ECE 445: Senior Design Project Laboratory

Design Document - Anti-Lock Braking for Bicycles

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1 Introduction

1.1 Problem and Solution

Bicycles present a challenge because they often lack or charge a premium for the features that cars have, like anti-lock braking systems (ABS). This happens because bicycles are primarily designed for short distance commuting. Unlike cars that come with a range of amenities, bicycles prioritize simplicity. However, this di erence in design leads to a discrepancy in safety and convenience features. Bicycle riders do not have the braking capabilities and automated speed regulation that many cars o er. This absence of features like ABS can be particularly dangerous as bicycles are prone to skidding; thus increasing the risk of accidents. As mobility solutions, bicycles sacri ce these functionalities, which means riders must navigate roads with heightened awareness and limited technological assistance.

In order to improve the safety of bicycles via cheaper, preventative features, we could consider adding technologies commonly used in cars. For instance, adding an Anti-lock Braking System (ABS) would reduce the risk of skidding by braking more e ciently; thereby improving overall safety. More importantly, the use of ABS ensures better stability for riders and helps prevent accidents like collisions at an intersection. By embracing these technologies, bicycles can o er riders safer, cheaper rides with improved ease of use.

We plan to use one of the bikes provided by the workshop and add a braking system that both detects locking and modulates braking to account for it. Our plan is to use a hall-e ect sensor to determine rotational speed. We then import this data into our microcontroller to detect situations such as locking and skidding. Then the microcontroller will send out pulse signals to the braking system to do pulse breaking to perform a more e cient stop.

1.2 Visual Aid

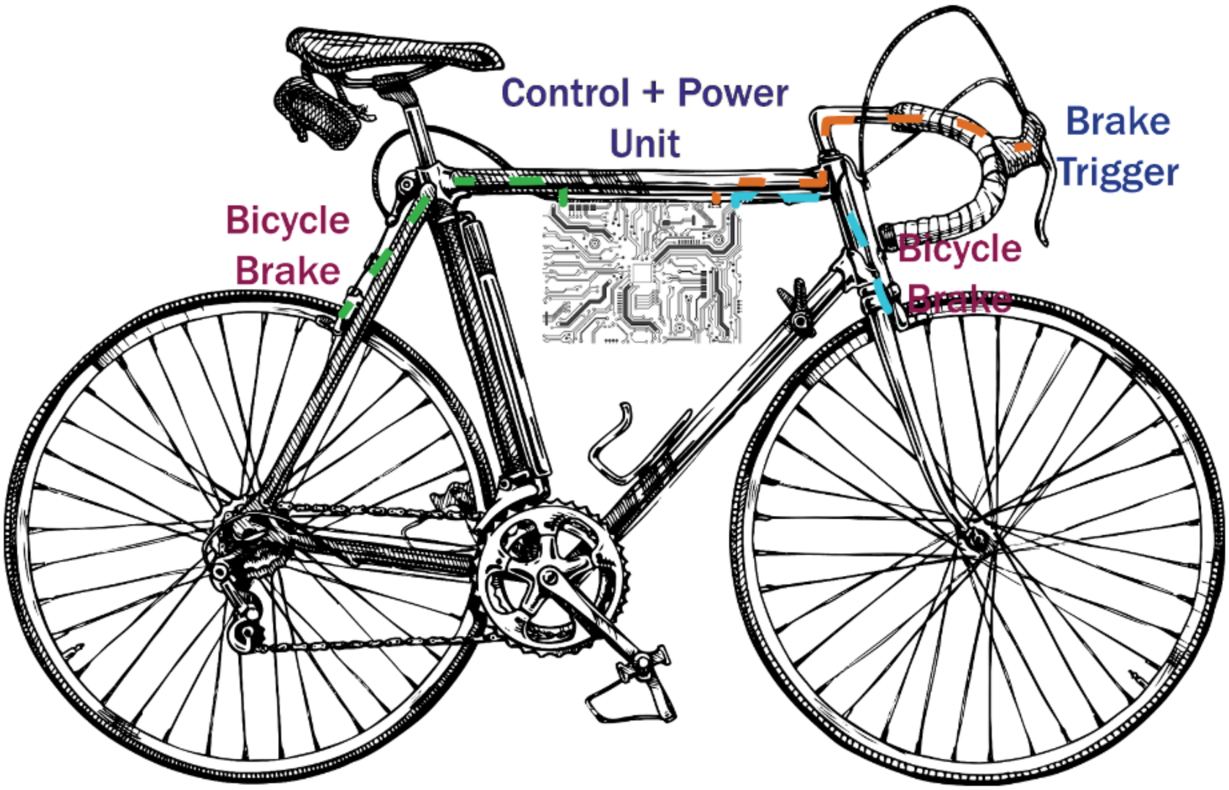

Figure 1: Visual aid.

