Team 30: Electronic Actuation of a Motorcycle Clutch

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1.0 EXECUTIVE SUMMARY

The problem that the Michigan Formula SAE Racing Team would like solved is how to reduce tire slip off the line in the straight-line acceleration event. Solving this problem will allow the car to accelerate quicker, resulting in the team scoring more points during the competition. Existing solutions include ABS traction control, engine control with fuel injection cuts, transmission gearing, and launch control through a “Rev Limiter”. However, as per the sponsor’s request, the solution will only be approached through the implementation of clutch-control, which is a form of launch control using a closed-loop system with wheel speed feedback. The main user requirements of the project include generating at least 10 ft-lbs of torque, avoiding bending moment damage with a safety factor of 1.2, disassembling the system from the vehicle within 20 minutes, and creating a high speed system that can adjust the clutch within .02 seconds. The overall goal is to beat the fastest acceleration time achieved by the 2015 MRacing vehicle by approximately 0.2 seconds.

Developing a functional decomposition was the first step taken in creating a final design concept, which was used to generate concepts for each of the six categories including power source, powertrain, drivetrain, sensors, controller, and user input. The best design for each category was chosen based on the score generated by a weighted selection matrix, where the characteristics used to determine a concept’s score was based on the user requirements, engineering specifications and general engineering judgement. The winning concepts were a 12V battery for power source, a motor for powertrain, gears for drivetrain, hall effect sensors for sensors, the Pi Innovo for controller, and a switch for user input. Based off these winning concepts, the AmpFlow A28-150 High Performance motor along with the MAE3 Absolute magnetic Encoder Kit were chosen for the final design that would be put on the vehicle with a motor mount system.

The parts that needed to be manufactured to assemble the system included the motor mount, encoder mount, the gusset, and truss. When finite element analysis (FEA) was completed on the motor mount system, it was determined that there could be significant deflection, resulting in the manufacturing of gussets and trusses to reduce this deflection. Manufacturing was completed using milling, turning, water jetting, and sawing on relatively cheap material including steel and aluminum resulting in the whole system being subjected to a relatively small amount of tolerance stacks. In addition to manufacturing, others steps at this time including developing a circuit and control system.

A proof-of-concept electrical circuit that is connected to a small DC motor has been built that allows the system to drive current from the power source and protect the motor from backwards flowing current by implementing an opto-isolator. The controls model in Simulink has also been created where mock signals were run through the code on the computer to determine the program’s validity. For torque validation, the motor was connected to the power source to affirm that the clutch lever can be easily actuated through its full range of motion, for stiffness validation, the truss was welded onto the mounting frame resulting in significant decrease of deflection, and for assembly time validation, the disassembly/assembly time was completed and recorded to be two minutes. The speed of the system could not be validated as there were issues getting the encoder to work with the Pi Innovo. The next steps for this project would be to create a more robust circuit involving thicker wiring for AmpFlow motor, determining coefficient for the PID controller, and testing vehicle lap times with the system integrated into the car.

2.0 PROBLEM STATEMENT

The Michigan Formula SAE Racing Team has presented a unique project dealing with controlling a motorcycle clutch on a Formula SAE (FSAE) car to reduce tire slip. The overall goal is to develop a control system and install a clutch-actuating mechanism that will allow the car to accelerate quicker, ultimately scoring more points in the competition. According to the sponsor, wheel slip is the most limiting factor in the acceleration event, and if a control system were to effectively reduce tire slip then the team would see a decrease the lap time by up to 7% [1]. MRacing engineers have researched and/or attempted simpler/alternate solutions to remedy the wheel slip issue, but ultimately came to the conclusion that clutch-control would be the best means to reduce tire slip. A solution for controlling wheel slip is through a “Rev Limiter”, which is a form of open-loop launch control where the engine’s RPM is limited at the start of the launch. Another solution is through the car’s traction control, where the Engine Control Unit (ECU) limits the spark and fuel injections on all cylinders. MRacing engineers have proved the spark/fuel limiting method to be inefficient and worse than a Rev Limiter launch control due to the engine’s delayed response time to wheel slip. After documenting and studying MRacing’s past research, it was decided that the overall objective will entail executing this clutch-control method.

3.0 SPONSOR BACKGROUND

The MRacing team is a part of the Formula SAE collegiate series, an engineering competition that designs, builds, tests, and competes an open-wheeled 400cc formula-styled race car each year. Michigan engineering students are responsible for designing 100% of the car, and are hopeful for a top 3 finish in each of the competitions they will be competing in during the upcoming year. With the help of this launch control system, the car will gain approximately 10 more points in the acceleration event.

4.0 TECHNICAL DETAILS FROM LITERATURE

Many of the project requirements translate into problems that need to researched extensively about. Research sources include SAE journals, books, Google searches, and discussions with MRacing engineers. The first step will be to investigate system components such as the clutch, powertrain, and tires of an FSAE vehicle.

4.1 Launch Control Theory

Launch control is a term that is commonly used in the racing industry, which refers to any electrical or mechanical system that is used to accelerate a car in a straight line with or without driver assistance. *Figure 1* below shows how launch control logic works; absent from it are technical details about car components. The clutch can be regulated with a PID controller, for which the gains can be calculated using theoretical methods or through physical testing [2].

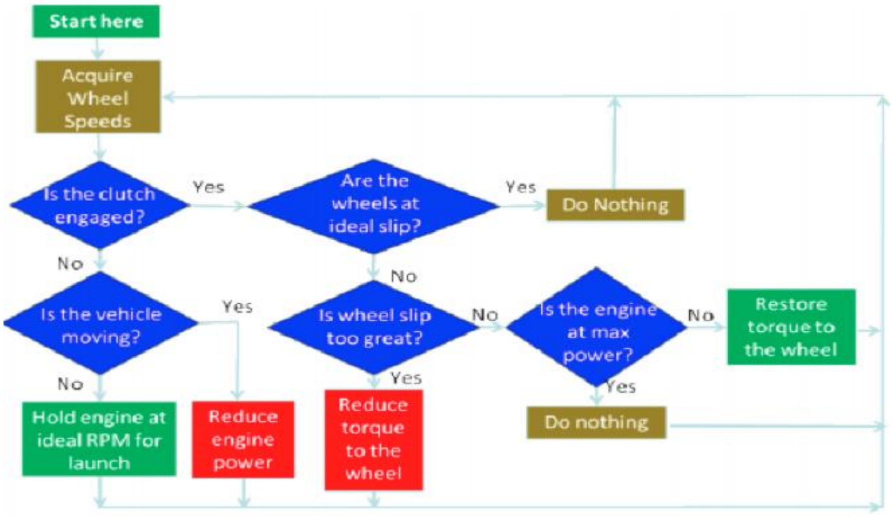


Figure 1: Launch control logic utilizes a network of if statements to determine which operation to perform next. [6]

4.2 Tire Mechanics

According to MRacing Suspension Lead, Jason Ye, "The most limiting aspect of the FSAE vehicle is the tire's ability to output enough force through means of friction [1]." During a launch, the engine's power exerts more torque than the tires can physically handle. This is apparent during the acceleration event when the rear tires spin and slip against the ground. The tire force is controlled through an independent variable called the slip ratio (SR), which is simply a ratio between the speed of the driving wheels and the speed of the free rolling wheels [3]. On the car, this is measured through the use of hall effect sensors that are mounted in order to record the speed of the front and rear wheels [4]. *Figure 2* below shows the relationship between tire friction and SR [5]. This led to the conclusion that the control system must be designed to adjust the tire slip such that the maximum force observed at the tires can be maintained.

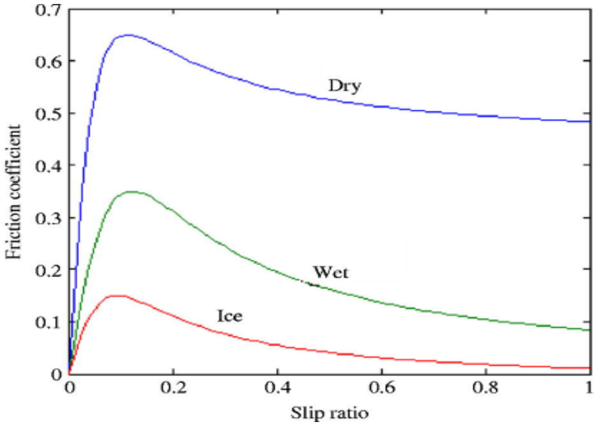


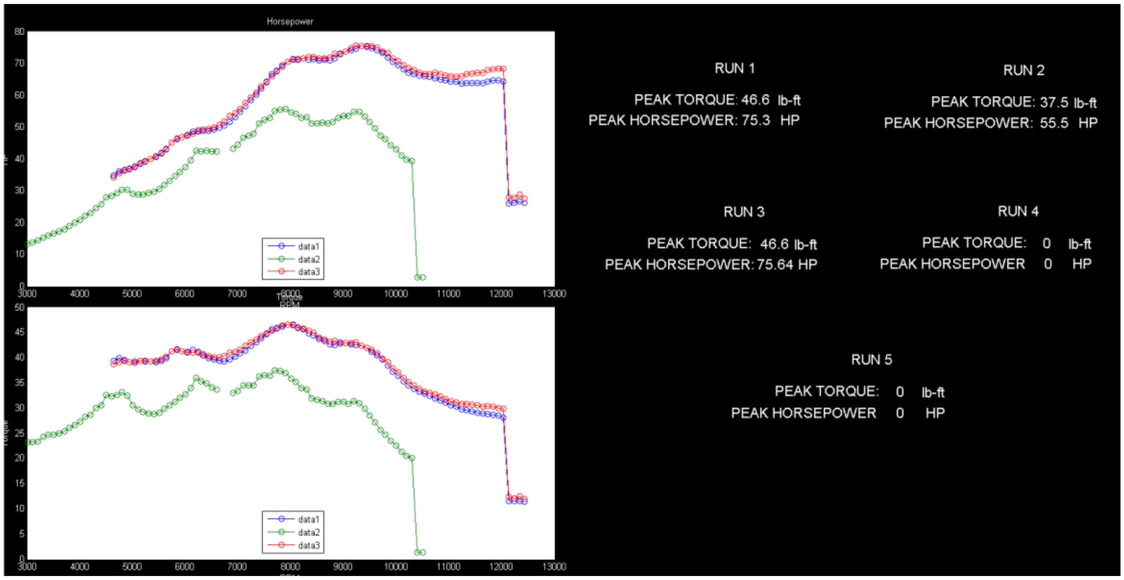
Figure 2: This graph of friction coefficient of the tires versus slip ratio (SR) shows how differing environmental conditions can have an impact on SR. [5]

4.3 Clutch Mechanics

The way a clutch works is fairly simple. The goal of a clutch is to separate the powertrain (engine) and drivetrain (transmission) through a series of simple friction plates and springs known as the “clutch pack” [6]. When the clutch is disengaged, the springs are compressed and the clutch plates are allowed to separate, thus resulting in no torque being transmitted from the engine to the transmission. When the clutch is engaged, the springs are released, allowing 100% of the engine torque to be transferred to the wheels, not accounting for efficiency losses. Controlling the exact engagement/disengagement of the clutch will allow for a specific amount of torque to be transmitted [7, 8].

4.4 Powertrain

The clutch-control design has to be integrated into the MR15 vehicle, which houses a Honda CBR600RR 4-cylinder, 4 stroke, naturally aspirated gasoline engine. The transmission of the vehicle, which includes the clutch, is integrated into the engine block. The basics of an engine, such as components and basic schematics, has been researched [9]. The inner workings of the engine has been understood by physically handling and tinkering with the internals of the motorcycle engine while working in the MRacing dyno room. Scott Trahan, MRacing’s Powertrain lead, was able to provide a map of Torque and Power vs. Engine RPM, as shown in *Figure 3* [8].



RUN 1

PEAK TORQUE: 46.6 lb-ft
PEAK HORSEPOWER: 75.3 HP

RUN 2

PEAK TORQUE: 37.5 lb-ft
PEAK HORSEPOWER: 55.5 HP

RUN 3

PEAK TORQUE: 46.6 lb-ft
PEAK HORSEPOWER: 75.64 HP

RUN 4

PEAK TORQUE: 0 lb-ft
PEAK HORSEPOWER 0 HP

RUN 5

PEAK TORQUE: 0 lb-ft
PEAK HORSEPOWER 0 HP

Figure 3: The torque and power curves for the Honda CBR600RR motorcycle engine both show that there is an optimal rpm at which maximum power will be developed. [8]

5.0 BENCHMARKING

The concept that is being attempted to implement exists in a very narrow market and applies only to a small number of race car series. Due to secrecy within the racing industry, it is extremely difficult to obtain an in-depth understanding of a product without actually purchasing or working directly with the product. However, it has been discovered that Formula 1 has been implementing launch control systems through clutch-control for almost 15 years [10]. In the automotive industry, products similar to the one implemented in this project will be of concern only to a limited degree. An exact patent application of this project has not been found, but instead listed below are several related products that deal with clutch-control.

Performance enhancing and starting process accelerating method for vehicle with hydrodynamic torque converter [11]: This patent outlines how a motorized vehicle will begin moving from standstill using automatic clutch-control in an automatic transmission. This concept is applied to the majority of vehicles on the road today, apart from anything with a manual transmission. The patent also has a section relating to how a race car will start, stating, "Racing vehicles with automatic transmissions" utilize a hydrodynamic torque converter as a "means and method for controlling" the start "of the vehicle". The patent explains that this method allows the engine to rev at high speeds, allowing for quick accelerations. It then goes on to say that this "...function is also referred to as a "launch control" and usually includes" a manually operable "switch ("launch button") to enable or disable this Quick Start function of the vehicle [11]." Due to the use of manual transmission, this project does not infringe upon this patent. However, the patent gives a general definition for launch control, which is valuable to consider.

Control method and controller for a motor vehicle drive train [12]: This patent relates to torque control of an automatic transmission by raising engine power and reducing output torque. Its goal is to initiate a launch with an automatic transmission through an electronic controller. Due to the use of manual transmission, this project does not infringe upon this patent.

Method and apparatus for operating a clutch in an automated mechanical transmission [13]: This patent is about an algorithm that calculates the "kiss point" of the clutch. In response to this mathematical point, the system will determine the engine power versus clutch position and feed a controller information about where it should be in order to launch the vehicle. It will continuously compare accelerator position to clutch position to recalculate the "kiss point". Due to the use of manual transmission, this project does not infringe upon this patent.

6.0 CURRENT SOLUTION

The current solution to prevent tire slip during launch control is by manually holding and dropping the clutch lever, which is connected to the clutch shaft, to engage/disengage the clutch plates. The problem with this is that it is extremely difficult for the driver to decide which position he/she should drop the clutch lever such that the engine will output maximum power without producing wheel slip [14]. Another solution is through traction control, which is where fuel is withheld from the cylinders. The problem with this method is that there are only four options for fuel cutting that can reduce the power output of the engine, thus reducing the acceleration of the wheels/car. Conversely, the clutch-control method has infinite adjustability [15, 16]. A pneumatic clutch is also one of the existing solutions on the market designed to remedy wheel slip. A pneumatic clutch can provide a smooth start-up from a standstill and can also actuate very quickly depending on your engineering needs. This can be done by regulating the air pressure being applied to the clutch [17]. However, a pneumatic clutch costs around $2000 [18], which exceeds the budget set by the MRacing team. Also, a pneumatic clutch is difficult to integrate with the current MRacing car.

7.0 USER REQUIREMENTS AND ENGINEERING SPECIFICATIONS

All user requirements and engineering specifications have been determined through discussions with the sponsor, physical testing on the vehicle and its parts, and internal discussions within the team. *Table 1* below summarizes the user requirements and engineering specifications.

Table 1: User requirements and engineering specifications spreadsheet with their relative priority, source and rationale for each item.

SYSTEMS	**USER REQUIREMENTS**	**ENGINEERING SPECIFICATIONS**	**PRIORITY (1 = highest)**	**SOURCE**	**RATIONALE**
Mechanical System					
General requirements	Large Torque Generation	> 10 ft*lb torque	1	Test	Determined via physical testing of the clutch torque.
	Volume Limitation	< 100 in^3	3	Test	Determined via space measurements of car.
	Light Weight	< 6 lbs	4	Sponsor	General guideline given by sponsor, determined via discussions with engineers.
Mechanical mounting	Avoid Bending Moment Damage	FEA safety factor > 1.2	1	Team (Internal)	Common practice within the team [3]
	Assembly Simplicity	< 20 min	3	Sponsor	Common practice for "Pull-off" systems on the team [7].
Drivetrain*	High system speed	Reduction, between 1 and 3	1	Sponsor	Minimum ratio of 1:1 based on engine spec, max ratio of 3 to not exceed volume limit.
	No backlash	pre-load > 0.5 ft*lb	4	Team (Internal)	Decided to maintain 1% of the total torque as pre-load.

