six inches which produced an opening time of 13.1 milliseconds. The ability to add additional cores was added to the program and an unbounded and bounded run produced 7.4 and 12.8 millisecond opening times, respectively. As the addition of multiple cores did not produce noticeable improvement and would require additional space, the decision was made to use the single-core design. Figure 18 shows a chart of the results of the best geometry from each condition.
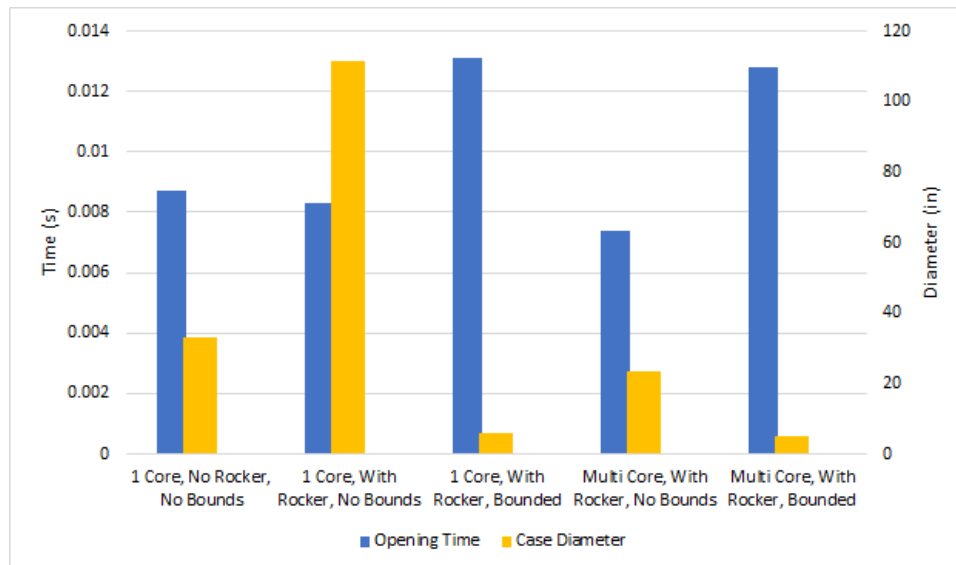
Figure 18. Opening time and case diameter of 5 optimization runs with various conditions

The force output of the constrained, single core actuator was used to produce a plot of valve opening. The return of the spring was modeled as mass-spring-damper system. A plot of a single valve event is shown in Figure 19 and a series of valve events is shown in Figure 20. The rise to the specified displacement can be seen as well as the actuation time. The equivalent engine speed was calculated based on the stock camshaft parameters of the Chevy small block engine. Because camshafts are designed to facilitate a range of engine operating speeds with a single cam profile, it is possible that the maximum engine speed achievable with the electromagnetic actuator is higher than as calculated.
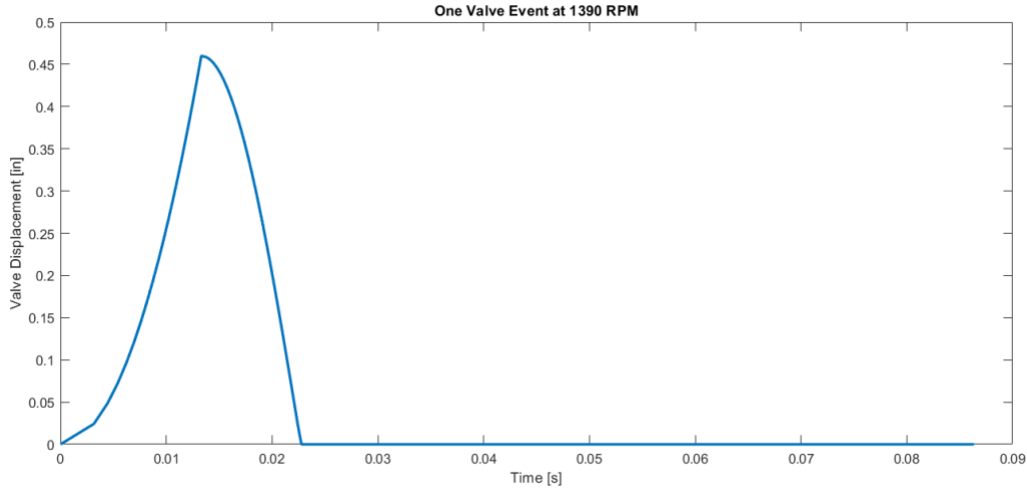
Figure 19. Single valve event with 6" diameter, single core actuator
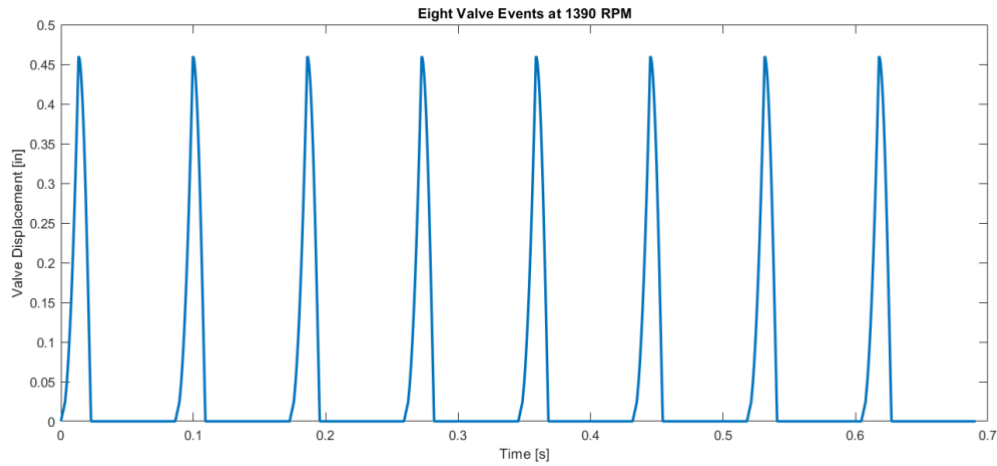
Figure 20. Multiple valve events with 6" diameter, single core actuator

The final dimensions of each component of the actuator, as determined by the optimization program, can be found in the engineering drawings in Appendix I.

The analytical solution for the force achieved by the actuator was found using Equation 1.

$$F = \frac{SN^2 i^2 \mu_r^2 \mu_0}{2(l_2 + l_{eq} + (\mu_r - 1)x)^2} \tag{1}$$

The derivation of this equation is in <u>Linear Electromagnetic Actuator Modeling for Optimization of Mechatronic and Adaptronic Systems</u>, a paper written to find the force provided by electromagnetic actuators [11]. Using this equation, along with others, allowed the simulation to be checked with an analytical solution. An analysis tool was created on Microsoft Excel that showed variours parameters. It gave insight to how the force produced increases with number of turns, current, and permeability. An

example can be seen below in Figure 21. By taking the size given from the simulation and the maximum current for each gauge wire, the maximum number of turns can be determined. From here, one find the total resistance of the length of wire, and henceforth the current for a given voltage. Knowing these values allowed us to use Equation 1 above to get the force. Figure 21 shows how the force changes with varying voltage sources, taking into account a saturation limit of 1.75.
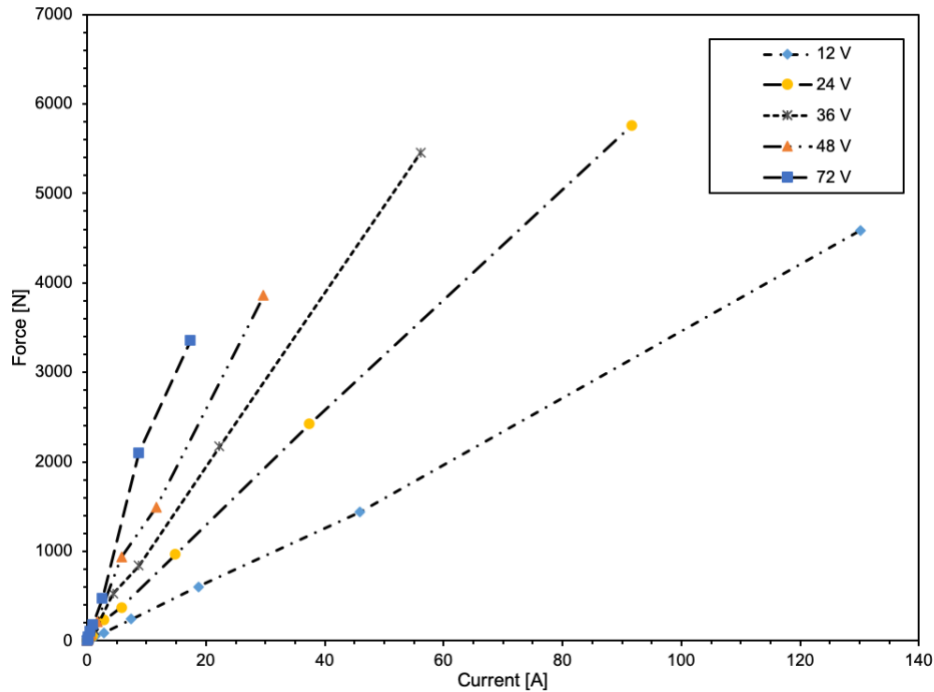
Figure 21. Force as a function of current and voltage sources.

One potential issue that has not been considered so far is the time it takes for the magnetic field to build. If the time it takes for the magnetic field to become strong enough to move the valve is longer than the resting time of the valve, the actuator will be unable to open the valve at the desired speed. Another potential issue is the heat generated by the current in the coil. As the duty cycle of the actuator is only 15% at the stock camshaft parameters, this is unlikely to be an issue but will be monitored closely. An additional source of heat may come from the development of eddy currents within the core. Eddy currents are an electromagnetic phenomenon that is often used in the melting of metals, as in an induction furnace. Eddy currents are a product of high frequency changes in the magnetic field, so they are unlikely to be a significant source of heat in our application. If eddy current heating is determined to be an issue, a laminated core, a core made of strips of metal separated by adhesive, will be implemented.

5.2 Electrical Components

The solenoid designed in the previous section is based on the idea of a pulsing direct current. In order to achieve this, the solenoid needs a control system to regulate the current coming from the battery. In this section, the electrical components needed and a design for the control system is explained.

5.2.1 Design Description

Our entire electrical system will consist of six main components. We will be using a standard power supply, motor driver, microcontroller development board, laptop computer, actuator, and accelerometer. The final control system is shown below in Figure 21. We chose to use a STM32 microcontroller. This is a relatively

cheap microcontroller at only $14, but it is reliable and commonly used in labs at Cal Poly. It is also compatible with MicroPython, which is our chosen programming language. To make physical connections easier, we also chose to integrate a separate board not shown to expose the pins from the microcontroller. This will make our system easy to assemble and reconfigure. Due to a 14V battery source, a motor driver will also be necessary to send out high current to the actuator. Lastly, the actuator will convert the electrical power to mechanical power, compressing the spring.
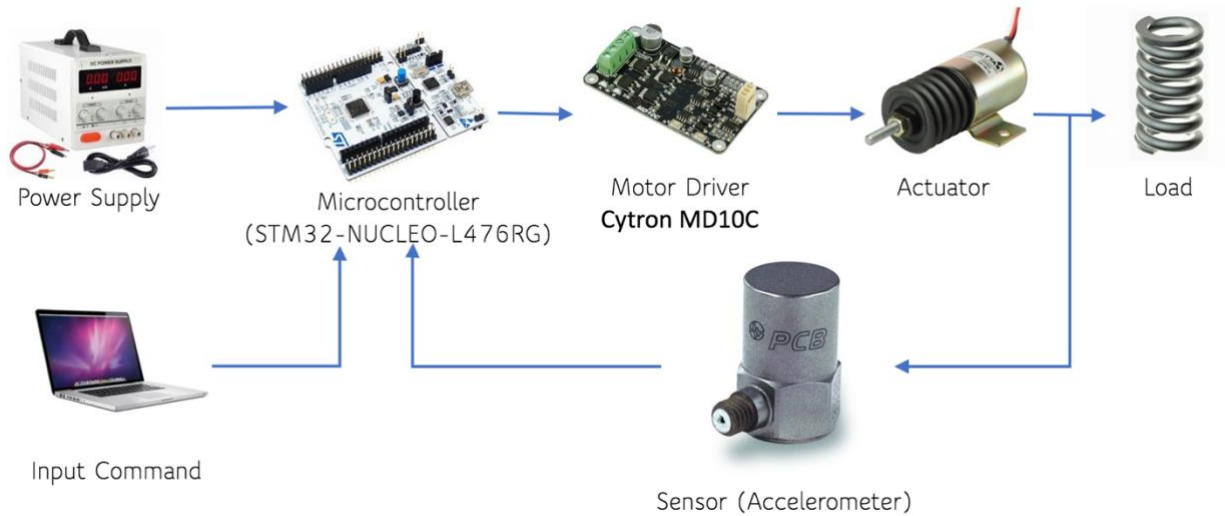
Figure 22. Final Control System Schematic

