6/20/2019

AVOCADO

(AUTONOMOUS VEHICLES OPERATING COLLABORATIVELY TO AVOID DEBRIS AND OBSTRUCTIONS)

FINAL DESIGN REVIEW

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ABSTRACT:

This document covers the design for a collision avoidance system for collaborative vehicle platooning**.** The scope of work includes the creation of two scale model vehicles and a test track for the demonstration of a collaborative vehicle platooning collision avoidance system for the 26th Enhanced Safety of Vehicles conference in 2019. This document covers the design goals of this project, basic background research performed that will define the design needs, intended design process, initial design concept, manufacturing plan, final design, and project management for the successful execution of this project. Collaborative vehicle platooning boasts significant fuel savings for the transportation industry but requires the close following of a lead vehicle. Without automated systems in place this is hazardous. This hazard can be mitigated using sensors to measure the environment, vehicle to vehicle communications, and path planning based on dynamic vehicle models. This design report has been written after upon the final completion of this project before the team members that are going to the regional competition in the Netherlands leave.

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1.0 INTRODUCTION:

The purpose of this project is to demonstrate the safety and increased fuel efficiency of an automated collision avoidance system in collaborative vehicle platooning. This project was cosponsored by Daimler Trucks North America headquartered in Portland, Oregon, as well as Dr. Birdsong, and Dr. DeBruhl of Cal Poly. The mechanical engineering team consists of Cole Oppenheim, James Gildart, Toan Le, and Kyle Bybee who worked in coordination with a team of computer engineers.

Vehicle platooning is a driving technique to increase the fuel efficiency of a group of vehicles by following a lead vehicle closely to reduce the drag experienced by the group. Specifically, large tractor trailer trucks could become more efficient utilizing vehicle platooning. To implement this system most effectively would require an automatic system for collision avoidance. The goal for the mechanical engineering team working on this project was build and design two scale model vehicles, a test track, and dynamic models of the vehicles. These were then interface with computer vision software and hardware (created in collaboration of a team of computer engineers) that allows the vehicles to autonomously platoon and avoid objects that would otherwise cause a collision.

Interactions with the computer engineering team occurred at minimum on a weekly basis and more whenever necessary. Interactions between the team's original occurred as meetings to determine each team individual progress until integration could be accomplished. When the systems were being integrated, meetings occurred regularly (2-3 times a week) to ensure the vehicles could properly execute their design function. The goal of this project is to demonstrate how this system could be implemented in truck platooning safely and to demonstrate the advantages of platooning with system developed. This project was intended and will be presented to compete at the Enhanced Safety of Vehicles conference in the Netherlands in June of 2019. This report covers the scope of work of this project, the preliminary design direction, and the final design direction, and the final design for the assembly of the two 1/10 scale cars, the track design, and the controls strategy to interface with the CPE's software.

2.0 BACKGROUND:

Daimler wants to investigate how automatic collision avoidance in platooning vehicles is a viable option to avoid collisions. The goal of this project which has been accomplished is to present this problem to the ESV competition in the Netherlands in June 2019. The original planned deliverable was to have two dynamically similar vehicles modeled after a front wheel drive sedan that run on a Figure 8 or oval track. These vehicles will be programmed to drive themselves around this track close together to simulate trucks platooning on the highway.

There were two large design constraints on producing this model. The most important limiting factor is the funding provided by Daimler for the procurement of the final deliverable. As of May 2018, Daimler has provided \$2000 in sponsorship for the hardware required by the mechanical engineering team and another \$1100 for the hardware required by the computer engineers. The second design constraint was the portability of this model. This model had to be made to transport to the Netherlands without incurring costs that could go over the funding available for the project. The driving factor for determining the overall size and weight of our design is the size of the micro-controller selected by the computer engineers. The selected micro-controller is a Nvidia Jetson tx2 which is about 17 cm by 17 cm (mechanical drawing of the Jetson is in Appendix I). With this size, the smallest scale car that we can use is a 1/10th scale car.

The final deliverable includes two 1/10th scale 4 wheel drive RC cars that have been outfitted with the Nvidia Jetson tx2 micro-controller, Zed mini stereoscopic cameras, an Arduino Mega controller, and a electronic speed controller for Anaheim automation for the motor, and a track 10 ft by 16 ft which will be brought to the Netherlands.

2.1 ESV COMPETITION

The competition that we will enter is the Student Safety Technology Design Competition (SSTDC). This competition is hosted by the International Technical Conference on the Enhanced Safety of Vehicles (ESV). The goal of this competition is to engage young engineers in working on automotive safety problems. The timeline of this competition is listed in table 4 in the Project Management section. Details for scoring of the abstract and competitions are below. For more information on the competition see ESV's website (www-esv.nhtsa.dot.gov).

2.1.1 ABSTRACT SCORING

The abstract will be scored out of 100 total possible points. The scoring is as follows:

1. 30 points will be given for potential impact on safety being addressed
2. 25 points for originality
3. 25 points for practicality for creating a functional scale model
4. 20 points for the quality and technical depth of supporting details

The abstract is limited to 300 words and will be completed in coordination with the computer engineering team with guidance from Dr. Birdsong and Dr. DeBruhl.

2.1.2 REGIONAL AND INTERNATIONAL COMPETITION SCORING

These competitions will be scored out of 100 points. Scoring is as follows:

1. 40 points for impact on the safety problem being addressed
2. 20 points for originality
3. 20 points functional scale model presentation
4. 10 points for the oral presentation
5. 10 points for the quality and technical depth of supporting details.

2.2 TECHNICAL RESEARCH

Technical research was conducted using the technical resources of the Kennedy Library at California Polytechnic State University and using the guidance provided to us by Dr. Birdsong. Platooning is important because of the fuel savings that could be achieved if this concept is proven to be safe to operate on public roads. Research has shown that trucks traveling at 65 miles per hour with a separation distance between trucks between 57 feet and 142 ft have shown about a 5% savings in fuel [1]. There are two million semi-trucks in the US alone. In the US a truck averages 45000 miles of driving per year. Semi-trucks combined haul 68% of all US goods being transported in semi-trucks [2]. Worldwide, a total of 140 billion miles is driven by semi-trucks per year [2]. Collaborative vehicle platooning will reduce carbon dioxide emissions resulting in a smaller environmental impact. Due to the efficiency increases, less money will be spent on fuel consumption by transportation companies resulting in lower prices of consumer goods.

The increase in efficiency of platooning vehicles stems from the reduced drag that vehicles in a platoon experience. Computational fluid dynamics (CFD) has been used to quantify by the change of the coefficient of drag that each vehicle in the platoon experiences. In a thesis defense by Watts, it was found that there is an optimal distance between trucks that lowers the coefficient of drag that matches what was used in McAuliffe [3] [1]. In the CFD model presented the front truck's coefficient of drag has little to no dependence on the distance of the following vehicle, while the following trucks have a strong correlation between the reduction of the coefficient of drag and the distance behind the vehicle in front [3]. Taking this knowledge into account, an effective way to increase fuel savings is to increase the number of vehicles in a platoon and reduce the distance between vehicles.

However, the time and place that the vehicles enter a platoon formation is important. According to an IEEE (Institute of Electrical and Electronics Engineers) paper on truck platooning, a large group of platooning trucks at low speeds in high traffic situations could hinder traffic flow because of increased lengths of bottle necks [4]. This would be due to the close spacing between trucks not allowing for other vehicles to maneuver around the platoon. The speed at which the fuel savings from a platoon will become desirable must also be considered. For example, it would not be productive for trucks to platoon from a fuel savings perspective at speeds less than 20 miles per hour as the force of drag is a much smaller magnitude than that at 65 or even 55 miles per hour. Drag due to air resistance is proportional to the square of velocity; at low speeds, drag from air resistance is negligible, but it grows with the square of velocity becoming far more significant the faster an object is traveling. The main benefit that was found by the IEEE research for low speed platooning is the space saved in traffic. A concise solution was not determined in this paper, but it was concluded that trucks should be able to platoon and operate independently when appropriate to help overall traffic conditions in high volume areas.

Due to these vehicles possibly traveling less than 100 ft. apart, path planning is needed to find the safest route in the event of an object being present that creates a collision hazard. Path planning is the computed trajectory that the onboard computer system predicts as the safest possible route around a road hazard for a vehicle. For our project we will be considering the following collision avoidance options: run over the object, turn around the object, stop before hitting the object, and reduce speed before hitting the object. To find the best collision avoidance path, the vehicle dynamics of the vehicles in the platoon must be known. Characteristics like stopping distance and maximum angle of turn before rolling over at different speeds must be known and coupled into the path planning algorithm.

To select an RC car to develop our systems with, we will have to consider the dynamic similitude between the small-scale car and an actual sedan. Buckingham Pi theorem evaluate similitude. This theorem compares dimensionless quantities using ratios formed from basic units. These ratios called *pi* groups, which are created from the physical parameters of the system, are used to compare two different systems of different sizes [5]. It is nearly impossible to get complete dynamic similarity between two systems. The *pi* groups for the large scale and the small scale will not exactly match each other. This will be difficult in the scope of this project as we are purchasing an RC car instead of making one from scratch to model a sedan. Compromises must be made to attempt to match the *pi* groups that directly affect desirable characteristics in the scale model. *Pi* groups to be considered when selecting an RC car will include the location of the center of gravity, mass, velocity, width of wheelbase, tire radius, and more. The goal of this project is not to produce a dynamically similar scale model, but to show the concept of automated object avoidance in platooning vehicles, so compromises will be made to stay within budget and to achieve a working representation of the automated object avoidance system.

2.2.1 CONTROLS

The RC car we purchase will have the micro-controller selected by the computer engineers integrated into it. This is not as simple as connecting the wires from the two systems. A controls analysis will have to be performed to ensure or limit steady state error and response time. Physical devices must be selected for the feedback in the system to determine velocity, acceleration and steering angle. Once the micro-controller has been integrated with the RC car, a calibration must be performed to determine the steady state gain or voltage input needed to achieve correct acceleration and steering input [6].

2.2.1 PATH PLANNING

Perhaps the most essential task of this project is to develop a path-planning algorithm to guide the vehicle around an obstruction. Upon sensing an obstruction in the path of the vehicle, the controller will have to decide between one of three possible options. If the obstruction is small enough to be driven over, the vehicle will not change course. If the obstruction is too large to navigate an adequate path around, the vehicle will brake to a complete stop in front of the obstruction. If the object is small enough to be avoided, but too large to run over, the vehicle will plan a path around that object and continue course on the other side of the obstruction.

2.2.3 RC CAR

A previous senior project at Cal Poly named Microlaren bought an RC car for their project. Their final design report defined the differences between hobby and toy RC cars as price, vehicle dynamics, and replaceable parts [7]. The hobby car is more robust, and parts of the suspension can easily be replaced to further increase the dynamic similarity between the model and a real sedan or in the case that a part is damaged. Also, hobby RC cars are mostly made from metal which will give a better structural base to attach the microcontroller. Another important consideration is designing a way to adjust the center of gravity to achieve the vehicle dynamics desired.

2.3 CARMAKER

Carmaker is a vehicle simulation software that will be used to develop the controllers for stopping the RC car and steering the RC car. Carmaker simulates the car and their dynamics as well as their environment. It allows us to adjust the simulation to the parameters that apply to us the most. A platoon and obstacles can be simulated and importantly it integrates with Simulink and Matlab. This allows us to have access to control all of the parameters and data created in each simulation for our own use. Once an RC car has been purchased, the characteristics of the RC will be put into the carmaker software to tune the controllers to decrease the testing time needed to fully tune them once they are implemented into the micro-controller.

2.4 PATENT RESEARCH

The focus of our patent search was technology used in truck platooning. They focus on the technologies used in controlling the vehicles themselves, in vehicle to vehicle communications, in detecting the position of vehicles relative to other platoon vehicles, and in maneuvering the platoon. Relevant patents for this project are found in Table 1.

Table 1: Patents researched with their respective number and a brief description

Number	Patent Name	Patent Number	Description
1	Vehicle Systems and Methods	WO 2014/145918 AI	Controllers used for vehicle to vehicle communications in relations to vehicle platooning
2	Platooning Control via Accurate Synchronization	WO 2016/065055 AI	Control and synchronization of platooning vehicles using relative distance measured by lasers
3	Platooning Methods for Application in Heavy Trucks	WO 2017/196165 AI	A method for controlling a heavy truck using cameras to read the lane lines and steering controllers
4	Platoon Vehicle Management	US 8,352,111 B2	Vehicle platooning controlled with data from GPS devices.
5	Lane Change System for Platoon of Vehicles	US 2017/0011633 A1	Platoon lane change assistance specializing in determining if there is room for a lane change.

The first patent focuses on the controllers used for vehicle to vehicle communications for vehicle in platooning. Using controllers and sensors onboard the truck (including forward and rearward facing cameras) "relative distance, relative acceleration/deceleration, and speed" can be monitored and controlled in accordance to the needs and demands of the drivers, environment, and roadway [8]. This is relevant to our project because using our micro-controllers, our two vehicles must monitor similar parameters such as speed and acceleration and be able to communicate these parameters to the other car wirelessly to remain in platoon and at the correct following distance. This patent also outlines long range communications for truck and user interfaces inside the truck, however, this is outside the scope of this project due to its small-scale nature.

The second patent is a control system for the accurate synchronization of platooning; which is the use of accurate measures to effectively control platoon parameters [9]. They use forward-facing lasers that reflect off the lead vehicle. Distance between the leading and following vehicles can very accurately be measured using these lasers. The vehicles can then be synchronized for platooning effectively. We will also need to determine the distance between vehicles to prevent crashes and maintain an effective platooning distance.

The third patent outlines a system using side mounted cameras tied into an active steering system to assist in the autonomous functions of a truck [10]. They use a system of cameras and a controller solely for the steering of the trucks so that the system can respond quicker than the vehicle to vehicle communications systems implemented in truck platooning and can dampen out any overshoot in the unstable nature of a tractor-trailer set up. We are modeling a rigid-body vehicle without a trailer, so this is not a concern. However, the use of image recognition to actively the steer vehicle inside a lane will be needed.

The fourth patent discusses a method for controlling a group of vehicles in platooning by monitoring vehicle to vehicle communication with data from GPS devices [11]. GPS devices allow vehicles to determine distance from the vehicle directly in front of it and then select a respective position. This process is used for each vehicle in the group. This will be useful for us in understanding real-world technologies used in platooning and support our claims in the competitions.

The last patent highlights the platoon control involved in determining if there is sufficient clearance in another lane for the platoon of vehicles [12]. In response to platoon control, vehicles will maneuver "from the initial traffic lane to the other lane in a manner that limits other vehicles from interrupting the platoon vehicles". In other words, the last platoon vehicle enters the other lane first, and the other platoon vehicles enter the other lane ahead of the last vehicle. This is useful because it suggests possible maneuvering procedures for RC car models in a demonstration at the competition.

2.5 INDUSTRY STANDARDS

In a meeting with representatives from Daimler Trucks North America, they outlined the safety standard ISO 26262. This industry standard defines safety compliance for the failure of electrical and electronic systems in vehicles and uses A.S.I.L. (Automotive, Safety, Integrity, Level) to define the compliance to ISO 26262. A.S.I.L. considers three factors (Exposure, Controllability, and Severity) at varying levels to define the hazard level of failure of a component in a vehicle [13]. This standard will be used in our project to define how we approach the design and safety of critical systems in our vehicles.

Another industry standard relevant to this project is SAE J0316 which defines the levels of autonomy a vehicle will have. See table 2 below for defining each level of autonomy. These definitions are important because it allows us to classify and refer to our level of autonomy. Our desired level of autonomy to achieve is level 5 because our vehicles will not have a driver.

Table 2: Levels of Autonomy as defined by SAE J0316 [14]

SAE Levels of Autonomy		
Level	**Name**	**Description**
1	Driver assistance	Driver is always necessary, supervises and intervenes when necessary
2	Partial Driving Automation	Driver supervises driving automation system, determines when engagement of the driving automation system is appropriate, the system is responsible for braking, steering and acceleration
3	Conditional Driving Autonomy	Driver verifies readiness of system, driver can safely look away when system is engaged
4	High Driving Automation	Driver only needed when system is not engaged, becomes a passenger when the system is engaged, must determine how to achieve minimum risk situation, may request driver takes over
5	Full Driving Automation	No human intervention required, no driver needed

2.6 CURRENT COMPETITORS

The nature of our project is a proof of concept research project. This means there is no direct competitor to automated vehicles that platoon. Table 3 below outlines current industry competitors that make products that relate to our project through autonomy, vehicle dynamics, and platooning.

Table 3: Summary of current competitors and their products

Number	Company	Description
1	Tesla	Tesla Autopilot offer enhanced sensor coverage, 40x more computing power, enhanced autopilot to match speed to traffic conditions, and autosteer that will enable full self-driving [15].
2	Subaru	Subaru Eyesight offers dual color cameras placed near rearview mirror to enable adaptive cruise control, lane keep assist, pre-collision braking, and pre-collision throttle management [16].
3	Peloton Technology	Peloton focuses on collision mitigation systems through radar sensors, vehicle to vehicle communication, a cloud-based system for truck platooning, and an intelligent pairing system based on location and anticipated route [17].
4	Marben Products	Marben offers software solutions for automotive industry to deploy intelligent, automation, and safety applications with key products in sharing information between vehicles and vehicles, vehicles and infrastructures, vehicles and pedestrians [18].
5	Cohda Wireless	Cohda focuses on software solutions to connect vehicles to each other, enable acurate vehicle positioning and cooperative collision avoidance in real time [19].

This research on competitors allowed for us to gain insight on how industry is approaching various autonomy problems and the hardware implementation used. The most popular current implementation of autonomy for consumers is mainly adaptive cruise control and automatic braking to avoid collisions and reduce the energy of collisions. Active object avoidance has not been introduced into the consumer market, let alone a system designed for platooning vehicles as we intend to design. There are companies developing different technologies that can be applied to collaborative vehicle platooning that give us insight on how they could be incorporated into our project.

3.0 OBJECTIVES:

This section is aimed at defining all the goals and objectives of this project. First a problem statement is defined to solidify in words the problem we are trying to solve.

3.1 PROBLEM STATEMENT

Trucking companies, such as Daimler, are interested in evaluating the benefits, efficiency, security, and the ability to apply current technologies in autonomous vehicles to truck platooning by manufacturing and testing scale models. These models will then be evaluated in terms of vehicle dynamics, vehicle to vehicle communication, and road safety. Two scale model vehicles will be required to autonomously avoid a variety of obstacles while collaboratively platooning on a designed test track. This model will need to demonstrate the increased road safety of autonomous platooning vehicle and the inherent economic benefits.

3.2 BOUNDARY DIAGRAM

Below is a basic boundary diagram illustrating the responsibilities of the mechanical engineering team compared to the team of computer engineers we are working with. Our team is responsible for the physical systems and there is overlap in the electronics portion of the project and the model we will be presenting at competition.

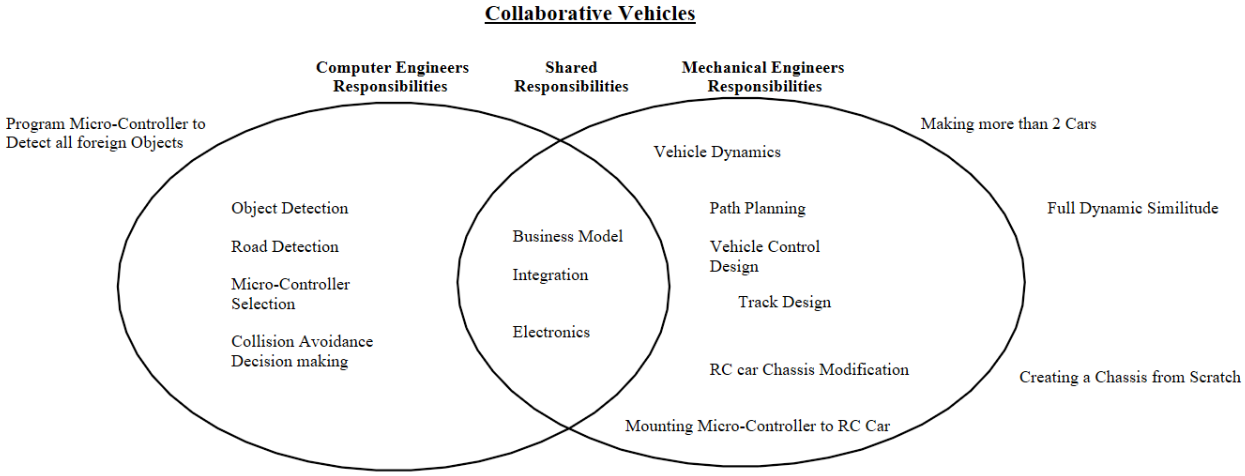


Figure 1. Boundary Diagram outlining the scope of our work compared to the computer engineers

3.3 CUSTOMER NEEDS

The needs we identified in this project are the construction of two scale model vehicles and a test track to demonstrate their ability to avoid objects autonomously while platooning. These vehicles need to be durable, so that when they inevitably crash, they do not break. At the same time, they cannot be so heavy that they cannot perform their intended task. They need to be able to handle various collision avoidance scenarios such as a blocked path and a large object avoidance scenario. The vehicles themselves should be dynamically similar to a passenger sedan and we need to be able to mathematically model the vehicles so that an algorithm can autonomously control the vehicles and avoid objects. Also, this whole proof of concept must be transportable with the intent to bring it to the international ESV competition in the Netherlands in June 2019.

3.4 HOUSE OF QUALITY

The QFD process (House of Quality can be found in Appendix A of this document) involved a collaborative effort between all members of our team to define in words the most important needs of this project as presented to us by Dr. Birdsong. After defining the most important needs, we decided on the testing of these parameters. The specifications can be found in the Specification Table below and in the House of Quality. Then we weighted the needs of each sponsor, Dr. Birdsong, Daimler, and Dr. Debrhul and the ESV competition itself, to gain an understanding of which needs are the most important and why they are the most important. We also ranked the relative correlation of each need to each specification. This allows us to quantitatively measure if we have met all the needs moving forward in this project using the specifications set.

3.5 SPECIFICATIONS TABLES

Table 4. Engineering specification table for collaborative vehicle platooning

Spec. #	Parameter Name	Requirement or Target	Tolerance	Risk	Compliance
1	Roll Over Crash Test	Still Functional	Min	M	A
2	Volume	62 linear in.	Max	M	I, A
3	Cost	2,000$	Max	L	A
4	Safe to Ship	FedEx Compliant	Min	L	I, A
5	Safe to Fly With	FAA Compliant	Min	L	I, A
6	Operating Speed	To Scale	±15%	M	T, A
7	Response Time	0.3 sec	± 0.1 sec	H	T, A
8	Wall Crash Test	Still Functional	Min	M	T
9	Large Object Test	Complete Avoidance	Min	H	T
10	Small Object Test	Complete Avoidance	Min	H	T
11	Blocked Path Test	Complete Avoidance	Min	H	T
12	Weight	100 lbs	Max	M	T, A

In the engineering specifications table, we listed the specifications that we have decided to measure our project against. The risk column is how challenging we expect it will be to meet a specification (high, medium, and low). The compliance column is how we will determine if a specification has been met through testing, analysis, inspection, or similarity. Basic requirements include weight, cost, volume, and the safety to ship or travel with.

1. Cost is driven by the budget given to us by DTNA (Daimler Trucks North America) at $2000 dollars for the hardware required by the mechanical engineering team.
2. The other basic specifications (volume, weight, and safety to travel/ship) are all in relation to our goal to represent the United States at the ESV competition in the Netherlands.

3. Our entire project must be capable of being shipped, so it cannot be too heavy or too large and must comply with all federal regulations.

These vehicles must be robust in case of an unintended crash, all system must remain intact and the vehicle must still function. To test our design for robustness, we will subject the vehicle to

1. A purposeful rollover crash test (using just the frame, simulated load)
2. A wall crash test (where the frame hits a wall at operating speed or the load is simulated)

To pass these tests the vehicles/frame must remain relatively undamaged and still possess all functionality. Due to the high likelihood of damage, specific parts or models may be tested for strength, but it is unlikely the whole vehicle will be tested. This is important in the case of the automatic collision avoidance system failing to avoid an object, the vehicle must still work for future demonstrations. The last three parameters are:

1. The blocked path test
2. The large object test
3. The small object test

These are our most critical tests. The blocked path test is when the two vehicles are presented a situation where the whole path is blocked. They must safely come to a stop without hitting the obstruction or each other. The large object test is when the system is presented with a large but avoidable object, both vehicles successfully drive around the object without crashing in anyway. The final test is a small object; the system is presented with an object in the path, small enough that no avoidance is necessary (like a plastic bag to a semi-truck). The two vehicles should not attempt to avoid the object and drive directly over the object.

High risk specifications are the object avoidance tests. These specifications are high risk because they are the most complicated to achieve. They require the successful integration and execution of all systems between the computer engineers and the mechanical engineers. If our vehicle is unable to successfully perform the object avoidance tests without either crashing into the object or crashing in the process of avoiding an object, a major goal of the project has not been reached. We have set out to demonstrate that platooning can be made safe with these technologies integrated into the vehicles. Failing these tests means we have failed to demonstrate this concept.

4.0 CONCEPT DESIGN

Concept design is the entire focus of this preliminary design review. This section will cover how ideas were generated, the top ideas selected, and the chosen design direction. The chosen design direction will be a recommendation of the functions outlined in section 4.1 and will require confirmation by our sponsor.

4.1 CONCEPT MODELS SELECTION PROCESS

Our team generated many ideas to meet the design specifications outlined in the objectives section and to meet the requirements demanded by the autonomous platooning of scale model vehicles. Before these ideation sessions, it was critical to outline the main design decisions of our project to develop concept models and a design direction around. As a team we decided that our critical tasks for PDR were:

1. The selection of an RC car,
2. A basic design for the mounting and protection of the microcontroller,
3. The design of the track,

4. A basic demonstration of the Car Maker software
5. The selection of a path planning algorithm

After making this decision, we focused on creating as many ideas as possible for the microcontroller protection and track design. We performed numerous ideation sessions (mostly focusing on brainstorming techniques) inside and outside of our lab section to create as many ideas as possible. An example of this can be seen in Appendix C where we recorded ideas for reducing the risk of roll over. Appendix D lists ideas we generated as a team for the main functions of this project. Once many significantly different ideas had been generated, we discussed them, and deselected ideas based on feasibility until we were left with 5-10 of the best options. For the selection of the RC car and the path planning algorithm the process was different because these things will not be made by our team. We performed research on both topics to generate a selection of available platforms.

Once the available ideas had been narrowed down to less than ten ideas for the critical design decisions, we selected the design direction for our project. To select the design direction, independent Pugh matrices were created by each member of the team and a weighted decision matrix. The Pugh matrix and weighted decision analysis are included in Appendices E and F. Each Pugh matrix included a small sketch of each design idea and a rating of how it would perform compared to a datum. To further confirm the results, weighted decision matrices were created. We then selected our final design direction using the results of the weighted decision matrices. Each matrix covers a function that will perform independently of the other functions, so the matrices were used to choose individual components rather than a whole system model.

4.2 TOP CONCEPTS

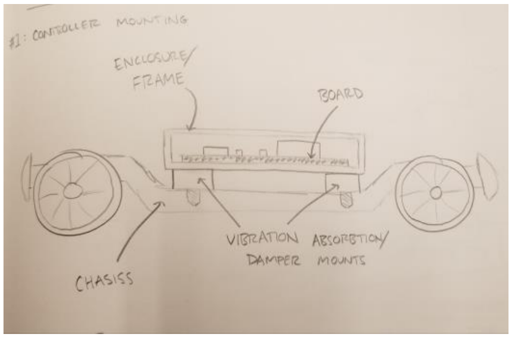
This section outlines the chosen concepts for each function we have outlined. The top concept for each function is the design direction that our project will take and is the focus of this section and of our preliminary design review.

4.2.1 MICROCONTROLLER HOUSING

The main functions of the microcontroller housing are to allow the microcontroller to easily be mounted to the RC car frame and to protect the microcontroller in the case that the car crashes. The Pugh matrices for the main concepts are in Appendix E. The two main orientations to mount the microcontroller are:

1. Horizontal Mounting
2. Vertical Mounting

Horizontal mounting refers to the plane of the microcontroller and the ground being parallel. Vertical mounting is when the plane of the microcontroller is perpendicular to the ground. Drawings of possibilities for both types of mounting and protection are shown below.



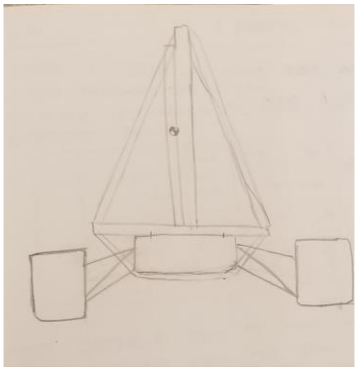


Figure 2. Drawing of a) horizontal and b) vertical mounting

The main constraints for the mounting of this controller are the size of the RC car itself and the aesthetics. The microcontroller itself is too large to fit within the front track width of a 1/10 scale RC car, so horizontal mounting would require the microcontroller to sit above the plane of the RC car. Vertical mounting allows for the microcontroller to sit within the footprint of the RC car. The main flaw of this design is the center of the gravity of the frame and microcontroller is placed above the car. The other most important aspect of the design of the housing is the protection of the microcontroller. For both orientations of mounting, there are two methods to protect it, using a frame style design or using a complete enclosure. A frame style design uses an open frame design to enclose the microcontroller and attaches the microcontroller to a base plate to mount to the RC car. This leaves the potential for debris to contact the RC controller. A full enclosure would eliminate much of this risk because the controller would be largely enclosed to reduce any chance of this happening. The final design selection can be found in section 4.3.1.

4.2.2 TRACK DESIGN

A track is needed to for the RC cars of this project to operate on. Design specifications for the track were taken from the QFD. The most important specifications for the track are for it to be modular (for transportation and assembly) and to have a high contrast between the road surface and the lane lines. Contrast allows the lane following software that is being developed by the CPE team to function properly. Three track designs are presented in this section can be seen in figures 3,4, and 5.

The first design presented in figure 3 below is a road surface that can consist of several different materials that are attached together using Velcro or zippers. The flooring surface could be industrial carpet, or some other type of flooring that lays flat. One problem with this idea is that the zippers could break, or the Velcro could have issues bonding to the track material. The second issue of this design is an uneven road surface caused by adding the Velcro/zipper. The Velcro/zipper could prevent the track from being modular requiring a unique assembly.

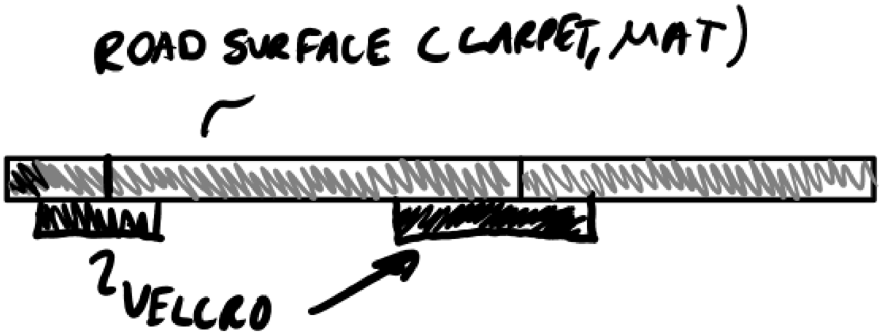


Figure 3. This picture shows the concept design for the track which has a material surface that is attached together using zippers or Velcro.

The second design that we came up with was a 3-D printed track as seen in figure 4. Individual sections of track could be printed and replaced in the future by changing the CAD model. This allows for quick design changes and iterations. The pieces would be assembled together like a puzzle which could be iterated to find the best design for attaching sections of track. The downside of this option is the time that it would take to make this track. The track will be large due to the scale of the RC car and microcontroller. 3-D printing the track would be time intensive and very expensive due to the size of the track.

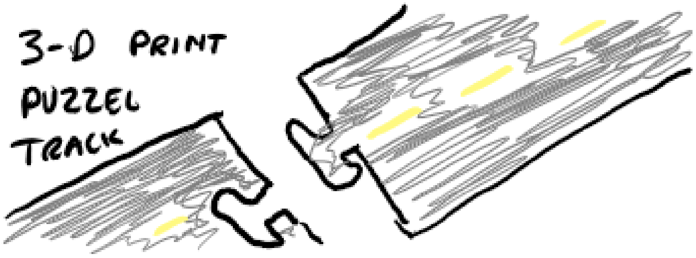


Figure 4: 3-D printed track that can be assembled like a puzzle and have interchangeable pieces

The simplest design of the track is using tape to mark out the lane lines as seen in Figure 4. This would be the easiest track to transport as only tape would be needed to set up the track and any design configuration could be made and changed on site. The downside of this is that the coefficient of friction would not be known at all locations and this track will not look very professional.

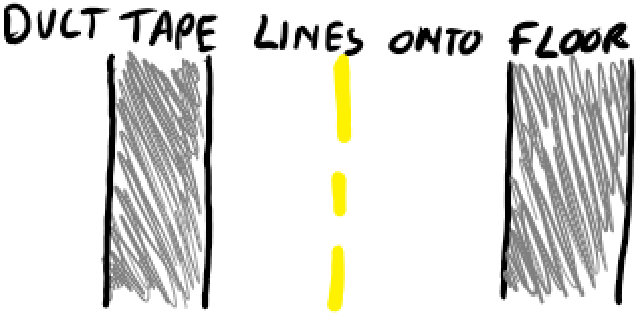


Figure 5. This is the most basic of the concepts. This is just putting tape onto the floor to allow for the microcontroller to identify lanes

These options for the track design were evaluated using a weighted decision matrix as seen in Appendix F. From this evaluation it was determined that the best design direction would be to use a material that would be modular similar to 3D printing puzzle like pieces. We selected a rubber flooring typically found in gyms that fit together like a puzzle for its modular nature and its durability. For the full explanation of why this design was chosen see section 4.3.2.

4.2.3 PATH PLANNING ALGORITHM

We will develop a path planning algorithm to avoid collisions with objects in the path of the vehicle. The algorithm will work as follows: When an object is detected, the path planning algorithm will be executed based on the known inputs. The inputs at the time of execution will be the size and location of the obstruction, the location of the vehicle, the location of each of the edges of the track, and the location of the end goal position. If the path planning algorithm can construct a viable path around the obstruction, that path will be executed by the vehicle control algorithm. If the path planner is unable to find a viable path, the vehicle will come to a complete stop in front of the obstruction.

Four types of algorithms are considered to plan the path around the obstruction. They are: Fixed Path, Rapidly Exploring Random Tree (RRT), A* Cells, and Tangent-Bug. The following figures and captions describe the function of each.

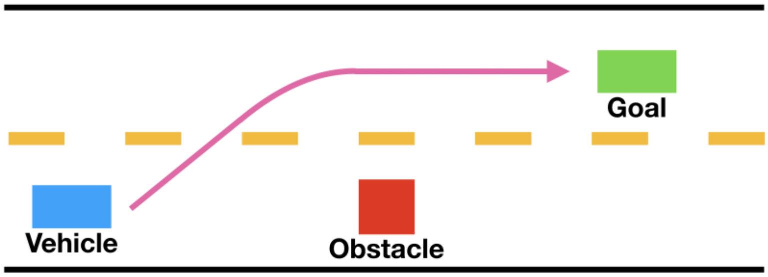


Figure 6. Fixed Path Algorithm

The simplest option is to navigate around obstructions by simply following a fixed path. In our case, this would likely be just be a lane change to avoid the obstacle. Although this would be easy to implement, it would not likely win us very many points with the judges at competition.