1.3 High Level Requirements

- This project must possess the ability to accurately determine bicycle wheel angular velocity at any point in time and consequently be able to prevent brake lock-ups.
- This project must demonstrate the advantages of Anti-Lock Braking (ABS) over traditional braking in emergency situations; this includes coming to a stop faster on adverse road conditions (shorter stopping distances) and the ability to maneuver while braking.
- This project must display the responsiveness required of ABS; the project must show that within one second of the brake system receiving input, the brakes will begin actuating from the ABS control.

2 Design

2.1 Block Diagram

The block diagram of the anti-lock braking system is shown in Figure 2.

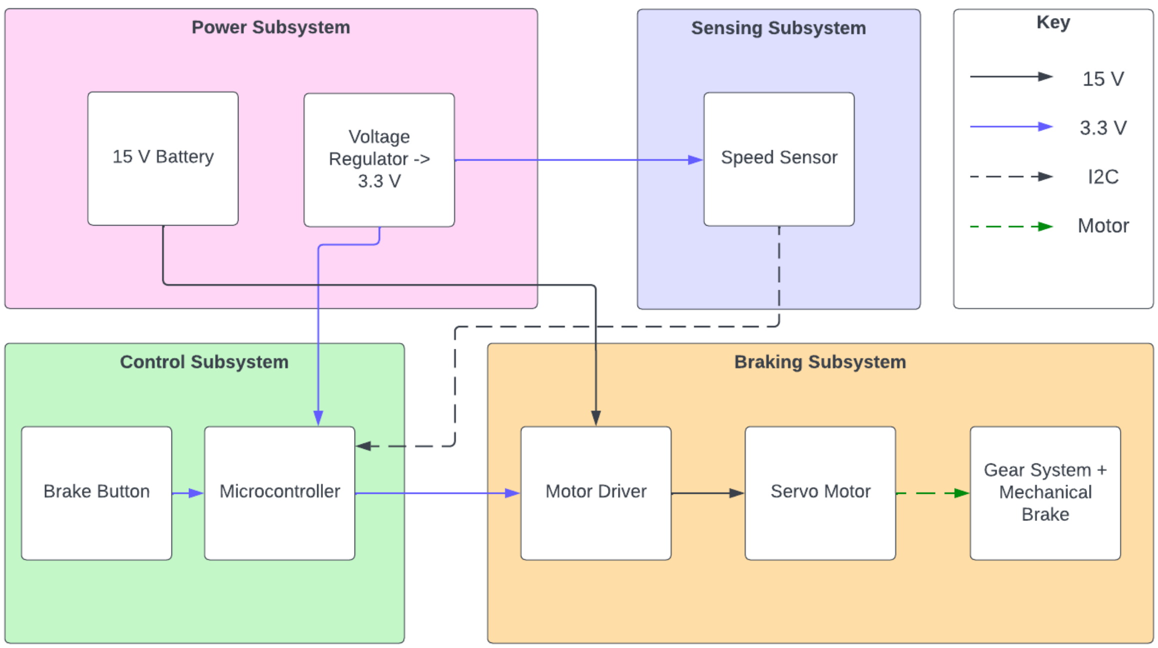

Figure 2: Block diagram of the anti-lock braking system.

2.2 Physical Design

2.3 Subsystem Overview and Requirements

2.3.1 Control Subsystem

The control subsystem will receive inputs from the sensing subsystem and send outputs to the braking subsystem to emulate a modern ABS. Below is a prototype controller implementing ABS based on the optimal relative slip ratio in cars.

Shown in Figure 3, the specific signals received from the sensing subsystem will be the angular velocities of the vehicle (ω_v) and the brake wheel (ω_w). These signals will be used to find the normalized relative slip ratio ($1 - \frac{\omega_w}{\omega_v}$), and that slip ratio will be compared against the optimal slip ratio as input to the motor controller. For the specific signals output by the controller, some will be variables that can be used to tune the controller, such as the estimation of the friction force and the estimation of the brake force, the other