5.2.2 Justification and Evidence

In order to control our system, we will be programming our microcontroller using Python. We will load the MicroPython firmware onto our microcontroller which will allow us to load python files to our microcontroller. The control system will be operated by a user at a computer using a terminal emulator called PuTTY. PuTTY will run our main control module which will import and call the other modules that are needed. We chose this methodology as our design choice because running MicroPython will allow us to easily program and debug our control system as well as allow us to create a user interface that a user can use to control the actuator. We will also take advantage of libraries, such as Matplotlib, to generate plots of position, velocity, and acceleration data coming from our accelerometer. C programming is also an option, but we chose to put our time into developing a better design for the actuator. Other design choices were to use a keypad and display, but it would take significantly longer to program firmware as well as test and debug our control system this way. Figure 21 shows a block diagram of the proposed control system. We decided to use a PCB Piezotronics accelerometer as our sensor because of its high accuracy and reliability. This accelerometer will also easily attach to the bottom of our spring and be easily integrated into our control system through the microcontroller.
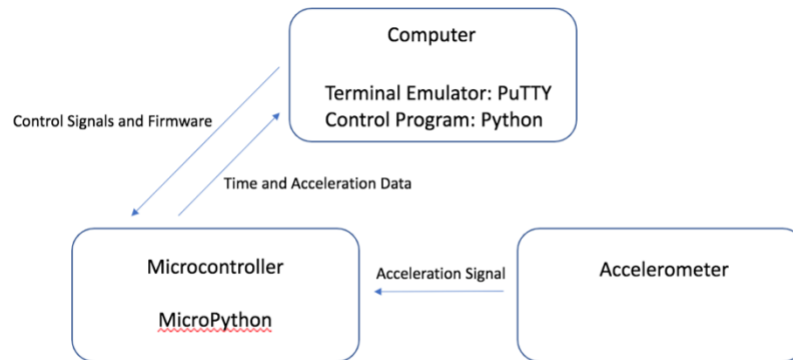
Figure 23. Control Software Block Diagram

At its basis, the control system will control the actuation by allowing current to flow at set intervals, effectively turning the actuator on and off at a set frequency. We have chosen the Cytron MD10C motor driver because it has a high current limit which we will need as a factor of safety for this project. Also, this motor driver is relatively cheap at a price of around $10. The frequency of the actuator will depend on the engine speed that is input by the user. A schematic of how the system will be connected can be seen in Figure 22. This program will take in engine speed and output a square wave for the actuator to run at. Due to the nature of the cam, the valve is only open for 15% of the time for each revolution. This helps in our design as a low duty cycle will help to prevent overheating in the core and coil. For safety considerations, we are considering integrating a thermocouple into our system to in order to monitor the temperature of our actuator to make sure that it does not overheat. The square wave pattern generated by the program will have a sinusoidal shape due to the build-up of magnetic field within the solenoid. This will not affect the functionality of the actuator if the valve is open for approximately 15% of each whole cycle.
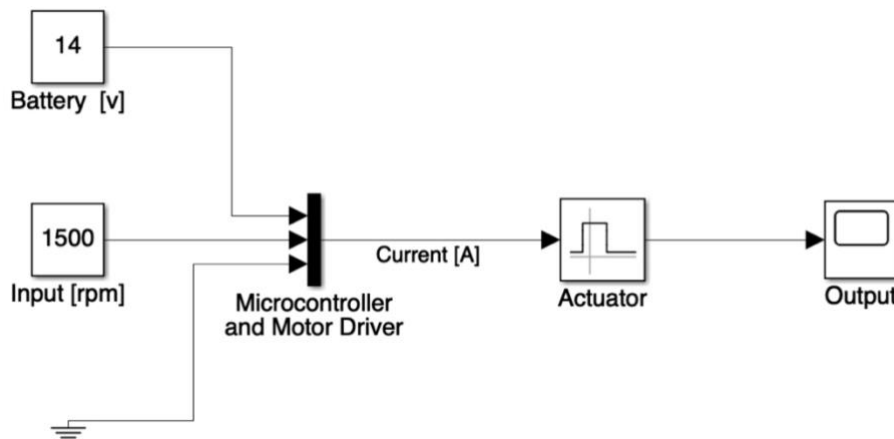
Figure 24. Schematic of how the input, battery, microcontroller and actuator work together

5.3 Project Budget

As mentioned in our project specifications, the target cost for this project was $500. Although the focus of the project shifted, the total cost of the project only be $471.23, as seen in Table 6. A full breakdown of cost, along with part details, can be seen in Appendix G, the bill of materials. Keeping the overall price low

was achieved by doing all necessary manufacturing at the Cal Poly machine shops, which is free to all students. We also designed our systems to use common sizes of hardware for the solenoid and test stand. This allows for quicker and cheaper shipment of parts. The design of the test stand will be further discussed in the following section: Project Plan.

Table 6. Condensed Project Budget

System	Part	Cost
Solenoid		**$350.00**
	Wire	$53.00
	Top steel plate	$25.00
	Bottom steel plate	$25.00
	Steel Tubing	$160.00
	Battery	$35.00
	Iron rod	$52.00
Microcontroller		**$50.75**
	Nucleo development board	$14.00
	Motor driver	$11.50
	2x19 female headers	$0.72
	10-pole screw terminals	$8.00
	5 pole screw terminals	$5.00
	Board	$11.53
Test Stand		**$70.48**
	6"x6" 1/4" Type 304 Steel	$10.13
	6"x6" 1/4" Type 304 Steel	$10.13
	1.5" ID steel pipe	$1.00
	7/16"-14, 5" long Hex Screw	$27.84
	1/4"-28, 3" long socket head	$0.10
	1/4"-28 locking nut	$0.40
	7/16"-14 nut	$6.63
	18-8 Stainless Steel Washer	$1.53
	1/2" SCH 40 Pipe	$12.72
Overall		**$471.23**

6.0 Manufacturing Plan

Our final design requires the machining of custom parts. Since our solenoid design consists of simple geometry, and the test stand is also built from geometrically simple parts, all the machining can be handled by us in the Cal Poly machine shops. The only problem we encountered while sourcing the required materials was a lost package of steel plate on the count of UPS. We were able to quickly source the metal from an alternative supplier, so the lost package did not delay our development timeline. Manufacturing will take 3 weeks to complete, and the exact dates for manufacturing are listed in the Gantt chart in Appendix E. For detailed drawings of all parts listed in the manufacturing plan, refer to Appendix I. Refer to Appendix G for the detailed Bill of Materials with a cost breakdown.

Procurement
- Actuator (for control testing): Purchased online from Amazon
- Actuator (Optimized): Raw materials purchased from McMaster
- Control System:
    1. STM32 Nuclear Developer Board ordered from Mouser
    2. Shoe of Brian custom PCB was ordered from OSH Park
    3. Accelerometer will be obtained from the vibrations lab
    4. Transistors and Diodes were ordered from Amazon

     5. Screw terminals and pin connecters from Ebay
- Power Supply: Supplied by Dr. Poshtan
- Test Stand:
    1. Base Plate and Top Plate: Raw material cut-to-size purchased online from McCarthy's Steel
    2. Support Spacers: Raw material purchased at Home Depot
    3. Hardware: Purchased online at McMaster
    4. Spring Perch tubing: Bought from Mustang 60

Manufacturing
- Test Stand:
    1. Mounting holes and slots will need to be machined into the top and bottom plates as per the engineering drawings using a vertical mill and ¼" and ½" end mills.
    2. Plate spacers will need to be cut into sections using a vertical band saw and then cut to the correct matching length by mounting them together in a vertical mill and facing both sides. Special care must be taken to ensure all cuts are square.
    3. The tube for the spring perch must be cut into two pieces each ½" in length.
    4. One piece of tube must be welded to the top plate. Before tacking it in place, ensure it is centered over the hole in the middle of the top plate.
    5. The other piece of the tube must be welded to the washer on the active end of the spring in order to ensure the spring is secured on both sides.
- Actuator (Optimized):
    1. Wind the motor wire around the unmachined iron core stock to make the coil and ensure that it is not too tight to slip off once finished.
    2. Slip the coil off the unmachined iron core.
    3. Actuator core must be turned down to the correct diameter on a lathe.
    4. Both end caps must be machined to drawing specifications on a lathe as well.
    5. Side casing must be cut to rough length before facing to the specified length on a lathe.
- Control System:
    1. Pin connectors and screw terminals will be soldered onto the development board and other PCB's using the soldering iron and solder wire in the mechatronics lab.
    2. Motor controller and the Shoe of Brian will be connected to the development board using the pin connectors
    3. Two pairs of wires will be used to connect power supply, controller, and accelerometer
    4. Control system will be mounted to an external housing separate from the test stand in order to isolate any vibrations that may occur.

Assembly:
- Test Stand:
    1. Run all four clamping bolts through the bottom side of the bottom plate.
    2. Run the spring restraint bolt through the hole in the center of the bottom plate.
    3. Flip the plate over and slide the plate spacers over the bolts.
    4. Align the spring perch with the slots in the center of the bottom plate.
    5. Place the spring on the spring perch and secure it at the top with a washer and a nut screwed onto the spring restraint bolt.
    6. Attach actuator to top plate with provided mounting hardware.
    7. Align the top plate with the bottom plate and secure it with nuts screwed onto the clamping bolts.
- Solenoid:
    1. Lay the top cap face down on a flat surface.
    2. Align the side casing and place it on top of the top cap.
    3. Insert the coil into the side casing, ensuring it fits around the inner raised portion of the top cap.

4. Drop the core into the center of the coil.
5. Place the bottom cap on top of the side casing.
6. Clamp the whole assembly tightly together with C-clamps.
7. Butt weld both end caps to the side casing.

7.0 Design Verification Plan

To verify the proper functionality of our valve actuator for the sponsor, we must make sure that we meet all our design specifications. Our weight must stay under five pounds. We will be utilizing a calibrated digital scale to confirm the weight of the prototype and final design. The actuator has been developed with the maximum size constraints in mind, and the external dimensions have been constrained within a 6x6x6 inch cube. Actuation speed is one of our highest risk specifications. We want to test the actuation speed as accurately as possible, since we are dealing with actuation speeds on the order of milliseconds, so we are using an extremely sensitive accelerometer on our test stand. Another high-risk specification is the actuation force since our findings show that optimizing for actuation speed within our space constraint adversely effects actuation force, and vise-versa. Testing of the actuation force will also be carried out by the accelerometer mounted on the spring nested in the test stand. Production cost will be analyzed simply by tallying the materials used and putting those numbers in an expense spreadsheet, as seen in Table 6. Finally, power is our final high-risk specification, and it will be tested with a multimeter and programmable power supply as the actuator is cycled at its maximum speed. The overall goal of testing the actuator and actuator control system will be focused on achieving the maximum force while maintaining minimum opening actuation speed. The accelerometer will be mounted on the active portion of the test stand spring to measure actuator displacement, speed, and force. We are working to incorporate real time accelerometer data recording into our control system in hopes to transition away from the nearly 30-year-old spectrum analyzers in the vibrations lab as soon as possible. As seen in the Gantt chart, testing will be broken up with data analysis in between. We are planning on allocating one week towards basic functionality testing, two weeks for force and frequency testing, and two weeks to develop a detailed force and velocity profile. Each test will be performed on our custom actuator, as well as an off-the-shelf actuator for reference. This timeline takes into account any delays we may encounter if the design has to be changed or programming takes longer than expected. A detailed breakdown of the testing plan can be found in Appendix J.