	Reliable and robust	FEA safety factor > 1.2	2	Team (Internal)	Common practice within the team [8]
Electronic/Control System					
Wiring	Safety	0 current during working sessions	1	Team (Internal)	A team voted on rule for the project.
	Reliability	> 500 launches (1 season)	3	Sponsor	To be cost-effective, it must last 1 season.
	Rules complient	kill switch = 1	1	FSAE Rules	A specific rule-not determined by us [19].
	Driver must activate/deactivate	on/off switch = 1	1	Sponsor	The simplest method we found [20].
	Must use vehicle sensors	wheel speed sensor = 4	2	Team (Internal)	Simplifies mechanical design, eliminates future issues.
Powertrain control	Sensitivity	reaction time < .02 s	3	Test	Specification given to us from vehicle data.
	Enviromental Independance	temperature < 130F	2	Sponsor	Maximum temperature the outer clutch cover will achieve, sometimes it rains.
Power Source	Avoid high pressure systems	Zero pneumatic or hydraulic sources	5	Sponsor	Reliability issues within the team in the past have occurred [7].
	Use car's power sources	12V battery or 75HP (mechanical)	5	Sponsor	Ease of integration into the car is preferable and eliminates weight [7].

8.0 USER REQUIREMENTS EXTENDED RATIONALE

Several user requirements need further rationale to be fully explained.

8.1 Light Weight Analysis: The overall concept behind the MRacing vehicles is to be light weight, considering the fact that weight is the most sensitive parameter on the car. This product, by rules, must not be removed from MRacing car during competition, unless it is causing failure. This causes an additional amount of dead-weight on the car during other events, such as the endurance race. To narrow down the maximum allowable weight, the team was able to compare lap-time simulations and tested track lap-times. Simulation vehicle weight was iterated until the change in lap time was greater than the standard deviation of a real life lap time. Standard deviations exist in reality due to driver error. The results of the simulation and track tests are shown below in *Table 2* and *Table 3*.

Table 2: Simulation lap times using VI-CarRealTime allows us to quantify weight sensitivity

Simulation Parameters and Results

Δ Weight (lbm)	*Weight (lbm)*	*CG_X (in)*	*CG_Z (in)*	*Δ Lap Time (s)*
Baseline	*591*	*33*	*11.8*	*+0.00*
+1	*592*	*33*	*11.8*	*+.031*
+2	*593*	*33*	*11.8*	*+.065*
+3	*594*	*33*	*11.8*	*+.089*
+4	*595*	*33*	*11.8*	*+0.129*
+5	*596*	*33*	*11.8*	*+.160*

Table 3: 2015 endurance race results give the standard deviation for the lap times.

2015 Competition Endurance Race Parameters and Results

Weight (lbm)	*CG_X (in)*	*CG_Z (in)*	*Avg Lap Time (s)*	*Lap Time Stddev (s)*
591	33	11.8	61.2	±.155

A resulting added mass of 5 lbm will be within the lap time standard deviation of an endurance race, not including center of gravity (CG) effects.

8.2 Adjustment of Clutch Within .02 Seconds: The rationale behind this is how quickly the wheel speed sensor can output a new signal. *Table 4* below show the results of a test, logging data at 100 Hz (the maximum allowable frequency by the Daq system used on the vehicle).

Table 4: An initial launch test with the vehicle shows the wheel speeds can read at ~50Hz (0.02 s)

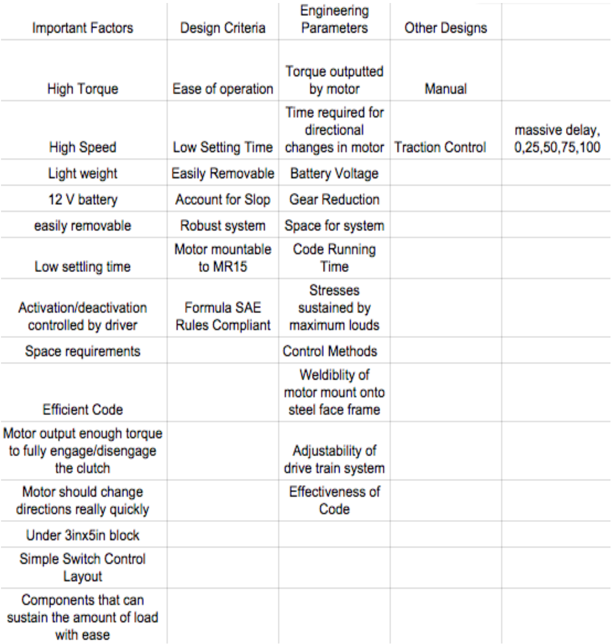
Time (s)	FL Wheel Speed (m/s)	FR Wheel Speed (m/s)	RL Wheel Speed (m/s)	RR Wheel Speed (m/s)
0.01	24.4609	23.9297	48.5	48.4766
0.02	24.8203	24.3047	50.375	48.3359
0.03	25.9609	25.6172	52.5547	54.4844
0.04	26.2109	25.7969	53.6641	54.8516
0.05	28.9063	28.2656	59.8359	58.8281
0.06	29.0729	28.474	60.6901	58.6042
0.07	30.4453	29.9141	61.8828	64.6094
0.08	30.7266	30.1875	62.3438	64.5391
0.09	32.4531	31.9063	64.8516	67.0234
0.1	32.7266	32.1094	64.8438	67.3672

From this data set, it can be seen that the wheel speed sensor outputs a new signal every 0.02 seconds, faster than the Daq system can log at. The clutch must be moved to its new position, faster than 0.02 seconds, before the next wheel speed signal is read by the controller.

9.0 QUALITY FUNCTION DEPLOYMENT (QFD)

Table 5 shows the QFD that translates the user requirements into engineering parameters that can be easily understood for design and manufacturing purposes.

Table 5: Quality Function Deployment that translated user requirements into engineering specifications



Important Factors	Design Criteria	Engineering Parameters	Other Designs	
High Torque	Ease of operation	Torque outputted by motor	Manual	
High Speed	Low Setting Time	Time required for directional changes in motor	Traction Control	massive delay, 0,25,50,75,100
Light weight	Easily Removable	Battery Voltage		
12 V battery	Account for Slop	Gear Reduction		
easily removable	Robust system	Space for system		
Low settling time	Motor mountable to MR15	Code Running Time		
Activation/deactivation controlled by driver	Formula SAE Rules Compliant	Stresses sustained by maximum louds		
Space requirements		Control Methods		
Efficient Code		Weldiblity of motor mount onto steel face frame		
Motor output enough torque to fully engage/disengage the clutch		Adjustability of drive train system		
Motor should change directions really quickly		Effectiveness of Code		
Under 3inx5in block				
Simple Switch Control Layout				
Components that can sustain the amount of load with ease				

10.0 CONCEPT GENERATION

To accomplish the goal of actuating the clutch of a motorcycle engine, the system was divided into a series of smaller subsystems through a functional decomposition. The functional decomposition tree, outlining the process of preventing wheel slip via clutch-control, is shown in *Figure 4* below.

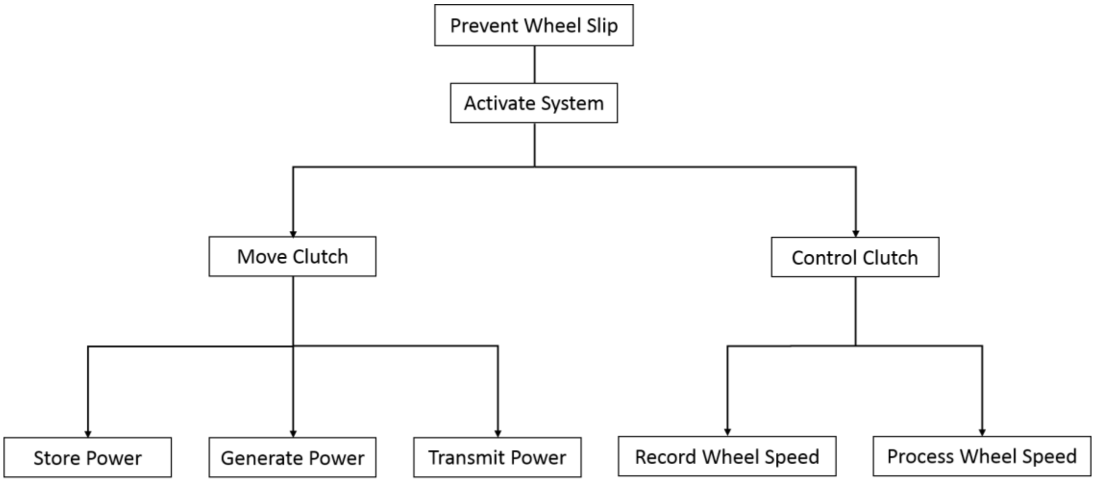


Figure 4: Functional Decomposition tree showing the breakdown process for controlling wheel slip.

The functional decomposition was then further divided into categories, which is where the concepts were organized. The descriptions for each category are listed below.

Power Source: Includes any ideas for energy storage on the car.
Powertrain: Includes any ideas for converting the stored energy into mechanical power.
Drivetrain: Includes any ideas for transmitting the mechanical power to the clutch.
Sensors: Includes mechanisms that will detect a desired car variable in real-time.
Controllers: Includes anything that can process a sensor signal and control the powertrain.
User Input: Includes any ideas for how to start/stop the system.
Major categories include a Power Source, Powertrain system, Drivetrain system, Sensors, Controller, and User Input mechanism. Each team member then came up with concepts for each category. *Table 10* in Appendix B outlines each generated concept.

11.0 CONCEPT SELECTION

After generating concepts, the team created weighted selection matrices for each category. Every matrix pitted each concept against a list of requirements. Each requirement was assigned a score on a scale of 1-10 (in order of increasing importance) based off of our discretion of importance. Then, each concept was scored on a scale of 0-10 based on how well it matched/met a requirement, as well as how feasible it was from the perspective of our team members. Some of the requirements that our concepts were compared against include “Reliability”, “Cost”, “Weight (mass)”, and “Ease of Use”. As a general rule, any concept that scored a 0 or a 1 for a category would not qualify as a viable concept, regardless of its total score. Appendix B shows the tables showing the scoring system used and results for each category.

***11.1 Power Source**:* The power source category contains ideas for how energy should be stored for the system. From past experiences, it was determined that the best ideas were the 12V battery, pressurized air, and gasoline. Pressurized air was ruled out due to a score of 1 for reliability, gasoline was ruled out due to a score of 1 for ease of control, and propane was ruled out due to a score of 1 for feasibility. Although the vehicle runs on racing fuel, gasoline scored very low for feasibility because another combustion engine would be needed to provide the power. Another notable concept was driver effort, but this also failed due to a score of 1 for strength. The winning concept for power source was the 12 V battery due to its high score for feasibility and ease of control. One disadvantage of the 12 V battery is that it has a short lifespan, but this will be accounted for this by swapping batteries whenever needed.

***11.12 Powertrain**:* The powertrain category contains ideas for transmitting energy from our power source to our drivetrain. The best ideas include the vehicle's 75 hp engine, a motor, and the driver. Both the engine and driver were ruled out immediately due to a score of 1 for ease of control. The winning powertrain concept was the motor due to its ease of control and its reliability. One downside to the motor is that it produces relatively low torque in comparison to the other generated concepts.

***11.3 Drivetrain**:* The drivetrain category contains ideas for delivering the energy from our powertrain to the clutch. Noteable concepts include a chain drive, gears, and a steel rod acting as a moment arm. The steel rod scored highly overall, but was ruled out because this would necessitate the need for a linear actuator - a powertrain device that is not feasible according to the team's standards. The top concepts were a chain drive and gears, but gears were chosen because it is believed that the gear is more feasible for packaging reasons and meeting the volume constraints. However, it is important to be cautious of how much is spent on gears since they are relatively costly.

***11.4 Sensors**:* The sensors category contains ideas for how to detect a desired car variable in real-time. Major ideas include a Hall effect or laser speed sensor for wheel speeds, an accelerometer, and a potentiometer. The Hall effect sensor scored the highest because it has already been implemented on the vehicle, thus making it easy to use, cost effective, and efficient with volume. One minor disadvantage to the Hall effect sensor is its poor accuracy compared to the laser speed sensor. However, laser speed sensors can cost around $300-$400, which exceeds the budget entirely.

***11.5 Receive/Transmit Signal**:* The receive/transmit category contains a list of controllers that would bridge the gap between the sensors and the powertrain. Major contenders include a Bosch MS4.4, a Pi Innovo M220, and an Arduino board. The Bosch MS4.4 was ruled out due to its difficulty of use, despite the fact that it has already been implemented into the vehicle. The Pi Innovo and the Arduino both ranked very highly in in ease of use, processing speed, and feasibility. However, the Pi Innovo was chosen because it is compatible with Simulink, which is something that the team members are familiar with using.

***11.6 User Input**:* The user input category contains ideas for how a driver may activate and/or deactivate the system. The simplest, most practical and cost-effective option is a toggle switch mounted into the cockpit. Since the user can easily distinguish whether the system is on or off with a toggle switch -

something that cannot be easily accomplished with a button- it was ranked slightly higher in ease of use, thus making the toggle switch the chosen concept.

11.7 Hand Drawings

Concept drawings of several ideas were generated to get a better visual representation of how they would operate within the system. *Figure 5* below shows some of the drawings that were produced.

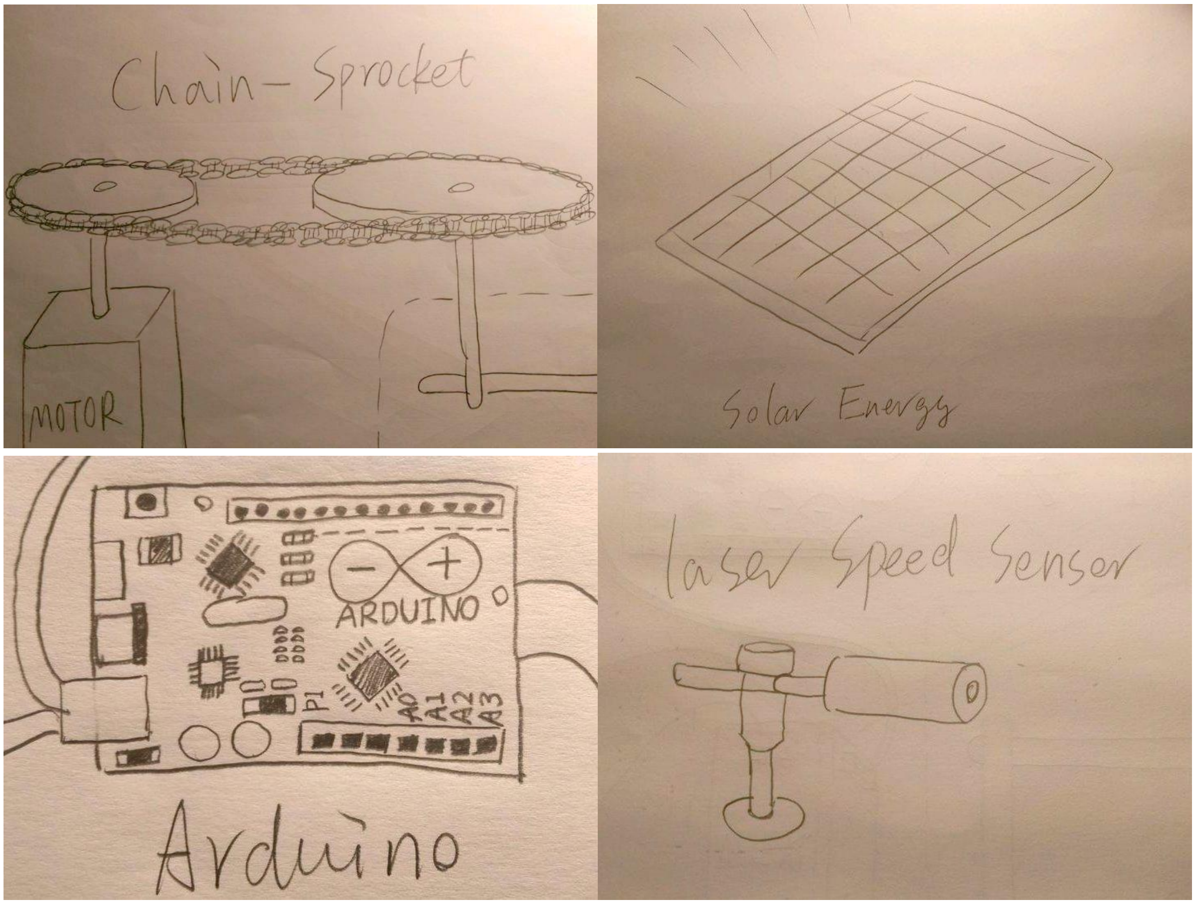


Figure 5: Drawings of concept ideas such as chain-sprocket, solar energy, arduino, and a laser speed sensor

11.8 Final Concept

The final concept will involve a 12 V battery powering a motor, as well as a gear drivetrain delivering the power from the motor to the clutch lever arm. The controller will be a Pi Innovo M220, which will read input signals from several Hall effect sensors mounted to measure the front and rear wheel speeds. To meet the user requirements listed in the previous section, the whole system will be kept external and easily accessible on the car. It was initially thought that designing a mount would prove to be a structural issue. However, when the mock-up was brought up to the car and realistic dimensions were assessed, it was realized that there would be quite a bit of freedom with system placement. *Figure 6* below shows a basic design scheme while *Figure 7* shows the foam mock-up of the final concept. *Figure 8* shows a picture of the Pi Innovo.

