March 14, 2019

Dr. Craig Scratchley
School of Engineering Science
Simon Fraser University
Burnaby, BC
V5A 1S6

Re: Capstone Project: Design Specification for Anthem Brakes

Dear Dr. Scratchley,

Please find the design specification for the Anthem Brakes system below. This document enumerates the design decisions of the system through three development stages: proof of concept, alpha-prototype, and beta release. The new system comprises an electrically actuated disc brake and an electromagnetic regenerative brake in one integrated package. We believe that the solution provided by Anthem Brake is reliable and more effective than the current use use hydraulic brake systems.

The purpose of this document is to provide different decision making aspects that would satisfy the functional specifications needed for the product. The document consists of the design overview during proof of concept phase, showcases the testbench that we will be using, and how we collect data to improve our design as time progresses. Finally, the document appendices for test plans and user interface design are included to show how Athem Brake meets the current automotive industries standard.

Thank you for taking your time to review our design specifications. Anthem Brakes consists of a team with diverse backgrounds, studying electronics, systems, and computer engineering. We are motivated to revolutionize the current use of automotive braking system. If you have any questions or concerns, please contact our chief communication officer, Jason, at jason_wang_10@sfu.ca.

Sincerely,

Jason Wang

Design Specification

ENSC 405W

Team 8:

Michael Akerman	301286444
Jason Trinh	301229013
Chun I (Jason) Wang	301248707
Derrick Lee	301235205
Elaine Crisostomo	301253391
Alex Hong	301087633

Due March 14, 2019

Abstract

Our team, *Anthem Brakes,* proposes an alternative solution to the widespread use of hydraulic braking systems. The new system is composed of two distinct devices that can work together to offer a fully electronic and regenerative system. This proposal defines the design specifications of the electronically actuated disc brake and regenerative apparatus from proof of concept to further development considerations. The goal of the design is to provide a safe, comfortable ride, and improve the lifespan and functionality of automotive brake systems.

The information in this paper should help the reader comprehend the purpose, requirements, and, challenges in the development of our braking system. The proposed system should meet the same requirements as existing braking systems, being able to bring a vehicle to stop during emergency and non-emergency situations. *Anthem Brakes* proposes an evolutionary solution to replace hydraulic lines and pumps that can be more easily integrated into the vehicle's powertrain.

This document also includes an appendix of supporting test plans, and a user interface appendix, outlining an easy transition for drivers to adapt to this cutting edge brake system. Our plan is to bring this solution to life, and improve upon current braking solutions.

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Glossary

ABC	Active Braking Control
ABS	Anti-lock Braking System
AC	Alternating Current
AEB	Automatic Emergency Braking
BLDC	Brushless Direct Current
CMRR	Common Mode Rejection Ratio
DC	Direct Current
ECU	Electrical Control Unit
EHB	Electro-Hydraulic Brake
EMB	Electro-Mechanical Brake (Hydraulic-less)
PID	Proportional Integral Derivative
PWM	Pulse Width Module
RPM	Revolution Per Minutes
VFD	Variable Frequency Drive

1. Introduction

1.1 Background

Automotive industries are constantly required to adapt to new technologies across different engineering disciplines. One area where improvements in safety and performance are continuously being achieved is braking. The current trend in braking (making its way from racing, to luxury cars, then finally into the mass market) is a technology called brake-by-wire, where hydraulic pressure at the brake pedal is decoupled from hydraulic pressure at the calipers via electrical signals and separate hydraulic pumps [1].

With constant innovation in electric and hybrid cars, electrical power and control systems are becoming more and more sophisticated. Automotive brakes are progressing toward fully electrical systems, where instead of hydraulic actuation, a "hydraulic-less" electro-mechanical brake (EMB) [2] is in place. The illustration in **Figure 1** shows the difference between an electro-mechanical brake (EMB) and a traditional hydraulic brake (EHB). In the latter, braking power comes from a vacuum actuated brake booster and control comes from a hydraulic control unit (HCU) via signals from the vehicle's electrical control unit (ECU).

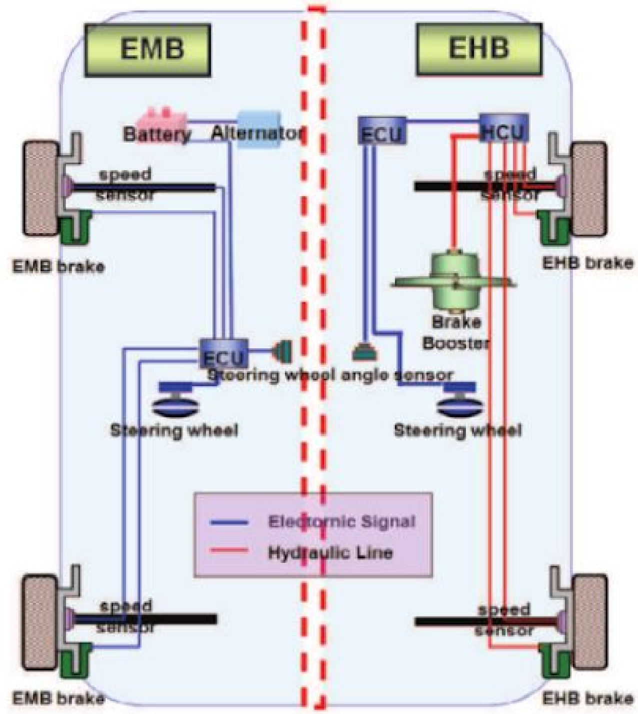

Figure 1.1: Comparison of Electro-Mechanical Brake (EMB) and Electro-Hydraulic Brake (EHB) [2].

By replacing hydraulic brakes with electrical components, production is simplified and there is an increase in flexibility for component placement. Furthermore, the fast development of battery-powered electric vehicles allows for bidirectional energy flow, which implies that when a vehicle's brake is applied, some kinetic energy can be recaptured [3] (i.e. using a generator). The buzzword typically applied to this mechanism is "regenerative braking."

1.2 Design Overview

1.2.1 Overall Project Scope

The *Anthem Brakes* system comprises an electrically actuated disc brake for primary stopping power and a secondary regenerative brake that returns power to the vehicle's battery while applying some stopping torque when engaged. The proposed design also features a feedback control system that can interface with a vehicle's main computer (ECU) so that braking can be modulated at each wheel when anti-lock braking (ABS), automatic emergency braking (AEB), or traction control systems come into play.

The brake system will run entirely on a vehicle's native 12VDC power system, and will also include a pedal that replicates the "feel" of a traditional hydraulic braking system. A high-level schematic of the proposed design can be seen in **Figure 1.2** below.

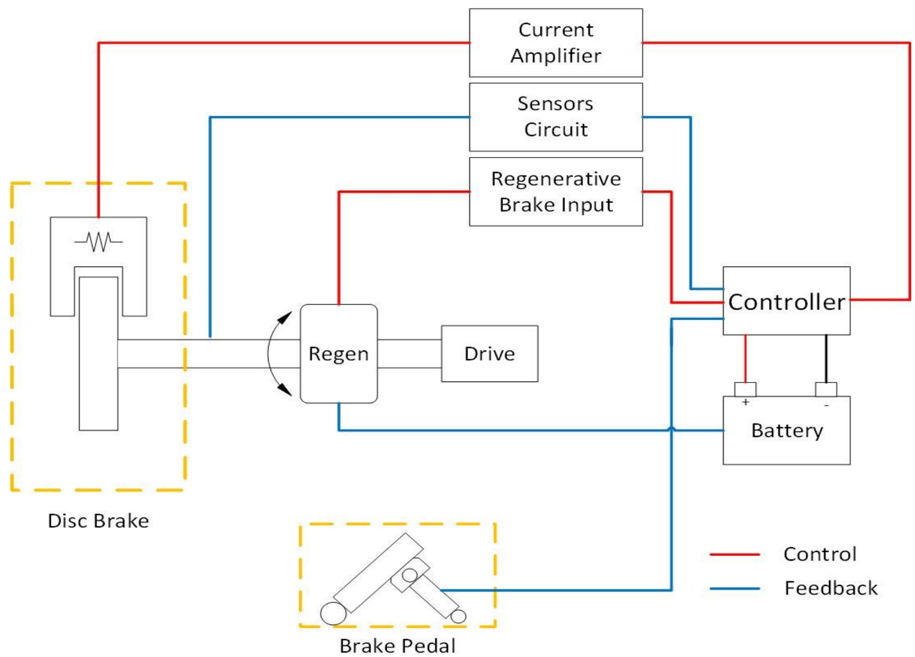

Figure 1.2: Electric Brake System Schematic

In the schematic, the controller takes driver input (via the brake pedal) and feedback input from the braking system. 12V battery power is channeled to both the disc brake and the regenerative brake via the controller for modulated control.

1.2.2 Proof of Concept Scope

For the POC, the design will focus on a subset of the overall project's scope. The key components are a reliable test bench (to be carried through to the final project), scaled down versions of the two proposed brake apparati (an electromagnet friction brake and a regenerative brake), and a rudimentary control system. The goal of the POC is to show that the proposed technologies are feasible, and to provide a foundation for the next design phase (alpha). A schematic of the POC system can be seen in the **Figure 1.3** below.

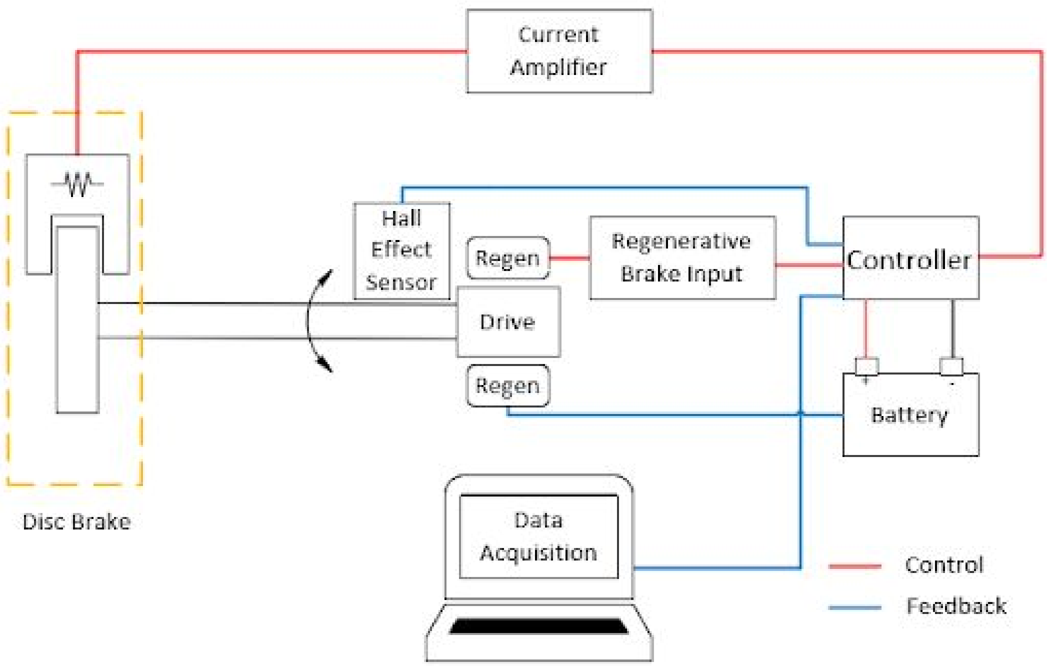

Figure 1.3: Electric Brake System Schematic

2. Proof of Concept Design Approach

This section outlines the reasoning behind some of the POC design decisions and provides some background for the reader.

2.1 Mechanical Design

2.1.1 Test Bench

A large part of the design of the *Anthem Brakes* system relies on the existence of a solid platform on which to test our design. For this reason, the test bench design must be robust and capable of providing conditions as close to the field (automotive) as possible. As shown in the model in **Figure 2.1** the design comprises a solid frame and a spinning shaft coupled to an automotive disc brake rotor.

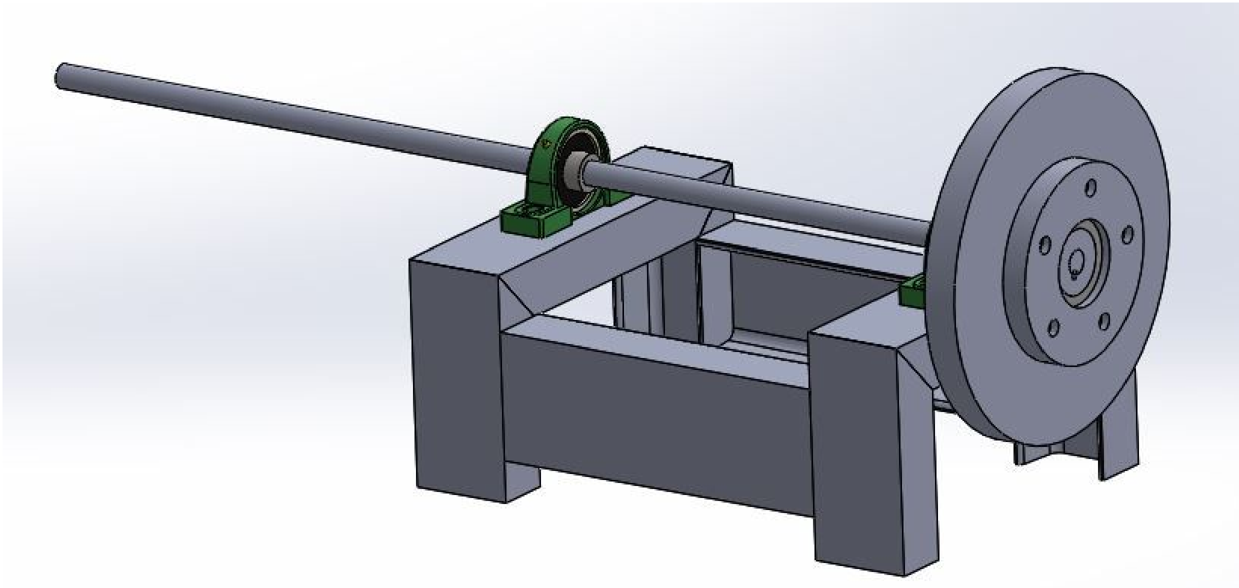

Figure 2.1: Test Stand Model (1)

