Guided Target Control System
Final Design Report

for Daimler Trucks North America

Team SLONav

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Statement of Disclaimer

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Executive Summary

Problem Summary

Daimler Automotive, the parent company of mercedes-benz requires improved methods for testing their Autonomous Emergency Braking Systems. To this end they have presented a series of four senior projects to California Polytechnic State University in San Luis Obispo. One of the Projects is to build a facsimile of a human crossing the street. The other three projects of which this is a part; are to produce an autonomous car facsimile. These projects are intended for use in testing new Autonomous Emergency Braking Systems and may serve as the basis for future senior projects.

Organisation

The Daimler/Cal Poly senior projects are as follows:

- Crosswalker
    - Human walker facsimile
- Target Practice
    - Soft, car shaped, target intended for safe, repeated impact testing at low speed
- Roadkill
    - Frame designed to move and carry the soft target during testing
- SLONav
    - Control System for the guided target frame

This report focuses primarily on the control and electrical systems of the guided target frame. For more details on the other projects please see their respective reports. There is no joint summary report.

Project Focus

The SLONav control system is intended to provide control and autonomous navigation to the guided target frame. The control system is intended to allow navigation between GPS based waypoints, provide precision control of vehicle velocity, and allow retrieval of test data. above all else the guidance system is intended to improve the safety of operator and test technicians.

Timeline

The full system as described in this report was developed over the course of nine months, as a standard three quarter senior project. The first quarter was primarily dedicated to the development of requirements, scope, and other managerial details. The second quarter was devoted to project design. The third quarter was devoted to construction of the final system and integration with the other teams.

Results

The final controls system developed for this project is electrically complete. It is capable of radio controlled operation and data collection. An autonomous control software framework is partially complete but not ready for deployment. Additionally closed loop control and multipoint waypoint mapping has been partially implemented but not deployed. The controls system is at a good stage to be continued as a mechatronics or software engineering project in further years.

1 - Introduction

1.1 - Problem Statement

Daimler Trucks North America has a need to test advanced driver assistance technology they are developing for use in their future vehicles. Daimler's current test methods involve towing a prop foam vehicle which emulates the rear end of a car, in front of the vehicle they are testing. Although this method is reliable, it does not provide them with the accuracy, nor the data acquisition, they hope to achieve with their tests. Alternative test vehicles provide the functionality that Daimler seeks, however they are expensive. The need for more effective testing at a cheaper cost has led Daimler Trucks, in cooperation with Cal Poly's Mechanical Engineering program to issue the Guided Target Control System project to our senior project group SLONav. Our goal for this project was to develop and build the mechatronics and control system necessary to navigate the guided target frame vehicle and to collect data during testing.

1.2 - Specifications

When developing our specifications we considered a few target customers for our product. The customers we considered for this project were the test technicians at Daimler who would use this equipment directly, the advanced driver assistance systems engineering team at Daimler whose systems this device would test, the guided target frame team, and future students who may be developing additional functionality for this system. The requirements we developed to address the needs of the customers are the following:

1. Electronics required to control the motors
2. Control system software for steering target frame
3. Software for controlling speed, acceleration, and deceleration of target frame
4. Integration of safety features such as an emergency stop protocol
5. Data acquisition system for recording of critical variables
6. Sensor integration and placement
7. Power supply for control and data acquisition electronics
8. Packaging of electronic bundle
9. Hardware necessary for interfacing with target frame
10. Velocity setpoints that need to be reached at the trigger positions during testing
11. Acceleration and deceleration profiles that occur in between trigger positions
12. An unlimited number of configurable trigger points
13. A maximum speed that the vehicle will be able to effectively control
14. Accuracy of the vehicle position along a straight path
15. Ability to integrate with target frame team's design
16. Total cost of development
17. Integration of an emergency stop (E-Stop) protocol
18. Integration of other appropriate safety features

19. Collection of critical data variables(i.e. position, velocity, and acceleration)
20. Modular and maintainable code base for future development
21. User interface
22. Power required to run electronics and sensors
23. Reliability of the system to conduct test procedure

With these requirements we utilized the quality function deployment (QFD) method to analyze our requirements compared to our customers, competitors and specifications. A copy of our QFD spreadsheet can be seen in Appendix A.

Table 1.1 Formal Engineering Specifications for Guided Target control system project. Risk refers to the difficulty of meeting the specification and is assigned as High (H), Medium (M), or Low (L). Compliance refers to validation methods which are Analysis (A), Test (T), Similarity to Existing Designs (S), and Inspection (I).

Spec. #	Parameter Description	Requirement/Target	Tolerance	Risk	Compliance
1	Controllable Speed	32.2 kph	Min	M	A, T
2	Number of trigger points	10	Min	H	A, T
3	Positional accuracy with regard to trigger points	±1.5 meters	Max	H	A, T
4	Straight line accuracy between trigger points	±0.5 meters	Max	H	A, T
5	E-Stop signal latency	100 ms	Max	M	A, T
6	Acceleration	1 m/s^2	± 0.12 m/s^2	H	A, T
7	Deceleration	3.5 m/s^2	± 0.12 m/s^2	H	A, T
8	Acceleration/Deceleration setting	0.25 m/s^2 increments	Min	H	A, T
9	Initial setup time	30 min	Max	M	T
10	Setup time between tests	10 min	Max	M	T
11	Percentage of successful tests conducted without control system faults	94%	Min	M	A, S
12	Latency for control loop feedback	28 ms	Max	H	A, T
13	Size	90% within 10cm x 20cm x 20cm	Max	L	I
14	Cost of control system/data acquisition hardware	$1200	Max	L	A
15	Power independent memory	Included	Min	L	I
16	Code Documentation	All major functions and modules commented	Min	L	S, I

The target values in our engineering specifications were developed in a few different ways. Some of our specifications were already defined in the Daimler project proposal or stated by our sponsor (David Smith) during our initial meeting. The specifications that were determined this way were the minimum max speed, minimum number of trigger points, and cost. The positional

accuracy and straight line accuracy specifications were determined during meetings with a representative of our sponsor (Thomas Stevens).

The E-Stop signal latency was based on the maximum required speed, our predictions of the stopping deceleration, and the typical latency of radio communication protocols [17]. Our acceleration and deceleration specifications were obtained from the guided target frame group, based on information provided by David Smith.

The initial setup time and setup time between tests specifications were suggested by our sponsor. The initial setup time specification was determined by roughly estimating how long it would take to upload a test protocol, for the GPS to get an initial position from a “cold” start, and any other initialization routines required by the software. The setup time between tests specification was based on the time needed to retrieve data in between tests.

The reliability specification was determined by reading a National Highway and Traffic Safety Administration (NHTSA) docket regarding the planned criteria for recognizing new vehicles as having a crash imminent braking system [8]. In the NHTSA docket they list that a new vehicle must have 7 out of 8 valid test trials for most of their test scenarios. Since our design will likely have to conduct tests similar to these trials we decided that it should have a reliability of two times the number of valid trials which makes the reliability rated at 15 out of 16 trials or approximately 94%.

The sensor cycle latency specification was determined by calculating the time necessary for the test vehicle to go outside of the 0.5 m straight line accuracy requirement which is approximately 56 milliseconds. We decided that if we need the test vehicle to maintain the positional accuracy it would need more than one sensor cycle to correct itself so we decided that a cycle latency 28 ms would be more robust and open up the possibility of controlling the test vehicle at higher speeds.

The size specification was determined by looking at similar vehicle data logging products like the OXTS RT2000 (Appendix B) which has GPS and inertial measurement tracking in a package that is approximately 9.25” by 4.75” by 3”. We believed that some of the sensors would likely need to be outside of the main electronics bundle so decided that the requirement would be that 90% of the electronics must fit in the 8” by 8” by 4” footprint.

The power independent requirement was included because we believed that the system would need some way of storing long term data regarding its operation routines and to have test data be retrievable if the system fails because of a power loss.

Lastly, the code documentation specification was determined from the fact that the code written for the system will need to have standardized formatting to simplify debugging and promote modularity of the code. The standardized formatting was also intended to make it easier for future teams to develop the code base further and implement more advanced features.

The risk of each specification was determined heuristically by the group members based on our previous project experiences and understanding of the specification. We defined the risk as being the perceived difficulty of meeting the specification. The highest risk specifications were determined to be positional accuracy of the test vehicle, the straight line accuracy of the test vehicle, the sensor latency timing, the configurable acceleration/deceleration, and the number of trigger points that need to be implemented. We determined these specifications were the highest risk because they require fast, accurate, and sensitive sensor feedback which put a higher emphasis on efficient control code. We determined the controllable speed to be medium risk because the timing constraints of that specification is significantly slower than the high risk specifications. The setup time specifications were determined to be medium risk because most of the system (microcontroller and sensors other than GPS) will likely need a few seconds to initialize. The GPS sensor and the physical manipulation of the test vehicle will have a much larger impact on the setup time. The E-Stop delay was determined to be medium risk because even though it has a moderate timing constraint, the code necessary to implement it was thought to be simpler than the control code. The size and cost were determined to be low risk specifications because microcontroller, embedded PCs, and other electronics are low cost, approximately 10 USD for a typical microcontroller (Appendix H), and very small, 10mm by 10mm footprint for a typical microcontroller (Appendix H). We determined that the code documentation was a low risk specification since limited time is the main deterrent of proper documentation.

The compliance for each specification states the general method of testing that will be taken to validate the specifications. The four methods of compliance we have defined are, analysis (A), test (T), similarity to existing designs (S), and inspection (I). The analysis method required that we have appropriate calculations or simulation code to prove that the specification has been satisfied. An example of this would be determining the execution time of the control loop to determine if we can control the vehicle traveling at 20 mph. The analysis compliance method will be the first compliance test for most of the specifications. The test method will require physical testing of the specification and verifying test data. An example of this would be having the target frame drive at 20mph using our control loop and observing the response over a set distance on a dry flat track with minimal wind (10 mph or less). The test compliance method was the last compliance test for most of the specifications. The similarity to existing designs method will require comparisons of our design to a system with known values for the specification being tested. An example would be comparing our electronics and enclosure design to a similar product that is used in a similar environment such as the OXTS RT2000 (Appendix B). The similarity method will depend on available information for comparable products. The inspection method requires verifiable measurements that the system meets the specification. An example of this would be measuring the final dimensions of the electronics bundle we developed to show that they meet the size specification. The inspection compliance will be conducted after the analysis compliance method.

1.3 - Project Management

For the purposes of organisation, members of the SloNav team were each assigned official responsibilities depending on their skills and interests. These assignments were not always followed strictly, however they provided the team with a rapid method for breaking up tasks throughout the project. As follows are the roles assigned to each member.

1.3.1 - Management

Ryan Mackintosh

- Communications Officer
    - Main point of contact with sponsor
    - Responsible for drafting any emails
    - Liable for keeping sponsor informed on meeting agenda and project progress
- Progress Progression Documentation
    - Maintain Critical Path Documentation throughout the course of the project
- Test plan developer
    - Aid the development of any necessary test plans to debug software
    - Lead the development of any hardware testing needed. (eg. Impact, vibrations testing, etc.)
- Lead support structure designer
    - Responsible to designing and prototyping all support structures. (eg. controller fixture)
- Assistant electronics technician
    - Assist in development and assembly of any custom circuit boards required

John Barry

- Secretary/Recorder
    - Maintain information repository for team (GitHub, Google Drive, etc.)
    - Complete weekly status report.
    - Assign due dates to all project tasks on a weekly basis.
    - Keep Log of all information discussed during sponsor meetings
- Information gathering
    - Compile all research documentation in info. repository
- Inventory manager
    - In charge of sourcing and tracking all required materials for testing
- Test plan developer
    - Aid the development of any necessary test plans to debug software

Zach Eagan

- Team Treasurer
    - Maintain team material budget
    - Update Bill of Materials as project progresses
    - Responsible for communicating any purchases need to sponsors
- Inventory manager

    - In charge of sourcing all required materials for testing
- Lead test plan developer
    - Lead the development of any necessary test plans to debug software
    - Assist the development of any hardware testing needed. (eg. Impact, vibrations testing, etc.)
- Codebase maintenance
    - Responsible for reviewing and maintaining all code implemented
- Lead electronics technician
    - Responsible for assembling circuits

1.3.2 - Project Timetable

In order to coordinate the project development through its three quarter duration we developed a comprehensive Gantt chart with our expected timeline. The full Gantt chart may be found in Appendix D. Listed below are the major project milestones.

- Preliminary Design Review → Nov 15th, 2016
    - Document chosen concept for design with supporting evidence
- Critical Design Review → Feb 7th, 2017
    - Provide detail overview of how chosen design will be achieved
- Manufacture and Testing Review → March 16th, 2017
    - Evaluation of manufacturing and testing procedures planned to construct and verify prototype
- Project Update Report → March 16th, 2017
    - Brief summary of project status
- Prototype testing → April 4th, 2017
    - Beginning of final design verification
- Final Design Review → June 2nd, 2017
    - Final project report which builds on Critical design review with final design specifications and results
- Design Expo → June 2nd, 2017
    - Presentation of final design at Cal Poly

2 - Background

2.1 - Advanced Driver Assistance Technology

The purpose of the project was to develop a test vehicle which Daimler can use to assist with testing the advanced driver assistance technology they are developing for trucks and buses. Advanced driver assistance technology encompasses a variety of systems that improve the driving experience and provide safety features to reduce accidents. Some examples of these systems are adaptive cruise control and autonomous emergency braking. Adaptive cruise control is a system for a vehicle that attempts to maintain the vehicle's speed but adjusts the speed to keep a safe distance from other vehicles. Autonomous emergency braking (AEB) is a

collision avoidance technology that is used to avoid or reduce the severity of imminent crashes. Through the project description and our meetings with Daimler it was suggested that this project will mainly be used to improve the testing of the autonomous emergency braking systems that they are developing. While we focussed on autonomous emergency braking test conditions, the test vehicle is designed to be capable of conducting tests for other systems Daimler is developing. The paper “Advanced Driver Assistance Systems” published in SAE International gives a overview of the current systems available today [1].

2.1.1 - Autonomous Emergency Braking (AEB)

Autonomous Emergency Braking (AEB) is a system that integrates sensors into the front of a vehicle to monitor proximity and relative speed of other vehicles to determine if a collision will be imminent. If a collision is imminent then the system will apply the vehicle brakes in an attempt to avoid the collision or minimize damage and injury. A report on AEB systems by the National Highway Traffic Safety Administration (NHTSA) states that these systems could potentially prevent up to 910,000 accidents within the United States, if widely adopted [2].

2.1.2 - Autonomous Emergency Braking (AEB) Testing

The testing of AEB systems is a new requirement for automotive manufacturers with standard testing procedures being first established as recently as 2012 for the NHTSA [2] and 2013 for the European New Car Assessment Programme (Euro NCAP) [3]. The testing procedures generally involve the vehicle under test trying to avoid crashing into a test vehicle under various relative speed conditions. The relative speed conditions are the following:

1. Vehicle under test moving at test vehicle with it stationary
2. Vehicle under test moving at test vehicle with it decelerating
3. Vehicle under test moving at test vehicle with it at lower speed

The procedures and specific test criteria are explained thoroughly in the standards from the NHTSA [2] and Euro NCAP [3].

2.2 - Existing Products

Through our research we found several existing solutions to the problem we are solving with this project. The existing solutions we found mainly fell into two categories which were an autonomous test vehicle with many advanced features, a car analog that was towed by another vehicle being driven manually, and a virtual simulation testing autonomous software.