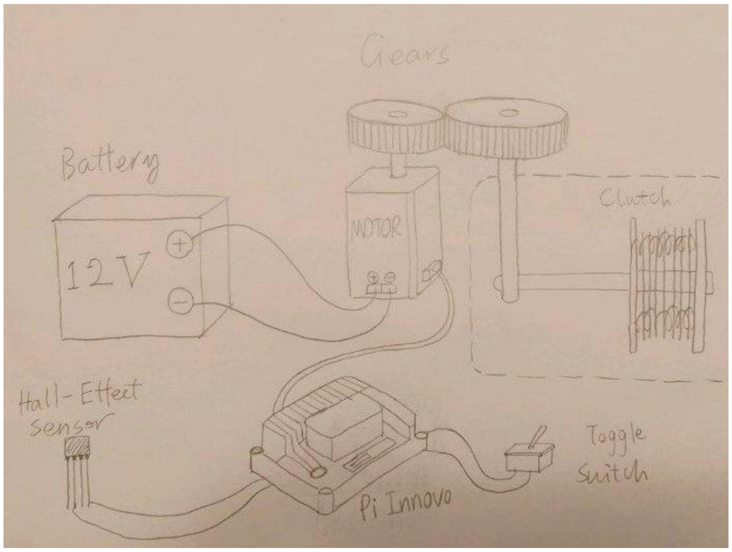


Figure 6: A free-hand drawing of our final concept.

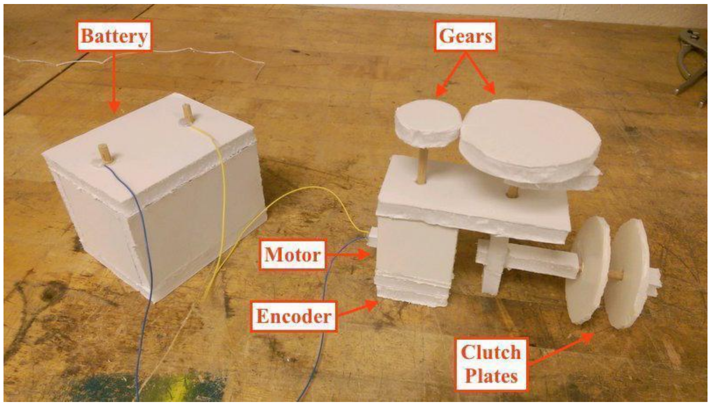
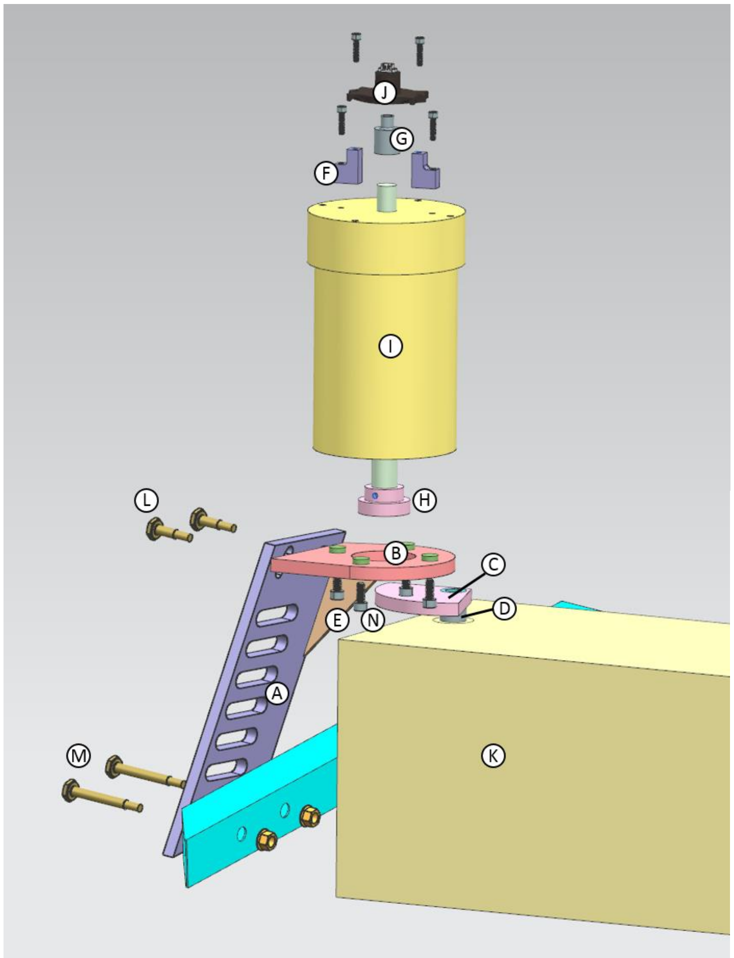


Figure 7: A foam mock-up of the final concept is shown below.

Figure 8: A mock-up of a Pi Innovo M220 controller was not produced because the sponsor was able to lend a spare model that they had on hand. Below is a picture of the controller that will be used.

12.0 CONCEPT DESCRIPTION

The general design concept that was chosen previously consisted of using a 12 V battery to power a motor, which would then deliver its power to the clutch lever through a one stage gear reduction. The motor would also be connected to the Pi Innovo that would in turn be connected to the toggle switch and the hall effect sensors. Upon further engineering analysis, it was determined that the AmpFlow A28-150 High Performance motor will be able to produce a torque of greater than 10 ft-lbs and actuate the clutch within 0.02 seconds (both with a 1:3 reduction ratio). It was also determined that the MAE3 Absolute Magnetic Encoder Kit would allow for an effective resolution of 0.012° (with a 1:3 reduction ratio), thus providing a very high level of precision. Using this knowledge, a computer aided design (CAD) model was created for the complete motor mount system as seen below in *Figure 9* and *Figure 10*. A close-up picture of the motor mount frame is shown below in *Figure 11*, while *Figure 12* shows the spacing between the motor and the gears.



- A: Motor mount frame
- B: Motor mount bracket
- C: Clutch gear
- D: Gear adaptor
- E: Motor mount gusset
- F: Encoder mount
- G: Encoder adaptor
- H: Motor gear
- I: Motor
- J: Encoder
- K: Engine
- L: Shoulder screws
- M: Shoulder Bolts
- N: Motor screws

Figure 9: The CAD model of the motor mount system with all parts labelled. All the part names can be referred to this figure.

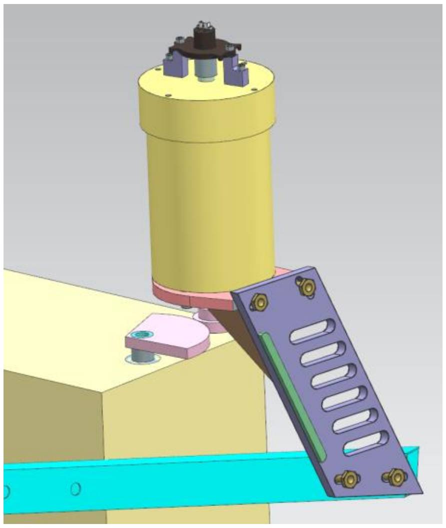


Figure 10: The CAD model of the motor mount system with the encoder at the top of the motor and the gears below the motor. The mount can also be seen with its two bolt slots.

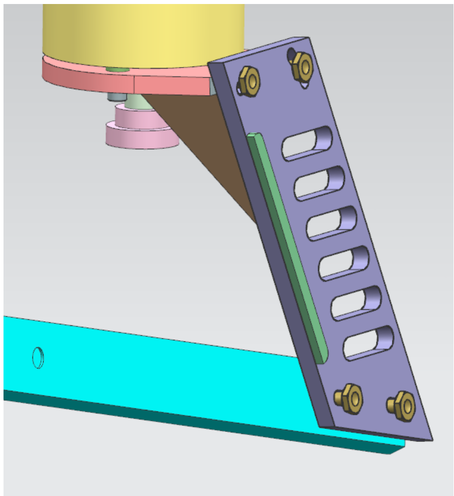


Figure 11: Close-up of motor mount structure

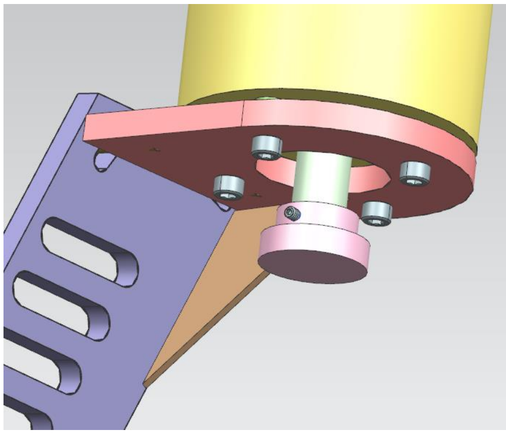


Figure 12: Close-up of the spacing between the motor shaft and its gear.

13.0 KEY DESIGN DRIVERS AND ENGINEERING ANALYSIS

In order to effectively accomplish the goal through implementing the final concept design, the following key design drivers were considered.

13.1 Torque Generation

The overall system must be able to produce enough torque in order to actuate the clutch lever on the motorcycle engine, which was measured to be approximately 10 ft-lbs at the lever. The torque production of the motor does not need to be 10 ft-lbs since a drivetrain consisting of a gear reduction designed to reduce the powertrain torque demand will be used. However, what is more challenging is that the clutch will need to move at very high speeds, thus requiring more power.

Implementing a motor into the system as a source of torque generation is a very effective means of delivering enough torque through the drivetrain in order to actuate the clutch. However, it is important that detailed calculations are performed to verify that the requirements of the *Torque Generation* design driver are met.

Being able to produce 10 ft-lbs of torque is key to the success of the project because outputting any less would result in a failure to actuate the clutch. In order to assure at least 10 ft-lbs of torque can be produced, a gear reduction will be implemented so that torque delivered through the output shaft can be increased. Although this may make it seem as if choosing the smallest reduction and overshooting the amount of torque generated would be the best option, the impact that a small reduction would have on the system could be very detrimental towards the project. Using a gear reduction decreases the actuation speed by a factor equivalent to the gear reduction. As a result, it is important to make sure that the smallest reduction possible is chosen that also meets the requirement of a 0.02 second actuation time. In order to properly analyze the system, in-depth calculations must be performed to evaluate the rotational dynamics of the motor to ensure that it fits the project's needs. This theoretical modeling method is the most appropriate because it is the closest that one can get to evaluating whether a motor will work or fail prior to actually testing the motor. The layout of a dynamic system identical to the one this project uses can be seen in *Figure 13* below.

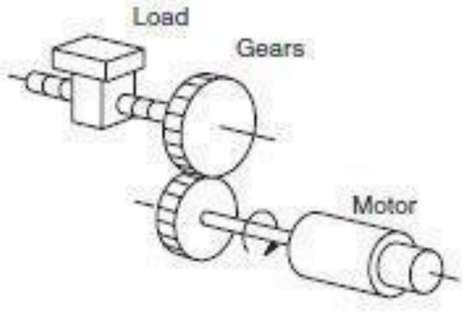


Figure 13: A motor driving a load through a one stage reduction. [21]

The previous figure depicts a scenario where a motor is driving a motor gear (gear 1), and that gear is driving a load gear (gear 2), which in turn is driving the load. The governing equation used to calculate the total inertia experienced by the motor is $J_{total}=J_{load}/N^2+J_{motor}$, where J_{load} is the inertial load contribution, J_{motor} is the motor inertia, and N is the gear ratio.

The first step taken before beginning the analysis was to empirically test the amount of force that was required to actuate the clutch lever. This resulted in a value of $F_{lever}=120\ [lbs]$. Then the distance between the axis of rotation of the clutch lever and the point on the lever where the safety wire was attached was measured to be $D=1.2\ [in]=0.1\ [ft]$. The torque was then calculated by $T=F_{lever}*D=10\ [ft*lbs]=13.6\ [N*m]$. It was then estimated that the maximum range of motion of the clutch lever would be $\theta=5°=0.0873\ [rad]$. Next,the angular speed was determined by calculating $\omega=\theta/t=4.365\ [rad/s]$; note that this is a steady state speed and is the best approximation which can be achieved. Similarly, the angular acceleration was determined by $\alpha=\omega/t=218.25\ [rad/s^2]$. After all of the preliminary values were obtained, the next step was determining which values were needed to calculate J_{total}. The inertia of the motor was determined by $J_{motor}=T/\alpha=0.061\ [N*m/s^2]$. The inertia of the load was calculated by $J_{load}=(W*r^2)/g=1.061\ [N*m/s^2]$, where W is the force required to actuate the clutch lever in Newtons and r is the radius of the load gear in meters. Since a 1:3 reduction ratio will be implemented, the gear ratio is 3:1, thus meaning that $N=3$. The reason this reduction ratio was chosen was due to the fact that any larger of a reduction ratio would result in a two stage reduction which is not feasible due to volume constraints. Finally, $J_{total}=J_{load}/N^2+J_{motor}=0.180\ [N*m/s^2]$.

The value for J_{total} means that the total inertia experienced at the motor (due to the loads of the system) is 0.180 $N*m/s^2$. This is important because, just like how the inertia in a braking car wants to keep one moving forward, the inertia of the motor keeps the spindle rotating from pole to pole. If the motor inertia is greater than the total load inertia, then the motor should work just fine for the application. However, if the motor inertia is less than the total load inertia, then the motor would either have the tendency to bog down and rotate unsmoothly or the motor just would not work for the application at all.

The motor that was chosen was the AmpFlow A28-150 High Performance motor, as shown below in *Figure 14*. This motor fits the engineering specifications exceptionally well for several reasons: a) It can generate 5.13 ft-lbs of torque (15.39 ft-lbs with the 1:3 reduction), b) It has a maximum speed of 3000 rpm when run at 12 V (1000 rpm with the reduction), which translates into very quick accelerations when coupled with the high torque output, and c) The system inertia that was just calculated does not seem like it would be too much for the A28-150 to overcome (the company was contacted to get specifications but their technicians did not have the information desired). After going over the analysis and ensuring that none of the technical issues were overlooked, the team is confident that they will not need to perform any further analysis.

Figure 14: Picture of the motor showing its front mounting plate, spindle, and housing. [23]

13.2 Clutch Position Accuracy

The amount of force between the friction plates is determined by the clutch position, which ultimately determines the amount of power transmitted to the wheels. The accuracy of our system is crucial to a quicker acceleration time than recorded without an automated clutch system. If the engagement of the clutch is overshot, then the wheels will slip too much, but if the engagement is undershot then the car will accelerate too slowly. An analytical model will be developed to determine how much the friction force will be needed under different circumstances (environmental conditions, quality of the track, etc). Extensive testing will also need to be conducted on our system to see if the clutch is being moved to the desired positions. This will be a challenge as the initial parameters values used may not work well when tests are performed on the track.

It is believed that the resolution of the encoder that is connected to the motor and the accuracy of the hall effect sensor will affect the accuracy of the clutch position while it is being actuated. The encoder that was chosen was the US Digital MAE3 Absolute Magnetic Encoder Kit , as shown in *Figure 15* below.

Figure 15: The encoder that will be mounted on the rear shaft of the motor to track the position of the motor. [22]

The positions per revolution (PPR) of the encoder peaks at 4096, which can be converted into degrees by calculating $R=360/PPR=0.0879°$, where R is the resolution of the encoder. Also, the 3:1 gear ratio makes the output gear spin 3 times slower than the input gear, resulting in an effective resolution of 0.029°. This means that there are nearly 170 options for the clutch position over the assumed 5° of travel, making this a very precise operation.

It is very difficult to quantify the impact that the hall-effect sensors have on the accuracy of the clutch position. For the hall-effect sensor that is used to record the wheel speed, mounted next to the spindle of the wheels, it is especially challenging to quantify its effect on the accuracy of the clutch position. However, specification sheets for the sensors on the car show that their accuracy error is ±0.001 m/s, which would not significantly affect the accuracy of the clutch position. This specification comes directly from the ability of the Bosch MS4.4 controller, which can output signals at a resolution of ±0.001 [7].

Something to note for this design driver is that it is extremely difficult to perform any major analyses prior to obtaining the encoder, assembling the system, and testing it. The only theoretical modeling that needed to be done was to convert the CPR of the encoder into degrees and check to see if the effective resolution was within the acceptable range. Although not written down, the team internally decided that an encoder capable of tracking the position of a motor to 100 positions within the desired range of motion would be chosen. After determining the estimated range of motion to be 5°, it was understood that the encoder resolution would have to be at or exceed (be lower than) 0.05°. Therefore, the MAE3 encoder meets the team's requirements and will be accurate enough to track the motor position according to the engineering analysis.

13.3 ECU/Motor Reaction Speed

The time that it takes the ECU and powertrain to react to an input wheel speed is vitally crucial to the success of the project. This is because a delayed reaction time may do nothing to the acceleration time or even hurt it. This issue can be overcome as long as the sensor and controller selection is adjusted as the project moves forward.

According to an interview with a design engineer on the MRacing team, as well as online research, the reaction times for the ECU (Pi-innovo) and the sensor are miniscule compared to the reaction time of a motor. This results in only considering the reaction time of the motor as the time it takes for the system to respond to a change in tire slip. However, the reaction time for the motor is quite unpredictable because the maximum travel range of motion that the motor is going to actuate within is around 5 degrees, which doesn't allow the motor to accelerate to a steady-state angular velocity. If it is assumed that the motor reaches the steady-state angular velocity instantly, then the minimum time needed to travel 5 degrees with the A28-150 motor can be determined by the equation *t=5°*60(second/min)/ 360(degrees)/speed(rpm).* The speed of the motor can be obtained from *Figure 16* below.