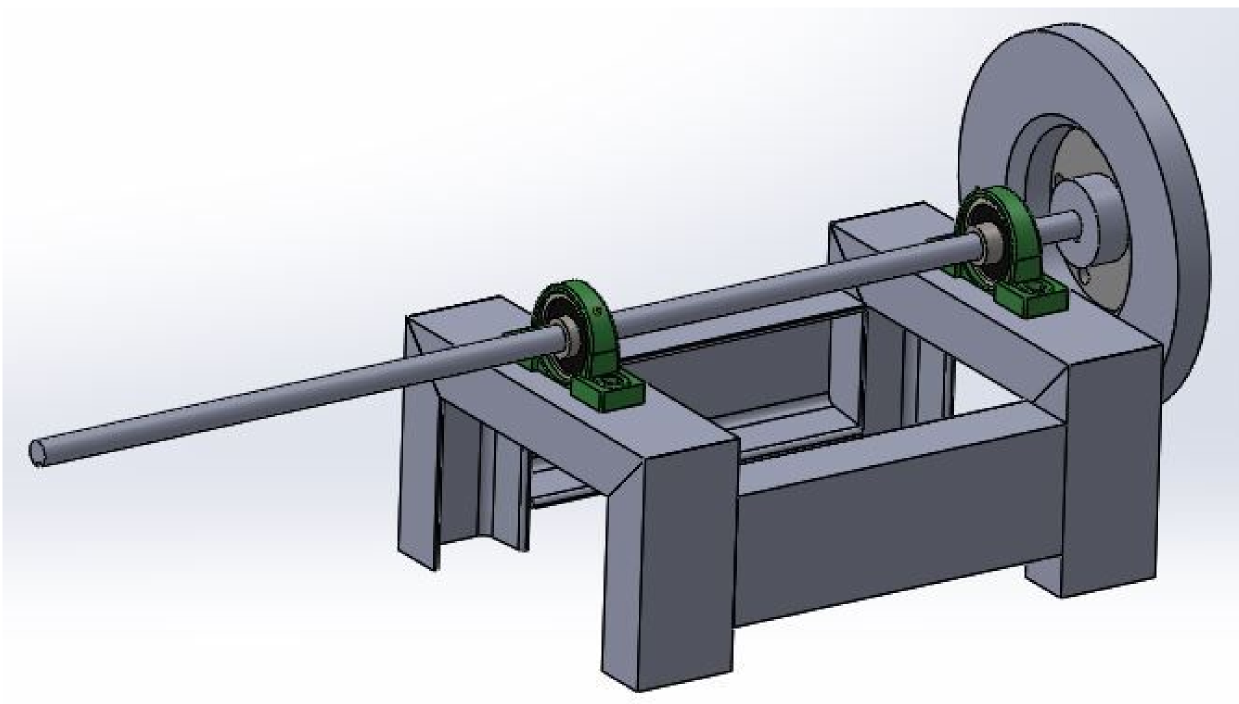

Figure 2.2: Test Stand Model (2)

For this stage of the design, the shaft will be coupled to some external source of motion (like an electric drill) to drive the rotor.

2.1.2 Electromagnet Friction Brake

The ultimate goal of the electromagnet friction brake is to replace a conventional automotive hydraulic brake caliper. As such, the end design should fit in a similar package and provide a similar amount of stopping power.

Powerful electromagnets can provide an impressive amount of holding force in a relatively small package. Commercially available units 3.5” in diameter can provide over 1000 pounds of force at zero air gap. Thus, the difficulty in using these magnets to provide a modulated holding force is maintaining a very small air gap, while not allowing the magnet itself to contact the rotor.

For this reason, the current PoC stage path for the friction brake is a simple rocker arm design, as shown in **Figures 2.3** and **2.4** below.

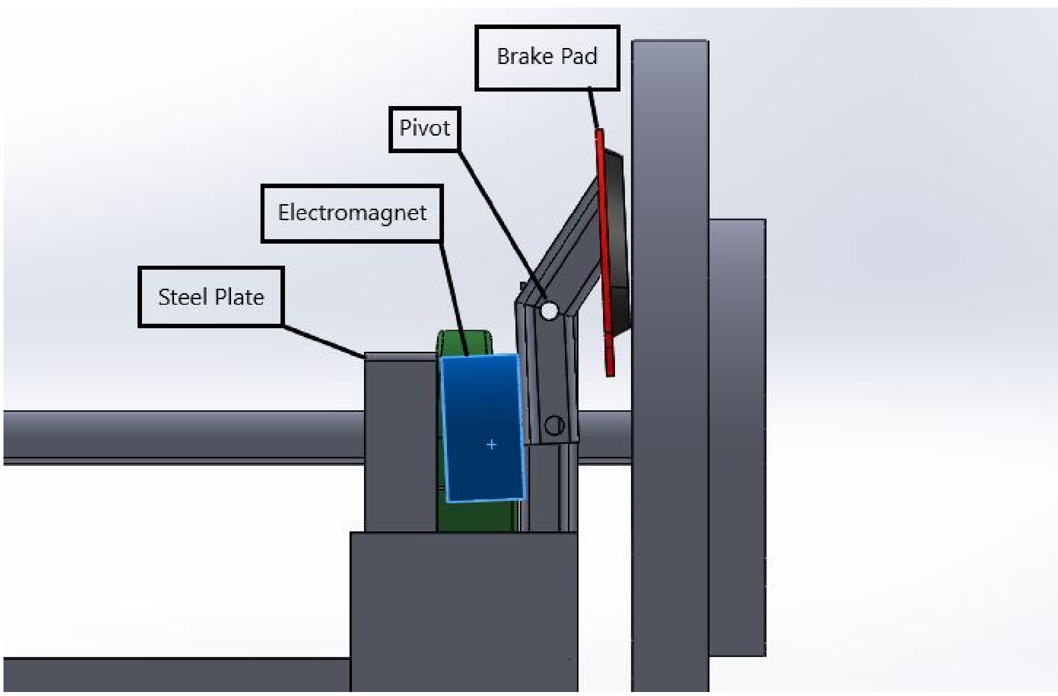

Figure 2.3: Electromagnet Friction Brake PoC Model (Demagnetized Position)

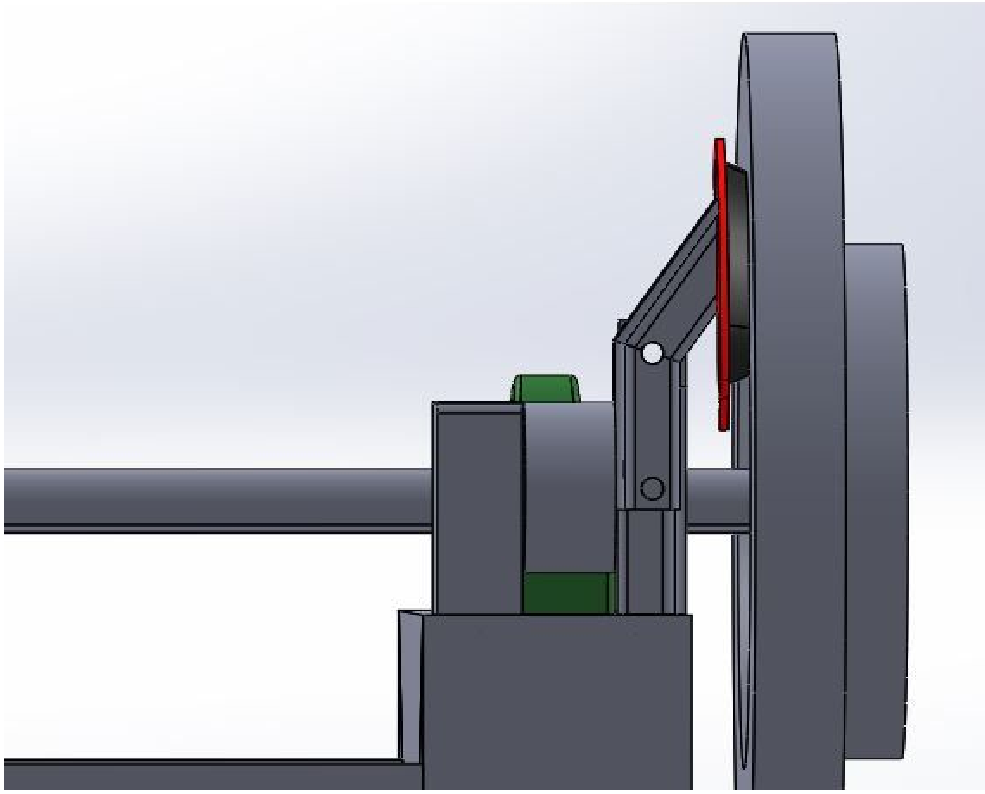

Figure 2.4: Electromagnet Friction Brake PoC Model (Magnetized Position)

As shown in the model, when energized, the electromagnet is attracted to the steel plate, which causes the rocker arm to swing about the pivot point anchored to the frame. The brake pad at the other end of the rocker arm is then engaged with the rotor.

This is a very simple design, incorporating only one weak (50kg holding force) electromagnet. No attempt has been made here to package the brake neatly, and we are not trying to provide field levels of braking power. By reducing the constraints on our design, we hope to first show whether the electromagnet/rocker arm approach is feasible by measuring the system's braking power on a small scale. If a reasonable braking force can be obtained relative to the magnet's output (holding force), then the concept will be proven.

Because an electromagnet's holding force decreases exponentially with an increasing air gap [4], a careful rocker design is required. Free software called *Linkage* [5] was used to optimize the geometry (see **Figure 2.5** below).

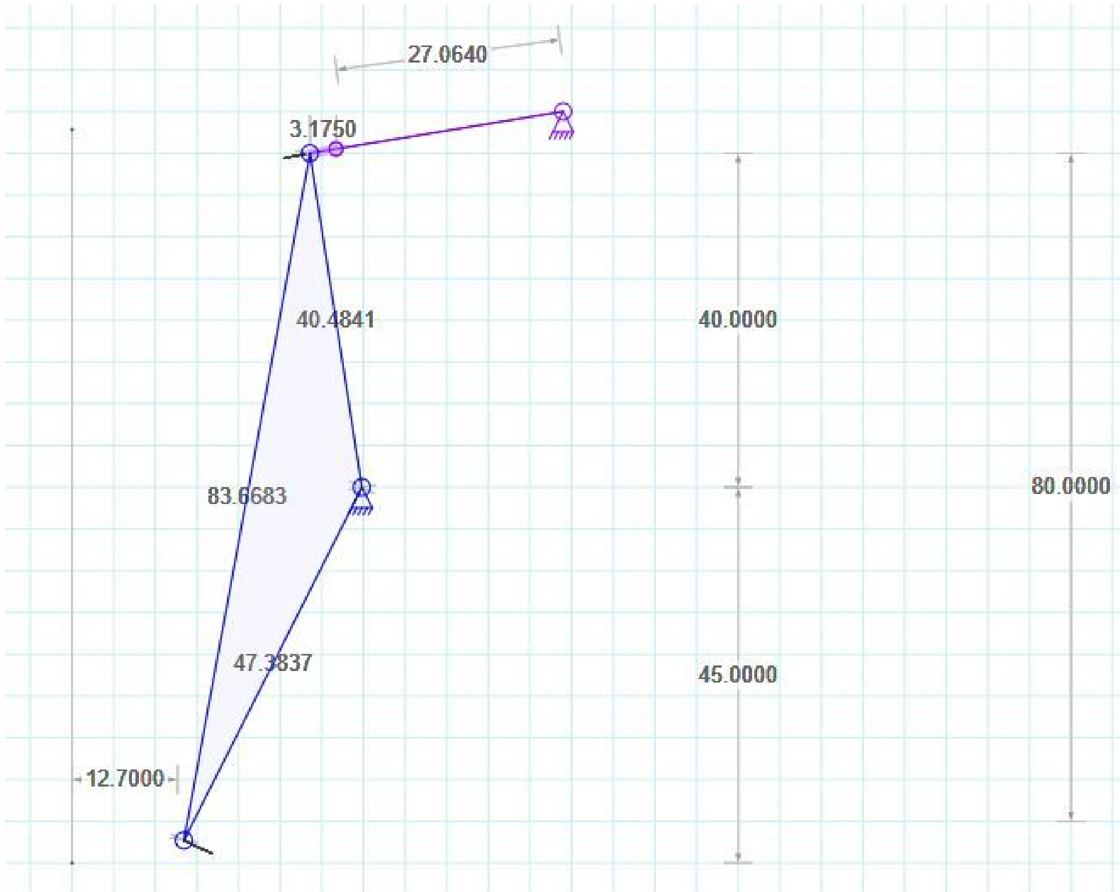

Figure 2.5: Electromagnet Friction Brake Linkage Simulation (Dimensions in mm)

In the simulation above, the electromagnet is modelled as a linear actuator (purple, at the top). The end-effector (brake pad) is at the bottom left. The black arc shows the movement of the link as it swings back and forth with an exaggerated motion caused by the magnetic holding force.

Since the air gap needs to be kept small, there is no opportunity to amplify the magnet's holding force. From a very simple static analysis, the ratio of the magnet-side moment arm length (40.4841mm in **Figure 2.5**) to the pad-side moment arm length (47.3837mm) must be kept close to unity to minimize loss of force transmission on the pad side, while maintaining the small air gap on the magnet side. The numbers shown in **Figure 2.5** allow for a small (15%) loss in force transmission from magnet to pad, following the (approximate) moment equation:

$$M_{pivot} = Fm * 40.48 = Fb * 47.38$$

Or

$$Fb/Fm = 0.854$$

Thus, roughly 85% of the magnet's holding force should be transmitted to the pad.

2.1.3 Supplementary Braking Options (Regenerative, Plugging, Dynamic Braking)

For the motor there are several considerations to be taken into account before selecting the right one for our product. Thus, we are comparing AC induction motors, brushed DC motors, and brushless DC motor (BLDC). These options are listed in **Table 2.1**. We are also comparing the relative difficulties of implementing supplementary braking techniques such as regenerative braking, plugging braking, and dynamic braking. Lastly we are comparing the difficulty of integrating each of these motors with the other components in this project.

Figure 2.6 below shows the difference in construction between the motors. For instance, AC does not use permanent magnets, which reduces the need to disengage the motor from the driveshaft because of reverse torque from permanent magnets creating a magnetic field that cannot be disabled. However, we will need to expend energy to create a magnetic field whenever we want to use any form of supplementary braking in this design.