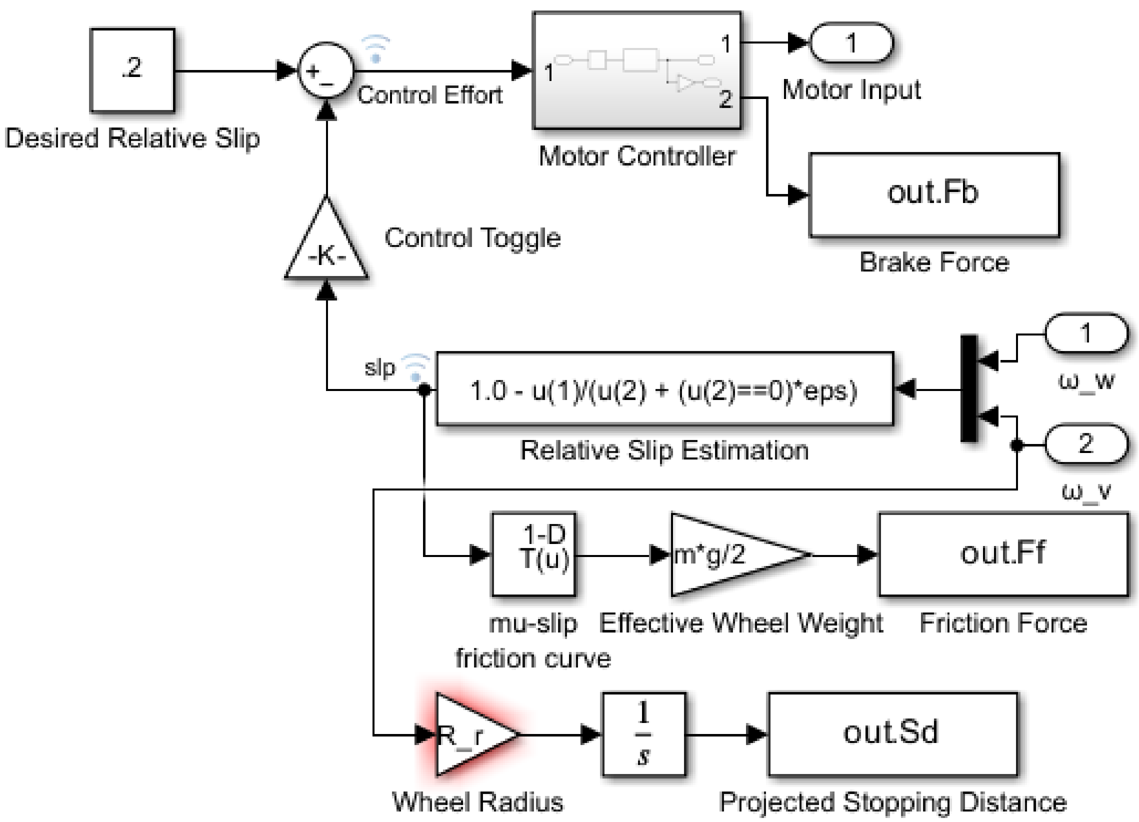

Figure 3: Prototype ABS Controller

signal will be the input to the braking subsystem, the motor input. The motor input signal will take the form of a pulse to properly replicate ABS.

For an inspection of the mathematics behind this controller's signals, the mu-slip friction curve table will be found online due to the impracticality of performing identi cation on a mechanical system that cannot be directly identi ed. This translates to an estimate of the friction force in the system by nding the normal force the rear wheel would experience ($\frac{mg}{2}$). Such that the weight of the system will be distributed evenly among both wheels, and friction force is given by $F_f = F_n \quad {}_f$. The Projected Stopping Distance of the system is found by integrating the linear velocity of the vehicle over time. The brake force will be determined after identifying the relationship between motor input and brake torque, but this relationship should be well-approximated by a line, so the estimation for brake force will simply be linear.

Additionally, for a preliminary model for the dynamics of the braking system, the following analysis has been performed to produce the model shown in Figure 5. Also, Figure 6 is a model of the forces and velocities on the rear wheel of the system. Positing the models as fact will allow us to model the braking force of the system as one proportional to some spring force and also proportional to some relation between the tension perceived by the calipers.

$$F_{braking} = k_1 k_2 x$$

Where x is the displacement of the end of the brake cable attached to the stepper motor and k_1, k_2 are experimental constants to be found by conducting system analysis.

Important to note is that the system will need to pull the cable some nite amount before the cable begins to act as if a spring. This relation can be seen in Figure 4.

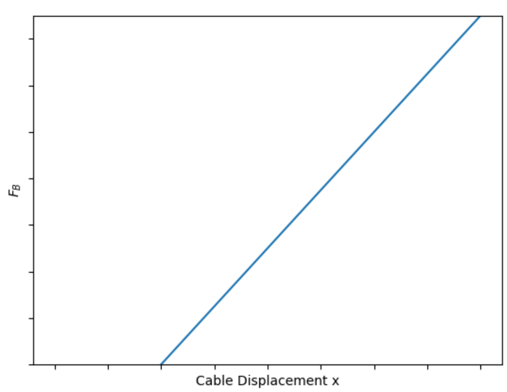

Figure 4: Initial Model of Brake Force

Regarding the motor controller, the expanded subsystem can be seen below in Figure 7.

Important to note in the prototype motor controller, is that bang-bang controllers cannot be implemented practically. These controllers fall into the category of ideal controllers, and as such, there will be