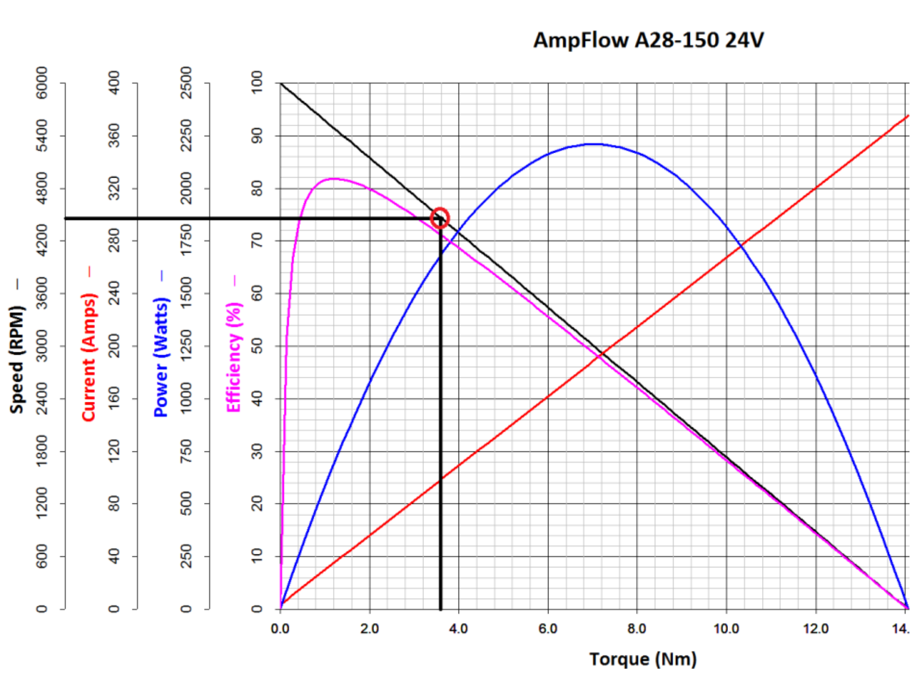


Figure 16: With the 10 ft-lbs torque requirement and 1:3 gear reduction, the torque the motor outputs would be 5.39 ft-lbs where the operating speed found under this torque is around 4500 rpm. [23]

Therefore, by using the equation mentioned above, the reaction time for the motor is 0.00019 seconds. However, this ideal reaction time assumes that the motor will reach this speed instantaneously. In conclusion, the reaction time of the motor is still an unpredictable factor and the only way to determine its true reaction time is to test the system.

13.4 Reliability/Robustness While Remaining Lightweight

Creating a reliable, robust, and easy to disassemble system is fairly simple in itself. Unfortunately, including the need for a lightweight system makes those previous goals much harder to achieve. Mass is the absolute most sensitive parameter on the car; reducing the mass of the car significantly improves the car's performance in every single dynamic event. Therefore, it is imperative that the mounting structure is light yet robust through the use of different structural geometries and materials.

The target range of system weight is set to be between 5 and 6 pounds (lbs) due to a simple weight sensitivity analysis using simulation tools and track data, with help from the sponsor. Over the course of an endurance event, driver lap time variability was anywhere from 0.25% to 1%. From these statistics, the mass should not be increased to offset a lap time by more than .25%. The MRacing Suspension Engineer, Jason Ye [1], was able to run simple full-vehicle lap time simulations, iterating mass until .25% increased lap time was achieved, resulting in the target weight of 5-6 pounds (see USER REQUIREMENTS EXTENDED RATIONALE).

The design must also pass the FEA with a safety factor of 1.2. A safety factor of 1.2 in load-driven analysis was derived from Doctor David G. Ullman's engineering handbook. The handbook states that a safety factor of 1.2-1.3 should be used "if the nature of the load is defined in an average manner, with overloads of 20-50%" [27]. The loads that the system will experience in this project are understood relatively well but not fully, therefore a safety factor of 1.2 was chosen.

In order to theoretically analyze this design driver, it became necessary to find the maximum possible displacement of the gears along with determining the stresses experienced by the motor shaft.

13.5 System-Level FEA

Stress and deflection analysis on the system level was conducted to proof our concept and show how to improve designs. Applied forces at the gear interface will create stress and deflection distributions on our shaft and mounts. The calculations for the loads, with a safety factor of 1.2, are as follows [26]:

$W_t = 1.2 * 60000 * H/(\square * d * n)$ [kN]

W_t = tangential force [kN] =.376 kN = 85.4 lbs
H = maximum power [kW] = .25 kW
d = gear pitch diameter [mm] = 25.4 mm
n = driven speed [RPM] = 600 RPM

$W_r = 1.2 * W_t * \tan\theta$ [kN]

W_r = radial force [kN] = .097 kN = 22.1 lbs
θ = pressure angle of the gears [Deg] = 14.5 deg

These two forces were used as inputs for the load simulation done in NX Nastran. *Figures 17* and *18* showed how the constraints, tangential force, and radial force were assigned on the model. *Figures 19, 20,* and *21* show how how the design has been modified based on the FEA to get less gear deflection. The results from the analysis picture in *Figure 21* showed that the final maximum displacement of the gears would be around 0.0133 in which correlates to a yellowish green color, the color of the gears. This value is well under the height of the gear teeth, which happens to be 0.1348, therefore meaning that the gear teeth will not slip. *Figures 22* and *23* show the FEA results in terms of stress.

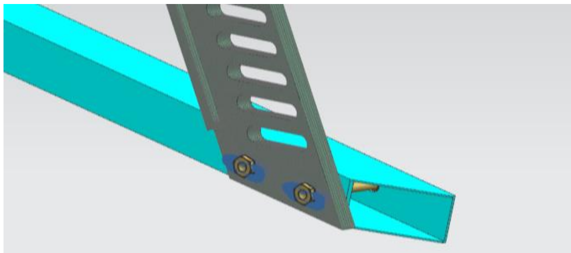


Figure 17: The bracket is constrained by bolt connections on the frame of the car.

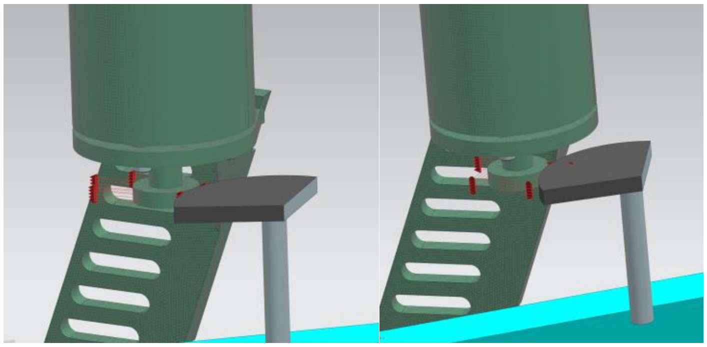


Figure 18: Radial and tangential forces are applied to the motor gear.

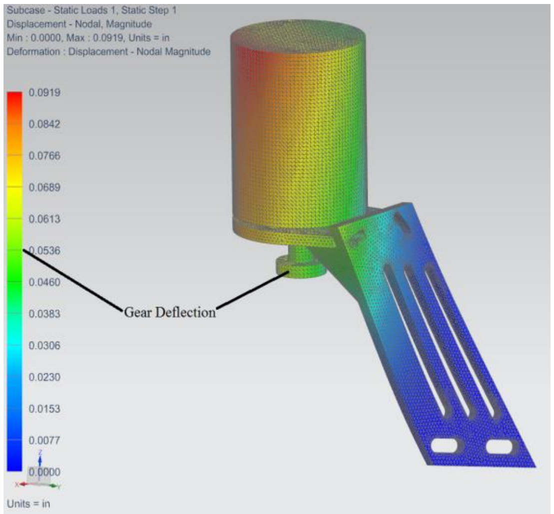


Figure 19: Gear displacement of the first iteration design set a baseline of ~.056 inches of gear deflection.

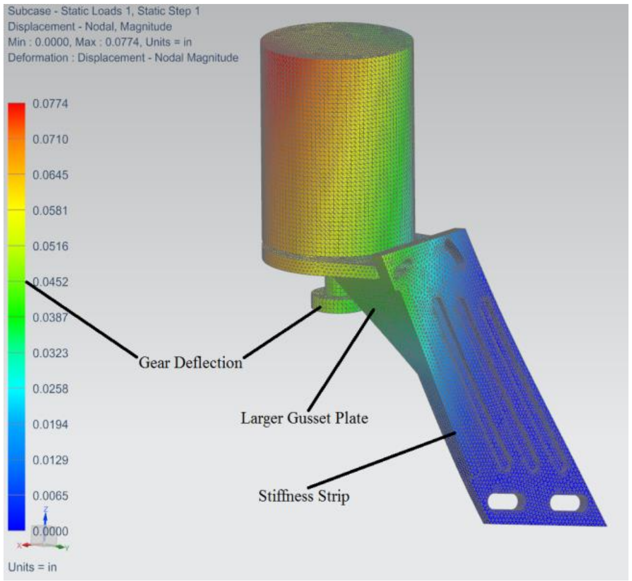


Figure 20: Gear displacement of second design iteration improves gear deflection to ~.045 inches.

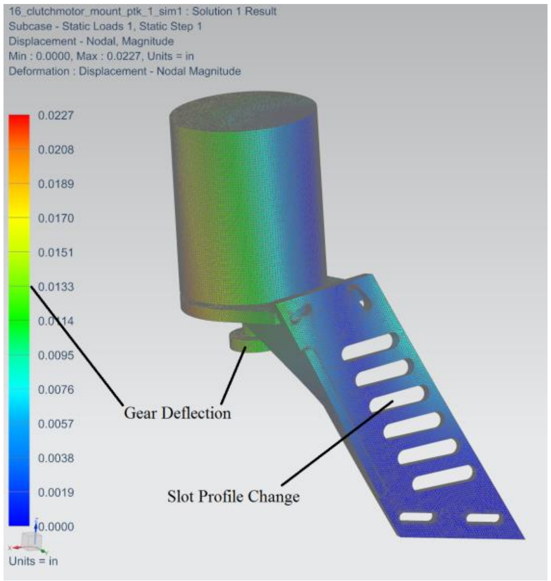


Figure 21: Gear displacement results of the third design iteration reduces gear deflection to ~.013 inches.

The results from the analysis picture in *Figures 22, 23* showed that the motor shaft would experience maximum stresses of around 8300 psi, which is well under the yield stress of steel (36000 psi). The low stress that the motor shaft will endure means that the motor shaft will not break under stress. Other areas of relatively high stress are in various regions of geometry changes and where the bolt connections exist. However, this value is still very low, around 6000 psi, with respect to the yield stress of 6061-T6 Aluminum (40000 psi) [25].

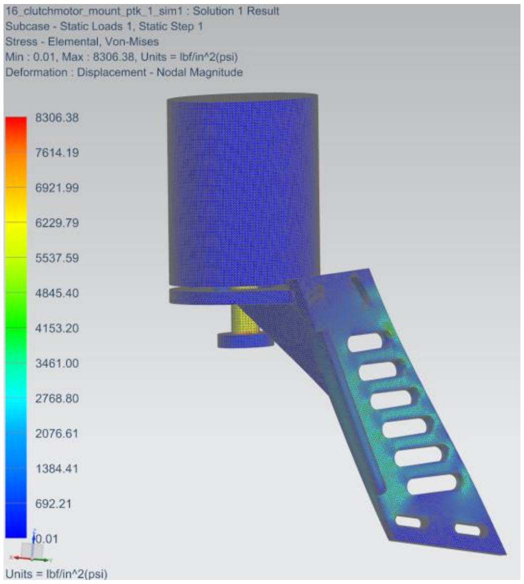


Figure 22: Visual of the motor mount that shows the expected stresses on the motor shaft to be about 8300 psi.

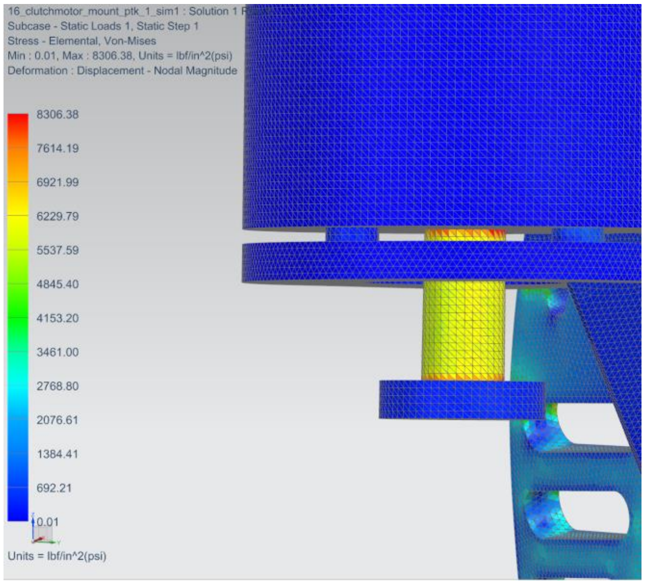


Figure 23: A close-up of FEA in terms of stress around where the max stress occurs.

As the results show that the design is feasible, the team is confident in the analysis. FEA on the opposite gear/shaft combination was not conducted for reasons such as the gear being three times larger, the shaft being a Honda-made part, and the moment arm from the gear to bearing (located inside the engine) being very small, as shown below in *Figure 24*.

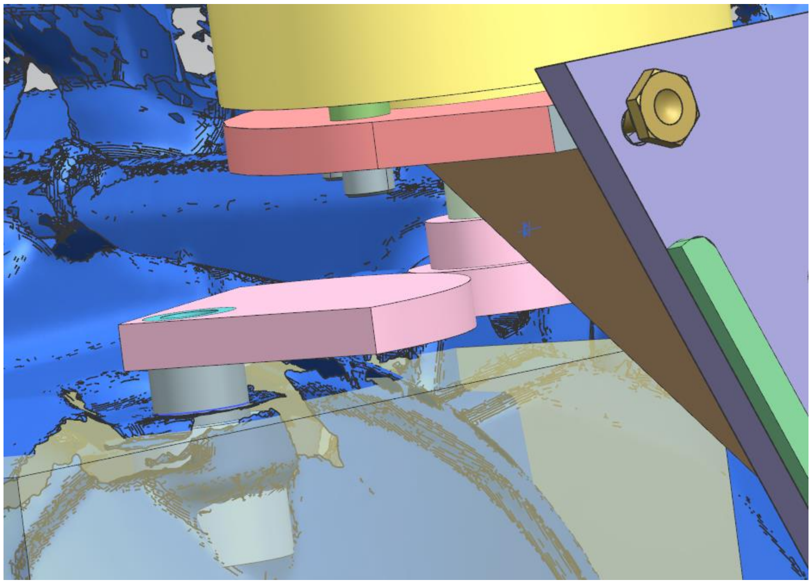


Figure 24: Clutch gear (left) is very large and attached to a Honda-made shaft.

13.6 Ease of Disassembly

Since the acceleration event is only one part of the Formula SAE competition, being able to remove the system from the car very quickly can prevent the team from missing any other events should the system malfunction and become a nuisance. This goal can be achieved by positioning the clutch-actuating system on the car such that the fasteners keeping the system constrained to the car are easily accessible.

It was verified that the system could be disassembled quickly by creating a CAD model of the motor mount. As seen from the CAD model in *Figure 25* below, the mechanical portion of our system can be removed from the car by simply removing two bolts from the mount. This will allow for the system to be removed from the car in under 20 minutes. One lesson that was learned from creating this CAD model is that the rigidity of the system could be increased by constraining it through more than the two bolt holes currently in the design, but doing so would add weight to the system and also make the system more complex to disassemble, thus making it an option that will not be pursued.

This mode of analysis is appropriate because it produces an approximate time that it will take to disassemble the system with the existing design - less than 5 minutes. This time of disassembly is well under the 20 minute user requirement. This design is functional because it includes all the functional components that were deemed necessary for operation, and its volume approximately 36 in^3 which is well under the maximum volume constraint of 100 in^3. This results in high confidence in the analysis.

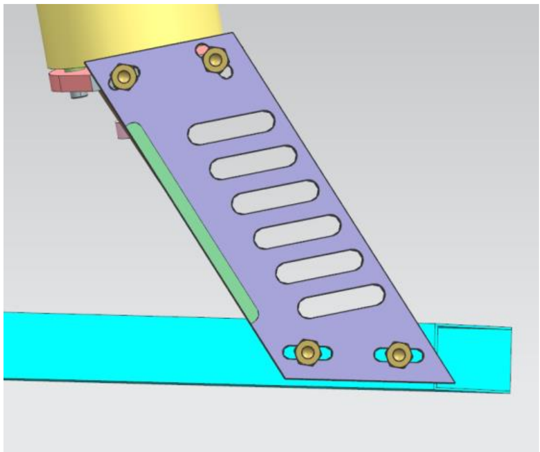


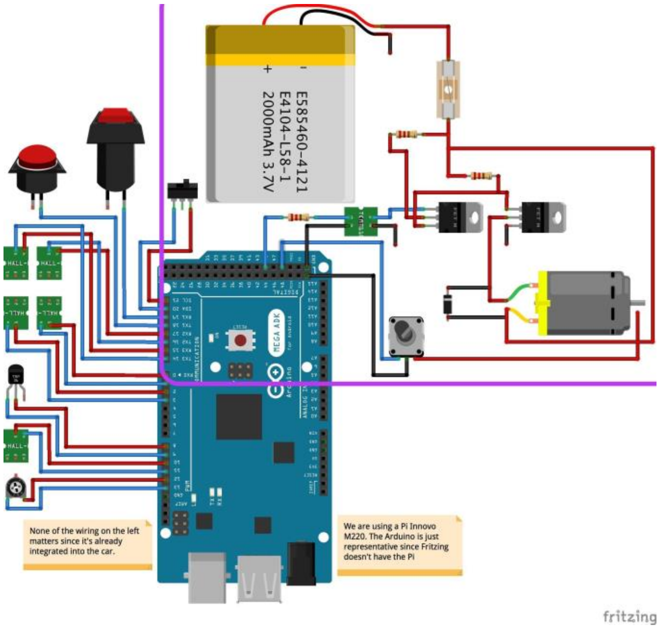
Figure 25: Close-up of the CAD model showing the two points at which the motor-system will be attached to the FSAE vehicle.