2.2.1 - ABD/DRI Guided Soft Target

The first device that we found when researching was the Guided Soft Target Vehicle produced by AB Dynamics (ABD) and Dynamic Research, Inc (DRI). This device is an example of an autonomous test vehicle.

Figure 2.1 Low profile guided soft target frame produced by ABD/DRI from the specification sheet provided by ABD (Appendix B).

The ABD/DRI guided soft target consists of a low profile frame and a breakaway car shaped shell that mounts to the frame. This product has GPS tracking capabilities and uses an inertial measurement unit (IMU) to keep the vehicle following a precise path. The vehicle has the capability to follow programmed paths with predefined speed profiles and coordinate its motion with other vehicles. It is also capable of being manually or autonomously driven. Perrone Robotics has a device that is similar to ABD/DRI's Guided Soft Target Vehicle called the Automated Vehicle Test System. The Perrone Robotics product has a higher top speed than ABD/DRI (55 mph versus approximately 42 mph) and uses the general purpose robotics and automated vehicle operating system that they have developed called MAX. Both the ABD/DRI and Perrone Robotics systems solve the problem, but our sponsor has suggested that they have more features than they need and the cost of these systems are high.

2.2.2 - Messring NHTSA Vehicle Target

The Messring NHTSA Vehicle Target is a partial vehicle shell that is connected by a long frame to a tow car. This product is similar to the current product that Daimler wants to replace. The tow car is driven by a person and the vehicle shell represents the rear end of a common vehicle. The low frame is to allow for the vehicle under test to stop after it hits the vehicle shell but before it reaches the tow car.

Figure 2.2 Messring NHTSA vehicle target attached to towing vehicle for testing from website. (www.messring.de/test-facilities-and-components/aeb-test-systems/mhtsa-vehicl e-target-ssv/)

This product provides a robust platform for collision testing but requires a human driver and a seperate car to be used for conducting any tests. The flexibility of having a human driver is helpful for conducting a variety of test speeds and conditions. The downside of this system is that having a human driver can lead to inconsistency in the velocity and acceleration requirements of the test since it is difficult to perform exact accelerations and decelerations consistently. This system lacks some of the data logging features required (i.e. velocity and GPS) without extra equipment.

2.2.3 - Virtual Vehicle Testing

In the past few years some autonomous vehicle manufacturers such as Google, have employed alternate test methods to validate their autonomous cars. Rather than solely conducting physical tests, Google has decided to complement its already impressive road testing initiative, with virtual simulation verifications [4]. Although these simulations only focus on validation of the vehicle software, it is has proven to be an invaluable part of the testing procedure since it allow for decades worth of data in a few hours. The simulations also enable companies to test thousands of unique scenarios, that would otherwise be too dangerous. Although the California DMV has acknowledged the value that simulated testing presents, it has not currently allowed for virtual simulations to replace physical test.

2.3 - Patents

During our research of existing products we found that DRI has applied for patents regarding the technology they have developed for Guided Soft Target Vehicle. The patents cover a variety of topics that are used within their product such as a method of trajectory planning [5], breakaway antennas, base station system architecture, and radar signature minimization [6].

These patents are thorough but very specific to the systems that DRI designed and are currently pending approval.

2.4 - Standards

During the course of our research we found a few standard test protocols developed by different entities. One was produced by the European New Car Assessment Programme (Euro NCAP) which is an organization that provides car safety information to the public. We used the Euro NCAP test specification on automatic emergency braking [3] as a resource to understand the type of testing our project will participate in. Another standard that we found was from the Insurance Institute for Highway Safety [7] which provided some information regarding data acquisition equipment used during their tests. A docket from the National Highway Traffic Safety Administration regarding Crash Imminent Braking systems [8] along with the their report on AEB systems [1] was used to further understand the type of testing our project will be used for. All of these standard protocols were used in determining our engineering specifications, which is explained in our objectives section.

2.5 - Technology

2.5.1 - GPS

Through our interviews with our sponsors at Daimler and our further research into alternative solutions we found one of the primary requirements of the project is the ability to accurately determine the position of the test vehicle. One option for determining the position of the test vehicle is to use a GPS location receiver. While standard GPS has a defined accuracy of 20ft under normal conditions [9] our project specifications require a minimum positional accuracy of 5ft. Additionally most GPS receivers have a maximum refresh rate of only 10 Hz, which, at our defined 20mph will be insufficient to correct for unexpected drift. For this reason we conducted research into augmented GPS systems including Wide Area Augmentation System (WAAS) and the Differential Global Positioning System (DGPS).

2.5.1.1 - WAAS

The Wide Area Augmentation system is designed primarily for aircraft control, but is common in many US based GPS systems. This network of augmentation satellites provides accuracy averaging 2–3 meters within the US [10].

2.5.1.2 - DGPS

Differential GPS relies on a nearby base station able to average the GPS signal over a 24-hour period and transmit the precise current inaccuracy to the receiver. This method supports up to 10 cm accuracy under ideal conditions depending on distance from the base station, calibration time, and environmental conditions [11]. A nationwide DGPS network is available though coverage and accuracy are dependent on location [12]. Additionally, single purpose base stations may be set up assuming compliance with FAA and FCC regulations.

2.5.1.3 - LAAS/GBAS

Local Area Augmentation System, or Ground Based Augmentation System. This system of ground based stations can be used to augment GPS to accuracies of less than a meter but require extensive permanent infrastructure [13]. With this method a series of local short range transmitters provide GPS updates by comparing current GPS measurements at each tower with the known fixed positions of the towers [14].

2.5.2 - Inertial Measurement Unit (IMU)

An inertial measurement unit is a packaged combination of sensors typically used to determine the position, velocity, and acceleration of a moving body. The sensors most commonly found in IMUs are accelerometers, gyroscopes, and magnetometers. The accelerometers are used to measure accelerations of the body it is attached to, typically in the three dimensions. The gyroscopes are used to measure the rate of rotation of the body, usually about three axises. The magnetometers measure the magnetic field strength the body is subjected to, usually in three dimensions. Unlike GPS devices, IMUs are not able to determine the absolute position of the object they are mounted to because they only measure movement from their previous position. A method of navigation called dead reckoning where the difference between the current reading and a previous reading is used to estimate how far the object has traveled.

2.5.3 - Kalman Filter

A Kalman filter is an algorithm that utilizes a linear model of a system, sensors, and their associated uncertainties to get more accurate predictions of what the system is doing than utilizing the information directly. Kalman filters are mainly used when you have multiple sensors with system that is continuously changing. The Kalman filter has two main steps which are the prediction and update. The prediction step utilizes the previous state of the system and estimates how the system has changed at the current time. The update step uses the predicted system change and compares it to sensor measurements to produce a more accurate estimate. The diagram in Figure 2.3 shows helps with visualizing the flow of data. Figure 2.4 shows a simple visual of how the values from the prediction step is combined with the measurements from the update step to produce a more accurate value.

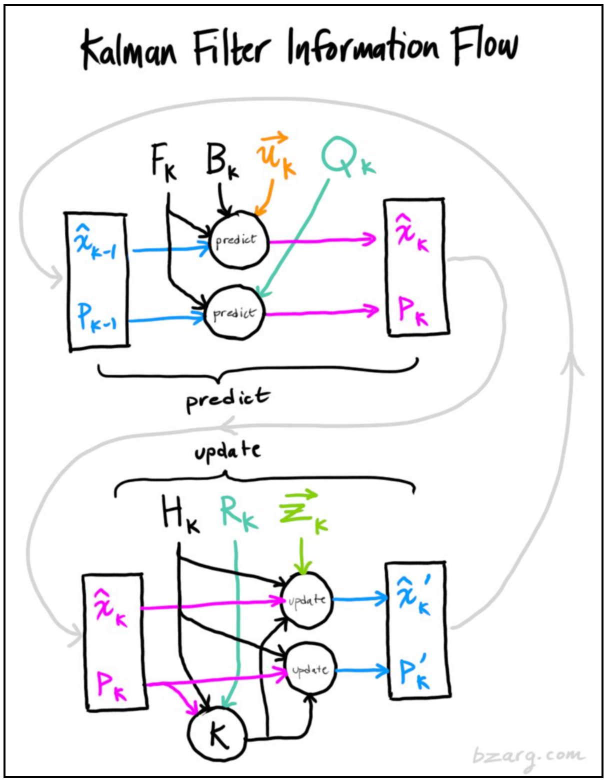


Figure 2.3 Drawing of a information flow for a generic Kalman filter [15]. The blocks represent a vector of variables that are being estimated. The *k* subscript represent the current value of that variable and the *k-1* subscript represents the previous value. The arrows coming from letters with *k* subscripts represent the models and uncertainties that influence the variable at the different steps.

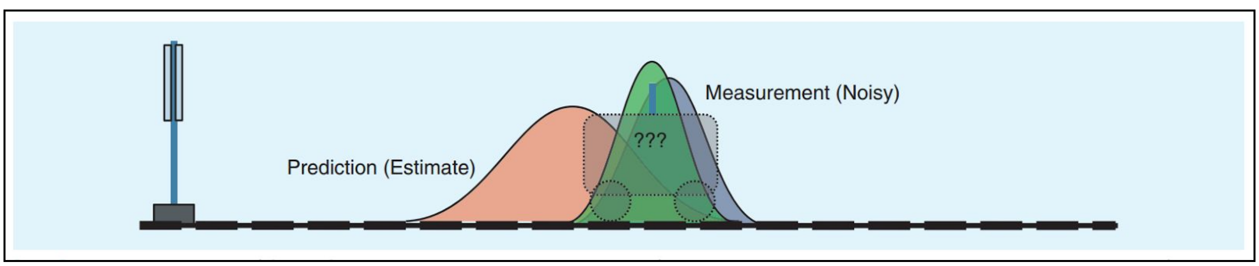


Figure 2.4 Drawing of the probability distribution functions for the position of a car as it is moving along a track [16]. The orange distribution represents the prediction of the position based on a model of the system. The gray distribution represents the position based on a sensor measurement. The green distribution represents the position based on combining the measurement and prediction using a Kalman filter.

2.6 - Technical Challenges

2.6.1 - Position Accuracy

Our positional accuracy requirement is specified as no more than ± 1.5 meters from any positional waypoint and no deviation of more than ± 0.5 meters from the straight line between waypoints. This is to ensure that the target frame is always in view of measurement systems on the Vehicle Under Test. This positional accuracy was one of the main challenges for our control system as this required algorithms to combine sensors and increase accuracy beyond that of any single sensor. The GPS system in particular is of concern for these specifications. Though GPS systems under ideal conditions can fix position within tens of centimeters, normal operation provides accuracy of only 0.5 - 3 meters. Additionally few GPS units provide updates at higher than 10 Hz and no GPS unit we have found so far provides higher than 20 Hz within our price range. These low accuracy specifications mean we are largely unable to rely only on absolute position measurements for determining our position on the track.

2.6.2 - Constant Acceleration and Deceleration

Daimler has specified that they want to be able to control the acceleration and deceleration of the test vehicle based on trigger points that are defined on the test vehicle path. This requirement was a technical challenge for two main reasons. The first reason is that the acceleration and deceleration rates depend on variables such as the final chassies design which were outside of our control. The other reason that this requirement is a challenge is that the drive and braking systems can have nonlinearities that the controls must compensate for. An example of a nonlinearity could be a deadband, which is an region where changes in the control signal do not affect the response. Dead bands can occur with electric motors, hydraulic systems, etc.

3 - Design Development

Once we defined our engineering specifications and confirmed them with our sponsor, we began our conceptual design process. We started by defining three main functions that our design concept had to accomplish which were locate itself, make decisions, and control outputs. We used these functions as topics for four ideation sessions. After we completed the last ideation session we used the ideas we generated to build design concepts for the different functions and compared them using a series of weighted matrices.

3.1 - Idea Generation

Over the course of several ideation sessions recorded directly in Appendix E we developed a comprehensive list of possible solutions to the three major challenges of this project. Namely, how the vehicle would locate itself, how it would then make decisions based on the position and

other sensor data, and how the control system would finally output its decisions to the chassis motors and actuators.

3.1.1 - Ideation Session 1

Our first ideation session focused on finding unconventional methods for our control system to locate itself relative to both its environment and the GPS coordinate system. We found many impractical solutions to replace conventional sensors, some of which should work given enough development like using star constellations for night only navigation, but most of which were unfeasible. This session was particularly important in getting the team to think about the inaccuracies inherent in conventional sensors as well as producing a list of possible alternatives to the standard GPS and IMU design. Some of the most notable of these ideas are discussed below.

- Computer Vision:
  - We considered several options for computer vision including stereo distance measurements, track marker identification, and motion tracking. These methods could provide all the information necessary to direct the vehicle however they are expensive in development, maintenance, and processing power.
- GPS:
  - As our specified nodes are defined by physical location as well as time and velocity we determined that GPS alone is not sufficient as it only provides position and low resolution velocity data. It is however essential as GPS is our only source of absolute spatial measurements.
- Revolution Sensor (Motor Shaft Encoder):
  - To adjust individual motor control algorithms we needed a way to directly measure the rotation of each powered motor. A revolution sensor allows us to take this measurement independent of external conditions.
- Inertial Measurement Unit (IMU):
  - An IMU allows our system to monitor its orientation, linear acceleration, and rotational acceleration which helps determine relative motion between GPS measurements.
- Track Markers (Magnetic, RFID, Paint/Chalk)
  - We considered various types of track markers to provide additional absolute information to our system. This system was later discarded as we hoped to avoid any modifications to the test track.
- Whiskers/Antenna:
  - A less conventional method this system would utilise direct contact sensors to locate the edges of the track. This method may be practical in the future as an emergency prevention feature to avoid injury or loss of control but would not be sufficiently adaptable to help with guiding the vehicle.

3.1.2 - Ideation Session 2

Our second session focused on the types of actuators we might need to control and the control signals associated with each type. This session allowed us to examine aspects common to most vehicles. Our first task in this ideation session was to make a list of possible actuators we might be asked to control. A few of these options are listed below.

- Brakes:
    - Hydraulic Disk
    - Drum
    - Inductive
- Drive:
    - DC Motor
    - Stepper Motor
    - AC Motor
    - Rocket
- Steering:
    - Wind Flaps
    - Electronic Differential
    - Steering Linkage

We next attempted to determine a few control signals which were sufficient for a large number of the possibilities. We determined that the most likely control scheme would be a combination of digital signals, analog signals, pulsed DC signal such as Pulse Width Modulation, and external control interface such as SPI or I2C the event that the chassis team selects motors with built in controllers.

3.1.3 - Ideation Session 3

In our third ideation session we focused on an overview of the control logic. During this session we were able to model the overall program flow of our system using sticky notes. This initial flow chart closely resembles the basis for our top level program design.

Our top level program flow chart from ideation session 3 is shown in Figure 3.1. Our program begins with a check of important safety features to ensure the system is ready to be safely operated at which point it notifies the operator. The system then loads the test map and compares it to GPS data to calculate a direct route to the next waypoint. Steering and control algorithms adjust the chassis motors before looping back to recalculate route based on new sensor data.