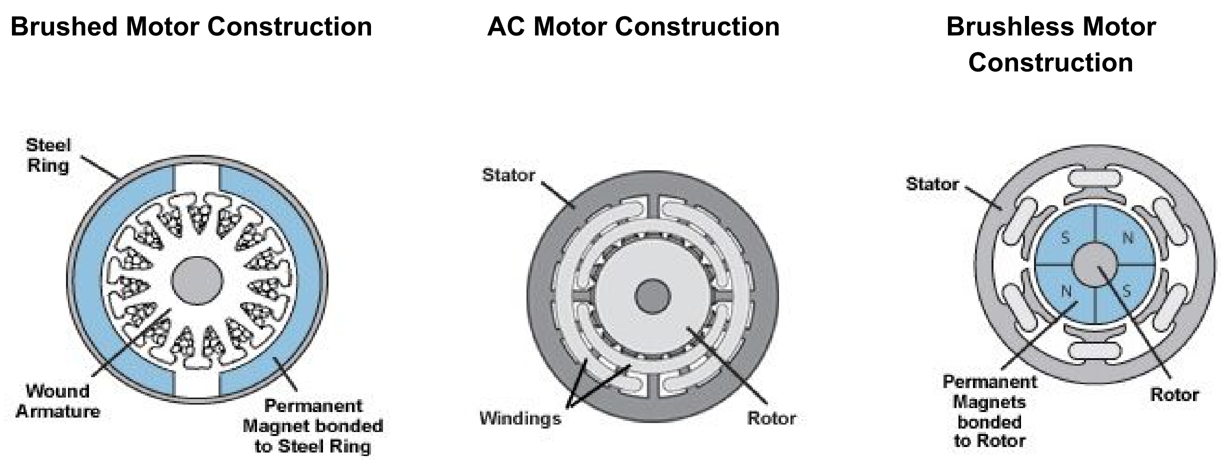

Figure 2.6: Motor Construction [6]

Formulas

Induction Motor Power Input: $P_{in} = 3VI_s cos(\varphi_s)$

Synchronous Speed: $s = \frac{120*freq}{\#poles}$

Slip: $s = \frac{\eta s - \eta r}{\eta s}$ where $\eta s = synchronous\ speed,\ \eta r = motor\ speed$

Forms of Supplemental Braking Involving Induction Motor, DC, BLDC

1. ***Regenerative Braking***

   Induction Motor:

Requires φs > 90 degrees therefore motor speed must be greater than synchronous speed. The synchronous speed can be adjusted using a VFD. The advantage of using this is the conversion of mechanical energy (spinning rotor) back to electrical energy. However, this requires a VFD to vary the frequency so it can regenerate at different speeds. The range of active regenerative braking is shown in **Figure 2.7** below.

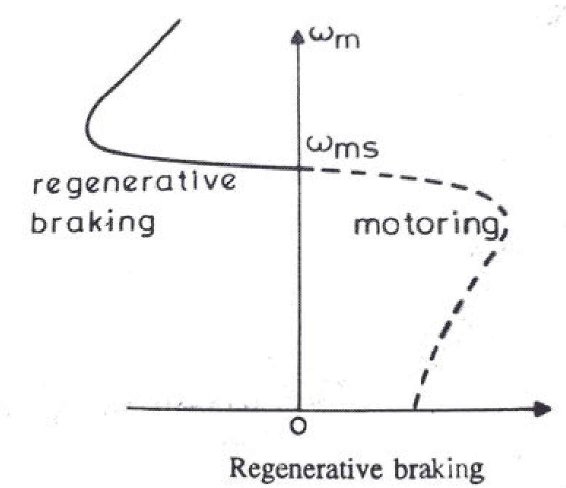

Figure 2.7: Induction Motor Speed and Synchronous Speed [7]

DC Motor:
Regeneration occurs when the motor is spinning faster than the rated value of the motor, such that for a given supply voltage and a resultant speed, if the motor manages to spin faster than this speed, it will generate energy and the current will flow back into the source.

BLDC Motor:
Similar to a synchronous AC motor, a BLDC can be used as a regenerative brake by having the the synchronous speed of the motor slower than the motor speed. Thus it will be utilizing an integrated inverter to convert a DC source to an AC source and it also utilizes an electronic speed controller in conjunction with PWM to lower the synchronous speed (similar to a VFD for AC).

2. ***Plugging Braking***

Induction Motor/BLDC:
Plugging is done by interchanging two of the phases in the stator relative to the supply terminal thus reversing the torque. As a result the slip (difference between the motor speed and synchronous speed) goes from *s* to 2-*s*. Given that *s* is usually around 0.01 - 0.06 (full load high horsepower motor to low load low horsepower motor) thus the slip is about 2-0.06 = 1.94 which equates to 194%. In this case, the motor will very quickly go

in the reverse direction, therefore we need to cut off the power to the motor once the motor stops. The advantage of plugging is it produces the most reverse torque of all the options shown in **Figure 2.8**, thus this is the quickest option to stop the rotor from spinning. However, the drawback is it requires energy and produces large amounts of heat.

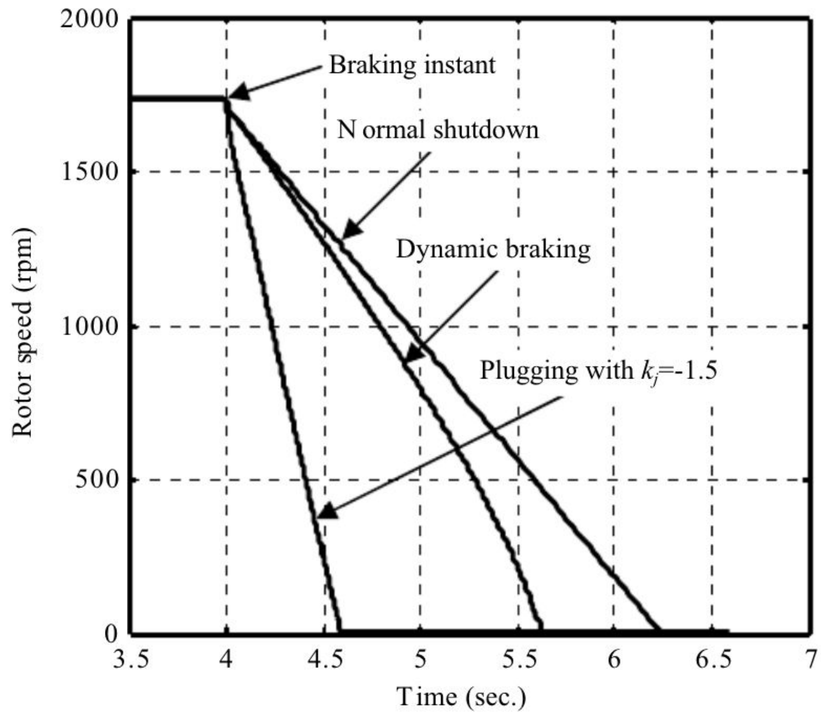

Figure 2.8: Induction Motor Braking Effectiveness [8]

DC Motor:

For this motor, plugging is performed by reversing the direction of the voltage source so that the torque is reversed. A series resistance can be added to the armature to supplement the reverse torque as well.

3. *Dynamic Braking*

Induction Motor/BLDC:

Another method of reversing the torque is by opening a single phase and connecting this open phase to another phase to create a negative net torque. This form of braking can be supplemented with capacitors or using a DC source. **Figure 2.9** shows the two methods of utilizing dynamic braking, two-lead and three-lead connections.

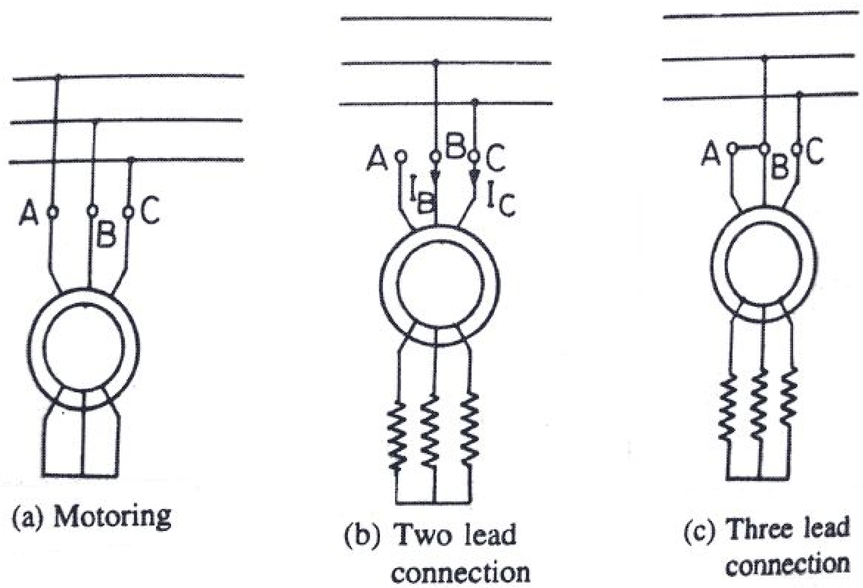

Figure 2.9: Induction Motor Dynamic Braking Phase Connections [7]

DC Motor:
Dynamic braking in a DC motor occurs when the armature of the motor is connected to a series resistance resulting in current going in the reverse direction thus slowing the motor down.

High Level Block Diagram of Motors

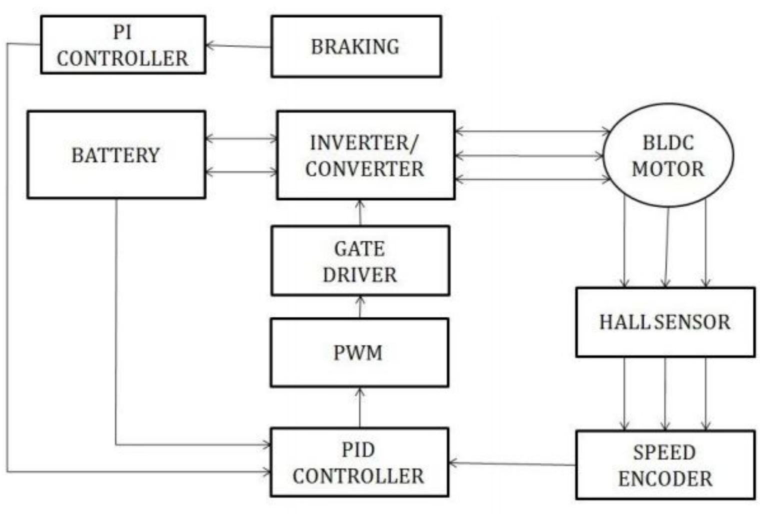

Figure 2.10: BLDC Motor Block Diagram [9]

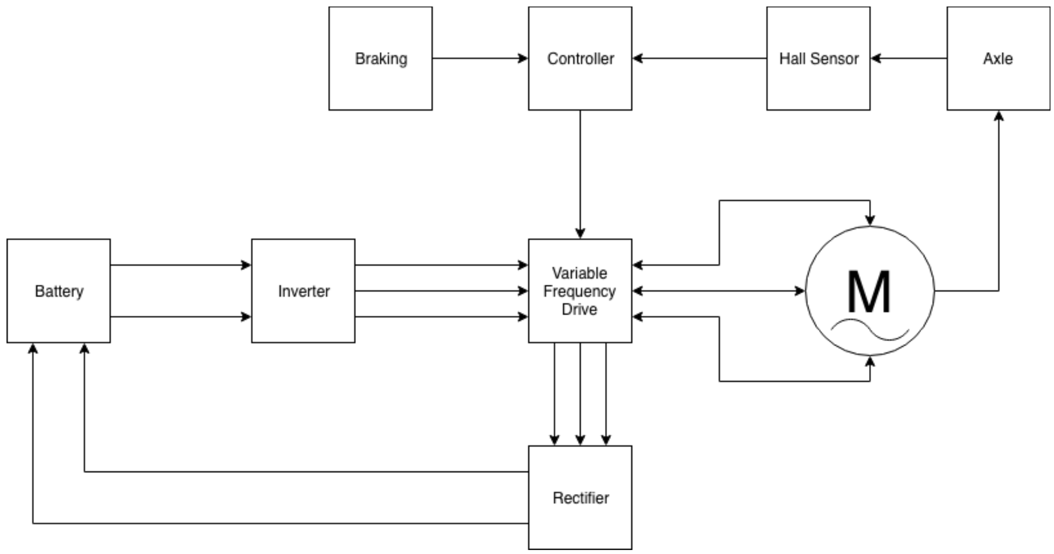

Figure 2.11: AC Motor Block Diagram

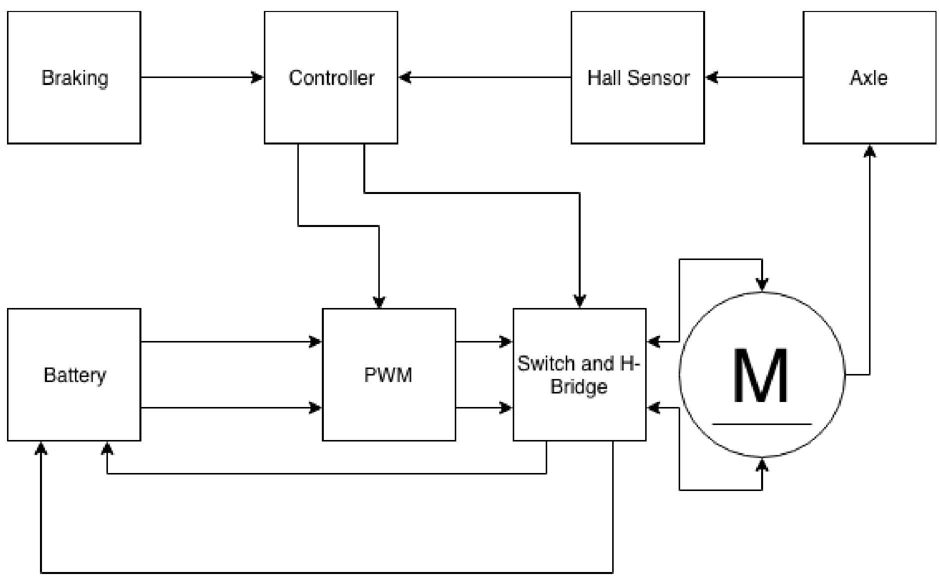

Figure 2.12: DC Motor Block Diagram

	AC Induction Motor	DC (brush)	DC (brushless)
Cost	~$350	~$175	~$175

Pro	- Is able to change direction of motor via a change in frequency (No extra components) - Less maintenance required - No loses as motor is scaled up	- Torque band is wide and flat - Around 75-80% efficiency - Low cost - Has permanent magnets, thus removes the need of energy to create a magnetic field	- Around 85-90% efficiency - Longer lifespan similar to AC - Low maintenance - Has permanent magnets, thus removes the need of energy to create a magnetic field
Con	- Needs more circuitry to convert to AC power - Needs variable frequency drive to change the speed - Loses torque as speed increases - Requires energy to create magnetic field - Largest in size	- More moving parts - Wear and tear - Requires an H-bridge in order to change the direction of motor - Requires pulse width modulator to control amount of voltage - Noisy - Magnetic loses increase as motor increases in scale	- Higher cost - Requires controller - Smallest in size - Magnetic loses increase as motor increases in scale
Regenerative braking	- Requires timing of the controller - Used in electric car industry	- Reverse the electrical input to the commutator	- Very similar to AC motor but will require more effort to convert DC to AC like voltage - Used in electric car industry
Extra circuitry	- No	- No	- Yes

Table 2.1: Comparison of Supplementary Braking Motors

At this point we are deciding between a brushless DC or an AC motor with an output of around 0.5 - 1 horsepower. The differences between the brush/brushless DC and AC motor are summarized in **Table 2.1** above. We have eliminated brushed DC motors because they are a wear component that would need to be changed. Although the AC motor is the most expensive, we believe that it will allow us to have better control since we only need to use the controller to manipulate a variable frequency drive (VFD). The purpose of regenerative braking is to assist the motor in braking while at the same time recapturing into a battery. The brushed DC motor is able to do this by flipping the polarity of the commutators which will induce a magnetic field that will oppose the rotation of the shaft. The AC/DC brushless motors work in the same way: running the stator frequency lower than the rotor frequency induces a magnetic field which creates an opposing torque to the spinning shaft.

