ECE 445: Senior Design Project Laboratory

Proposal - Anti-Lock Braking for Bicycles

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1 Introduction

1.1 Problem

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 difference 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 offer. 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 sacrifice these functionalities, which means riders must navigate roads with heightened awareness and limited technological assistance.

1.2 Solution

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 efficiently; 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 offer 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-effect 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 efficient stop.

1.3 Visual Aid

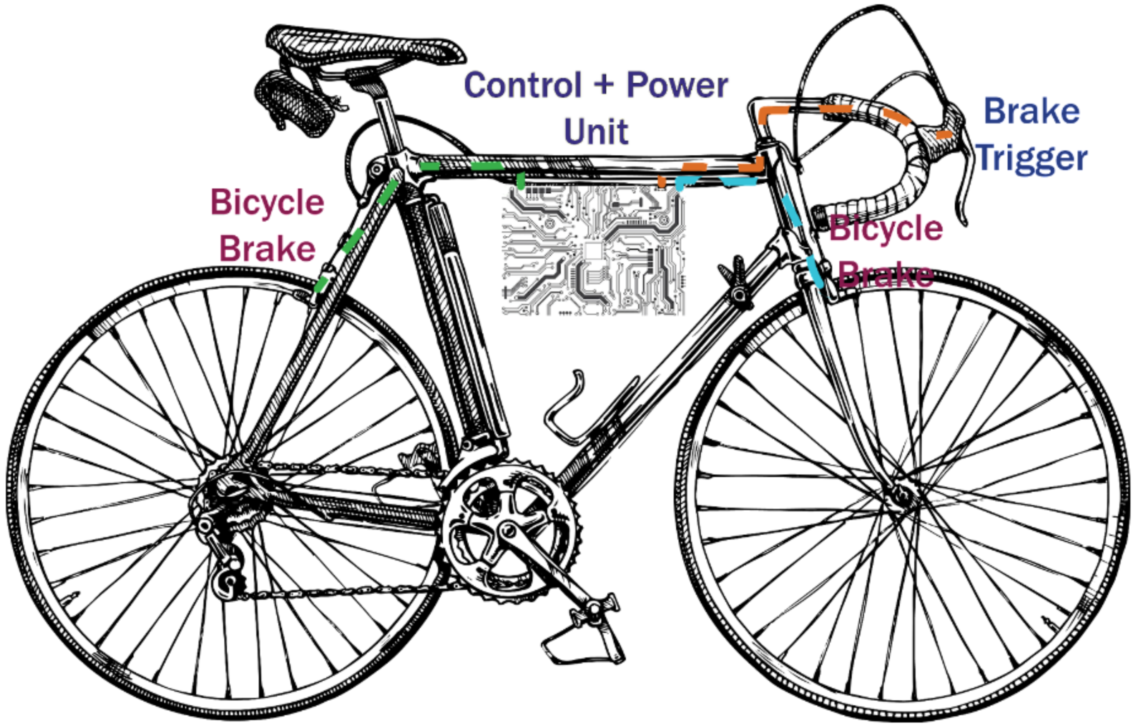

Figure 1: Visual aid.

1.4 High Level Requirements

The high level requirements for this project, which must be completed for it to be considered successful, are outlined below.

- 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.