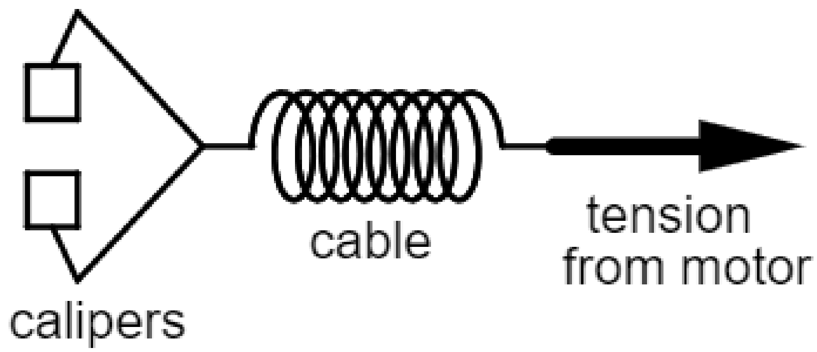

Figure 5: Model of Brake System

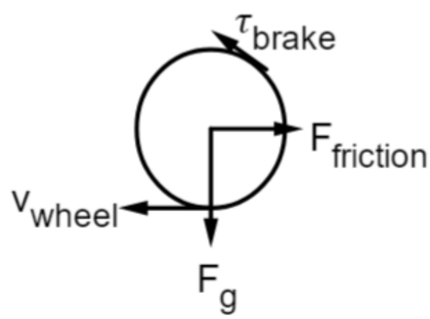

Figure 6: Model of Rear Wheel Vectors

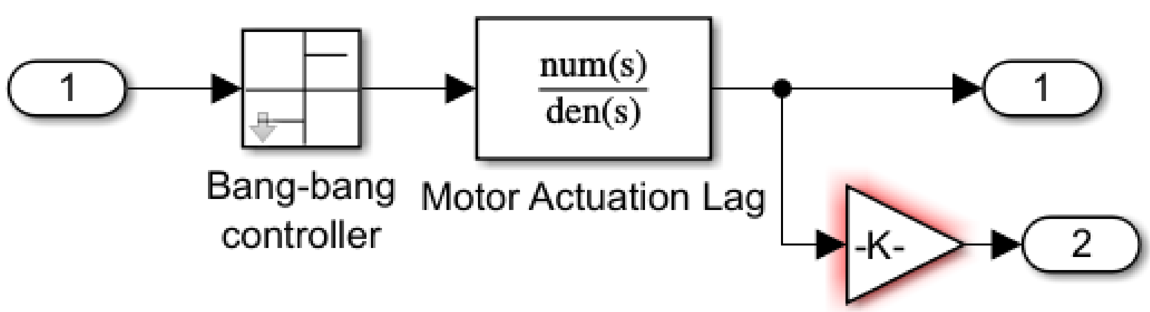

Figure 7: Prototype Motor Controller

an approximation for this controller in the implementation phase of this project. Next, before explaining the speci cations for a practical implementation of the bang-bang controller, there will be an introduction to the terms used to quantify the e cacy of a controller. First, is that controller speci cations are found by inspecting the step response of the controller, in which the controller input is stepped up to some constant value at time equal to zero. Next, regarding the speci cations themselves, rst, the rise time (t_r) of a controller is the time it takes the step response of a controller to rise from 10% of the input value to 90% of the input value. Second is the settling time (t_s) of the controller, this is how long it takes the controller from the beginning of the step input to when the controller settles within 5% of the input value. Third is the maximal peak (M_p) of the controller, this is the ratio between the maximum value the step response outputs and the input value.

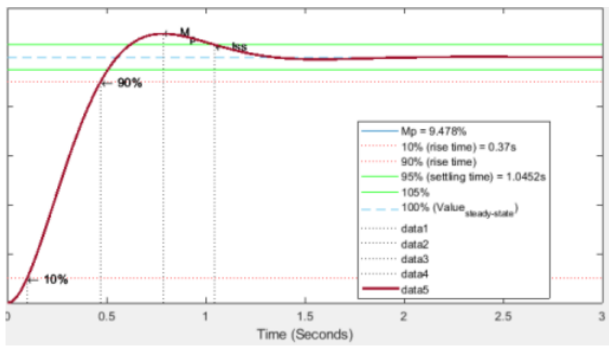

Figure 8: Example Step Response

Next, to explain the speci cations required of a practical implementation for the bang-bang controller will be a su ciently fast rise time, for example, 75 milliseconds, and a settling time that is also su ciently fast, for example, 120 milliseconds. Regarding the maximal peak of the controller, while it will not be the main focus of the controller, the maximal peak value should not exceed 15% to avoid disturbing the torque required by the braking subsystem. These values were all picked in order to e ectively produce a controller that can not only mimic an ideal bang-bang controller but also to produce a controller that can reasonably perform ABS control. That is, a reasonable expectation for an ABS system is to produce a system that can switch the brakes on and o within fractions of a second.

The current prototype controller will aim to lead to plots such as the following found by a MathWorks example simulation of ABS in a car. Additionally, the controller type will be a Proportional-Integral-Derivative (PID) controller. The initial controller will be one that follows an ordinary second-order di erential:

$$\frac{\omega^2}{s^2+\omega\zeta s+\omega^2}$$

In this ordinary second-order differential, ω is the natural frequency of the system and ζ is the damping factor.