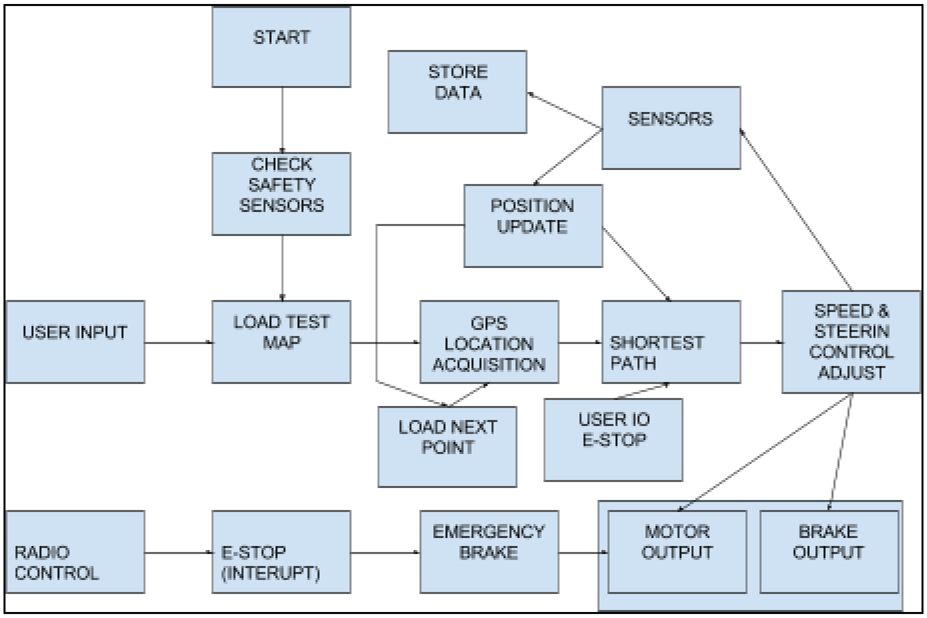


Figure 3.1 Initial program flow.

3.1.4 - Ideation Session 4

In our final official ideation session we looked at possible hardware architectures, with an aim to find as many different ways as possible to bridge the gap from our sensors to our actuators. Our primary architectures shown below were designed with consideration to major issues, such as control loop latency and complexity.

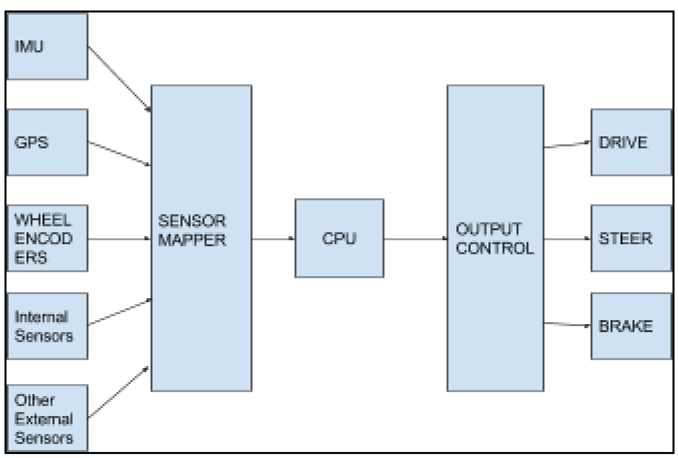


Figure 3.2 Partially distributed architecture.

Our first model shown in Figure 3.2 utilises hardware abstraction which distributes multiple types of communications signals and evaluation of sensor data on external processors to reduce code complexity for the CPU. By utilizing a dedicated hardware block to handle input and output the CPU can spend more time monitoring the system performance.

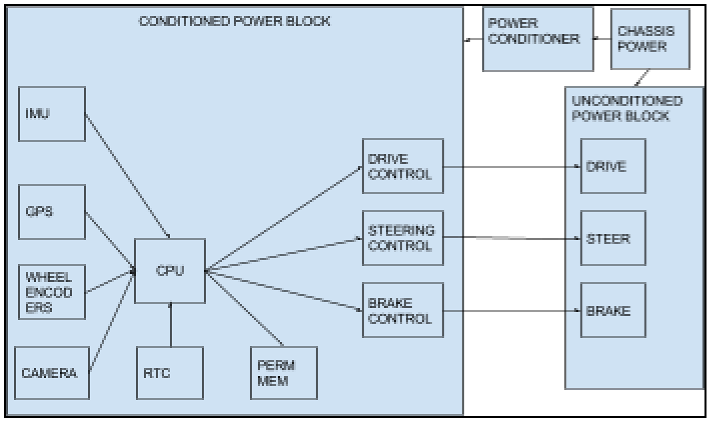


Figure 3.3 Centralised architecture.

Our second model, put all the computation on a single central processor. This model also began to look at additional sensors and requirements such as the need for smooth power to the sensors.

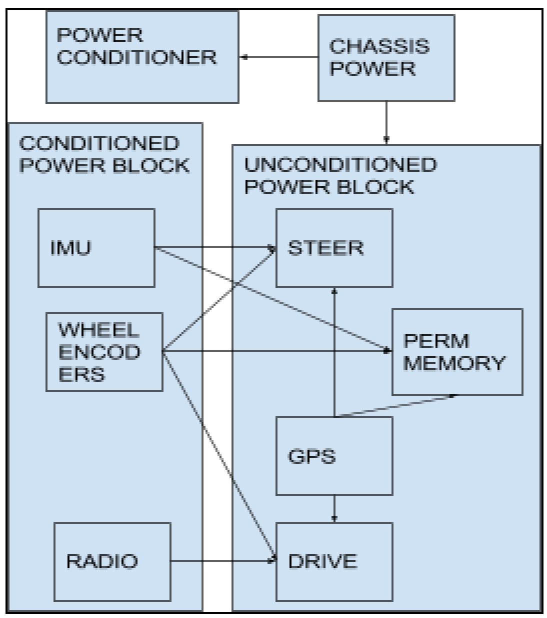


Figure 3.4 Fully distributed architecture.

Our third model focused entirely on hardware abstraction. By removing the CPU entirely we considered a system where no single failure would disable the system. Here the sensors are buffered directly into separate control blocks each of which makes it's own decision based on the input data.

3.2 - Concept Selection

In order to select the best concepts from our ideation sessions we employed a series of Pugh matrices, included below. For each aspect of the design, we compared our top options against a

set of criteria developed specifically for that aspect. Our final design matrix compares different combinations of the best options from the two subcategories, sensor type and processor type, which we believed were most influential to our overall project. These options were ranked based on a further set of weighted criteria. The more unconventional and infeasible ideas were quickly eliminated, leaving us with a small selection of designs with a large amount of prior development and infrastructure. Our top option uses a single multi-core microprocessor for logical control taking input from a combination of GPS, IMU, and wheel encoders outputting via dedicated motor controllers to the larger chassis.

Symbol Key	
+	Better than Datum
-	Worse than Datum
S	Same as Datum

Figure 3.5 Symbol key used by all the following Pugh matrices as a method of rating various concepts against one another.

3.2.1 - Sensor and Actuator Concept Selection

The Pugh matrix in Figure 3.6 illustrates the outcome of the selection process used to determine how the vehicle should locate itself during testing. From these results we determined that an RFID, IMU, RPM sensor, and GPS receiver would all provide useful location data. After some discussion, it was decided that it would be advantageous to consider using a collection of sensor types. This would provide more data as well as serving as a method of checking our sensors to ensure they are all working properly. We chose to include the IMU, GPS receiver, and RPM sensor in this collection. The RPM sensor was chosen because we felt it to be the most reliable since it functioned in a semi-mechanical way. The IMU was selected because it would provide the most accurate velocity and acceleration data, as well as being easy to embed into our microcontroller. The GPS was chosen because it provided the most effective positioning data, which was vital to our testing procedure. The RFID was not included because we did not feel it could provide any additional data that wasn’t covered by the other sensors.

Locate Itself							
Criteria \ Concept	GPS Receiver	RFID	VGA Camera w/ Depth Sensors	RPM Sensor	IMU Encoder	IR Lazer	Analog Winch
Overall Cost	D	+	-	+	+	-	+
Durability	A	+	-	+	S	-	-
Reliability	T	+	-	+	+	+	-
Accuracy	U	-	-	-	+	+	-
Overall Size	M	+	-	+	+	-	-
Σ+		4	0	4	4	2	1
Σ-		1	5	1	0	3	4
Σ_{Tot}		3	-5	3	4	-1	-3

Figure 3.6 Pugh matrix evaluating different methods the vehicle could use to locate itself during testing.

The orientation data acquisition matrix in Figure 3.7 was fairly similar to the previous location matrix, however it was more focused on ensuring that the vehicle would have reference to the direction it was traveling in. This matrix was crucial to determining our success in meeting our ±0.5 meters course deviation specification. The results revealed that we should consider the viability of utilizing a dual gps system, with the hope of improving the vehicle's ability to determine its direction. It also reinforced our previous decision to include an IMU.

Acquire Data (Orientation)							
Criteria \ Concept	Accelerometer	Magnetometer	Gyroscope	IMU	Vibration Sensor	Dual GPS Units	Sonar
Overall Cost	D	-	-	+	S	-	-
Durability	A	S	-	S	S	+	S
Reliability	T	-	S	S	-	+	-
Accuracy	U	-	S	S	-	S	-
Available Data	M	-	+	S	-	+	S
Σ+		0	1	1	0	3	0
Σ-		4	2	0	3	1	3
Σ_{Tot}		-4	-1	1	-3	2	-3

Figure 3.7 Pugh matrix evaluating different methods of determining the orientation of the vehicle.

The Pugh matrix shown in Figure 3.8 highlighted our decision process in selecting the primary types of linear actuator present in our system. Both the electromagnetic and piezoelectric actuators proved to be reasonable options, primarily due to their controllability and simplicity with respect to system integration. However, we chose electromagnetic actuators due to their availability and intuitive nature.

Actuators				
Criteria \ Concept	Electromagnetic	Piezoelectric	Hydraulic	Pneumatic
Speed	DATUM	S	S	S
Complexity		S	-	-
Flexibility		S	+	+
Robustness		S	-	S
Controllability		S	-	-
Prevalence		-	+	S
Σ+		0	2	1
Σ-		1	3	2
Σ_{Tot}		-1	-1	-1

Figure 3.8 Pugh matrix evaluating different types of linear actuators the controller would operate to control the vehicle's braking.

3.2.2 - Controller Concept Selection

The control signal outputs matrix in Figure 3.9 was used to determine the best type of signal transmission to use with the components chosen to operate the vehicle. As anticipated, the outcome indicated that either discrete or digital voltages would be preferable, due to their commonality and processing power. However, the actual chosen signal types were determined by the requirements of the frame's actuators.

Control Outputs (Signals)								
Criteria \ Concept	Discrete voltage	Digital voltage	Analog voltage	Analog current	Pulse width modulation	I2C/TWI	SPI	Serial
Speed	DATUM	S	S	S	-	-	-	-
Complexity		S	-	-	-	-	-	-
Flexibility		S	+	+	+	+	+	+
Robustness		S	-	S	-	-	-	-
Processing Power		S	-	-	-	-	-	-
Prevalence		+	+	S	+	+	S	+
Σ+		1	2	1	2	2	1	2
Σ-		0	3	2	4	4	4	4
Σ_{Tot}		1	-1	-1	-2	-2	-3	-2

Figure 3.9 Pugh Matrix evaluating different types of output signal the controller would send to our system's actuators and the vehicle motors.

The outcome of our communications matrix in Figure 3.10 indicated that radio signals were the optimal method of communication with our vehicle. It was decided that the primary function of the communications system would be to indicate to the vehicle when the user wanted to begin and end the test. More importantly it would serve as our method of transmitting an emergency

stop command. As a result of these needs, we determined that the distance and frequency at which the user could communicate with the vehicle was of major importance. Both the RC Radio and base station with radio satisfied these categories, however the base station with radio was chosen because it exceeded the RC radio‘s user interface. Later in the design process additional research showed the added complexity of the base station was too high, and the cost of useing an existing system was sufficiently low that we opted for a high quality long range model aircraft remote control.

Long Range Communications				
Concept / Criteria	RC Radio	Optical Control	Microwave (wifi/shortwave)	Base Station w/ radio
Portable	DATUM	-	S	S
Easy to Use		-	S	+
Long Range		-	-	+
Constant Signal (E-stop)		-	-	S
Obstruction Proof		-	-	S
Σ+		0	0	2
Σ-		5	3	0
Σ_{Tot}		-5	-3	2

Figure 3.10 Pugh matrix evaluating different types of long range communications that the test engineer could use to communicate with the vehicle.

The operating system style Pugh matrix in Figure 3.11 was one of most influential decisions for the microcontroller selection. The results of the matrix revealed that a hardware only or embedded control style would be preferable due primarily to their ease of design and low latency. Upon further consideration, embedded control was selected, since a hardware only approach would have only been practical if the system was chosen to be FPGA based.

Operating System Style				
Concept / Criteria	Embeded Control	Embeded Linux	RTOS	Hardware Only
Low Latency	DATUM	-	S	+
Easy Maintenance		-	-	-
High adaptability		+	+	S
Fail Safe		-	S	+
Ease Of Design		-	-	S
Σ+		1	1	2
Σ-		4	2	1
Σ_{Tot}		-3	-1	1

Figure 3.11 Pugh matrix evaluating different styles of operating system that could be embedded in our controller.

The outcome of the processor style Pugh matrix shown in Figure 3.12, rivaled the vehicle location method as the function that most heavily influenced our overall project direction. The results from the processor matrix revealed that there were three feasible processor styles that could form the bedrock of our control system: a Harvard based microcontroller, distributed control, and FPGA (field-programmable gate array). These three options stood out primarily due to their low latency, and ability to implement a fail-safe program, both of which were crucial to our system operations. All three types were considered in the final design matrix.

Processor Style							
Criteria \ Concept	Harvard Based Microcontroller	Multicore	Distributed Control	Single CPU	Full Motherboard	FPGA	ASIC
Low Latency	DATUM	-	S	-	S	+	+
Easy Maintenance		-	S	-	S	S	-
High adaptability		+	+	+	+	+	-
Fail Safe		-	+	S	-	S	+
Ease Of Design		-	-	S	-	-	-
Σ+		1	2	1	1	2	2
Σ-		4	1	2	2	1	3
Σ_{Tot}		-3	1	-1	-1	1	-1

Figure 3.12 Pugh matrix evaluating different types of processors that our control system would be based on.

The results of our data upload and download pugh matrix shown in Figure 3.13, reinforced the decision to select a USB type data storage. USB was chosen as the primary method of data storage and retrieval in order to meet the power independent memory specification. This specification was chosen to increase the system's convenience. Since the removable type of USB further supported this philosophy it was selected as the final choice of data storage.

Program Upload/Data Download				
Criteria \ Concept	USB (non-removable)	USB (removable)	Radio	Ethernet or IP
Easy to Use	DATUM	+	-	-
Two-way Communication		S	S	S
Self Powering		S	-	S
Σ+		1	0	0
Σ-		0	2	1
Σ_{Tot}		1	-2	-1

Figure 3.13 Pugh matrix evaluating different methods to collect and transfer any valuable data.

The list of potential designs for the final design matrix shown in Figure 3.14, was formed by listing every possible combination of the system's two most influential functions, locate itself and processor style. The concepts in this list were then compared to a weighted list of criteria that needed to be satisfied. The criteria chosen for our matrix was based on the specifications listed in the project's QFD analysis. From this list control feedback latency was given the highest weight factor do to its importance in our system's basic functionality and data accuracy. Positional accuracy was also weighed highly, since the test vehicle's ability to follow a straight path was deemed to be critical to successfully test Daimler's autonomous vehicles systems. E-stop signal latency was also highly ranked due to its influence in safely operating the test vehicle. The outcome of the matrix revealed that a system which employed all three sensor types, controlled by a microcontroller was the best option. These results confirmed our suspicion this type of system would be the best option due to its high performance across all noteworthy criteria, specifically in positional and straight line accuracy. Although the choice of using a microcontroller somewhat sacrificed our signal and feedback latency compared to FPGA or distributed control, we believed it would excel in maintainability, as well as being more approachable for future students working on our system.