14.0 ELECTRONICS AND CONTROLS

The following sections describe the electronics and controls engineering analysis and design portion of the project.

14.1 Electrical Wiring

The electrical wiring for this project was not an incredibly difficult design, but due to the high amount of current that the motor will be drawing (~127 Amps, taken from *Figure 11*), safety precautions had to be taken to ensure no components, such as the Pi Innovo M220, or users would be harmed. *Figure 26* below shows the most up-to-date wiring schematic.



None of the wiring on the left matters since it's already integrated into the car.

We are using a Pi Innovo M220. The Arduino is just representative since Fritzing doesn't have the Pi

Figure 26: Wiring diagram consisting of all components related to the project. Note that the controller the team will be using is a Pi Innovo M220, not an Arduino.

The controller that is in the wiring schematic is not the one that will be implemented in the project. The program, Fritzing, did not have a Pi Innovo M220 in its database, therefore an Arduino Mega ADK was used as a placeholder. Also, the components to the left of the battery are already integrated into the car and therefore were not carefully wired. The components to the right of the purple border are directly associated with the project.

The components that were used to produce this wiring are as follows: 1) One 12V 4.6 Amp hours battery to provide the power, 2) One 150 Amp fuse to break in case the system somehow draws above 127 Amps, 3) One optoisolator to prevent high currents from back-flowing and destroying the control unit, 4) One 300 ohm resistor to bring down the voltage being applied to the optoisolator, 5) One 10 kohm and One 1 kohm resistor to act as pull-up resistors, 6) One n-channel metal-oxide-semiconductor field-effect transistor (MOSFET) to act as a signal delivering field-effect transistor (FET), 7) One n-channel MOSFET to allow the current from the battery to flow to ground, 8) One DC brushed motor, 9) One rectifier diode to prevent voltage spikes from damaging the motor, 10) One motor encoder to read absolute motor positions, 11) One toggle switch to turn the system on/off.

The way in which this circuit functions is actually quite simple. The yellow pole of the motor is constantly at 12 V, but because there is no input signal into the system, the MOSFET on the right effectively does not have a voltage difference between its gate and its source and thus the circuit is open. Once the controller sends a signal to the optoisolator, the isolator produces a voltage difference between the gate and the source of the MOSFET on the left. Afterwards, a signal-level current flows from the gate to the source, thus providing a voltage difference between the gate and the source of the MOSFET on the right. Once this happens, the circuit is grounded and there is a voltage difference between the yellow and green poles of the motor, thus causing the motor to spin. In the event of a voltage spike, the rectifier diode will prevent the high voltages from damaging the motor.

14.2 Control Architecture

The fundamental goal behind the control architecture will be to limit output torque from the engine to the wheels through a closed-loop feedback system. The output torque will be limited by comparing rear wheel torque to generated engine torque to find an output equilibrium torque through modulation of the clutch. To simplify the schematics, the architecture has been broken up into three separate categories: tire slip control, wheel torque control, and clutch force control. The map below shows a simplified breakdown [24].

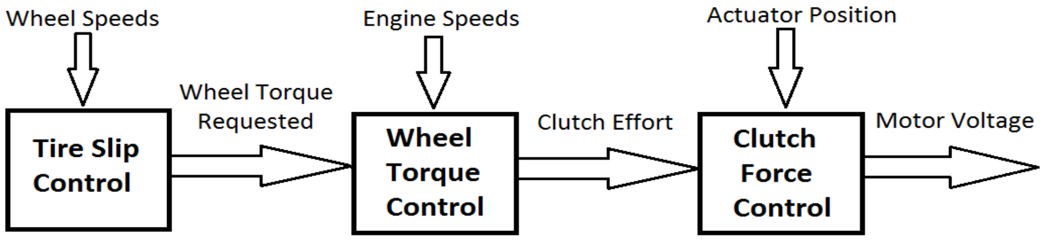


Figure 27: Control map displaying how wheel speeds are used to control the clutch's position. [24]

The first block represents tire slip control where the inputs are the wheel speeds of the four tires while the output is torque requested. Essentially, an average speed is taken for the front wheels and the rear wheels. Then a constant of 1 is subtracted from the ratio of the rear wheel average speed to the front wheel average speed – this is called the slip. This slip ratio is used to determine the torque generated at the wheels by using a look-up table of slip ratio vs wheel torque. *Figure 28* below shows the relationship between the slip ratio and the force on the wheels; the y-axis of this graph will have to multiplied by 3.11 to translate the units from force to torque. The three curves represent three different normal forces on the tires.

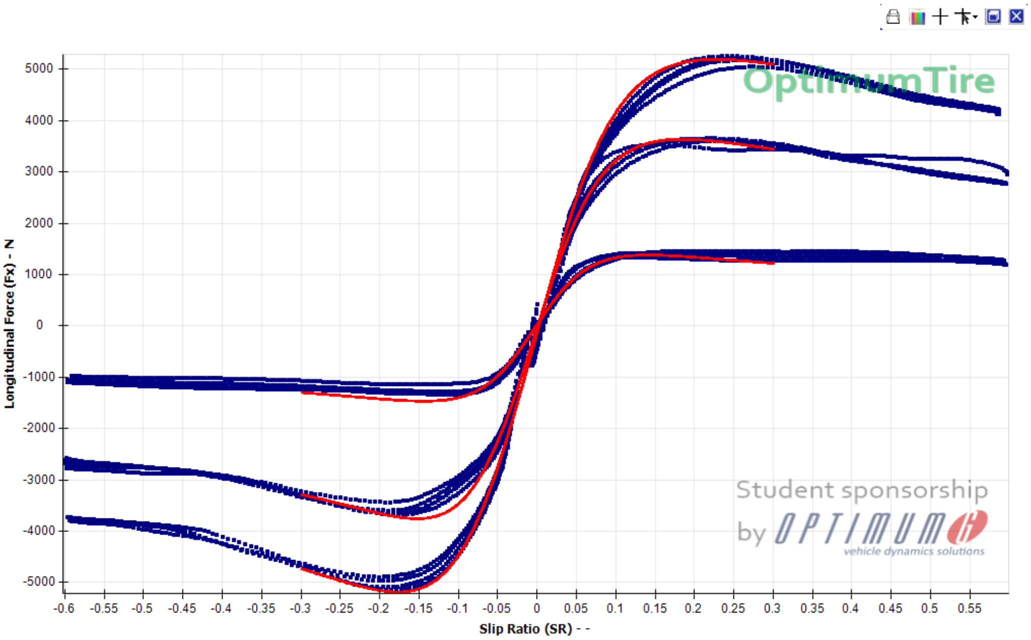


Figure 28: Team-derived Hoosier LC0 tire map showing the relationship between slip ratio and force on the wheels.

Once the generated wheel torque is found from the look-up table, it is subtracted from the maximum possible wheel torque to get the torque requested. As seen from the graph in *Figure 28* above, the maximum torque is at slip ratios of about .155, however, if the slip ratio is higher than these values, the torque requested will have to be negative. Part of this algorithm determines whether the slip ratio is higher than .155 and then multiplies the torque requested by negative one if that scenario is satisfied. The block diagram for tire slip control that has been created in Simulink is below in *Figure 29*.

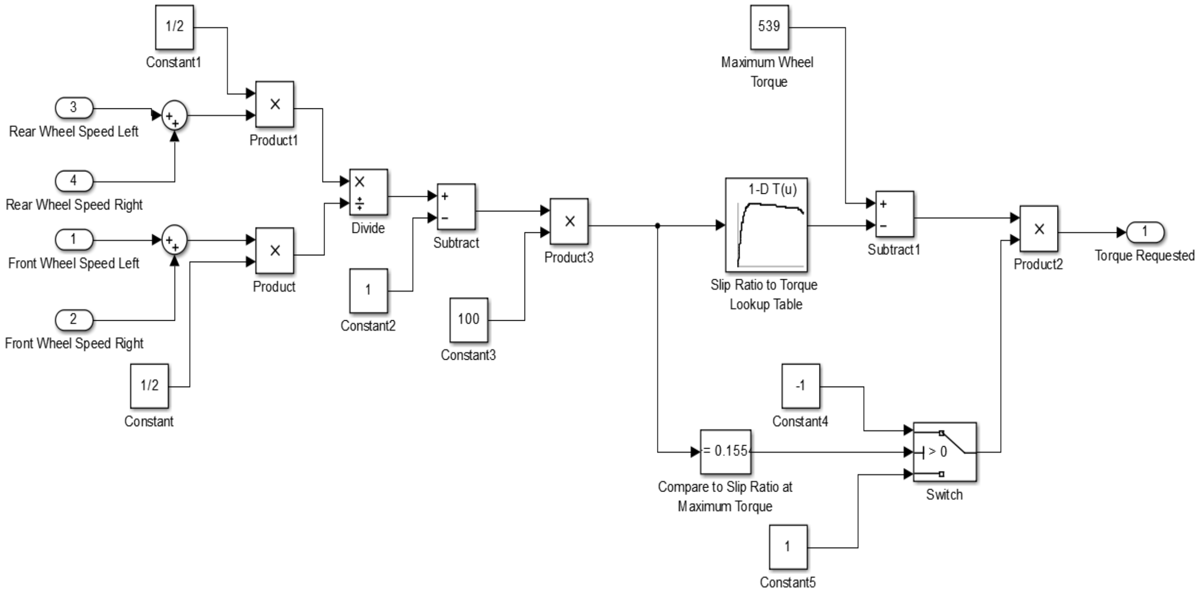


Figure 29: Block diagram of tire slip control in Simulink.

The second block represents wheel torque control. The input of this block is engine speed and wheel torque. The engine speed is put into a look-up table of engine speed against engine torque which is shown in *Figure 30* below. Next, the ratio of the requested torque to the generated engine torque is calculated - this is called the clutch effort. The Simulink block diagram of the wheel torque control is below in *Figure 31*.

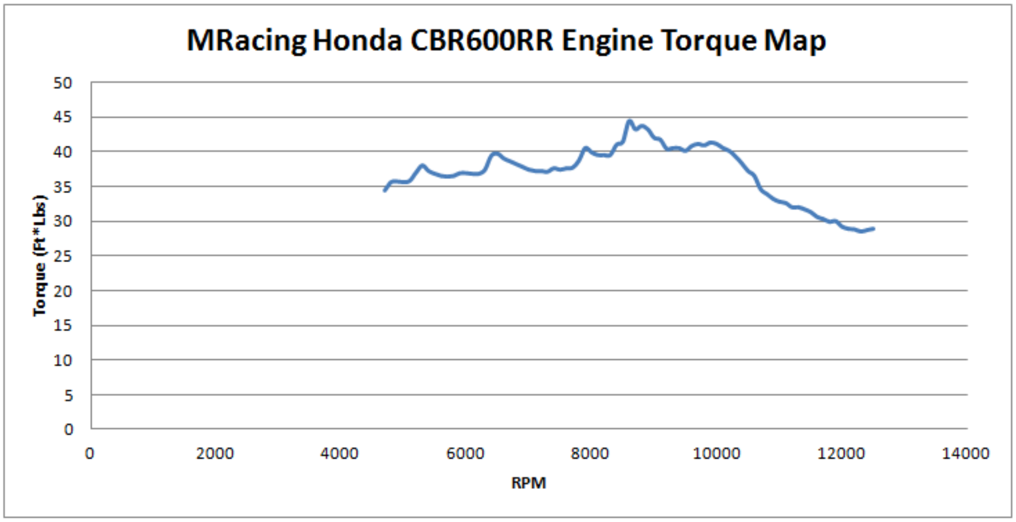


Figure 30: Engine torque map showing the relationship of engine speed (RPM) to engine torque (ft-lbs).

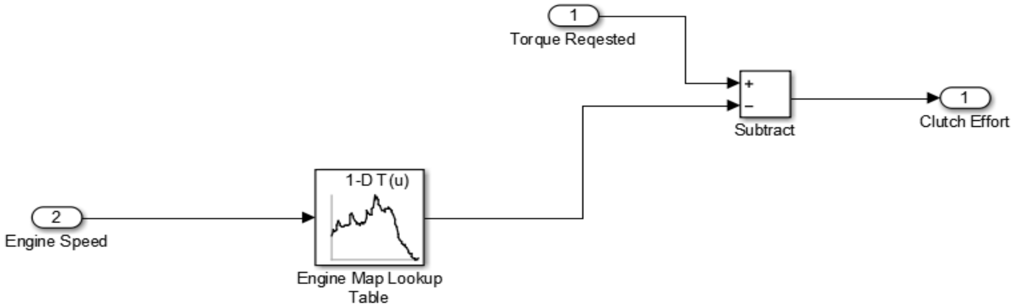


Figure 31: Block diagram of wheel torque control in Simulink.

The third block represents the clutch force control. For this block diagram, a look-up table of clutch effort against motor position must be created, which will be empirically tested once the system has been assembled on the car. In order to test clutch effort against motor position, the team will produce a spindle adapter which will mate with the head of a torque wrench. Then, a motor position will be chosen, held (stalled), and the team members will use a torque wrench to determine how much torque is required to cause the clutch plates to slip. The team will perform many tests at different motor positions in order to obtain a graph of clutch effort versus motor position.

For this third block diagram, as shown in *Figure 32* below, an input of actuator position is used to determine an initial clutch effort using the clutch effort graph. This initial clutch effort is summed with the clutch effort output from the second block diagram and again inputted into the clutch effort graph to obtain the new actuator position. This new actuator position is inputted into the PID controller that will determine the voltage required using a pulse width modulation signal. Pulse width modulation will be used to adjust the motor to a specific position. The constants for the PID controller will need to be obtained through testing (K_P, K_I, K_D). First K_I and K_D will be set to zero to determine the optimal K_p that will be large enough without any overshoot. Next K_D will be determined to minimize oscillation and finally K_I will be determined to reduce the steady state error.

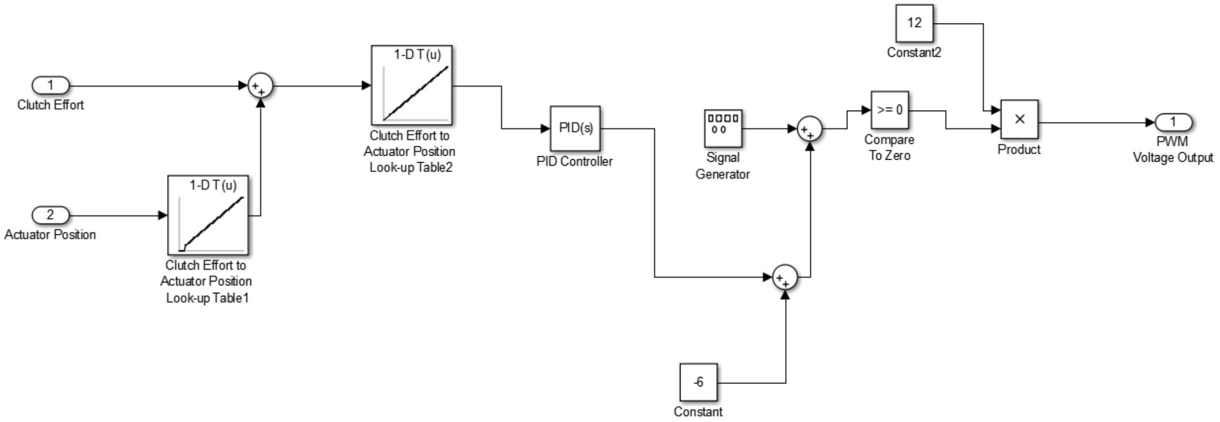


Figure 32: Block diagram of clutch force control in Simulink.