8.0 New Project Scope & Results

The COVD-19 outbreak and subsequent shutdowns forced us to change our expectations for the project and reevaluate our project scope. The shutdown of school facilities following the outbreak severely limited our ability to execute the final design plan presented at CDR. With no access to the machine shops, and no access to the mechanical vibrations lab or any equivalent facility, neither our manufacturing plan nor or testing plan could be carried out as originally intended. Because of these unforeseen complications, our problem statement and objectives changed significantly.

8.1 New Problem Statement and Objectives

Since physical development and testing of our CDR solenoid design had to be halted, our new project scope focuses on developing our control methodology and delivering our findings so far in order to help future senior project students further develop the technology. Our goal is to help future students by giving them a head start with the resources we've collected as well as provide insights into pitfalls to avoid and simply tell them what worked for us and what didn't.

8.2 Control System Validation

One area of the project that we were still able to research and develop was the electronics, control system, and firmware for the software and control diagrams shown in Figure 22 and 23. We decided to use an STM32 microcontroller as well as an ADXL345 digital accelerometer in order to capture data. The ADXL345 was chosen because it was cost effective and could be communicated with the STM32 microcontroller via an I2C communication protocol. I2C was the protocol of choice because it can be easily implemented on this system and is usually available to use on most sensors. I2C works by establishing two common bus lines, SDA and SCL, which can be used to read data from multiple sensors simultaneously.
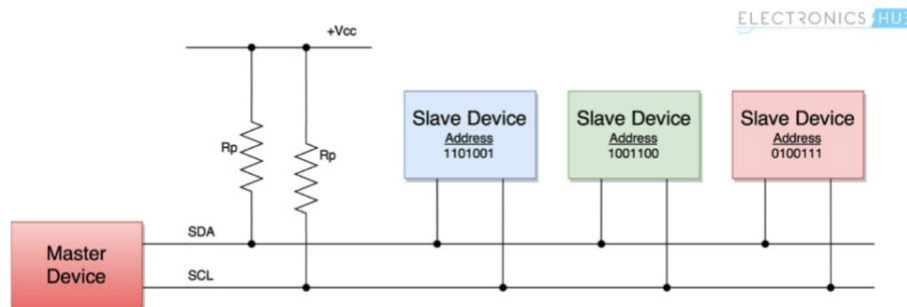
Figure 25. I2C Communication Schematic [12]

In our case, the master device is the microcontroller and the slave device is the accelerometer. Future work involves incorporating temperature sensors to record temperature data and also serve as an emergency stop signal if the temperature becomes too high in the actuator. As described earlier, Micro Python is the software we are using in order to program our microcontroller. By using certain libraries in Micro Python such as I2C and serial, we will be able to communicate with our microcontroller.

Once all the components were soldered and wired together correctly, the first step in creating the firmware for our control system is to load the Micro Python firmware onto the STM32. The firmware was download from https://micropython.org/download/stm32/ , and once this was done we can run python on our microcontroller. The next step was to set up the firmware to control the actuator as well as initialize the accelerometer. This was accomplished by using an object-oriented programming approach where the solenoid and accelerometer are instances of a class. This allows us to write methods to easily use each component as well as provide a clean way of organizing the code. An example of the solenoid class is shown below.

```python
import pyb
import time

class Solenoid:
    ''' This class implements a solenoid driver'''

    def __init__ (self, pin_1):
        ''' Controls Solenoid by initializing GPIO
        pins and turning the motor off for safety. '''
        #print('Creating a motor driver')
        self.pin1 = pyb.Pin (pin_1, pyb.Pin.OUT)

    def start(self):
        self.pin1.high()

    def stop(self):
        self.pin1.low()
```

Figure 26. Solenoid Class

This class is relatively simple but shows the fundamentals of how we structured our code. By passing a pin object to the constructor, and instance of the class can be created. This constructor initializes the specified GPIO (General Purpose Input Output) pin to be an output pin, and by using the pyb module we can set the pin to high or low using the "start" and "stop" methods. This will start and stop our actuator based on a circuit that was built using a high power MOSFET (IRFR3707) and a diode (1N4004) to protect the solenoid. A schematic of the circuit to control the actuator is shown below. The MOSFET acts as a switch and only allows current to flow through the solenoid if the pin connected to its gate is set to high.
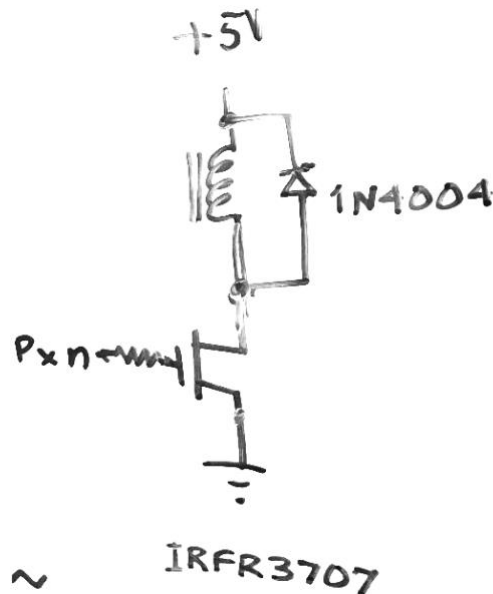
Figure 27. Solenoid Circuit Diagram

The other class that was used in this project was the accelerometer class. With the accelerometer class, things get a little more complicated because we need to set up the I2C protocol as well as set certain registers on the accelerometer in order to get the desired output. The ADXL345 documentation was referenced heavily in order to ensure proper use of the accelerometer. The constructor of the accelerometer is shown in Figure 28.

```python
from machine import I2C
import pyb, utime, time

x_data = const(0x32)
y_data = const(0x34)
z_data = const(0x36)
bw_rate = const(0x2c)
data_format = const(0x31)
power_control = const(0x2d)
accel_address = const(0x53)


class Accelerometer:
    ''' This class implements and initializes an ADXL345 digital accelerometer
        using I2C communication protocol and micropython'''

    def __init__ (self, pin_1, pin_2):
        self.scl = pyb.Pin(pin_1, mode=pyb.Pin.AF_OD, af=pyb.Pin.AF4_I2C1, pull=pyb.Pin.PULL_UP)
        self.sda = pyb.Pin(pin_2, mode=pyb.Pin.AF_OD, af=pyb.Pin.AF4_I2C1, pull=pyb.Pin.PULL_UP)
        self.i2c = I2C(scl=self.scl, sda=self.sda, freq=400000)
        self.i2c.writeto_mem(accel_address, power_control, b'\x00')
        self.i2c.writeto_mem(accel_address, power_control, b'\x08')
        self.i2c.writeto_mem(accel_address, data_format, b'\x09')
        self.range = 2
        self.i2c.writeto_mem(accel_address, bw_rate, b'\x00')
        self.i2c.writeto_mem(accel_address, bw_rate, b'\x0a')
        self.data = bytearray(6)
```

Figure 28. Accelerometer Class Constructor

A few things are different when initializing the accelerometer as compared to the solenoid. First, we needed to set up two pins, one for SDA and another for SCL. SDA is the wire that with transmit data to and from the master and slave, and SCL is the clock. By using the I2C module imported from machine, we can set up and I2C protocol with a clock frequency of 400 kHz. The final step is to write to the accelerometers registers in order to get the correct output. For example, writing to the data_format register allows us to determine the resolution of our accelerometer. By writing x09, for example, we are specifying +/- 4g resolution. This class also contains other methods that read data from the accelerometer, sets the resolution, and determines an initial offset.

With our solenoid and accelerometer class uploaded to the microcontroller, the only piece of firmware left is a "main" program to run it. In our case, main will create instances of both accelerometer and solenoid class and take in two inputs, one for the number of cycles and another for the frequency. It will then run the solenoid, read the accelerometer, and simultaneously print the output data. The final piece of the puzzle is to get the data from the microcontroller onto a computer. This was accomplished by establishing serial communication in order to read and write to the microcontroller. With main running on the microcontroller in an endless loop, we wrote a program to run on a PC that will write to the microcontroller and read its

output. This program runs in a terminal and prompts the user to enter a number of cycles and frequency. It checks to make sure these are valid inputs and then writes to the microcontroller. It then reads data from the microcontroller until exit data is read, and then plots the data using PyPlot. Figure 29 shows the first part of this program.

```python
import serial, time
from matplotlib import pyplot

ser = serial.Serial("/dev/tty.usbmodem1412", 115200, timeout = 1)
ser.bytesize = serial.EIGHTBITS

while True:
    ser.flushInput()
    ser.flushOutput()
    try:
        num_cycles = int(input("Enter the number of cycles (1-10): "))
    except ValueError:
        print("Enter a number");
        continue
    if num_cycles < 1 or num_cycles > 10:
        print("Enter a number between 1 and 10, inclusive")
        continue
    try:
        frequency = float(input("Enter frequency (Hz): "))
    except ValueError:
        print("Enter a number");
        continue
```

Figure 29. PC Program to Read, Write, and Plot Data

Finally, after the data is read and displayed, the program takes the data and creates and excel file for further analysis. The name of the excel file is specified by the user, and on each run a new excel file is created. Full versions of all the software/firmware written can be found online at

https://github.com/daryadarvish/EM_Actuator_Senior_Project

9.0 Accomplished Testing

Due to the unforeseen circumstances surrounding COVID-19, our group had to change the direction of our project in March 2020. Campus, and all labs, were shut down, forcing us to work from home, utilizing programs such as Zoom and GroupMe. Because the campus machine shops were closed during this time, we were unable to manufacture and test our actuator design as planned. Of the tests we had originally planned to carry out, we were only able to perform one preliminary test of an off-the-shelf actuator. The purchased actuator was connected to our control system, as shown in Figure 23, and accelerometer data was recorded. This baseline test was originally intended to both verify the functionality of the control system and provide a reference for comparison to our custom actuator. Because we were unable to build the custom actuator, this test only serves to validate the control system.
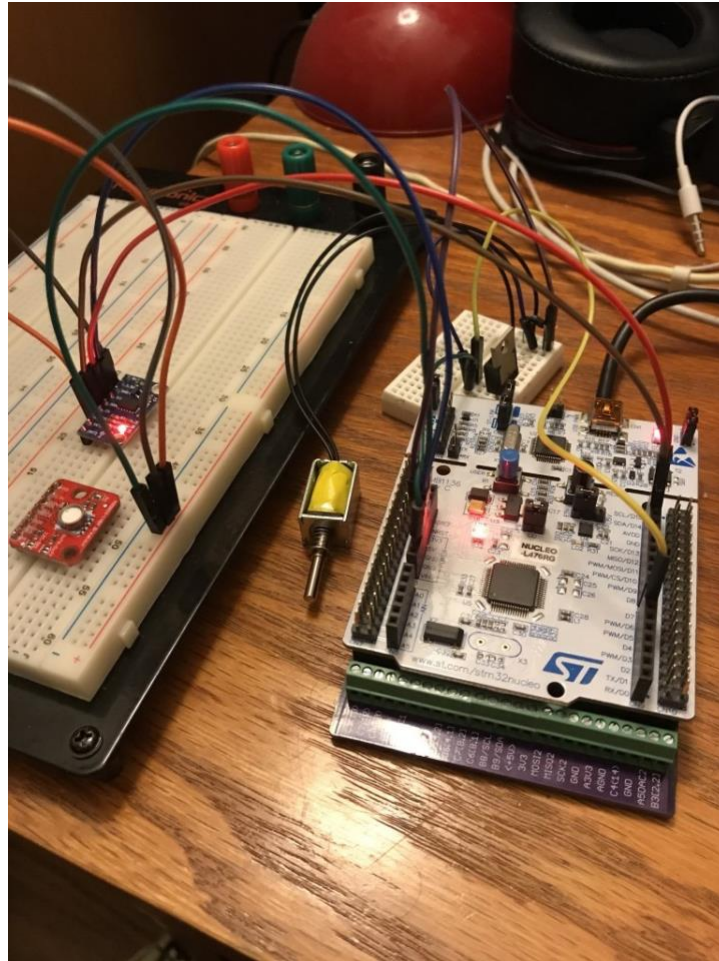
Figure 30. Purchased Actuator Test Setup