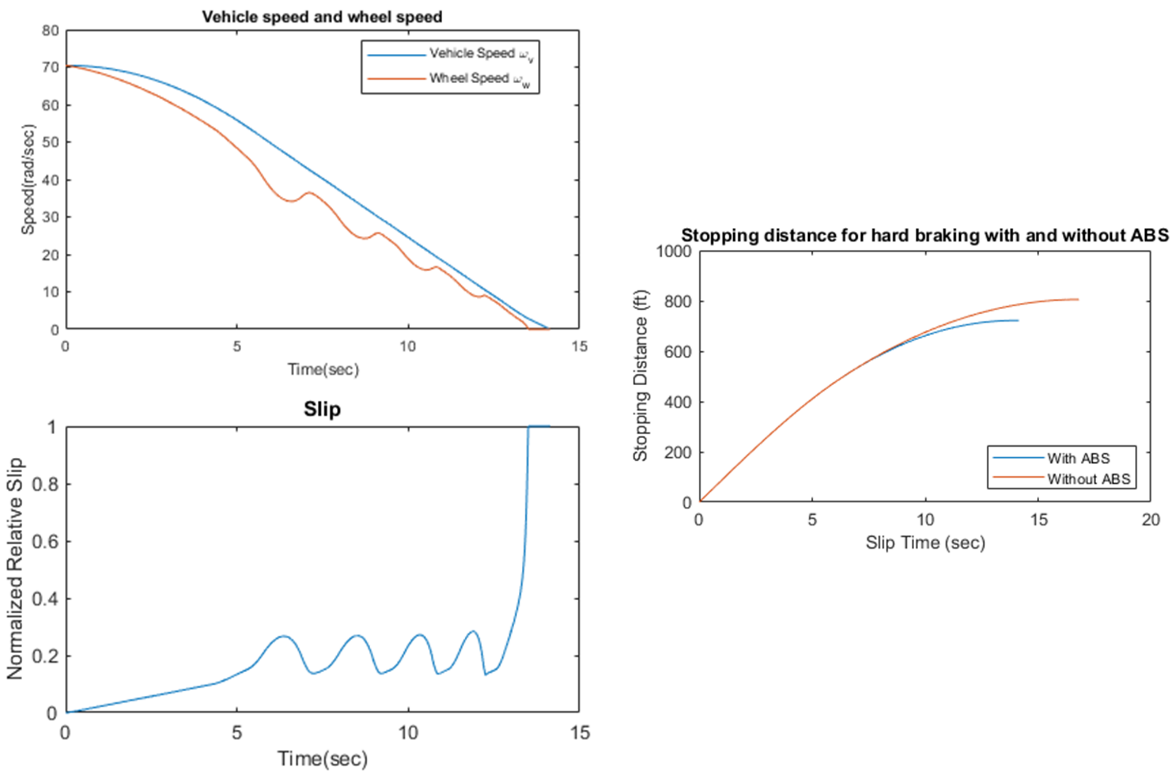

Figure 9: MathWorks Simulation of Car ABS

Additionally, this subsection will contribute to the completion of the high-level requirements by controlling the brakes in such a manner that the wheels never lock up, by displaying projected stopping distances in comparison to stopping distances without ABS, and by outputting control signals in a timely manner to preserve the responsiveness of the system.

Table 1: Control subsystem requirements and veri cation.

Requirements	**Verification**
Motor Controller Rise Time t_r 75 ms	Simulation of the Motor Controller's step response and by plotting data collected from the system.
Motor Controller Settling Time t_s 120 ms	Simulation of the Motor Controller's step response and by plotting data collected from the system.
Motor Controller Maximal Peak Ratio Mp 15%	Simulation of the Motor Controller's step response and by plotting data collected from the system.

2.3.2 Power Subsystem

The power subsystem is used to deliver power to the other subsystems, speci cally to the microcontroller, speed sensor, manual braking trigger, and servo motor. As this project will be used with a bicycle, power supply from the grid is not available, and thus this subsystem consists of a battery, a battery management system, and a voltage regulator. To ensure the battery is within safe operating conditions and that the user is aware of the battery's state of charge, a DS2775 battery management integrated circuit will be used. The datasheet describes a typical circuit for use with the DS2775, shown in Figure 10 [3], which will also be used in the project design.