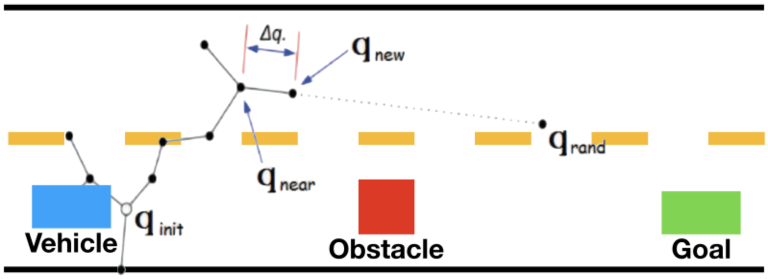


Figure 7. Rapidly Exploring Random Tree Algorithm

The Rapidly Expanding Random Tree (RRT) is a powerful pathing algorithm that can navigate complex geometries. It functions by randomly expanding a tree of nodes through space and terminating branches that hit obstructions or edges of the track. If this tree finds a suitable path to the goal, the branches to the goal are highlighted as the path. While this algorithm is powerful, we are concerned that it may be too difficult to implement, and that its capability is unnecessary for our task.

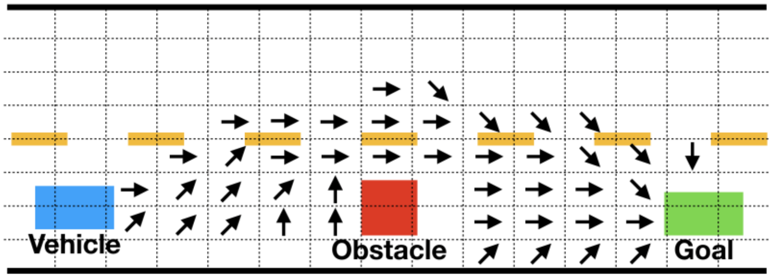


Figure 8. A* Cells Algorithm

Like the RRT path, the A* algorithm is a powerful and complex path planning algorithm. It functions by dividing the track area into a matrix of cells, and then assigning a value to each of those cells for how much it ‘costs’ to move into that cell. Cells over obstructions and track edges would have an impossibly high cost to enter. The algorithm then back tracks from the goal to populate each cell with a vector pointing to the neighboring cell with the least total cost to the goal. Once these vectors find the start position, the path is found.

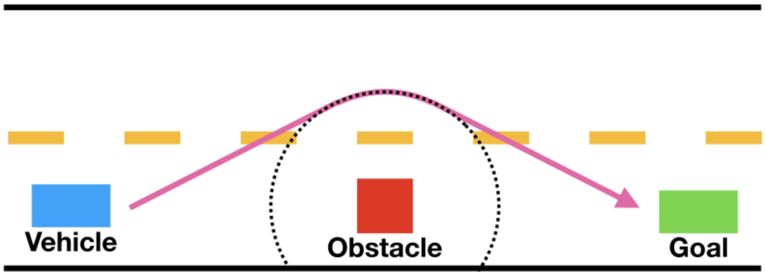


Figure 9. Tangent-Bug

The Tangent-Bug algorithm is the algorithm that we have ultimately decided to pursue. We have chosen it for its simplicity, and ability to achieve our goal without overly complicating the process. Algorithms like the RRT and the A* are overly complex and are too powerful for our relatively simple avoidance task. The Tangent-Bug algorithm is brought into more detail in section 4.3.3.

4.2.4 RC CAR OPTIONS

The selection of an RC car is one of the top priorities for our team this quarter. In the decision matrix (Appendix F), different factors were considered, such as whether the components are high quality, if it is easy to purchase replacements, whether it is four-wheel drive, etc. Table 5 below shows four shortlist options, their prices, and the corresponding manufacturer.

Table 5. Models, manufacturer, price and if additional purchase is necessary.

Model	Manufacturer	Price	Additional Purchase (Y/N)
TT-02R	Tamiya	$156	Yes
TA-07 Pro	Tamiya	$293	Yes
Ford GT/Mustang GT	Traxxas	$290	No
TA-07R Limited Edition	Tamiya	$515	Yes

TT-02R is the most affordable option among the four. It features several options to improve performance of the car, such as aluminum propeller shaft and joint. The issue with this option is that the electronics package, wheels, tires, motor, servo, and radio controller must be purchased separately from the chassis and suspension. However, this allows our team to choose these components specifically to meet our requirements and standards. Hence, our team can create a better RC car model that will better exhibit the vehicle dynamics of a sedan, as this is one of the main requirements for the project. Below is the picture of TT-02R in figure 10A.

Figure 10A. Tamiya TT-02R

Figure 10B. Tamiya TA-07 Pro

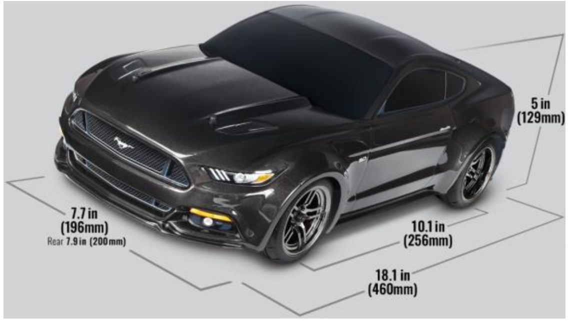


Figure 10C. Mustang GT

Figure 10D. TA-07R Limited Edition

The TA-07 Pro is an upgrade from TT-02R, featuring narrow lower deck and an upper frame, which adds more torsional rigidity to prevent body roll. TT-02R has more aluminum components for suspension than the TT-02R, which allow for better structure and quality, especially during crashes that will break plastic components easily. Like the TT-02R, this option requires additional purchases of wheels, tires, electronic packages, a radio controller and receiver, motor, and servo. Figure 10B shows the TA-07 Pro RC car.

Figure 10C shows the Mustang GT RC car. Both the Mustang GT and Ford GT share the same chassis and suspension components, and the only difference is the body cover. At about the same price of TA-07 Pro, the Mustang GT, which is a 1/10 replica of an actual car, is a ready-to-go option out of the box. Traxxas is a brand name producer in RC car and replacements can be found easily for this option. However, most components will be plastic, and the body will be removed to make room for the microcontroller housing. As a result, although this option is appealing in terms of having the ratio between length, width, wheelbase, wheel diameter, etc. of an actual sedan, it is unsure whether this car is robust against collision. In addition, it allows for little adjustments, which will be a challenge in making the dynamics of the car similar to that of an actual sedan.

The TA-07R Limited Edition (Figure 10D) from Tamiya is an upgrade from the TA-07 Pro with more aluminum suspension parts, a low-friction belt for drivetrain, and a stabilizer set to further reduce body roll beside the upper frame structure. Some parts are brought to this model from more expensive RC cars to improve the performance, such as the stabilizer set is from the TRF418 RC car that is in the range of $1,000 worth. Similar to TA-07 Pro, this option requires additional purchases of wheels, tires, servo, motor, radio controller and receiver, and electronic packages. As discussed above, freedom to choose additional parts allows our team to modify the RC car so that it best matches the vehicle dynamics of a sedan.

4.3 SELECTED DESIGN

This section outlines the selected design direction that we intend to move forward with for this project for the controller housing, RC car selection, track material and design, and path planning algorithm.

4.3.1 CONTROLLER HOUSING

The result of the weighted decision matrix and advice from Professor Birdsong for the mounting and protection of the microcontroller on the RC car is vertical mounting in a covered enclosure. A detailed drawing of the concept model produced for this is in Appendix G. Vertical mounting was chosen so no part of the microcontroller and frame are hanging outside the track width of the car. The microcontroller is so large that if it were to be mounted horizontally on a 1/10 scale RC car, it would have to sit above the car because it is wider than the car. This would be unaesthetic, and it would put the controller at an increased risk of clipping objects on a track that the car would otherwise avoid. A SolidWorks model of the prototype for vertical mounting can be seen in the figure below.

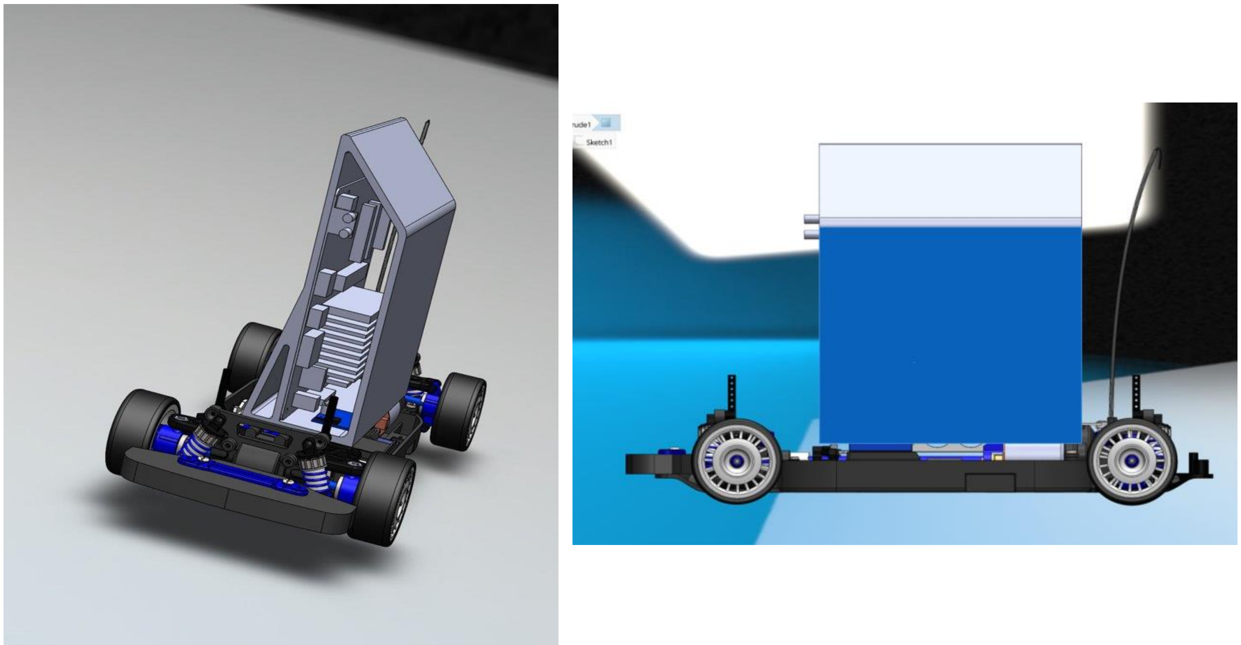


Figure 11. SolidWorks model of the microcontroller frame and an RC car

The first step in designing this concept prototype was modeling the microcontroller itself. The CPE team provided the assembly drawing from Nvidia and can be seen in Appendix I. This drawing was insufficient, so we also measured the dimensions of the heat sink and the location of the antennas. To mount to the microcontroller to the enclosure, there are four holes to attach it to our frame using a threaded fastener and a nut. The design of the frame itself (referenced as tenting frame in the Pugh matrix) provides total coverage of the microcontroller. If the vehicle falls on its side, the risk of debris or objects hitting the microcontroller is reduced and instead debris will contact the frame itself. A support was also added to the side at the vertical location of the heat sink for additional lateral stability. The thickness of each member is 5mm and is designed to be 3D printed using PLA plastic. Our concept model, seen below, of this frame was printed in full scale and at 20% density. 3D printing this allowed us to see any flaws or weak points in the frame and to visualize how it could potentially be mounted to a chassis.

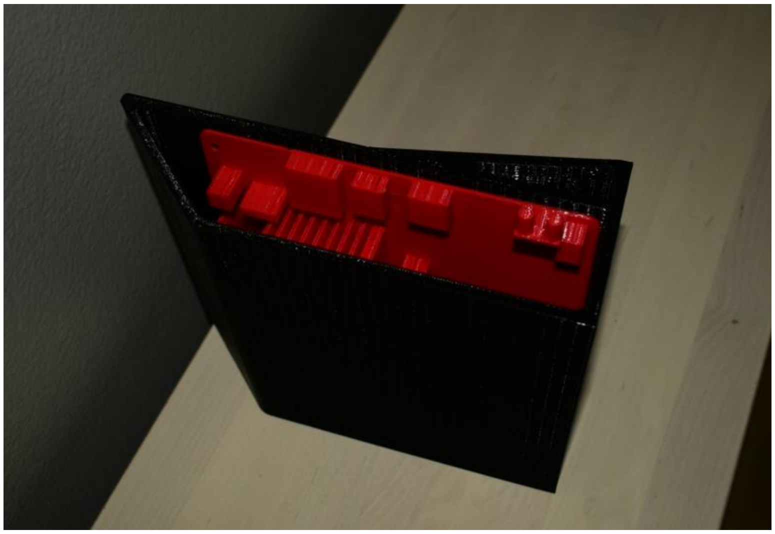


Figure 12. 3D printed concept model of microcontroller frame

A preliminary calculation using the impulse momentum theorem and basic stress analysis confirmed this design would be strong enough to withstand a rollover crash at the operating speeds expected. This calculation is shown in Appendix H.

Once the design of the enclosure is finalized and the RC car selection is finalized, the frame can be mounted on the car. Since the car selection has not been approved the exact method of mounting is unknown, but to reduce vibrations and loads on the controller the enclosure will be mounted on rubber dampers with threads seen below.

Figure 13. Rubber damper with threaded ends

The dampers shown above were bought for concept modeling, but we realized they are too stiff and will not reduce vibrations sufficiently. Further analysis is required to determine the loads that these will carry and the vibrational characteristics of the RC car and enclosure.

4.3.2 TRACK MATERIAL

The selected track material is rubber interlocking gym flooring as seen in figure 14 below. This flooring fits most of the design specifications that are needed for the track. The rubber material is durable, modular, aesthetic, within the budget of this project, and easy to set up. The downside of using this is the transportability. Each one of these tiles weighs 5.2 pounds and is 2ft by 2ft with a ¼ inch thickness. If all the given 100 square feet (we will likely be given more than 100 sq ft, although still awaiting confirmation) at the Netherlands competition is used the total weight of the track will come to 130 pounds. This might become an issue if this project needs to be shipped to the Netherlands as shipping costs will be expensive at this weight. The cost of this track material is $2.09 a square foot and using the allotted room for the Netherlands competition will put the cost just over $200 which is about 10% of the total budget for this project.

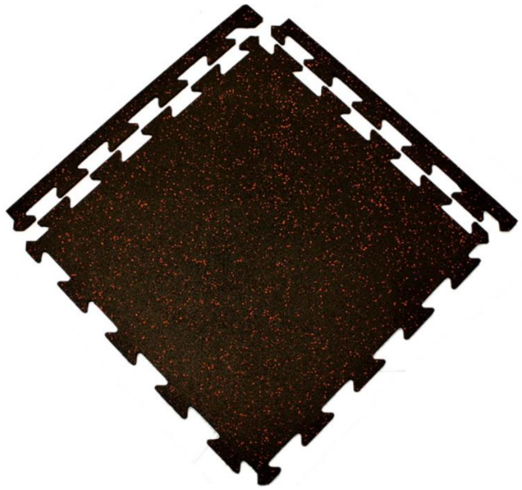


Figure 14. Image of the intended track surface to be used for project

The decided upon track configuration is a figure 8 (Figure 15 below) since this will allow the RC cars to show that they are operating autonomously rather than driving at a constant steering angle. The figure 8 configuration will require the RC cars to be able to constantly change their steering angle to stay within the lanes. The color of this black track surface will allow there to be high contrast lane lines which will help the micro-controller easily detect the lanes. There will be two lanes on the track and they will be painted onto the rubber mats with yellow paint.

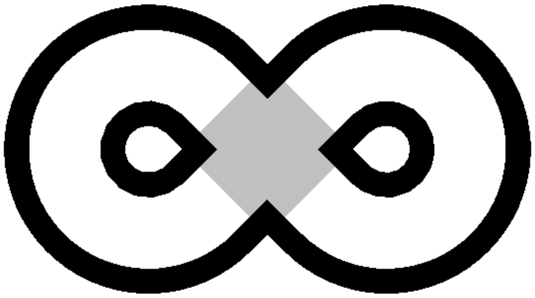


Figure 15. Selected track shape

4.3.3 PATH PLANNING ALGORITHM

The chosen path planning algorithm is called Tangent-Bug.

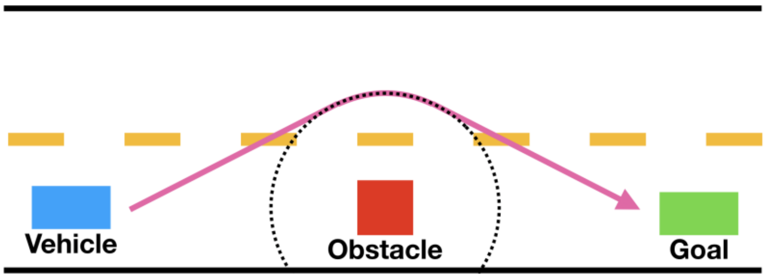


Figure 16. Diagram of the Tangent-Bug Path Planning Algorithm

To determine a path, a circle or ellipse will be drawn around the obstruction, with radius equal to the approximate radius of the obstruction, plus the width of the vehicle, plus a factor of safety. The algorithm will then:

1. Draw a path from the vehicle to the tangent of this radius
2. Follow the radius around the obstruction
3. Before breaking off on a tangent toward the goal position

This is illustrated in the figure above. If there exist multiple obstacles that prevent a direct line from being drawn from the tangent of the first radius to the goal, the path will plot course to the tangent of the next obstacle. A limitation of this algorithm is that it may not be used for moving obstacles.

4.3.4 RC CAR SELECTED

The selected RC car is Tamiya TA-07R Limited Edition seen in figure 17. This model features a new low-friction belt, double cardan drive shafts, front direct coupling, and aluminum counter pulley. The suspension has been fine tuned for a traction boost, employing medium rigidity arms, carbon fiber reinforced uprights and hub carriers, TRF418 stabilizers, aluminum suspension mounts, TRF big bore dampers and carbon fiber damper stays. The big bore damper allows for more oil (10%) to improve shock absorption and to enhance grip.

Figure 17. TA-07R Limited Edition featuring direct coupling and differential with aluminum gears, big bore damper and double wishbone suspension, and low-friction white belt (from left to right)

Aluminum steering arm and bridge components give direct and responsive steering path in conjunction with an aluminum servo mount. The three selectable motor positions are still available for great freedom of setup. For this model, electronics parts will be purchased in addition to the chassis and suspension from Tamiya. Table 6 outlines the prices of these components.

Table 6. Prices for each component and total price for both cars

Component	Quantity	Price $	Total $
Battery	2	40	80
Charger	2	30	60
ESC &Motor	2	210	420
Servo	2	30	60
Wheels & Tires	2	20	40
RC Equipment	1	45	45
Car	2	515	1030
		Total	1735

It was decided this car is too unnecessarily expensive at the preliminary design review. The final selection is the Traxxas 4TEC 2.0 RC. The final cost breakdown is in the bill of materials in Appendix K.

4.4 CHALLENGES AND UNKNOWNS

This project has many systems that will need to be integrated into an overall system. These individual systems are complex and integrating them is not trivial. The sections below outline some of main concerns of our chosen design direction that have not been resolved and potential hazards that could arise in our design.

4.4.1 CARMAKER

The team will determine how to integrate the chosen path planning algorithm into Carmaker and determine the inputs and outputs of the path planning algorithm. This will allow us to determine if it can be integrated into the Carmaker software and begin designing the controllers for braking and steering. If the path planning algorithm can be implemented into the Carmaker Simulink model it will replace part of the DrivMan block as shown in the figure below. The DrivMan block is the driver for the Carmaker program insuring that the simulated car stays on the track. The output of the DrivMan Block is the input to the VehicleControl block which outputs the vehicle dynamics of the RC car. The controllers will be placed between the DrivMan and VehicleControl blocks as shown in figure 6. The braking and steering controllers will mostly likely be PID (Proportional, Integral, Derivative) controllers as they will allow for the manipulation of steady state error, transient error, and response time.

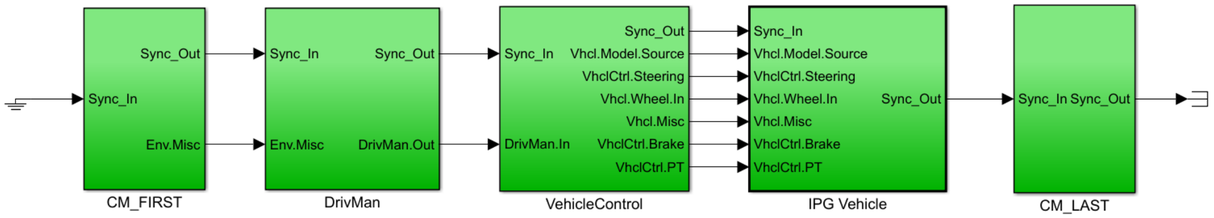


Figure 18. The generic Simulink model in the Carmaker program

Once an RC car is purchased, characteristics of the car such as the damping, track width, and inertia will be inputted into the Carmaker software to accurately simulate the RC car. This might become difficult as it is not known how hard it will be to measure and find all the data that Carmaker needs to accurately simulate the RC car. This error will then propagate to the actual use of the RC cars and will require testing to tune the controllers to account for any differences. In our final design, it was decided to use Carmaker to not entirely simulate the RC car, but to establish sound control logic.

4.4.2 MICROCONTROLLER MOUNTING AND PROTECTION

The method of attaching the frame to the RC car is unknown because we have not yet purchased an RC car. Once the RC car is purchased and the vehicle chassis is inspected, we can begin to prototype how to mount the enclosure to the chassis. The other challenge with our chosen design is its effect on vehicle dynamics. By positioning the controller vertically, the center of gravity is placed very high off the chassis. The microcontroller was positioned with the heat sink on the low side to reduce this effect as much as possible, but the dynamics will still be affected. This will make our car more prone to rollover. We will have to compensate with accurate vehicle models and an appropriately designed controller to avoid rollovers. Another option is to position weights to manipulate the center of gravity of the assembly. Further testing and analysis will be required to ensure that the vehicles do no roll over.

4.4.3 DESIGN HAZARDS

Design hazards must be addressed to insure this project is operated safely. This project could have problems with the automated control of the RC car allowing for the car to obtain a high speed and hit an observer. This is being addressed by retaining the off button from the RC car when it will be autonomously driving around the test track. The second major hazard that could be presented while operating these RC cars is the presence of rotating parts spinning at high speeds. This will be prevented by viewing the RC car from a safe distance while it is operating. Also, if any tests occur on a test stand, special care will be taken to prevent injuries. For the full design hazard checklist see Appendix J.

5.0 FINAL DESIGN

This section covers the final design proposed for this project. The controllers developed using carmaker for acceleration, deceleration, steering, lane keeping, and object avoidance will be discussed along with the new design orientation of the microcontroller and the mechanical set up of its associated parts.

5.1 DESCRIPTION OF DESIGN

The final design of this project is made up of four components:

1. The mechanical setup of the RC car
2. The electrical wiring with new components
3. The computer algorithms that have been developed to control the RC car
4. The track design

Please see section 5.2 for a full explanation of the algorithms that have been developed using Carmaker and Simulink.

5.1.1 MECHANICAL DESIGN DESCRIPTION

The overall mechanical CAD design for the RC car can be seen below in figures 19 and 20. The selected and purchased car is the Traxxas 4TEC 2.0 RC car. Figure 19 below shows the side view of the RC car and shows the naming scheme for each part added to the RC car. Each of the housings that will be mounted to the RC car will be attached to the aluminum bridge which will then be bolted to existing tapped holes on the RC car. Figure 20 is an isometric view of our CAD model and figure 21 is an isometric view of the selected RC car with some of the parts on it.

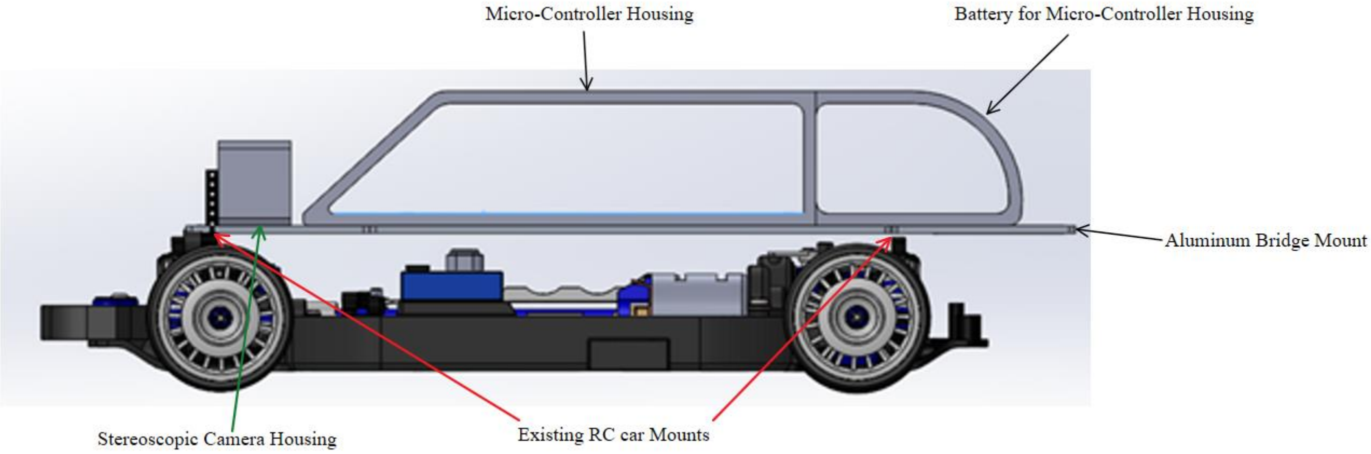


Figure 19. A side view of our intended final design for the additions for the RC car. Note this CAD model is not to scale as the RC car used in the CAD model is not the RC car that we are using, but a similar one that is slightly shorter

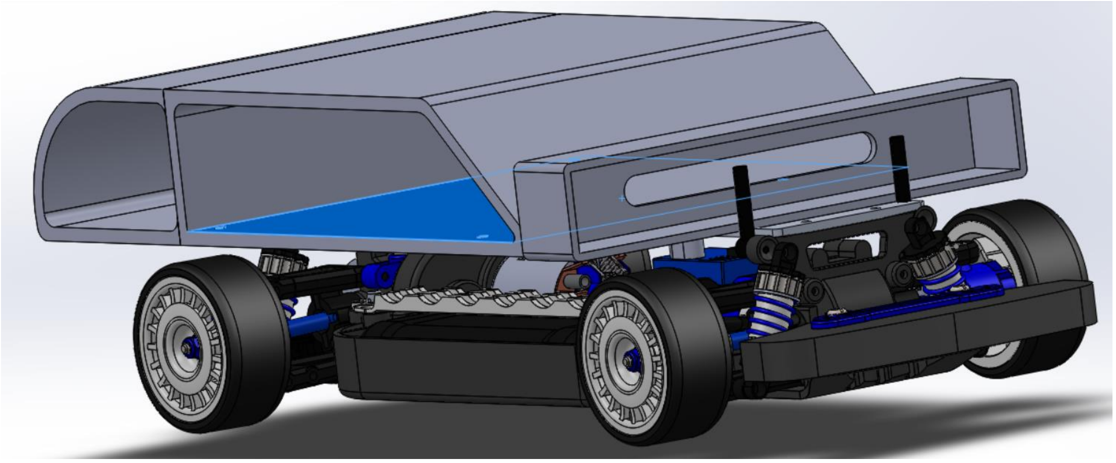


Figure 20. Isometric view of the microcontroller housing, the micro-controller battery housing, the stereoscopic camera housing, and how they will be oriented on the RC car

Figure 21. Isometric view with microcontroller housing and battery housing on Traxxas 4TEC 2.0 RC car. Velcro mounting is only temporary and used for purposes of this picture.

There have been several changes to our design since the preliminary design review (PDR). The first major change from the preliminary design has been the change in orientation of the micro-controller housing. Originally, we thought that the micro-controller and its housing would have to be mounted vertically to fit within the wheel base of the RC car. This changed once we purchased the Traxxas 4tec 2.0 RC car in which it was determined that the micro-controller and its associated housing could fit within the wheel base without raising the center of gravity greatly and still look aesthetically pleasing.

The second major change since PDR has been the addition of another lithium ion battery. This was a recommendation from professor Birdsong as previous projects have had issues regulating voltage from one battery to the motor and the micro-controller. The added battery has created the need to have a housing to protect it from damage during a crash that could cause a fire.

The third addition since PDR has been the addition of stereoscopic cameras. The CPE team has determined that they will add stereoscopic cameras which will allow for a second way to detect objects along with lane line detection. The CPE team has decided to not include lidar in this project.

5.1.2 ELECTRICAL WIRING AND NEW COMPONENTS

This project has a good amount of wiring needed to be completed for the RC car to be ready for software to be uploaded and the calibration testing ready to begin. Below is a list of current components that need to be wired before testing can begin.

1. New RC Motor
2. New Motor Speed Controller
3. Motor Battery
4. Steering servo
5. Jetson Battery
6. Jetson Micro-Controller
7. Lidar Sensor
8. Stereoscopic Cameras
9. Relay for dead man’s switch

Figure 22 below is a simplified wiring diagram for all the components listed above. This wiring diagram is subject to change when wiring begins because unforeseen issues may arise. Size 20 AWG wiring, rated to a capacity of 11 amps, will be used between the motor battery and the motor controller, as well as between the motor controller and the motor. The peak current draw from the motor controller is 10 amps. All other wiring for control signals will be size 26 AWG.

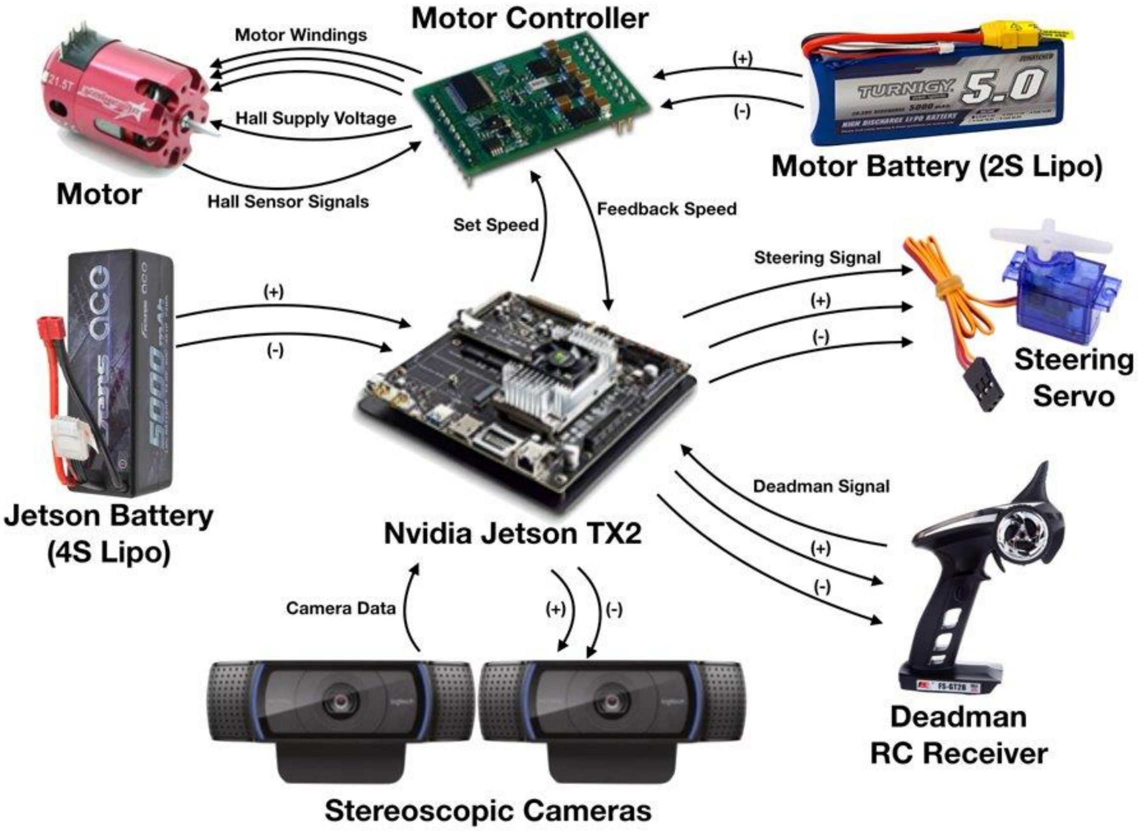


Figure 22. Simplified electrical wiring diagram with all current components to be added to RC car

5.1.3 FINAL TRACK DESIGN

We have verified that we will be allotted a 10 by 20-foot space for part of the conference in the Netherlands with a guaranteed 10 by 10-foot space for the entire duration of the conference. This has influenced the track design that is planning on being implemented. The track layout can be seen below in figure 23

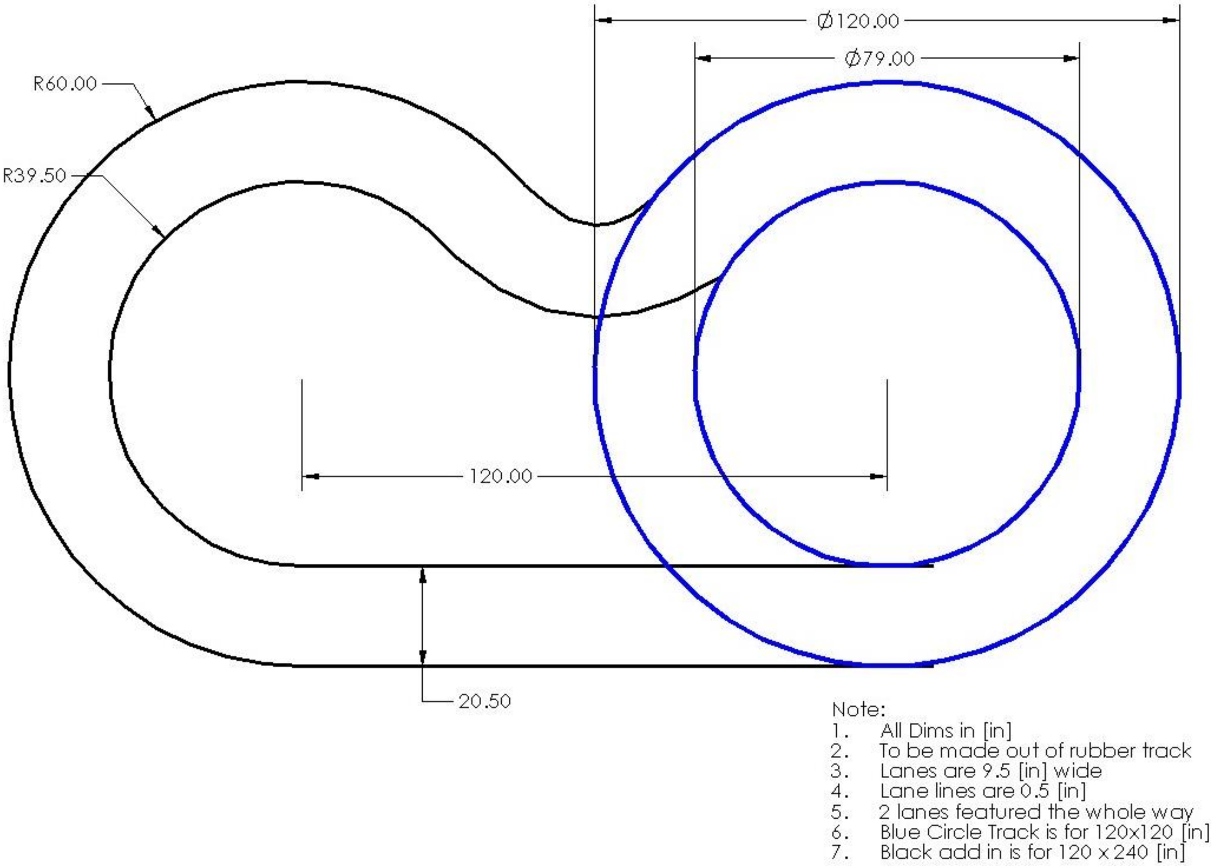


Figure 23. Drawing of intended track layout for the use of the space that has been confirmed for our team at the ESV conference

We determined that a different track orientation other than a figure 8 track would be used since we wanted a straight away where the RC cars could gain some speed and demonstrate object avoidance. We still wanted a configuration that allows our RC cars to demonstrate that they do not operate at a fixed steering angle and can handle both left and right-hand turns. With these design considerations in mind our proposed track will be modular so when we will only have a 10 ft by 10 ft space, the track will be a simple circle as highlighted in yellow in the figure above. When our team can use a 10 ft by 20 ft space the track configuration will change to include the orange highlighted portion. When the larger track is in use part of the circle track lane lines will be covered to prevent any operating issues with the software.