Although the results of the test, shown in Figure 24, give little insight into the response we had originally hoped to achieve with our custom actuator, the ability of the control system to effectively provide a desired response from the actuator was proved. In the performed test, a simple sinusoidal input was given to the system, and the accelerometer data displayed a sinusoidal response.
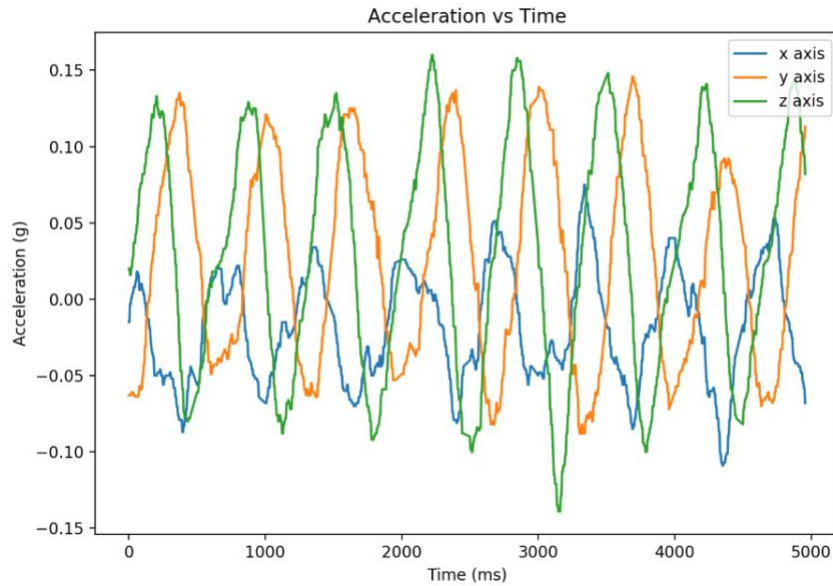
Figure 31. Accelerometer Response Data

The test additionally provides insight into the response time of generic linear actuators. The tested actuator was virtually unloaded and was able to achieve an opening time of approximately 400ms. Compared to the initial design specification of 3ms and the revised goal of 15ms, the off-the-shelf actuator proved to be orders of magnitude too slow. This was expected given the small and low power nature of the purchased actuator, which was not designed with rapid movement in mind. While we were unable to prove the theoretical opening time of our custom actuator, the 14ms predicted by our model would have been significantly faster than the 60-80ms opening time advertised by specialty high-speed actuators.

10.0 Project Management

Over the course of the year, project management has been crucial to the success of this project. The overall design process we followed includes seven key phases: defining the problem, conceptualizing, evaluation, detailed design, manufacturing, testing, and writing the final report. Each of these phases contained iterative steps to perfect the project before moving on. These phases and steps of our design process are listed in Appendix E, the Gantt chart. By using the Gantt chart, our plan for the year was laid out by date of completion. Individual tasks could be added and assigned to somebody at any point in the project, making coordination easy. Another aspect of project management important for our project was communication. There were four members of the group and two sponsors on the project. There were also several professors who we have contacted for their professional experience in electromagnetism, control systems, and engine mechanics.

Unfortunately, we were unable to complete the original manufacturing and testing portions of our project. As aforementioned, this is due to COVID-19. The pandemic forced Cal Poly to close all labs, shops, and classes, where manufacturing and testing were set to take place. Nevertheless, our group was still able to complete the project by coming up with alternatives. As seen in Table 7, many sections of our senior project were completed. We successfully researched and designed an electromagnetic actuator. We also included

our original manufacturing and testing plans for future undertakers. The manufacturing and testing sections were adjusted to abide by the "social distancing" guidelines and work with the materials we had. For manufacturing, we successfully assembled the control system with an accelerometer and an actuator. In total, we manufactured two of the main three components: the test stand and the control system. In our revised plan, we bought a small actuator was off Amazon, allowing us to test the control system and see acceleration data of electromagnetic actuators. Along with this, a simulation test was run on MATLAB to see the ideal results of this test. Ideally, we would have been able to use the control system and test stand on our built linear actuator, but these tests sufficed as an alternative learning experience for all members.

Table 7: Project Overview

Design Phase	Completed (Original Plan)	Completed (Adjusted Plan)
Defining Problem	✓	
Conceptualization	✓	
Evaluation	✓	
Detailed Design	✓	
Manufacturing		✓
Testing		✓
Final Report	✓	

11.0 Conclusions

This document serves to define the scope of this project and present an initial design path, final design, manufacturing plan, and test plan. All research, tables, concept design methods, and planning tools so far developed are presented for reference. The ultimate result of the project was to develop a design tool for high speed linear actuators and a control system to provide precise actuator movement. Unfortunately, limited manufacturing and testing was achieved, so no verification of the design tool can be provided. Our team recommends the continued testing and validation of the design tool through physical testing of a manufactured actuator. Additionally, our team recommends additional research into the functionality of voice coil actuators for completely electromagnetic valve actuation, or pneumatic and hydraulic alternatives. The conclusion of the analysis performed is that moving core linear actuators are incapable of producing adequate opening speeds for the operation of an internal combustion engine.

References

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Appendices

        A.   QFD House of Quality
        B.   Sticky Note Ideation
        C.   Concept Model Ideation
        D.   Valve Testing Data
        E.   Gantt Chart
        F.   Design Hazard Checklist
        G.   Indented Bill of Materials
        H.   Failure Modes & Effects Anaylsis
        I.   Drawing Package
        J.   DVP&R

Appendix A - QFD House of Quality

QFD House of Quality

Project: Electromagnetic Actuator for Camless Engines

Revision Date: 10/16/19

Correlations

Positive	+
Negative	–
No Correlation	

Relationships

Strong	●
Moderate	O
Weak	▽

Direction of Improvement

Maximize	▲
Target	◇
Minimize	▼

WHAT: Customer Requirements / HOW: Engineering Specifications (Tests)

Row #	Relative Weight	Sponsor (Dr. E)	Manufacturers	End Users	Maximum Relationship	Customer Requirements (Needs/Wants)	Actuator Weight	Number of Moving Parts	Actuating Force	Actuation Frequency	Product Lifespan	Heat Dissapation	Noise Level	Adjustability Range	Koenigsegg Freevalve	Fiat MultiAir
						Column #	1	2	3	4	5	6	7	8		
						Direction of Improvement	▼	▼	◇	◇	▲	▲	▼	▲		
1	6%	3	3	3	9	Low Weight	●	O	O	O	▽	▽	▽		2	3
2	5%	4	2	2	9	Low Inertia	●	●		●	▽	▽	▽		4	4
3	10%	9	3	4	9	High Force *	▽	O	●	O	●	O	O		4	4
4	9%	9	3	3	9	High Speed *	O	●	●	●	●	O	O		4	4
5	16%	7	8	9	9	Reliable	▽	●	O	O	●	●	▽			3
6	11%	8	9	1	9	Programmable *			▽	▽				●	4	
7	0%															4
8	8%	3	9	1	9	Easily Manufacturable	▽	●			▽	▽	▽		1	2
9	8%	1	2	7	9	Low Noise	O	▽		▽			●		4	4
10	9%	6	3	5	3	Improved Engine Performance	O			O					4	4
11	9%	7	3	4	3	Small Footprint	O	O	O			▽	▽		2	4
12	9%	4	9	1	9	Low Mechanical Complexity *	▽	●	O		O	O			1	2
13	0%															
14	0%															
15	0%															
16	0%															

HOW MUCH: Target Values

	25 lbs.	10	250 lbf.	50 Hz	> 10 years	Stays below 250 °F	< 70 Db	5-50 Hz and 0-1 in. of lift								
Max Relationship	9	9	9	9	9	9	9	9								
Technical Importance Rating	248.2	507.9	304.6	272.6	365.6	258.3	171	96.84	0	0	0	0	0	0	0	0
Relative Weight	11%	23%	14%	12%	16%	12%	8%	4%	0%	0%	0%	0%	0%	0%	0%	0%
Our Current Product																
Koenigsegg Freevalve	2	3	5	1	1	4		3								
Fiat MultiAir	3	0	4	5	2	4	3	4								
0																
0																
Column #	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16

Appendix B - Sticky Note Ideation

Force Ideation:

- Multiple Coils
- Motor
- Rotational to Linear Motion
- Two Solenoids to Provide More Force
- Permanent Magnet
- Two on Top vs Two on Bottom
- Two coils with Linkage
- Rotational Motion with Magnets
- V shaped Hinge Design

Adjust Distance Ideation:

- Enter RPM -> microcontroller -> actuator
- Minimize force required
- Current control
- Adjustable arm stopping cam
- Hinge point can be rotated to change distance
  a. Moving force
  b. Multi Coil
  c. Multiple coils actuate 1, 2, n valves

Appendix C - Concept Model Ideation
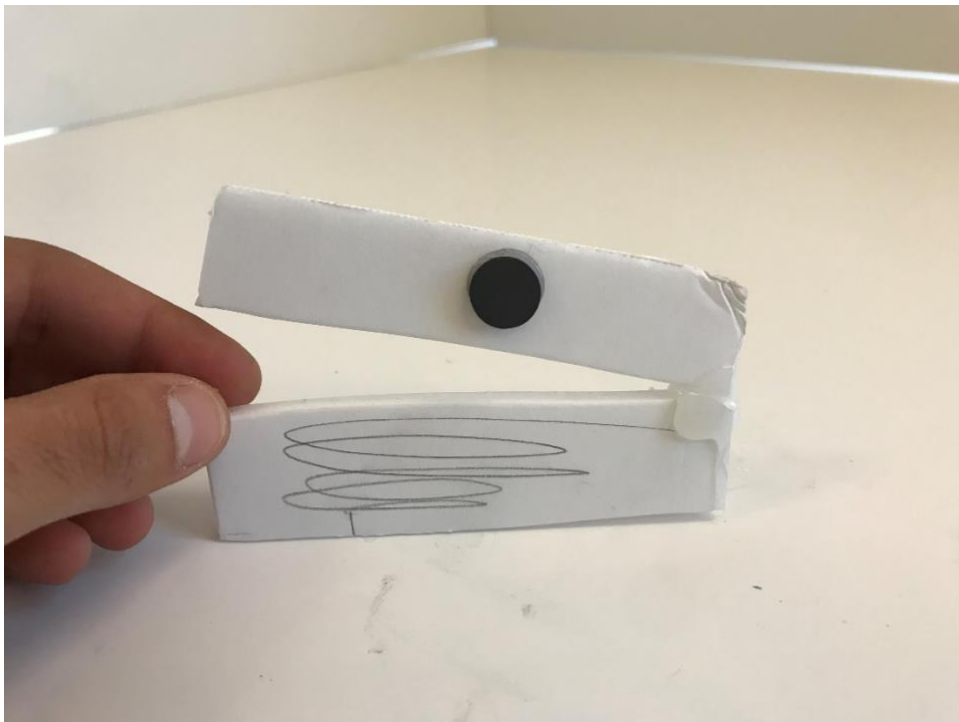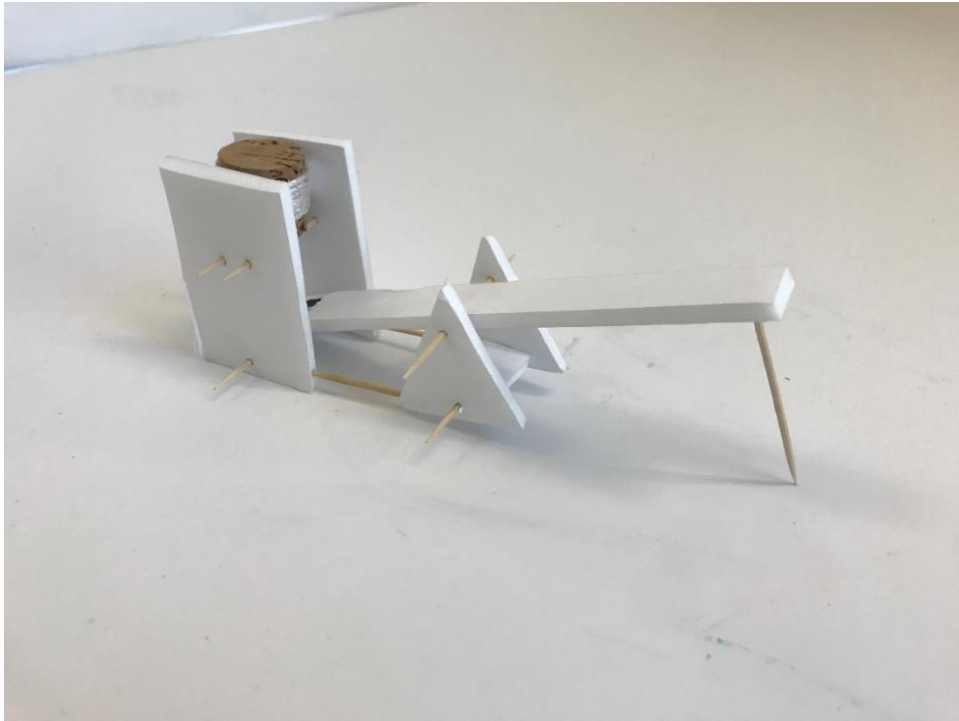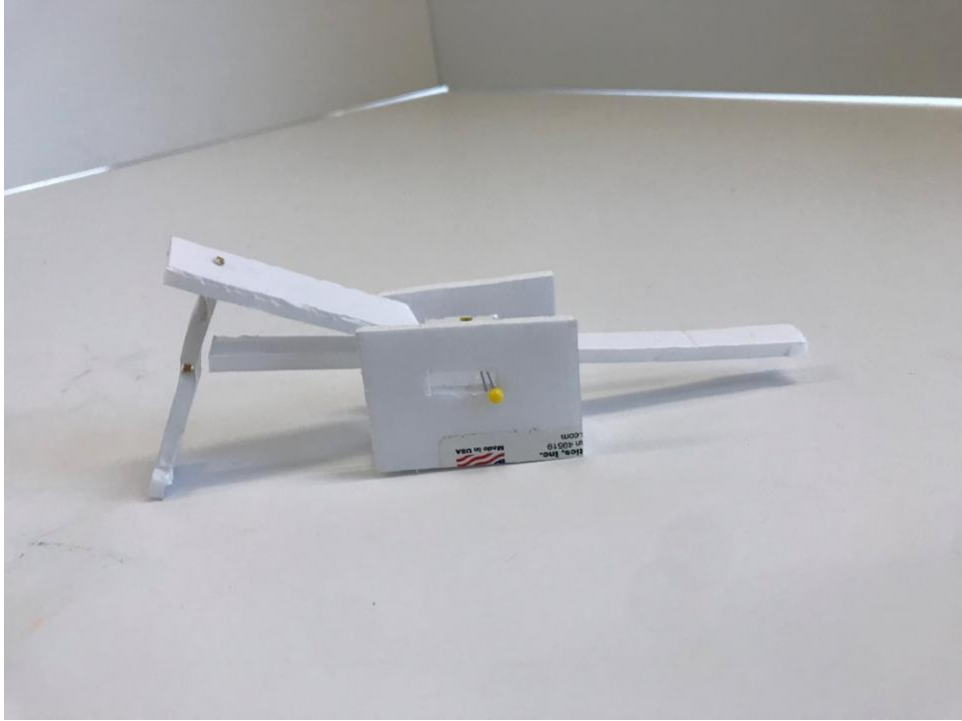
Appendix D – Valve Testing Data