2.1.4 Battery (Regenerative Brake)

There are many types of battery like nickel cadmium (Ni-Cad) batteries, lead acid batteries, lithium ion (Li-Ion), and lithium ion polymer. Each of these types have different properties but for the PoC, *Anthem Brakes* will use Li-Ion (polymer) batteries because they are lightweight and almost all power banks are made of Li-Ion batteries. In the future and this project’s alpha phase, *Anthem Brakes* will likely use lead acid batteries because they are reliable and normally used in cars. A comparison of each type can be found in **Table 2.2**.

	NiCd	Lead Acid	Li-Ion	Li-Ion polymer
Energy Density	Low	Low	High	High
Self-Discharge	High	Low	Low	Low
Weight	Medium	Heavy	Low	Low

Table 2.2: Comparing Different Types of Batteries [10]

There are multiple ways to measure the battery level. Just measuring the voltage across the terminals is not viable because most batteries do not have a linear relationship with the battery level and the voltage output, so we decided to measure the current by applying coulomb counting. Other ways to measure the battery level include current shunt, hall effect, and giant magnetoresistance [11]. We will discuss the method with current shunts because it is the cheapest and most effective option.

2.2 Hardware Design

2.2.1 Rotational Speed Measurement

To validate the proposed braking system, some data needs to be collected and compared with the current standards in the automotive industry. This means that there should be a sensor in place to measure the rotational speed of the driveshaft. This can be done with a Hall-Effect sensor and a magnet as shown in **Figure 2.13**

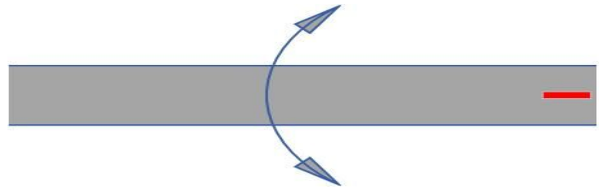

Figure 2.13: Rotational Shaft With a Piece of Magnet Attached

When the shaft rotates, the magnet indicated in red will rotate with it, and when the sensor detects the magnetic field, the controller can accumulate the counts over time, giving the shaft speed in rpm, which can then be converted to a vehicle's highway speeds.

2.2.2 Force Measurement

Throughout the development of the system, the amount of force that can be generated to stop the rotor must be monitored. While the PoC demonstration of the system is on a smaller scale, ideally the sensing system can be implemented with field values as well. By monitoring how much the force can be generated by the electromagnetic friction brake onto the rotor, we can compare to automotive standards to see the practicality of the system developed by *Anthem Brakes*. One way to do that is mounting the brake in a cantilever configuration like the one shown in **Figure 2.14**, but setting it up vertically as shown in **Figure 2.15**. By attaching the beam to the electromagnetic brake, the beam will bend when the brake force is applied, and bending strain of the beam can be measured with a strain gauge.

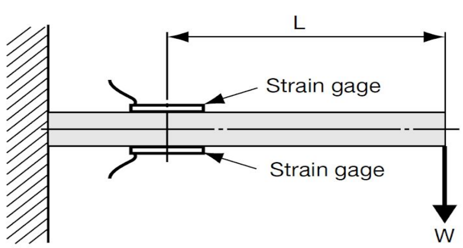

Figure 2.14: Bending Stress and Bending Moment [12]

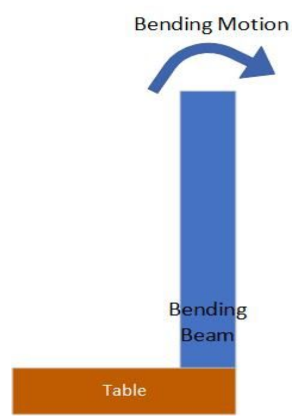

Figure 2.15: Setup of the Beam

The following equations describe the relationship between strain, bending moment, section modulus, and material properties (encapsulated in Young's modulus) in a cantilever configuration.

$$\varepsilon_0 = \frac{Bending\ Moment\ (M)}{Section\ Modulus(Z) \cdot young's\ modulus\ (\gamma)}$$

$$M = WL$$

Following **Figure 2.14.** above, the bending moment at the strain gauge is defined as the load (*W*) multiplied by the distance *L* between the strain gage and the point of load application. The target value of *W* is stated in the *Functional Specification* document (**3.2.4-A**), where the clamping force should consistently reach 4500N [13]. As for Young's Modulus (γ), the material used to construct the beam will be mild steel with a stiffness of 210 GPa or $210x10^9$ $kg \cdot m^{-1} \cdot s^{-2}$ [14]. Lastly, the section modulus is the cross sectional configuration *Z*, which depends on the beam's cross-sectional area and shape (see **Figure 2.16**, for example).

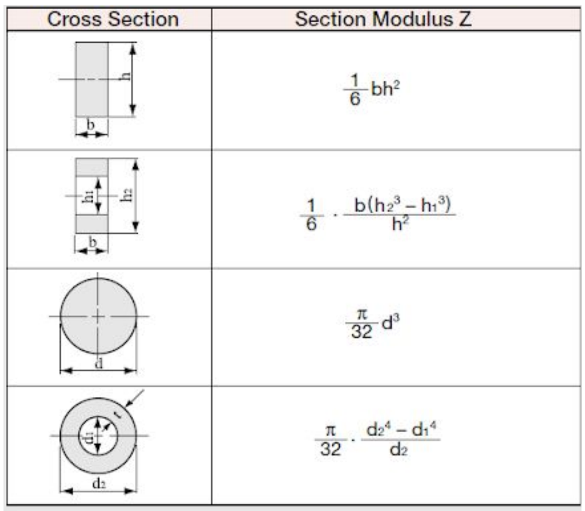

Figure 2.16: Typical Equations For Section Modulus [12]

The strain gauge that we will be using is shown in **Figure 2.17** with the part number BF350-3AA, where *B* indicates that it is foil type gauge, *F* is the backing material (phenolic resin), 350 is the gauge resistance, 3 is active gauge length in millimeters, and *AA* is the soldering-tab geometry [15]. Moreover, the sensitivity coefficient, also known as gauge factor (K_S), is between 2.0 to 2.2, with a strain limit of 2.0%. This information can help as define the size limit of the beam we need by applying the values from the equation shown earlier. The calculation shown below gives a minimum for the theoretical ratio of the beam.

$$0.02 = \frac{(4500)L}{Z(210x10^9)}$$

$$\frac{L}{Z} = \frac{0.02(210x10^9)}{(4500)} = 933333.33$$

Strain gauges are set up in a full bridge configuration as shown in **Figure 2.18**. The advantage of this configuration is to have temperature compensation where the expansion in strain gauges caused by temperature can be neglected. This configuration also increases the sensitivity of the measurement [12]. In addition, separation of normal and bending strain is achieved, and it is excellent for common mode rejection (CMR) [16].

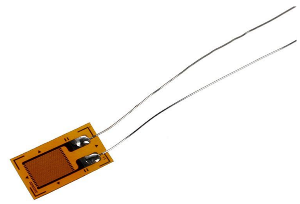

Figure 2.17: Strain Gauge (BF350-3AA)

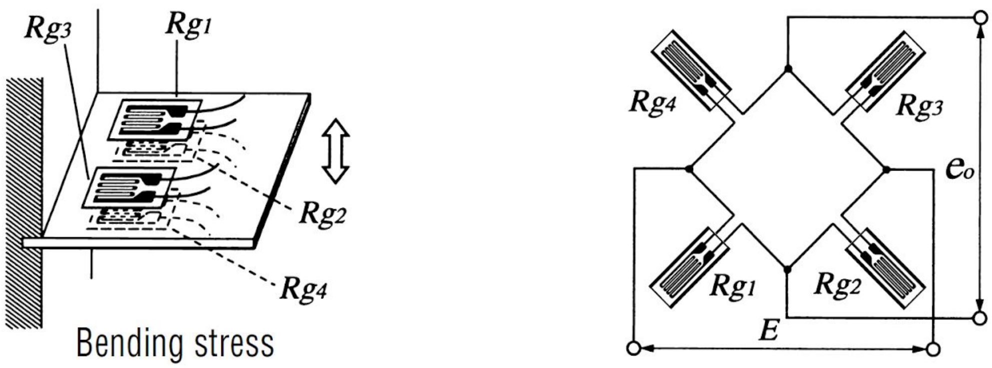

Figure 2.18: Bending Stress and Strain Gauge Setup [17]

The output voltage is described by the equation below:

$$E = e_0 K_s \varepsilon_0$$

Where E is the output voltage, e_0 is bridge voltage, K_s is gauge factor, and ε_0 is strain. The change in R_{g1} and R_{g3} results in positive bending strain (ε_0), R_{g2} and R_{g4} results in negative bending strain ($-\varepsilon_0$) [18]. Since this voltage change is very small, an amplification process is used to reject signal noise as well as to amplify the measuring voltage with a differential amplifier.

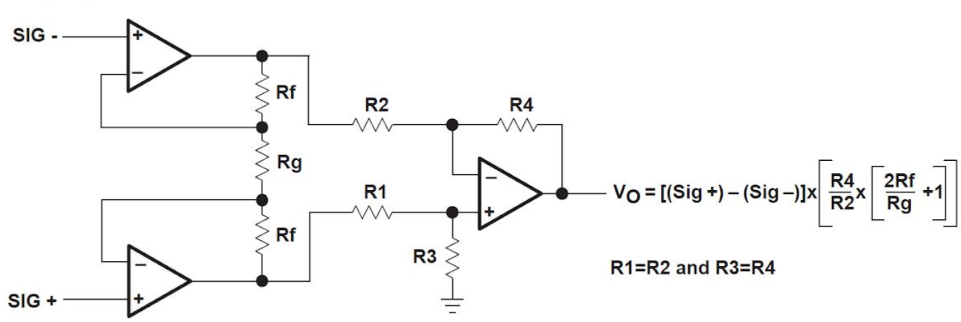

Figure 2.19: Three Op-Amp Instrumentation Amplifier [19]

To achieve better Common Mode Rejection Ratio (CMRR) of a differential amplifier, which is a metric used to quantify the rejected portion of the signal common to both the **Sig -** and **Sig +** signals shown in **Figure 2.19**, the resistors are specified as follows:

$$R = R_1 = R_2 = R_3 = R_4 = R_f$$

Then the differential amplifier gain (A) can be simplified as shown below, and resistor R_g is used to adjust the desired gain of the amplifier.

$$A = \frac{V_o}{V_{in}} = \frac{R_4}{R_2}(\frac{2R_f}{R_g} + 1) = \frac{2R}{R_g} + 1$$

2.3 Software Data Acquisition

The approach of the data acquisition flow is to first read sensor values from the microcontroller, then plot these data using wxPython. These data will be plotted in real time as a desktop application for the designers at *Anthem Brake* to closely monitor the behaviour of the proposed system. The collected data will also be stored externally (i.e. in a text or csv file) to keep track of the performance of the overall brake system. This will be discussed in more detail in **Section 3.3.2**.

3. Proof of Concept Design Specifications

This section provides specifications to be met in the PoC design implementation.

3.1 Test Bench

3.1.1 Bench Frame

The frame will be constructed of a robust material (mild steel C-channel: 3x5 and 4x5.4) and will be stiff and strong enough to withstand the motion of the spinning rotor at speeds approaching those in the field (~1000 rpm at highway speed). The frame will also be able to house/mount the regenerative braking system and the electromagnet friction brake and sensors for data acquisition.

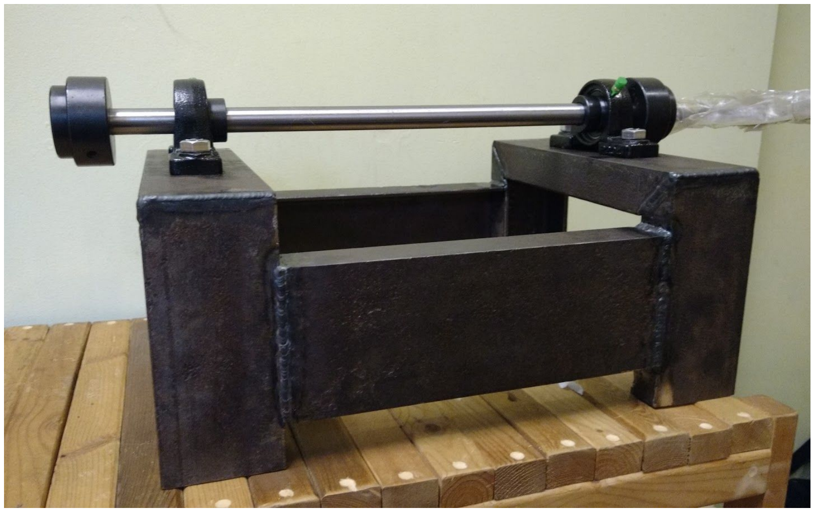

Figure 3.1: Partially Finished Test Stand Base and Axle Assembly

3.1.2 Axle Assembly

The axle assembly will be rigidly mounted to the frame via two ¾” pillow block bearings, each rated for 2000 pounds of radial load, 1100 pounds of axial load, and a max speed of 4400 rpm [20]. The keyed driveshaft will be ¾” diameter with a 3/16” keyway. The shaft will be constrained radially by the bearings and axially by locking collars at each bearing, held to the shaft with set screws that fit into the keyway.