The track configuration that has been selected takes into consideration the size of the RC cars, the lane width necessary, and the lane line thickness. The total width of the track which includes two lanes and the lane lines will be 20.5 inches wide. The lanes will be 9.5 inches wide and the lane lines will be half an inch wide. This allows for enough space for objects to be placed on the track and the RC cars to avoid the objects without simply completing a lane change.

5.2 CARMAKER ALGORITHMS

The final design (for the critical design review) for the control algorithms includes control logic for acceleration, braking, and steering. These were developed using the Carmaker software described earlier in the report and using Simulink. We decided that it is more important to establish robust control logic, and not simulate the actual parameters of the car accurately. These algorithms were developed using a Tesla Model S in Carmaker using a simulated road sensor to simulate lane tracking to test the steering controller. The car was run on a figure eight course and an open 3 lane highway to develop these algorithms. An important difference between the Carmaker model and the RC cars are in the RC cars the signal to the electric motor controls acceleration and braking. In the simulated model, the Tesla Model S has an electric motor for acceleration and brakes for deceleration. This difference was accounted for in the design of the control logic. The control algorithms were made inside the vehicle control block of the generic car model provided by Carmaker as seen in figure 18. CarMaker provides its own driver simulation. To insert out own control logic the signals from the Carmaker, some driver signals were disconnected in the appropriate places and replaced with Simulink control signals that we developed. Larger pictures of each control algorithm can be found in Appendix N.

The first step in developing algorithms was developing logic to speed up the car and then stop it while traveling in a straight line. The logic created for both accelerating and braking are very similar. The accelerator control loop that will be used for the development of our car is below in figure 24.

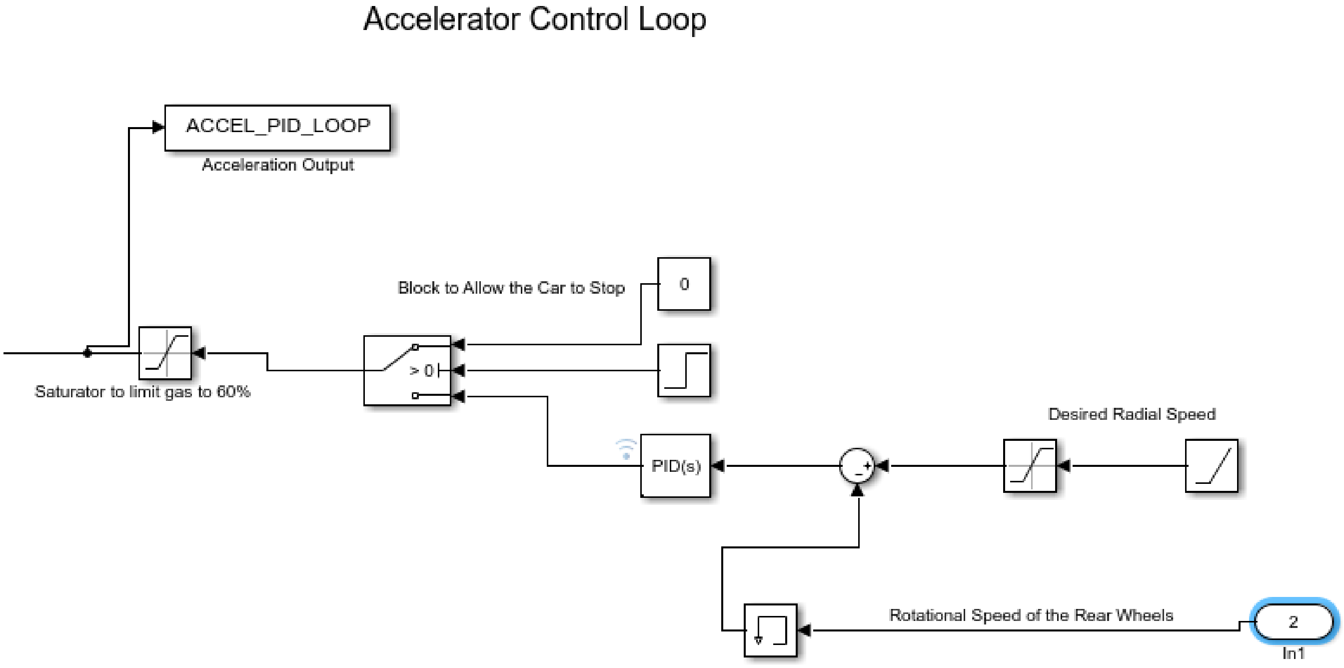


Figure 24. Accelerator control logic in Vehicle Control in Simulink Generic Car Model

This loop uses a PID controller with feedback from the rotational speed of the rear wheels. The desired speed is set by a ramp input, so that the desired speed would ramp up gradually resulting in a smooth acceleration from a stop. The saturator after the ramp block functions to set the desired steady state speed of the car. The difference between the rear wheel speed from this desired value is then fed into a PID controller whose output has been tuned to output values from 0 to 1 where 1 is full acceleration and 0 is no acceleration. This is then fed into another saturator that limits the output to 0.6 to prevent any wheelspin in the simulation. The output of the PID controller was designed to output 0 to 1 because that is the signal carmaker uses to determine how hard the driver is pressing the accelerator pedal. In our RC cars there is no accelerator pedal, only a voltage input to the ESC to set the desired speed. The 0 to 1 output will have to be modified with a gain to convert to the proper magnitude of voltage to set a motor speed. The switch after the PID controller is a method used to stop the car. To test stopping the car the switch is activated with a step input and the desired speed is set as 0 so the accelerator signal is changed to 0.

The brake loop was designed in the same way as the accelerator loop. It is seen in figure 25.

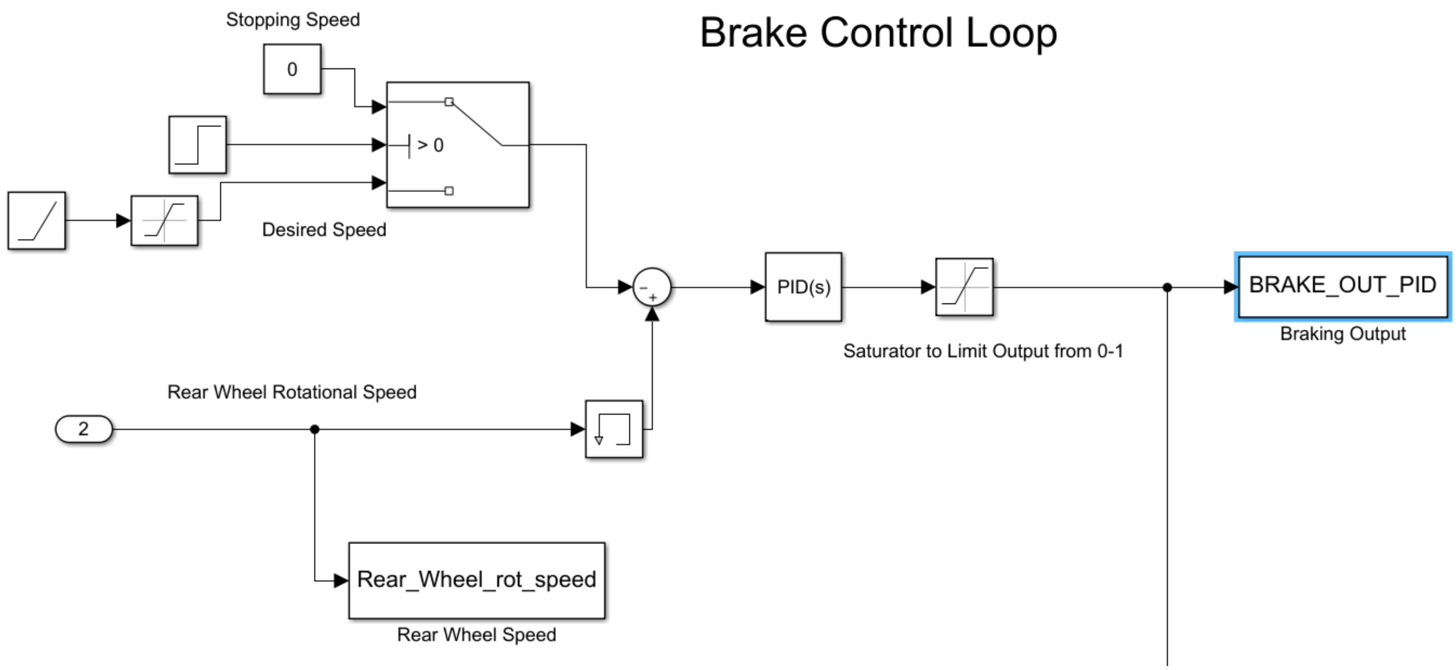


Figure 25. Braking control loop in Simulink interfaced with Carmaker

The input into the switch before the step input is a ramp with a saturator the same as the one that sets the speed for the accelerator loop. This is fed into the summing junction as feedback and the rotation speed of the rear wheels is the desired speed. This means that if the accelerator overshoots the desired speed in the ramp, the PID in this loop will activate the brakes to slow the car until steady state is reached. Once the step input is activated the feedback signal goes to 0 and the PID outputs a signal to the brakes to stop the car. The loop is also designed to output signals from 0 to 1 for the same reasons as the accelerator loop.

The final control logic developed was for steering the car. The logic was developed to output a value in radians for steering angle input from the driver. It will need to be modified by gains to convert it into the correct pulse width modulated signal when applied to the RC cars. The first part of this algorithm was developed to accomplish lane keeping. This part of the logic is everything to the right of the section labeled “Simple Dodging Mechanism” in the figure 26.

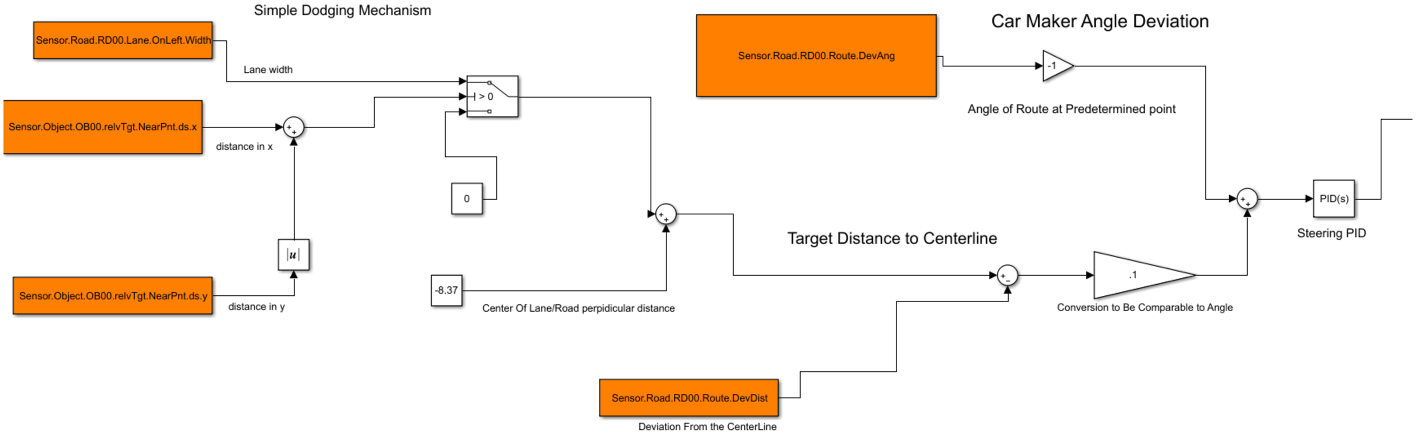


Figure 26. Steering controller and simple dodging mechanism in Simulink for interfacing with Carmaker (a large version can be found in appendix N)

Lane keeping is accomplished by establishing a goal point at a certain distance in front of the car. In Carmaker, this goal point is set using a road sensor that previews a point at a user-controlled distance in front of the car. The difference between the angle of the road and the angle the car is facing is called the deviation angle. This is the initial value fed into the PID controller. This functions as a feedback to the controller and the desired angle between the car and the road is 0 (the car should be facing the same direction as the road to effectively steer). When using this as the only parameter to accomplish lane keeping, the car slowly drifts out of the lane due to the car accumulating error. It takes time for the system to respond to the inputs and even if the car matches the angle of the road there is nothing to compensate for the distance between the center of the car and the center of the lane. To fix this drift, the negative perpendicular distance between the center of the car and the center of the lane is multiplied by an appropriate gain and then subtracted from the deviation angle. This perpendicular distance is called the "Route Deviation Distance" in Carmaker and is also provided by the road sensor. Because the desired distance is zero, even if the angle of the car is matched with the angle of the road the car will steer if the center of the car does not match the center of the lane. This proved to be a robust method of maintain lane keeping in both the simulation of a freeway setting and a tight figure eight course.

The left part of the control algorithm labeled "Simple Dodging Mechanism" is a proof of concept for how path planning can be executed using the steering control logic. The way steering is controlled tries to both match the angle of the road and minimize the distance to an arbitrary set point. Path planning can be executed by manipulating this set point. The above logic uses an object sensor in Carmaker and dictates that is an object is detected in either the X or Y plane the car's setpoint is offset by the perpendicular distance of one lane. This forces the car to change lanes is an object is detected to the front of it and it will change back once the object is no longer detected. The method of tangent bug can be implemented by moving the desired perpendicular distance linearly as the car moves. This results in a tangent path. A simple calculation must be done to determine the slope of the line to ensure that the car moves fast enough. The development of this algorithm has been delayed until the RC cars have been set up and fully integrated with the CPEs.

5.3 DESIGN SPECIFICATIONS MET

Referencing table 4 in section 3.5 for the design specifications of this project we have only met some of the design specifications due to the current progress for our project. In terms of object avoidance verification, these design specifications will not be verified until we have begun testing. Cost requirements of this project and are under budget for a full cost analysis overview see section 5.5.

Specifications 1 and 8 for crash are being designed for, but intentional tests will not occur out of fear of damage. The design includes multiple housings 3D printed to protect electronics. As well as a bumper that is 3D printed to protect the front suspension from impact. Unintentional crashes may happen where our systems robustness will be tested. It must also be noted that the center of gravity of the RC cars is low enough where roll over is very difficult and will be avoidable at the low speeds that we intend on running the RC cars at when the micro-controller is driving the car.

In terms of our design meeting shipping standards is a pass or fail standard. Most of our project will be able to safely ship or fly with exception the lithium ion batteries which we cannot fly with and we might run into issues shipping them. In terms of weight we are currently over the 100 pounds we originally have allot for ourselves. This is due to the high weight of the RC car track material and the increased available area. This will be solved by trimming the track material to remove excess weight.

Finally, the specification related to operating speed has not been fully verified as finding the scale RC car speed is not a simple task. However, with our current set up the RC car can be run at a range of speeds up to 20 miles per hour which should be in the range of the scaled speed. The only thing that can prevent operation at the scaled speed is the track. The RC car might not be able to make all the turns at the scaled speed or might not have enough space on the straightaway to accelerate to the scaled speed and deaccelerate to make the next turn.

5.4 SAFETY, MAINTENANCE, AND REPAIR

No new safety hazards have been added to this project since the PDR report so the design hazard checklist in Appendix J remains unchanged. A new safety measure that has been decided on between the ME and CPE team is the addition of a dead man's switch. The RC receiver will be retained in the new design; while running the car someone will hold the RC trigger down. If the RC trigger is released, the Jetson will have a built-in kill switch to stop the autonomous function and bring the car to a stop. This will allow us to control the operation of the car from a distance and allow us to safely test autonomous functions.

The maintenance and repair of our system is simple. If anything was to break on the RC car that we purchased from Traxxas their website offers replacement parts to fix nearly anything that breaks on the RC car. In terms of the housing breaking it will not take long to make a new iteration of the design and make it as all the housings are 3-D printed. The biggest possible slowdowns in repairs to the RC car are involved with the motor speed controller and the Jetson micro-controller. The motor speed controller would likely take several weeks to be delivered. The issue with replacing a Jetson micro-controller is the cost for a replacement. These micro-controllers were provided by the CPE team and would cost around $600 for a replacement.

5.5 COST ANALYSIS

For this project we have been allotted $2,000 to purchase all the materials needed for an RC car, the materials needed to mount the micro-controller, its battery, and the cameras provided by the CPE team to the RC car, and to make a track for the RC car to run on. With those components purchased which can be seen in Appendix L we have used $1,631.40 of the $2,000 available. For a complete overview of each individual cost associated with this project please see Appendix L for the budget spreadsheet and see Appendix K for the Bill of Materials for each sub assembly.

5.6 CHANGES SINCE CRITICAL DESIGN REVIEW

Multiple changes were made to the proposed final design. A list of the items that were changed can be seen below which is then followed by a discussion of each change.

1. Track design
2. Addition of controller for platooning
3. Change of location and type of cameras used
4. Updated microcontroller and battery housing for cable management
5. Addition of a bumper
6. Addition of Arduino mega controller

Changes made to the track only included removing part of the circular portion of the track, since it has been confirmed that we will have the space necessary to operate of the full-size track throughout the duration of the competition.

The following diagrams are illustrations of how the controls work inside of the code of the car. The control algorithms were adapted from the ones developed in CarMaker and programmed in coordination with the CPE team.

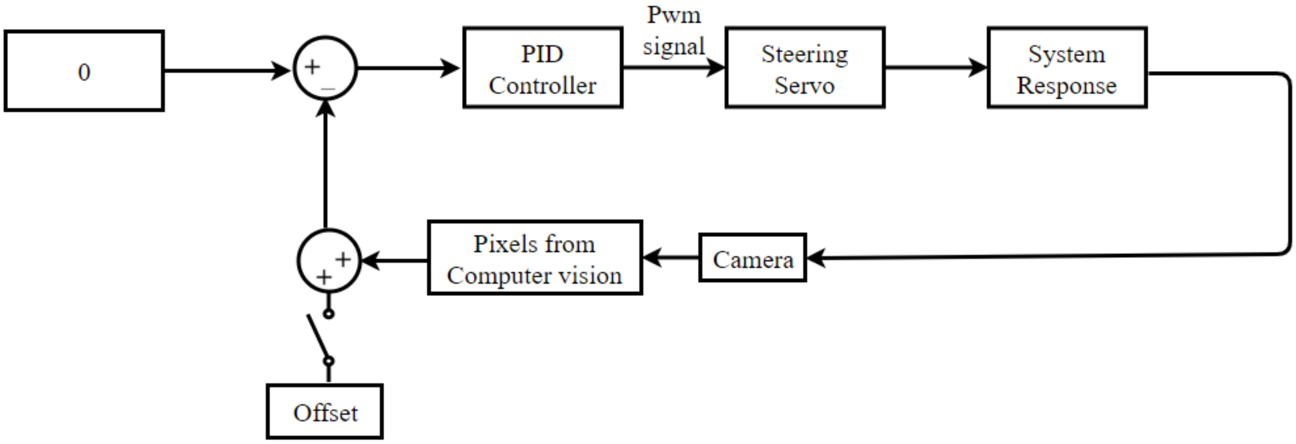


Figure 27. Steering control diagram executed in cars' software

The main differences between the control logic executed on the car and the control logic developed in CarMaker is the information provided to the controller about the distance from the center of the road and a programmed offset. The information provided from the lane detection software provides the number of pixels from what it perceives as the center of the lane. This value is converted into a steering PWM by the PID controller. The PID controller only uses proportional and derivative control because there is nothing in the system to force a steady state error. Integral control is therefor unnecessary. The offset is used when the camera cannot see a whole lane. When the offset is activated the center of the lane is offset from the location of lane that the lane detection software can see. This provides an accurate number of pixels for the PID to steer the car appropriately.

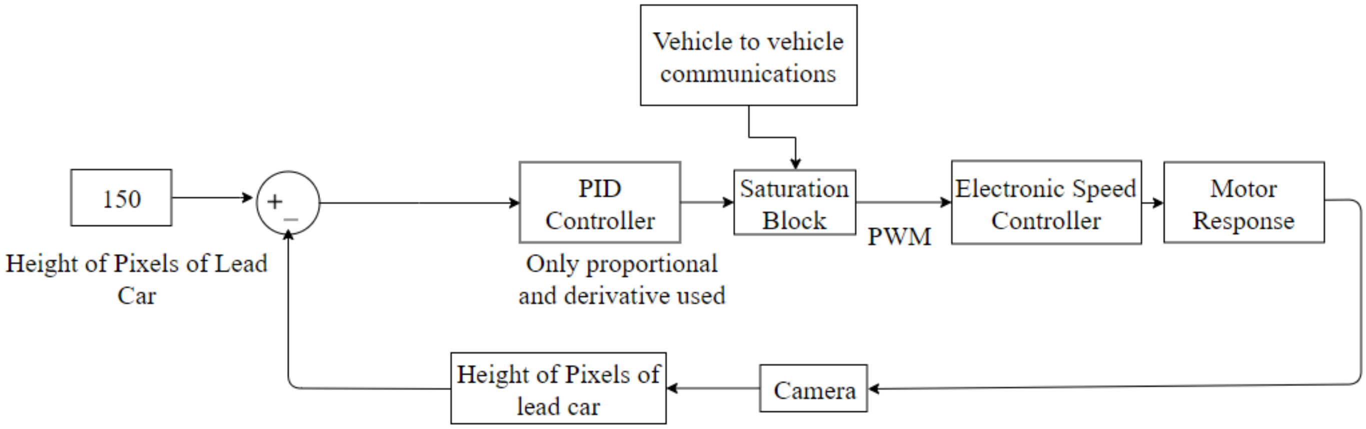


Figure 28. First iteration of a platooning controller using vehicle to vehicle communication

The first iteration of a platooning control was developed from the CarMaker model used to control speed when following a car in traffic. In CarMaker, the speed control diagram was modified using a sensor that tracks the speed and position of an object detected in front of the car. A control loop was then developed to match the speed of the lead car while maintain a present distance. The above figure demonstrates the first design of the control logic applied to the cars using vehicle communication hardware. The software used to execute the platoon functionality uses only color images and not distances. The distance between vehicles is correlated to the number of pixels the lead car occupies in the following cars vision. The control loops hold the follow car at a certain distance by commanding it to keep the lead car the same size in its view. Using this technique alone without vehicle to vehicle communications is a form of adaptive cruise control. Vehicles to vehicle communication was integrated to increase the stability of the platoon and to enable fast reactions to disturbances.

The vehicle to vehicle communications was enabled initially using a saturator at the output of the PID controller. The lead vehicle communicated the duty cycle of the PWM signal it was sending to its own motor, and the rear vehicles would saturate the duty cycle it could send to its own motor around the duty cycle of the lead car. The hardware on each car is nearly identical so sending the same duty cycle forces the speed of each car to be close. By allowing the rear car to send a duty cycle slightly higher or lower than the lead car, it allows the following car to adjust its position relative to the lead car.

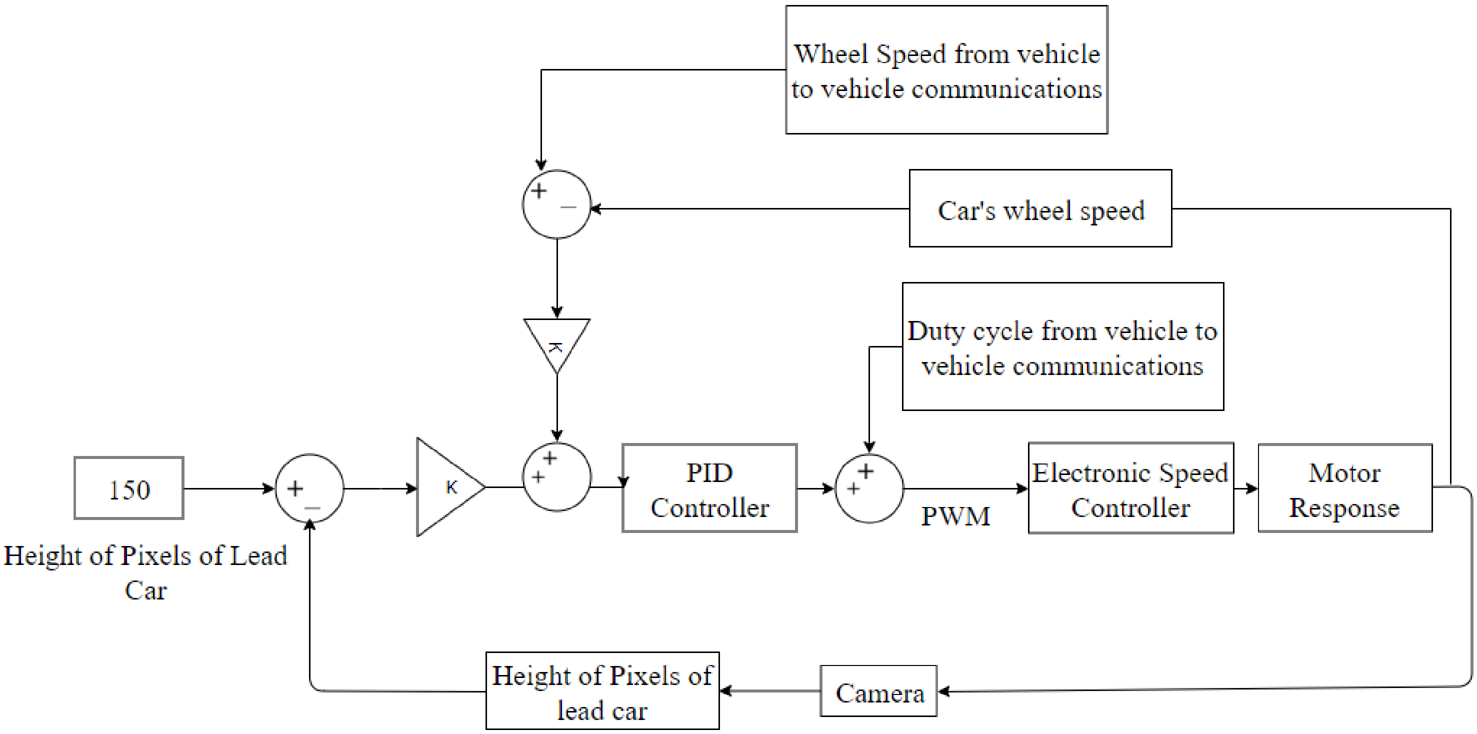


Figure 28. Final iteration of the platooning controller using vehicle to vehicle communications with both duty cycle and wheel speed

The final iteration of the platooning controller can be seen above. It was changed because the original control algorithm was non-linear due to the saturator block. This can make the system unstable and makes it difficult to prove that the system is stable even if it operates effectively. In this iteration, the hardware ability to read the output shaft speed from the ESC was added. This as well as the perceived distance to the lead vehicle is sent to the PID controller. This value is then offset by the other cars duty cycle. This allows for the PID controller to change the PWM sent to its motor from a base point set by the other car without the use of non-linear control logic.

The cameras were changed from the original cameras seen in figure 22 to Zed mini stereoscopic cameras. This decision was made on the recommendation from Dr. Birdsong and Dr. Debruhl as synchronizing two different cameras to make a stereoscopic camera for depth perception is very difficult. It was determined that our time would be better spent focusing on other parts of the project. The funding for these stereoscopic cameras were acquired through MESFAC, which prevented these cameras from affecting the remaining budget of this project.

The 3-D printed housings for the Jetson microcontroller and its battery housing were modified from the original design. The modifications were made to incorporate internal wiring in the RC car, and allow for better cooling from the heat sink of the Jetson microcontroller. The drawings for these updated parts can be seen in Appendix M. For new pictures of these parts see figure 29 in the manufacturing section for the final version of the RC cars.

Another addition to the RC car was the addition of a bumper to the front of the car. The bumper was added to extend protection from the existing bumper to protect the front wheels of the RC car. This was done on the recommendation of Dr. Birdsong and Dr. Schuster, as in previous projects when an RC car has crashed the drive terrain of the front wheels has been damaged.

The final change to our design since CDR has was the addition of an Arduino mega. The Arduino mega was needed to produce a hardware PWM signal as the Jetson microcontroller does not have a port for hardware PWM signals.

6.0 MANUFACTURING

This section will discuss the process of how the micro-controller and its associated parts were made, how they will be mounted to the RC car chassis, and the budget status for manufacturing.

6.1 FINAL BUDGET STATUS

The mechanical engineering team has spent \$1,631.40 for the procurement of the two RC cars and has a remaining budget of \$368.60 out of the original \$2,000. It must be noted that these numbers only account for the items purchased in Appendix L by the mechanical engineering team and does not account for other awarded funds for this project. More funds have been awarded to this project to cover costs of travel and are not discussed here as they are not a part of the cost for manufacturing.

The costs that were not included in our budget were for the Jetson microcontrollers, and the Arduino Mega controllers. These controllers cost \$699 and \$40 each respectively. These costs were not included in our budget as the computer engineering team acquired the controllers for free through Dr.Debuhl. The total cost to reproduce this project would come to \$3,905.94 if these controllers had to be purchased.

6.2 PROCUREMENT

All the parts needed for the completion of this project were purchased from the internet from various sources. Appendix L has the list of every part that has been purchased to date, the source, use of material, and a website link to the place of purchase.

6.3 MANUFACTURING

This section will discuss the manufacturing plan that was used to produce the final product, the RC cars. The plan is separated into two different sections mechanical and electrical manufacturing.

6.3.1 MECHANICAL

For this project there are 4 mechanical parts that were manufactured, all of which are used to mount various accessories to the vehicle. The accessories to be mounted are the Jetson microcontroller, the battery for the Jetson, and the stereoscopic cameras. The bridge of aluminum is purchased with the desired final thickness and width which was then cut to the proper length. The mounting holes are drilled in the aluminum bridge, and then it is mounted to the exiting RC car body mounts. The holes drilled into the aluminum bridge are sized for the screws already used on the RC car chassis itself. This was done with a cordless drill. The 3D printed Jetson enclosure is then attached to the aluminum bridge with self-tapping screws. In order to protect the front wheels in the case of an accident a bumper was 3D printed in two pieces and glued together at its center. This bumper seen in figure 27, was designed to cover both the front wheels and is attached to the foam bumper already included on the car by a press fit.

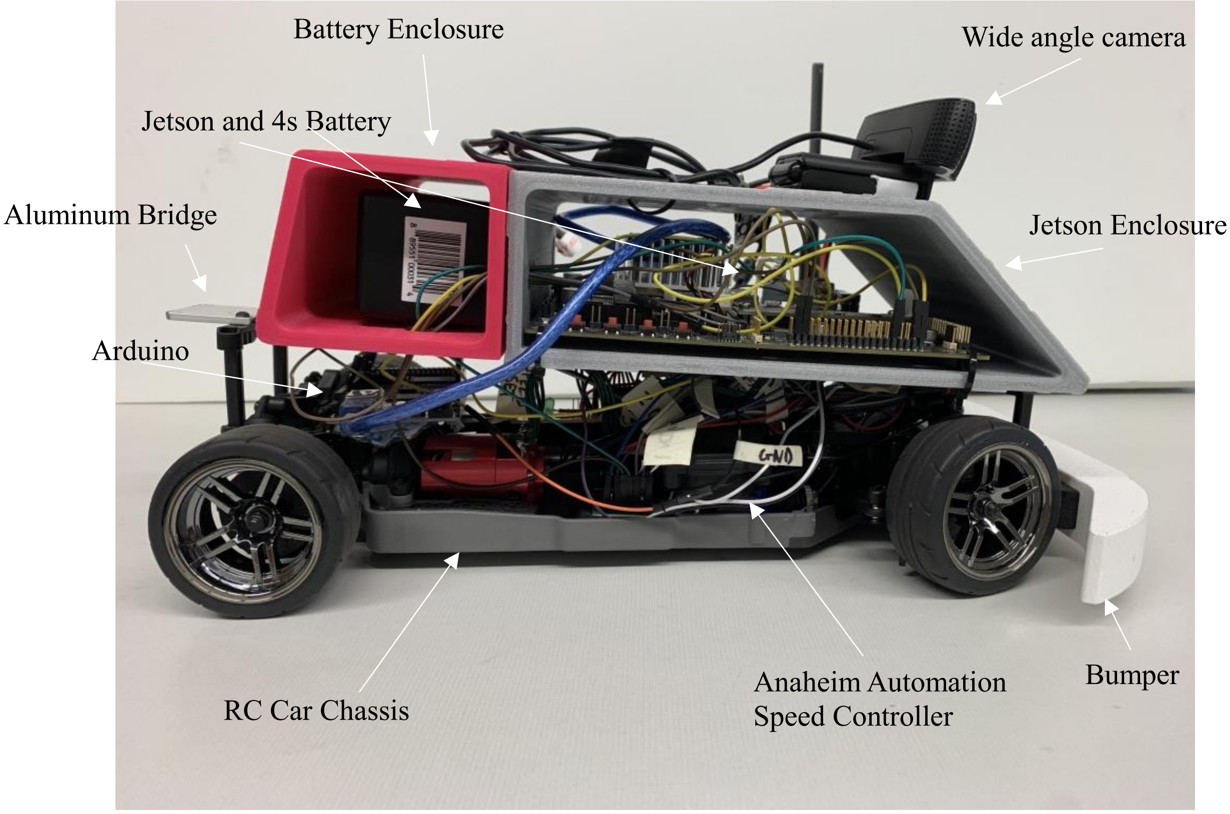


Figure 27. Cross section view of one of the two assembled cars

The battery enclosure is mounted on the aluminum bridge, just aft of the microcontroller enclosure and is attached to the microcontroller enclosure and the bridge with Velcro, which allows for easy battery swapping. Figure 27 shows the second car that was assembled with labeled components. Figure 28 shows both cars in their current state.

Figure 28. Both cars as of 4/24/2019

The Zed Mini stereoscopic cameras have been mounted to the top of the Jetson microcontroller housing using a third 3D printed bracket. Additionally, the enclosures have been updated with features to more easily manage the packaging of the cables, as suggested in section 5.6 above. A photo of the final iteration of the car is shown below.

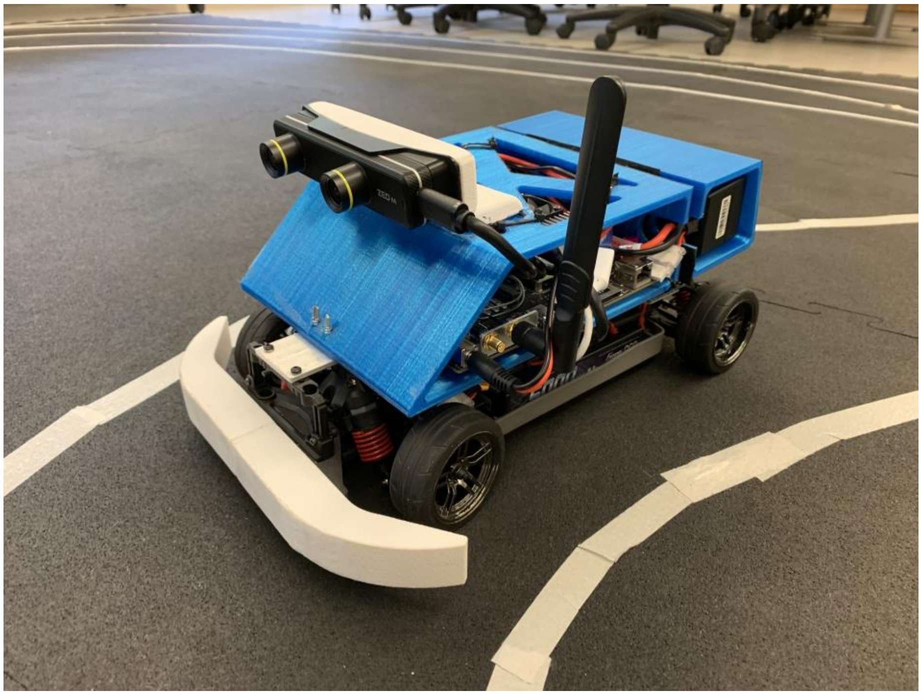


Figure 29. Final iteration of the car, with Zed Mini stereoscopic camera and final enclosures

Both cars were assembled with nearly identical hardware. The main difference between the two is the enclosure design. The more recent enclosure is on the car with the pink battery enclosure. Internal slots were included on this car to keep the wiring internal. A cross beam frame was also added to the top of the Jetson enclosure to allow the Jetson to cool more effectively. The battery enclosure was shortened, and the rounded top edge was flattened. This allows the battery enclosure to sit flush with the Jetson enclosure and improves aerodynamics and the aesthetics.