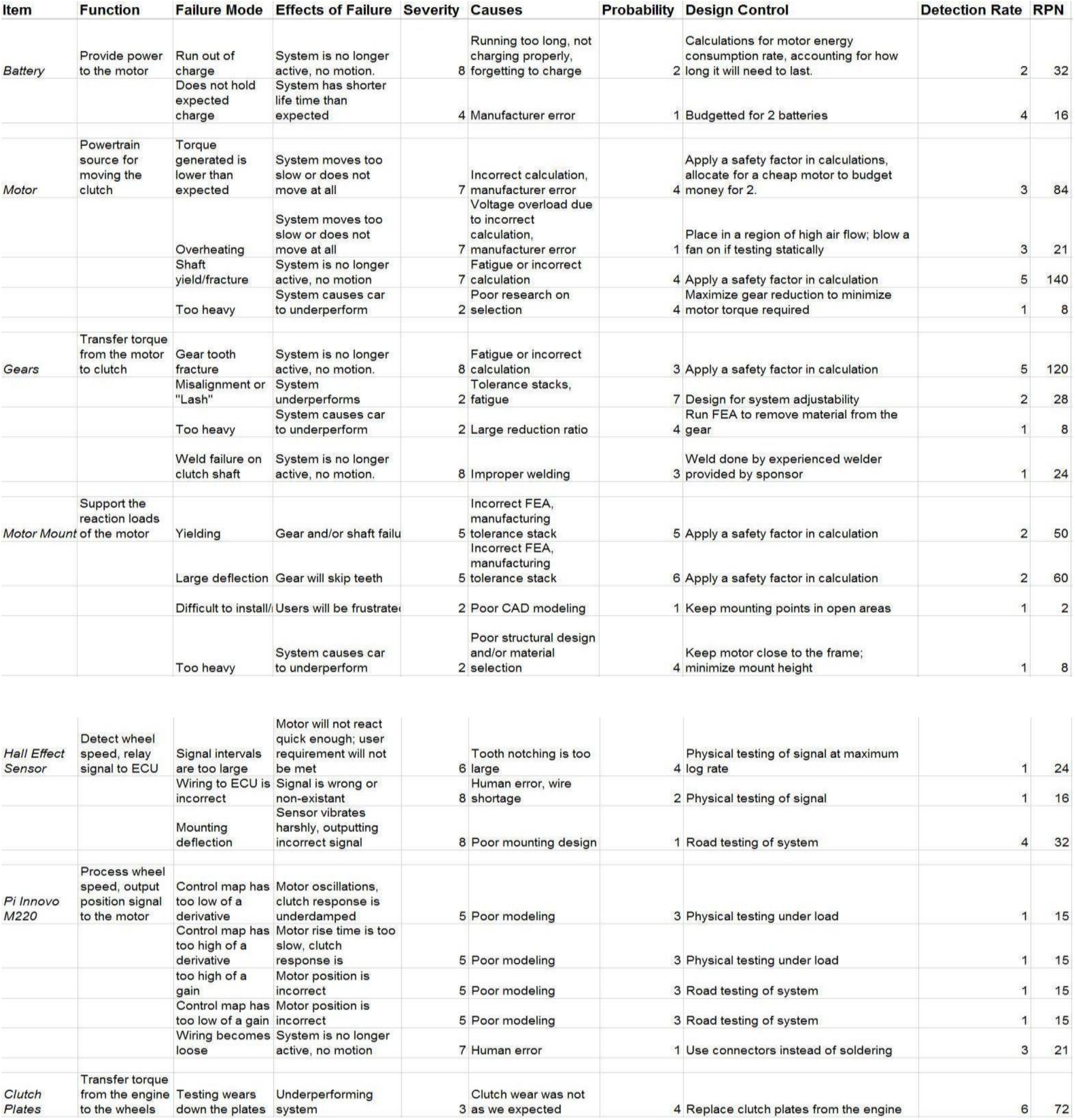
15.0 FMEA/RISK ANALYSIS

The following sections describe the analysis of the FMEA and Risk Analysis.

15.1 FMEA

Table 6 below shows all the failure modes in an FMEA chart.

Table 6: The FMEA



Item	Function	Failure Mode	Effects of Failure	Severity	Causes	Probability	Design Control	Detection Rate	RPN
Battery	Provide power to the motor	Run out of charge	System is no longer active, no motion.	8	Running too long, not charging properly, forgetting to charge	2	Calculations for motor energy consumption rate, accounting for how long it will need to last.	2	32
		Does not hold expected charge	System has shorter life time than expected	4	Manufacturer error	1	Budgetted for 2 batteries	4	16
Motor	Powertrain source for moving the clutch	Torque generated is lower than expected	System moves too slow or does not move at all	7	Incorrect calculation, manufacturer error	4	Apply a safety factor in calculations, allocate for a cheap motor to budget money for 2.	3	84
		Overheating	System moves too slow or does not move at all	7	Voltage overload due to incorrect calculation, manufacturer error	1	Place in a region of high air flow; blow a fan on if testing statically	3	21
		Shaft yield/fracture	System is no longer active, no motion	7	Fatigue or incorrect calculation	4	Apply a safety factor in calculation	5	140
		Too heavy	System causes car to underperform	2	Poor research on selection	4	Maximize gear reduction to minimize motor torque required	1	8
Gears	Transfer torque from the motor to clutch	Gear tooth fracture	System is no longer active, no motion.	8	Fatigue or incorrect calculation	3	Apply a safety factor in calculation	5	120
		Misalignment or "Lash"	System underperforms	2	Tolerance stacks, fatigue	7	Design for system adjustability	2	28
		Too heavy	System causes car to underperform	2	Large reduction ratio	4	Run FEA to remove material from the gear	1	8
		Weld failure on clutch shaft	System is no longer active, no motion.	8	Improper welding	3	Weld done by experienced welder provided by sponsor	1	24
Motor Mount	Support the reaction loads of the motor	Yielding	Gear and/or shaft failu	5	Incorrect FEA, manufacturing tolerance stack	5	Apply a safety factor in calculation	2	50
		Large deflection	Gear will skip teeth	5	Incorrect FEA, manufacturing tolerance stack	6	Apply a safety factor in calculation	2	60
		Difficult to install/	Users will be frustrate	2	Poor CAD modeling	1	Keep mounting points in open areas	1	2
		Too heavy	System causes car to underperform	2	Poor structural design and/or material selection	4	Keep motor close to the frame; minimize mount height	1	8
Hall Effect Sensor	Detect wheel speed, relay signal to ECU	Signal intervals are too large	Motor will not react quick enough; user requirement will not be met	6	Tooth notching is too large	4	Physical testing of signal at maximum log rate	1	24
		Wiring to ECU is incorrect	Signal is wrong or non-existant	8	Human error, wire shortage	2	Physical testing of signal	1	16
		Mounting deflection	Sensor vibrates harshly, outputting incorrect signal	8	Poor mounting design	1	Road testing of system	4	32
Pi Innovo M220	Process wheel speed, output position signal to the motor	Control map has too low of a derivative	Motor oscillations, clutch response is underdamped	5	Poor modeling	3	Physical testing under load	1	15
		Control map has too high of a derivative	Motor rise time is too slow, clutch response is	5	Poor modeling	3	Physical testing under load	1	15
		too high of a gain	Motor position is incorrect	5	Poor modeling	3	Road testing of system	1	15
		Control map has too low of a gain	Motor position is incorrect	5	Poor modeling	3	Road testing of system	1	15
		Wiring becomes loose	System is no longer active, no motion	7	Human error	1	Use connectors instead of soldering	3	21
Clutch Plates	Transfer torque from the engine to the wheels	Testing wears down the plates	Underperforming system	3	Clutch wear was not as we expected	4	Replace clutch plates from the engine	6	72

The failure mode in the FMEA with highest risk for the project’s design was *Shaft Yield/Fracture* under the *Motor* category. Since the shaft that is connected to the clutch pack was designed by Honda and has already been tested on the motorcycle, the shaft that causes concern is the one on the motor. Although the shaft is designed for the motor and definitely won’t fail under the rotational forces generated by the motor itself, it was important to be cautious since implementing a one stage gear reduction to transmit torque (this would introduce bending stresses. The likelihood of this failure was determined to be moderate, however, contrary to the prior section discussing the stresses experienced by the motor shaft, the true stresses experienced by the motor shaft is relatively unpredictable since it is not known quickly the motor will accelerate when the system draws maximum current. If this mode fails, then another motor shaft would need to be manufactured that would need to be heat treated for increased strength and rigidity.

15.2 Risk Analysis

Table 7 below shows the analysis for all the possible risks.

Table 7: Risk analysis

Hazard	Hazardous Situation	Likelihood	Impact	Level	Technical Performance	Schedule	Cost	Action to minimize hazard
Electrical Shock	When operating the system, staff could be shocked due to touching exposed wire or battery terminals.	High	1	2	Mionr reduction in technical performance or supportability, can be tolerated with little or no impact on system.	Minimal or no impact	Minimal or no impact	Ensure insulation are well implemented.
Broken Parts	When running the system, drive train or power train might fail due to having too much torque resulting in broken parts flying out after breaking and cause injuries.	Mid	4	5	Significant degradation in technical performance and can cause the failure to our system and need rebuild.	Postpone design progress significantly	Budget increase. (>10%)	Make sure engineering analysis and parts selection done correctly.
Rotating Drive Train	When running the test for our drive train, staff's hands or anything might accidentally stick in between the drive train.	Low	4	3	Minor reduction in technical performance but can cause significant impact under certain circumstances.	Postpone design progress slightly	Budget increase. (>5%)	Make sure that power is off when assembling. Emergency switch might be installed.
Car Accident	When running the system, the car might go out of control and hit someone nearby or any obstacle.	Low	5	3	Minor reduction in technical performance and however can be significant when it is bad.	The range of the postpone can be minor or significant depend how bad it is	Budget increase. (10%-infinity)	Ensure that enough space is provided and people stand far enough and braking system is working well.

In the risk analysis, the *Broken Parts* category would be of the highest risk. Although it doesn't seem as though it has high probability of occurring, if it did happen, then broken parts from gears, shafts, and any other broken components would fly out and may cause severe injuries. Also, once any part breaks, it will be necessary to re-design and re-manufacture a new set to replace the broken components. The ways to minimize the potential for hazards is to design the parts to meet the strength requirements by properly running FEA and ensure that they have a safety factor of 1.2. Also, when the system is tested, everybody in the vicinity will be required to wear long sleeve clothing, long pants, cover-toe shoes and safety glasses.

16.0 MANUFACTURING PLANS AND DRAWINGS

The manufacturing plans have been moved to Appendix A. Please reference the "Bill of Materials" and "Manufacturing Plans" in Appendix A.

16.1 Manufacturing Pros and Cons

The prototype contains a relatively small number of parts to be manufactured, as well as a very low number of manufacturing method needed to produce the parts: milling, water jetting, and sawing. This is a huge "Pro" for the project, because it means the system will be subjected to a relatively small amount of error and stackup tolerances, which could greatly affect the performance of the system in a negative manner. Another “Pro” is that the material that will be used is fairly cheap- steel and aluminum. Exotic, expensive materials, such as Titanium and carbon fiber, are not required for this system. A concern that has been come across in the prototyping is the manufacturing error and tolerance stackups on the frame/engine combination. The position of the engine in the overall CAD is approximated because the engine model was produced by scans from a coordinate measuring machine (CMM), and could be off by .05-.10” in any direction. This issue is completely uncontrollable, which is why a large amount of adjustability was incorporated into the design of the mount. The combination of the upper and lower slots give the motor two degrees of (limited) freedom.

17.0 ASSEMBLY PLAN

Assembly drawings have been created to make sure our system is going to be built correctly. *Figure 33* shows an overall assembly view with steps. All of the steps will be explained on the next page.

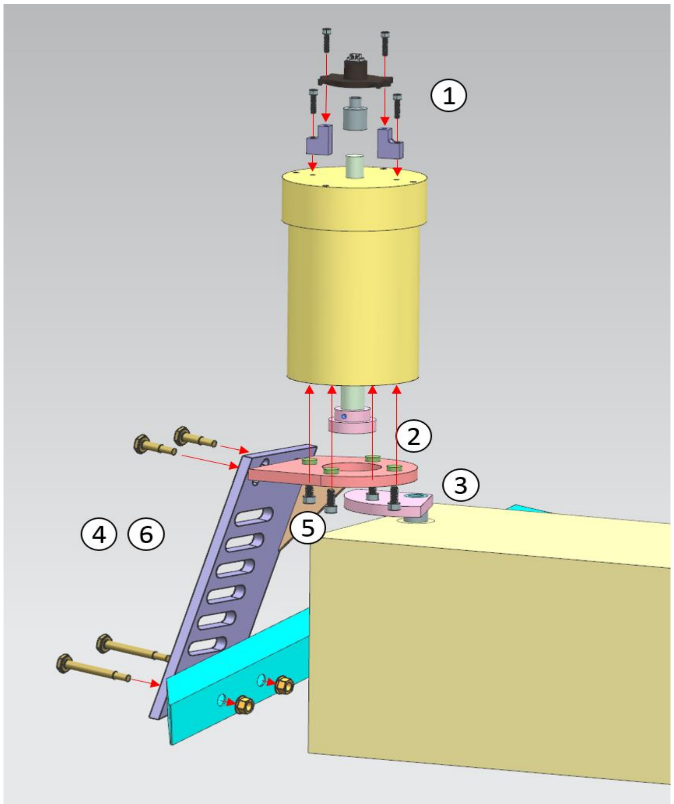


Figure 33: Shows the overall assembly view with step numbers and the instruction for each step is show below.

Step 1:
Screw encoder mount on the top of the motor and press fit the encoder adaptor onto the rear shaft. Then press fit the encoder on the other side of the encoder adaptor and screw them on to the encoder mount.

Step 2:
Screw the motor onto motor mount bracket with washers in between.

Step 3:
Weld the quarter gear and gear adaptor to the clutch shaft.

Step 4:
Adjust the position of the bolts relative to the four slots until two gears mesh perfectly with each other, then tighten the upper two screws that connect the motor mount frame with the motor mount bracket.

Step 5:
Take out the two bottom bolts that fix the motor mount frame on the chassis and then weld the gusset plate between the motor mount frame and the motor mount bracket.

Step 6:
Adjust the bottom two bolts until the gears mesh perfectly with each other and then tighten them.

18.0 VALIDATION PLAN

The validation segment can be broken up into three categories before the entire system is tested on the vehicle. Individually, the mechanics, electronics, and code (controls) must all pass validation testing in order to minimize full-vehicle testing and other potential failures. This section describes each individual plan, followed by a full-vehicle validation plan. The full validation plan has been moved to Appendix C.

19.0 VALIDATION RESULTS

Progress and current results are explained in the following sections.

19.1Mechanics

The mechanical validation results of the weight, torque generation, stiffness, and failure (stress) have been complete with passing grades. *Figure 34* below shows the final mechanical product mounted on the vehicle.

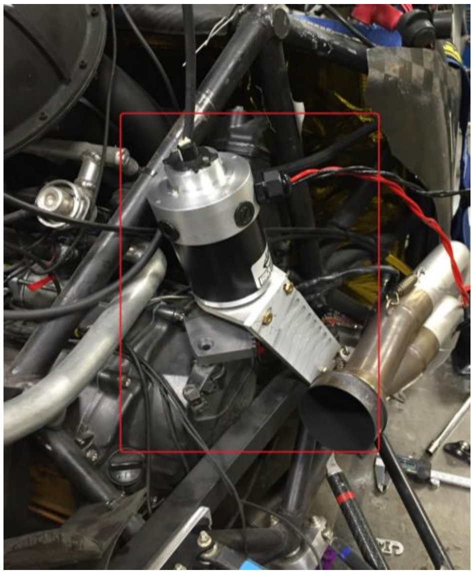


Figure 34: The final mechanical product has been mounted and tested on the vehicle.

Torque, stiffness, and failure were tested by running the motor, slowly, over its maximum range of motion (~10 degrees). A power box was used to control the current flow to prevent a quick and unwarranted lash. The results are shown in *Table 8* below.

Table 8: Incrementing the current shows that the static clutch torque is 11.7 ft-lb.

Current (Amp)	**Voltage (V)**	**Full-Range Movement (Y/N)**	**Motor Torque (ft-lb)**	**Clutch Torque (ft-lb)**
25	12	N	2	6
30	12	N	2.51	7.53
35	12	N	3.02	9.06
40	12	N	3.53	10.59
45	12	Y	3.9	11.7

The clutch moved under 11.7 ft-lbs of torque, 1.7 ft-lbs over the user requirement. This can be accounted for in motor and gear efficiency losses. Significant deflection was observed by the engineers, instigating the welding of a stiffening truss onto the mount. A second test at 12 V, 45 A proved that deflection was noticeably reduced. This validated our FEA model, as well as the fact that failure did not occur. The final system weight measured in at 5.09 lbm, as shown below.

Figure 35: The weight of the system is below 6 lb, meeting the user requirement.

The original target of 5 lb was only missed by +0.09 lb.

The speed validation (under .02 seconds) has not yet been validated for safety concerns on the controls end. Encoder/controller issues delayed testing and raised concerns within the team, causing a decision to be made to prove the system on a test bench first. Any sudden lash or unwarranted motion from the motor could cause major failure to our entire project or the MR15 Honda CBR 600 engine, which could be catastrophic for the entire MRacing team.

19.2 Electronics

The team has proven that the designed circuitry is fully functional through a proof-of-concept model that is hooked up to a dummy motor (very cheap motor that draws low current), as shown in *Figure 36*, below. The next step is to remake the circuitry with thicker wires and with heat sinks for the MOSFETs without the use of a breadboard. Afterwards, the team will implement the wiring into the wiring system of the vehicle.