Spring Data						
Height [cm]	Height [in]	Force [N]	Force [lbf]	Displacement [cm]	Displacement [in]	Spring Constant [lbf/in]
4.6	1.81	0.0	0	0	0	
4	1.57	222.4	50	0.6	0.24	
3.5	1.38	449.3	101	1.1	0.43	**k = 256**
3	1.18	693.9	156	1.6	0.63	
2.5	0.98	1000.8	225	2.1	0.83	

$F = 256.74x$

32 - EM Actuator for Camless Engine	start	end	assigned
Problem Definition	09/22/19	10/18/19	
Choose Project	09/22	09/26	
Meet Team	09/27	10/01	
Customer/Need Research	09/30/19	10/12/19	
Interview Sponsor	10/02	10/06	
Interview Assisting Professors	10/07	10/12	
Search online for complaints	09/30/19	10/05/19	
Current IC Engine Complaints	09/30	10/05	
Current Actuator Complaints	09/30	10/05	
Technical Research	09/27/19	10/01/19	
Identify technical challenges	09/27	10/01	
Product Research	09/29/19	10/07/19	
Find case studies	09/29	10/07	Nicholas Olesk
Search online for current products	09/29	10/07	Timothy Wills DeTone
Ask sponsor/users about current products	09/29	10/07	
Find relevant journal articles	09/29	10/07	Charles Glenwright
Search patents for similar products	09/29	10/07	Charles Glenwright, Timothy Wills DeTone
Look for standards	09/29	10/07	Nicholas Olesk
Find textbooks for reference	09/29	10/07	Darya Darvish, Nicholas Olesk
Find research reports	09/29	10/07	Charles Glenwright
Write Problem Statement	10/08	10/08	Darya Darvish
Capture Customer Needs/Wants	10/08	10/08	Charles Glenwright, Nicholas Olesk
Perform QFD	10/10	10/14	Timothy Wills DeTone
Create Specification Table	10/10	10/14	
Write Specification Descriptions	10/10	10/14	
Create Initial Project Plan (Update Gantt)	10/15	10/16	Nicholas Olesk
Write Scope of Work	10/09/19	10/16/19	
Write Background	10/09	10/16	Charles Glenwright, Darya Darvish
Write Objectives	10/09	10/16	Timothy Wills DeTone
Write Proj Mgt	10/09	10/16	Nicholas Olesk
Write Intro/Concl	10/09	10/16	Charles Glenwright, Darya Darvish
Scope of Work Milestone	10/18	10/18	
Concept Generation / Selection	10/22/19	11/15/19	
Update SOW	10/22	10/29	Charles Glenwright, Timothy Wills DeTone
Ideate Many Ideas	10/22	10/29	
Concept Models	10/28	11/01	
Review/Change Specifications	10/28	11/01	Darya Darvish, Nicholas Olesk
Decision Matrices	10/28	10/31	Timothy Wills DeTone
Basic CAD	11/02	11/07	Charles Glenwright
Concept Prototype	11/03	11/08	Timothy Wills DeTone
PDR Presentation	11/07	11/11	
PDR Report	11/07	11/14	
Preliminary Design Review	11/15	11/15	
Detailed Design	11/17/19	01/30/20	
FMEA	11/17	11/21	
Safety	11/17	11/21	
DFMA	12/02	12/05	
FEMM/MATLAB - Solenoid Analysis	12/18	01/14	Charles Glenwright, Darya Darvish
Test stand design	12/18	01/11	Nicholas Olesk, Timothy Wills DeTone
Update PDR	12/18	12/23	Timothy Wills DeTone
BOM - test stand, MC, actuator	01/05	01/11	Nicholas Olesk
Order benchmark actuator	01/05	01/11	Charles Glenwright, Nicholas Olesk
Order microcontroller	01/05	01/11	Darya Darvish, Nicholas Olesk
Order test stand parts	01/05	01/11	Timothy Wills DeTone
IDR - Interim Design Review	01/16	01/16	
Build Test Stand	01/16	01/30	Timothy Wills DeTone
Finalizing Design	01/26/20	02/12/20	
Solenoid CAD	01/26	02/02	Charles Glenwright
Solenoid Drawings	01/26	02/02	Charles Glenwright
Test Stand Drawings	01/26	02/02	Nicholas Olesk, Timothy Wills DeTone
Find appropriate motor driver	01/28	02/04	Nicholas Olesk
Write/assemble CDR	01/28	02/04	
CDR - Critical Design Review	02/04	02/04	
Update Solenoid Design (if needed from CDR)	02/10	02/12	Charles Glenwright
Update Controls Design (if needed from CDR)	02/10	02/12	Darya Darvish
Update Test Stand Design (if needed from CDR)	02/10	02/12	Timothy Wills DeTone

Task	Start	Finish
Manufacturing and Testing - OLD PLAN	**02/05/20**	**04/30/20**
Assemble/solder Shoe of Brian	02/05	02/09
Assemble microcontroller	02/12	02/17
Order parts for Solenoid	02/16	02/29
Mnfg and Test Review	03/12	03/12
Program	02/16	03/31
Machine solenoid housing	03/06	03/23
Make the winding	03/06	03/23
Machine core to within tolerance	03/06	03/23
Assemble all parts of solenoid	03/24	03/28
Testing solenoid for force and speed	03/14	04/02
Analyze data	03/15	04/03
Build changes and add-ons (if needed)	04/01	04/14
Update program (if needed)	04/01	04/14
Testing for vel, acc, and force profile	04/15	04/30
Compare final results	04/15	04/30
Manufacturing and Testing - NEW PLAN	**04/21/20**	**05/26/20**
Add to Final Report - Manufacturing and Testi...	04/21	05/11
Actuator simulation	04/21	05/11
Run small actuator/microcontroller	04/21	05/11
Add to Final Report - Update Final Design	04/21	05/11
Project expo website	05/07	05/26
Intro video for website	05/17	05/26
Final CAD	05/17	05/26
Final Reports	**05/14/20**	**06/04/20**
Finish Final Design Report	05/14	05/27
Virtual Expo	05/26	05/26
Final Design Report Due	06/04	06/04

Appendix F – Design Hazard Checklist

PDR Design Hazard Checklist   <u>**Project #32 Camless Engine**</u>

Y	N	
✖		1. Will any part of the design create hazardous revolving, reciprocating, running, shearing, punching, pressing, squeezing, drawing, cutting, rolling, mixing or similar action, including pinch points and sheer points?
✖		2. Can any part of the design undergo high accelerations/decelerations?
✖		3. Will the system have any large moving masses or large forces?
	✖	4. Will the system produce a projectile?
	✖	5. Would it be possible for the system to fall under gravity creating injury?
	✖	6. Will a user be exposed to overhanging weights as part of the design?
	✖	7. Will the system have any sharp edges?
	✖	8. Will any part of the electrical systems not be grounded?
	✖	9. Will there be any large batteries or electrical voltage in the system above 40 V?
✖		10. Will there be any stored energy in the system such as batteries, flywheels, hanging weights or pressurized fluids?
	✖	11. Will there be any explosive or flammable liquids, gases, or dust fuel as part of the system?
	✖	12. Will the user of the design be required to exert any abnormal effort or physical posture during the use of the design?
	✖	13. Will there be any materials known to be hazardous to humans involved in either the design or the manufacturing of the design?
	✖	14. Can the system generate high levels of noise?
	✖	15. Will the device/system be exposed to extreme environmental conditions such as fog, humidity, cold, high temperatures, etc?
	✖	16. Is it possible for the system to be used in an unsafe manner?
	✖	17. Will there be any other potential hazards not listed above? If yes, please explain on reverse.

For any "Y" responses, on the reverse side add:
 (1) a complete description of the hazard,
 (2) the corrective action(s) you plan to take to protect the user, and
 (3) a date by which the planned actions will be completed.