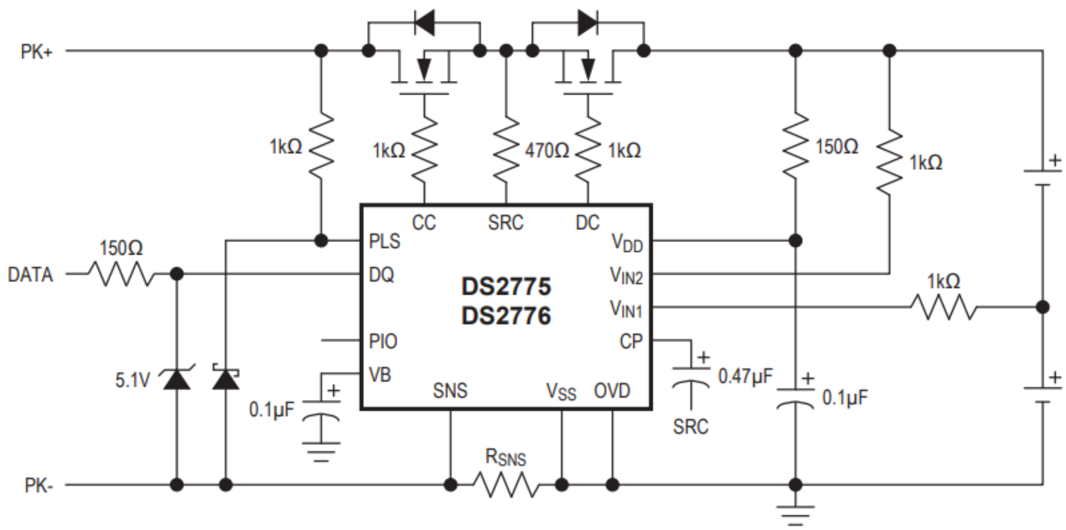

Figure 10: Application of the DS2775 battery monitoring IC [3].

The battery monitor IC will communicate with the microcontroller using the 1-Wire communication protocol. The microcontroller will monitor the state of charge of the battery and report this to the user using LEDs. Because the motor needs 5 V and the sensor and microcontroller will be operated at 3.3 V, a voltage regulator is also necessary for this project. The subsystem requirements for the power subsystem are outlined in Table 2 along with the tests to be performed for veri cation of these requirements.

2.3.3 Braking Subsystem

The braking system will be controlled electronically. This means that we are no longer using the original mechanical brakes. Although we are not using it, we will still keep it for demo purposes. The focus is on showcasing the e ciency of the newly implemented electronically controlled Anti â Lock Braking System (ABS) during a slipping scenario. Our current plan on electronic braking is to use a potentiometer powered by the power subsystem, to model how hard you squeeze the bike lever. In other words, by adjusting the potentiometer, we get to change the braking intensity. The higher braking intensity, the faster we will perform a braking motion (without anything slipping condition). The signal will then be sent to our controller. It will then send out a signal to our motor to activate our braking system.

Table 2: Power subsystem requirements and veri cation.

Requirements	Verification
The power subsystem must be able to supply up to 100 mA at 3.3 V with 2% peak-to-peak voltage ripple.	To verify the voltage and current output of the power subsystem, a digital multimeter (DMM) and an electronic load will be used. The input of the system will be connected to the battery. The output of the system will be connected to the DMM and electronic load, which will measure the voltage and current output, initially under no load conditions. The electronic load will then be set to 100 mA, and the voltage will be measured again with the DMM. For both conditions, the voltage must be within the range of 4.9 to 5.1 V.
The power subsystem must operate at an e ciency greater than 90% for loads of up to 100 mA.	To verify the e ciency of the power subsystem, two wattmeters will be used. The input of the voltage regulator will be connected to one wattmeter, and the output of the voltage regulator will be connected to the other. The output power will be measured with the other wattmeter. The e ciency, de ned as the output power over the input power, will be calculated for loads of up to 100 mA. The e ciency must be 90% or greater for all loads.

The bike we are using is provided by the workshop. The bike came with only the rear brake, which is perfect because it aligns seamlessly with our original plan to add ABS only on the rear brake. This allows for a comprehensive demonstration of the performance of ABS in comparison to the traditional mechanical brake controlled by brake lever.

Our braking mechanism (when slipping is detected) will receive a series of pulse signals generated from the controller. The pulse signals will then actuate our 23hs22-28043 stepper motor and the accompanying gear attached to it. The synchronized motion then precisely facilitates the brake cable placing at the center of the bike. The pulse signals sent from the controller result in pulse braking at the braking subsystem. This helps achieve a faster stop while providing the ability to maneuver under braking conditions.

Securing the e ectiveness of the braking system is essential, as it directly a ects the force applied during braking. Therefore, it is important to make sure our motor + gear system is able to provide enough force. Looking into the datasheet, it reveals that the 23hs22-28043 stepper motor provides a torque of 1.2 Nm. The torque is su cient for the task at hand. On top of that, we added a gear to easier interact with the cable brake.

Another thing worth mentioning is that we would certainly need a separate driver for the motor. The stepper motor we are using has a rated current of 2A, which is impossible for our STM32F4 microcontroller to output directly. Therefore, we are going to use the L298N driver to support our stepper motor. It has the ability to reach max 3A, or a continue current of 2A.