Final Design Chioce										
Criteria	Controllable Speed	Positional Accuracy	Straight Line Accuracy	E-stop Signal Latency	Setup Time	Intermediate Setup Time	Control Loop Feedback Latency	Overall Control System Cost	Maintainability	Weighted Total
Concept	0.05	0.15	0.1	0.15	0.05	0.1	0.2	0.1	0.1	1
Control System using RPM sensor and Microcontroller	3	1	0	3	5	5	4	5	5	3.3
Control System using RPM sensor and Distributed Control	3	1	0	4	5	4	5	3	3	3.15
Control System using RPM sensor and FPGA	3	1	0	5	5	5	5	3	1	3.2
Control System using GPS receiver and Microcontroller	1	3	3	3	2	4	2	4	5	3.05
Control System using GPS receiver and Distributed Control	1	3	3	4	2	3	3	2	2	2.8
Control System using GPS receiver and FPGA	1	3	3	5	2	4	3	2	1	2.95
Control System using IMU and Microcontroller	2	2	4	3	3	4	3	4	5	3.3
Control System using IMU and Distributed Control	2	2	4	4	3	3	4	2	2	3.05
Control System using IMU and FPGA	2	2	4	5	3	4	4	2	1	3.2
Control System using all previously listed sensor types and Microcontroller	4	5	5	3	1	3	3	4	4	3.65
Control System using all previously listed sensor types and Distributed Control	4	5	5	4	1	2	4	1	2	3.4
Control System using all previously listed sensor types and FPGA	5	5	5	5	1	3	4	1	1	3.6

Figure 3.14 Final design matrix evaluating the best overall combination of sensors and control system layouts.

In order to begin testing of our designs as soon as possible we developed an additional design matrix, shown in Figure 3.15, to select an appropriate microcontroller and development package. Our highest ranking option for controller is the STM32 Nucleo-64 line of development boards. These boards have good support because they are compatible with Arduino shields developed for the Arduino Uno (Appendix H) and STM has developed their own versions of shields for these boards. The Nucleo-64 boards also have a good amount of processing power and all the peripherals we found important (Appendix H). The peripherals which we weighted

the highest were the timers, analog to digital converters (ADC), hardware floating point units (FPU), and communications protocols. The Nucleo-64 boards ranked the highest in almost all of those categories.

Final Design Chioce													
Criteria	Frequency	Language support	Support	OS?	Instruct. Bit Size	Multicore	Timers	Interrupts	ADC (Built in)	FPU	Comms. Protocol	DAC	Weighted Total
Concept	0.08	0.13	0.13	0.05	0.02	0.05	0.1	0.07	0.11	0.1	0.1	0.06	1
Arduino (AVR based)	1	3	5	2	1	1	3	4	3	1	3	1	2.66
Arduino (ARM based)	2	3	5	4	3	1	3	4	4	1	3	3	3.11
Raspberry PI	5	5	5	5	5	3	1	1	2	5	4	1	3.55
Beagleboard	5	5	4	5	5	3	1	1	2	5	3	1	3.32
STM32 Nucleo/Discovery	3	4	3	4	3	1	5	5	5	5	4	5	4.06
TI Launchpad	2	4	3	3	3	1	4	5	4	3	4	5	3.52
Parallax Propeller	1	2	2	3	3	5	1	2	2	1	1	1	1.78
Intel Gallieo	4	5	2	5	3	1	1	1	3	5	4	1	3.05
WiPy	3	2	3	2	3	3	3	4	4	5	5	1	3.28
LoPy	3	2	3	2	3	3	3	4	4	5	5	1	3.28
PyBoard	3	3	3	3	3	1	5	5	5	5	4	5	3.88
General ARM processor (no dev board)	3	3	2	4	3	1	5	5	5	5	4	5	3.8
General PIC processor (no dev board)	1	2	2	2	1	1	1	5	2	1	2	2	1.86
ESP32/ESP8266 (no dev board)	3	3	3	3	3	3	3	4	4	4	4	1	3.26

Figure 3.15 Design matrix evaluating the best overall microcontrollers to control our system.

3.3 - Description of Lead Concept

Based on the idea generation, Pugh matrices, and weighted decision matrices we produced (as shown in sections 3.1 and 3.2) our lead concept was as follows:

- STM Nucleo-64 (microcontroller) based central processing unit
  - This component will provide the primary processing power for our system. It has sufficient I/O capabilities and processing power and a good support community.
- GPS, IMU, and motor encoder based control system
  - These three sensors together we expect will provide sufficient positional, velocity and acceleration data to maintain course even at high speeds.
- Single threaded embedded code
  - Due to the need for low latency algorithms we have opted to avoid the use of any abstracting operating system. The program will run as a single thread with short interrupts only.
- Removable USB storage for test protocol upload and sensor data download

    - As a simple method of transferring data between the vehicle and the user we have selected a removable storage medium which can be loaded with test waypoints and from which test data can later be retrieved.
- Focus on controlling electromagnetic actuators
    - For ease and accuracy of control we recommend the use of standard electric motors and actuators. Though this is ultimately not our decision we will plan for this until informed otherwise.
- Base station radio communication
    - To allow easy feedback and control to and from the vehicle during a test we have opted for minimal user control using a radio base station. This system will be based on a minimal computer interface connected to a radio transceiver. E-stop and some other minor controls will be included but the primary purpose is to provide feedback during a test.

The STM Nucleo-64 board was used as the primary processing unit for the control system and data acquisition unit. The Nucleo board handles all control algorithm processing, interfacing with sensors, sending control outputs to any actuator driver boards, and saving data to a memory storage device. The main sensors in the system are a GPS, IMU, and motor encoder. We planned on implementing sensor fusion algorithms (such as a Kalman filter) to get our position, velocity, or acceleration data from these sensors when possible. The code written for the system was written without utilizing a real time operating system. The USB removable storage was eventually replaced with and SD card and reader and is used for both uploading the test protocol code and saving the critical sensor data for test evaluation. The removable storage utilises a simple filesystem to differentiate data files from testing protocols. The hierarchy of signals was be used during our critical design phase to help with determining the specific sensor signals for use with our system. The hierarchy also helped us with determining our recommendations to other test vehicle groups regarding components or actuators. Radio communication is primarily used to have the test vehicle initiate the current loaded test protocol and as a manual emergency stop by the operator.

3.3.1 - Lead Concept Vs. Engineering Specifications

Many of our specifications depend on how quickly we can receive data from our sensors and process it. Specifications that depend on this latency are our max controllable speed, positional accuracy, straight line accuracy, and a few others. These specifications contributed to our sensor feedback latency specification of 28 milliseconds. To ensure that we would be able to meet this latency specification we did some preliminary calculations regarding the time required by the processor to calculate a PID (Proportional, Integral, Derivative) control algorithm and the update frequency of an IMU, GPS, and motor encoders.

To calculate the time required by the processor to calculate a PID control algorithm some assumptions were made. First, the velocity form of the PID algorithm [18] was assumed and the number of operations needed to process the algorithm were estimated. The estimated number

of arithmetic operations was 16 and the number of read or write operations was 18. Next, the number of clock cycles for the two types of operations were estimated assuming an ARM Cortex M4 based microcontroller. The number of clock cycles necessary for an arithmetic operation was determined to be 12 and read/write operation was determined to be 5 [19]. Next, the number of clock cycles needed for the PID calculation was determined to be approximately 280. We assumed that the clock speed of the microcontroller was 32 MHz because that is the lowest clock speed available out of the STM Nucleo-64 boards. We determined that the processing time necessary for the controller to calculate the PID algorithm was 8.8 microseconds which is much less than the 28 millisecond latency specification.

To determine the IMU sensor latency we used the specifications from the Bosch BNO055 IMU [20]. We based the latency on this sensor because it has an integrated microcontroller (ARM M0+) which performs a sensor fusion algorithm which means that we can get positional data (Euler angles or quaternions) directly from the sensor. The BNO055 latency can also be used as a rough estimate for the latency of other IMU sensors in which we implemented the sensor fusion algorithm on our microcontroller. The latency of the BNO055 is approximately 10 milliseconds which is less than the 28 millisecond latency specification.

To determine the GPS latency we looked at various GPS modules available. We found that most GPS modules update in a range of 50 milliseconds to 1 second. The latency of the GPS will be too low to be used by itself for positioning the test vehicle but it can be used in conjunction with the IMU. The GPS provides absolute position feedback which can be used to correct the IMU if the absolute position begins to drift. Since the GPS is not used as the primary navigational sensor then the high latency of the measurements does not greatly affect the positional accuracy.

To determine the motor encoder latency we had to make a few assumptions. First, we assumed that the encoder readings would be handled by an interrupt service routine on the microcontroller which takes approximately 12 clock cycles to start [19]. Next, we assumed that the amount of processing required in the interrupt service routine would take approximately 50 clock cycles. The last assumption we made was that we were using a medium resolution magnetic encoder (64 counts per revolution). With these assumptions we determined that it would take 1.4 microseconds to process the shaft turning one degree. While the result from this calculation is tough to use, it does show that the processing time necessary is much less than the 28 millisecond latency.

3.3.2 - Risks and Challenges

The chosen design has a few potentially dangerous failure methods. Since the system relies on GPS, a failure in this system could lead to dramatic and unexpected behavior such as the vehicle traveling rapidly in the wrong direction. Another possible source of failure is the use of a single CPU. If this component reaches an infinite loop or encounters some other unexpected

error it could leave the motor controllers in an on state with no limiting input. This could again cause the vehicle to drive in unexpected directions or stop suddenly. Please note: this exact event has been observed when software was not fully checked before uploading. To avoid such events in the future all programs should be thoroughly tested to ensure latency under all logical paths is within bounds.

The most difficult challenges of this design are to ensure we are getting sufficient sensor data to make informed decisions. Since no single sensor has both accuracy and refresh rate necessary to guide the vehicle by itself. We have to rely on sensor fusion algorithms to ensure the accurate position, velocity, and acceleration. Considering the complexity of some of these algorithms ensuring the control loop will never fail or reach an infinite loop is another important challenge.

4 - Final Design Description

4.1 - Overall Design Summary

The SLONav autonomous target control system is based on a single embedded microcontroller. The system actuates two brushless DC motors via electronic speed controllers. The microcontroller interfaces with an H-Bridge circuit to operate a linear actuator controlled hydraulic brake. To avoid severe electronic noise from high power systems for the brushless motors, the electronic speed controllers provide opto-isolation between the microcontroller input and the motor output. Power for the braking actuator and emergency stop release servo is provided by a LiPo battery within the control system enclosure. The microcontroller operates off of a 9V battery supply.

To gather data about the motion of the vehicle, the system utilizes an IMU, a GPS, and shaft encoders. The IMU provides relative acceleration and both absolute and relative orientation data, the GPS module provides absolute position and time data, and the pair of shaft encoders provide real time velocity approximations. The sensor data provides the position, velocity, acceleration, and heading of the vehicle which is stored on a microSD card for later analysis. The operator interfaces with the system using a radio controller that provides inputs for throttle, brake, emergency stop, and mode selection.

A map of waypoints and velocity setpoints is loadable via SD card allowing rapid and safe modification of test parameters for autonomous operation. Under autonomous operation the system controls the heading and acceleration of the vehicle using proportional-integral-derivative (PID) controllers to compensate for disturbances and produce the desired performance.

4.2 - Detailed Design Description

4.2.1 - Microcontroller

Our final microcontroller selection is the STM32 Nucleo. This microcontroller provides the processing speed, power output, hardware based signal acceleration, and number of GPIO pins necessary to control this system. The Nucleo is powered by a 9V supply which is separate from the other power systems. The Nucleo has the capacity to supply 5V and 3.3V power to the sensors used in the system.

Hardware accelerated signal processing built into the Nucleo will be used to interface with components via numerous common signal protocols without slowing or interrupting program flow. Our design calls for communications over SPI, I2C, and UART simultaneously which makes the hardware acceleration desirable. Additionally the Nucleo has multiple hardware timers which were used to set the control loop latency and schedule other tasks.

4.2.2 - Sensor Feedback System

The sensor feedback system allows for monitoring all of the crucial motion parameters need to autonomously control the vehicle. Due to the selected motor controller’s limited programming capacity; the central microcontroller handles almost all of sensor input directly. Sensor data is sampled and logged for analysis as well as used for autonomous operation.

Absolute position and time are given by the GPS receiver module. This allows the system to update its position at a rate of 10Hz. Current physical and simulated testing shows this is sufficient at low speed however ongoing modeling and testing may prove that a 20Hz GPS or Kalman filter is needed later on. The GPS receiver communicates via UART, has built in data logging and and optional independent power supply.

Absolute orientation and acceleration of the vehicle is provided by the IMU. Absolute orientation data is based on a built in 3 axis magnetometer, 3 axis acceleration, and 3 axis angular velocity which is filtered by an on chip processor. Acceleration data is based on a three axis accelerometer with updates at 100 Hz. This IMU has sufficient resolution to achieve our goal of 0.25 m/s^2 increments. In conjunction with absolute values from that GPS our simulations show this sensor is sufficient to achieve the 1.5m positional accuracy required by specification.

Vehicle velocity is provided by a pair of shaft encoders mounted to the motor shafts. The refresh rate is dependent on the speed of the vehicle. These sensors are monitored using pin change hardware interrupts on the Nucleo. The velocity provided by the encoders is in pulses per update rate. Calculating the linear velocity of the vehicle is done by using the encoder pulses per revolution, transmission gearing ratio, and wheel radius These sensors can be used as a continuous safety check to show the motors are behaving as expected.

Feedback from the braking linear actuator is provided by a built in linear potentiometer. This data is sampled by the Nucleo analog to digital converter (ADC). The potentiometer is used to determine the position of the linear actuator for providing variable braking. We have not mapped the linearity of the braking actuator however preliminary tests suggest it is capable of providing the 0.25 m/s^2 braking increments required by our specifications.

Also considered as external sensor inputs are the remote control inputs from the radio receiver. The radio receiver provides user control to the system. Using the radio controller the user may start or stop the autonomous operation, engage the emergency stop, and take direct control of the vehicle. The E-Stop will also engage automatically when the radio is out of range. The radio receiver has a refresh rate of approximately 50 Hz.