6.3.2 ELECTRICAL

Electrical components include the Jetson, motor controller and motor, Arduino, servo motor, and batteries. The purpose of the Arduino is to act as a pulse width modulator (PWM) to send PWM signals to the motor controller and the steering servo, since the Jetson does not have pulse width modulators in its hardware. The Jetson therefore sends signals to the Arduino to control both the vehicle's steering and speed. All signals are carried on standard breadboard jumper wires that connect to 2.54 mm sockets (same as those found on an Arduino). Separate batteries are used for the Jetson and for the motor in order to avoid a peak current draw from the motor causing the Jetson to lose power. All wires that carry current are either the standard wire size that comes with the 2S and 4S battery or multiple 22-gauge wires used in parallel to decrease their current load. These parallel wires were used to transfer power from the ESC to the motor windings. The Jetson is secured to its enclosure using small black zip ties and 5 mm nylon spacers in each of its existing holes. These holes were also designed into its enclosure for ease of assembly. The Arduino is also mounted on a piece of foam sitting on the car's chassis and then utilize zip ties to secure it to the chassis. Wi-Fi is used to communicate with the Jetson to remotely send commands and software changes. An electrical schematic is presented below.

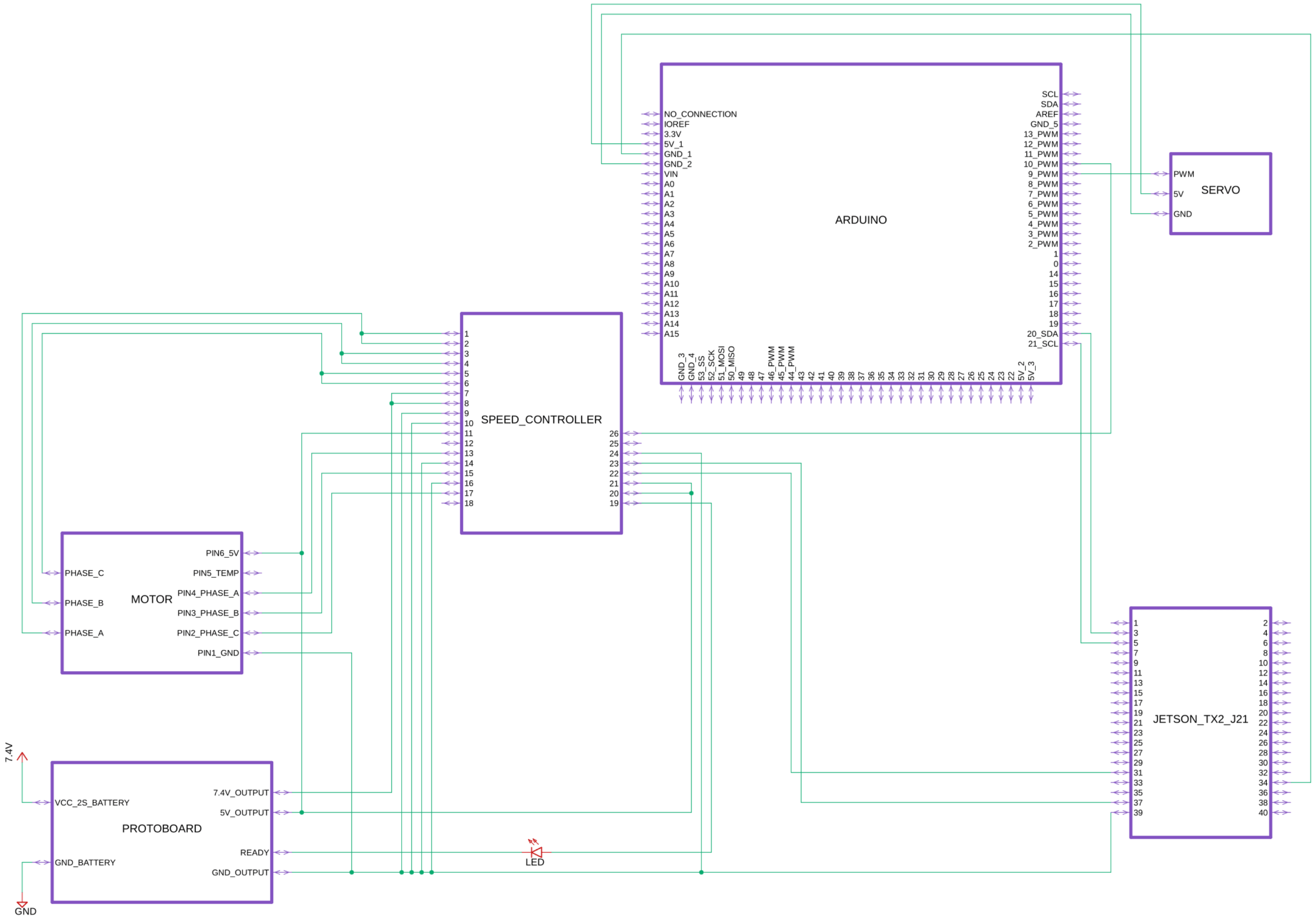


Figure 30. Electrical diagram for each of the RC cars

The positive and negative terminals of the 2S LiPo battery are wired to the protoboard first before two 22-gauge wire are wired from the protoboard to the speed controller, and an array of male pins are soldered to the protoboard, which is a common ground for the whole system. An LED will light up to indicate the system is ready to run. For simplicity in the electrical diagram, the NPN BJT and resistor, which allow the LED to function, is ignored since this circuit diagram can be found in any electrical textbook. The speed controller will output 5V signal, which will then be wired back to the protoboard and will act as a common 5V source for the motor's Hall sensor, DigIN1, and DigIN2 ports in the speed controller. The USB connection between the camera and the Jetson as well as the USB connection between the Arduino and the Jetson are neglected in this electrical diagram.

6.4 CHALLENGES AND LESSONS LEARNED

The most difficult part of the assembly of the RC car has been the wiring for the motor speed controller to the motor. The reason this is the most difficult part of the assembly is due to the small gauge of the wires used for inputs and outputs and the lack of comprehensive literature on trouble shooting issues with this electronic speed controller.

In the design of the control algorithms, the most difficult part was the Carmaker software. There are no tutorials instructing on how to use Carmaker, let alone develop an autonomous vehicles control strategy. The most effective way to learn to develop these controls strategies is to become familiar with the Simulink model and then slowly look up functions in the Carmaker user manuals. There are thousands of pages documenting each feature and function built into Carmaker and its relation to Simulink.

An additional assembly and hardware tuning challenge we faced was the tuning of the timing on our brushless DC motor. Due to current limitations of the ESC, the cars when first assembled struggled to start from a stand still. They often required a push start to begin to drive. To fix this issue we tried changing the gearing, although this had little effect. We then made the timing more negative. This allows the electric motor to produce more torque on start up with the same amount of current. Now the cars start up on their own without issue. The timing was changed to approximately halfway between the most negative timing and 0 degrees of timing. The scale of timing of the motor is in Figure 29.

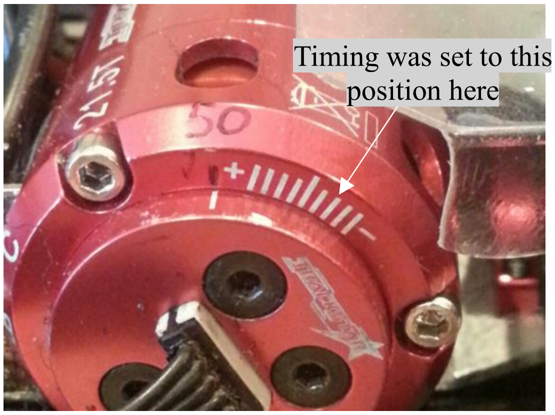


Figure 31. Timing scale for a Turnigy Trackstar 21.5 turn DC brushless motor

6.5 OUTSOURCING

For this project no manufacturing of parts has been outsourced as there are no complicated parts to be manufactured. The 3D printed housings were either printed by our own 3D printers or Innovation Sand Box. All assembly of components was done by us.

6.6 RECOMMENDATIONS FOR FUTURE PRODUCTION

Future production would benefit from the rapid selection of a car chassis so the additional components can more easily be sized and designed. The wiring and layout were the most challenging part of production and it is best to keep the wires internal to the car for aesthetics and to avoid wires getting pulled out by outside objects. To accomplish internal wiring, enclosures should be designed with passthroughs on the inside to allow the wires in and out without hanging outside of the car. 3D printing enclosures is recommended because they are easy to design, fit any shape, quick to produce, and strong enough to protect the system in a crash. The speed of production of the 3D printed enclosures has allowed us to produce multiple iterations with update features for more seamless wiring of the cars. It has also ensured that the critical components of the cars have survived many crashes.

7.0 DESIGN VERIFICATION

This section will discuss how the final design has met our design specifications through testing and calibration of the microcontroller.

7.1 SPECIFICATIONS

Based upon the specifications table seen in table 4 all specifications have either been met or have changed throughout the design process as we learned more about how the goal of this project would be accomplished. Specifications that do not meet the original goal are the specifications associated with the volume and weight of transporting the project to the Netherlands, the operating speed, and the response time of the car.

The weight of all items being brought to the Netherlands is very likely to be greater than the original 100-pound goal. This is due to the weight of the track we intend on bringing to the Netherlands and the packaging necessary (pelican cases) to protect the RC cars from damage during transport. The original volume specification will be met based upon each individual piece of luggage. The team will fly with the track in multiple boxes to reduce the weight of individual boxes which will reduce the cost of checking the bags at the airport. There will also be several pelican cases to transport the RC cars and the associated tools and hardware needed to operate the cars.

The operating speed of the RC car has not been set to 1/10 the scale of a full-sized car. This is due to the maximum speed that we can run the RC car around our track being limited by the PWM signal. The maximum duty cycle that can be sent to the motor speed controller is 20% as faster duty cycles creates speeds that are too fast for the car to drive around the track. It was also determined that our time would be better spent achieving the goal of the ESV conference for getting lane keeping, platooning, and object avoidance while platooning to work effectively. Focusing our efforts on these tasks paid off as the team made it to the competition in the Netherlands.

Finally, the response time that we initially specified will not be met. According to the CPE team the response time from when our system detects an object to when the system sends a signal to the motor or the steering servo will more likely be around 0.6 seconds. Unfortunately, this is not something that the mechanical engineering team can help fix as more efficient coding on the CPE teams' part will affect this value. If the system can respond fast enough to effectively lane keep, dodge objects, and platoon effectively, this specification not being met is of little importance.

7.2 TESTING

The testing phase of this project has lasted several months starting from the first integration with the CPE team and will end a few days before the ESV conference in the Netherlands. Several of the tests that have been performed include non-intentional crash testing, operating speed, lane keeping, and object detection. These tests were conducted initially in the mechatronics room and the Bonderson high bay, until the spring quarter at which point all testing was performed in the Capstone lab. For a complete list of testing that was performed in the order which testing was completed see the below list from the DVP&R.

1. Rollover test on enclosure alone
2. Unloaded wheel speed
3. Loaded speed
4. Lane Keeping
5. Crash Testing (non-intentional)
6. Object recognition (stop signs, speed signs, and obstacle dodging)
7. Platooning

The first test that was done was the initial hardware testing included testing the new ESC, motor, battery, and Jetson. We tested that we can control the speed of the motor using the speed controller that is receiving a signal from the Jetson to set the speed of the motor. This was performed while powering the speed controller with the battery we have purchased. The Jetson has been tested to be capable of powering and controlling the steering servo. We found that it can achieve and hold max steering angle in both directions and return to steering straight. While executing a straight command, noise in the angle was observed which was due to noise in the PWM coming from the Jetson. This noise was eliminated by incorporating the Arduino mega controller to hardware PWM signals could be used.

Once the initial hardware testing was completed calibration testing was performed for acceleration, braking, and steering. Acceleration and braking calibration were first completed in a straight line on a track. The steering is controlled using a PID controller that was calibrated first with the CPE team's lane identification software. This was performed while the car was motionless on a track and while the car was pushed within the lane lines of a track. The initial calibration of the steering servo was considered complete when the wheels appeared to be pointing in the right direction on the track through all turns. The results for the gains in the PID controller for the steering controller are presented in the below table.

Table 7. Tabulated values for the final gains used in the PID controller for the Steering servo.

Controller	Proportional Gain	Derivative Gain	Offset [pixels]
Steering	24/300	2.8/300	196

After the initial calibration all these functions were combined, and testing was performed on a circular track. Through observation the software was calibrated to allow the RC cars to achieve lane keeping. Lane keeping testing and calibration has been performed continuously due to camera angle changes, changes in operating speed, and when new features were added in the software. Lane keeping had to also be completely recalibrated with the addition of the Zed Mini cameras. The values in table 7 reflect the most recent values.

Table 8. Speed setting and lane keeping response of cars

Speed Setting	Lane Keeping [Pass or Fail]	Notes
Crawl	Pass	On crawl mode the cars struggle under hard steering angle due to the additional stiction
Slow	Pass	Cars lane keep easily
Medium	Pass	Cars lane keep easily
Fast	Pass	Cars lane keep easily
Ludicrous	Pass	Some oscillations visible in the steering, but stays within lane and is stable for multiple laps at this speed

The Zed Mini has a difference field of view than the original cameras used on this project. This forced us to increase the radius of the sharpest corner on the track as well as retuning the control logic. With these new settings the car was able to navigate the track successfully on all the programmed speed settings. At the highest speed setting the car does have visible oscillations but can navigate the track consistently.

Table 9. Speed setting and corresponding duty cycle

Speed Setting	Duty Cycle [%]
crawl	9
slow	12
medium	14
fast	16
ludicrous	20

Once the RC cars had lane keeping software working reliably the CPE team developed computer vision software to achieve object detection. This software was tested by determining if the RC car could stop and change speed at different signs that were placed on the side of the track.

The next step our testing process built upon the computer vision developed for object detection to achieve platooning. Platooning testing was performed on an observational basis. The initial controller that was used for platooning incurred large oscillations in the platoon when the following car lost sight of the lead car through turns. The following car is programmed to stay a certain distance behind the lead car. During a turn when the lead car was out of sight the following car would speed up and then once the lead car was back in view the following car would slow down greatly to achieve the programmed set distance. This was fixed once vehicle to vehicle communication was integrated and the oscillations in platooning through the turns was nearly eliminated. A plot showing the reduction of oscillations in the system by integrating vehicle to vehicle communication can be seen in the figure 32. The plot shows the height of the battery enclosure (in pixels) of the lead car measured by the following car over time while the RC car travels around the track. The change in the height of the battery enclosure can be related to the distance between the RC cars and can be treated as distance between the RC cars in the below figure.

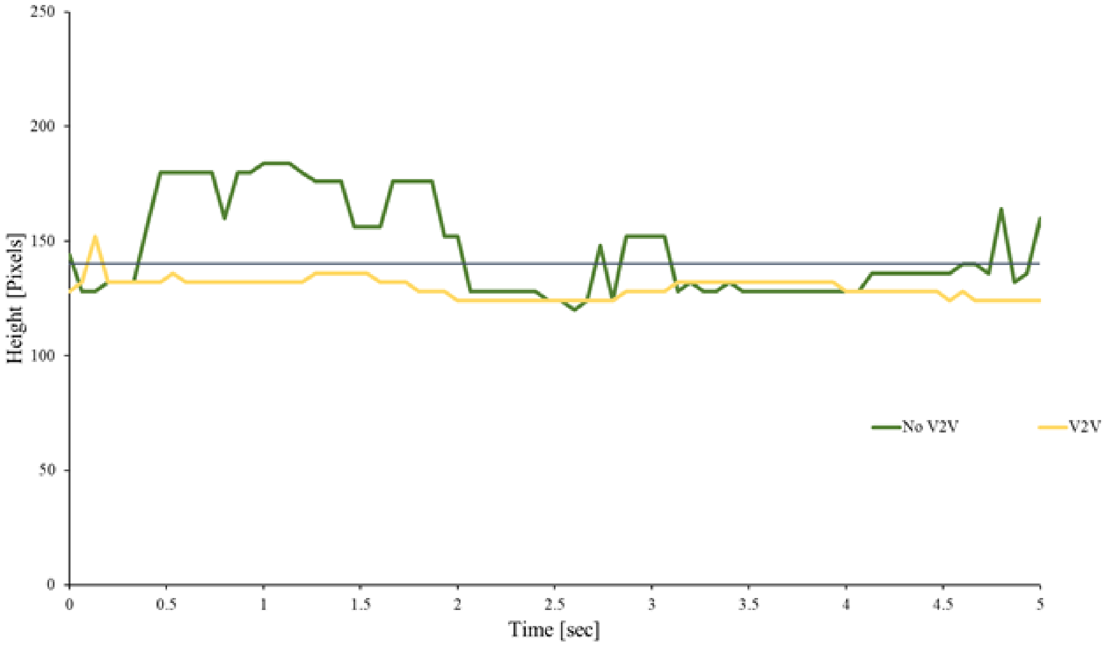


Figure 32. Plot of the comparison of platooning stability with and without vehicle to vehicle (V2) communication with the original Logitech cameras. (This plot shows the height of the battery housing that the rear car sees over time which is used to determine distance. The y axis is correlated to the distance between cars.)

The final resulting controller values set in the platooning controller can be seen in the figure below. All testing of the control logic values can be seen in Appendix P with the notes regarding how each change in controller affected the platoon.

Table 10. Tabulated values for the final controller values used in the platooning controller

Position Influence	Frequency Influence	Proportional Gain	Derivative Gain	Height Set Point [Pixels]
0.075	0.03	0.8	0.05	115

With the platooning settings tuned, they were tested in coordination with the CPE's against disturbances. The cars were programmed to detect stop signs. When a stop sign was detected both cars can successfully stop in unison at the stop sign and start again without crashing into each other. Further, the cars under user command can change speeds together without disrupting the platoon. Also, the platoon has been tested by physically disturbing the following car. The following car can be pulled backwards or to the side and respond appropriately. When pulled to the side the car steers to the center of the lane and stabilizes itself. When pulled backwards the car increases the duty cycle it is sending to the motor to try and catch up to the lead car.

To test full load speed, one of the cars was placed on the track and time needed to complete one round was recorded. Then, uncertainty analysis was performed to find mean, standard deviation, and the uncertainty of recorded data. Mean and standard deviation can be found easily by using corresponding commands in Excel. The total uncertainty is comprised of three components: bias, precision, repeatability. Bias is defined as the uncertainty from manufacturer. We assume this is the least count of the recorded data, which is 0.01 s. Precision is half of the least count, which is 0.005 s. Repeatability, or standard uncertainty, is defined as the ratio of the standard deviation of the sample over the square root of sample population. The combined uncertainty is the squared root of each component squared. Table 11 below outlines the mean, standard deviation, and uncertainty components for data collected in Test 3: Full Load Speed (Appendix O).

Table 11. Uncertainty analysis for data collected in Test 3: Full Load Speed

Mean [s]	Standard Deviation [s]	Bias [s]	Precision [s]	Repeatability [s]	Combined Uncertainty [s]
14.111	0.427	0.001	0.005	0.101	0.101

The next step in testing for object avoidance was to test and calibrate the manual lane change. The first iteration of the CPE's lane change code featured very aggressive lane changes. The aggressiveness of the lane changes was reduced by reducing the proportional gain in the lane change PID controller along with changing the new set point for the car from being the middle of the next lane to close to the original lane the car was in. This was then tested on the platoon of vehicles. When the lead vehicle executes a lane change, it communicates to the following vehicle to do so in unison. With enough space on track the vehicles can change lanes in unison.

The final step in the testing process was combining all the previous testing results to calibrate and combine the lane change code with the object detection code to autonomously avoid objects. For a single car then later a second car was added into the testing a calibration process. For the complete testing procedures and results see Appendix O.

7.3 FUTURE WORK

Future work for this project may include the addition of more intelligent software. In its current form, the object recognition and avoidance are simple and can be expanded upon easily. The hardware necessary to do so is incorporated into the car. Path planning can be further developed as well as the integration of a fully-fledged machine learning algorithm to read traffic signs. As well as adding features, the technology we have developed can be used to study how a platoon of autonomous vehicle reacts to various disturbances.

8.0 PROJECT MANAGEMENT:

A project of this scale and timeline demanded thorough project planning. We spent most of the month of October researching the technology involved and laying out project requirements. We also determined all major deadlines associated with this project which are outlined in the table below. An abstract was submitted to the ESV competition on November 9th. A preliminary design review (PDR) was in mid-November. At this presentation, we discussed conceptual design choices for the track, microcontroller housing, RC car selection, and path planning algorithm. Power requirements, battery type and sensors requirements for feedback control, and communication requirements for collaborating was outlined at PDR.

Table 10. Important deliverables and respective dates

Deliverable #	Deliverable	Due Date
1	Scope of Work	10/19/2018
2	ESV Contest Abstract	11/09//2018
3	PDR Presentation	11/15/2018
4	PDR	11/16/2018
5	Interim Design Review	1/17/2019
6	CDR Presentation	2/7/2019
7	CDR	2/8/2019
8	ESV Regional Design Review	03/06/19
9	Manufacturing and Test Review	3/14/2019
10	Hardware/Safety Demo	4/25/2019
11	Expo	5/31/2019
12	ESV Conference	6/10/2019

The winter months were spent finalizing our detailed design for the track and cars. The track design was completed by the end of May as the track was changed for different iterations of the software. After the PDR, the design of the control algorithm began, along with integrating the path planning algorithm with our controller and Carmaker. An interim design review was presented in mid-January, and a critical design review (CDR) was presented during the first week of February. At the CDR, we presented our specific designs, a cost analysis of the materials required, and all necessary equipment was specified and demonstrated.

The month of January was used to construct the vehicles and track. Significant time was spent in carmaker in order to simulate and developed controllers that would be used for the RC cars. Due to the complex nature of the technology, we spent significant time troubleshooting, and calibrating the system before competition. We accomplished having both cars built for the regional ESV competition, along with lane keeping, platooning, and object detection working on our test track with the RC cars, and simulations in carmaker for lane changes for a single vehicle based upon object detection.

After completing the regional presentation for the ESV competition, the CPE team and the mechanical engineering team determined that the next goals of this project were to integrate lane changes into the software, stereoscopic cameras onto the RC cars in order to achieve depth perception and paint the track. These goals are to be completed before the ESV competition in the Netherlands.

9.0 CONCLUSION:

This document has been made to set out the goals for this project, from our design process, our final design, to the final product. It was our goal as a team to build two vehicles and a test track to integrate hardware and software in coordination with a team of CPE students from Cal Poly. We have accomplished collaborative vehicle platooning and object avoidance which can be used to demonstrate the safety of using autonomous collision avoidance systems and the benefits of applying it to truck platooning. The goal of this project to be selected to compete in the ESV competition in the Netherlands has been met by demonstrating a functional prototype and composing a thorough report and presentation on all our work up to the regional ESV presentation.

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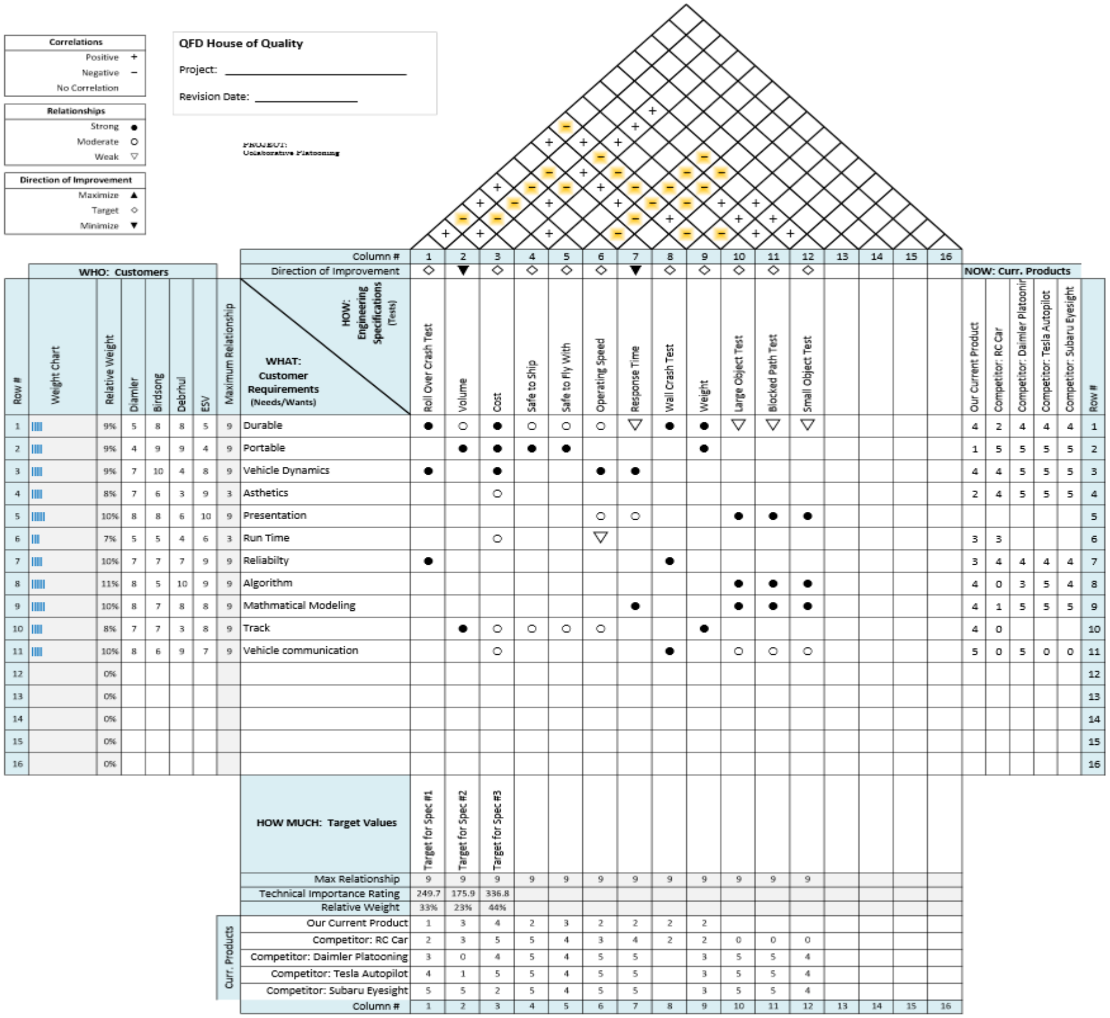
APPENDIX TABLE OF CONENTS

APPENDIX A – QFD House of Quality Development



Correlations	
Positive	+
Negative	–
No Correlation	

Relationships	
Strong	●
Moderate	○
Weak	▽

Direction of Improvement	
Maximize	▲
Target	◇
Minimize	▼

QFD House of Quality

Project: ______________________

Revision Date: ____________

PROJECT:
Collaborative Platooning

WHO: Customers

Row #	Weight Chart	Relative Weight	Diamler	Birdsong	Debrhul	ESV	Maximum Relationship	WHAT: Customer Requirements (Needs/Wants)
1	▮▮▮▮	9%	5	8	8	5	9	Durable
2	▮▮▮▮	9%	4	9	9	4	9	Portable
3	▮▮▮▮	9%	7	10	4	8	9	Vehicle Dynamics
4	▮▮▮▮	8%	7	6	3	9	3	Asthetics
5	▮▮▮▮▮	10%	8	8	6	10	9	Presentation
6	▮▮▮	7%	5	5	4	6	3	Run Time
7	▮▮▮▮	10%	7	7	7	9	9	Reliabilty
8	▮▮▮▮▮	11%	8	5	10	9	9	Algorithm
9	▮▮▮▮▮	10%	8	7	8	8	9	Mathmatical Modeling
10	▮▮▮▮	8%	7	7	3	8	9	Track
11	▮▮▮▮	10%	8	6	9	7	9	Vehicle communication
12		0%						
13		0%						
14		0%						
15		0%						
16		0%						

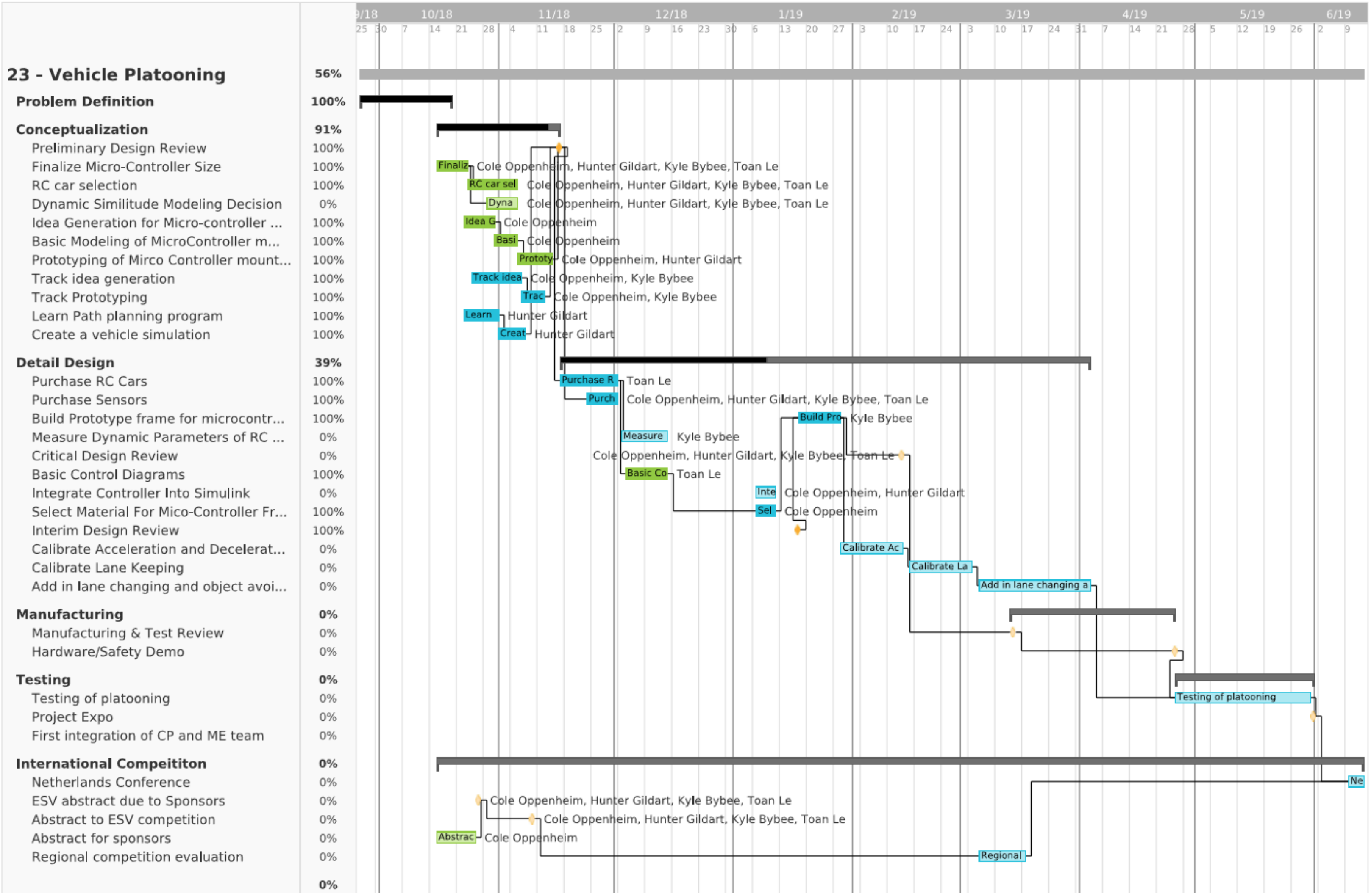
Column #	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Direction of Improvement	◇	▼	◇	◇	◇	◇	▼	◇	◇	◇	◇	◇				
HOW: Engineering Specifications (Tests) / WHAT: Customer Requirements (Needs/Wants)	Roll Over Crash Test	Volume	Cost	Safe to Ship	Safe to Fly With	Operating Speed	Response Time	Wall Crash Test	Weight	Large Object Test	Blocked Path Test	Small Object Test				
Durable	●	○	●	○	○	○	▽	●	●	▽	▽	▽				
Portable		●	●	●	●				●							
Vehicle Dynamics	●		●			●	●									
Asthetics			○													
Presentation						○	○			●	●	●				
Run Time			○			▽										
Reliabilty	●							●								
Algorithm										●	●	●				
Mathmatical Modeling							●			●	●	●				
Track		●	○	○	○	○			●							
Vehicle communication			○					●		○	○	○				

NOW: Curr. Products

Our Current Product	Competitor: RC Car	Competitor: Daimler Platoonir	Competitor: Tesla Autopilot	Competitor: Subaru Eyesight	Row #
4	2	4	4	4	1
1	5	5	5	5	2
4	4	5	5	5	3
2	4	5	5	5	4
					5
3	3				6
3	4	4	4	4	7
4	0	3	5	4	8
4	1	5	5	5	9
4	0				10
5	0	5	0	0	11
					12
					13
					14
					15
					16

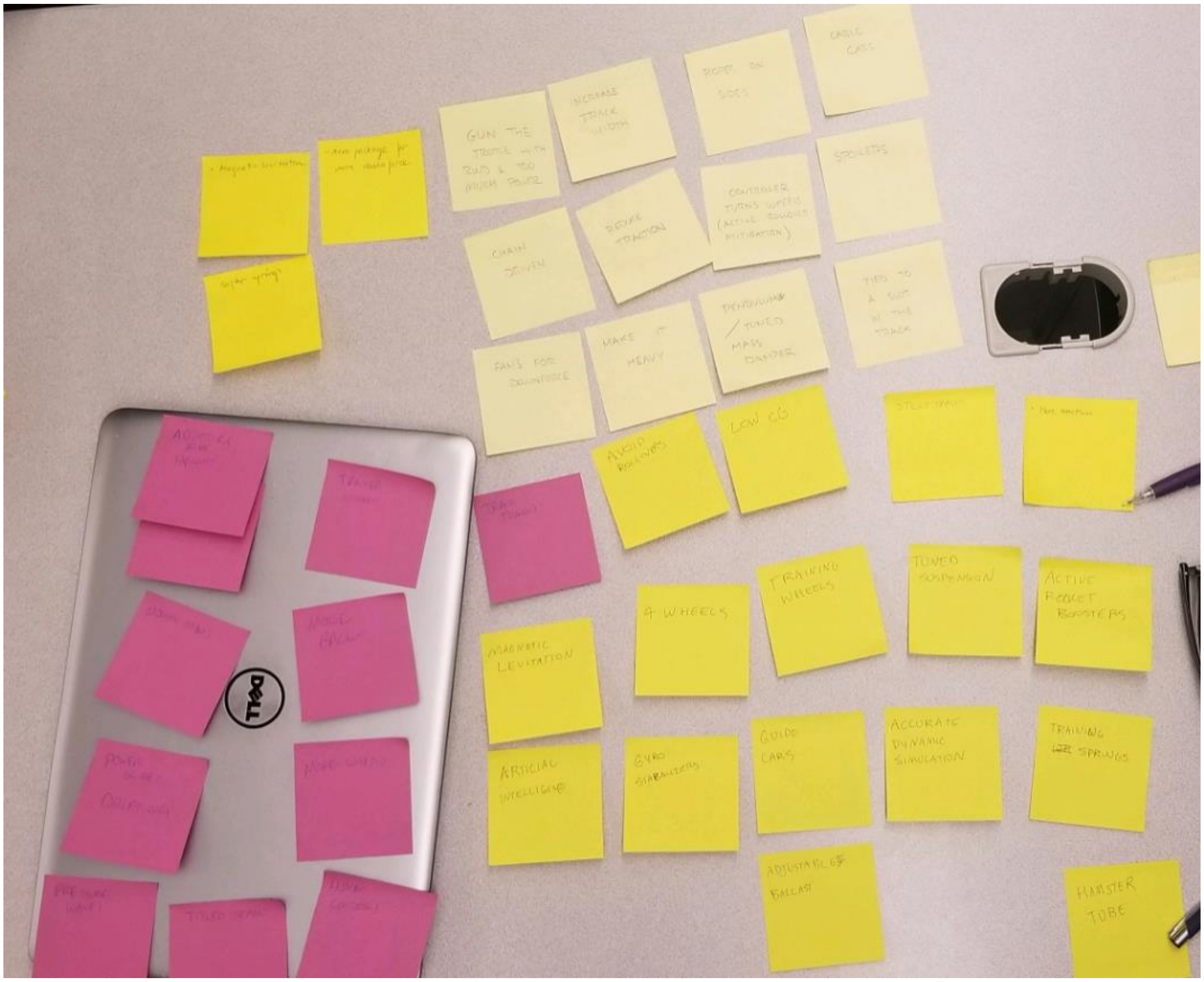
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
	HOW MUCH: Target Values	Target for Spec #1	Target for Spec #2	Target for Spec #3													
	Max Relationship	9	9	9	9	9	9	9	9	9	9	9	9				
	Technical Importance Rating	249.7	175.9	336.8													
	Relative Weight	33%	23%	44%													
Curr. Products	Our Current Product	1	3	4	2	3	2	2	2	2							
	Competitor: RC Car	2	3	5	5	4	3	4	2	2	0	0	0				
	Competitor: Daimler Platooning	3	0	4	5	4	5	5		3	5	5	4				
	Competitor: Tesla Autopilot	4	1	5	5	4	5	5		3	5	5	4				
	Competitor: Subaru Eyesight	5	5	2	5	4	5	5		3	5	5	4				
	Column #	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16