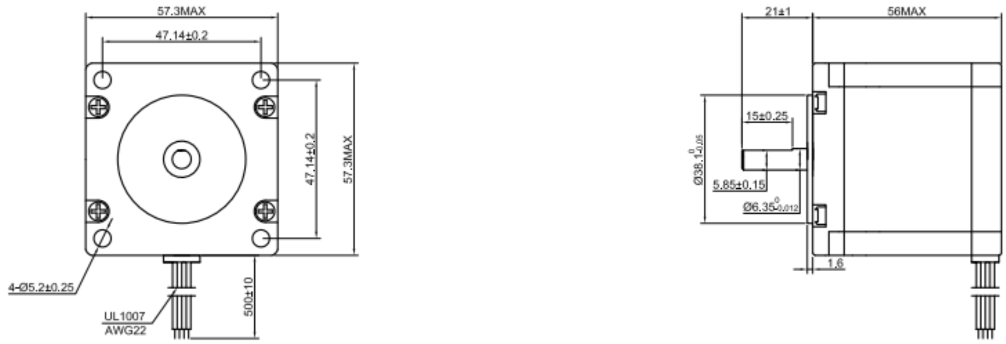

Figure 11: Stepper Motor Dimensions

Table 3: Braking subsystem requirements and veri cation.

Requirements	**Verification**
The driver has to drive the motor at least 100 RPM in order to perform a quick stop	Measure rotational speed using hall e ect sensor
The motor and gear system has to provide enough force pulling the brake cable	Measure the distance between the brake caliper and the rim (they should be touching), and see if a successful brake is performed.

2.3.4 Sensing Subsystem

The sensing system will use a Hall e ect sensor to detect the rotation of the rear wheel, e ectively measuring the wheel's speed. The sensor needs to communicate with the microcontroller using a digital communication protocol, so a TMAG5273 sensor will be used. Since only the rear brake is applied with ABS, we would also need a Hall E ect sensor to detect lateral speed. The lateral speed will also be used as an input for the controller to help detect slipping. According to the datasheet [4], this sensor needs a voltage of 3.3 V, so this subsystem will be supplied 3.3 V from the power subsystem. The data from this sensor will be sent to the microcontroller using the I^2C protocol and then be processed and recorded in the control subsystem. The typical application of the TMAG5273, which will be followed in this project, is shown in Figure 12. Accuracy and response time are essential for this subsystem, as any errors in detection can result in the control system applying brakes improperly, which can potentially be a safety hazard. It may be necessary to implement edge detection within this subsystem. The subsystem requirements for the sensing subsystem are outlined in Table 4 along with the tests to be performed for veri cation of these requirements.

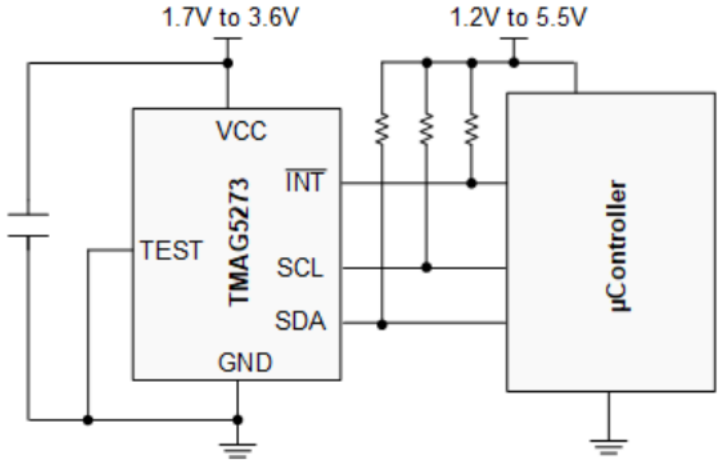

Figure 12: Application of the TMAG5273 [4].

Table 4: Sensing subsystem requirements and veri cation.

Requirements	Verification
The hall e ect sensors will have to correctly indicate the each wheel turn to helps us determine wheel speed	spin the wheels and compare it with the recorded spins
the sensor has to create a steep spike which indicates each spin	if that is not met, we will add edge detection to help x the gentle curve

2.4 Tolerance Analysis

The block that is most critical to the success of our project is the control subsystem. To ensure the proper operation of this subsystem, we will be using the STM32F401RCT6TR because it has a oating-point unit to properly handle the tracking of normalized slip ratios.

Regarding components that will be working in conjunction with the control subsystem, there will be tolerances for the accuracy of the Hall e ect sensors and the speed of the stepper motor. If the speed of the stepper motor is not su cient, then our system will be unable to meet the requirement of activating the ABS within one second of the brakes being toggled. The speci cations of the stepper motor from the datasheet of the stepper motor show that the step-angle is 1.80 degrees, and considering how our current braking system uses a worm gear to pull the brakes, this should be su cient to actuate the brakes in a timely manner. For the Hall e ect sensors, the sensing accuracy is within the range of 40 mT for the magnetic sensing and within the range of 1% for the linearity error and axis mismatch. These errors are all within the acceptable bounds for our sensing purposes. The event when these parts would not meet the requirements of our project would fall into the speed of operation. Though, the Hall e ect sensors are rated for sensing cycles of 1000-400 KHz; this is more than enough for our project.

The insights discovered during this process was that there is a very real consideration for both the power requirements of the components used in this project, the sensing rate of the components used in this project, and the speed requirements for the motor used in this project. These insights will allow for the creation of the responsive system this project is meant to be.