3.1.3 Hub/Rotor Assembly

The hub/rotor assembly has three parts (not including fasteners): the hub (shown on the far left of the shaft in **Figure 3.1** above), the rotor adapter plate, and the rotor itself. As shown in **Figures 3.2** and **3.3** below, the rotor will be coupled to the adapter, which is coupled to the hub, which is coupled to the driveshaft.

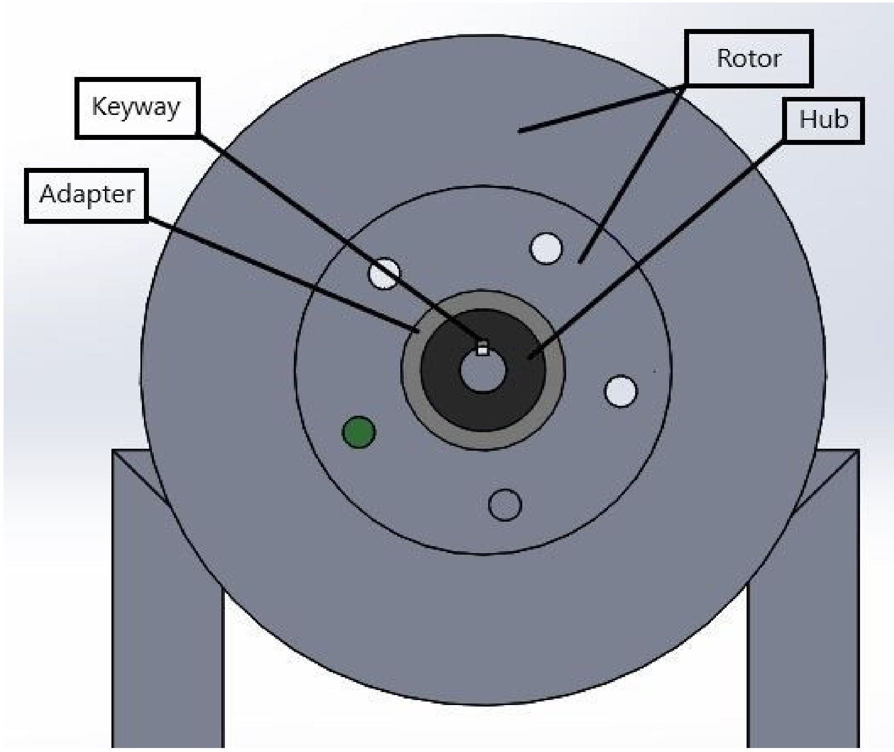

Figure 3.2: Rotor Assembly (Front View)

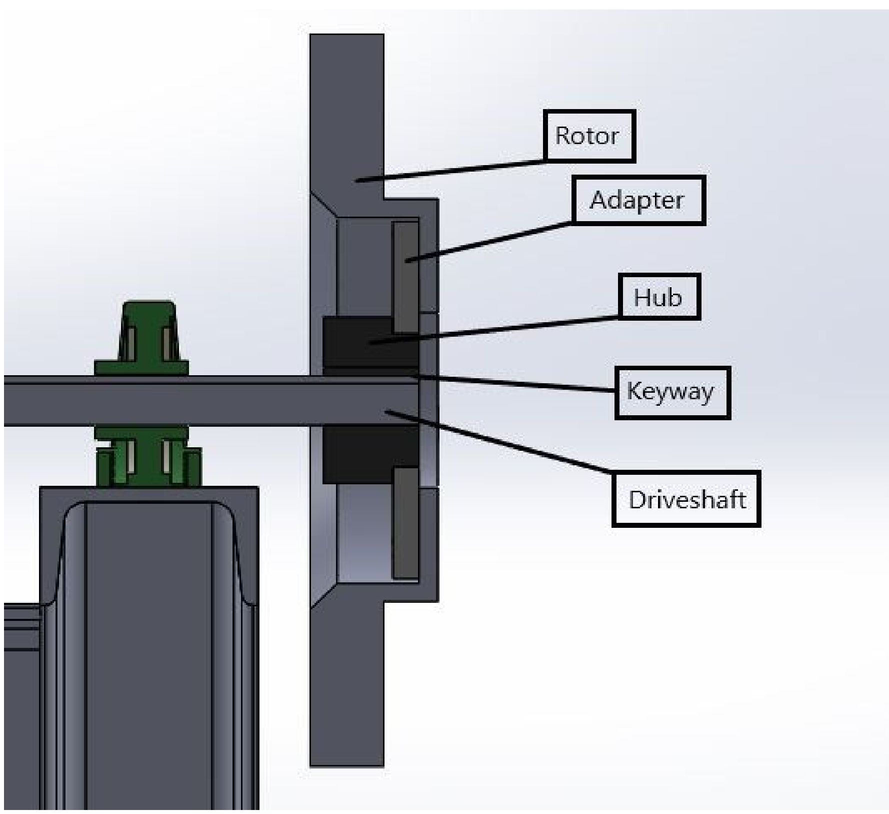

Figure 3.3: Rotor Assembly (Section View)

The hub is keyed to the shaft with 3/16” keystock for rotational constraint, and it is also fixed to the shaft with two set screws (one to the shaft itself, and another to the keystock) for axial constraint and welded. The rotor adapter plate is located by a step in the body of the hub (see **Figure 3.3** above), where the two are welded together. The hub-to-shaft connection is not ideal and will likely result is some runout. This may need to be dealt with by using shims or grinding down the front surface of the adapter plate.

The brake rotor itself is located to the adapter only by the bolt pattern. While a better method of concentric location would be preferred, it was abandoned in the interest of saving machining costs. Instead the bolt pattern has been controlled reasonably well (very tight on the rotor side, and reasonably tight on the adapter side), and the rotor may need to be located manually to some degree (i.e. by tightening the mounting bolts fully when the rotor is in the concentric position). The drawing for the rotor adapter plate can be seen in **Figure 3.4** below, and the adapter and rotor installed on the driveshaft can be seen in **Figures 3.5** and **3.6**.

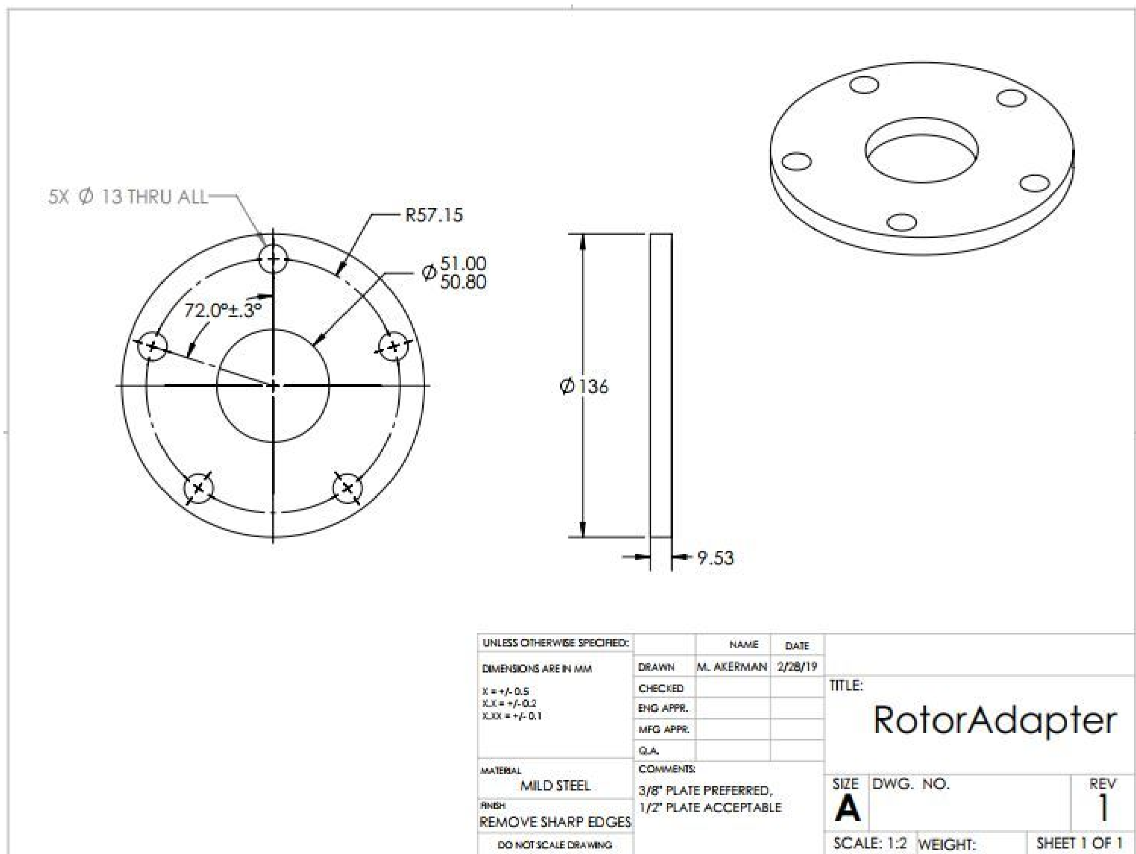

Figure 3.4: Rotor Adapter Drawing

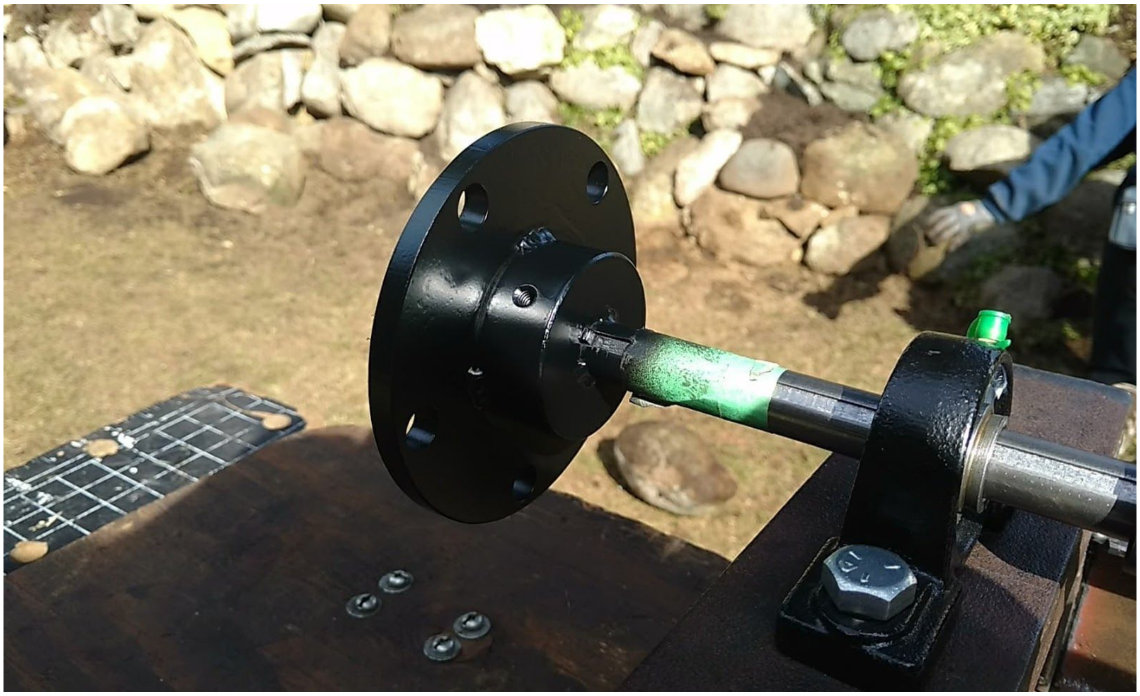

Figure 3.5: Rotor Adapter and Hub Installed on Shaft and Painted (Rear View)

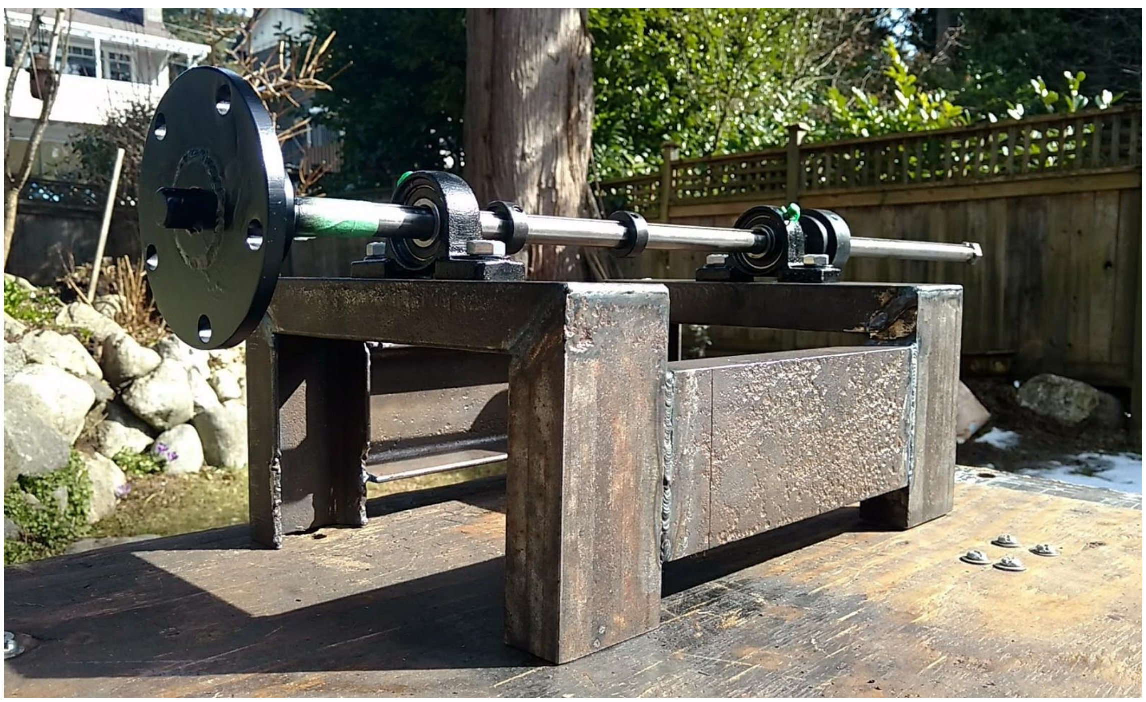

Figure 3.6: Rotor Adapter and Hub Installed on Shaft and Painted (Front View)

3.1.4 Drive

The current goal for the alpha stage of this project is for the drive mechanism to originate from the same source as the regenerative braking mechanism. However, for the PoC and for initial testing of the electromagnet friction brake, a separate drive mechanism is required. The current plan is to weld a hex nut to the driveshaft and spin up the system with an electric ½" impact wrench, which runs at about 2000 rpm (no-load) [21]. The nut can just be seen on the end of the drive shaft in **Figure 3.6** above.