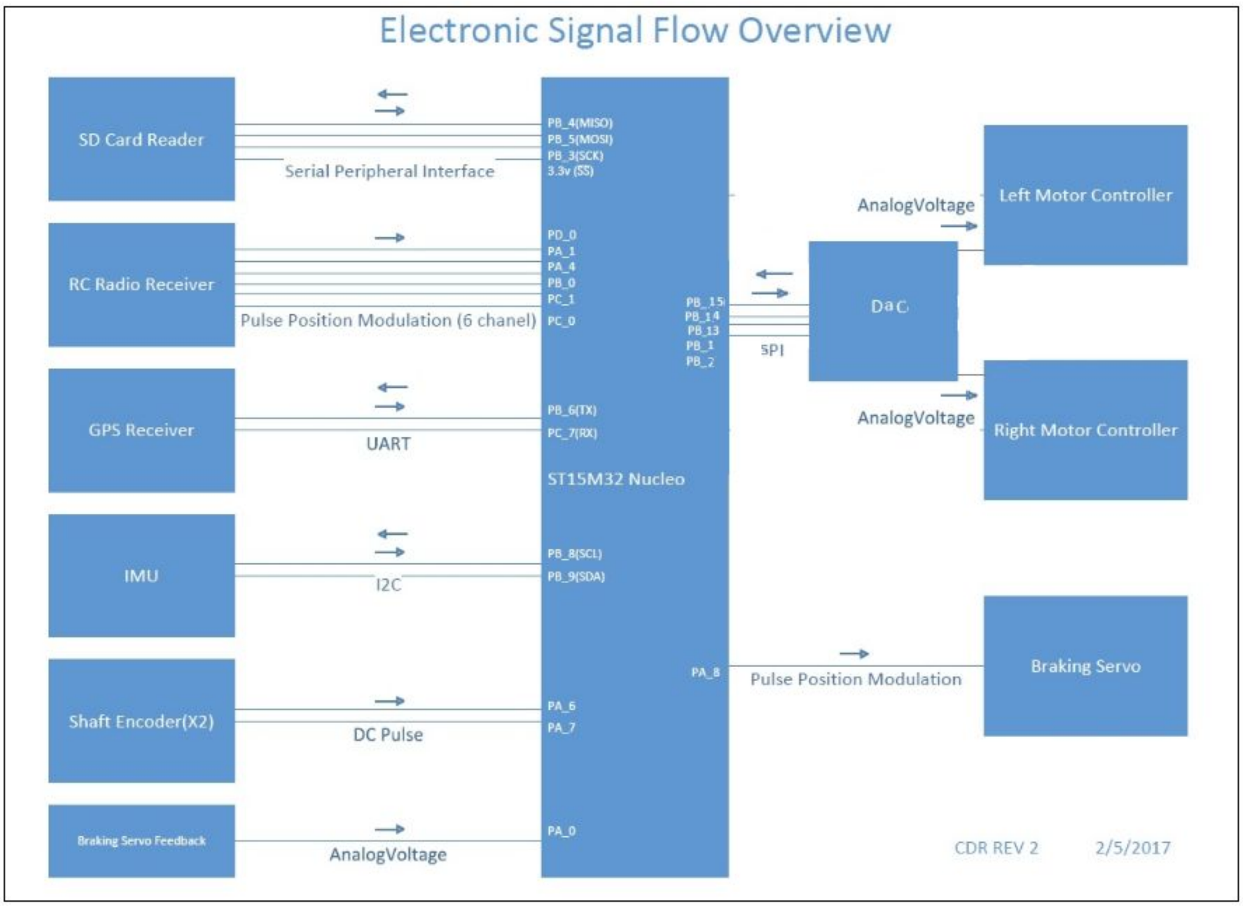


Figure 4.1 Signal flow diagram.

As shown in Figure 4.1, each sensor utilizes a separate signal protocol. This was the result of the sensors we chose and adds some wiring complexity to the controls system. However the STM32 Nucleo has sufficient pins and hardware acceleration to manage all these sensors simultaneously without impeding program flow. Utilizing a separate accelerator for each sensor also reduces the chance of bus contention.

4.2.3 - Control Systems

The vehicle will have two main control systems, one that controls the steering of the car and another that controls the acceleration of the vehicle. The steering control system is used to keep the vehicle on a straight line path for the length of the test being conducted. The acceleration control system will be used to reach the velocities desired at points on the track specified by the user using constant acceleration or deceleration between the points. The main control mechanism that will be be used for the steering control is a proportional-integral-derivative (PID) controller and the acceleration control will utilize a PID controller.

4.2.3.1 - Steering Control

The steering control system will employ a follow the carrot path tracking approach for maintaining a straight line path. The follow the carrot method utilizes “carrot points” which are points along the path that are ahead of the vehicle based on chosen “look ahead” distance. The angle between the vehicle and the carrot point determines our desired vehicle heading which we will compare with the heading feedback from our IMU sensor. A basic illustration of this method, which comes from a thesis on skid steering control [21], can be seen in Figure 4.2.

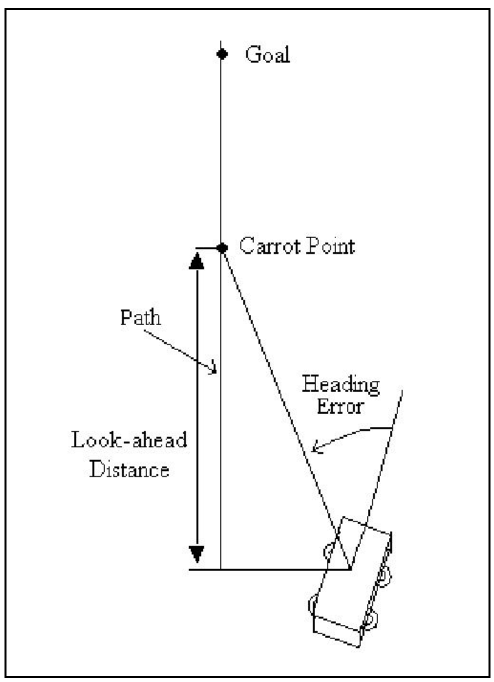


Figure 4.2 Illustration of follow the carrot method for path tracking.

The heading error found by the follow the carrot method will be used as the input of a PID controller to produce a steering adjustment signal. The steering adjustment signal is added to the desired velocity signal for one motor and subtracted from the velocity control signal of the other motor to produce the difference in motor velocities that will steer the vehicle. The sign of

the heading error also determines which motor increases velocity and which motor decreases velocity.

To analyze our steering control system we developed a model of the vehicle dynamics and the motors. This model was translated into Simulink to conduct simulations of the different PID controller types to determine which parts of the PID were essential and the approximate gains of those coefficients. The Simulink model contains three major subsystems which compartmentalize parts of the system so that the control loop is easier to identify. The major subsystems are the motor control and the vehicle dynamics. The overall view of the Simulink model is given by Figure 4.3.

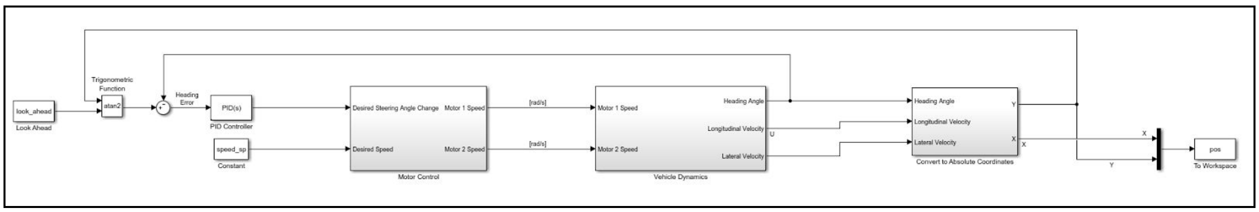


Figure 4.3 Steering control Simulink model overview. This model shows the subsystems, the input signals, feedback loop, and PID controller.

The motors were modeled as independent first order systems because it introduces some delay to the response of the motors which compensates for the inertia of the rotor. The motor control block of our Simulink model can be seen in Figure 4.4.

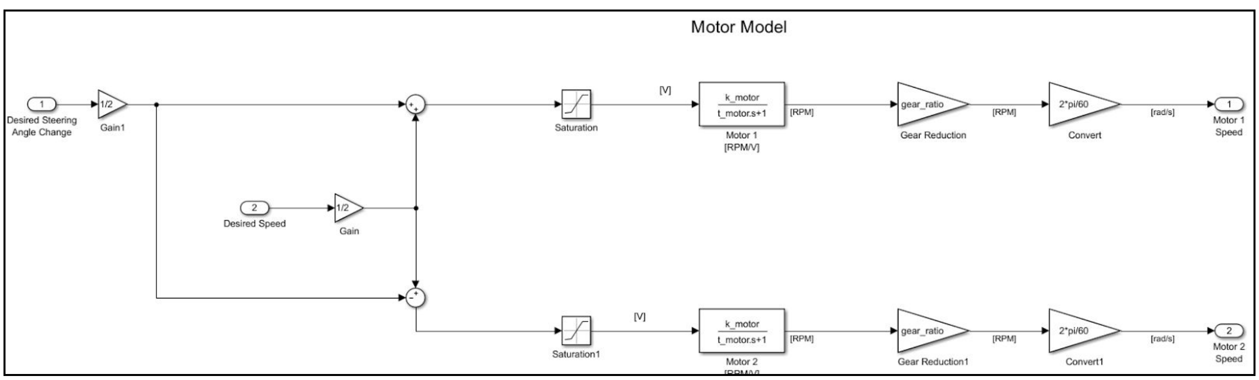


Figure 4.4 Simulink subsystem that models the two brushless motors which drive the vehicle. The values of the variables can be found in Table 5.1 and in the Matlab script (Appendix F). Saturation blocks were included to limit the output of the motors to the maximum voltage available from the batteries.

Table 4.1 Summary of motor model variables. Motor gain and gear ratio are based on values given to us by the frame design team and the motor time constant was an educated guess since the specifications were not available.

Motor Model Variable	Value	Units
Motor Gain (k_motor)	167	RPM/V
Motor Time Constant (t_motor)	0.025	1/sec
Gear Ratio (gear_ratio)	0.2439	RPM/RPM

The vehicle dynamics of the vehicle was modeled using a skid steering model of the vehicle. Skid steering is a method of where each side of the vehicle has wheels which are driven at the same rate but the two sides are independently controlled. This method of steering is the style of steering that vehicles with treads or rigid frames tend to use. We chose to use this model because it was the closest model we could find to the design of the vehicle. The actual vehicle has two independent motors driving the rear wheels and a solid front axle. The skid steering model we used was from a paper by Zhang Yu from the Intelligent Vehicle Symposium 2013 [22]. The paper derives a model of the lateral dynamics of a skid steered vehicle which assumes that the velocity of the center of gravity is constant, the tire properties are in the linear region, the center of gravity is close to the ground, and the air resistance and gyroscopic effects are negligible. The equations derived are the following,

$$m(\dot{v} + u\omega) = -\frac{2}{u}(aK_{\alpha f} - bK_{\alpha r})\omega - \frac{2}{u}(K_{\alpha f} + K_{\alpha r})v$$

$$I_z\dot{\omega} = \frac{1}{u}\left[\frac{B^2}{2}(K_{xf} + K_{xr}) + 2(a^2K_{\alpha f} + b^2K_{\alpha f})\right]\omega - \frac{2}{u}(aK_{\alpha f} - b\,K_{\alpha f})v + \frac{B}{2}(K_{xf} + K_{xr})\frac{\Delta u}{u}\ .$$

Illustrations of the system are provided by Figure 4.5 and Figure 4.6.

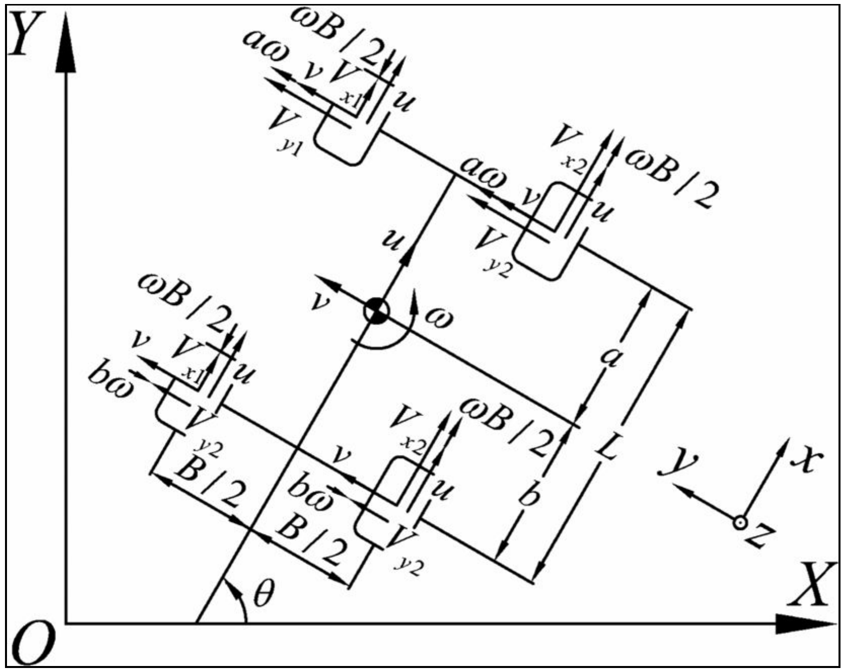


Figure 4.5 Illustration of the kinematic diagram for the skid steering model [22].

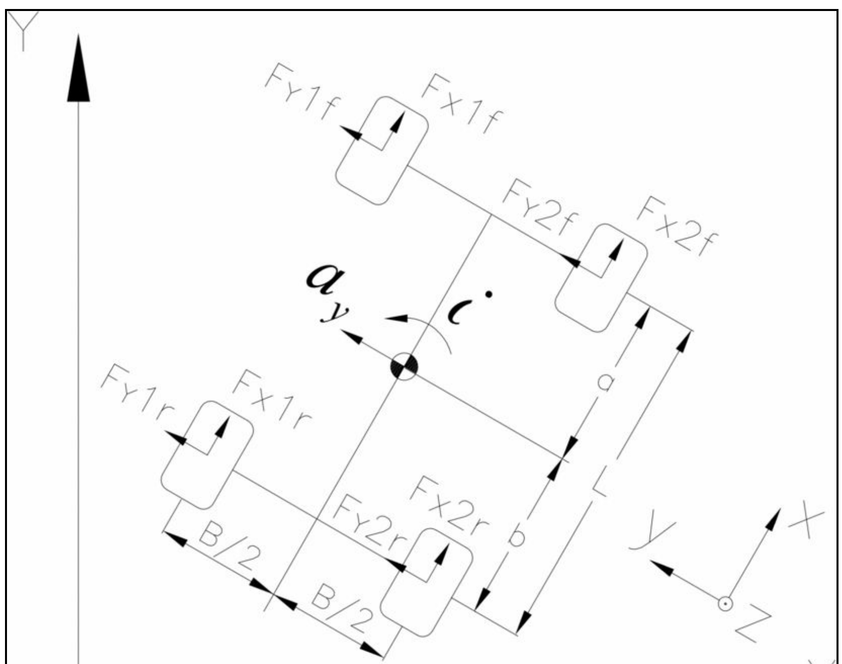


Figure 4.6 Illustration of the kinetic diagram for the skid steering model [22].

The K_α and K_x variables given in the equations represent the cornering stiffness and longitudinal stiffness of the tires. Since the frame team is planning on using the same tires for all the wheels we were able to simplify the model equations slightly, so the equations we used in the Simulink model were the following,

$$\dot{v} = -\frac{2K_\alpha}{um}(a - b)\omega - \frac{4K_\alpha v}{u} - u\omega$$

$$\dot{\omega} = \frac{1}{I_z u}[B^2 K_x + 2K_\alpha(a^2 + b^2)]\omega - \frac{2K\alpha}{I_z u}(a - b)v + \frac{B^2 K_x}{I_z}\frac{\Delta u}{u}\ .$$

These equations were used to develop the vehicle dynamics subsystem in the Simulink model which can be seen in Figure 4.7.

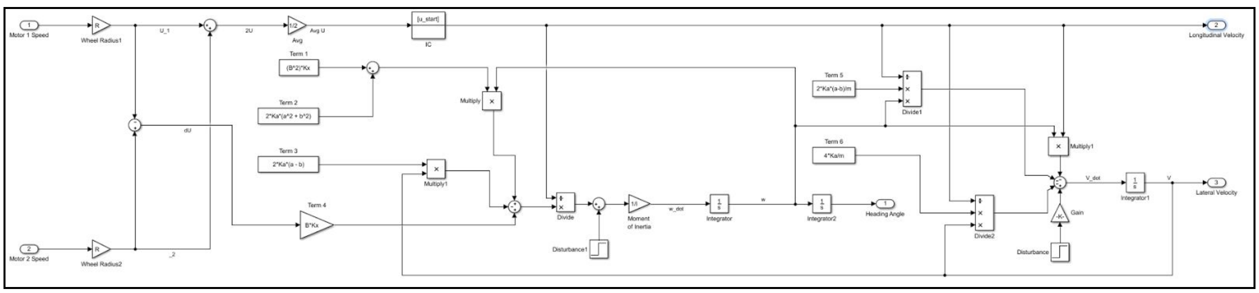


Figure 4.7 Simulink subsystem that models the skid steering vehicle dynamics. The values of the variables can be found in Table 4.2 and in the Matlab script (Appendix F).