APPENDIX B – Gantt chart for task management



23 - Vehicle Platooning	**56%**
Problem Definition	**100%**
Conceptualization	**91%**
Preliminary Design Review	100%
Finalize Micro-Controller Size	100%
RC car selection	100%
Dynamic Similitude Modeling Decision	0%
Idea Generation for Micro-controller ...	100%
Basic Modeling of MicroController m...	100%
Prototyping of Mirco Controller mount...	100%
Track idea generation	100%
Track Prototyping	100%
Learn Path planning program	100%
Create a vehicle simulation	100%
Detail Design	**39%**
Purchase RC Cars	100%
Purchase Sensors	100%
Build Prototype frame for microcontr...	100%
Measure Dynamic Parameters of RC ...	0%
Critical Design Review	0%
Basic Control Diagrams	100%
Integrate Controller Into Simulink	0%
Select Material For Mico-Controller Fr...	100%
Interim Design Review	100%
Calibrate Acceleration and Decelerat...	0%
Calibrate Lane Keeping	0%
Add in lane changing and object avoi...	0%
Manufacturing	**0%**
Manufacturing & Test Review	0%
Hardware/Safety Demo	0%
Testing	**0%**
Testing of platooning	0%
Project Expo	0%
First integration of CP and ME team	0%
International Compeititon	**0%**
Netherlands Conference	0%
ESV abstract due to Sponsors	0%
Abstract to ESV competition	0%
Abstract for sponsors	0%
Regional competition evaluation	0%
	0%

APPENDIX C – Ideation Session



APPENDIX D – Computer Based Ideation Session

Frame/crash protection (protect microcontroller)

- 3d printed
- Machined aluminum
- Machined steel
- Using fasteners to attach members
- Welding member together
- Collapsible bumpers
- RC chassis reinforcement
- Wood frame
- Rubber bumpers
- Modular parts
- Airbags
- Crumple zone
- Titanium reinforcements
- Car body shell for protection
- Low cg to prevent rollovers
- Make stuff out of plastic straws like the dynamics project
- Reinforce flimsy frame with truck bed linning

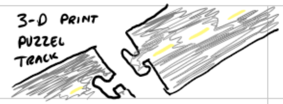
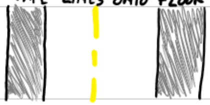
Mounting (attach microcontroller to frame and RC car)

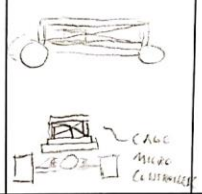
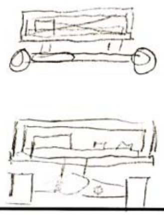
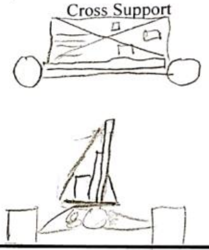
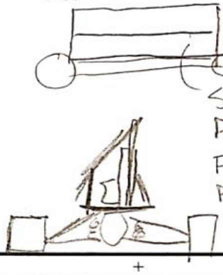
- Bolts
- Screws
- Zip ties
- Glue
- Self-interlocking
- Rubber bands
- Have micro controller separate and wirelessly connect micro controller to car or connect by wires
- Springs & rubbers for vibration isolation
- Binder clips
- Velcro
- Duct tape
- Slotted inserts
- Snap in plastic mount
- Attach to dampers to isolate controller from RC car vibes
- Base plate with designed attachment point
- Rail connections
- Weld it on
- Suction mounts
- Playdough
- Super glue
- Mount in on sliders with damper

Track design

- Self-interlocking
- Tape on simple black surface
- 3-d printable in sections
- Painted carpet
- Model concrete or asphalt for desired coefficient of friction
- Trees and shrubbery for looks
- Realistic object design incorporated into the track
- Realistic lane design
- Yoga mats
- Interlocking modular design for transportability
- Well-lit for visibility
- Oval
- Complex turns
- Pass over
- Varying degrees of turns
- Woodland creatures
- Reflective tape
- Spray painted lanes using stencils
- Barriers to prevent car from hitting someone incase it decides to run away for whatever reason

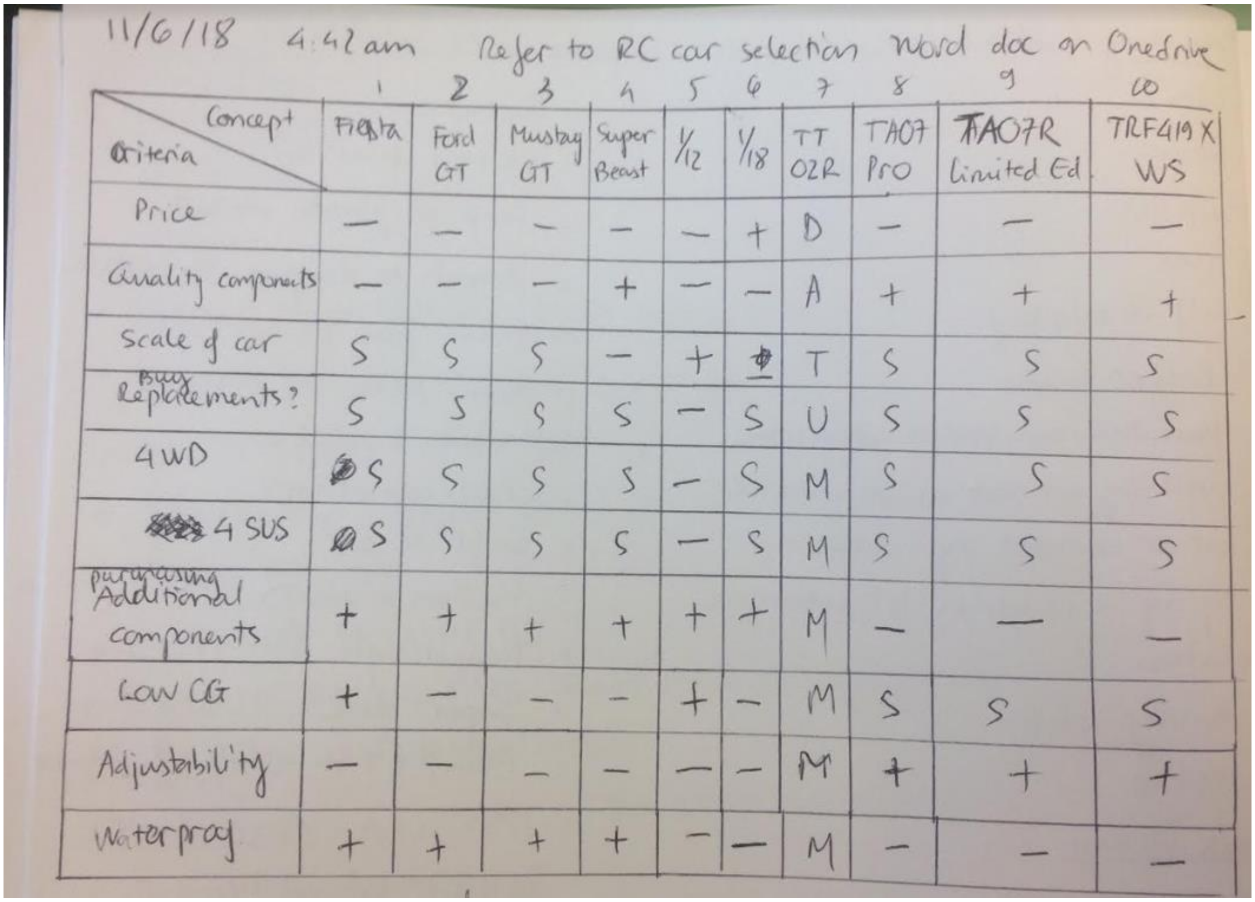
APPENDIX E – Pugh Matrices

Concept Criteria	3-D PRINT PUZZEL TRACK 	DUCT TAPE LINES ONTO FLOOR 	ROAD SURFACE (CARPET, MATT)  VELCRO	ROAD SURFACE (CARPET, MATT)  ZIPPERS	Road Surface Printed on plastic Surface and Pre Cut
Durable	S	S	S	-	S
Portable	S	+	+	S	+
Aesthetics	S	-	+	S	+
Modular	S	+	-	-	-

Concept Criteria	Horizontal Mounting Inside Track Width  CAGE MICRO CONTROLLER	Horizontal Mounting on Top of Car 	Vertical mounting (Microcontroller on side) with Cross Support 	Vertical Mounting with Tenting Support and Protection  SOLID PANEL FOR PROTECTION
Durable	S	-	S	+
Portable	S	-	-	-
Vehicle Dynamics	S	-	-	-
Asthetics	S	-	+	+

MICROCONTROLLER TOO LARG

FITS



11/6/18 4:42 am Refer to RC car selection word doc on Onedrive

	1	2	3	4	5	6	7	8	9	10
Concept / Criteria	Fiesta	Ford GT	Mustang GT	Super Beast	1/12	1/18	TT 02R	TA07 Pro	TA07R Limited Ed	TRF419 X WS
Price	−	−	−	−	−	+	D	−	−	−
Quality components	−	−	−	+	−	−	A	+	+	+
Scale of car	S	S	S	−	+	−	T	S	S	S
Buy Replacements?	S	S	S	S	−	S	U	S	S	S
4WD	S	S	S	S	−	S	M	S	S	S
4 SUS	S	S	S	S	−	S	M	S	S	S
purchasing Additional components	+	+	+	+	+	+	M	−	−	−
Low CG	+	−	−	−	+	−	M	S	S	S
Adjustability	−	−	−	−	−	−	M	+	+	+
waterproof	+	+	+	+	−	−	M	−	−	−

APPENDIX F – Weighted Decision Matricies

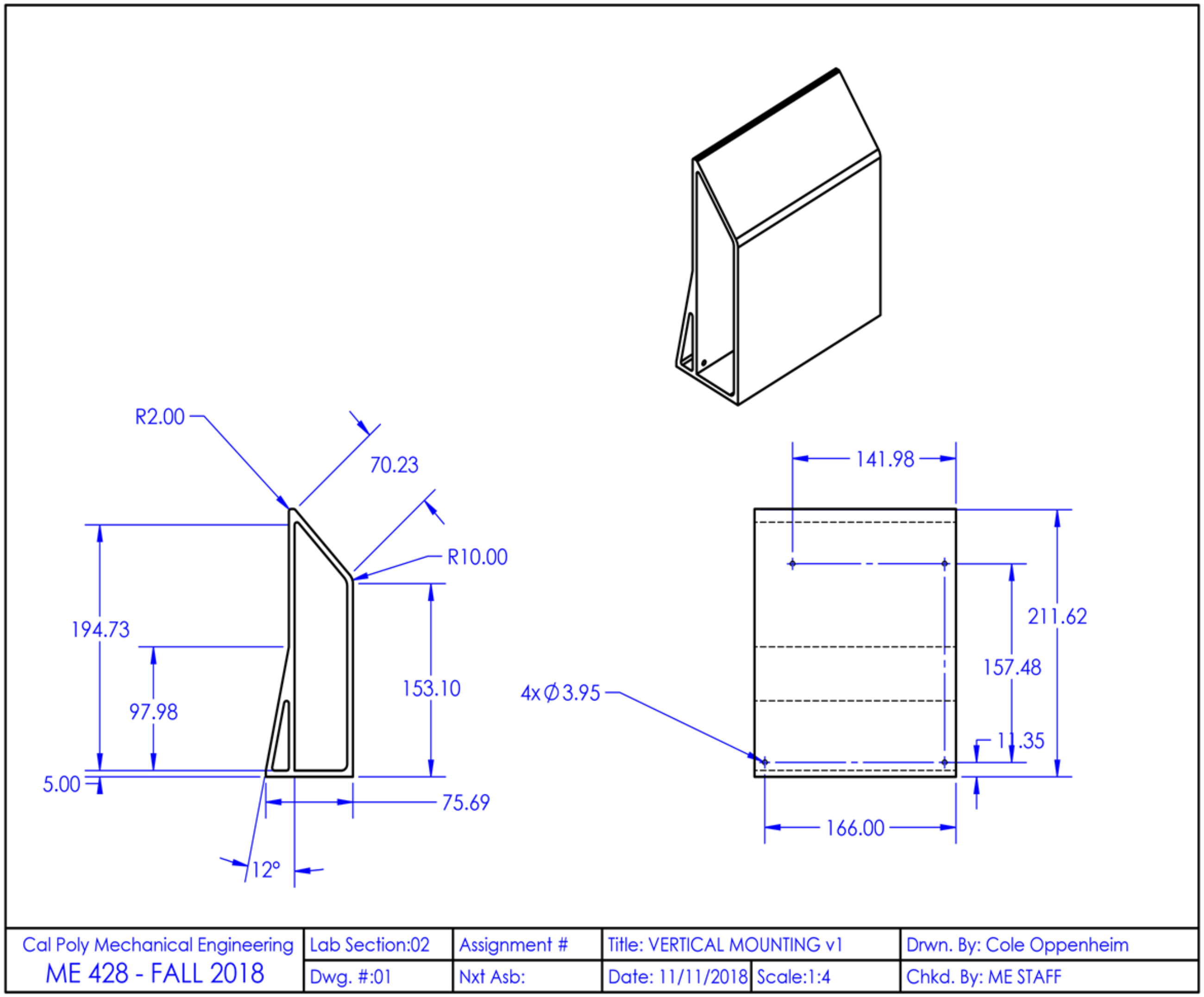
Weighted Decision Matrix for Track													
Track Weighted Matrix		**3-D printed puzzel Track**		**Duct Tape Lines onto Floor**		**Carpet Velcroed together**		**Surface held together with**		**Interlocking Rubber**		**Rubber Floor Matt**	
Criteria	**Weight**	**Rating**	**Score**	**Rating**	**Score**	**Rating**	**Score**	**Rating**	**Score**	**Rating**	**Score**	**Rating**	**Score**
Durable	0.3	0.5	0.15	0	0	1.5	0.45	0	0	2	0.6	2	0.6
Portable	0.3	1.5	0.45	2	0.6	-2	-0.6	1	0.3	0	0	0	0
Aesthetics	0.15	2	0.3	-2	-0.3	1	0.15	2	0.3	2	0.3	2	0.3
Modular	0.25	1	0.25	2	0.5	0	0	-1	-0.25	2	0.5	0	0
Totals	1	**5**	**1.15**	**2**	**0.8**	**0.5**	**0**	**2**	**0.35**	**6**	**1.4**	**4**	**0.9**
Rank		2		4		5		4		1		3	

Weighted Decision Matrix for Path Planning Algorithm									
Criteria	**Weight**	**Tangent Bug**		**RRT**		**A***		**Fixed Path**	
		Score	**Total**	**Score**	**Total**	**Score**	**Total**	**Score**	**Total**
Difficulty of Implementation	0.36	4	1.43	2	0.71	2	0.71	5	1.79
Processing Time	0.21	4	0.86	3	0.64	3	0.64	4	0.86
Dynamic Capability	0.14	2	0.29	5	0.71	4	0.57	0	0.00
Impressiveness	0.29	3	0.86	3	0.86	3	0.86	1	0.29
Total Score	1	**3.43**		**2.929**		**2.79**		**2.929**	
Rank		1		2		3		2	

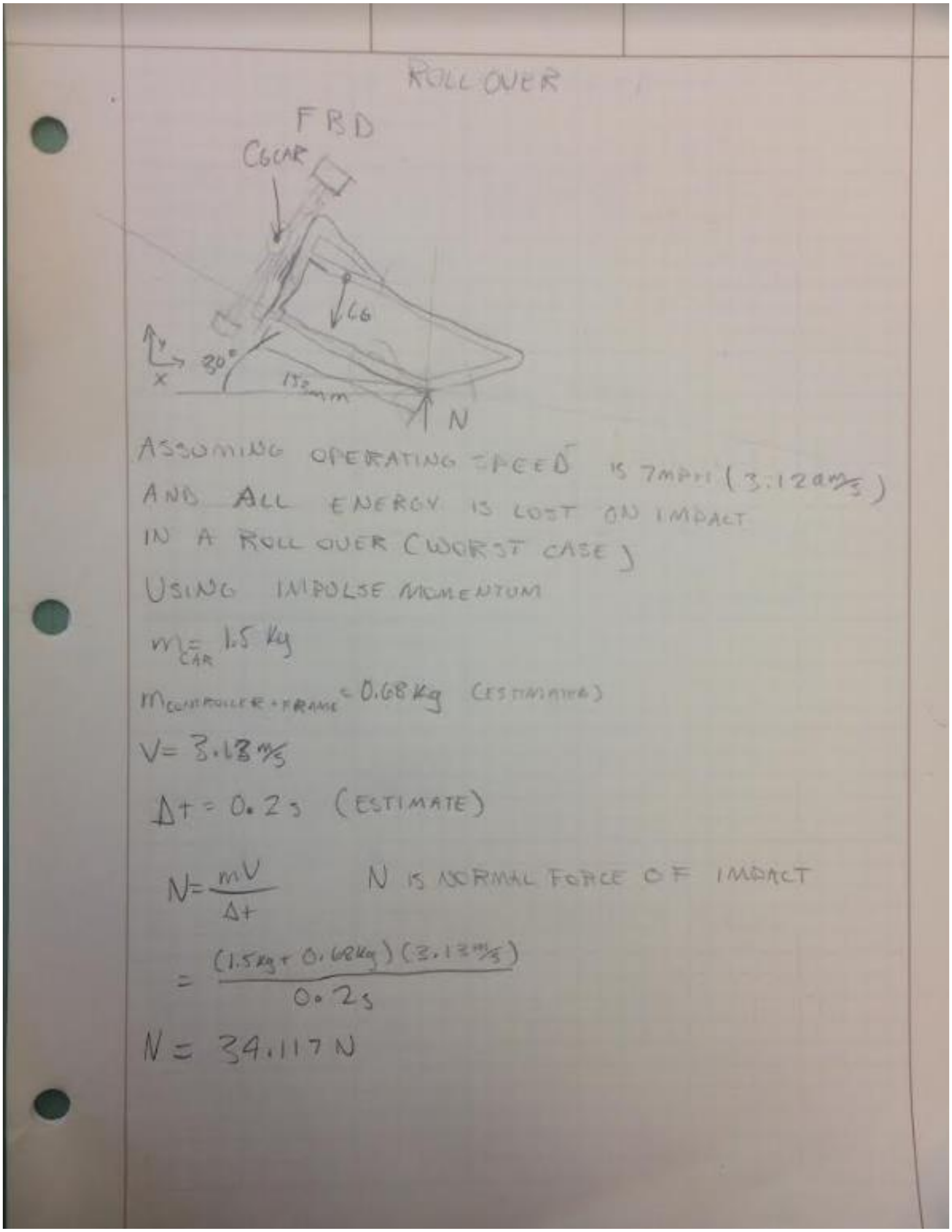
Weighted Decision Matrix for Controller Mounting Design					
Concept Criteria	**Weighting**	**Horizontal Mounting Inside Track Width**	**Horizontal Mounting on Top of Car**	**Vertical mounting (Microcontroller on side) with Cross Support**	**Vertical Mounting with Tenting Support and Protection**
Durable	0.3	0	-0.1	0	0.3
Portable	0.2	0	-0.1	-0.2	-0.1
Vehicle Dynamics	0.2	0	-0.1	-0.5	-0.2
Asthetics	0.3	0	-0.5	0.5	0.6
Total	1	0	-0.22	0.01	0.21
Rank		(Likely not possible)	3	2	1
Continue					Yes

Weighted Decision Matrix For RC Cars																					
		Fiesta		Ford GT		Mustang GT		Super Beast		1/12 Scale		1/18 Scale		TT 02R		TA07 Pro		TA 07R Limited Ed.		TRF419X WS	
Criteria	Weighting																				
& Quality Compo	0.15	4	0.61	4	0.61	4	0.61	2	0.30	4	0.61	5	0.76	5	0.76	4	0.61	3	0.45	2	0.30
Scale of car	0.15	5	0.76	5	0.76	5	0.76	1	0.15	3	0.45	2	0.30	5	0.76	5	0.76	5	0.76	5	0.76
to find replacem	0.15	4	0.61	4	0.61	4	0.61	4	0.61	3	0.45	2	0.30	5	0.76	5	0.76	5	0.76	5	0.76
ensions for VD Si	0.15	4	0.61	5	0.76	5	0.76	4	0.61	1	0.15	5	0.76	5	0.76	5	0.76	5	0.76	5	0.76
4WD	0.12	5	0.61	5	0.61	5	0.61	5	0.61	1	0.12	5	0.61	5	0.61	5	0.61	5	0.61	5	0.61
re additional pur	0.12	5	0.61	5	0.61	5	0.61	5	0.61	5	0.61	5	0.61	4	0.48	3	0.36	3	0.36	4	0.48
Adjustability	0.09	1	0.09	1	0.09	1	0.09	1	0.09	1	0.09	1	0.09	3	0.27	4	0.36	5	0.45	5	0.45
Waterproof	0.06	5	0.30	4	0.24	4	0.24	5	0.30	1	0.06	1	0.06	1	0.06	1	0.06	1	0.06	1	0.06
Total	1		**4.18**		**4.27**		**4.27**		**3.27**		**2.55**		**3.48**		**4.45**		**4.27**		**4.21**		**4.18**
Rank			4		2		2		6		7		5		1		2		3		4

APPENDIX G – Micro-controller Housing Drawing version 1



APPENDIX H – Preliminary Load calculations for strength of microcontroller housing



ROLL OVER

FRD

ASSUMING OPERATING SPEED IS 7MPH (3.129 m/s)
AND ALL ENERGY IS LOST ON IMPACT
IN A ROLL OVER (WORST CASE)

USING IMPULSE MOMENTUM

$m_{CAR} = 1.5\ kg$

$m_{CONTROLLER + FRAME} = 0.68\ kg$ (ESTIMATED)

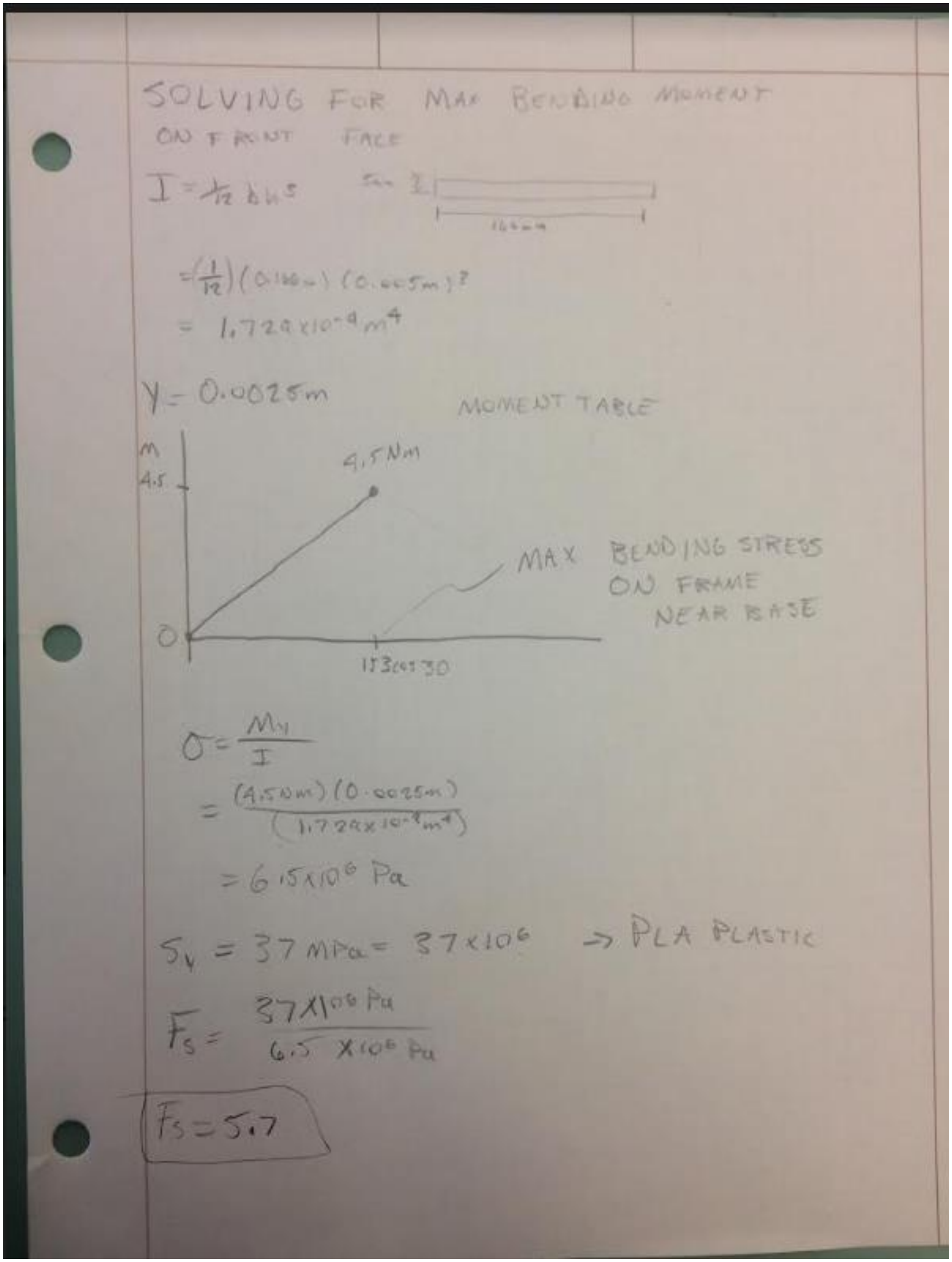
$V = 3.13\ m/s$

$\Delta t = 0.2\ s$ (ESTIMATE)

$N = \frac{mV}{\Delta t}$ N IS NORMAL FORCE OF IMPACT

$= \frac{(1.5\ kg + 0.68\ kg)(3.13\ m/s)}{0.2\ s}$

$N = 34.117\ N$



SOLVING FOR MAX BENDING MOMENT
ON FRONT FACE

$I = \frac{1}{12} bh^3$

5mm
166mm

$= \left(\frac{1}{12}\right)(0.166m)(0.005m)^3$
$= 1.729 \times 10^{-9} m^4$

$y = 0.0025m$

MOMENT TABLE

M
4.5
4.5Nm
0
153cos30
MAX BENDING STRESS ON FRAME NEAR BASE

$\sigma = \frac{My}{I}$

$= \frac{(4.5Nm)(0.0025m)}{(1.729 \times 10^{-9} m^4)}$

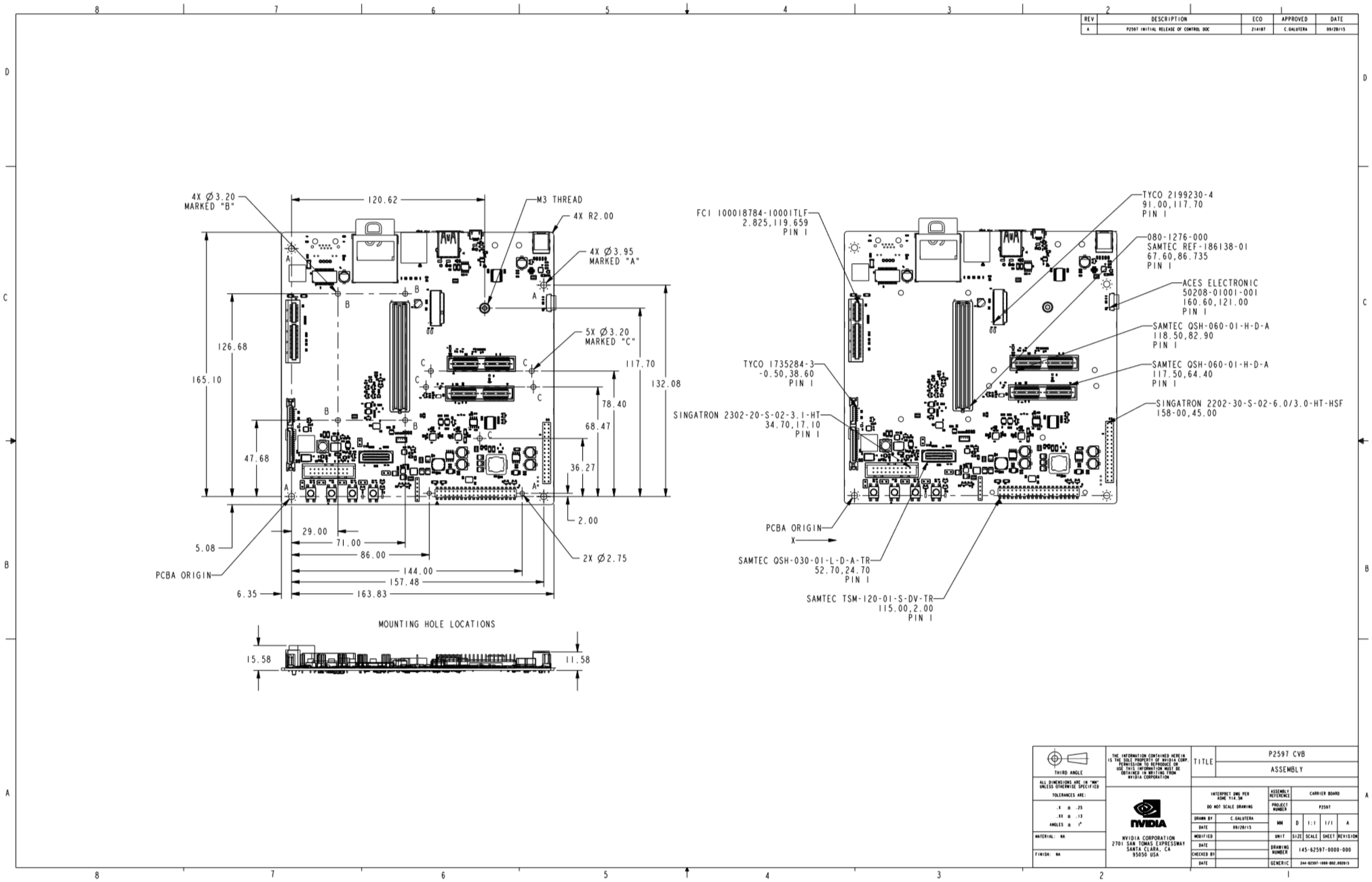
$= 6.15 \times 10^6 \ Pa$

$S_y = 37 \ MPa = 37 \times 10^6$ → PLA PLASTIC

$F_s = \frac{37 \times 10^6 \ Pa}{6.5 \times 10^6 \ Pa}$

$\boxed{F_s = 5.7}$

APPENDIX I – Microcontroller assembly drawing by Nvidia



APPENDIX J – Design Hazard Checklist

DESIGN HAZARD CHECKLIST

Team: AVOCADO Advisor: SCHUSTER/BIRDSONG Date: 11-13-18

Y / N

☑ ☐ 1. Will the system include hazardous revolving, running, rolling, or mixing actions?

☐ ☑ 2. Will the system include hazardous reciprocating, shearing, punching, pressing, squeezing, drawing, or cutting actions?

☐ ☑ 3. Will any part of the design undergo high accelerations/decelerations?

☐ ☑ 4. Will the system have any large (>5 kg) moving masses or large (>250 N) forces?

☑ ☐ 5. Could the system produce a projectile?

☐ ☑ 6. Could the system fall (due to gravity), creating injury?

☐ ☑ 7. Will a user be exposed to overhanging weights as part of the design?

☐ ☑ 8. Will the system have any burrs, sharp edges, shear points, or pinch points?

☐ ☑ 9. Will any part of the electrical systems not be grounded?

☐ ☑ 10. Will there be any large batteries (over 30 V)?

☐ ☑ 11. Will there be any exposed electrical connections in the system (over 40 V)?

☐ ☑ 12. Will there be any stored energy in the system such as flywheels, hanging weights or pressurized fluids/gases?

☐ ☑ 13. Will there be any explosive or flammable liquids, gases, or small particle fuel as part of the system?

☐ ☑ 14. Will the user be required to exert any abnormal effort or experience any abnormal physical posture during the use of the design?

☐ ☑ 15. Will there be any materials known to be hazardous to humans involved in either the design or its manufacturing?

☐ ☑ 16. Could the system generate high levels (>90 dBA) of noise?

☐ ☑ 17. Will the device/system be exposed to extreme environmental conditions such as fog, humidity, or cold/high temperatures, during normal use?

☑ ☐ 18. Is it possible for the system to be used in an unsafe manner?

☑ ☐ 19. For powered systems, is there an emergency stop button?

☐ ☑ 20. Will there be any other potential hazards not listed above? If yes, please explain on reverse.

For any "Y" responses, add (1) a complete description, (2) a list of corrective actions to be taken, and (3) date to be completed on the reverse side.