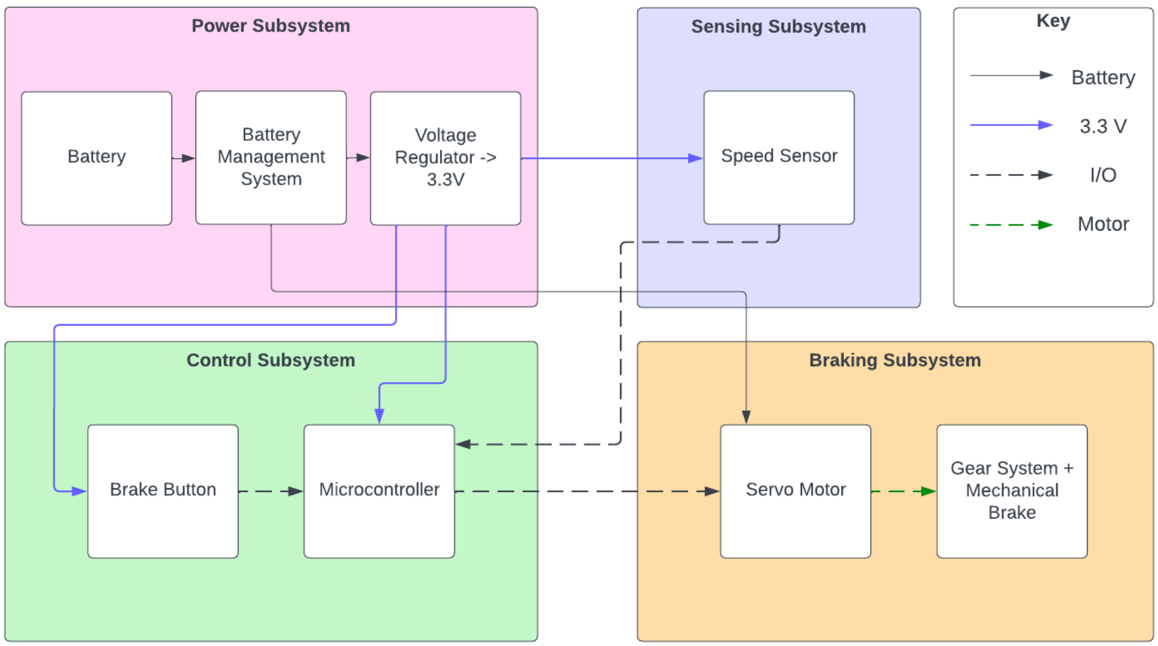

Figure 2: Block diagram of the anti-lock braking system.

2.2 Control Subsystem

2.2.1 Overview

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 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.

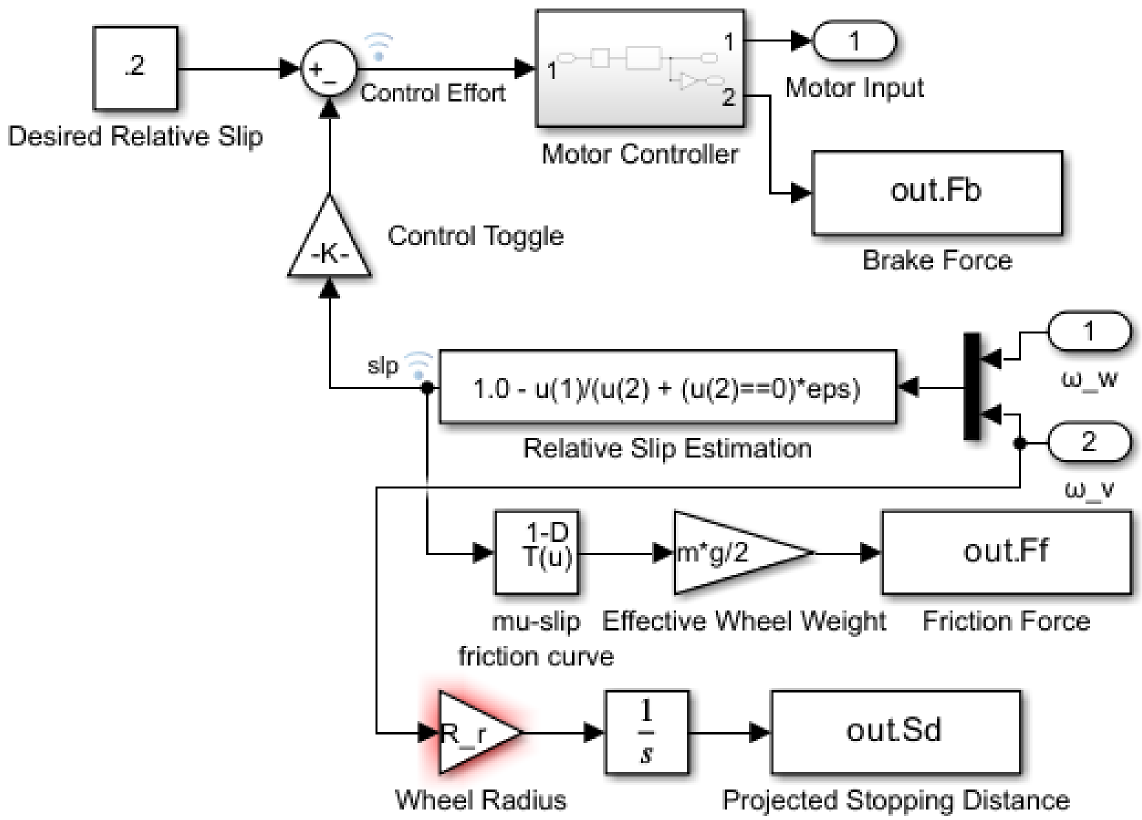

Figure 3: Prototype ABS Controller

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 identification on a mechanical system that cannot be directly identified. This translates to an estimate of the friction force in the system by finding the normal force the rear wheel would experience ($mg/2$). Such that the weight of the system will be distributed evenly among both wheels, and friction force is given by $F_f = F_n * \mu_f$. 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.