Table 4.2 Summary of vehicle model variables. The track width, length, moment of inertia, mass, and radius of tire were estimates give to us by the frame design team. The center of gravity distances were assumed to be slightly skewed towards the motor since the batteries will likely be closer to the motors. The cornering stiffness coefficient was estimated by using 15% of the load on the vehicle (300 lbs evenly distributed per degree) and the longitudinal slip stiffness coefficient was assumed to be the same.

Vehicle Model Variable	Value	Units
Track Width (B)	5	ft
Length (L)	7	ft
Distance between solid axle and center of gravity (a)	3.75	ft
Distance between motor axles and center of gravity (b)	3.25	ft
Mass of vehicle (m)	9.31	lb_m
Moment of inertia (I)	1458	lb/ft^2
Radius of tire (R)	0.33	ft
Longitudinal slip stiffness (Kx)	2150	lb
Cornering stiffness (Ka)	2150	lb/rad

With the motor and vehicle dynamics subsystems we were able to simulate the response of the system by adding a disturbance force in the lateral direction and plot the path of the vehicle. After running a few simulations it became clear that this system would not be stable without some derivative control so we decided to tune a PID controller since we would need some integral control to compensate for steady state error. An example of one of the tuned PID responses is given by Figure 4.8.

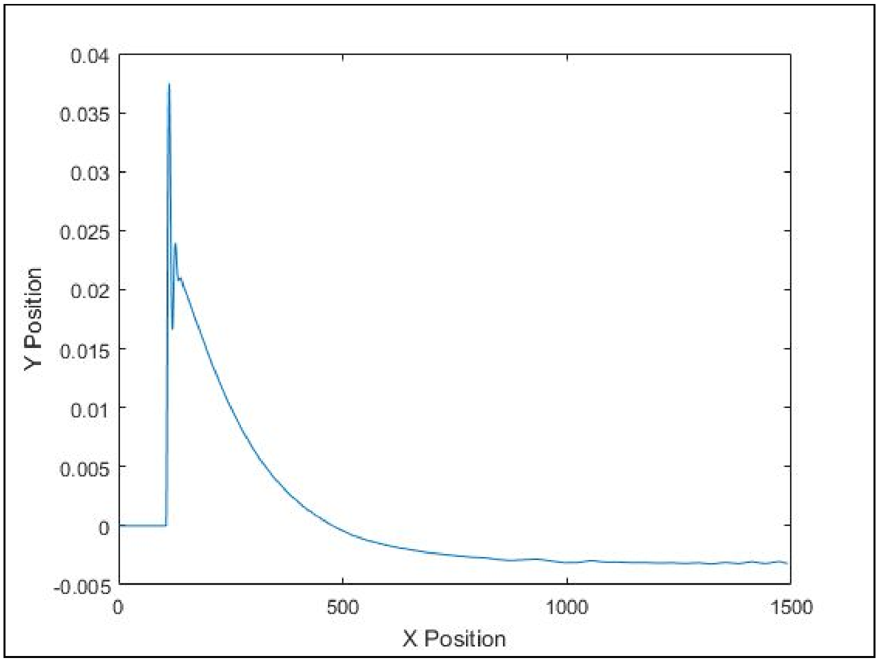


Figure 4.8 Response of the model to a lateral force step disturbance of 30 lb. The PID gains are a proportional gain of 1, integral gain of 0.15, and derivative gain of 0.2. The PID is calculated using the standard ideal form.

While the simulation we created proves the feasibility of the steering control scheme, there are some assumptions that were made which could have a significant effect on the response of the final system. The simulation makes the assumption that the wheels do maintain contact with the ground at all times. This may not be the case if large steering angles are required because either the front or driven wheels will likely lose traction. Another issue will be the resistance to turning because of the solid front axle which will need to take a torsional load to allow for the speed difference between the wheels when turning. Further testing was done on this control scheme using the scale model we built, discussed in Section 6.1, to validate it and make modifications as necessary.

4.2.3.2 - Acceleration Control

The goal of the acceleration control system is to achieve a constant acceleration and deceleration rate of the vehicle. The control system will have to actuate two motors and a linear actuator connected to a hydraulic brake. Since the motors will be controlled using an electronic speed control (ESC) our control system will need to generate an speed input for the ESC. To accomplish this we will implemented a PID controller that will operates on acceleration feedback provided by the IMU.

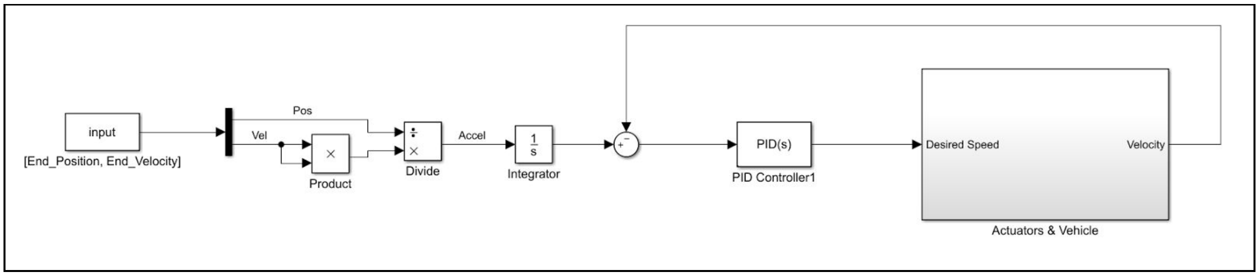


Figure 4.9 Illustration of the acceleration control loop.

There will be three cases that the system will have to deal with which are acceleration, constant velocity, and deceleration. The acceleration case will be actuated by evenly splitting the controller output between the two motors. The constant velocity case will require some braking to respond to disturbances but the motor controller can provide some braking which should be enough for the constant velocity case. The deceleration case will require actuating the braking system as well as a decrease in the motor speed. The control output will be split amongst the motors and braking actuation.

There are a few possible problems with this design which may lead to modification of the scheme. The frame design team's proposition of a using a linear actuator to engage a hydraulic brake will have a significant dead time associated with it. This will make it difficult to work in tandem with the motor actuation for the deceleration case and may require some predictive control tools, such as a feedforward loop, which will help compensate for the dead time. This issue may be encountered in the acceleration case because of the delay resulting from the inertia of the motors when changing velocity. This delay could lead to the vehicle not quite reaching the proper velocity at the next trigger point and could be compensated for with some predictive control as well. Lastly, accelerometers inherently provide noisy data which could lead to erratic behavior from the controller if not filtered properly.

As with the steering control, we performed nearly all testing and validation of this control scheme using the scale model.

4.2.4 - Final Enclosure

To ensure that our control system would be able to perform without hinderance, the physical enclosure layout of our final design had several requirements. Most importantly our enclosure had to adequately protect all of our core electrical components during regular testing. We did not design the enclosure for direct impact since, based on preliminary research, it would over complicate the design, dramatically increase the price, and limit the number of routing options provided to the control system.

Our enclosure provides the user with easy access to all of our components for maintenance and calibration purposes. We restricted our list of options to enclosures that could be purchased off the shelf, and later modified to meet our needs. This decision was made to limit the amount of

time spent on fabrication and increase control system development time. Finally, our system needed to be relatively inexpensive, since a large portion of our budget had already been committed to the control components.

We were able to meet almost all of our requirements, with a latched steel electrical enclosure with knockouts, from McMaster-Carr shown in Figure. 4.10. The enclosure was 12’’ x 12’’ x 4’’ giving us ample room to fit all of our protected components as well as fitting within the frame teams maximum size requirements. An additional feature of the enclosure selected was that it latched shut to ensure that it will not open while the vehicle is moving.

We also considered a polycarbonate enclosure with a viewing window but it was decided that the higher cost did not warrant the slight improvement in user interaction. It should be noted that our chosen enclosure is larger than the dimensions originally listed in the specifications, however, we did not see this as an issue as that specification was listed exclusively to ensure we fit within the frame.

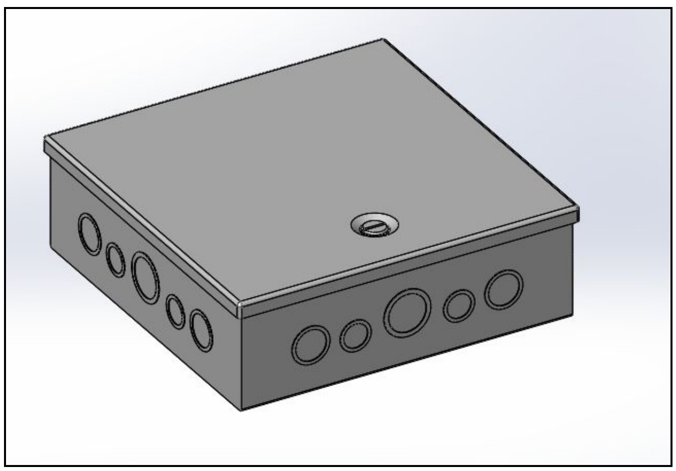


Figure 4.10 CAD model of selected electrical enclosure.

4.2.5 Component Mounting Plate

For the internal layout of Inside of our enclosure, we wanted a design that would give all of our components easy access to the enclosure breakouts as well as maximizing the number of options for wiring routes throughout the enclosure. To do this we selected a layout which placed all of our components on a raised mounting plate shown in Figure 4.11. This configuration ensured that we would have a high level of flexibility on our component placement as well as easy wiring through the knockouts which were at a center height of 4cm above the base of the enclosure. Additionally, we designed the mounting plate to be fully removable with the use of a few hex keys to improve its transportability as well as the ease of maintenance.

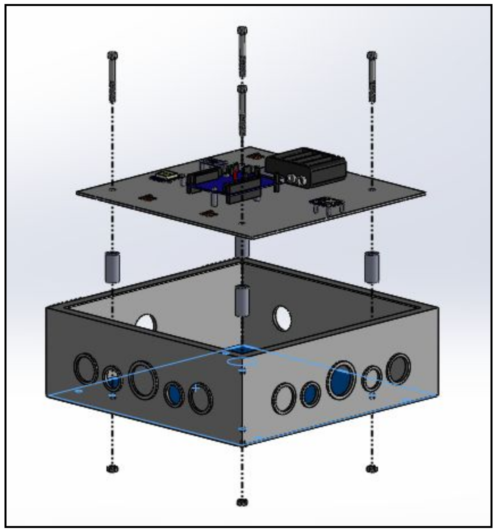


Figure 4.11 Exploded view of full enclosure assembly.

We also wanted a design that minimized the amount of machining that needed to be done. To achieve this specification, we limited our material options to those that could be fabricated using the laser cutter located in the Mustang 60 machine shop on campus. Both, aluminum and wood were considered, but we chose a 12" x 12" x 7/64" Acetal plastic sheets to minimize the possibility of an electrical arc forming to the board, as well as it's easy manufacturing capabilities. It should be noted that the board size will be cut down, using a table saw, to a size of 10.62'' x 10.75'' x 7/64'' to ensure that the board can be easily removed pats the lip of the enclosure.

The final component layout on the board was chosen by our team to minimize the distance that wires had to travel within the enclosure. To accomplish this we placed the Nucleo microcontroller near the center of the platform with open paths to each of our sensors and battery, shown in Figure 4.12. Each of the individual components locations were chosen to place them near the closest breakout to try to limit the complexity of the final system wiring. Additionally the battery used to power our control system was to be placed within the enclosure near the front, held in place by a velcro strap and a small fabricated plastic wedge.

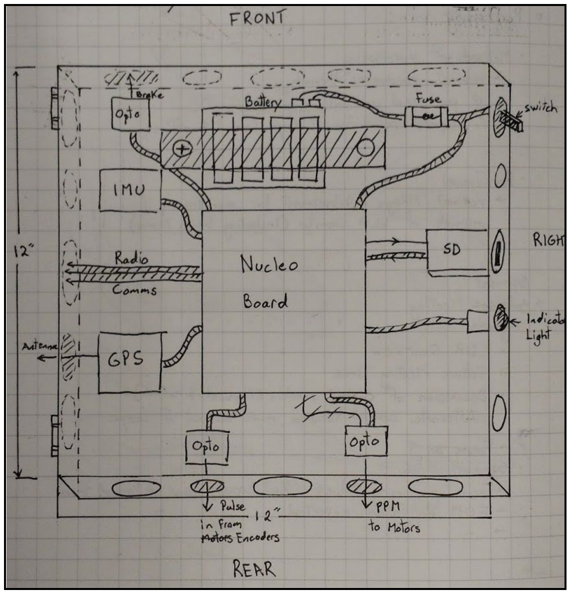


Figure 4.12 Final component layout. Nucleo board (center), GPS (lower left), IMU (upper right, SD Card (middle right), Battery (top center), Iso Optilators (top right and bottom).

The location of our SD Card breakout was of high importance to us as we wanted to be placed in a way that the user could easily load the micro SD card into the enclosure without having to open the entire enclosure. Our solution to this was to use one of the enclosure’s knockouts as an SD card port shown in Figure 4.13, where the user could easily load the test plans before each vehicle run. The final construction did not implement this feature, instead opting to place the SD card within the enclosure without utilising the knockout.

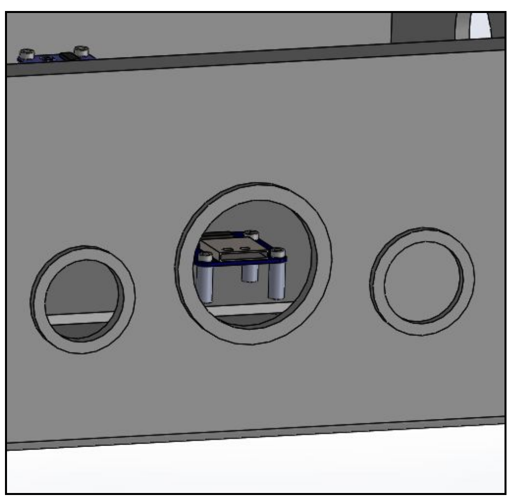


Figure 4.13 MicroSD card knockout.

4.3 - Cost Analysis

According to our updated Bill of Materials. The total cost for the controls system, associated wiring, enclosure and safety features totals $1406. This estimate is slightly over our initial budget of $1200 . The highest cost items are the high power systems. The two motor controllers at $638 combined are the most significant cost followed by the radio controller at $179 and the polarity protection for the power systems at $102. There were a few low cost items that were purchased and not used in the final design. See Appendix C for the full detailed Bill of Materials.

4.4 - Physical System Wiring

The electrical system is separated into two discrete blocks. To avoid noise from the large motors and controllers we initially planned to use optical isolator breakout boards to isolate the main power system from the control system. When implementing the system we discovered the electronic speed controllers already had these built in, so the isolation boards were unnecessary.