Description of Hazard	Planned Corrective Action	Planned Date	Actual Date
(1) The car will be rolling on wheels and rotating drivetrain components	There should no human interaction with these cars while they are operating. They will either operate autonomously or by remote control	Current	
(5) If the cars become uncontrollable due to a fault in the code, it could become a projectile. In addition, if it crashes parts could fly off.	To protect against runaway cars a power off switch will remain in the system. To avoid parts flying off the cars will autonomously avoid collisions.	03/2019	
(18) System could potentially achieve very high speeds	System will have electronically controlled speed limiters as well as an emergency shut off switch.	01/2019	
(19) An emergency shut off switch will be included	Why is answering yes to this question a hazard	Current	

APPENDIX K – Indented Bill of Materials for RC car assembly

Indented Bill of Material (BOM)

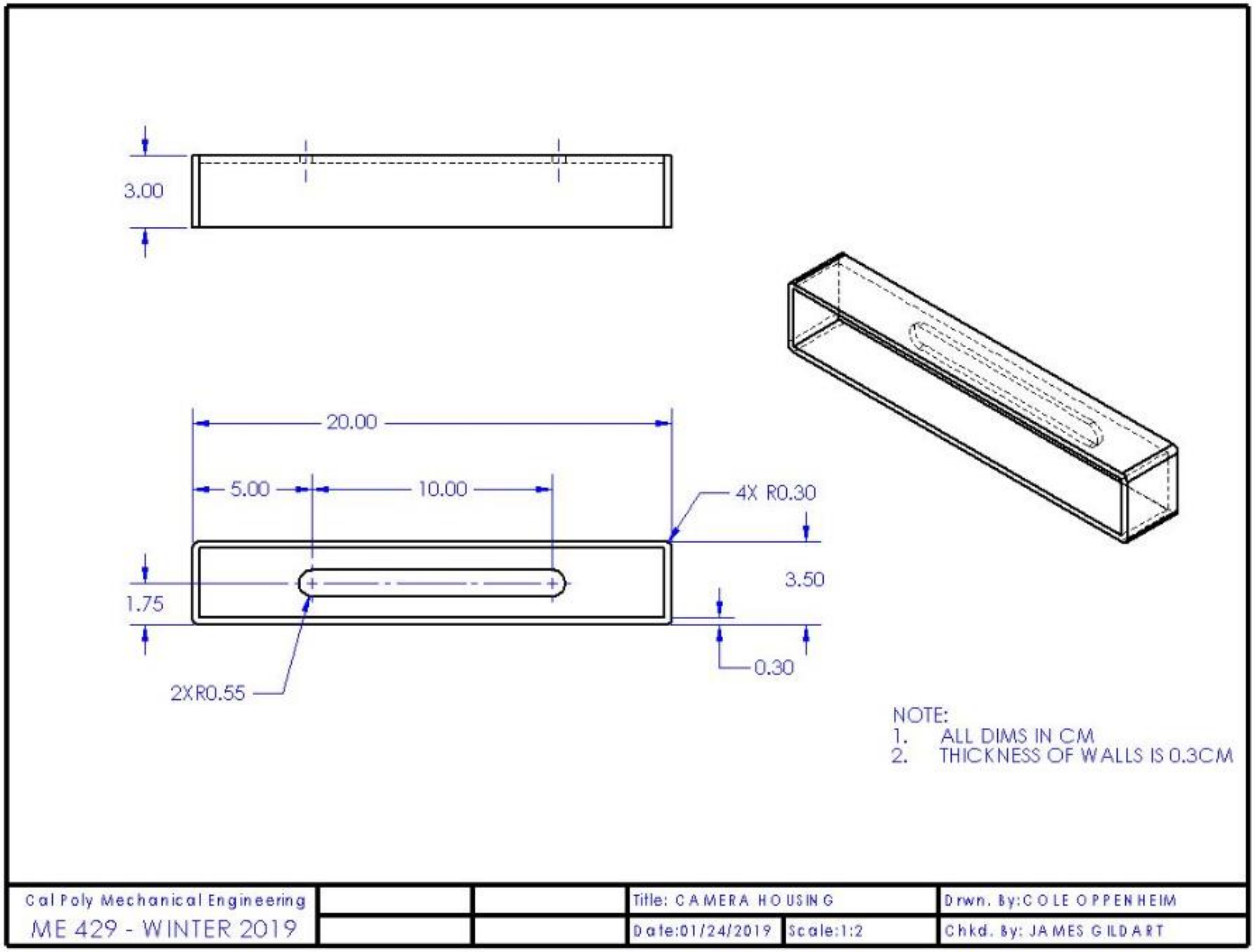
RC Car Assembely

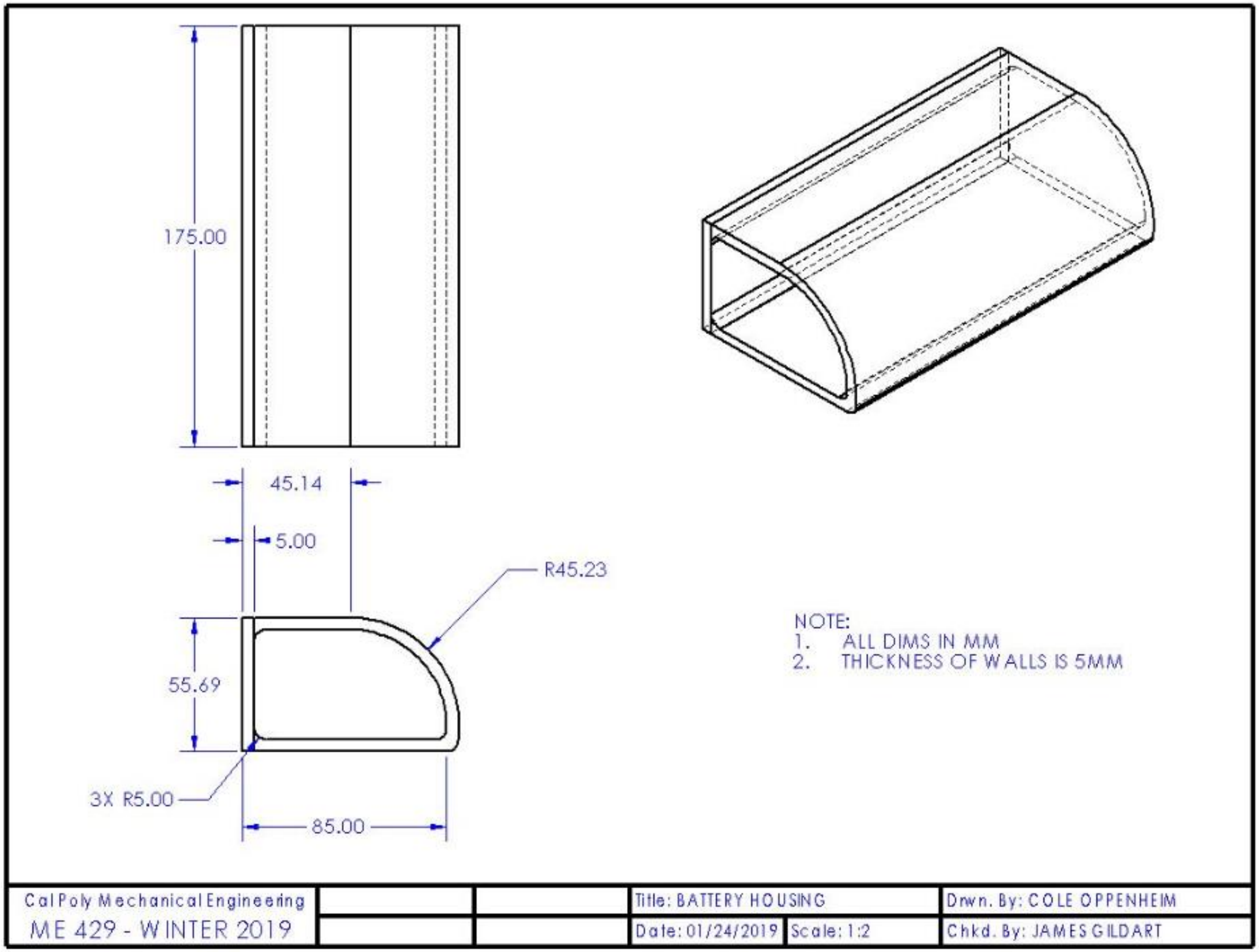
Assy Level	Part Number	Description			Matl	Vendor	Qty	Cost	Ttl Cost
		Lvl0	Lvl1	Lvl2					
0	A	MicroController Mounting			------	------	------	------	------
1	A1		Microcontroller Housing		PLA plastic	We are 3-D printing	1	$ -	$ -
2	A1a			Brass Screw to expand inserts	Brass	McMaster-Carr	1	$ 10.63	$ 10.63
2	A1b			Velcro to attach battery	Velcro	Amazon	1	$ 13.00	$ 13.00
2	A1c			Battery	-----------	amazon	1	$ 75.59	$ 75.59
1	A2		Camera Housing		PLA plastic	We are 3-D printing	1	$ -	$ -
				Stero Scopic cameras		Zed	2	$ 492.27	$ 984.54
1	A3		Mounting Bridge Plate		6061 Aluminum	McMaster-Carr	1	$ 36.03	$ 36.03
2	A3a			M3 x 25 socket head screw	Alloy Steel	McMaster-Carr	1	$ 5.00	$ 5.00
2	A3b			Gorilla Glue Epoxy	Epoxy	Amazon	1	$ 5.48	$ 5.48
2	A3c			M3.5 X .6mm socket head screw	Alloy Steel	McMaster-Carr	1	$ 13.33	$ 13.33
0	B	RC Car							
1	B1		RC Car Base Chasis		--------	Amain Hobbies	2	$ 189.95	$ 379.90
1	B2		New RC Car Motor		--------	Hobby King	2	$ 34.77	$ 69.54
1	B3		New RC Car Motor Controller		--------	Anaheim Automation	2	$ 99.13	$ 198.26
1	B4		Motor connection to controller		--------	Amazon	2	$ 3.75	$ 7.49
1	B5		RC Car battery		--------	Amain Hobbies	2	$ 42.99	$ 187.71
2	B5a			Battery Charger	--------	Hobby King	1	$ 44.40	$ 44.40
2	B5b			Battery wire connector to RC Car	--------	Amazon	2	$ 7.99	$ 15.98
1	B6		Stiffer RC Car Springs		--------	Traxxas	8	$ 2.50	$ 20.00
1	B7		Gears			Traxxas/Amazon	3	$ 8.86	$ 26.58
0	C	Track			Rubber	Rubber Flooring inc	200	$ 2.44	$ 487.94
1	C1		Duct tape		---------	duct tape for lines	3	$ 5.66	$ 16.97
0	D	Electronics			--------	--------	--------	--------	--------
1	D1		20 cm wire harness kit		--------	Amazon	1	$11.99	$11.99
1	D2		40 cm wire harness kit		--------	Amazon	1	$5.49	$5.49
								Purchased Parts Total:	**$2,615.85**

APPENDIX L – Budget tracking and vendor information

Order	Item	Quantity	Price per unit	Total Price	Source	Part number	Use/notes	Link
1	Traxxas 4-Tec 2.0 1/10 Brushed RTR Touring Car Chassis (NO Body)	2	$189.95	$379.90	Amainhobbies	See Link	No batteries or tool set, just the cars	https://www.amainhobbies.com/traxxas-4tec-2.0-1-10-brushed-rtr-touring-car-chassis-no-body-tra83024-4/p682535
1	Gens Ace 2S Stick 50C LiPo Battery w/T-Style Connector (7.4V/5000mAh) (Type 2)	2	$42.99	$85.98	Amainhobbies	See Link	2S Hard case batteries	https://www.amainhobbies.com/gens-ace-2s-stick-50c-lipo-battery-w-tstyle-connector-7.4v-5000mah-type-2-ga-b1104/p779339
1	2PCS Male Deans T to Female TRX Traxxas to Connector Adapter Cable	1	$7.49	$7.49	Amazon	See Link	2PCs Male Deans T to Female TRX Cable	https://www.amazon.com/Youme-Traxxas-toConnector-Adapter-Conversion/dp/B07DZXQ1QX/ref=sr_1_2?ie=UTF8&qid=1545224840&sr=8-2&keywords=female+traxxas+to+t-style+adapter
1	IMAX B6AC V2 Professional Balance Charger/Discharger (US Plug)	1	$44.40	$44.40	Hobby King	See Link	Battery charger	https://hobbyking.com/en_us/imax-b6ac-v2-professional-balance-charger-discharger.html
2	6061 aluminum sheet 1/8x 4"x48"	1	$36.03	$36.03	McMaster	89015K234	Mounting bridge	https://www.mcmaster.com/89015k234
2	M3 x 25 socket head screw	1	$5.00	$5	McMaster	91274A111	Screws to mount bridge to RC Car	https://www.mcmaster.com/91274a111
2	Gorilla Glue Epoxy	1	$5.48	$5.48	Amazon	See Link	attach mircocontroller housing to bridge	https://www.amazon.com/Gorilla-Epoxy-Minute-ounce-Syringe/dp/B001Z3C3AG/ref=sr_1_5?ie=UTF8&qid=1547163509&sr=8-5&keywords=epoxy
2	M3.5 x .6mm socket head screw	1	$13.33	$13.33	McMaster	91290A383	Screws to mount Jetson to Micro-Controller Housing	https://www.mcmaster.com/91290a383
2	Brass screw to expand inserts	1	$10.63	$10.63	McMaster	94510A035	Threaded insert for 3-d printed frame for micro-controller	https://www.mcmaster.com/94510a035
2	Velcro	1	$13.00	$13	Amazon	See Link	Mount batter for Jetson	https://www.amazon.com/XFasten-Adhesive-10-Foot-Industrial-Resistant/dp/B01HQOV17S/ref=sr_1_6?s=industrial&ie=UTF8&qid=1547163052&sr=8-6&keywords=velcro+adhesive
2	RC car Springs (Pack of 2)	4	$20.00	$20	Traxxas	8364	Stiffer Springs for Car	https://traxxas.com/products/parts/8364
3	New RC Car Motors	2	34.77	69.54	Hobby King	See Link	New motors	https://hobbyking.com/en_us/turnigy-trackstar-21-5t-sensored-brushless-motor-1855kv-roar-approved.html
3	RC Car motor Controllers	2	99.13	198.26	Anaheim Automation	See Link	Motor Controller	https://www.anaheimautomation.com/products/brushless/brushless-driver-controller-item.php?sID=350&serID=16&pt=i&tID=999&cID=23
3	20 cm wire harness	1	11.99	11.99	Amazon	See Link	Wire Harnes	https://www.amazon.com/dp/B07GD1TH2K/ref=sspa_dk_detail_0?pd_rd_i=B07GD2BWPY&pd_rd_w=EtLlT&pf_rd_p=f0dedbe2-13c8-4136-a746-4398ed93cf0f&pd_rd_wg=5PKzp&pf_rd_r=VE3HTDPTF26ZVCVQ2HXE&pd_rd_r=191d60a5-1e85-11e9-81c1-55944d4ed8db&th=1
3	40 cm wire harness	1	5.49	5.49	Amazon	See Link	Wire Harnes	https://www.amazon.com/dp/B07GD1TH2K/ref=sspa_dk_detail_0?pd_rd_i=B07GD2BWPY&pd_rd_w=EtLlT&pf_rd_p=f0dedbe2-13c8-4136-a746-4398ed93cf0f&pd_rd_wg=5PKzp&pf_rd_r=VE3HTDPTF26ZVCVQ2HXE&pd_rd_r=191d60a5-1e85-11e9-81c1-55944d4ed8db&th=1
3	100 square ft of rubber flooring 6mm thickness	25	9.7588	243.97	Rubber Flooring Inc	See Link	track material	https://www.rubberflooringinc.com/interlocking-tile/6mm-energy-rubber-tile.html
3	motor battery connection to motor controller	2	4.995	9.99	Amazon	See Link	motor Controller to battery	https://www.amazon.com/WGCD-Female-Connector-Adapter-Battery/dp/B071Z7R995/ref=sr_1_6?crid=17DBJFQ897O8R&keywords=lipo+battery+connectors&qid=1548189524&s=Electronics&sprefix=lipo+battery+conne%252Celectronics%252C195&sr=1-6
			TOTAL COST to Date	**$1,160.48**				

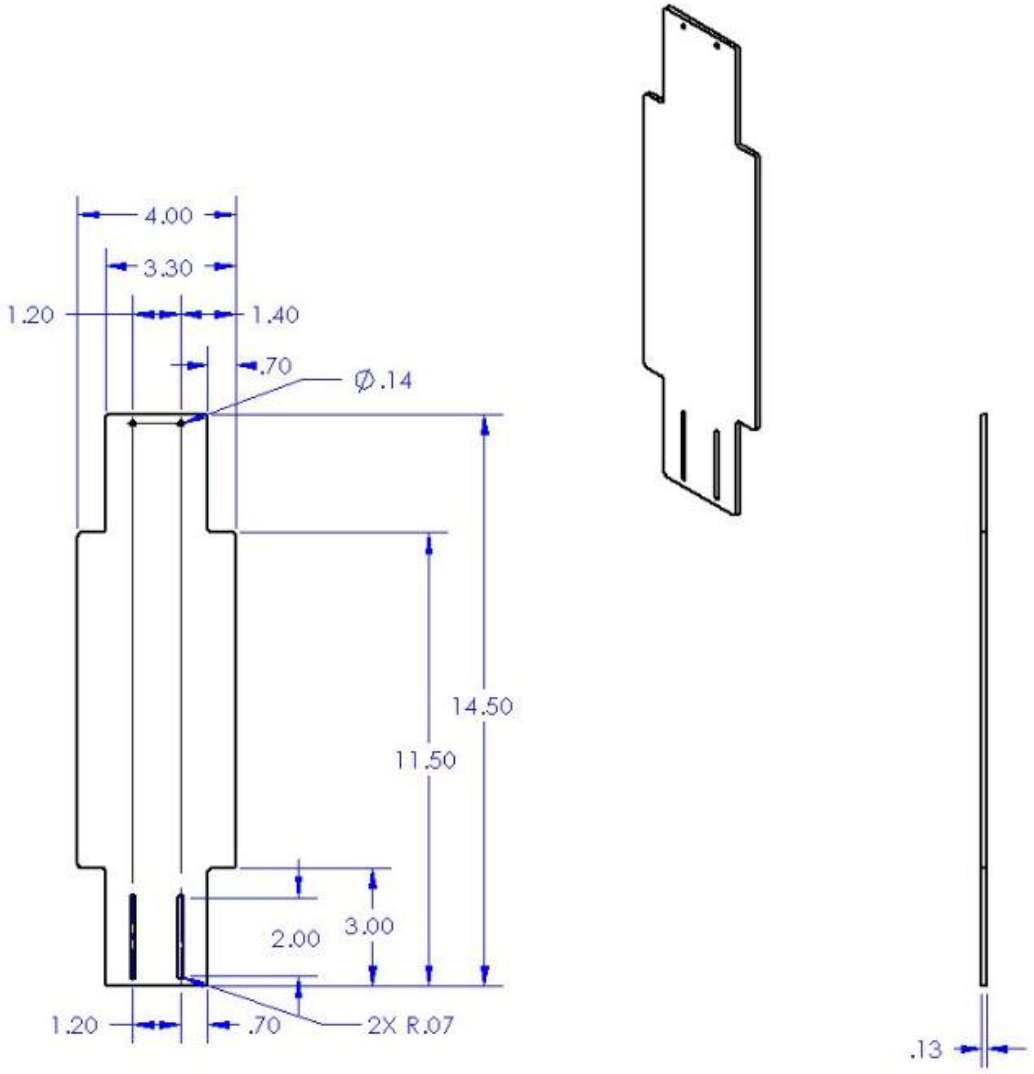
APPENDIX M – Drawing package for all parts that are needed to be manufactured for project Original drawings





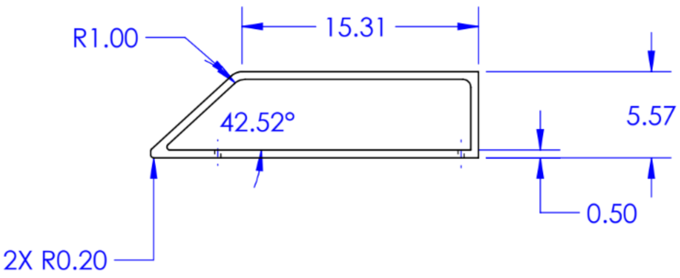
NOTE:
1. ALL DIMS IN MM
2. THICKNESS OF WALLS IS 5MM

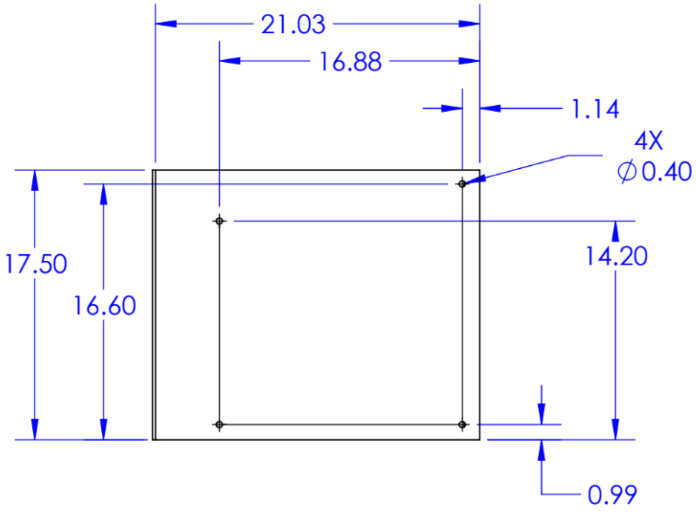
Cal Poly Mechanical Engineering			Title: BATTERY HOUSING	Drwn. By: COLE OPPENHEIM
ME 429 - WINTER 2019			Date: 01/24/2019 Scale: 1:2	Chkd. By: JAMES GILDART

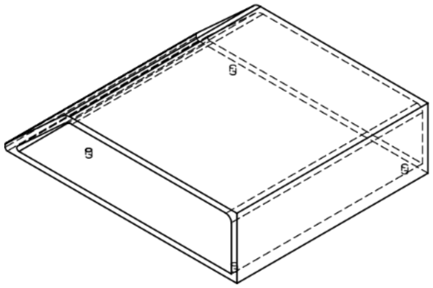


Note:
1. All Rounds R0.10 in`
2. All Dims in IN
3. All Tolerances ±0.1 in

Cal Poly Mechanical Engineering			Title: Bridge Support		Drwn. By: Cole Oppenheim
ME 429 - Winter			Date: 01/29/2019	Scale: 1:4	Chkd. By: James Gildart

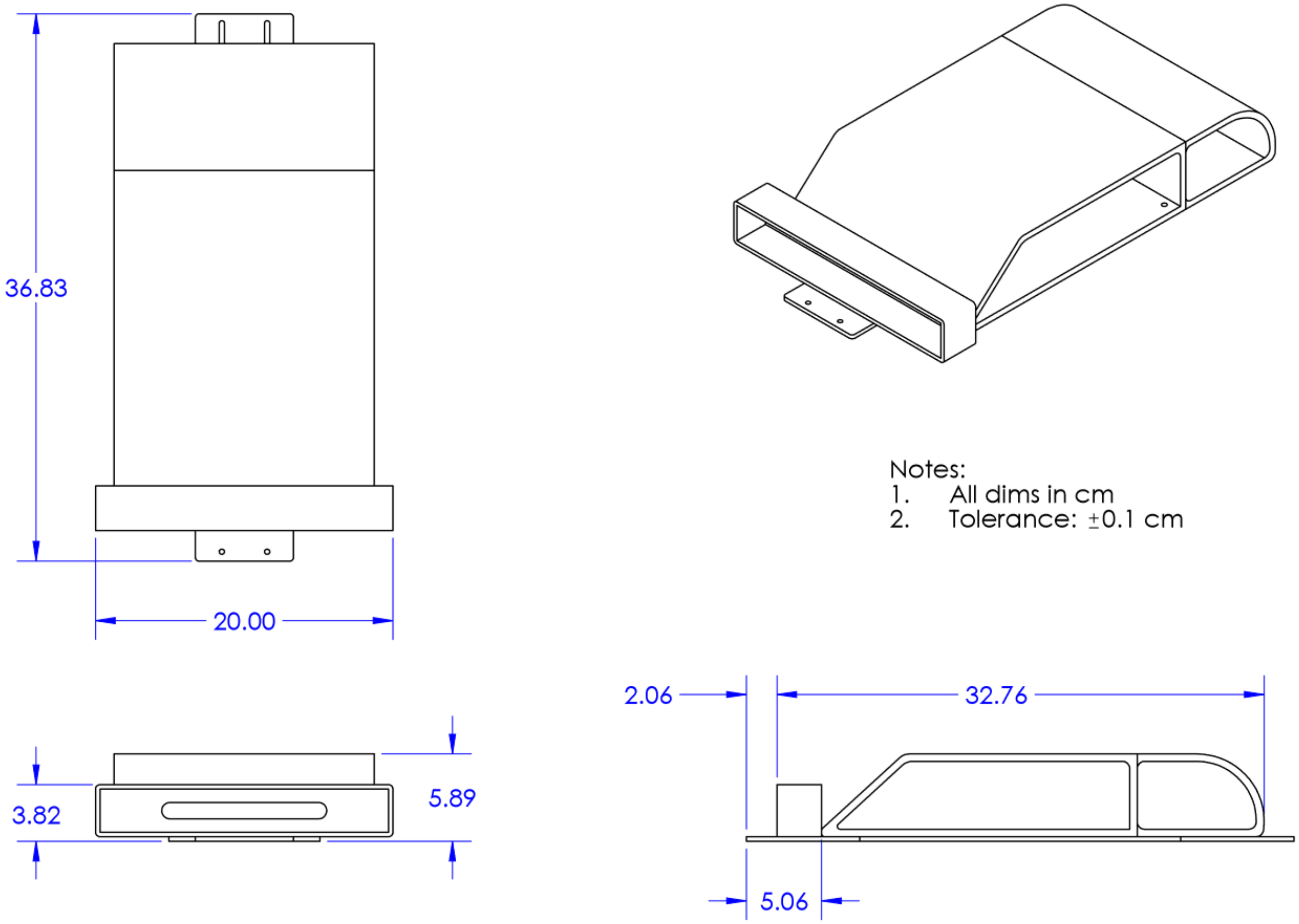






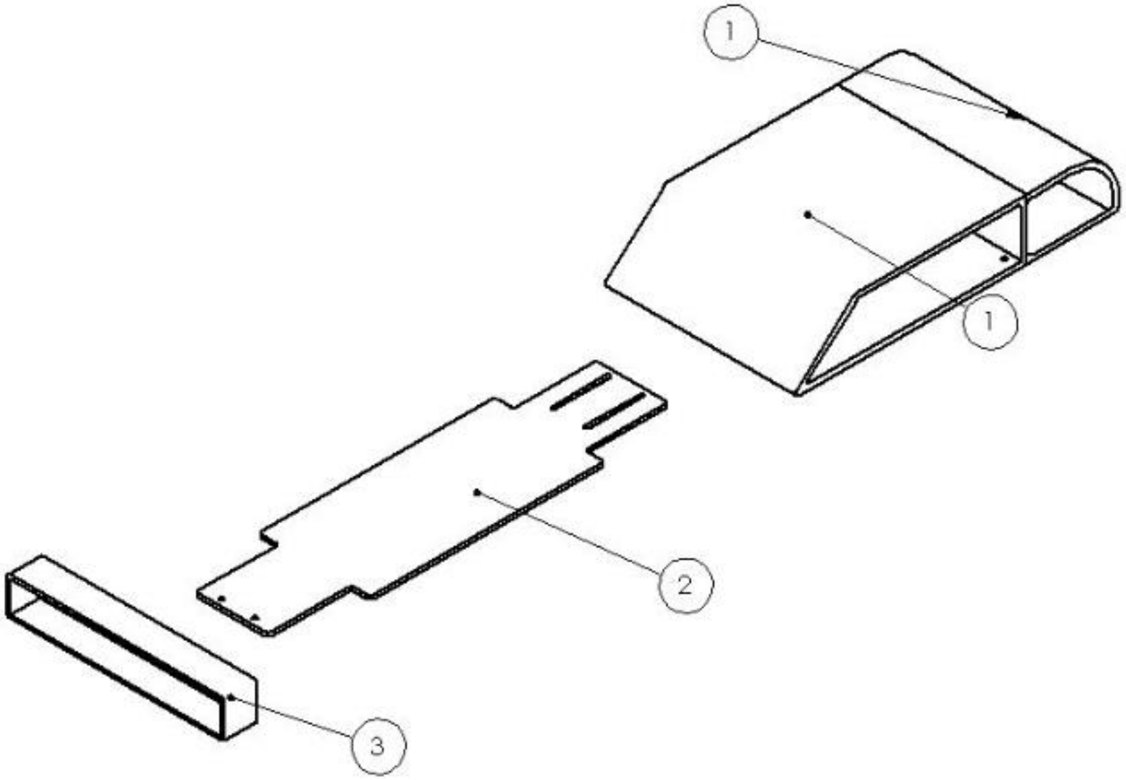
NOTE:
1. ALL DIMS IN CM
2. THICKNESS OF WALLS IS 5MM

Cal Poly Mechanical Engineering ME 429 - WINTER 2019			Title: MICROCONTROLLER FRAME	Drwn. By: COLE OPPENHEIM
			Date:01/24/2019 | Scale:1:4	Chkd. By: JAMES GILDART



Notes:
1. All dims in cm
2. Tolerance: ±0.1 cm

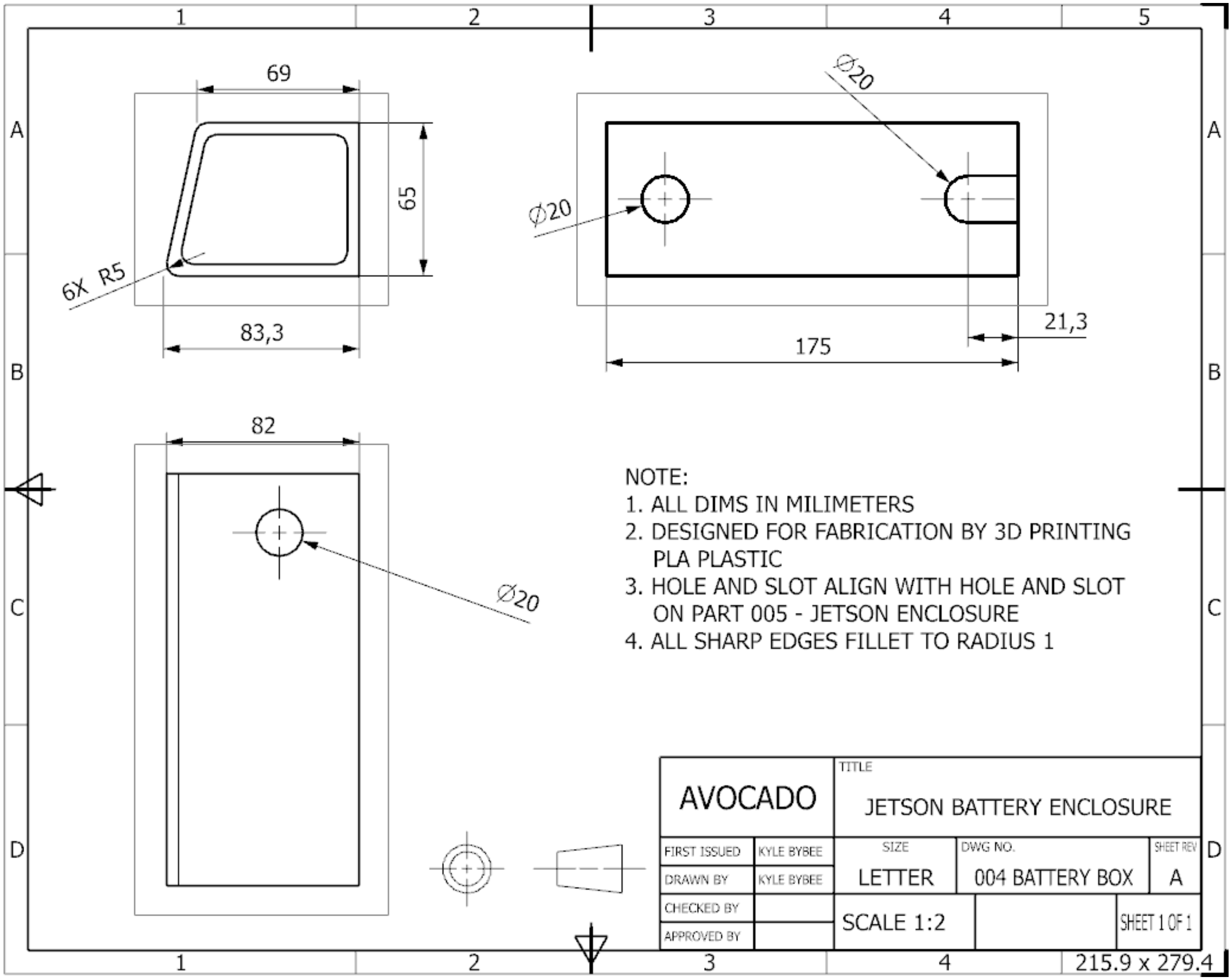
Cal Poly Mechanical Engineering ME 429 - Winter 2019			Title: Assembly Drawing View		Drwn. By: Cole Oppenheim
			Date: 02/02	Scale: 1:4	Chkd. By: James GIldart



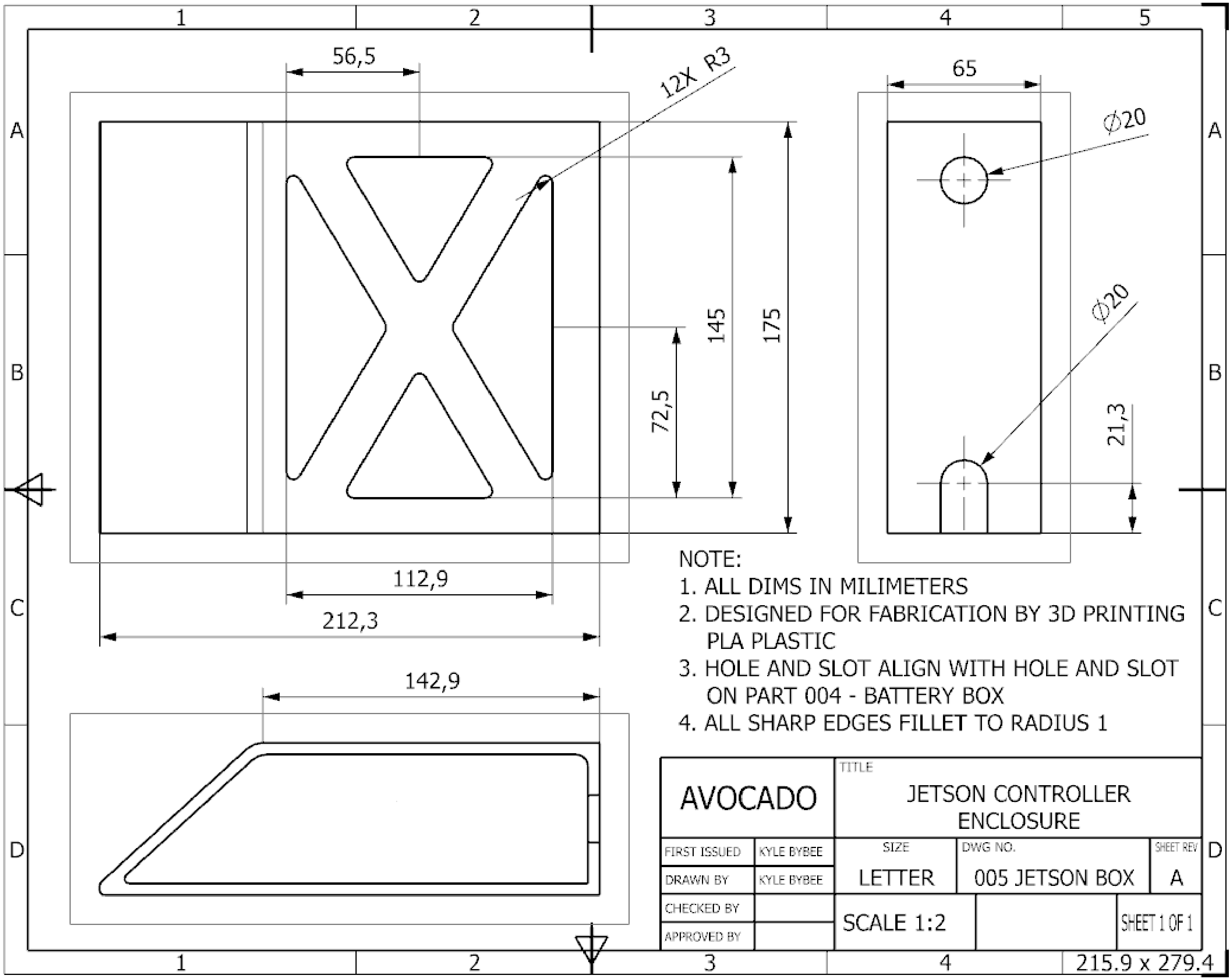
ITEM NO.	PART NUMBER	DESCRIPTION	Exploded View/QTY.
1	Microcontroller and Battery Frame	Protect and House Microcontroller and battery	1
2	Mounting Bridge	Mounting plate for RC car and Micrcontroller Frame	2
3	Camera Housing	Housing for Stereoscopic Cameras	3

Cal Poly Mechanical Engineering			Title: Exploded View		Drwn. By: Cole Oppenheim
ME 429 - Winter 2019			Date: 02/02/2019	1:4	Chkd. By: James Gildart

APPENDIX M – Drawing package for all parts that are needed to be manufactured for project FINAL drawings