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

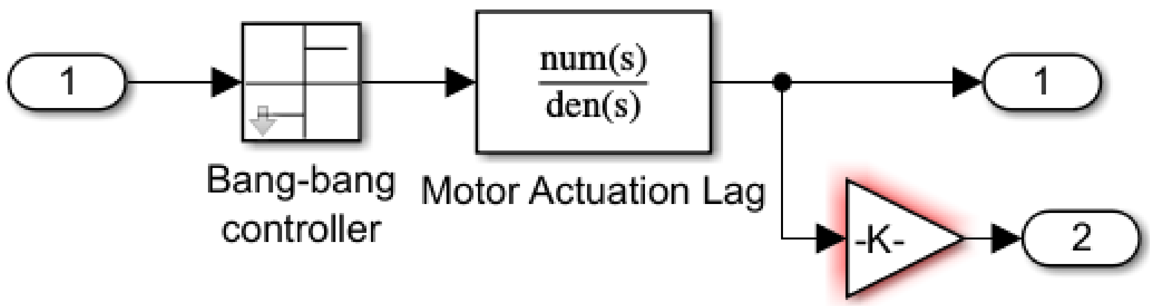

Figure 4: Prototype Motor Controller

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 an approximation for this controller in the implementation phase of this project. Next, before explaining the specifications for a practical implementation of the bang-bang controller, there will be an introduction to the terms used to quantify the efficacy of a controller. First, is that controller specifications 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 specifications themselves, first, the rise time 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 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 of the controller, this is the ratio between the maximum value the step response outputs and the input value. Next, to explain the specifications required of a practical implementation for the bang-bang controller will be a sufficiently fast rise time, for example, 75 milliseconds, and a settling time that is also sufficiently 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.

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.

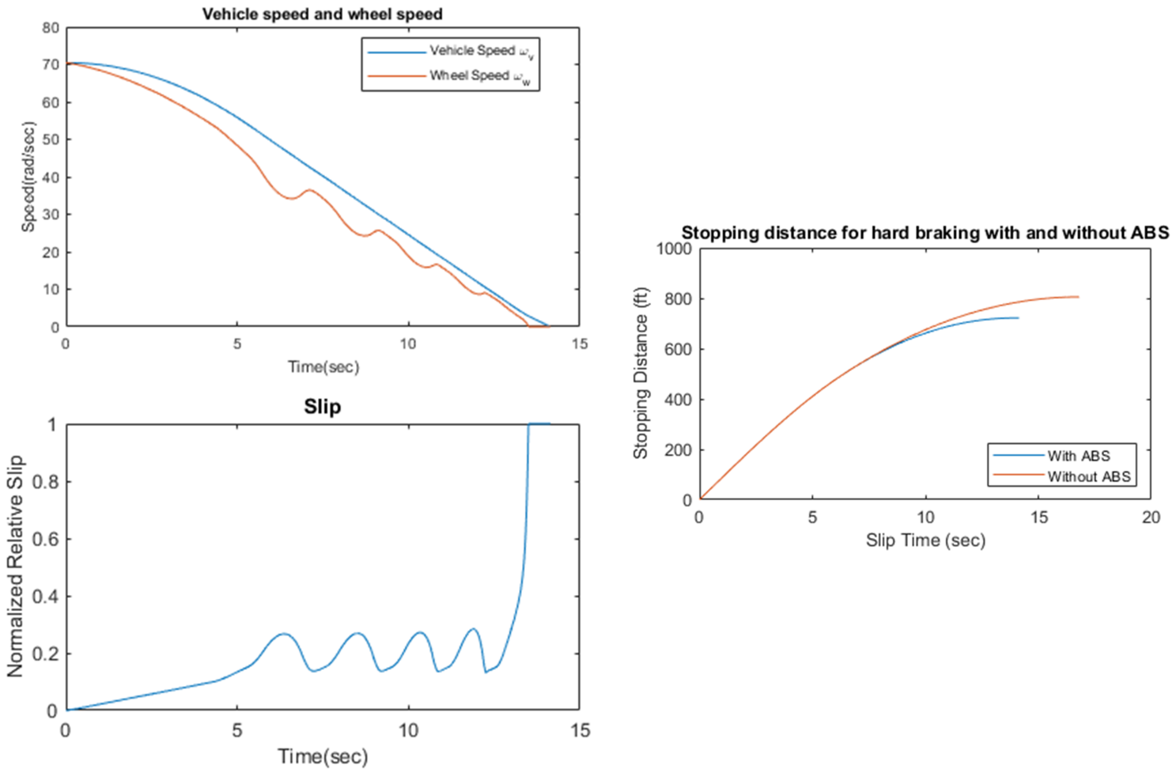

Figure 5: MathWorks Simulation of Car ABS

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.