3.2 Hardware (Power, Control, and Data Acquisition)

3.2.1 Power

For the PoC, Power for the microcontroller will come directly from a laptop. This is for data to be acquired and shown on the PoC GUI. As for the test bench shaft, external AC power will be used to run the drive mechanism. The electromagnet friction brake will be run on a 12VDC deep cycle automotive/marine battery. Eventually the entire system will be integrated to run on 12VDC. For the PoC, the regenerative brake will run on a separate battery as outlined in **Section 3.4** below.

3.2.2 Data Acquisition

At this stage, the angular speed of the driveshaft can be measured with the Hall Effect Sensor, and braking force will be measured with strain gauges as described in **Section 2.2.1**.

3.2.3 Control

For control of the electromagnet, power from the 12V battery will be modulated with a PWM (pulse-width modulation) signal from the microcontroller. The regenerative brake will be controlled as stated in **Section 3.4** below.

3.3 Software (Control and Data Acquisition)

3.3.1 Control

For the prototype design of this project, the controller will have a simplified active control braking system (ABC). When not active, the braking is done manually through the brake pedal (note that this pedal is theoretical in the PoC stage). To activate the ABC, the velocity must surpass a set threshold. Once active, the controller will apply the appropriate torque for this prototype. To deactivate the ABC, the velocity must go below the speed threshold. **Fig 3.7** shows a state diagram of this system.

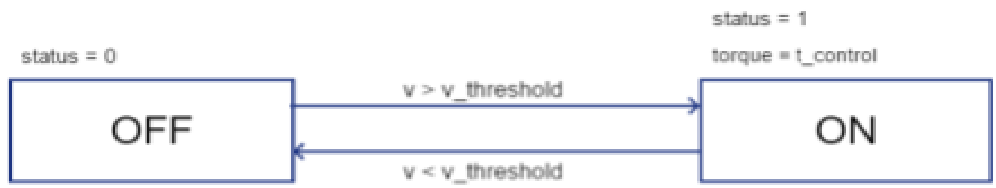

Figure 3.7: Prototype Design For Controller [22]

From **Figure 3.7**, t_control is the torque calculated by the controller which will be applied onto the brakes and status shows the status of the ABC. The value of v_threshold will be at zero as there's no pedal to be applied and the goal of this prototype is to show how the brake will engage and disengage. This prototype also establishes the base structure of the controller for future stages to build upon on.

3.3.2 Data Acquisition

Python will be used to gather data because of its versatility, accessibility, and adaptability. Aside from data acquisition and analysis, Python can be used for the UI of the project which will detailed in the next section of this document. For the prototype stage of this project, the data will be projected on a desktop app using wxPython--a Python based UI framework to create desktop applications.

3.3.3 User Interface

The user interface for the prototype shows a simple application with torque and rpm plots. The data presents live readings gathered from the sensors on the brake. **Figure 3.8** shows a mock-up of the prototype.

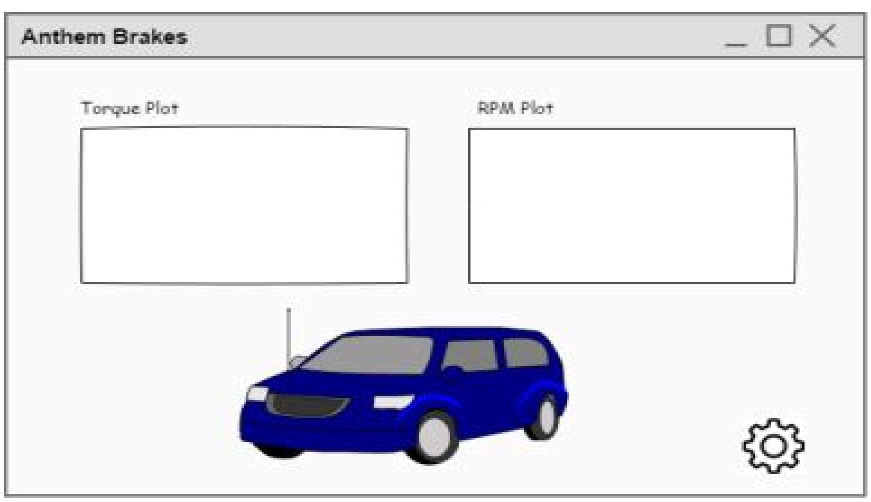

Figure 3.8: User Interface Prototype

The car under the plots is a stand in for future stages which is further discussed under the Graphical User Interface section in the Appendix. From the main screen, the user can select the gear icon at the bottom and be led to a different screen as shown in **Figure 3.10**.

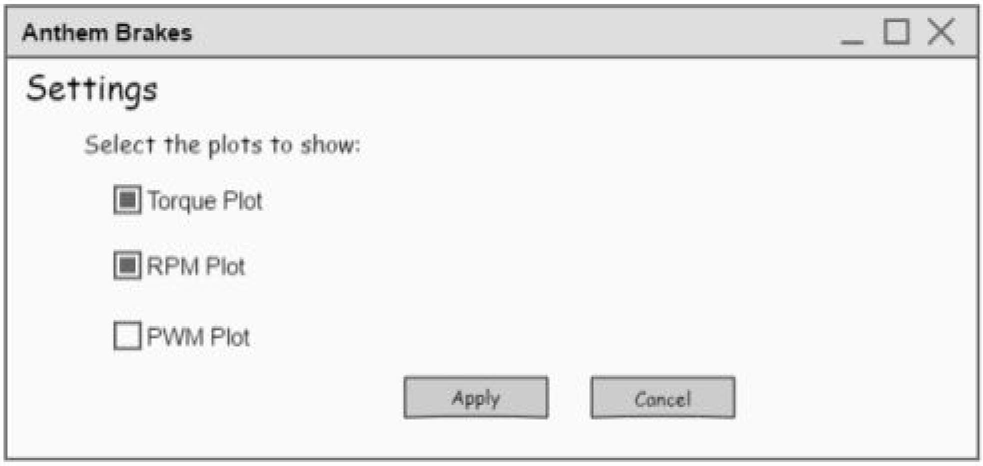

Figure 3.9: Settings Screen For Prototype

On the settings screen, there will be options that the user can filter. Once the 'Apply' button is selected, only the selected plots are shown on the main screen in **Figure 3.8**. If 'Cancel' is selected, the figures on the main screen should not change. Note that the options shown on **Figure 3.9** are examples of the expected behaviour and some options may not be included in the final prototype.

3.4 Supplementary Braking

3.4.1 Motor

For the final design we will likely use an AC motor with a VFD that will act as our driver motor for the shaft as well as for the regenerative braking purpose and utilize a similar design as shown in **Figure 2.11**. The reason for using an AC motor is because of the fact that you can always be in regeneration mode as long as you control the frequency of the VFD. In regenerative mode, the VFD will be controlled to stay below the RPM of the rotor because there will be feedback from the controller and its sensors. In addition, most industrial VFD's such as Galt Electric G2000 provide more built in functionalities for braking such as dynamic braking, DC injection, and plugging. For the PoC design we will not use the same motor as for the final project. We will use a DC brushed motor that we to act as a generator to create a current to drive into our battery. The block diagram of the DC brushed motor is shown in **Figure 2.12**. The DC motor will be implemented like in **Figure 3.10** and any regenerated current will be fed to a battery source. Because the initial current generated from the DC motor isn't very large, we aren't going to connect extra circuits to help protect the battery from overcurrent. But in the final version of the regenerative portion there will be circuits to allow the sudden increase current generated when regeneration mode is engaged on the motor.

3.4.2 Battery

For the PoC design we will use a battery from a power bank in place of the battery for the final product. To measure the battery level of the source we will apply coulomb counting by applying a current shunt parallel to the battery. We're applying coulomb counting instead of just measuring the voltage across the nodes because this method will give us a more accurate representation of the battery state of charge. We will hook up the arduino across the shunt so it can measure the current of the battery. By comparing this information to the current of the battery when it's fully charged, we can calculate the percentage state of charge of the battery. If the battery is nearing the fully charged state, the arduino will disconnect the battery and ground the excess voltage. The schematic for the battery can be seen in **Figure 3.10** below.

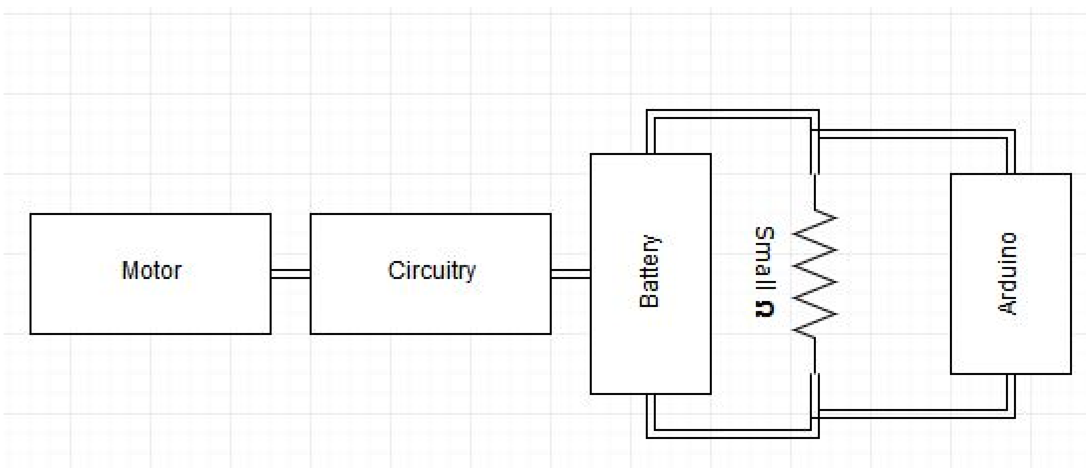

Figure 3.10: Setup For Battery

3.5 Electromagnet Friction Brake

3.5.1 Electromagnet

For the PoC design, a cylindrical (solonoidal) electromagnet (model XRN-XP50x27) with a two inch diameter and a length of 1 1/16 inches will be used. This electromagnet runs on 12VDC power and has a rated holding force of 50kg (110 pounds) at zero air gap. The magnet is shown in **Figure 3.11** below.

Figure 3.11: Generic 50 kg Electromagnet

The electromagnet will actuate against a steel plate (>0.25”) that will be fastened to the frame as shown in **Figures 2.3** and **2.4** above, and in **Figure 3.12** below.

3.5.2 Rocker Arm

As shown in **Figures 2.3** and **2.4**, and in **Figure 3.12** below, the magnet will be connected to one side of a rocker arm. The rocker arm design was outlined in **Section 2.1.2** above. The geometry and dimensions will follow the *Linkage* simulation shown in **Figure 2.5**. The rocker arm will be made of 20x20mm angle iron.

The rocker arm will pivot on a roller bearing that is mounted to a rigid post connected to the frame (also 20x20mm angle iron). This pivot joint must be able to withstand the braking force of the system, which for the PoC will be relatively small (bounded by the electromagnet’s holding force).

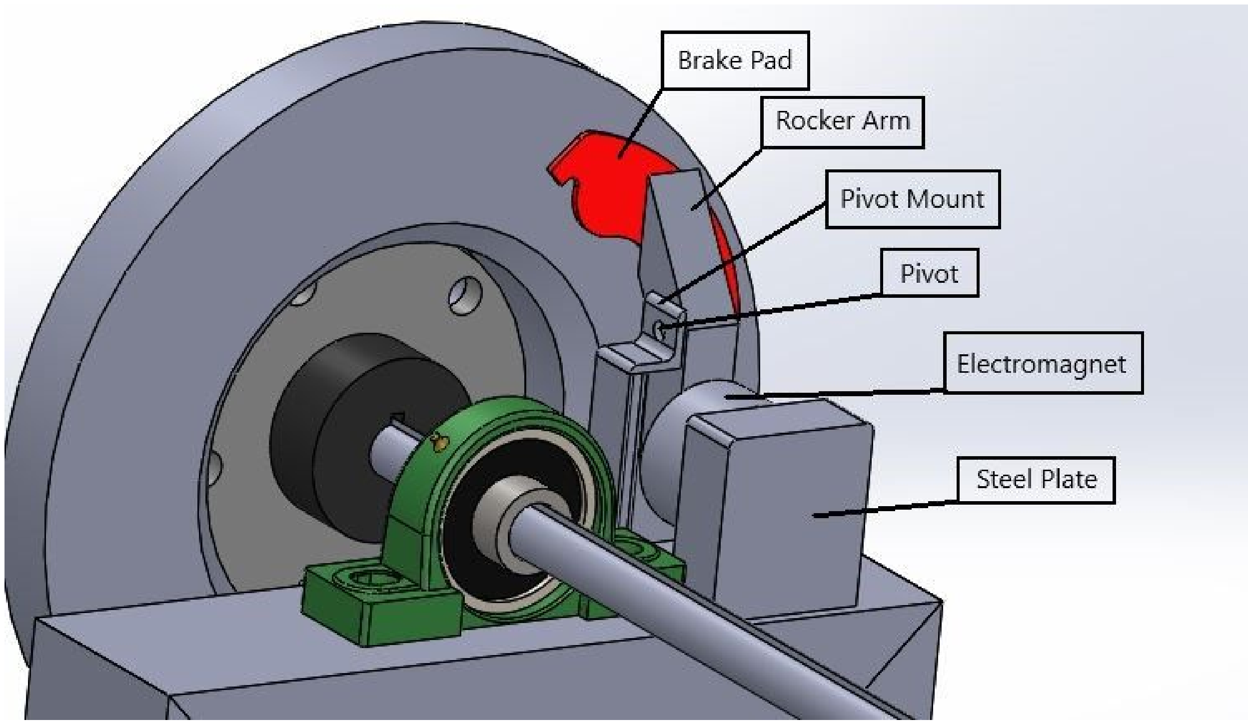

Figure 3.12: Rotor with Red Moustache

3.5.3 Brake Pad

For the brake pad, a standard automotive pad will be used (either ceramic or semi-metallic). The backing plate will be made of steel so that the pad can be welded to the rocker arm.