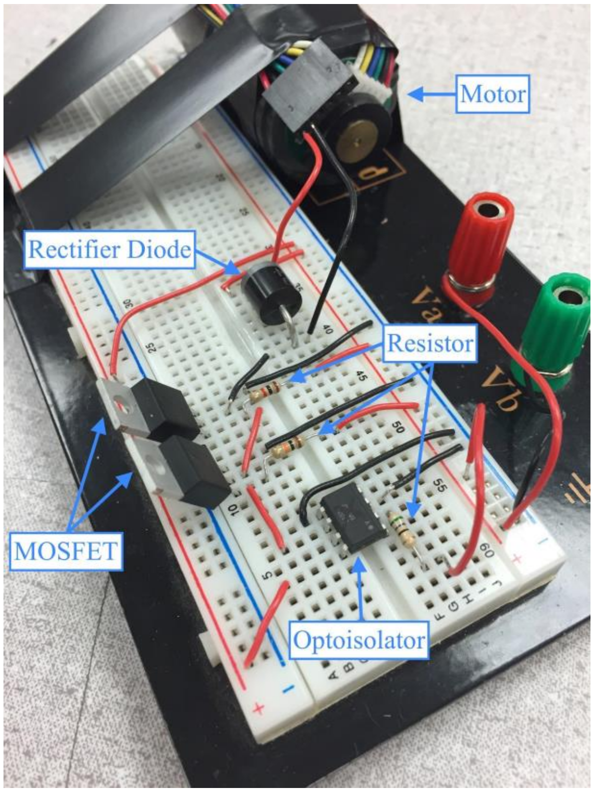


Figure 36: A proof-of-concept circuitry makes it much easier to troubleshoot wiring issues prior to vehicule implementation.

This concept was validated by running power through the circuit and verifying that the optoisolator completed the circuit to the motor when a voltage (5 V) was applied.

19.3 Controls

Basic proof of concept trials were ran, with the results shown in *Table 9* below. The reason only a couple data sets were taken was due to the fact that the code at this moment still does not account for incredibly high slip ratios where the torque requested would essentially be infinite. To solve this problem, the code will have to have a default torque requested for when the slip ratio is too high.

Table 9: Input wheel speeds and engine speeds create a simulated launch, resulting in a "Clutch Effort"

Left Front Wheel Speed (mph)	Right Front Wheel Speed (mph)	Left Rear Wheel Speed (mph)	Right Rear Wheel Speed (mph)	Torque Requested (Nm)	Engine Speed (RPM)	Clutch Effort (Nm)
33.18997	33.02487	46.64166	46.81645	-33.5	8434	-785
35.85019	36.65604	43.05908	44.58337	-9.64	8969	-784
38.33729	39.27419	42.13026	42.14641	32.3	9112	-727

A basic test bench, using the small motor provided in Figure 36, above, to prove the controller outputs could be translated physically through the PWM. Using the same fake signals from above, the results were positive, and the motor responded in the same manner. The only difference between this motor and the actual motor are the PID coefficients.

20.0 PROJECT DEVELOPMENTS

The team constructed a steel frame on which some of the project components were mounted. For the project components that could not be mounted, the team decided to use placeholder parts in order to represent the parts not on the model. *Figure 37* below shows the steel frame that was built by team 30.

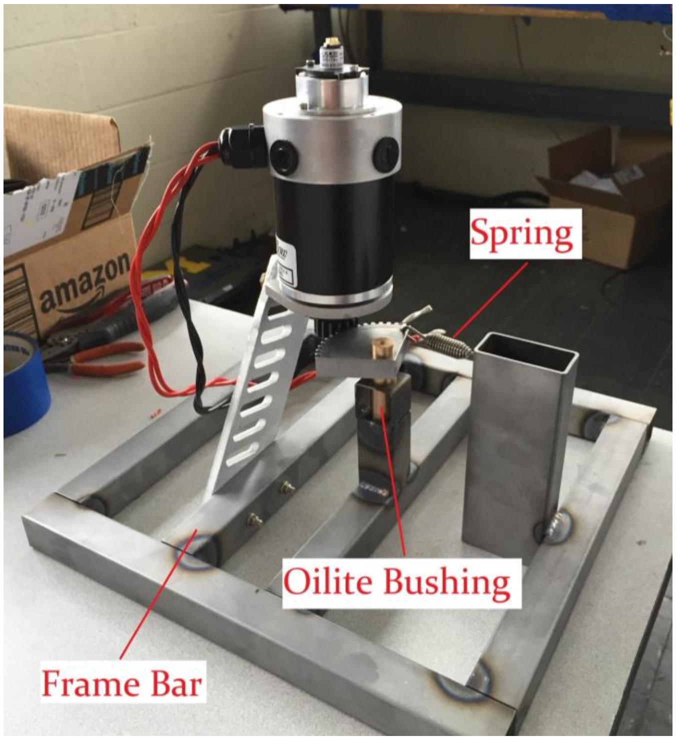


Figure 37: Steel frame consisting of a representative frame/motor/gear/clutch model off of the vehicle.

The photo above shows the visualization model that was built by the team. The model consists of a frame bar to represent the chassis bar on the vehicle that the motor and mount are mounted to. The oilite bushing on which the big gear is mounted to is meant to represent the clutch lever that is partially encased inside of the engine. This component rotates and engages/disengages the clutch pack by pulling on a set of 5 springs, which are represented by the 1 spring in the visualization model.

21.0 ENGINEERING CHANGE NOTIFICATION

An engineering change occurred during the encoder assembly process, which lead to the recognition of a missed variable in our encoder mount. The encoder specification sheet indicates an axial tolerance of ± .025", which was not met by the original mount. The new mount was engineered and manufactured with much higher precision. This design change has not affected the team in any way. The drawings in *Figure 38* and *Figure 39* below show the design change.

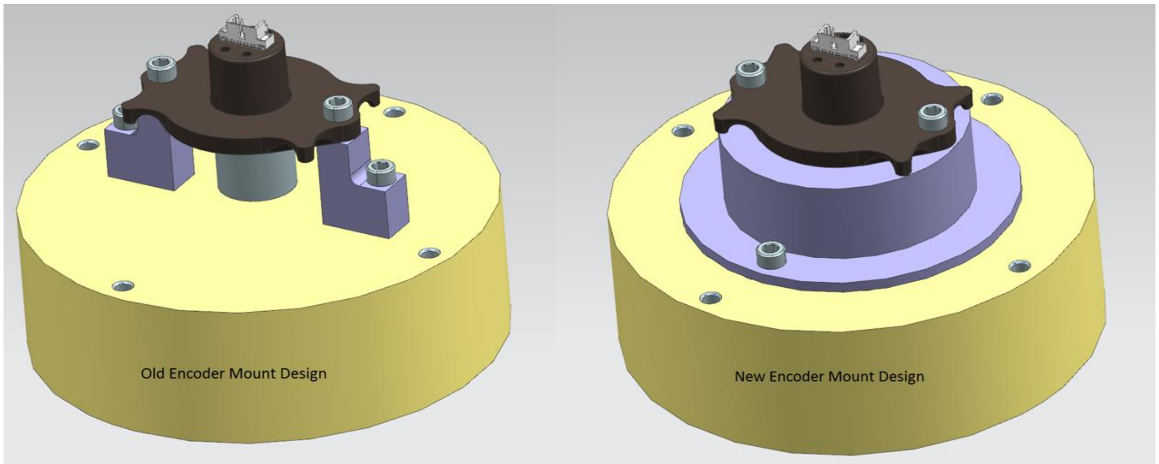


Figure 38: Engineering change on the encoder mount allows higher precision from the encoder.

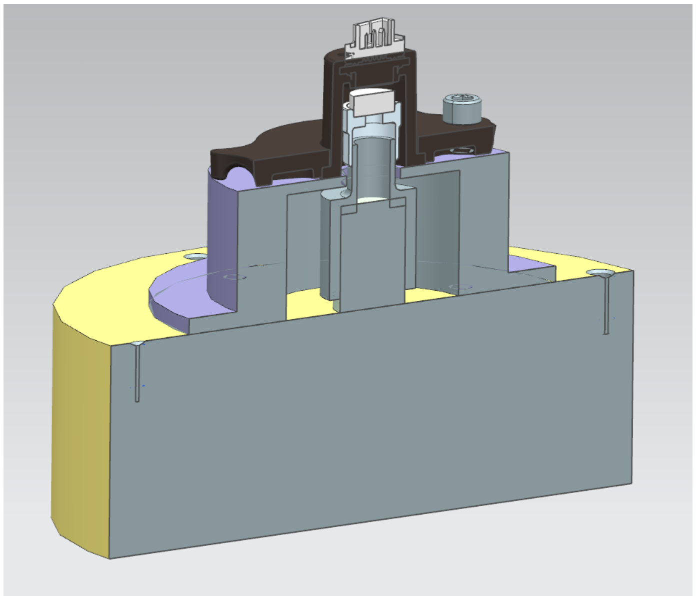


Figure 39: Cross-section view of the new encoder mount shows a better representation of the system.

This new encoder mount has been manufactured and assembled onto the motor without any issues. *Figure 40 below* shows the manufactured product.

Figure 40: New encoder mount is installed properly onto the motor.

22.0 DISCUSSION

This section discusses the design critiques and work that needs to be completed post-ME450.

22.1 Design Critique

Several engineering critiques can be made after completion of this project. Some include spending more time on the controls sub-system, verifying the CAD model before manufacturing, and working with the Pi Innovo M220 more closely.

Controls: The methodology behind the controls system was loosely understood and became a time issue once the mechanics were complete. Implementation of the model also became difficult once the methodology was fully understood. For the future, the team recommends having a suspension engineer and electrical engineer work together, where the suspension engineer handles the methodology and electrical engineer implements the code.

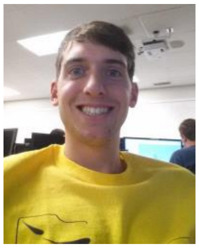
CAD: It was understood from the MRacing team that the frame/engine CAD model was not exact. Adjustability was built into our design for this reason, but the magnitude of CAD error on the engine model was much higher than expected. For the future, the team recommends redesigning the bracket for a higher range of adjustability.

Pi Innovo M220: Using the built-in MATLAB software on the Pi was difficult and not complying with our original code. For the future, the team recommends building all of the code directly inside the software.

22.2 Future Work

The next steps for this project are creating a circuit based on the proof-of-concept circuit for the prototype system that is able to withstand a much higher current and finding PID coefficients and incorporating them into the Simulink model to control the movement of the motor effectively. After this is completed, the system can be hooked up onto the car and testings can be conducted to assess the performance of the system and validate how helpful the system is to the acceleration performance of the car. The team recommends taking high precautions as these steps are carried out- any error in the circuit or code has potential for heavy damage. In particular, the electronic circuit must have thick enough wire to carry the current, and the components (MOSFETS, diode, resistors) must be mechanically attached to a very good heat sink. The code must also be able to comply with any error signals from sensors, or odd scenarios that could occur on track.

23.0 AUTHORS



Peter Karkos is a Mechanical Engineering student in his 4th year here at Michigan. He is currently the Technical Director of the MRacing Formula SAE Team, specializing in vehicle dynamics and suspension design. In his spare time, he enjoys playing hockey. He is essentially a permanent resident at the Wilson Student Team Project Center due to the amount of hours spent there.

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Shashwati Haldar is a Mechanical Engineering student in her 4th year at Michigan. She is pursuing a minor in Electrical Engineering which has contributed to her interest in the field of controls. In her spare time, she likes to go shopping for clothes and shoes.

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25.0 APPENDIX A: MANUFACTURING

Bill of Materials

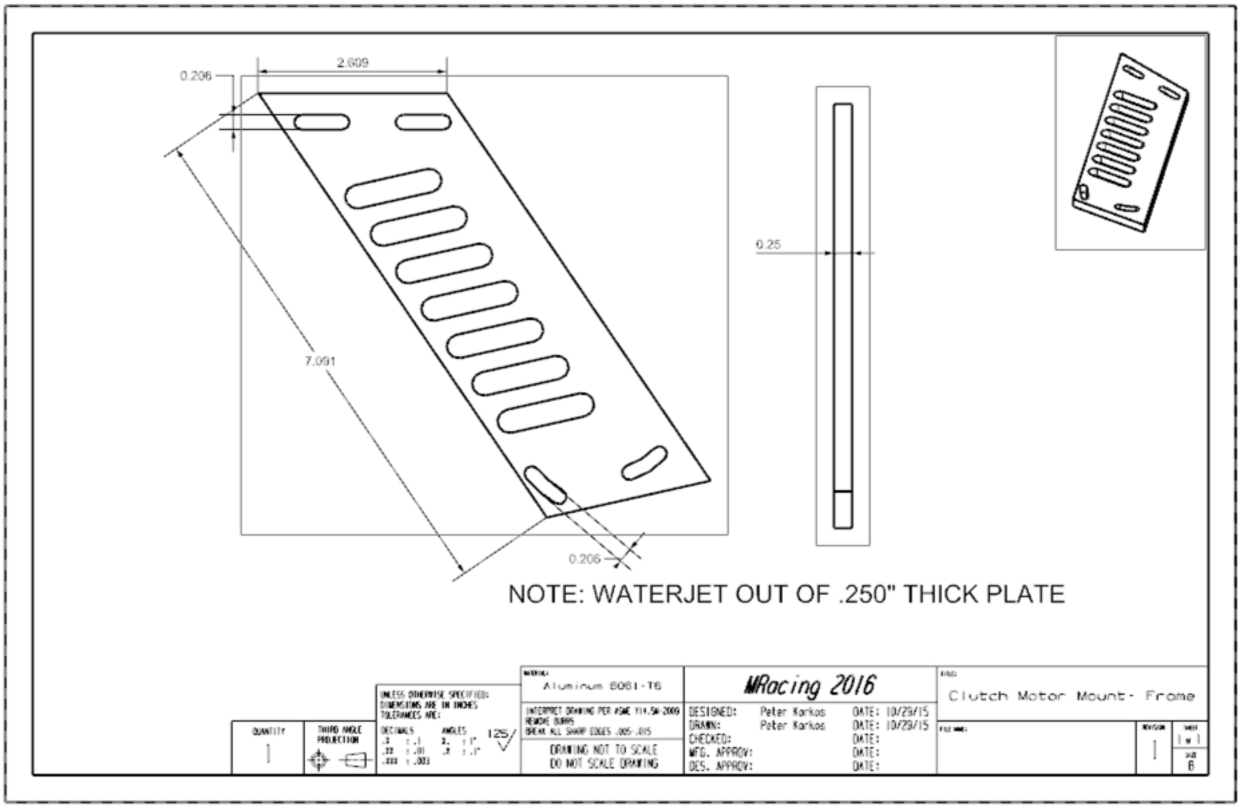
Material	**Type**	**Purpose**	**Length (in.)**	**Width, Radius (in.)**	**Height (in.)**	**Quantity**	**Manufacturer**	**Part Number**	**Cost**
Aluminum 6061-T6	Sheet	Motor mount Frame	7	4	0.375	1			
Aluminum 6061-T6	Sheet	Motor mount	4	4	0.25	1			
18-8 Stainless Steel	Bar	Key Stock	1	0.125	0.125	1	McMaster-Carr	92530A100	$3.18
Steel	Gear	Clutch Gear	0.25	1	-	1	McMaster-Carr	6325K21	$50.61
Steel	Gear	Motor Gear	0.25	3	-	1	McMaster-Carr	6867K41	$46.05
316 Stainless	Washer	Motor Washer	0.038	0.438		100	McMaster-Carr	90107A011	$4.80
Motor	AmpFlow A28-150	Motor	5.6	3		1	AmpFlow	A28-150	$309

Manufacturing Plans

Part Number: ME450-Team30-001
Part name: Motor Mount Frame

Raw Material: 6061 Aluminum Plate, 3/8" x 7" x 4"					
Step #	**Process Description**	**Machine**	**Fixtures**	**Tool(s)**	**Speed (RPM)**