Description of Hazard	Planned Corrective Action	Planned Date	Actual Date
The electromagnet and spring will be reciprocating when voltage is supplied to system.	There will be a casing around the electromagnet and the test stand.	3/1	
The solenoid core will undergo a high acceleration.	The casing surrounding the magnet will protect user from any accident.	3/1	
There will be large forces coming from the valve spring and the electromagnet.	These two large forces will cancel out. In case of any unintended scenario, the casing will hold it in a contained area.	3/1	
Energy will be stored in the car battery used.	When working with the battery, a cautious procedure will be taken by assuring the battery is grounded.	3/1	
Processor may overheat and catch on fire.	Use a Temperature monitoring system to regulate and shut off the system if necessary.	3/1	

Indented Bill of Material (BOM)
Electromagnetic Actuator for Camless Engine

| Assembly Level	Part Number	Description Lvl0	Lvl1	Lvl2	Lvl3	Lvl4	Qty	Cost	Ttl Cost	Source	More Info
0	100000	Actuator								------	
1	110000		Solenoid							------	
2	111000			Wire			1	$53.00	$53.00	McMaster	160 ft copper wire
2	111100			Housing						------	
3	111110				Top steel plate		1	$25.00	$25.00	McMaster	Top of housing
3	111120				Bottom steel plate		1	$25.00	$25.00		Bottom of housing
3	111130				Steel Tubing		1	$160.00	$160.00	McMaster	6" diameter side of housing
2	111200			Battery			1	$35.00	$35.00		Power source
2	111300			Iron rod			1	$52.00	$52.00	McMaster	Core
1	120000		Microcontroller							------	
2	121000			Nucleo development board			1	$14.00	$14.00	L476RG?qs=%2Fha2pyFadu	
2	121100			Motor driver			1	$11.50	$11.50	Cytron	
2	121200			Shoe of Brian PCB						------	
3	121210				2x19 female headers		4	$0.18	$0.72	Pin-Dual-Row-Straight-Conne	
3	121220				10-pole screw terminals		1	$8.00	$8.00	PCB-Screw-Terminal-Block-C	
3	121230				5 pole screw terminals		1	$5.00	$5.00	CB-Screw-Terminal-Block-Co	
3	121240				board		1	$11.53	$11.53	npark.com/shared_projects/	
0	200000	Test Stand								------	
1	210000		6"x6" 1/4" Type 304 Steel				1	$10.13	$10.13	McCarthy's Steel	Top Plate
1	220000		6"x6" 1/4" Type 304 Steel				1	$10.13	$10.13	McCarthy's Steel	Bottom Plate
1	230000		1.5" ID steel pipe				1	$1.00	$1.00	Mustang 60	Spring perch
1	240000		7/16"-14, 5" long Hex Screw				4	$6.96	$27.84	McMaster	Clamping Bolts
1	250000		1/4"-28, 3" long socket head				1	$0.10	$0.10	McMaster	Spring securing bolt
1	260000		1/4"-28 locking nut				4	$0.10	$0.40	McMaster	
1	270000		7/16"-14 nut				1	$6.63	$6.63	McMaster	
1	280000		18-8 Stainless Steel Washer				1	$1.53	$1.53	McMaster	Spring Top Cap
1	290000		1/2" SCH 40 Pipe				2	$6.36	$12.72	Metals Depot	Plate Spacers
	Total Parts						**31**		**$471.23**		

Appendix H - Failure Modes and Effects Analysis (FMEA)

System / Function	Potential Failure Mode	Potential Effects of the Failure Mode	Severity	Potential Causes of the Failure Mode	Current Preventative Activities	Occurrence	Current Detection Activities	Detection	RPN	Recommended Action(s)	Responsibility & Target Completion Date	Actions Taken	Action Results			
													Severity	Occurrence	Criticality	RPN
Control System/Control the Output Voltage	System Becomes Unstable	a) large oscillations b) damage to actuator c) engine may get damaged	8	1) incorrect system modeling 2) inaccurate sensor feedback 3) power supply malfunction	1) add saturation blocks to simulink 2) plot root locus	2	Visual Inspection	3	48	Double check simulink model and review with professors, test and choose correct power supply and circuit breaker	Darya D. 1/30		4	2	5	40
Spring/Regulate Distance	Spring becomes dislodged or is too stiff	valve will jerk back and forth and make lots of noise and potentially break	6	1) spring not installed properly 2) spring fails due to oscillation 3) spring fails due to heat	1) FEA on spring 2) assembly testing to make sure correct positioning	1	Visual inspection	3	18	test all springs and make sure they can tolerate load and are not too stiff	Darya D. 1/30		5	3	4	60
Rocker/Transmit Actuator force to valve	Rocker arm breaks	Actuator no longer opens valve	3	1) excessive force from actuator 2) actuator pushes at odd angle 3) bearing binding	1) use stock rocker arm 2) lubricate rotating parts frequently	1	Visual inspection	2	6	incorporate oiling to test stand or lubricate frequently	Charlie G. 1/30		3	1	2	6
Power Supply/Provide power to actuators	Overload	FIRE or permanent damage	9	1) system draws too much power at sustained load 2) oscillation of current creates heating 3) Short	1) careful with wiring 2) monitor temperature	2	Visual inspection	3	54	Fuses, factor of safety on power rating	Charlie G. 1/30		2	3	4	24
	Fails to power on	Whole system doesn't do anything	8	1) Internal supply issues 2) unplugged	1) verify functionality before use	2	check plug	2	32	Buy reliable power supply and avoid droping/abusing	Charlie G. 1/30		1	2	2	4
	Stuck on	Valves stay open	9	1) Internal supply failure 2) Controller failure	1) Controller redundencies	2	engine stops running	1	18	Power supply failsafe	Charlie G. 1/31		5	5	4	100
Actuator/ Apply Force	Overheats	Lower performance	8	1) High Current Load 2) Engine overheating 3) Duty cycle too high	1) Isolate actuator from heat of engine 2) Over current prevention 3) Duty cycle limit	3	Automatic Temp Cutoff	1	24	Temp warning and limp mode	Tim W. 1/30		6	1	5	30
	Slotted Joint wears out	Actuator no longer connected to valve rocker	8	1) Friction in slotted joint	1) Lubricate joint	2	visual inspection for wear	4	64	Switch to lower friction joint design	Tim W. 1/30		3	2	2	12
Control System/ Control Output Voltage	Fails to control actuator	Actuator does not move	8	1) Bad connections to power supply or actuator 2) Damaged circuit components	1) Check connections before operating	2	Visual inspection of connectors	3	48	Protect controller in enclosure and source high quality connectors.	Tim W. 1/30		2	5	4	40
Mounting System/Secure Actuator to Cylinder Head	bolts or other mounting components fail	actuator will become unattached to system	8	1) insufficient fasteners 2) poor mechanical design	1) stress calcuations on bolt size 2)	1	Check bolt torque with torque wrench	6	48	Test all bolts and do fea on assembly	Darya D. 1/30		4	3	2	24
Wires/transmitting power	short or damaged wire	Could short circuit if comes into contact with metal on engine	8	1) Pinched wire 2) solder contacting engine	1) Insulation on wires	2	Visual inpsection	4	64	Put casing or insulation on solders	Nick O. 1/30		3	2	5	30
Moving core / providing force from actuator	core not secured	core flies out	8	1) casing comes loose	1) casing	1	Visual inpsection	3	24	Be sure casing or end is secure on solenoid	Nick O. 1/30		6	3	4	72

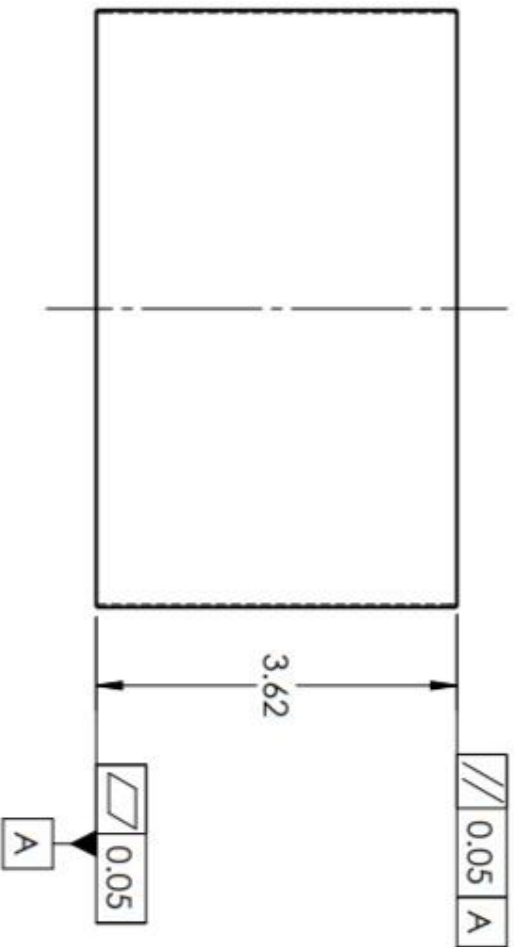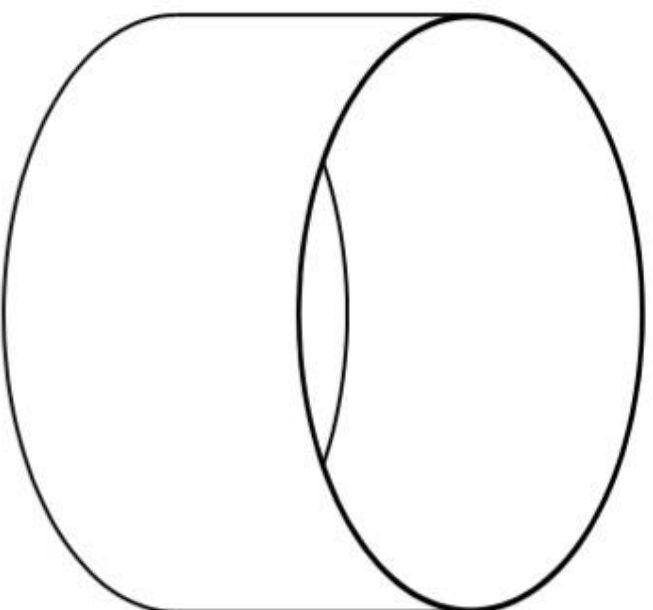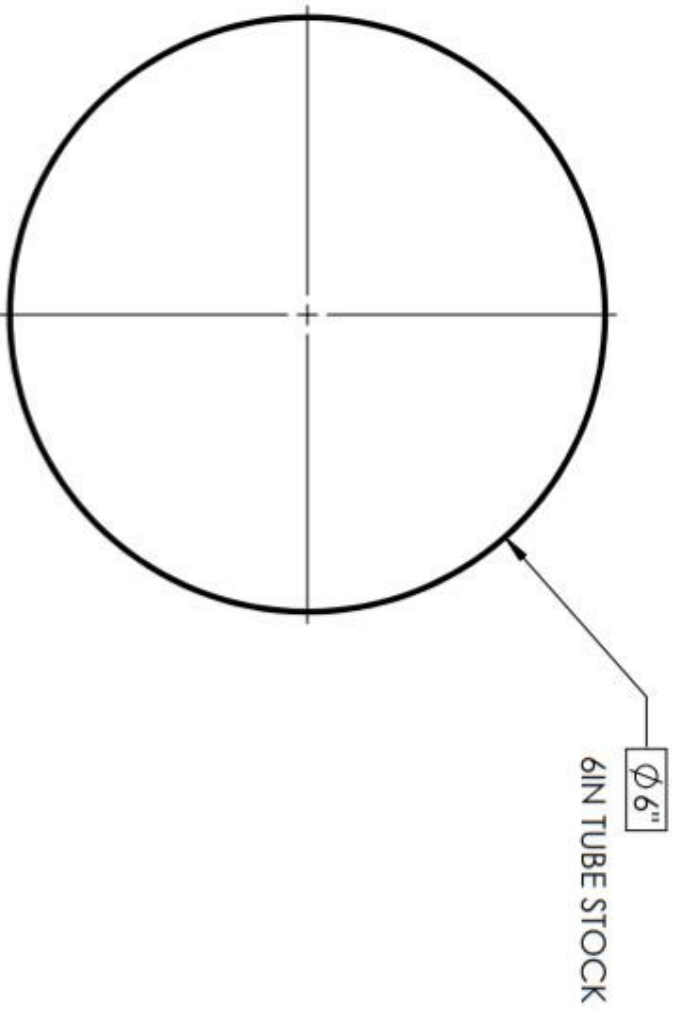Appendix I – Drawing Package