2.2.2 Requirements

The subsystem level requirements for the control subsystem are outlined below.

1. Motor Controller Rise Time $t_r \leq 75$ ms

2. Motor Controller Settling Time $t_s \leq 120$ ms

3. Motor Controller Maximal Peak Ratio $Mp \leq 15\%$

Should any of these requirements be missing, the control system may still function at a lower frequency of operation. However, this invalidates our high-level requirement to have a sufficiently responsive ABS. Therefore, the subsystem will fail should any of the aforementioned requirements be missed.

2.3 Power Subsystem

2.3.1 Overview

The power subsystem is used to deliver power to the other subsystems, specifically 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 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 driver needs 5 V and the sensor and microcontroller will be operated at 3.3 V, a voltage regulator will also necessary for this project.

2.3.2 Requirements

The subsystem requirements for the power subsystem are outlined below:

1. The power subsystem must be able to supply up to 100 mA at 3.3 V with 2% peak-to-peak voltage ripple.

2. The power subsystem must operate at an efficiency greater than 90% for loads of up to 100 mA.

2.4 Braking Subsystem

2.4.1 Overview

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 efficiency of the newly implemented electronically controlled anti-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. The signal will then be sent to our controller. It will then send out a signal to our motor to activate our braking system.

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 effectiveness of the braking system is essential, as it directly affects 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 sufficient 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.

2.4.2 Requirements

1. The braking subsystem must be able to supply over 1 Nm of torque to effectively actuate the brakes.

2. The braking subsystem must have a response time, the time between when data is first sent to the motor and when the brake is first applied, of under 20 milliseconds.

2.5 Sensing Subsystem

2.5.1 Overview

The sensing system will use a Hall effect sensor to detect the rotation of the rear wheel, effectively 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 Effect 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. 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.

2.5.2 Requirements

The subsystem requirements for the sensing subsystem are outlined below.

1. The sensor must be able to measure the speed of the rear wheel at an accuracy of ±1%.

2. The sensing subsystem must have a response time of under 50 μs, to ensure safety through prompt braking.

2.6 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 floating-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 effect sensors and the speed of the stepper motor. If the speed of the stepper motor is not sufficient, then our system will be unable to meet the requirement of activating the ABS within one second of the brakes being toggled. The specifications 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 sufficient to actuate the brakes in a timely manner. For the Hall effect 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 effect 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 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 significant 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 different 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 affect the safety of our project, in compliance with this code.

4 Ethics

This part commits to address the potential ethical issues related to the Anti lock Braking System. There are a few points worth mentioning, one being Cybersecurity. With ABS, our vehicle is connected and reliant on electronic systems. This means multiple values are being measured, in our case we are using a Hall Effect sensor attached to the front wheel to detect lateral speed. However, other ABS could have a function of GPS. Which is essential that these data are not leaked or else it can be a potential cyber threat and attack.This is also brought up in the IEEE Code of Ethics 1-1, "strive to comply with ethical design and sustainable development practices, to protect the privacy of others"

Another potential ethical issue is the environmental impact caused by ABS. The production of ABS can cause damage to our environment if done wrong. It is important to take in consideration of topics such as using environmentally friendly materials and disposal of ABS systems. Perhaps some parts can be broken down and reused, resulting in the reduction of trash. In the IEEE Code of Ethics 1-1, "disclose promptly factors that might endanger the public or the environment;"

References

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

[2] "Modeling an Anti-Lock Braking System." MathWorks, www.mathworks.com/help/simulink/slref/modeling-an-anti-lock-braking-system.html.

[3] DS2775/DS2776/DS2777/DS2778 2-Cell, Fuel Gauge..., www.analog.com/media/en/technical-documentation/data-sheets/DS2775-DS2778.pdf.

[4] TMAG5273 Low-Power Linear 3D Hall-Effect Sensor With I2C Interface, https://www.ti.com/lit/ds/symlink/tmag5273.pdf

[5] https://components101.com/modules/l293n-motor-driver-module

[6] https://www.omc-stepperonline.com/nema-23-bipolar-1-8deg-1-26nm-178-4oz-in-2-8a-2-5v-57x57x56mm-4-wires-23hs22-2804s