3 Cost and Schedule

3.1 Cost Analysis

Description	Manufacturer	Part	Quantity	Cost
Low-Power Linear 3D Hall-E ect Sensor With I2C Interface	Texas Instruments	TMAG5273	1	$1.58
2-Cell, Fuel Gauge with FuelPack, Protector, and SHA-1 Authentication	Analog Devices	DS2775	1	$4.54
IC MCU 32BIT 256KB FLASH 64LQFP	STMicroelectronics	STM32F401RCT6TR	1	$6.49
Motor Drive Controller Board Module Dual H Bridge DC Stepper	Qunqi	L298N	1	$6.99
CRYSTAL 5.9904MHZ SERIES TH	ECS	X161-ND	2	$1.40
Total				$21.00

Table 5: Parts list.

The average yearly salary of an electrical engineering graduate at the University of Illinois is $87,276, which is about $42 an hour for a 40 hour work week. At this salary, if 15 hours a week is spent by each team member in labor costs, with a project duration of 6 weeks after the completion of the design review, the cost of labor totals to 3 15 6 $42 = $11,340. This brings the total expected cost for this project to $x.

3.2 Schedule

The schedule by which each member of the team will abide this semester is listed below.

Week of	**Task**	**Team Member**
February 26	Design review.	All
	Order parts for initial prototype.	All
March 4	Begin working on PCB.	All
	Begin prototype of control subsystem.	Ethan
	Begin prototype of power subsystem.	Aidan
	Begin prototype of braking and sensing subsystems.	Leon
March 11	Enjoy spring break.	All
March 18	Order more parts needed for the prototypes.	All
	Finalize power and braking subsystem design and prototype.	Aidan
	Finalize sensing and braking subsystem design and prototype.	Leon
	Complete initial PCB design and order PCB.	All
	Continue working on prototype control subsystem model. Begin implementation on development board.	Ethan
March 25	Individual progress reports.	All
	Begin soldering and testing the PCB. Make necessary changes to the PCB design and place a new order if necessary.	Aidan and Leon
	Finalize implementation of control subsystem on development board.	Ethan
April 1	Solder and test updated PCB. Finalize and debug power, sensing, and braking subsystems.	Aidan and Leon
	Begin implementation of control subsystem on microcontroller.	Ethan
	Begin integration of prototype nal design.	
April 8	Continue integration of prototype nal design. Make nal PCB order if necessary.	All
April 15	Finalize and debug the nal design.	All
April 22	Final demo.	All
	Perform measurements and collect data necessary for the nal presentation and nal paper.	All
April 29	Final presentation.	All
	Finish nal paper.	All

Table 6: Schedule.

4 Discussion of Safety

We plan to use a motor to mechanically pull the brakes. As brakes naturally wear down over time, a system that monitors the condition of the brakes may be necessary to notify the user of this issue. As the anti-lock braking system will almost certainly be tested on a bicycle with brakes that have not been worn down, the operation of the system with brakes that have been worn down may be unclear, which could be dangerous. It will be important to check the brake's condition before applying ABS in order to comply with the IEEE Code of Ethics, which states that it is important "to hold paramount the safety, health, and welfare of the public" [1].

Another safety concern is to ride with a failed ABS system, accidentally or intentionally, can cause serious injuries due to the signi cant increase of stopping distance. It could be a good idea to implement an ABS indicator to show if it is working properly. The operation of the brakes of a bicycle unquestionably varies with the surface and weather conditions in which the bicycle is being used. The ABS system must be tested in many di erent surface conditions, namely slippery, icy, and dry conditions.

Safety is unequivocally our highest priority as engineers. Indeed, improving the safety of bicycles is the primary motivator of this project. The IEEE Code of Ethics urges engineers "to disclose promptly factors that might endanger the public or the environment" [1]. We commit to being fully transparent regarding any issues that may negatively a ect the safety of our project, in compliance with this code.

5 Discussion of Ethics

In the fth point of IEEE Code of Ethics, it emphasizes the importance of ensuring that the project should avoid harming people's safety and belongings [1]. It is crucial to keep this in mind during the development of our projects. This would include when we design our PCB, we had to make sure all components has the correct spec meaning each component does not have to handle a voltage or current beyond the design limit. We will have to do a thorough risk assessment going through safety procedures when we handle the bicycle and battery. Through these e orts, we uphold our standards to prevent our users from harm.

In the sixth of IEEE Code of Ethics, it emphasizes the importance of undertaking technical challenges only if quali ed with training or experience [1]. In our project, other than the circuit design and control system, we will also face mechanical issues. Therefore it is essential to consume advice from experienced people on the topic. One example for this project would be attaching the brake cable to our motor to perform braking. We have been constantly talking with the machine shop back and forth about the project. Throughout the process, we have learned alot not just from our own research, but the professional advice given by the machine shop. The knowledge has helped us understand more and view issues from a different perspective. With this in mind, I believe we can grow alot as engineers through this project.

References

[1] "IEEE Code of Ethics." IEEE, www.ieee.org/about/corporate/governance/p7-8.html.

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