Index

1. Solenoid Assembly
2. Solenoid Case – Side
3. Solenoid Case – Top
4. Solenoid Case – Bottom
5. Solenoid Core
6. Test Stand Assembly
7. Test Stand Top Plate
8. Test Stand Spacer
9. Test Stand Base Place
10. Solenoid Assembly – Weld Drawing
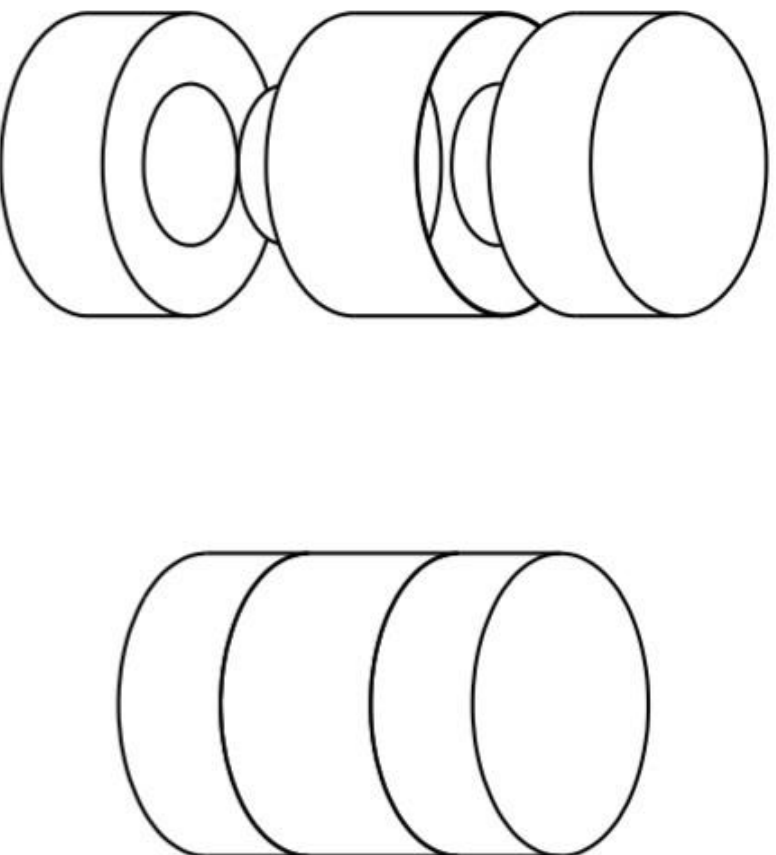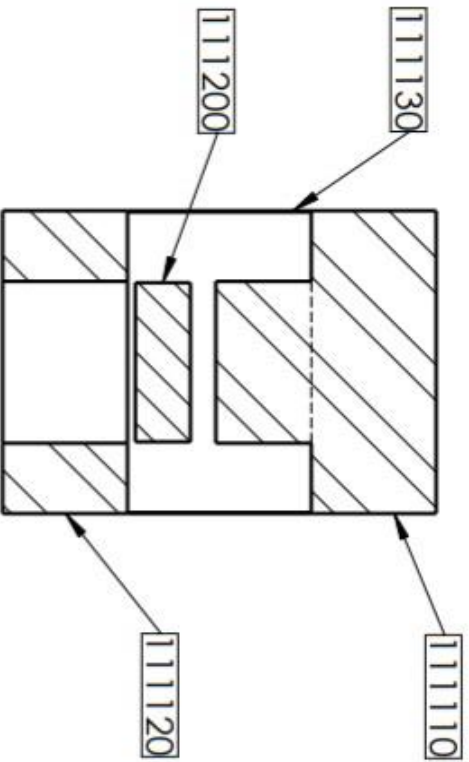
PART NO.	DESCRIPTION	MATERIAL	QTY.
111200	SOLENOID CORE	GREY CAST IRON	1
111130	SOLENOID CASE - SIDE	HOT ROLLED STEEL	1
111120	SOLENOID CASE - BOTTOM	HOT ROLLED STEEL	1
111110	SOLENOID CASE - TOP	HOT ROLLED STEEL	1

Cal Poly SLO Mechanical Engineering	ME 429: SENIOR PROJECT Part Number: 110000	Title: SOLENOID ASSEMBLY	Drwn. By: CHARLIE GLENWRIGHT
		Date: 2/3/2020	Scale: 1:4	Chkd. By:

Cal Poly SLO
Mechanical Engineering

ME 429: SENIOR PROJECT

Part Number: 111130

Title: SOLENOID CASE - SIDE

Date: 2/4/2020

Scale: 1:2

Drwn. By: CHARLIE GLENWRIGHT
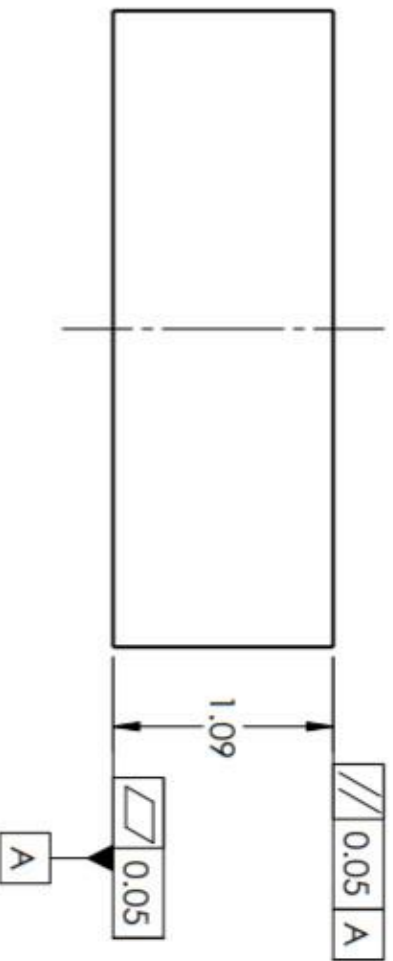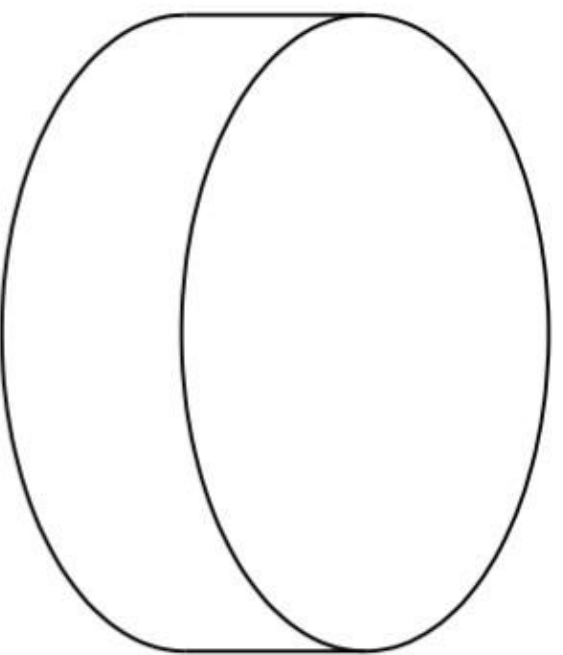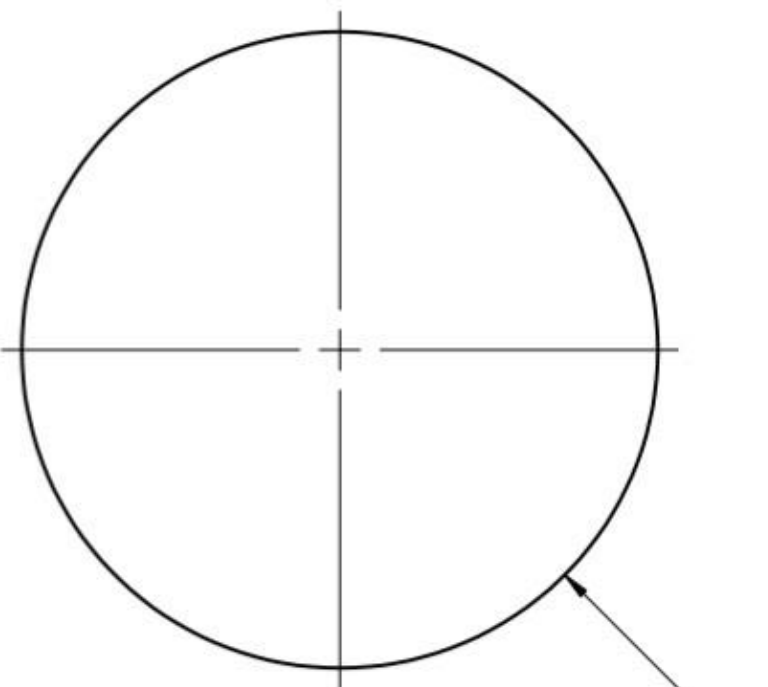
Chkd. By:

Ø 6"

6IN TUBE STOCK

3.62

// 0.05 A

▱ 0.05

A

NOTES (UNLESS OTHERWISE SPECIFIED):
1. TOLERANCES:
   X.XX = ±0.05
   X.X = ±0.1
   ANGLES = ±1°
2. CLEAN AND DRY

⌀ 0.05 B

⌀3.20

1.88

4.34

0.05

A

∥ 0.05 A

⌀ 6"

0.05

B

NOTES (UNLESS OTHERWISE SPECIFIED):
1. TOLERANCES:
   X.XX = ±0.05
   X.X = ±0.1
   ANGLES = ±1°
2. CLEAN AND DRY

∅6"

∅3.20
◎ | ∅ 0.05 | B

⟋ | 0.1
[B]

2.46

▱ | 0.05
[A]

∥ | 0.05 | A

Cal Poly SLO Mechanical Engineering	ME 429: SENIOR PROJECT	Title: SOLENOID CASE - BOTTOM	Drwn. By: CHARLIE GLENWRIGHT
	Part Number: 11120	Date: 2/4/2020	Scale: 1:2	Chkd. By:

Ø3.15

⌀ 0.05

// 0.05 A

1.09

▱ 0.05

A

NOTES (UNLESS OTHERWISE SPECIFIED):
1. TOLERANCES:
   X.XX = ±0.05
   X.X = ±0.1
   ANGLES = ±1°
2. CLEAN AND DRY
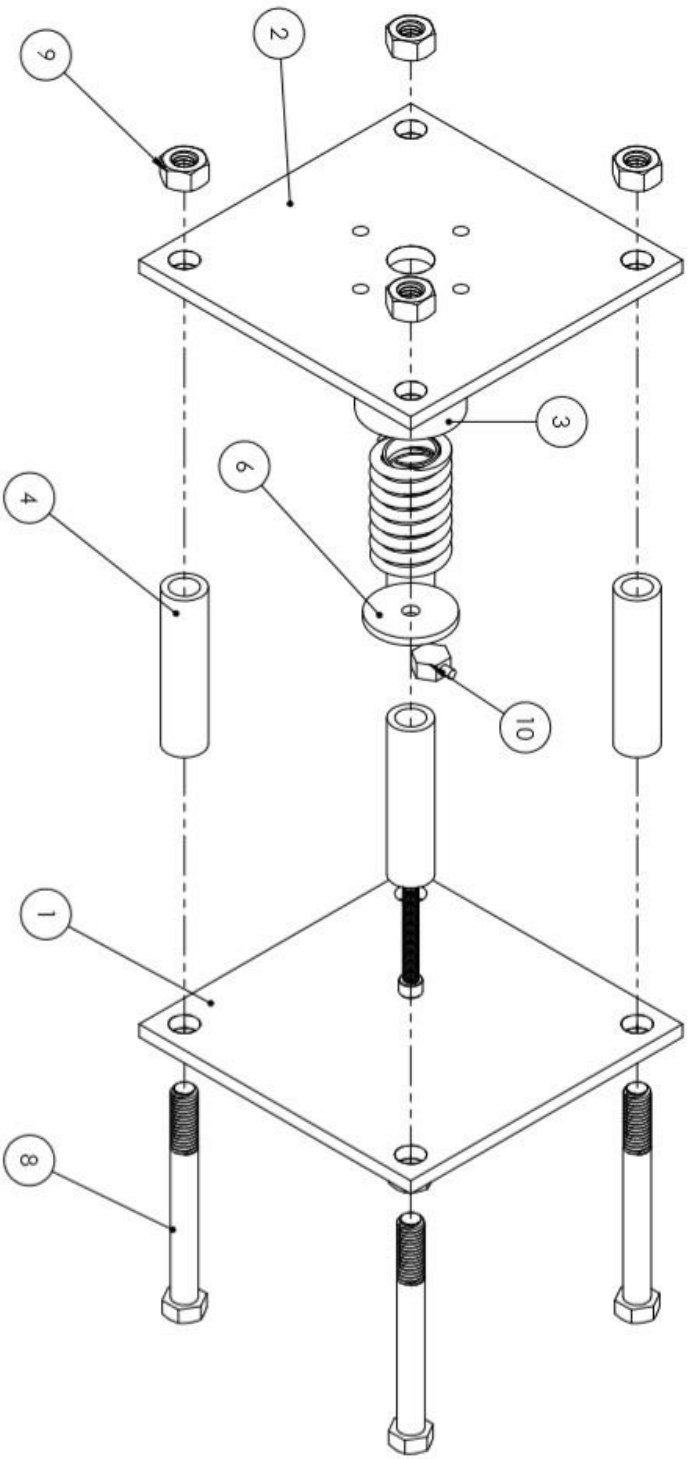
ITEM NO.	PartNo	DESCRIPTION	QTY.
1	210002	Bottom Plate	1
2	210001	Top Plate	1
3	220000	Spring Cup	1
4	280000	Spacer	4
6	270000	Flat Washer	1
7	240000	Socket Head Screw	1
8	230000	Hex Bolt	4
9	250000	Locking Hex Nut	4
10	290000	Accelerometer	1