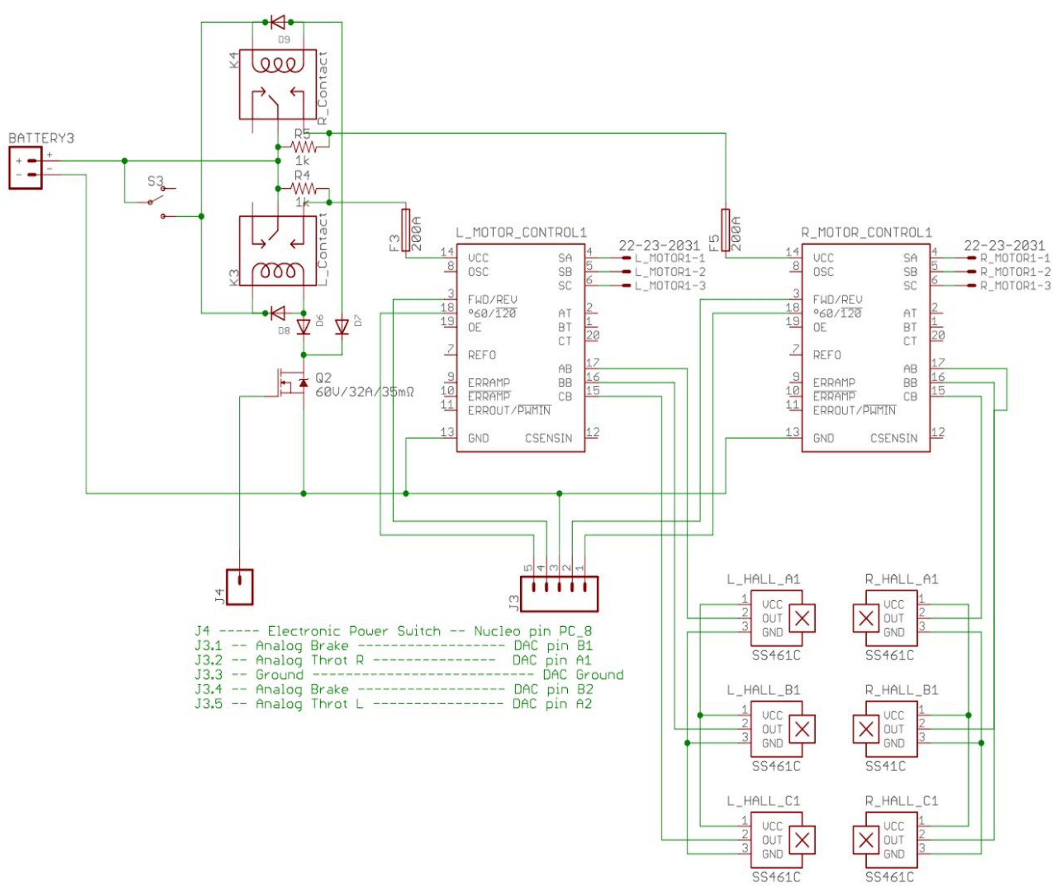


Figure 4.14 Motor power schematic.

The main power system, as shown in Figure 4.14 refers to those electrical systems which are directly related to powering or controlling the two main motors. This system is composed of two brushless DC electronic speed controllers, circuit protection, main batteries, and controller interface connector. The main power system is wired with 6awg wire and 6awg battery lugs between the main batteries and the motor controllers. A 400A thermal breaker ensures that the system will not remain active after a major short. During implementation the thermal breaker was replaced with two 200A main contactors, as suggested by the specification sheet, which also allowed for microcontroller to enable or disable power. Additional 200A inline fuses allow immediate severing of power in the event either motor controller exceeds its maximum rated current draw. The battery connection to the main circuit is hardwired must be manually broken before charging.

It is recommended to remove and charge the batteries individually. It is recommended that the main contactors are turned off when breaking the power circuit. Reverse polarity protection handled by two automotive starter solenoids ensures that the primary motor controllers will not be damaged in the event of maintenance error.

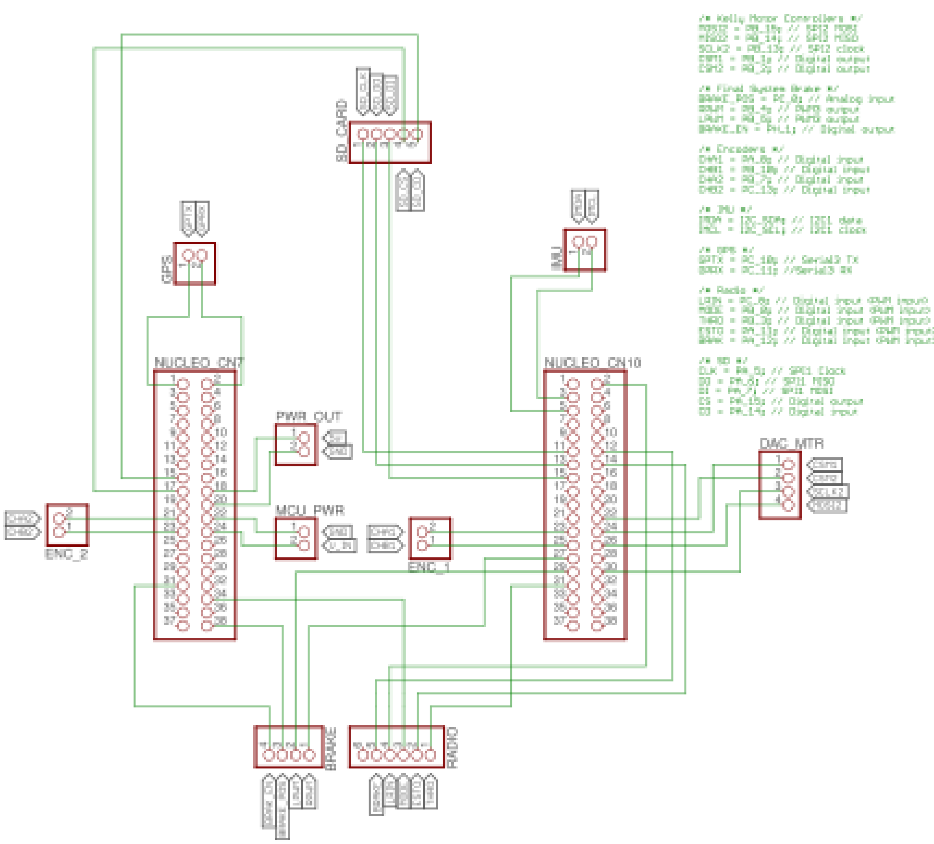


Figure 4.15 Electronic control schematic.

The controls system circuit, as shown in Figure 4.15 refers to all components dedicated to sensor input, user input, and decision making. The control system also contains a low power motor controller for the braking linear actuator actuator and sufficient power for all controls system components. Power for the braking actuator is supplied by the LiPo battery contained in the enclosure.

The control system circuit is almost entirely contained within the controls enclosure. The only external components are the GPS antenna, and the RC receiver. The RC receiver supplies data to the control system via seven standard servo wires. Connections between control system components utilise standard male pin headers and female head ribbon cables.

To increase sensor accuracy and decrease communications failures, there is no direct electrical connection between the power system and the control system. If electrostatic build up proves to be an issue later on a single high impedance connection may be allowed between the controls system enclosure and the frame.

4.6 - Software Overview

The overall program flow has three major parts, system power on, system ready, and failsafe. The system power on section is shown in Figure 4.16 This section handles initialization of all sensors including any necessary startup calibration. If any sensor fails to respond or behaves in an unexpected manner the sensor is aborted and the system records the error. When all sensors have been initialized the initialization function returns success or failure. If any sensor has failed the system then aborts startup indicates which sensors failed and enters a hard loop until reboot. This helps ensure that the system will not function in an unsafe manner. In the event that the sensors successfully initialise the system will initialise all actuators and check the preloaded map, if the map is invalid the system indicates the error and again enters a loop until reboot. A valid map is required even if an autonomous test is not intended, this is a sanity check for the operator and in later revisions the map may be used to restrict operator control to a region defined in both velocity and physical space. When fully initialized the program enters the system ready phase.

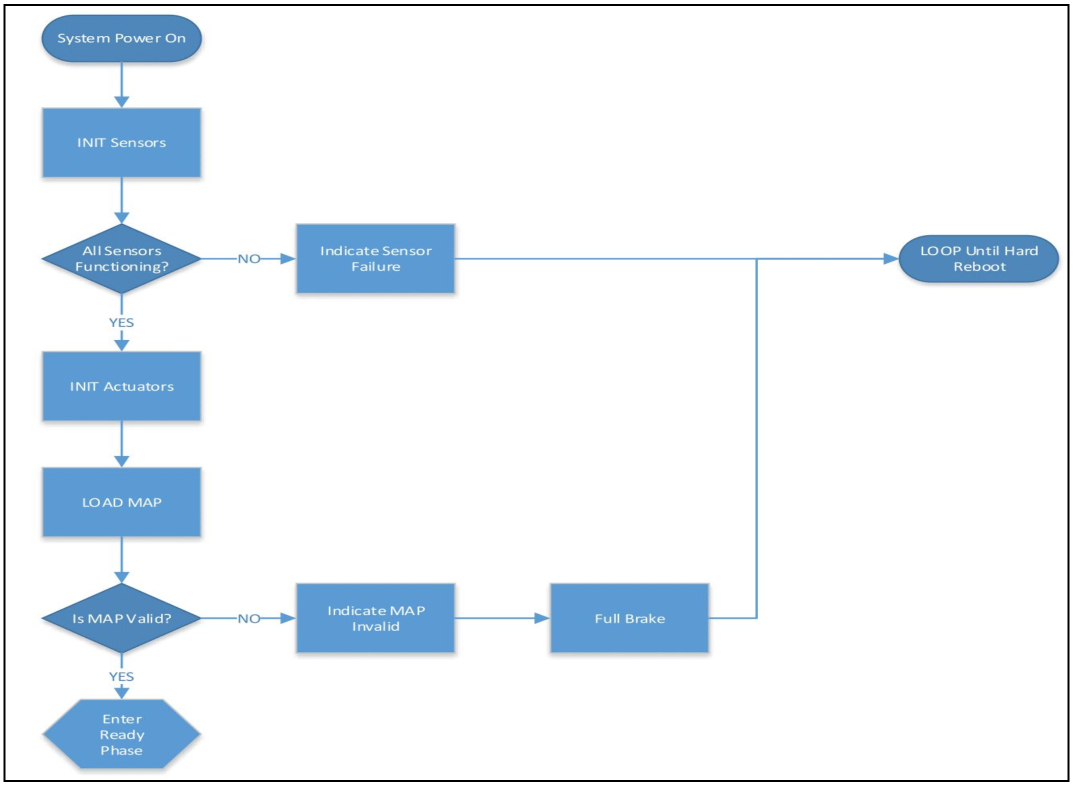


Figure 4.16 Power on flowchart.

The system ready phase shown in Figure 4.17 constitutes the the primary control loop. This phase begins with a proximity check to ensure the system has sufficient room to move without injuring itself or others. This feature is included as a strong safety recommendation for future iterations however was implemented in the final design.

The software design provides two modes of operation, autonomous and radio manual control. In autonomous mode the system samples each sensor value at the maximum refresh rate for that sensor. This tactic of polling sensors at their individual refresh rate allows the control loop to achieve latencies well within our spec of 28 ms per cycle. Polling of the sensors at their individual refresh rate was not implemented in this design because of the complexity of polling scheduling. Values are then passed through a Kalman filter using the control filters scheme to provide a continuous approximation of vehicle position, velocity, acceleration, and orientation. The Kalman filter was not implemented in this version of the design due to time constraints but portions of the necessary code are supplied in the code repository. The filtered values are then compared to the preloaded test map, and the control algorithm updates an array of actuator values to the next checkpoint. When a checkpoint is reached, or missed the system updates the current checkpoint to the next in the map. When the last checkpoint is reached or if the system exceeds test parameters, the test is ended and the system enters failsafe.

In operator control mode signals from the radio controller are interpreted and relayed directly to the drive system allowing the vehicle to be driven much like a hobby RC car. This mode is

intended for use primarily as a retrieval method. In this mode radio signal latency is the limiting factor on operating latency since standard hobby RC vehicles operate at a 50 Hz (20 ms) refresh rate.

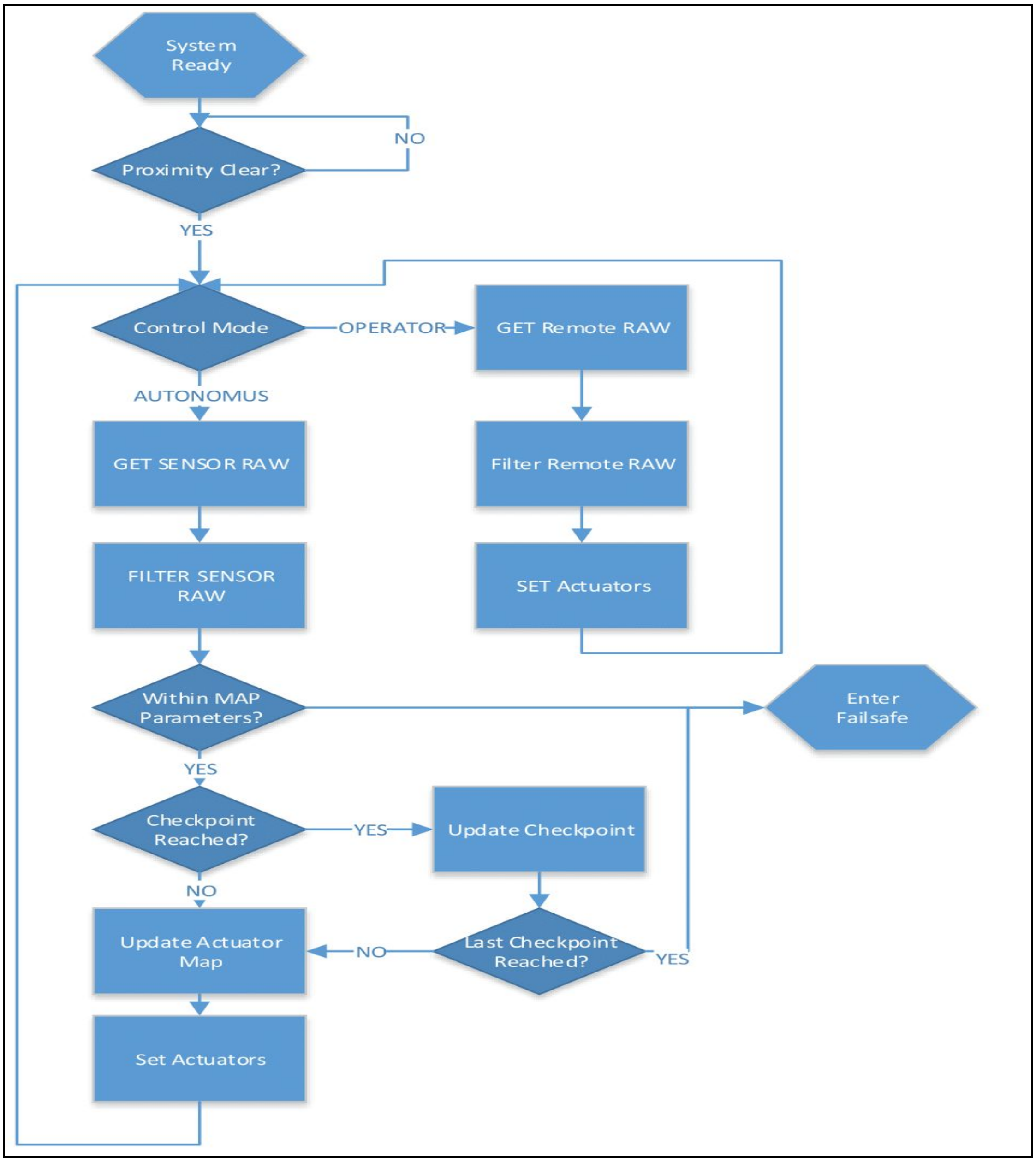


Figure 4.17 System ready flowchart.