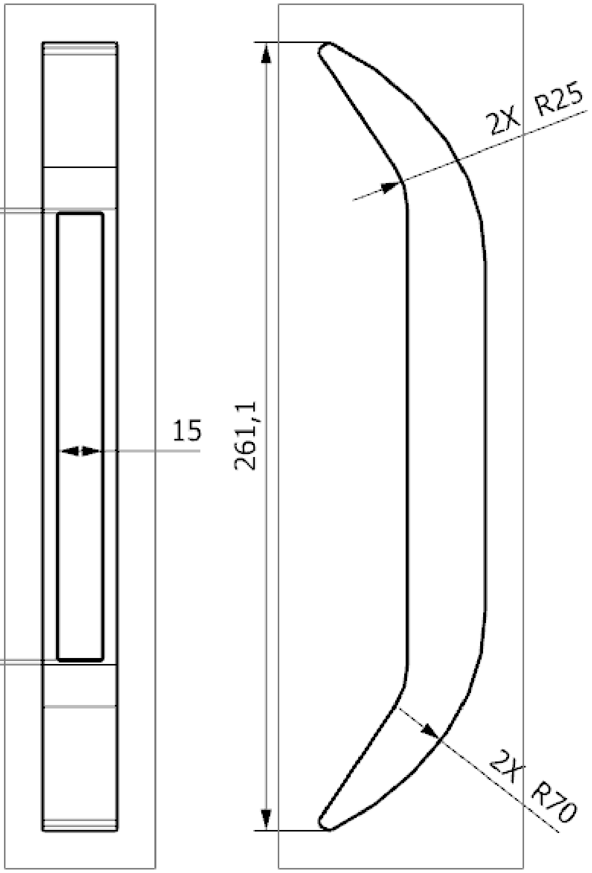


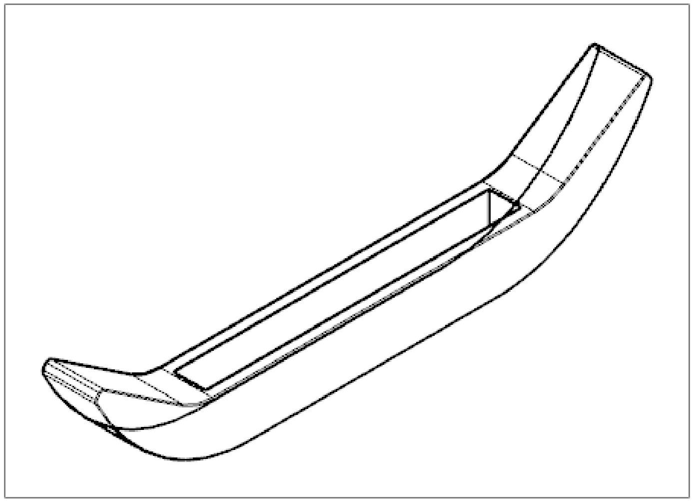
NOTE:
1. ALL DIMS IN MILIMETERS
2. DESIGNED FOR FABRICATION BY 3D PRINTING PLA PLASTIC
3. HOLE AND SLOT ALIGN WITH HOLE AND SLOT ON PART 005 - JETSON ENCLOSURE
4. ALL SHARP EDGES FILLET TO RADIUS 1



NOTE:
1. ALL DIMS IN MILIMETERS
2. DESIGNED FOR FABRICATION BY 3D PRINTING PLA PLASTIC
3. HOLE AND SLOT ALIGN WITH HOLE AND SLOT ON PART 004 - BATTERY BOX
4. ALL SHARP EDGES FILLET TO RADIUS 1

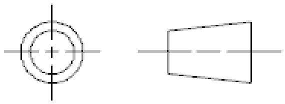
AVOCADO
TITLE JETSON CONTROLLER ENCLOSURE
FIRST ISSUED KYLE BYBEE
DRAWN BY KYLE BYBEE
CHECKED BY
APPROVED BY
SIZE LETTER
DWG NO. 005 JETSON BOX
SHEET REV A
SCALE 1:2
SHEET 1 OF 1





NOTE:

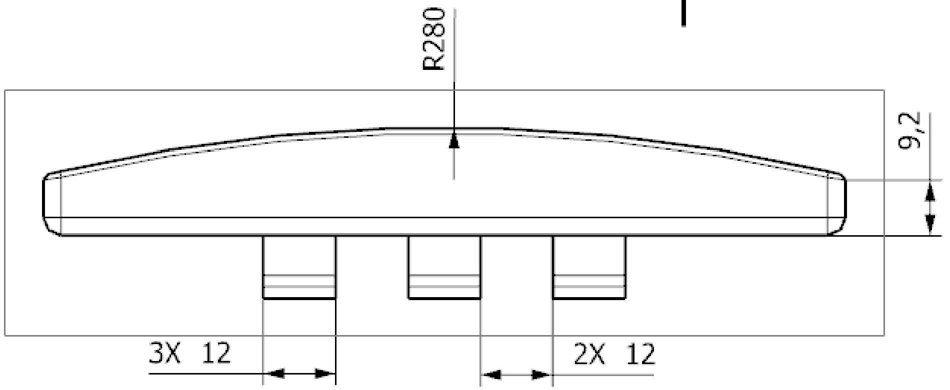
1. ALL DIMS IN MILIMETERS
2. DESIGNED FOR FABRICATION BY 3D PRINTING PLA PLASTIC
3. RECTANGULAR SLOT PRESS FITS ONTO EXISTING FOAM BUMPER
4. ALL SHARP EDGES FILLET TO RADIUS 1



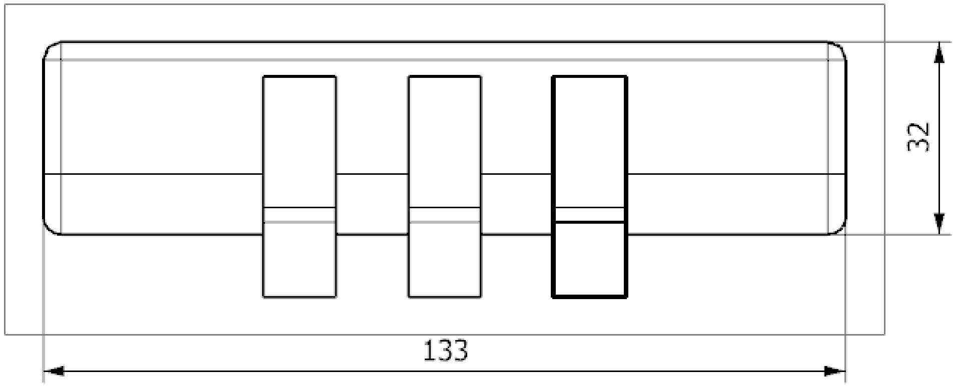
ALL DIMENSIONS IN MM

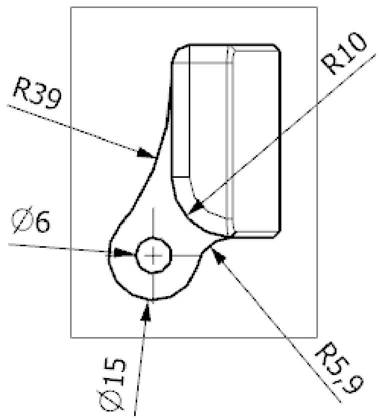
AVOCADO		TITLE FRONT BUMPER		
FIRST ISSUED		SIZE LETTER	DWG NO. 001 BUMPER	SHEET REV A
DRAWN BY				
CHECKED BY		SCALE 1:1		SHEET 1 OF 1
APPROVED BY				

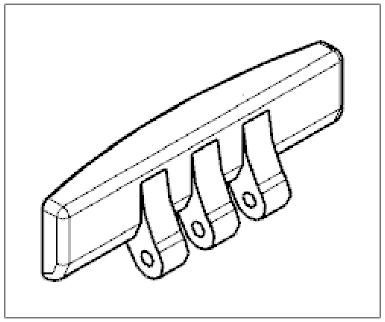
215.9 x 279.4



NOTE:
1. ALL DIMS IN MILIMETERS
2. DESIGNED FOR FABRICATION BY 3D PRINTING PLA PLASTIC
3. TO BE ASSEMBLED VIA HINGE WITH 003 CAMERA MOUNT
4. ALL SHARP EDGES FILLET TO RADIUS 1

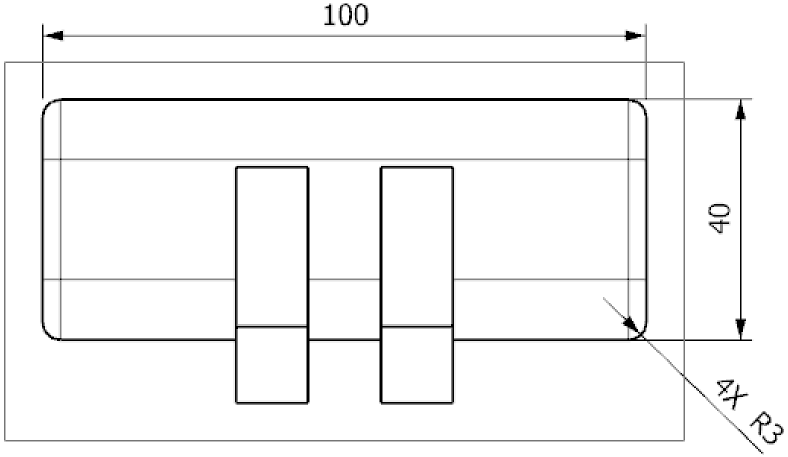


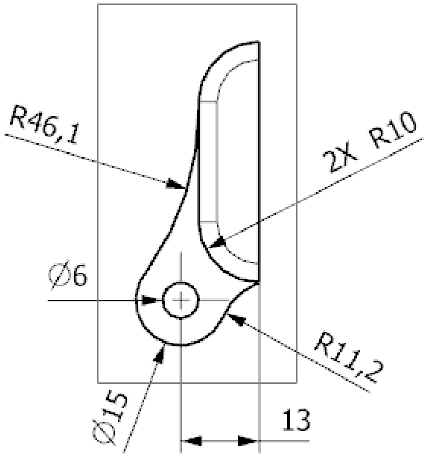


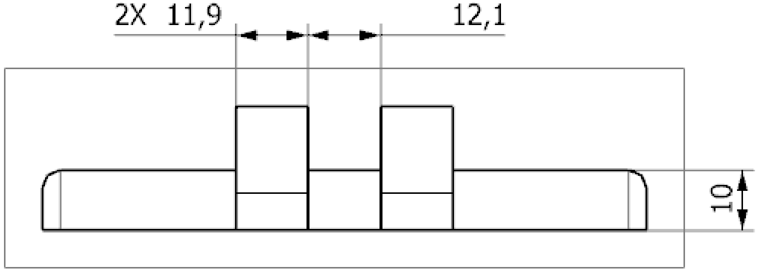


AVOCADO	TITLE STEREOSCOPIC CAMERA MOUNT - PART 1		
FIRST ISSUED	KYLE BYBEE	SIZE LETTER	DWG NO. 002 CAMERA MOUNT
DRAWN BY	KYLE BYBEE		SHEET REV A
CHECKED BY		SCALE 1:1	SHEET 1 OF 1
APPROVED BY			

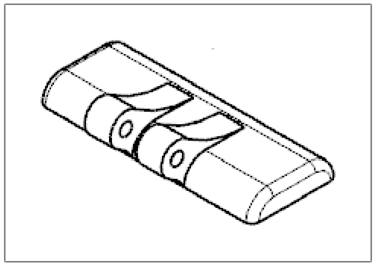
215.9 x 279.4







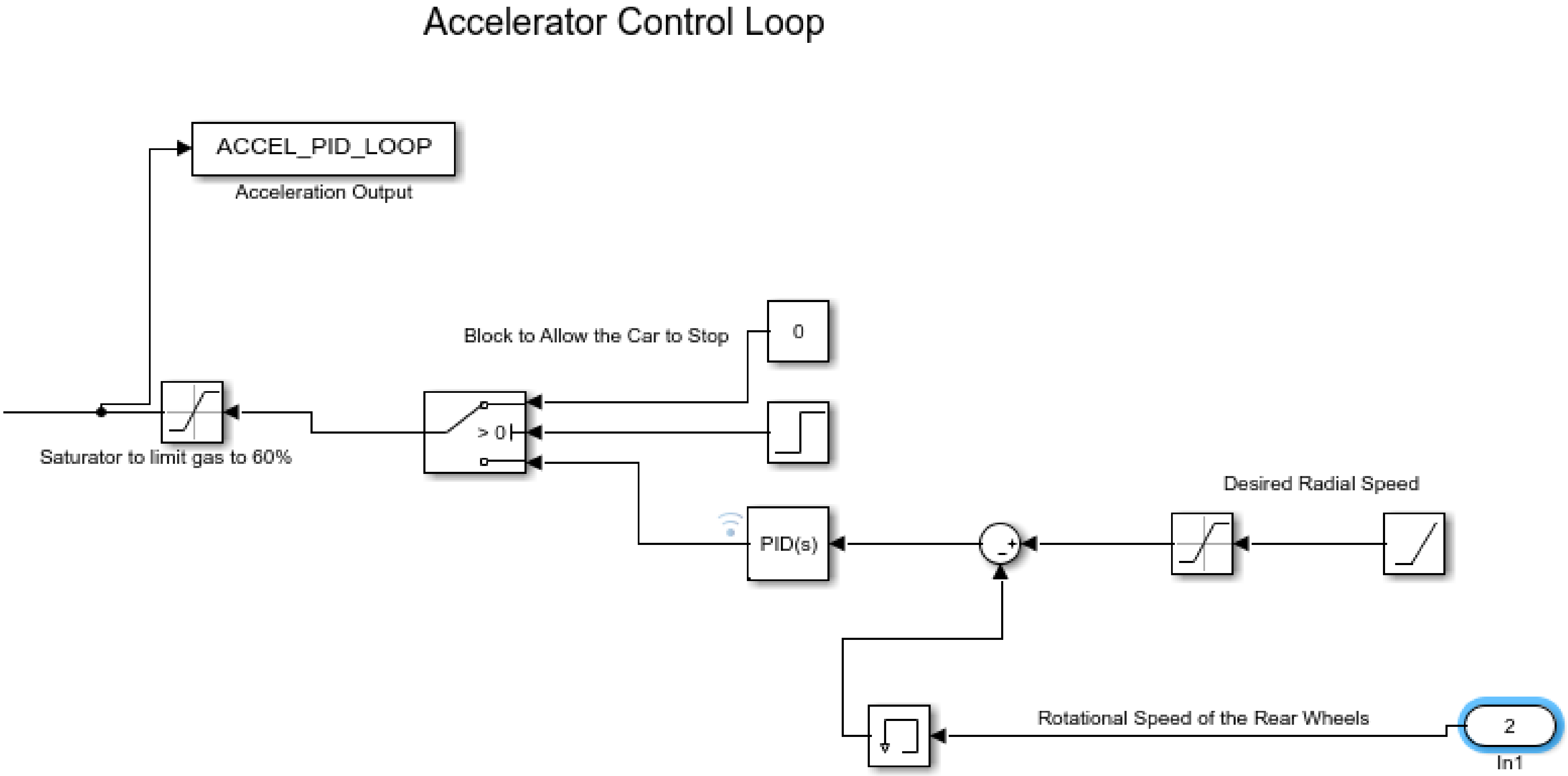
NOTE:
1. ALL DIMS IN MILIMETERS
2. DESIGNED FOR FABRICATION BY 3D PRINTING PLA PLASTIC
3. TO BE ASSEMBLED VIA HINGE WITH 002 CAMERA MOUNT
4. ALL SHARP EDGES FILLET TO RADIUS 1

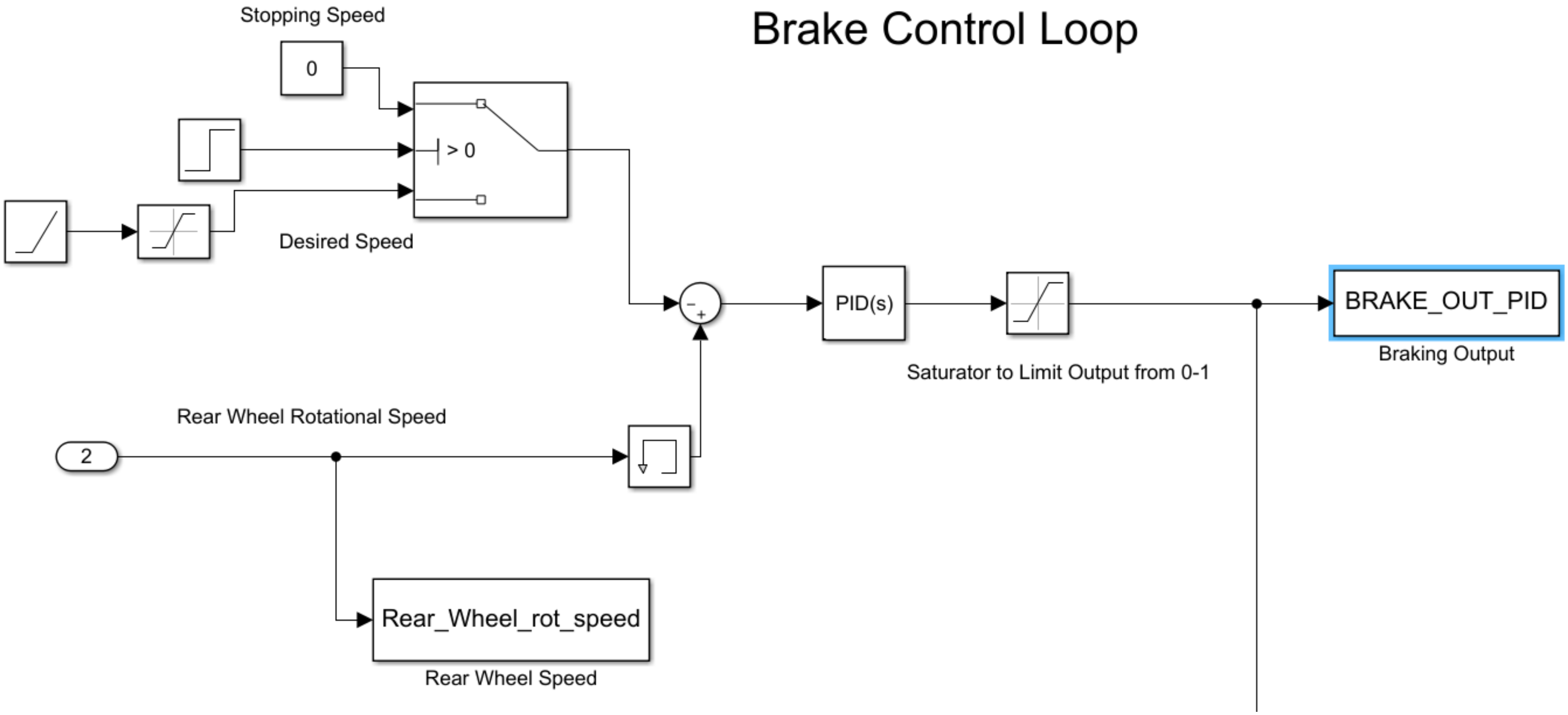


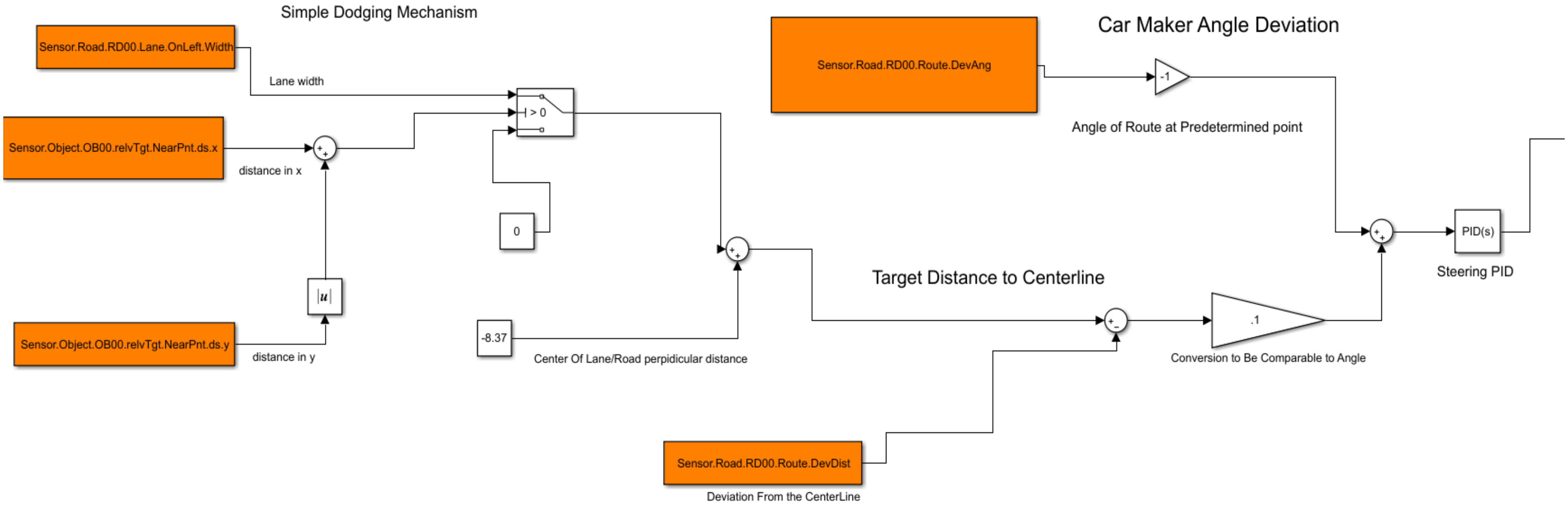
AVOCADO		TITLE STEREOSCOPIC CAMERA MOUNT - PART 2		
FIRST ISSUED	KYLE BYBEE	SIZE LETTER	DWG NO. 003 CAMERA MOUNT	SHEET REV A
DRAWN BY	KYLE BYBEE			
CHECKED BY		SCALE 1:1		SHEET 1 OF 1
APPROVED BY				

215.9 x 279.4

APPENDIX N – Control Algorithms




Brake Control Loop
Stopping Speed
0
> 0
Desired Speed
PID(s)
BRAKE_OUT_PID
Braking Output
Saturator to Limit Output from 0-1
Rear Wheel Rotational Speed
2
Rear_Wheel_rot_speed
Rear Wheel Speed


Simple Dodging Mechanism
Sensor.Road.RD00.Lane.OnLeft.Width
Lane width
Sensor.Object.OB00.relvTgt.NearPnt.ds.x
distance in x
> 0
0
|u|
Sensor.Object.OB00.relvTgt.NearPnt.ds.y
distance in y
-8.37
Center Of Lane/Road perpidicular distance
Sensor.Road.RD00.Route.DevAng
Car Maker Angle Deviation
-1
Angle of Route at Predetermined point
Target Distance to Centerline
.1
Conversion to Be Comparable to Angle
PID(s)
Steering PID
Sensor.Road.RD00.Route.DevDist
Deviation From the CenterLine

APPENDIX O – Testing Procedures and Results

Test 1: Crash testing and Roll Over Crash Testing

Description of Test:

Any time the car crashes during testing record the number of crashes that occur and inspect the car to ensure that no damage has occurred.

Test Location:

Capstone Lab 20-145

Acceptance Criteria:

Pass/Fail Criteria. If the car crashes and there is no damage to the car it passes. If there is damage to the car then it fails

Required Materials:

1. RC cars
2. Test track with solid or striped lane lines

Safety Procedure:

This test is not hazardous to the people performing the test. The safety procedure is to ensure the RC car will not be damaged in the event of a crash. A safety checklist that should be performed before testing is below

1. Check to ensure bumper is attached properly to RC car
2. Check to ensure that the Jetson microcontroller is secured within its housing
3. Check to make sure there are no loose wires hanging outside of the housings
4. Check to ensure batteries are secure within their housings

Testing Protocol:

1. This is not to be intentionally tested only follow test protocol if the car accidently crashes
2. Record number of crashes that occur
3. Inspect the car(s) after a crash to insure damage
4. Record any notes of damage or important information

Data:

Crash Number	Pass	Fail
1	X	
2	X	
3	X	
4	X	

Test 2: Unloaded Wheel Speed

Description of Test:

Measure wheel speed with no load (car on the test stand).

Test Location:

Capstone Lab 20-145

Acceptance Criteria:

Wheel speed varies with duty cycles spanning from 0 – 100%. Both vehicles should have similar wheel speeds since the motors are tuned to have similar timing.

Required Materials:

3. RC cars
4. Reflective tape

Safety Procedure:

This test is not hazardous to the people performing the test. The safety procedure is to ensure the RC car will not be damaged in the event of a crash. A safety checklist that should be performed before testing is below

5. Check to ensure bumper is attached properly to RC car
6. Check to ensure that the Jetson microcontroller is secured within its housing
7. Check to make sure there are no loose wires hanging outside of the housings
8. Check to ensure batteries are secure within their housings

Testing Protocol:

5. Place RC cars on a test stand
6. Plug in the Jetson 4s battery and the motor’s 2s battery
7. Insert 3xAA batteries into tachometer
8. Put reflective tape on tire
9. Keep the tachometer about 6 inches away from the wheel
10. Angle the laser output of tachometer straight onto the reflective tape and hold still
11. Read the average RPM displayed on the tachometer and record into spreadsheet

Data:

Car: Salsa			Car: Chips				
Duty Cycle and Speed			Duty Cycle and Speed				
Duty Cycle	**RPM**	**Descriptions**	**Duty Cycle**	**RPM**	**Descriptions**	**Difference**	**% Difference**
10	180	Smooth	10	181	Smooth	1	0.6
11	209	Smooth	11	210	Smooth	1	0.5
12	231	Smooth	12	238	Smooth	7	2.9
13	262	Smooth	13	270	Smooth	8	3.0
14	287	Smooth	14	290	Smooth	3	1.0
15	310	smooth	15	315	smooth	5	1.6
20	310	smooth	20	437	smooth	127	29.1
30	525	fast	30	630	fast	105	16.7
40	525	fast	40	588	fast	63	10.7
60	525	fast	60	640	fast	115	18.0
100	525	fast	100	620	fast	95	15.3

Test 3: Full Load Speed

Description of Test:

Measure vehicle loaded speed (car on track).

Test Location:

Capstone Lab 20-145

Acceptance Criteria:

Wheel speed varies with duty cycles spanning from 0 – 100%. Both vehicles should have similar wheel speeds and loaded speed giving the weight and driving conditions are similar.

Required Materials:

1. Digital tachometer
2. Reflective tape
3. Track with painted or taped lines
4. One equipped/modified RC car

Safety Procedure:

This test is not hazardous to the people performing the test. The safety procedure is to ensure the RC car will not be damaged in the event of a crash. A safety checklist that should be performed before testing is below

1. Check to ensure bumper is attached properly to RC car
2. Check to ensure that the Jetson microcontroller is secured within its housing
3. Check to make sure there are no loose wires hanging outside of the housings
4. Check to ensure batteries are secure within their housings

Testing Protocol:

1. Ensure the track is set up with appropriate lane lines
2. Plug in the Jetson to the 4s battery and press the on button
3. Plug in the ESC to the 2s battery and ensure green ready light is on.
4. Place the car in the center of a lane on a straight away
5. SSH into the Jetson
6. Activate drive mode on the Jetson
7. Choose a speed and note its corresponding duty cycle
8. Time a lap
9. Activate the brake to stop the car

Data:

Lap	Speed Setting	Duty Cycle	Time [s]	Lane Keeping
1	Medium	5.5	14.16	Pass
2	Medium	5.5	14.01	Pass
3	Medium	5.5	14.18	Pass
4	Medium	5.5	14.24	Pass
5	Medium	5.5	14.31	Pass
6	Medium	5.5	13.71	Pass
7	Medium	5.5	14.09	Pass
8	Medium	5.5	15.09	Pass
9	Medium	5.5	12.83	Pass
10	Medium	5.5	14.42	Pass
11	Medium	5.5	13.90	Pass
12	Medium	5.5	14.15	Pass
13	Medium	5.5	14.22	Pass
14	Medium	5.5	14.23	Pass
15	Medium	5.5	14.00	Pass
16	Medium	5.5	14.00	Pass
17	Medium	5.5	14.20	Pass
18	Medium	5.5	14.37	Pass

Test 4: Individual car disturbance

Description of Test:

A test of the functionality of a single car to affectively handle disturbances

Test Location:

Capstone Lab 20-145

Acceptance Criteria:

This is a pass fail test based upon the version of software being used along with the gains in the controllers being used.

Required Materials:

1. One fully assembled autonomous RC car platform
2. Track with painted or taped lines
3. Computer with Putty
4. Any signs or objects for disturbance testing

Safety Procedure:

This test is not hazardous to the people performing the test. The safety procedure is to ensure the RC car will not be damaged in the event of a crash. A safety checklist that should be performed before testing is below

1. Check to ensure bumper is attached properly to RC car
2. Check to ensure that the Jetson microcontroller is secured within its housing
3. Check to make sure there are no loose wires hanging outside of the housings
4. Check to ensure batteries are secure within their housings

Testing Protocol:

1. Ensure track is set up with appropriately painted or taped lane lines.
2. Plug in the Jetson to the 4s battery and press the on button
3. Plug in the ESC to the 2s battery and ensure green ready light is on.
4. Place the car in the center of a lane on the track. Ensure the placement is on a straight section of track for the most consistent results
5. SSH into the Jetson using Putty (or with the assistance of a CPE)
6. Read programmed hotkeys once SSH'd into the car for operation instructions
7. Using the correct keys on the computer keyboard activate drive mode (this may change with different software versions created by the CPE team)
8. Disable vehicles if control is lost using the brake function
9. Test disturbances listed below on the system with the final software version.
    a. Disturbances

    i. Stop signs
    ii. Speed limit signs
    iii. Speed change initiated by user
    iv. Stop command initiated by user
    v. Object avoidance

10. Adjust PID controllers and the various variables that interact with the controller to change the behavior of the cars.
11. Repeat step 10 until all testing criteria are passed.

Test	**Pass**	**Fail**
Stop Sign	X	
Speed limit Sign	X	
Speed change initiated by user	X	
stop initiated by user	X	
object avoidance	X	

Test 5: Platooning disturbance testing

Description of Test:

A test of the entire system performing platooning functionality. Both RC cars will run simultaneously to demonstrate their platooning capability on the designed test track.

Test Location:

Capstone Lab 20-145

Acceptance Criteria:

The platoon must be able to successfully form a platoon. Stability must be reached relatively quickly without the presence of significant oscillations. For the entirety of the test both cars should be able to perform lane keeping on their own without losing control. The lead car must be able to change speed and come to a stop without disturbing the following car. For the input to the controller each test will be performed on a pass fail criteria.

Required Materials:

5. Two fully assembled autonomous RC car platforms
6. Track with painted or taped lines
7. Computer with Putty
8. Any signs or objects for disturbance testing

Safety Procedure:

This test is not hazardous to the people performing the test. The safety procedure is to ensure the RC car will not be damaged in the event of a crash. A safety checklist that should be performed before testing is below

1. Check to ensure bumper is attached properly to RC car
2. Check to ensure that the Jetson microcontroller is secured within its housing
3. Check to make sure there are no loose wires hanging outside of the housings
4. Check to ensure batteries are secure within their housings

Testing Protocol:

12. Ensure track is set up with appropriately painted or taped lane lines.
13. Plug in the Jetson to the 4s battery and press the on button
14. Plug in the ESC to the 2s battery and ensure green ready light is on.
15. Place the car in the center of a lane on the track. Ensure the placement is on a straight section of track for the most consistent results
16. SSH into the Jetson using Putty (or with the assistance of a CPE)
17. Read programmed hotkeys once SSH’d into the car for operation instructions
18. Using the correct keys on the computer keyboard activate drive mode (this may change with different software versions created by the CPE team)
19. Repeat start up procedure for second car

20. Put one or both cars into platoon mode (depending on software version)
21. Disable vehicles if control is lost using the brake function
22. Test disturbances listed below on the system with the final software version.
    a. Disturbances
        i. Stop signs
        ii. Speed limit signs
        iii. Speed change initiated by user
        iv. Stop command initiated by user
        v. Object avoidance
23. Adjust PID controller that controls the speed of the following car and the various variables that also interact with the controller to change the behavior of the cars

Data:

Controller Settings for platooning controller

Position Influence	Kp	ki	kd	Braking	Desired	Saturation	Comments	Note
0.2	2.5	0	0	250	175	5-15	Too much oscillation	Velocity backwards

Test	**Pass**	**Fail**
Stop Sign	X	
Speed limit Sign	X	
Speed change initiated by user	X	
stop initiated by user	X	
object avoidance	X	

Full controller Testing Iterations (Next 2 pages):

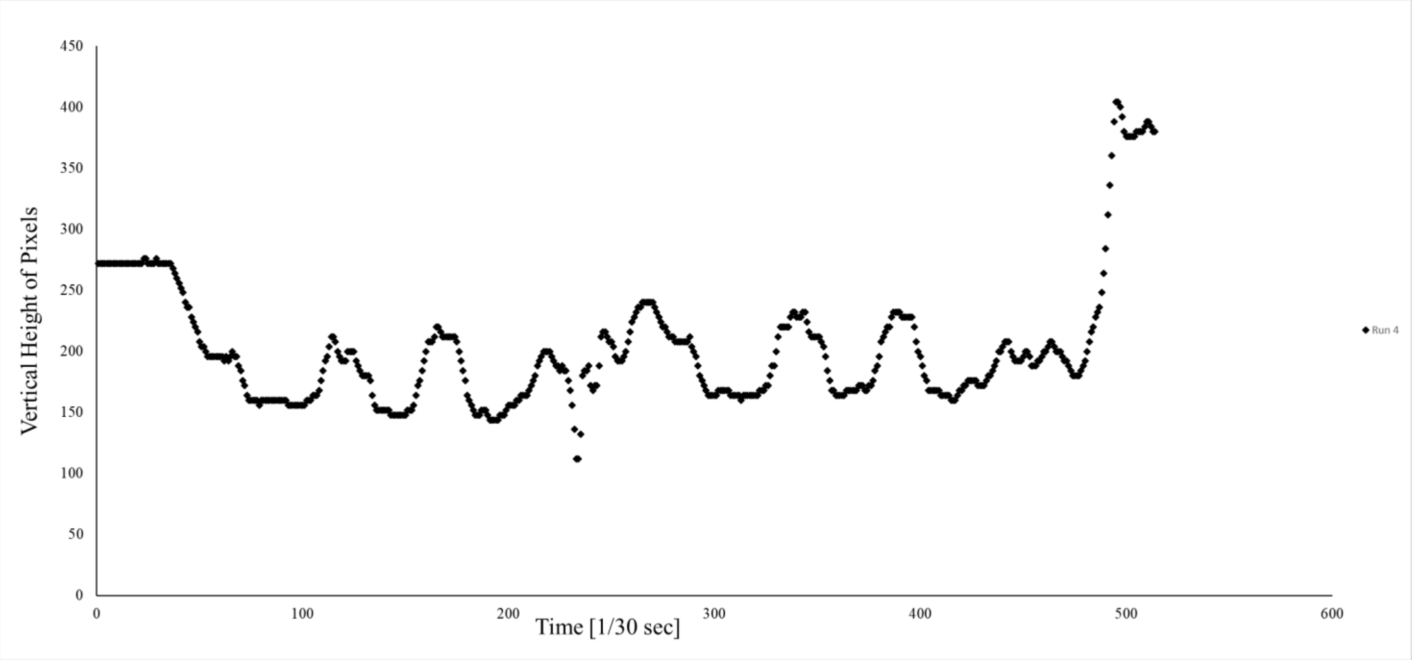
Position Influence	Kp	ki	kd	Braking	Desired	Saturation	Comments	Note
0.2	2.5	0	0	250	175	5-15	Too much oscillation	Velocity backwards
0.2	2.5	0	0	250	175	7-16	too much oscillation 16 is possibly too high	Velcity is fixed
							better?	
0.0825	6	0	0	250	175	7-15	sudden braking bad, but not terrible setting	
0.037125	12.5	0	0	250	175	7-15	good but some oscillations at crawl speed	set saturtaion on min velocity value
0.02784375	12.5	0	0	250	175	7-15	good but some oscillations at crawl speed, slower to catch up, pwms the duty cycle	turned off
0.0495	10	0	0	250	175	8-15	oscillations (amplitude small) but smooth kinda	
0.0495	8	0	0	250	175	8-15	not the best	
0.0495	4	0	0	250	175	8-15	better	
0.0495	2	0	0	230	175	8-15	very bad	
0.5	2	0	0	230	175	8-15	too aggressive	
0.5	4	0	0	230	175	8-15	good at medium but bad at crawl	
0.066	7.5	0	2	215	150	7-15	best run yet, slight oscillations at crawl	
0.066	7.5	0	1	215	150	7-15	too slow but good for crawl	
0.066	12	0	1	215	150	7-15	still smooth but struggles to catch up	
0.066	15	0	1	215	150	7-15	still to0 slow	
0.066	15	0	0.5	215	150	7-15	still too slow	
0.066	15	0	0.25	215	150	7-15	better, some oscillations, still slow	
0.066	15	0	0.1	215	150	7-15	not aggressive	
0.2	15	0	0.1	215	150	7-18	too aggressive	
0.2	15	0	0.5	215	150	7-18	oscillates	
0.2	15	0	1	215	150	7-18	closer some oscillations still	
0.2	15	0	2	215	150	7-18	too much derivative	
0.2	15	0	1.5	215	150	7-18	some oscillations	
0.2	14	0	1.5	215	175	7-18	too close	
0.2	14	0	1.6	215	165	7-18	oscillations unusal bad at crawl	
0.1	14	0	1.6	215	165	7-18	oscillations	
0.1	10	0	1.6	215	165	7-18		

(Testing with Logitech wide angle cameras)

Testing with Zed:

Position Influence	Frequency Influence	Kp	Kd	Height Set Point	Comments
0.12	0.04	0.8	0.05	165	BAD
0.12	0.04	0.8	0.05	130	Maybe a little too close but pretty good
0.2	0.04	0.8	0.05	115	oscillations still prevalent
0.075	0.03	0.8	0.05	115	best yet, might be slow to catch up in platoon

Full Lap of Track Plotting Distance Between Cars [Pixels]:



Full sheet of excel data of testing could not be included due to size

Test 6: Lane Keeping

Description of Test:

Run a single car on the designed test track to test its lane keeping abilities at different speeds.