Cal Poly Mechanical Engineering
ME 429 - WINTER 2020

SENIOR PROJECT

Title: TEST STAND ASSEMBLY
Date: 2/1/20
Scale: 1:2
Dwn. By: TIM WILLS DETONE
Chkd. By: ME STAFF
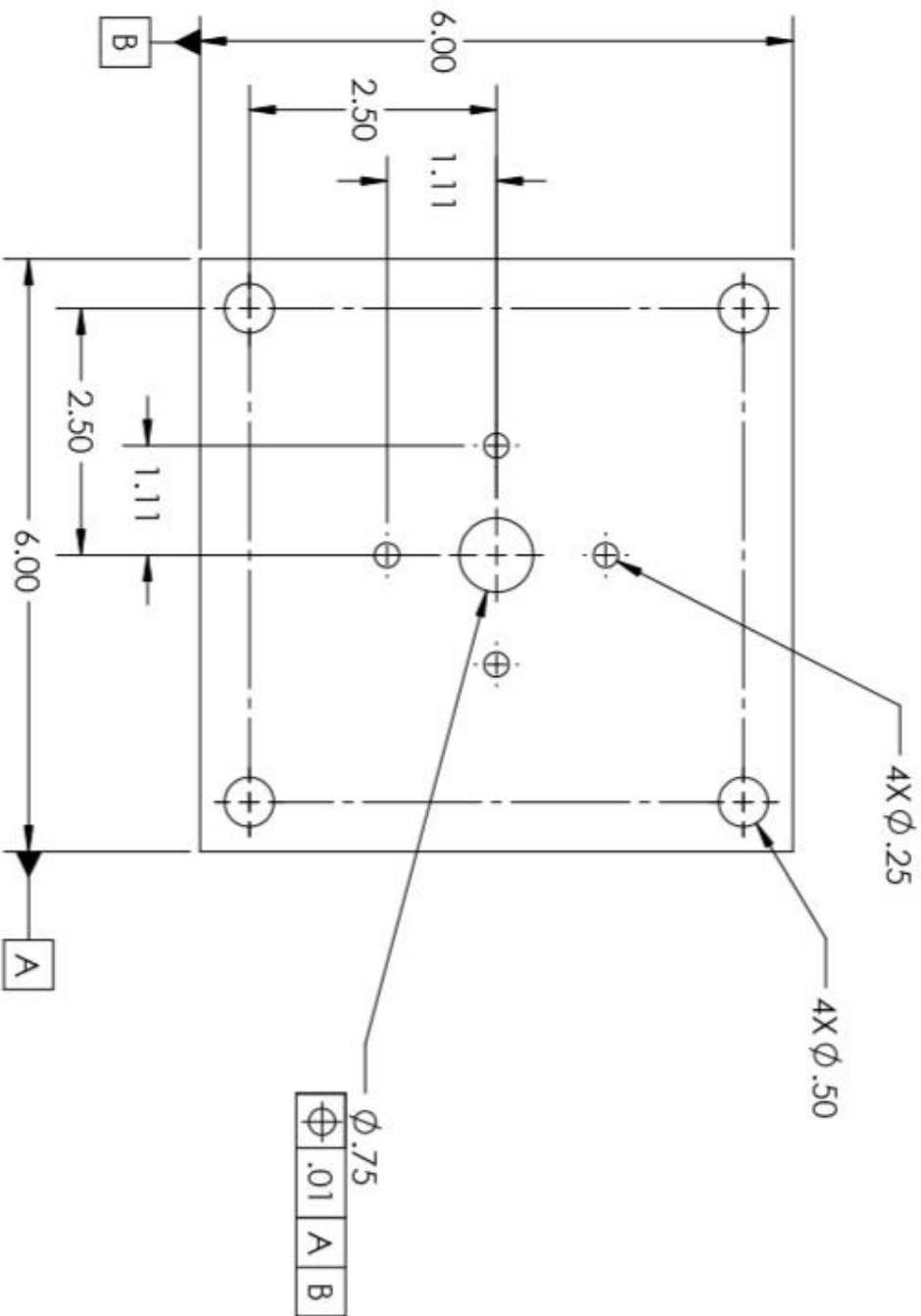
NOTE:
- MATCH DRILL TOP AND BOTTOM PLATE TOGETHER
- USE 1/4" A36 STEEL PLATE
- ALL TOLERANCES ±.01

6.00

2.50

1.11

2.50

1.11
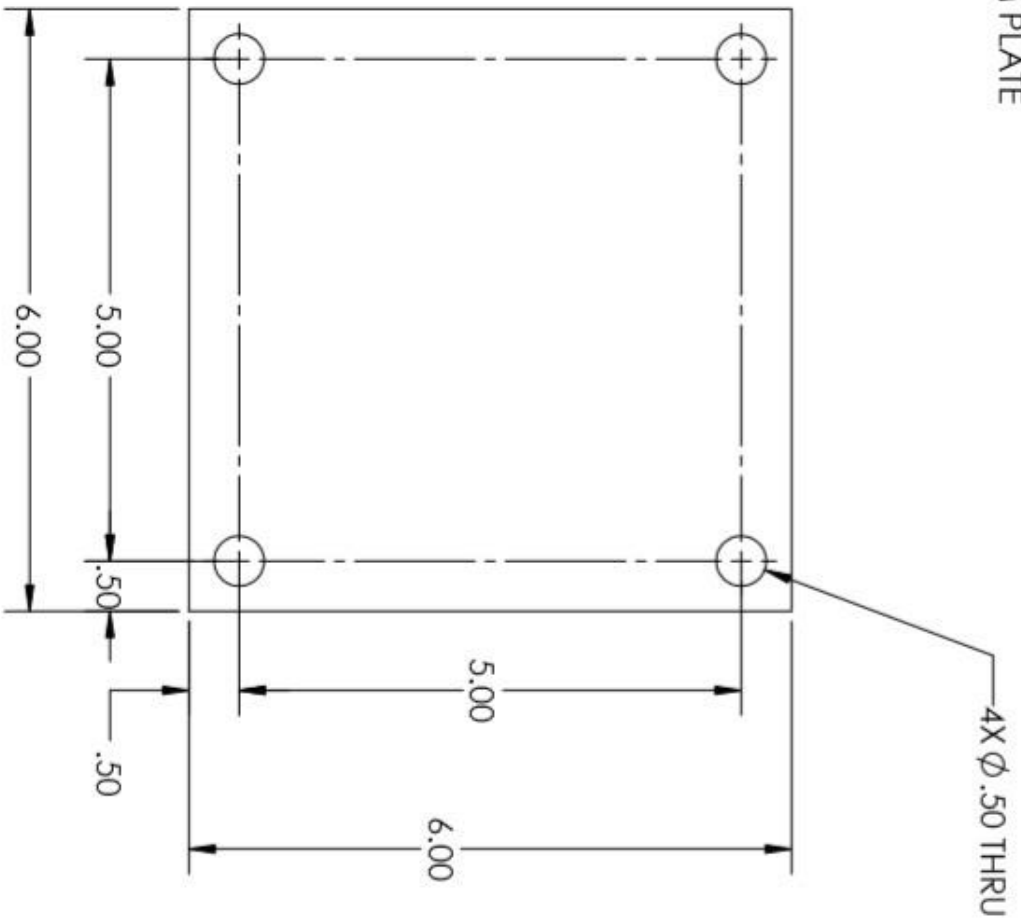
6.00

B

A

4X ∅.25

4X ∅.50

⊕	∅.75		
	.01	A	B

$\emptyset$.500

$\emptyset$.750

3.000

NOTES:
1. ALL TOLERANCES ±0.005
2. 4 SPACERS MUST BE FACED ON MILL TOGETHER FOR CONSISTENT HEIGHT
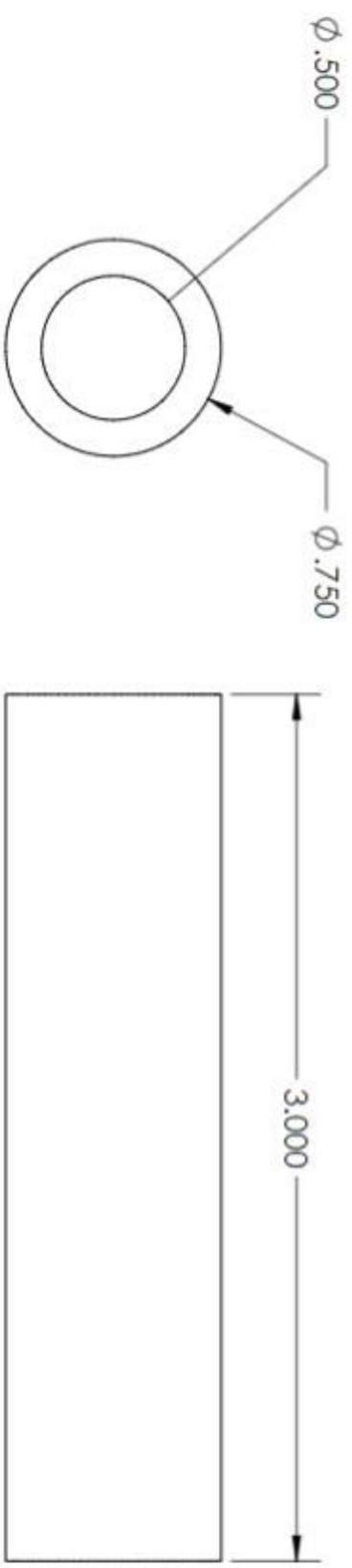
NOTE:
MATCH DRILL TOP AND BOTTOM PLATE TOGETHER
USE 1/4" A36 STEEL PLATE

4X Ø.50 THRU

6.00
5.00
.50
.50
5.00
6.00

Cal Poly Mechanical Engineering
ME 429 - WINTER 2020

Part No: 220000

SENIOR PROJECT

Title: TEST STANDBASE PLATE

Date: 1/28/20

Scale: 1:2

Drwn. By: TIM WILLS DETONE

Chkd. By: CHARLIE GLENWRIGHT

⌀ 0.05 | A

A

⌀ 0.05 | A

A

1/16

Senior Project DVP&R

Date: 2/3/20	Team: 32 Camless Engine	Sponsor: Dr. E	Description of System: A single action solenoid connected to a valve spring in order to provide compresive force.	DVP&R Engineer: Tim Wills DeTone

			TEST PLAN								TEST REPORT			
Item No	Specification #	Test Description	Acceptance Criteria	Test Responsibility	Test Stage	SAMPLES		TIMING		TEST RESULTS			NOTES
						Quantity	Type	Start date	Finish date	Test Result	Quantity Pass	Quantity Fail	
1	1	Weight	5 lb	Charlie	SP	1	Sub	2/20/2020	2/23/2020				
2	2	Size	6 in^3	Tim	SP	1	Sub	2/21/2020	2/24/2020				
3	3	Actuation Speed	3 ms goal	Darya	FP	1	Sys	3/4/2020	3/9/2020				
4	4	Mechanical Complexity	<3 moving parts	Nick	SP	1	Sub	2/8/2020	2/9/2020				
5	5	Actuation Force	250 lbf	Charlie	FP	1	Sys	3/4/2020	3/9/2020				
6	6	Production Cost	<$500	Tim	FP	1	Sys	2/10/2020	2/14/2020				
7	7	Power	140 Watts (max)	Nick	FP	1	Sys	3/4/2020	3/9/2020				
8													
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