4. Alpha Phase Considerations

There are several major changes to be incorporated into the alpha phase design. These include scaling up the clamping force delivered by the electromagnet system described in **Section 3.5.2**, adding a brake pedal with appropriate feel, and improving control and data acquisition to prove that the solution developed by *Anthem Brake* satisfies the current automotive standards. The aspects of software control listed in the following section are primary concerns during alpha phase consideration.

4.1 Software Design

4.1.1 Active Braking Control

The braking system includes both emergency braking and normal braking where the driver controls the braking torque depending on the situation. Active braking control (ABC) is used to activate the brake automatically if the driver is braking in an emergency situation (i.e. “stomping on the pedal”). This is done by accessing the driver’s pressure applied on the brake pedal and translating it to a safe emergency stopping mechanism. The ABC system is also responsible for supplying appropriate braking torque to each wheel [23]. The ability to tune for preferable braking torque comes from Proportional Integral Derivative (PID) control, a closed loop feedback system, which will be implemented in the ECU.

The diagram (**Figure 4.1**) below shows a flow chart illustrating the emergency braking system for our project. The following section will further discuss the different components in the diagram.

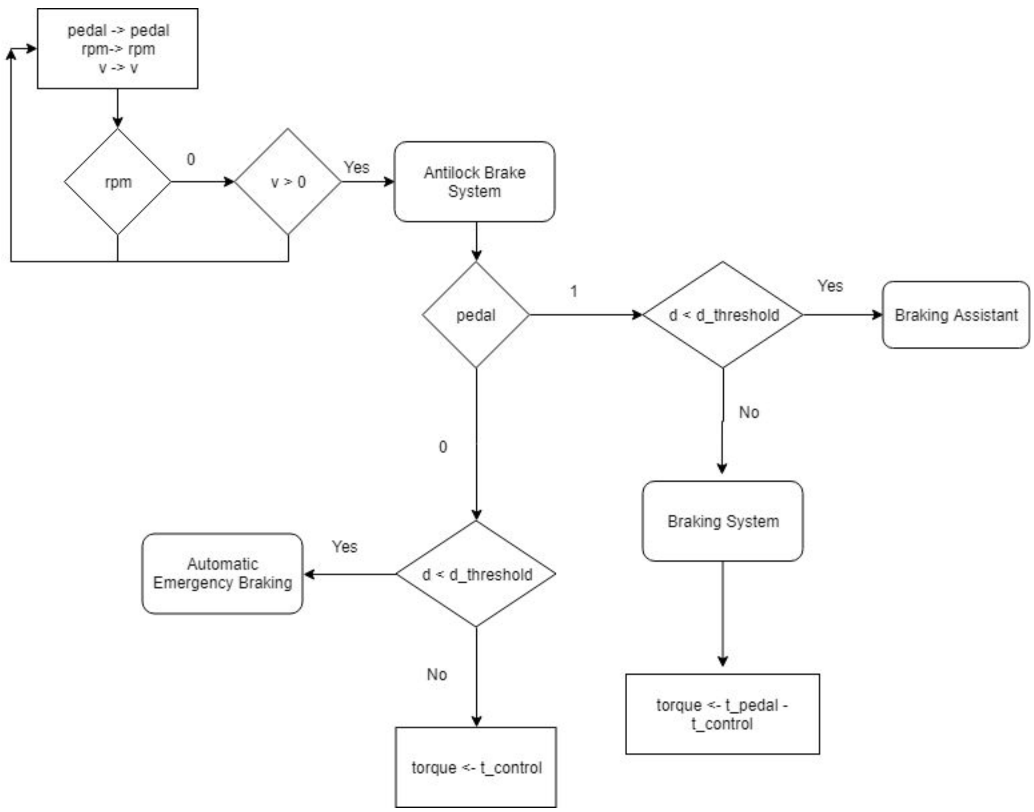

Figure 4.1: Emergency Braking Protocol

4.1.2 Automatic Emergency Braking (AEB)

For the alpha stage, the goal is to have an automatic emergency brake applied when the driver fails to stop the vehicle safely. As shown in **Figure 4.1**, *Anthem Brakes'* AEB is modified to include an Antilock Brake System (ABS) and a braking assistant. The braking assistant helps the driver if they fail to press the pedal hard enough to stop the vehicle. The ABS ensures that the shaft keeps rotating to provide braking traction. If the shaft stops, a signal is sent to the controller and checks if the vehicle is still in motion. Should the vehicle be in motion, the controller will apply the ABS.

Once the antilock brake system is applied, the controller checks if the pedal has been pressed (1) or not (0). If the pedal is not pressed, and the distance between the car and an object is below a certain threshold, the controller will apply the AEB. If the pedal is not pressed but the distance of the car and an object is above the threshold, the controller applies the appropriate torque to stop the vehicle.

For the case where the pedal is pressed, there are two solutions. If the distance is below a certain threshold, a braking assistant is applied to help the driver stop the vehicle. Should the vehicle's distance from the object be higher than a certain threshold, the controller will apply a torque based on the pedal input.

This system ensures that the vehicle stops safely in most situations the driver finds themselves in.

5. Conclusion

The requirements and specifications outlined in this document specify what *Anthem Brakes* aims to accomplish in the proof of concept development phase, and outlines some considerations for the next phase (alpha). While designing and creating our product we will maintain the cradle to cradle methodology, getting maximum use out of each part and disposing of things appropriately at the end of life cycle.

To demonstrate the *Anthem Brakes* system, a proof of concept will be presented to showcase how it can be done on a single rotor. The concept of the electromagnet friction brake will be shown on a test bench incorporating an automotive brake rotor. The bench will have sensors to measure driveshaft speed, the current used to power the electromagnet, the power required to activate the entire electronically actuated brake system, and the voltage that can be recaptured through the regenerative process.

A simplified graphical interface will be implemented to monitor and keep track test results during development, and to showcase the overall performance of the proposed idea. Later in the development of this braking system, the software and control system will become more advanced, and the braking power of each system component will be scaled up to meet current automotive industrial standards.

6. References

[1] Z. Palmer. “Why Brake-By-Wire Is Coming To Your Car,” *Popular Mechanics*, Jul., 2018 [Online]. Available: https://www.popularmechanics.com/cars/car-technology/a22126727/brake-by-wire/. [Accessed: Feb. 3, 2019].

[2] S. Hwang, H. Kim, D. Kim and K. Jung. *Analysis of a Regenerative Braking System for a Hybrid Electric Vehicle Using Electro-Mechanical Brakes, Urban Transport and Hybrid Vehicles*, Aug., 2010. Seref Soylu (Edited), Available: InTech, http://www.intechopen.com/books/urbantransport-and-hybrid-vehicles/analysis-of-a-regenerative-braking-system-for-hybrid-electric-vehicles-using-anelectro-mechanical-b. [Accessed: Feb. 1, 2019].

[3] G. Solberg. “The Magic of Tesla Roadster Regenerative Braking,” *Tesla Blog*, Jun., 2007. [Online]. Available: https://www.tesla.com/en_CA/blog/magic-tesla-roadster-regenerative-braking?redirect=no. [Accessed Feb. 3, 2019].

[4] Binder Magnetic, “Technical Explanations for Holding Magnets - Electromagnetic Holding Magnets,” 2019. [Online]. Available: https://www.binder-magnetic.com/documentation/technical-explanations-for-holding-magnets/?lang=en. [Accessed Mar. 7, 2019].

[5] Rector, D. *Linkage,* [Online]. Sept. 2018. Available: http://blog.rectorsquid.com/linkage-mechanism-designer-and-simulator/. [Accessed Mar. 7, 2019].

[6] “Brushless DC Motor vs. AC Motor vs. Brushed Motor,” Oriental Motor U.S.A. Corp. [Online]. Available: https://www.orientalmotor.com/brushless-dc-motors-gear-motors/technology/AC-brushless-brushed-motors.html. [Accessed: 10-Mar-2019]

[7] "Induction Motor Braking Regenerative Plugging Dynamic Braking of Induction Motor | Electrical4U", *Electrical4U*, 2019. [Online]. Available: https://www.electrical4u.com/induction-motor-braking/. [Accessed: 10- Mar- 2019].

[8] H. Hairik, R. Thejel and W. Kadhem, "Proposed scheme for plugging three-phase induction motor", *Melecon 2010 - 2010 15th IEEE Mediterranean Electrotechnical Conference*, 2010. Available: 10.1109/melcon.2010.5476349 [Accessed 10 March 2019].

[9] G. pandian, S. kumar and D. nandam, "Design and Implementation of BLDC Motor Using Regenerative Braking for Electric Vehicle", *International Journal of Advanced Research in Electrical, Electronics and Instrumentation Engineering*, vol. 04, no. 02, pp. 694-701, 2015. Available: 10.15662/ijareeie.2015.0402027 [Accessed 12 March 2019].

[10] Battery Reconditioning Tips, “Types of Rechargeable Batteries” [Online]. Available:

http://www.batteryreconditioningtips.com/types-rechargeable-batteries/ [Accessed Mar 12, 2019]

[11] Electropedia, State of Charge (SOC) Determination", [Online]. Available: https://www.mpoweruk.com/soc.htm. [Accessed Mar. 12, 2019].

[12] "How strain gages work," Kyowa. n.d. [Online]. Available: https://www.kyowa-ei.co.jp/english/products/gages/pdf/howsgw.pdf. [Accessed Mar. 3, 2019].

[13] "Positioning Strain Gages to Monitor Bending, Axial, and Torsional Loads," OMEGA. n.d. [Online]. Available: https://www.omega.com/faq/pressure/pdf/positioning.pdf. [Accessed Mar. 1, 2019].

[14] "Properties of Metals," Nov., 17, 2010. [Online]. Available: http://www.roymech.co.uk/Useful_Tables/Matter/prop_metals.htm. [Accessed Mar. 5, 2019].

[15] "Coding System of Strain Gauge", AGS-TECH. n.d. [Online]. Available: https://www.elecrow.com/download/Coding%20System%20of%20Strain%20Gauges-AGS-TECH%20Version.pdf. [Accessed Mar. 5, 2019].

[16] "The Wheatstone Bridge Circuit," HBM. n.d. [Online]. Available: https://www.hbm.com/en/7163/wheatstone-bridge-circuit/. [Accessed Mar 5, 2019].

[17] "How to Form Strain Gage Bridges," Kompozity. n.d. [Online]. Available: http://www.kompozity.info/clanky/odpor_ten/schema_tenzometry.pdf. [Accessed Mar. 1, 2019].

[18] "How to Form Strain Gage Bridges," Kompozity. n.d. [Online]. Available: http://www.kompozity.info/clanky/odpor_ten/schema_tenzometry.pdf. [Accessed Mar. 1, 2019].

[19] J. Karki. "Signal Conditioning Wheatstone Resistive Bridge Sensors," Texas Instruments. Sept. 1999. [Online]. Available: http://www.tij.co.jp/jp/lit/an/sloa034/sloa034.pdf. [Accessed Mar. 6, 2019].

[20] Princess Auto. "¾ in. Standard Duty Pillow Block Bearing Assembly," 2019. [Online]. Available: https://www.princessauto.com/en/detail/3-4-in-standard-duty-pillow-block-bearing-assembly/A-p3870029e. [Accessed Mar. 8, 2019].

[21] DEWALT. "½" (13mm) Impact Wrench Kit," 2019. [Online]. Available: https://www.dewalt.com/products/power-tools/impact-drivers-and-wrenches/12-13mm-impact-wrench-kit/dw292k. [Accessed Mar. 8, 2019].

[22] B. Truong, "Development of an active braking controller for brake systems on electric motor driven vehicles." Stockholm, 2014. [Online]. Available: http://www.diva-portal.se/smash/get/diva2:818048/FULLTEXT01.pdf [Accessed Mar. 14, 2019].

[23] B. Truong. "Development of an Active Braking Controller for Brake Systems on Electric Motor Driven Vehicles," 2014. [Online]. Available: http://www.diva-portal.se/smash/get/diva2:818048/FULLTEXT01.pdf. [Accessed Mar. 13, 2019].

7. Appendix: Supporting Test Plans

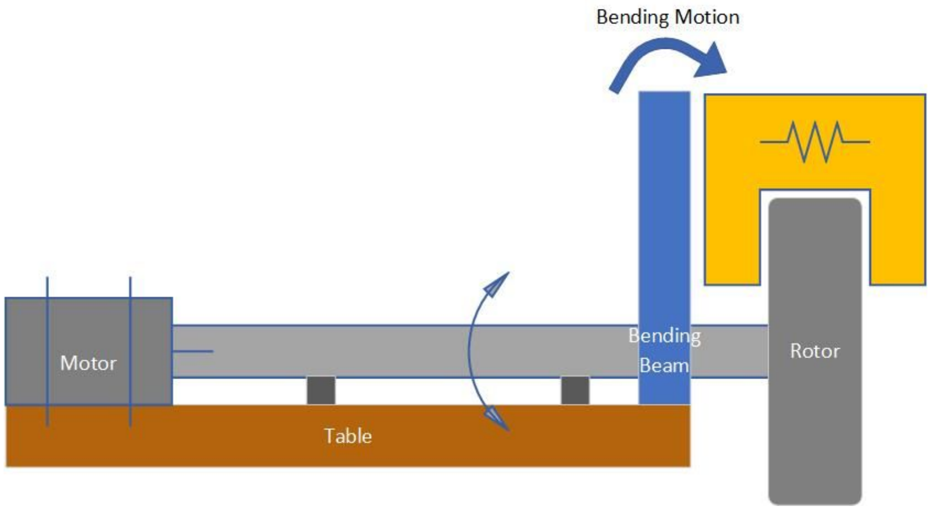

Figure 7.1: Simplify Version of the Testbench

This section outlines a test plan for the proof of concept prototype of the *Anthem Brakes* system. The tests enumerated here reflect the PoC specifications in **Section 3** above. They have been split up into tests for the disc brake, the regenerative brake, and the controller. These tests have been designed to be pass/fail and to not put undue constraints on the PoC.