Test Location:

Capstone Lab 20-145

Acceptance Criteria:

Car does not lose control for the duration of the test. Car remains almost entirely within the lanes for the duration of the test. On turns some cutting is acceptable, although not preferable.

Required Materials:

1. Track with taped or painted lane lines (Solid lines and dashed lines)
2. One RC car with the necessary hardware equipped (Jetson, Arduino, camera, ESC, motor, mounting bridge, enclosures, and wiring)
3. Computer to activate Jetson

Safety Procedure:

This test is not hazardous to the people performing the test. The safety procedure is to ensure the RC car will not be damaged in the event of a crash. A safety checklist that should be performed before testing is below

1. Check to ensure bumper is attached properly to RC car
2. Check to ensure that the Jetson microcontroller is secured within its housing
3. Check to make sure there are no loose wires hanging outside of the housings
4. Check to ensure batteries are secure within their housings

Testing Protocol:

1. Ensure track is set up to the final version and has either painted or taped lane lines.
2. Plug in the Jetson to the 4s battery and press the on button
3. Plug in the ESC to the 2s battery and ensure green ready light is on.
4. Place the car in the center of a lane on the track. Ensure the placement is on a straight section of track for the most consistent results
5. SSH into the Jetson using Putty (or with the assistance of a CPE)
6. Read programmed hotkeys once SSH’d into the car for operation instructions
7. Using the correct keys activate drive mode

8. Once drive mode is selected, choose a desired operating speed (Note: All current choices are crawl, slow, medium, fast, and ludicrous all of which correspond to a chosen duty cycle sent to the ESC)
9. Observe the car as it travels around the track
10. If the car loses control use the brake (b) command in the command line to stop the car
11. Tune the position of the camera to adjust which side of the lane the car is hugging (pushing the camera to look further will move the car towards the inside lane, closer will move it towards the outside lane)
12. Also tune controller values for proportional and derivative gains for the steering servo if needed.

Data:

Lap	Speed Setting	Duty Cycle	Time [s]	Lane Keeping
1	Medium	5.5	14.16	Pass
2	Medium	5.5	14.01	Pass
3	Medium	5.5	14.18	Pass
4	Medium	5.5	14.24	Pass
5	Medium	5.5	14.31	Pass
6	Medium	5.5	13.71	Pass
7	Medium	5.5	14.09	Pass
8	Medium	5.5	15.09	Pass
9	Medium	5.5	12.83	Pass
10	Medium	5.5	14.42	Pass
11	Medium	5.5	13.90	Pass
12	Medium	5.5	14.15	Pass
13	Medium	5.5	14.22	Pass
14	Medium	5.5	14.23	Pass
15	Medium	5.5	14.00	Pass
16	Medium	5.5	14.00	Pass
17	Medium	5.5	14.20	Pass
18	Medium	5.5	14.37	Pass

Kp	Kd	Speed	Pass/Fail	Comments/Other Changes
28/300	2.4/300	Medium	Fail	Close
28/301	7/300	Medium	Fail	Oscillates
30/300	3/300	Medium	Pass	Fails at ludicrous
30/300	3/300	Fast	Pass	Hugs inside lane
30/300	2.4/300	Fast	Fail	adding offset, results were better, sharpest turn throws it off
30/300	2.4/300	Fast	Pass	Adding conditional statement to lanekeeping software to ensure the software accurately tracks the lanes on the tightest turns, oscillates at ludicrous
27/300	2.4/300	ludicrous	fail	Still oscillates on ludicrous
24/300	2.4/300	ludicrous	fail	Cant make sharpest turn need to increase offset proportionally, much smoother on steering inputs (offset=225)
24/300	2.4/300	ludicrous	fail	still cant make sharpest turn with increased offset, make offset larger
25/300	2.4/300	ludicrous	fail	Oscillates on ludicrous, make it on fast
25/300	1.5/300	fast	pass	more jumpy
25/300	2/300	fast	fail	offset of 210, lost road
25/300	2.4/300	fast	pass	offset of 200, best setting yet
25/300	2.4/300	fast	fail	offset of 195, couldn’t make sharpest turn
25/300	2.4/300	fast	pass	offset 197, best yet, very smooth, CHOSEN SETTING
25/300	2.4/300	fast	fail	offset 196, smooth until crash on second lap

APPENDIX P – User Manual

This is the user's manual for AVOCADO's Senior project. This document will tell the user how to recharge batteries properly, how to set up the track, and setting up the RC cars to run autonomously on the track.

Battery Charging

Batteries for this project are all lithium ion batteries and require care when charging the batteries to prevent overheating of the batteries which can become a potential fire hazard. Included with the equipment for this project is a special battery charger which mitigates this risk and is required to be used to charge the batteries. See the charger manual for the charger provided for the proper operating instructions for charging batteries. Both the 2S and 4S batteries can be charged at a maximum of 5A and should be charged everyday when the cars see heavy use. A rotation of battery charging can be achieved using the extra batteries procured in this project.

Track Setup

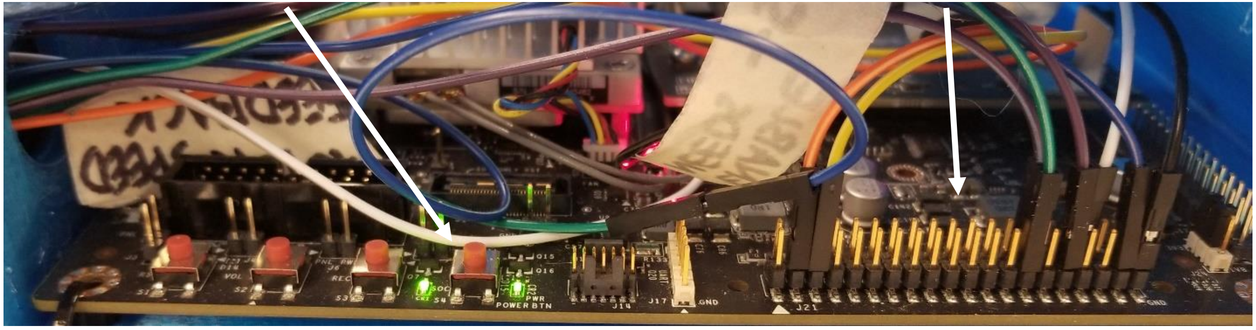
The track setup for the RC car is to be pieced together in a grid. On the bottom side of each rubber flooring tile there is a number. The tiles are to be assemble as the figure shows below with the numbers facing the floor and with the same orientation.

1	9	17	25	33
2	10	18	26	34
3	11	19	27	35
4	12	20	28	36
5	13	21	29	37
6	14	22	30	38
7	15	23	31	39
8	16	24	32	40

Setting up RC Car to Run Autonomously

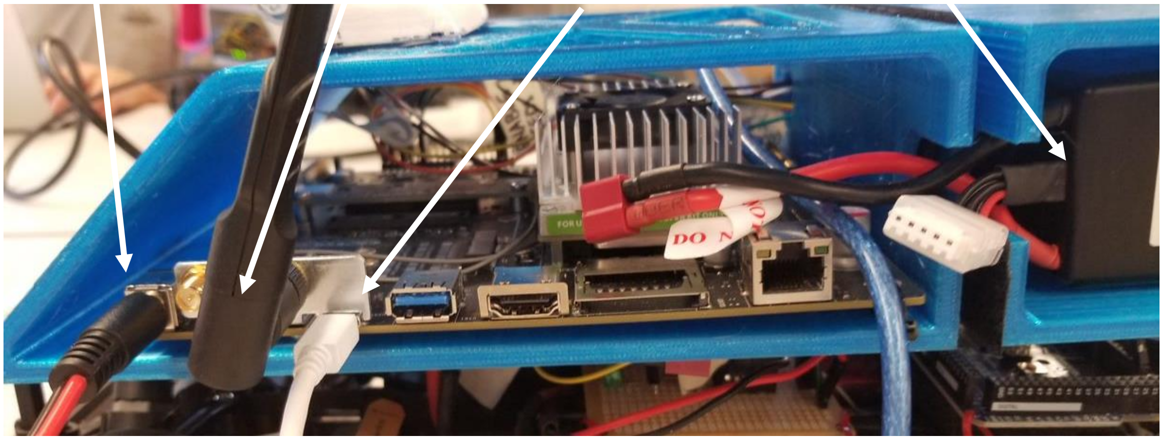
1. Plug in battery to motor
2. Ensure the LED on the protoboard turns green (ON), indicating that the speed controller and motor are wired correctly (see picture below of ON green light).
3. Plug in battery to Jetson microcontroller
4. Press the power button on the Jetson. Green light will turn ON on the Jetson microcontroller
5. Use PuTTY (or similar application) to remotely login into Jetson microcontroller (to "SSH" into Jetson)
6. Place car(s) in center of a straight away lane on the track
7. Repeat steps 1-6 and place second car several feet behind first car
8. Read the inputs that can be performed from the PuTTY application and use keyboard buttons on computers to start the cars. "d" is for drive and "b" is for break. There are various other hot keys programmed in for control of speed, lane changes, and platoon. All are outline in the PuTTY output.
9. For further documentation on the software see the handoff document created by the computer engineers

WIRING GUIDE



Jetson power on button

J21 port block

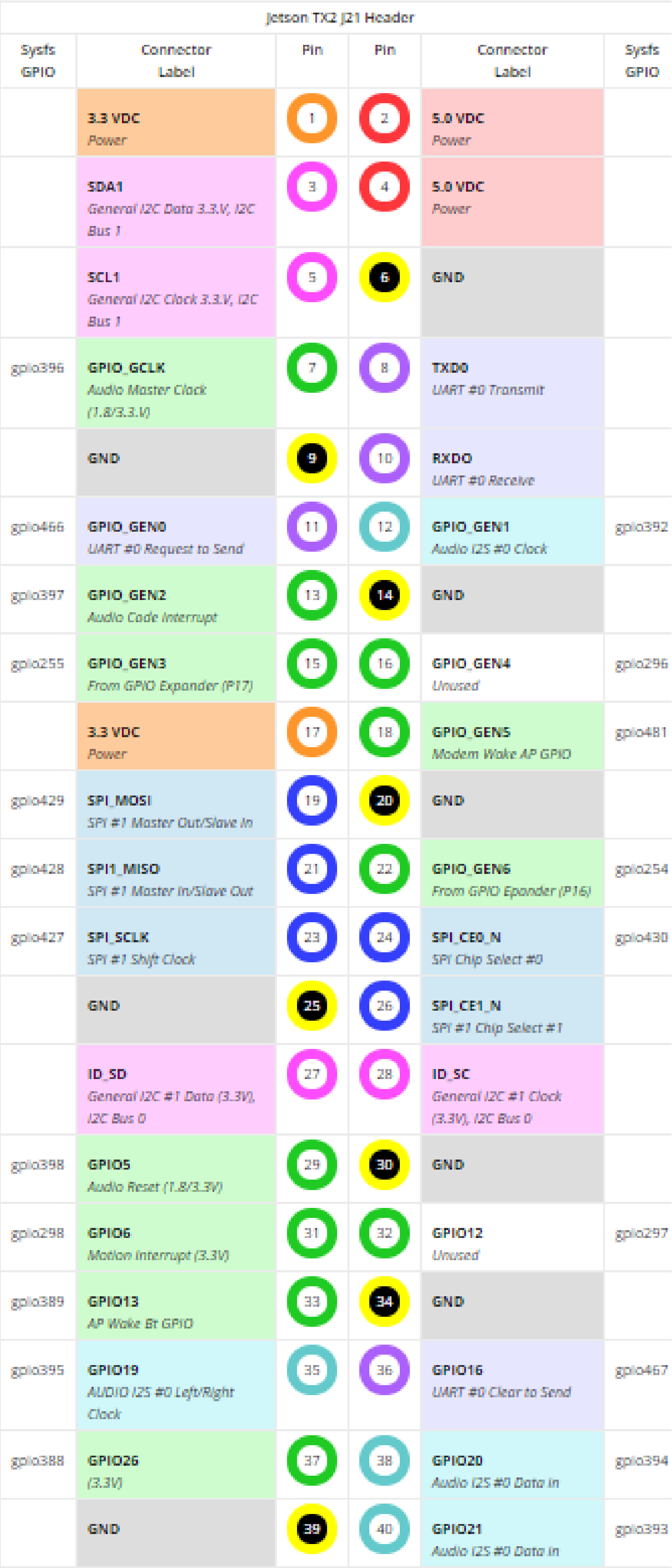


Power jack for Jetson

Wi-Fi antenna

USB connections

4S battery location

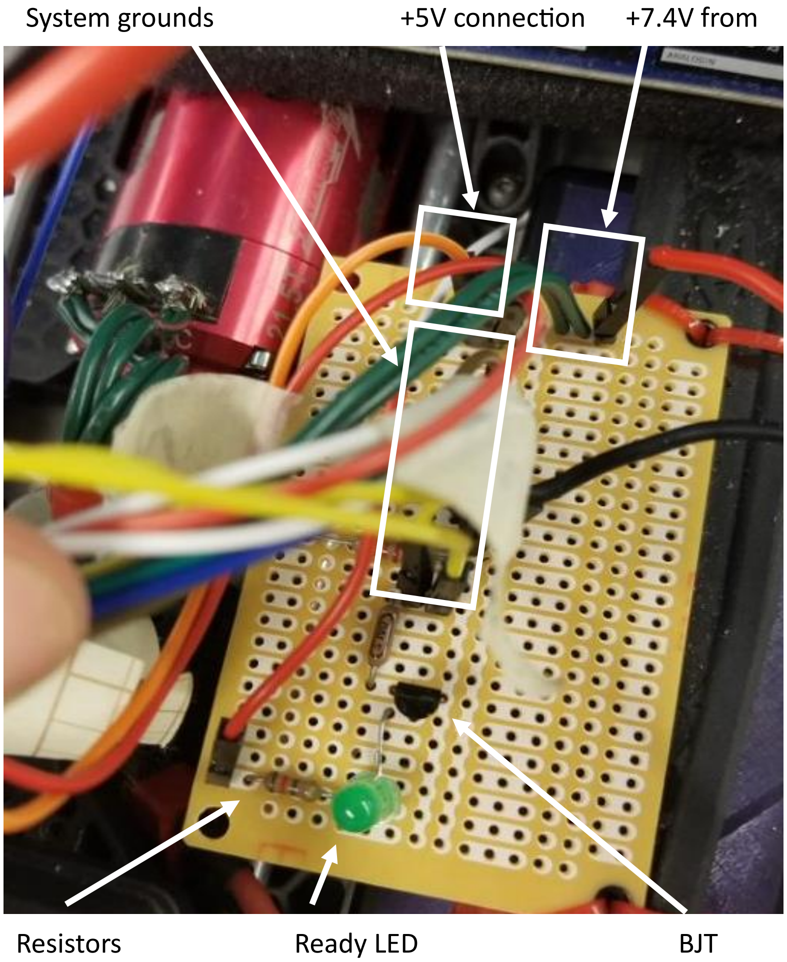


Jetson TX2 J21 Header

Sysfs GPIO	Connector Label	Pin	Pin	Connector Label	Sysfs GPIO
	3.3 VDC *Power*	1	2	**5.0 VDC** *Power*	
	SDA1 *General I2C Data 3.3.V, I2C Bus 1*	3	4	**5.0 VDC** *Power*	
	SCL1 *General I2C Clock 3.3.V, I2C Bus 1*	5	6	**GND**	
gpio396	**GPIO_GCLK** *Audio Master Clock (1.8/3.3.V)*	7	8	**TXD0** *UART #0 Transmit*	
	GND	9	10	**RXDO** *UART #0 Receive*	
gpio466	**GPIO_GEN0** *UART #0 Request to Send*	11	12	**GPIO_GEN1** *Audio I2S #0 Clock*	gpio392
gpio397	**GPIO_GEN2** *Audio Code Interrupt*	13	14	**GND**	
gpio255	**GPIO_GEN3** *From GPIO Expander (P17)*	15	16	**GPIO_GEN4** *Unused*	gpio296
	3.3 VDC *Power*	17	18	**GPIO_GEN5** *Modem Wake AP GPIO*	gpio481
gpio429	**SPI_MOSI** *SPI #1 Master Out/Slave In*	19	20	**GND**	
gpio428	**SPI1_MISO** *SPI #1 Master In/Slave Out*	21	22	**GPIO_GEN6** *From GPIO Epander (P16)*	gpio254
gpio427	**SPI_SCLK** *SPI #1 Shift Clock*	23	24	**SPI_CE0_N** *SPI Chip Select #0*	gpio430
	GND	25	26	**SPI_CE1_N** *SPI #1 Chip Select #1*	
	ID_SD *General I2C #1 Data (3.3V), I2C Bus 0*	27	28	**ID_SC** *General I2C #1 Clock (3.3V), I2C Bus 0*	
gpio398	**GPIO5** *Audio Reset (1.8/3.3V)*	29	30	**GND**	
gpio298	**GPIO6** *Motion Interrupt (3.3V)*	31	32	**GPIO12** *Unused*	gpio297
gpio389	**GPIO13** *AP Wake Bt GPIO*	33	34	**GND**	
gpio395	**GPIO19** *AUDIO I2S #0 Left/Right Clock*	35	36	**GPIO16** *UART #0 Clear to Send*	gpio467
gpio388	**GPIO26** *(3.3V)*	37	38	**GPIO20** *Audio I2S #0 Data in*	gpio394
	GND	39	40	**GPIO21** *Audio I2S #0 Data in*	gpio393

J21 Pinout from:

https://www.jetsonhacks.com/nvidia-jetson-tx2-j21-header-pinout/



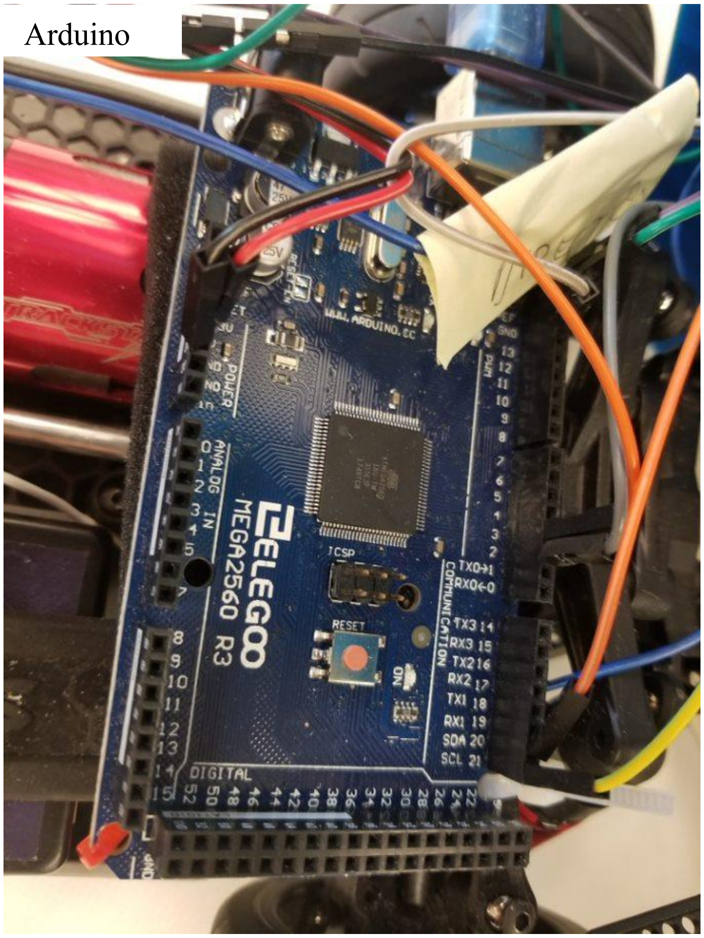
+5V Connections

- Comes from Vcc Hall (Pin 11 on Speed Controller)
- Goes to DigIN1 (Pin 20 on Speed Controller)
- Goes to DigIN2 (Pin 21 on Speed Controller)

+7.4 Connection

- Comes from 2s battery
- Goes to +Vcc input to Speed Controller (Pin 7 & 8 on Speed Controller)

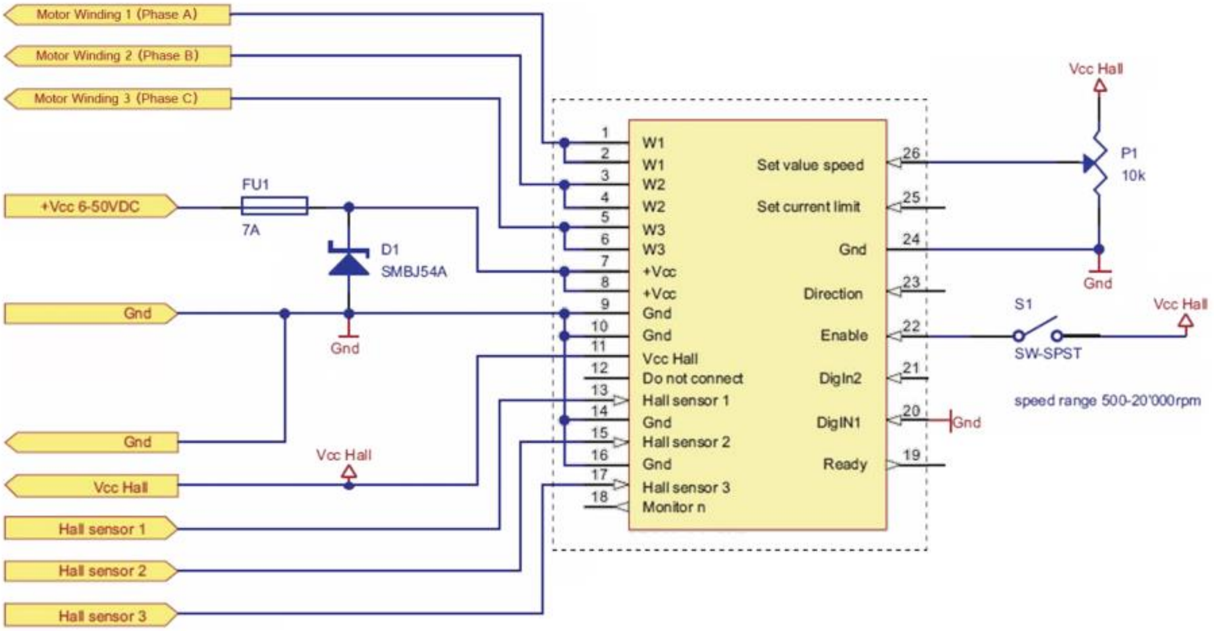
Arduino



Connections

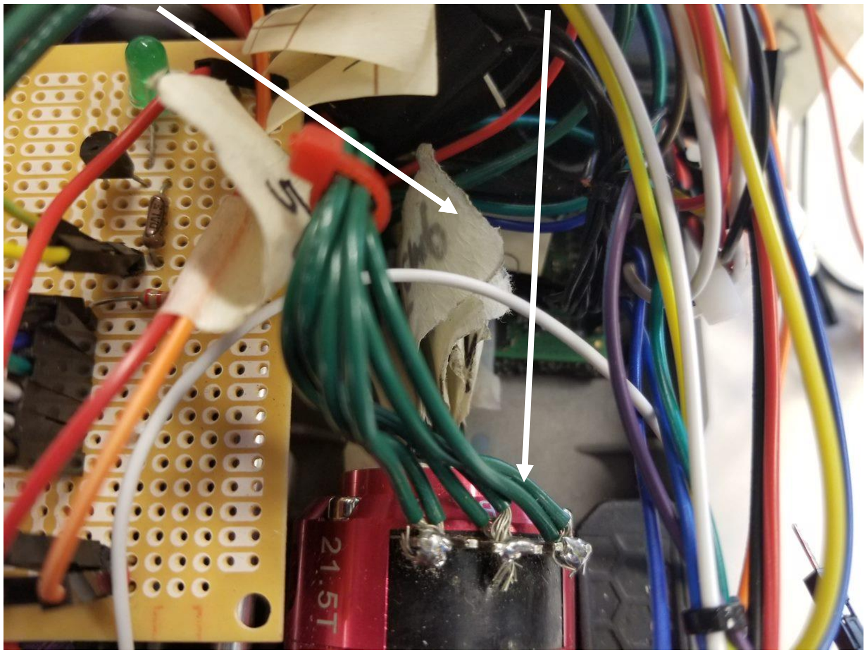
- Powered by USB connection from the Jetson
- Provide +5V and GND for servo
- Output PWM signal through pin 9 (9_PWM on Electrical Diagram) to Servo
- Output speed set value from port 10 into pin 26 (speed value set) on Speed Controller
- Receive PWM signals from Jetson through port 20_SDA (data line) and 21_SCL (clock line)
- Receive ground from pin 34 of Jetson

Speed Controller Pinout Diagram

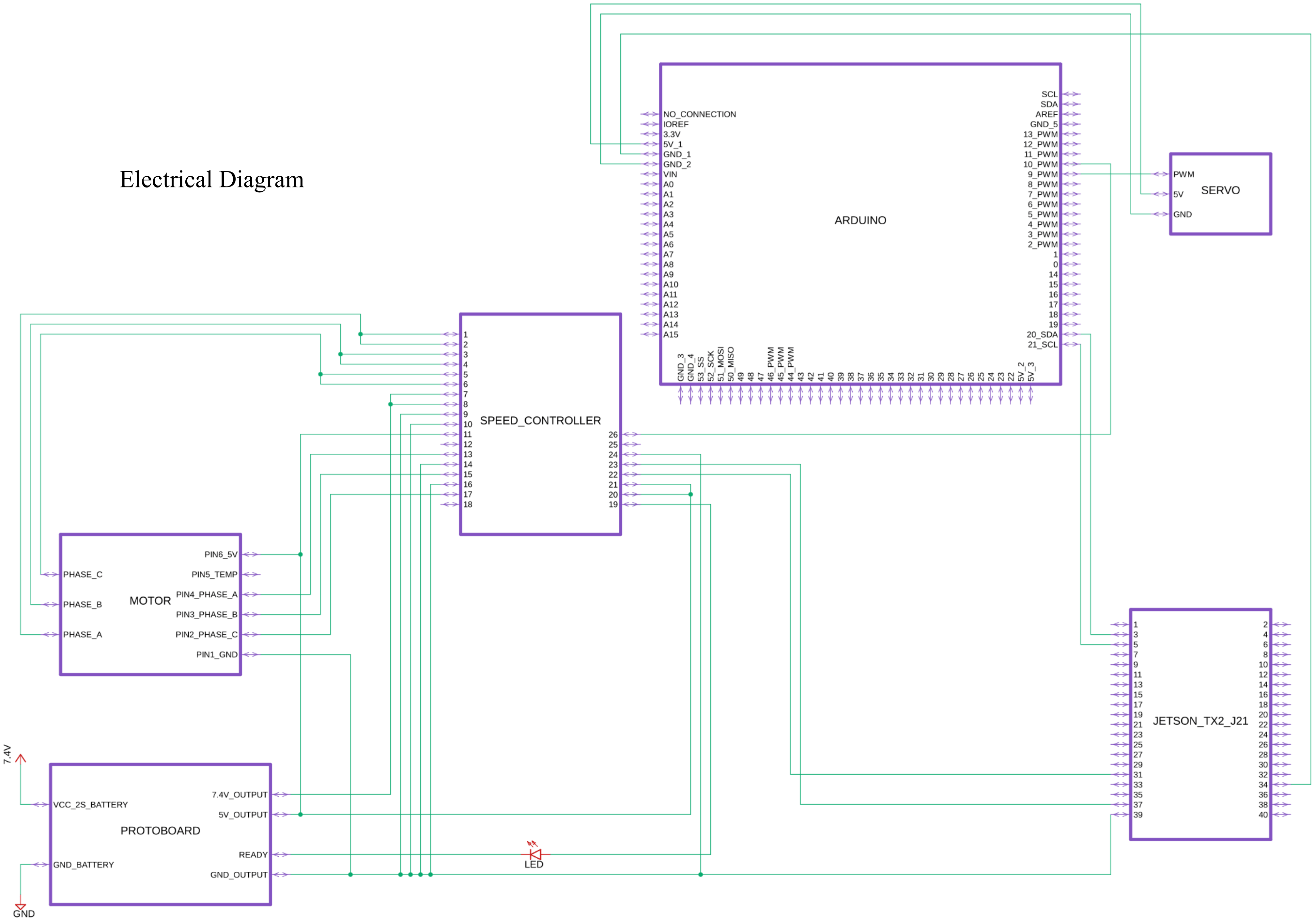


Speed Controller

Motor



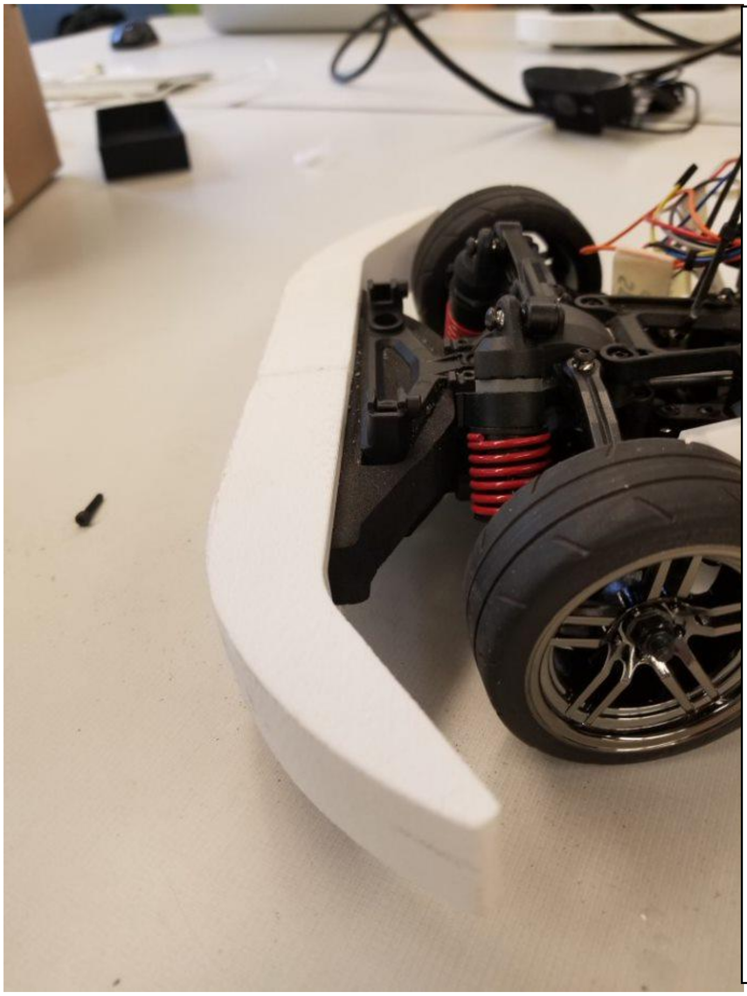
Electrical Diagram



MAINTENANCE GUIDE

Clamp Location for motor battery (2S battery)

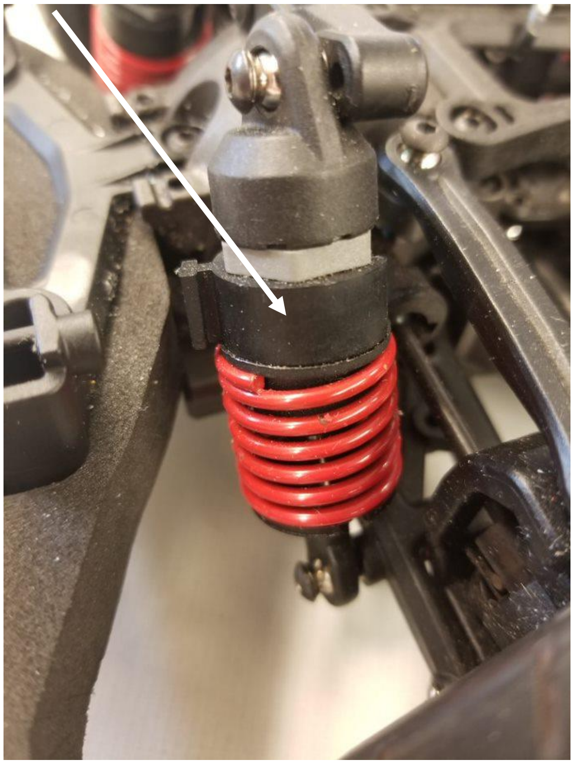
At this location the clamp can be undone, and the motor battery can be removed without disassembling the car. The battery’s t-connector must be unplugged before removal.



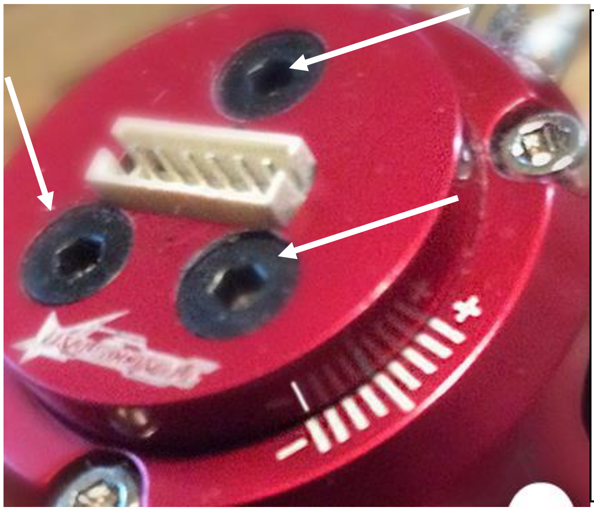
Car bumper is made of two pieces of 3D printed plastic and press fit onto the stock foam bumper as seen on the left. If the bumper breaks into its two pieces in a crash, we recommend it to be glued back together, assuming no damage, and press fit it back onto the car.

The wheels are attached by a center lock nut. If the wheel is wobbling more than expected there is a pin holding in the wheel bearing that has come loose. It can be accessed by removing this nut and taking off the wheel.

Spacer



The suspension has been modified with the addition of spacers at each of the four corners. If more equipment is added to the cars and the additional ground clearance is need more spacers can be added. In the picture, the highest spacers were used on all 4 suspensions of both cars.



The motor timing can be changed by loosening the three bolts (shown in picture) on the front most face of the motor and turning the face to the desired timing position. The more negative it is pushed, the more low-end torque the motor is able to produce