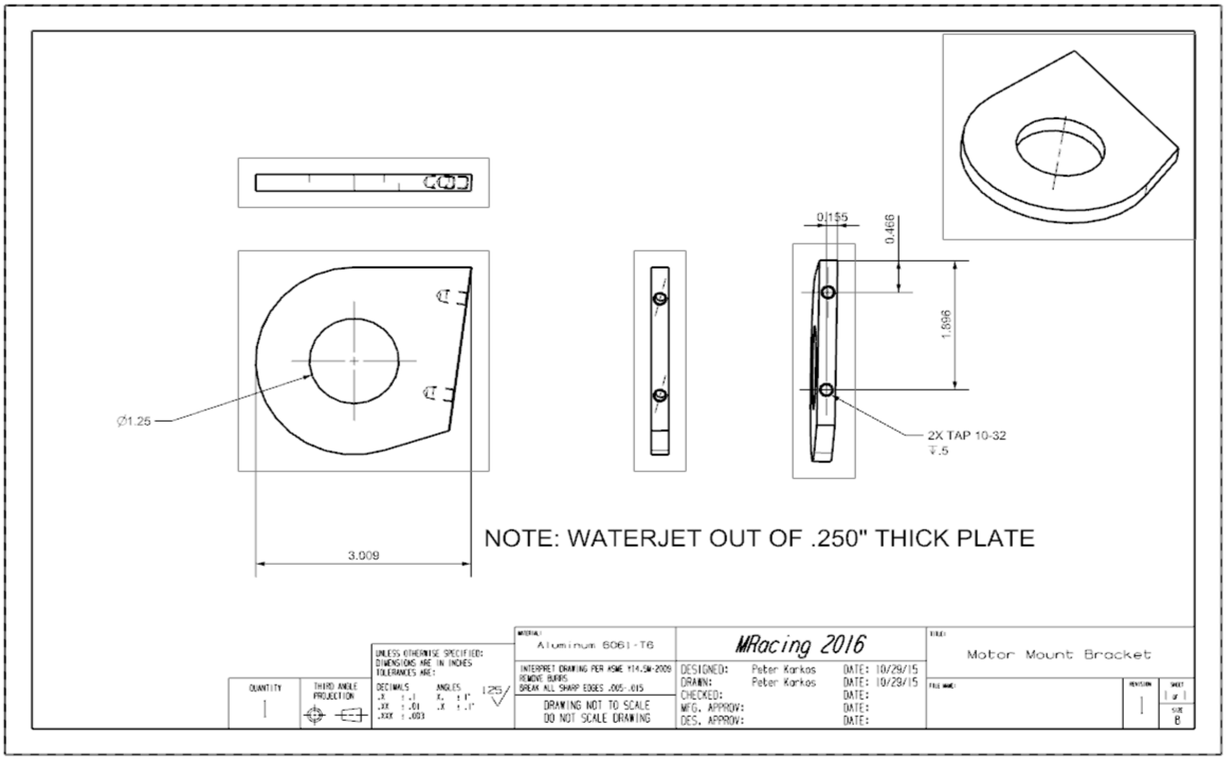
1	Save the model as dxf file with the necessary post-processing modifications.	PC			
2	Save the dxf file to the waterjet.	designated PC for water jet			
3	Follow computer station instructions of waterjet to appropriately compile the file to .ord file	designated PC for water jet			
4	Start waterjet to cut the component profile.	waterjet			



Part Number: ME450-Team30-002
Part name: Motor Mount Bracket

Raw Material: 6061 Aluminum Plate, 1/4" x 4" x 4"					
Step #	**Process Description**	**Machine**	**Fixtures**	**Tool(s)**	**Speed (RPM)**

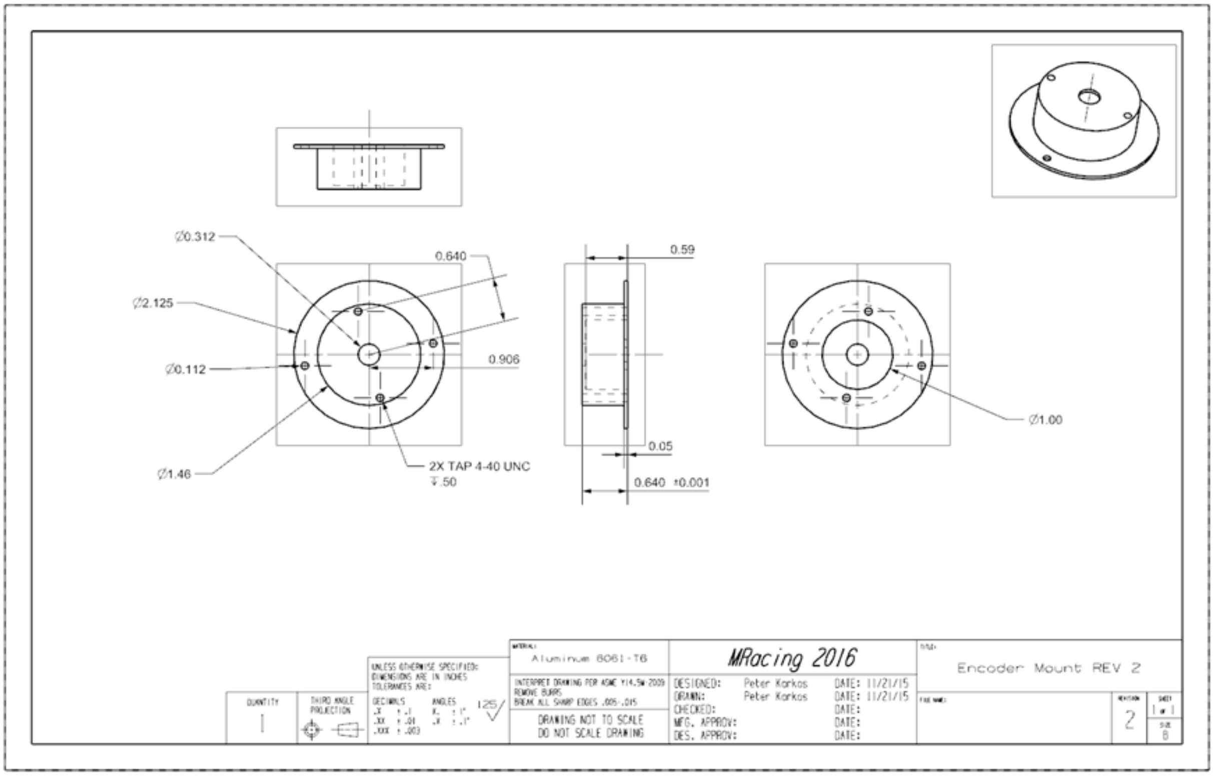
1	Save the model as dxf file with the necessary post-processing modifications.	PC			
2	Save the dxf file to the waterjet.	designated PC for water jet			
3	Follow computer station instructions of waterjet to appropriately compile the file to .ord file	designated PC for water jet			
4	Start waterjet to cut the component profile.	waterjet			
5	Install drill chuck and hold part in vise.	Mill	vise		
6	Find datum lines for X and Y.	Mill	vise	edge finder, drill chuck	900
7	Centerdrill both holes	Mill	vise	Center drill, 19/64" drill bit, drill chuck	1000
8	Drill both holes	Mill	vise	#21 Drill bit	1000
9	Tap both holes	Mill	vise	10-32 Tap	0



Part Number: ME450-Team30-003
Part name: Encoder Mount

Raw Material: 6061 Aluminum Plate, 1/4" x 4" x 4"					
Step #	**Process Description**	**Machine**	**Fixtures**	**Tool(s)**	**Speed (RPM)**
1	Save the model as dxf file with the necessary post-processing modifications.	PC			
2	Save the dxf file to the waterjet.	designated PC for water jet			
3	Follow computer station instructions of waterjet to appropriately compile the file to .ord file	designated PC for water jet			
4	Start waterjet to cut the component profile.	waterjet			
5	Install drill chuck and hold part in vise.	Mill	vise		
6	Find datum lines for X and Y.	Mill	vise	edge finder,	900

				drill chuck	
7	Write down the location of all the holes			pencil	
8	Centerdrill both holes on each mount	Mill	vise	center drill, 19/64" drill bit, drill chuck	1000
8	Drill all the tap holes	Mill	vise	#43 Drill bit	1000
	Drill all the through holes	Mill	vise	#32 Drill bit	1000
9	Tap all the tap holes	Mill	vise	4-40 Tap	0



Part Number: ME450-Team30-004
Part name: Clutch Gear-Weight Reduction

Raw Material: 3" Steel Gear				

Step #	Process Description	Machine	Fixtures	Tool(s)	Speed (RPM)
1	Use protractor and marker to estimate a 45 degree pie-slice on the gear			Protractor	
2	Mark center of gear with hole punch			Hole punch	
3	Cut along marked lines	Bandsaw			150
4	Deburr and/or file edges			Deburring tool	

Part Number: ME450-Team30-005
Part name: Motor Mount Strip

Raw Material: 1/16" Steel Plate					
Step #	**Process Description**	**Machine**	**Fixtures**	**Tool(s)**	**Speed (RPM)**
1	Save the model as dxf file with the necessary post-processing modifications.	PC			
2	Save the .dxf file to the waterjet.	designated PC for water jet			
3	Follow computer station instructions of waterjet to appropriately compile the file to .ord file	designated PC for water jet			
4	Start waterjet to cut the component profile.	waterjet			

Part Number: ME450-Team30-006
Part name: Motor Mount Gusset Plate

Raw Material: 6061 Aluminum Plate, 1/4" x 4" x 4"					
Step #	**Process Description**	**Machine**	**Fixtures**	**Tool(s)**	**Speed (RPM)**
1	Save the model as dxf file with the necessary post-processing modifications.	PC			

2	Save the dxf file to the waterjet.	designated PC for water jet			
3	Follow computer station instructions of waterjet to appropriately set up the software.	designated PC for water jet			
4	Start waterjet to cut the component profile.	waterjet			

26.0 APPENDIX B: CONCEPT GENERATION AND SELECTION

Table 10: Concept generation matrix

Power Source	**Powertrain**	**Drivetrain**	**Sensors**	**Controllers**	**User Input**
Driver Effort	*Vehicle’s 75 hp engine*	*Chain*	*Hall effect*	*Bosch MS4.4*	*Button*
12 V Battery	*Motor*	*Belt*	*Laser speed sensors*	*Pi Innovo*	*Switch*
Pressurized Air	*Pneumatic actuator*	*Gear*	*Human eye*	*Arduino*	*Motion sensor*
Pressurized Liquid	*Hydraulic actuator*	*Spool*	*Human touch*	*Human brain*	*Heat sensor*
Solar energy	*Linear motor*	*CVT*	*Load cell (or torque cell)*	*Beagleboard*	
Biofuel energy	*Driver's arm*	*Very strong magnets*	*Microphone*	*Radio communication*	
Coal energy		*Carbon fiber rod*	*Temperature sensor*	*XBox*	

Hydroelectric energy via random waterfall		*Steel Rod*	*Potentiometer*	*Raspberry Pi*	
Nuclear energy		*Safety wire*	*Accelerometer*	*MSP430*	
Burning propane (or any -ane gas)		*Titanium rod*	*Pressure sensor*	*Nanode*	
Potato battery			*Strain gauge*	*Pinguino*	
Lemon battery			*Variable reluctance sensor*	*STM32*	
Exhaust energy (wind energy)			*Throttle position sensor*	*Teensy 2.0*	
Gasoline			*MEMS magnetic field sensor*	*Intel Galileo*	
			Yaw rate sensor		

Power Source Weighted Selection Matrix

	Weight	Driver Effort	12 V Battery	Pressurized Air	Pressurized Liquid	Solar Energy	Biofuel Energy	Coal Energy
Strength	**8**	1	5	10	10	1	2	7
Reliability	**8**	10	5	1	4	1	1	6
Volume	**7**	10	5	5	3	0	2	0
Ease of control	**7**	5	8	6	6	5	6	6
Feasibility	**10**	0	10	6	6	0	0	0
Cost	**6**	10	9	7	3	0	1	2
Weighted Total		288	325	267	253	5	8	158

	Weight	Hydroelectric Energy	Nuclear Energy	Burning Propane	Potato Battery	Lemon Battery	Exhaust Energy	Gasoline
Strength	**8**	3	10	10	1	1	1	10
Reliability	**8**	6	9	10	1	1	7	7
Volume	**7**	0	8	8	3	3	9	10
Ease of control	**7**	0	4	5	8	8	2	1
Feasibility	**10**	0	0	1	0	0	2	2
Cost	**6**	0	0	6	10	10	5	10
Weighted Total		72	236	320	184	184	208	320

Powertrain Weighted Selection Matrix

	Weight	Vehicle’s 75 hp Engine	Motor	Pneumatic Actuator	Hydraulic Actuator	Linear Motor	Driver's Arm

Ease of Control	**10**	1	10	5	6	8	1
Reliability	**10**	10	10	1	1	9	10
Strength (Power)	**3**	10	4	10	10	1	5
Cost	**5**	10	7	5	1	1	10
Weight	**7**	10	7	5	1	8	10
Weighted Total		260	296	150	112	234	245

Drivetrain Weighted Selection Matrix

	Weight	Chain	Belt	Gear	Spool	CVT	Strong Magnets	Carbon Fiber Rod	Steel Rod	Safety Wire	Titanium Rod
Efficiency	**5**	8	6	10	8	8	10	10	10	6	10
Reliability	**9**	10	7	10	7	5	10	4	10	4	10
Rigidity	**7**	9	7	10	7	8	1	8	10	2	10
Accuracy	**10**	8	6	10	6	9	10	7	9	6	9
Cost	**5**	7	8	5	10	1	6	1	10	10	1
Weight	**7**	7	8	6	7	0	5	10	3	9	8
Feasibility	**10**	9	9	10	9	0	2	5	5	6	5
Weighted Total		447	388	477	401	236	332	337	421	313	411

Sensors Weighted Selection Matrix

	Weight	Hall effect	Laser Speed Sensor	Human Eye	Human Touch	Load Cell or Torque Cell	Microphone	Temperature Sensor	Yaw Rate Sensor
Accuracy	**10**	5	8	1	1	5	4	7	7
Ease of use	**7**	10	6	10	10	7	6	7	6
Reliability	**9**	8	8	2	2	5	6	5	6
Cost	**5**	10	3	10	10	8	7	8	6
Volume	**6**	9	9	10	10	9	5	9	9
Weighted Total		296	263	208	208	238	201	258	250

	Weight	Potentiometer	Accelerometer	Pressure Sensor	Strain Gauge	Variable Reluctance Sensor	Throttle Position Sensor	MEMS Magnetic Field Sensor
Accuracy	**10**	7	7	5	5	6	7	7
Ease of use	**7**	7	7	7	6	5	6	4
Reliability	**9**	6	6	6	6	5	5	5
Cost	**5**	8	8	7	6	3	8	1
Volume	**6**	7	7	8	9	7	9	8
Weighted Total		255	255	236	230	197	251	196

Receive/Transmit Weighted Selection Matrix

	Weight	Bosch MS4.4	Pi Innovo M220	Arduino	Human brain	Beagleboard	Radio communication	XBox
Ease of use	**7**	1	10	8	10	3	5	8
Processing Speed	**8**	10	7	8	10	3	10	8
Cost	**5**	10	10	8	10	7	1	1
Feasibility	**10**	10	9	10	0	9	3	3

Weighted Total		237	266	260	200	80	70	155

	Weight	Raspberry Pi	MSP430	Nanode	Pinguino	STM32	Teensy 2.0	Intel Galileo
Ease of use	**7**	10	3	3	5	6	3	5
Processing Speed	**8**	0	5	8	6	8	6	10
Cost	**5**	8	1	2	8	4	4	1
Feasibility	**10**	0	3	3	2	3	2	0
Weighted Total		110	96	125	143	156	109	120

User Input Selection Matrix

	Weight	Button	Toggle Switch	Motion Sensor	Heat Sensor
Ease of Use	**7**	8	10	2	1
Cost	**5**	10	10	2	2
Practicality	**10**	10	10	2	1
Weighted Total		206	220	44	27

27.0 APPENDIX C: VALIDATION PLAN

Mechanics

The validation for bracket stiffness can be verified by running the FEA for von mises stress and deflection. This has already been done in previous design process and has been shown in previous section of the report (Page 23-26). According to the results of the FEA, the maximum stress that occurs in our design was far below the yield strength of the material we are using. However for the deflection, we couldn’t determine a certain value as our target, so we decided to do the validation by running our basic design (without any additional truss and gusset) and evaluate its performance based on our engineering judgement. If the performance is considered bad, truss and gusset will be welded to our mounting structure.

To validate the 10 ft*lbs of torque that needs to be generated from the motor, we are going to observe the system running and see if the motor can move the clutch for a full range of motion which determines if the motor can provide enough torque to move against the full-loaded springs inside of the clutch pack.

In order to validate the 0.02-second motor reaction speed requirement, which is the hardest one among all the user requirement we have, data from the encoder will be used to determine how long it takes for the motor to travel for the full range of motion.

Electronics

The electronics portion of this project can be validated through empirical testing. The validation can be done in two steps: 1) Hook up the completed circuitry to a power source and use a multimeter to test each component and each node to ensure that the voltage readings make sense, 2) Implement the circuitry into the electrical system of the car and test it to see if the motor functions properly.

If the voltage readings that are acquired in step 1 demonstrate that the circuitry is in working order, then it is okay to proceed to step 2 (jumping straight to step 2 is dangerous and can be very time consuming should the system not function properly).

Controls

Validation for each control block (tire, engine, and clutch) will be tested by running mock-signals into each sensor port via Simulink, and comparing the outputs to manual hand-calculations. This is a relatively simple concept, but helps eliminate problems experienced during odd scenarios. Below is a list of scenarios that must pass, virtually, before implementing it physically on the motor.

> **Scenario 1:** Extremely high wheel slip off of the line. In this case, the slip ratio goes to infinite, because the front wheels will be at zero velocity.
>
> **Scenario 2:** Extremely low wheel slip off of the line. In this case, slip ratio goes to zero or negative.
>
> **Scenario 3:** Large difference between front wheels (left/right) and/or rear wheels. In this case, a sensor error, or unknown driving situation, causes the difference between front left and front right to be large (or rear left/rear right).
>
> **Scenario 4:** Grip is fully gained on the vehicle, and the motor is no longer needed. In this case, the motor must be shut off completely

Running this code in real-life will follow the completion of the scenarios listed above.

Full-Vehicle

Full-vehicle testing will, theoretically, be the most simple step, considering the fact that the individual sub-system validations have all passed. This will include running low-speed trials through first gear on different surfaces, such as dry asphalt, wet asphalt, and concrete. Proof of functionality will be determined on whether or not wheel slip can be controlled appropriately. Wheel speed data will be logged to determine this.