7.1 Disc Brake

Following the above requirements, the disc brake should provide braking torque to a spinning disc that is scalable to the torque requirements at later development stages (A, B). The following tests provide a benchmark for the PoC design.

Test	Acceptance Condition	Result
Power Consumption	Power consumption under 0.1kWh at continuous load	☐ Pass ☐ Fail
Performance Test	4 stops within 3 minutes without any braking issues	☐ Pass ☐ Fail
Stopping Power	Provides expected stopping torque when engaged, scalable to later development stages	☐ Pass ☐ Fail
Heat Dissipation	Heat generated under load does not surpass the threshold of components	☐ Pass ☐ Fail
Test Bench Robustness	Test bench is rigidly constructed and does not impede component testing	☐ Pass ☐ Fail

Axle Speed	Test bench axle capable of adequate speed to display braking torque (~1000 rpm)	☐ Pass ☐ Fail

Table 7.1: Acceptance test plan - PoC disc brake

7.2 Regenerative Brake

The PoC regenerative brake should be shown to provide some stopping power when engaged as well as providing some amount of current to the battery, these being scalable to the final (alpha stage) requirements.

Test	Acceptance Condition	Result
Regeneration	Able to generate a measured output current that exceeds input current	☐ Pass ☐ Fail
Stopping Power	Generates measurable torque in the opposite direction of rotation	☐ Pass ☐ Fail
Storing Charge	Regenerated current provides a measurable increase in battery voltage	☐ Pass ☐ Fail

Table 7.2 Acceptance test plan - PoC regenerative brake

7.3 Control System

The PoC control system should be developed as far as possible to provide a template for the final, integrated system. Integration software should be debugged as far as possible without physical actuation. The PoC control system should at least provide a safe and reliable means of actuating the disc brake and the regenerative brake independently, without modulation or feedback.

Test	Acceptance Condition	Result
Disc Brake Actuation	Able to safely engage and disengage the electro-mechanical braking system at a given voltage	☐ Pass ☐ Fail
Regenerative Brake Actuation	Able to safely engage and disengage the electro-mechanical braking system	☐ Pass ☐ Fail
Pulse Frequency	Able to produce a PWM signal with enough resolution (to be determined) for control of brakes in later design stages	☐ Pass ☐ Fail
Sampling	Able to sample input from the proposed	☐ Pass ☐ Fail

	sensors at speeds adequate for PID loop feedback	
Calculation/Running Speed	Able to take inputs at the desired frequency, process them, and produce outputs fast enough to be functional in a PID loop	☐ Pass ☐ Fail

Table 7.3: Acceptance Test Plan - PoC Control System

8. Appendix: User Interface Design

8.1 Introduction

The purpose of this appendix is to layout the design focus of *Anthem Brakes*, and provide an in-depth interface system of the proposed revolutionary braking system. This document will address the interface requirements for showcasing, then discuss how those requirements can be met to minimize the learning curve for drivers. When designing the system, seven elements of UI interaction will be discussed: discoverability, feedback, conceptual models, affordances, signifiers, mapping, and constraints. Furthermore, engineering standards, analytical usability testing, and empirical usability testing are discussed in detail to help eliminate design flaws and improve the reliability of *Anthem Brakes*, as the system evolves.

8.2 User Analysis

The target market is the automotive industry, which predominantly uses conventional hydraulic brakes. The end design should also, however, provide drivers (as the users) with a seamless interface. To assist automakers with the transition, the solution provided by *Anthem Brakes* will follow the current practices and standards (discussed in **Section 8.4** below), allowing for smooth integration with existing vehicles. As for users of the brake system, it is expected that the brake pedal (as the primary user input) should provide a similar user experience to current hydraulic pedals to reduce the learning curve of the drivers.

8.3 Technical Analysis

8.3.1 Conceptual Model/Discoverability

Like existing hydraulic systems, the brake pedal is located near the acceleration pedalas an intuitive conceptual model. Data collected at each wheel should also be available for display on the graphical user interface, and if users are interested, it should be easily discoverable at the vehicle's monitor.

8.3.2 Feedback

The feedback of the brake system is active immediately when the driver presses the brake pedal. Other feedback functionalities might be displayed on the graphical user interface, such as indicating whether the brake assistant, automatic emergency brake, or anti-lock brake systems are active. This allows the driver to see prioritized information during an emergency, and it allows the system to provide the driver with warnings.

8.3.3 Affordance

Affordance of a system is determined by how the object could be used by interacting agents [1]. In this case, it is the relationship between the driver and the brake pedal. The brake pedal should afford the driver the ability to slow the vehicle or bring it to a complete stop. This also means that the driver is required to depress the brake pedal with some relative amount of force. In some emergency stopping situations, however, failure to engage the brake pedal appropriately may result in collision. This can be resolved with current power assisted braking techniques, where the driver’s braking characteristics are collected using adaptive learning. In this case the controller can amplify braking to maximize braking effort for an emergency stop [2]. Overall, the key affordance for the driver is that the vehicle comes to a stop safely.

8.3.4 Signifiers

There are many aspects of this brake system that can be communicated to the driver, to automakers, and to mechanics. From the driver’s point of view, it is important to know whether the system needs maintenance, or when emergency systems are engaged. For automakers and mechanics, the system’s overall condition is important, and data from sensors could provide important information as well.

8.3.5 Mapping

The most important mapping aspects are appropriate delivery of signifiers for driver understanding. This includes the data collected from brake performance, speed, and power consumption at each wheel. It is also important for the driver to easily opt out of the information from the graphical user interface which is discussed in the next section.

8.3.6 Graphical User Interface

Anthem Brakes will show the data collected from various sensors and display the information through various plots. The user can filter these plots based on the information they wish to see through the settings icon. **Figure 8.1** below shows a proposed UI.

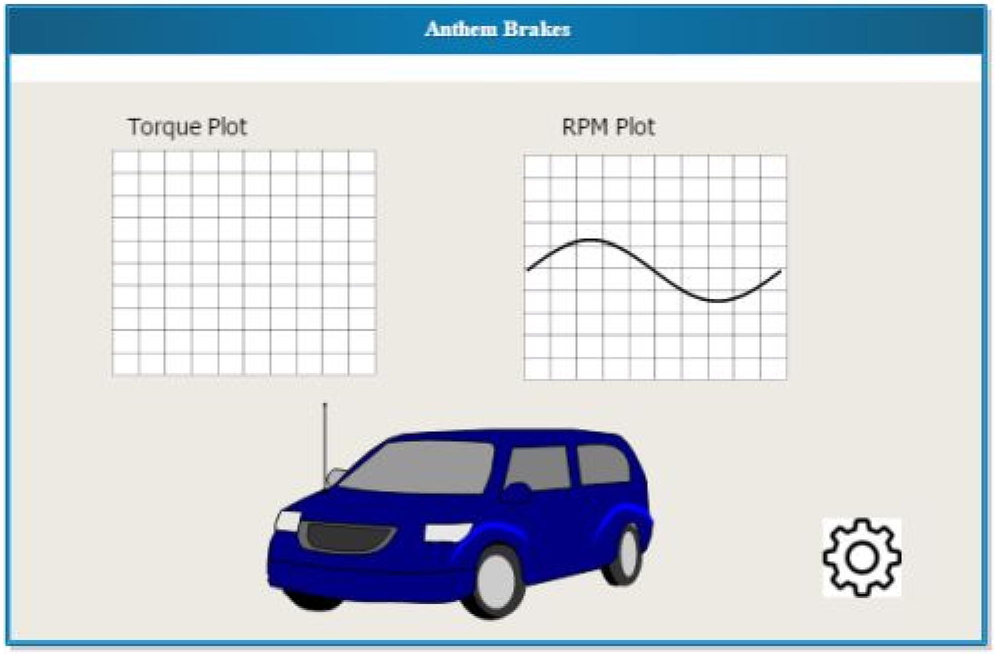

Figure 8.1: GUI for Anthem Brakes' Main Screen

Upon selecting the settings icon, the user will be led to a different screen where they can select which plots they want to show and not show. The user interface for this screen will be similar to **Figure 3.10**, albeit more sophisticated and have more options. A vertical scrollbar will appear on the screen to accommodate the number of plots the user wants to see. The vehicle on the screen will be transparent and highlight the different components of *Anthem Brakes*.

As mentioned in **Section 8.3.5**, various signifiers will appear based on the status of the brakes. When accessing the app, a splash screen will appear telling the user about the condition of the brakes and the battery. A dialogue box will pop up if the automatic emergency brake (AEB) or the braking assistant has been applied.

8.3.7 Constraints

One physical constraint is to minimize the chance of the product being used inappropriately [1]. Since the user-machine interface is the brake pedal itself, the only way to apply the brake is to push against it. The controller is expected to take over the braking mechanism during an emergency situation to bring the car to complete stop safely.

8.4 Engineering Standards

To design a braking solution for the automotive industry, we must meet current engineering standards. **Table 8.1** showcases the most relevant standards for the *Anthem Brakes* system.

ISO 26262	Safety standard for automotive software development: includes passive systems, active systems, by-wire systems, and electronic stability control throughout automotive industry [3]
Transport Canada TSD 105	Section on hydraulic and electric brake systems from Transport Canada's Motor Vehicle Safety Regulations [4]
ISO 15118-3:2015	The requirements for controller and sensors to have a physical data link that exchanges information with higher level communication [5]
B.C. Reg. 26/58	Motor Vehicle Act Regulations provide some characteristics of brake systems for on-road vehicles [6]

Table 8.1 Automotive Related Standards

8.5 Analytical Usability Testing

Five aspects of usability are shown in **Table 8.2**. These can affect the product's performance, safety, and user experience. To maximize user experience, analytical testing will be done using the GUI we develop. This interface will include the rotational speed of our testbench, current draw by the electromagnet, clamping force generated by the electromagnet, and braking force and current applied to the regenerative brake. This data will be compared with current hydraulic systems for power consumption, stopping distance, and efficiency.

Objective	Expectation of the Design
Learnability	Drivers coming from hydraulic brakes should be able to transition to the electronically actuated brake with ease.
Efficiency	To bring the car to a complete stop, braking distance must satisfy current standards, and automatic brake control should engage when necessary.
Memorability	The design of the brake system should be similar to hydraulic brake system, which is easy for the user to come back to.
Errors	When a driver fails to apply the brake pedal in an emergency situation, the controller should automatically take over the brake control to ensure the safety of the driver.
Satisfaction	Users should feel comfortable using the pedal and the force applied should be proportional to the stopping distance during non-emergency situations. During emergency situations, the automatic brake system is active to ensure safety of the user.

Table 8.2 Analytical Usability Aspect

8.6 Empirical Usability Testing

The *Anthem Brakes* solution focuses on both interactive and experiential design, which utilize principles of psychology, design, and emotion to provide a smooth braking experience [1]. The focus is on how drivers interact with the brake pedal when coming to a stop. The system needs to have a similar feel to a hydraulic brake pedal, and pedal application should be proportional to braking power. Pedal feel will be tested by participants who drive often, who will be asked to provide feedback.

8.6.1 Sensor Accuracy Testing

The clamping force measurement provided by the strain gauge configuration will be calibrated with spring scales This is crucial for development and testing.

8.6.2 Brake Pedal Feel Testing

The pedal not only needs to have a comfortable feel, but also a sensor that measures how much force is applied by the user (or alternatively, the pedal's position). The braking force should be relative to the user input, similar to how hydraulic brake systems work with pressure.

8.6.3 Non-Emergency Brake Testing

In a non-emergency situation, the only input to the braking system is the brake pedal. This testing is to ensure good user experience when the car is to be slowed while driving or in a casual stopping scenario. The system should be able to supply enough clamping force to stop the rotor and meet the standards listed in **Section 8.4** while keeping those in the vehicle comfortable.

8.6.4 Emergency Braking Testing

The system should be able to bring the vehicle to a complete stop while minimizing impact during an emergency. When the distance to an obstacle is below a threshold and user input is not detected, AEB will be active to reduce the collision impact. If user input is detected, but the force applied by the user is not enough to bring the car to a complete stop in time, the brake assistant will be active helping to keep passengers safe.

8.6.5 Regenerative Braking Testing

The regenerative brake system will be engaged and disengaged by the controller depending on the state of the brake pedal. When pressed down the motor will enter regenerative mode and provide stopping torque while charging the battery. The battery level will be monitored by measuring the current over a current shunt and if it is close to full, the controller will route the extra current to ground to prevent overcharging.

8.7 Conclusion

The braking system is designed to provide safety of passengers and others on the road. Throughout the design process, test data will be collected for continued improvement. A GUI will be used to allow the system to be monitored during test, and will display data in a way that allows designers to compare system performance in different modes. *Anthem Brakes* aims to provide a solution that the user can easily adapt to, and a solution that is adaptable to current industry standards to make for an easy transition.

8.8 References

[1] D. Norman, The Design of Everyday Things, New York: Basic Book, 2013 http://www.nixdell.com/classes/HCI-and-Design-Spring-2017/The-Design-of-Everyday-Things-Revised-and-Expanded-Edition.pdf. [Accessed Mar. 04, 2019].

[2] "High-Tech Vehicle Safety Systems", Canadian Association of Road Safety Professional. N.d. Online. Available: http://www.carsp.ca/research/resources/high-tech-vehicle-safety-systems/brake-assist/. [Accessed Mar. 10, 2019].

[3] "ISO 26262-1:2018, Road Vehicles - Functional Safety", Developing Standards. n.d. [Online]. Available: https://www.iso.org/standard/68383.html. [Accessed Mar. 12 2019].

[4] "Technical Standards Document No. 105, Revision 5: Hydraulic and Electric Brake Systems," Transport Canada. Feb., 2015. [Online]. Available: https://www.tc.gc.ca/eng/acts-regulations/regulations-crc-c1038.htm. [Accessed Feb. 3, 2019].

[5] S. Cater, Ed., "TC 69 Electric road vehicles and electric industrial trucks," International Electrotechnical Commission . [Online]. Available: https://www.iec.ch/dyn/www/f?p=103:23:4786039386214::::FSP_ORG_ID,FSP_LANG_ID:1255,25 . [Accessed: Feb. 4, 2019].

[6] Ministry of Attorney General, "Motor Vehicle Act Regulations," Consolidated Regulation of British Columbia, Jan., 7, 2019. [Online]. Available: http://www.bclaws.ca/civix/document/id/crbc/crbc/26_58_multi [Accessed: Feb. 4, 2019].