The failsafe mode may be entered any time an error is detected, the system determines it is outside safe operating conditions, or the test is completed. The failsafe mode may also be entered in the event the operator initiates the E-Stop, radio communications are lost, or if the GPS detects that the vehicle is outside the map boundary. As shown in Figure 4.18 the failsafe mode simply sets all motors to full stop or coast depending on speed and initiates the braking

system. The operator may then take control of the system to return it to the track start however the system will no longer move without direct operator control.

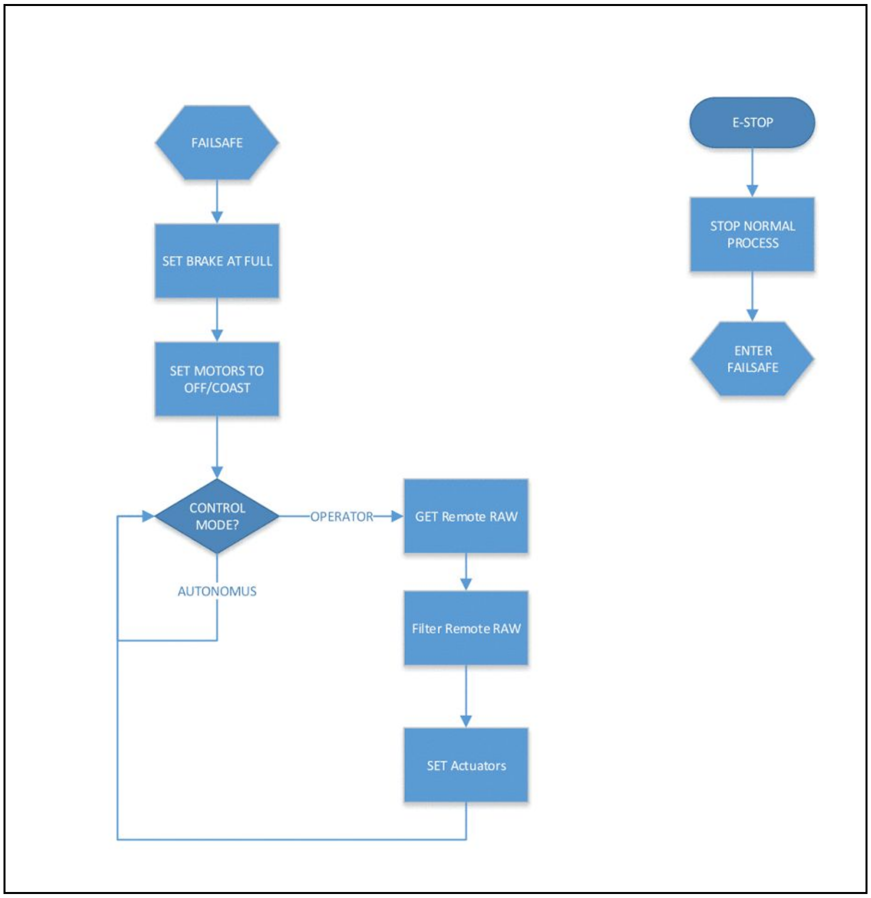
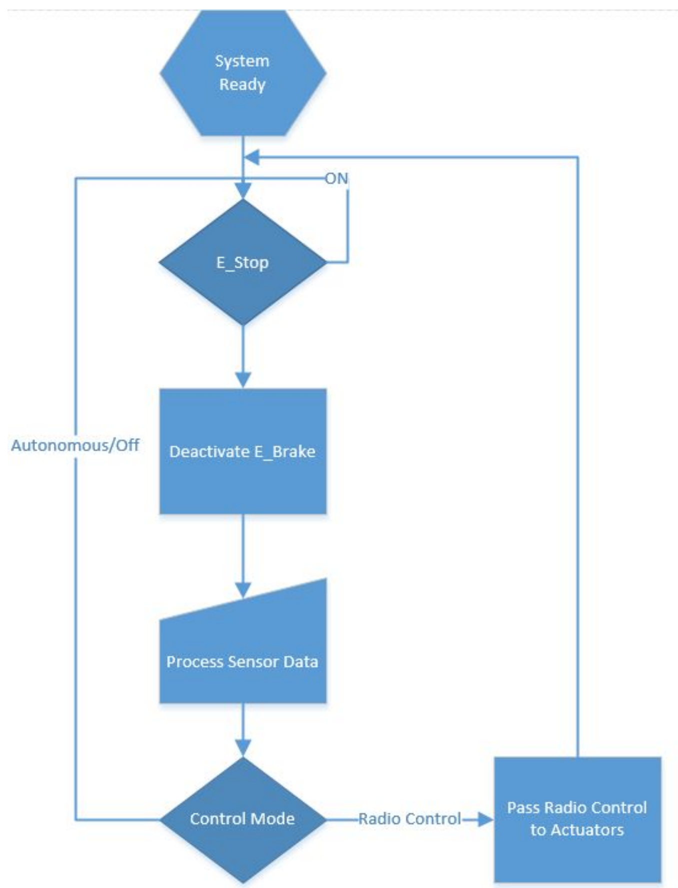


Figure 4.18 Failsafe and E-stop interrupt flowchart.

Though other versions in the development repository match the software for design more closely, the final program uploaded to the controls system is a much simplified version. Once initial system power on checks such as the Map Valid check are complete The final program used for full scale vehicle testing follows the flowchart in **Figure 4.18.1** and **Figure 4.18.2.** This program is intended to increase safety by ensuring the operator is in control of the vehicle at all times. Autonomous mode and all high latency functions have been removed providing the minimum possible delay between operator command and vehicle actuation.



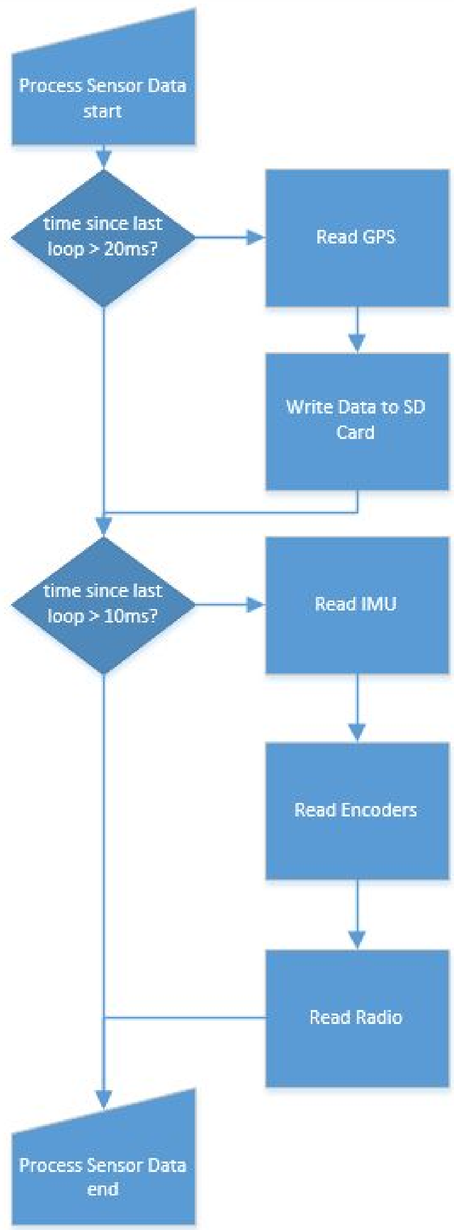


Figure 4.18.1 Full scale test primary control loop. **Figure 4.18.2** Full scale test sensor loop.

4.7 - Manufacturing and Assembly

The control focused nature of this project resulted in relatively little fabrication to be done. The majority of our components were electrical or electronic hardware, almost all of which are off the shelf, with a few exceptions. The assembly time for this project was much more significant since it required soldering and cable routing.

4.7.1 - Initial Component Test Rig Assembly

To ensure that we would be able to test our vehicles control system without relying on the other Daimler sponsored teams, we developed a 1:5 scale model of the final vehicle. This initial test platform was fabricated with low cost and high adjustability in mind to enable us to redesign it cheaply and quickly should any of the specifications from the other teams change. To meet these requirements, we used parts that had either been donated by the Cal Poly Mechatronics department or that we already owned. Since we had very little time to select our components and test them, we were concerned with the development time of the platform. As a result, we chose to use off the shelf physical hardware parts to mount the wheels and shafts.

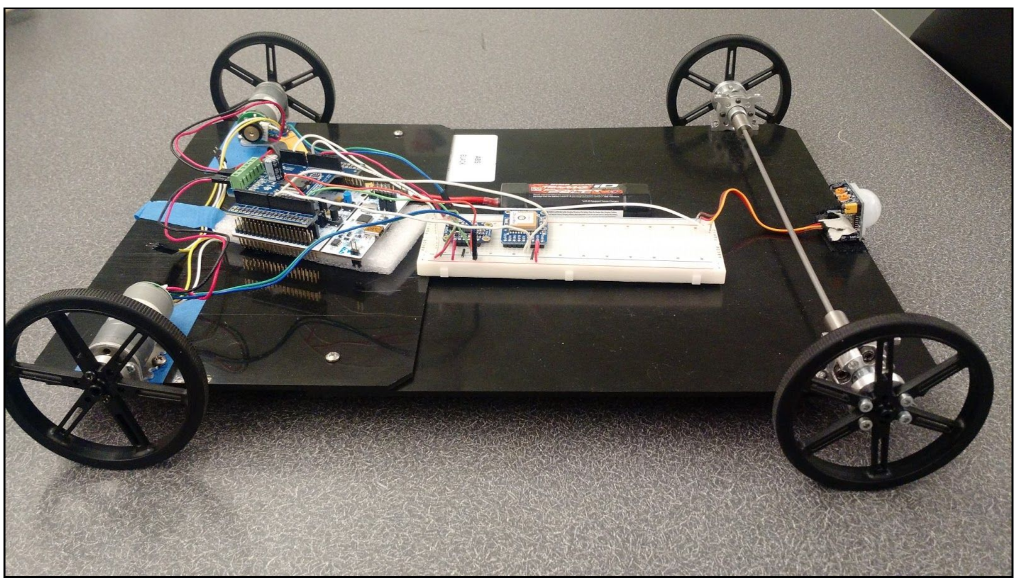


Figure 4.19 Initial vehicle test rig.

4.7.1.1 - Building the Test Board

To find the dimensions of our test platform we consulted the frame team on their planned wheelbase and track, which was chosen to be approximately 7’ x 5’ respectively. To feasibly produce a model of the final vehicle, we chose to scale the final dimensions by 1:5, resulting in a wheelbase and track of 16.8’’ x 12’ respectively.

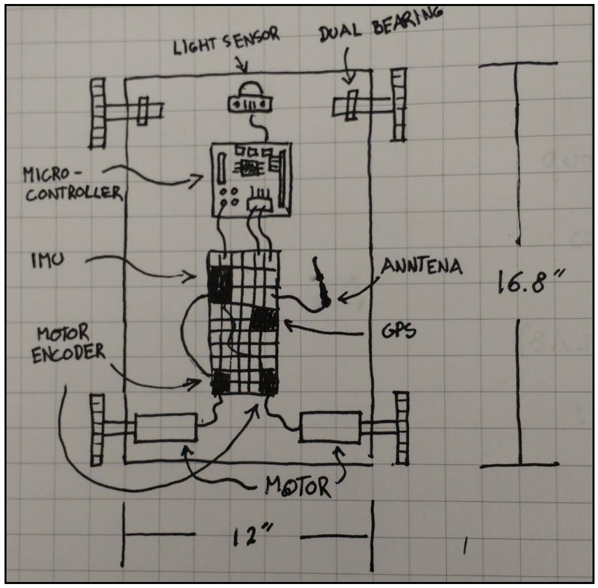


Figure 4.20 Concept drawing detailing vehicle layout and dimensions.

To construct the base of the vehicle, we used Acrylonitrile butadiene styrene (ABS) sheets supplied by Mechatronics department. Unfortunately, these were only available in a 12'' x 12'' size, so we chose to offset two layers to achieve our vehicle size requirements.

The next step was to select our platform's wheels. We only had a few options readily available to us, but to save time and cost we decided to choose a set of 3.5'' hobby wheels that were available to us from a previous mechatronics vehicle project. Although they did not match the scaled size chosen for the full vehicle, we determined that for the initial testing of our sensors and control system they would be adequate. The front wheels were initially mounted to the base using off the shelf hobby bearing blocks on two separate axles. However, this design was later changed to a layout in which they were connected together by a solid shaft to more accurately mimic the final vehicle design. Despite the knowledge that the frame team would be using a transmission system the rear wheels were directly mounted to two independently driven dc motors. We excluded the transmission from our model since we did not feel that the model's capability to test our components would be improved by the inclusion of a scaled transmission system, as well as the higher cost that such a model would entail.

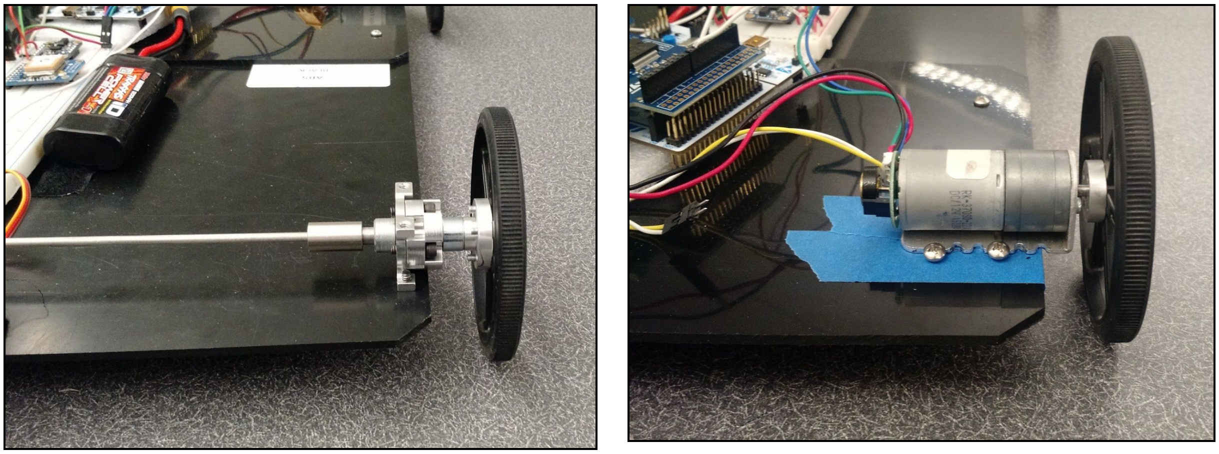


Figure 4.21 Front (left) and rear (right) wheel mounts of test platform.

The brushed DC motors mounted to the base, were chosen to accurately reflect the frame team's initial motor selection, as well as our motor encoder specification. However, since our initial prototype, they have revised their choice to a set of brushless DC motors without encoders. Fortunately, to limit costs we were using motors donated by the Mechatronics department and therefore, have not suffered any additional costs. For further iterations of the test platform, we will switch to a set of brushless motors with electronic speed controllers.

The final element of our test platform was to mount our electronics. We wanted each component to be attached to the platform both securely and adjustably. To meet these requirements we decided to place velcro strips between a breadboard and the ABS sheet. Using a breadboard allowed us to easily prototype and reconfigure our circuits as well as remove our components for individual testing.

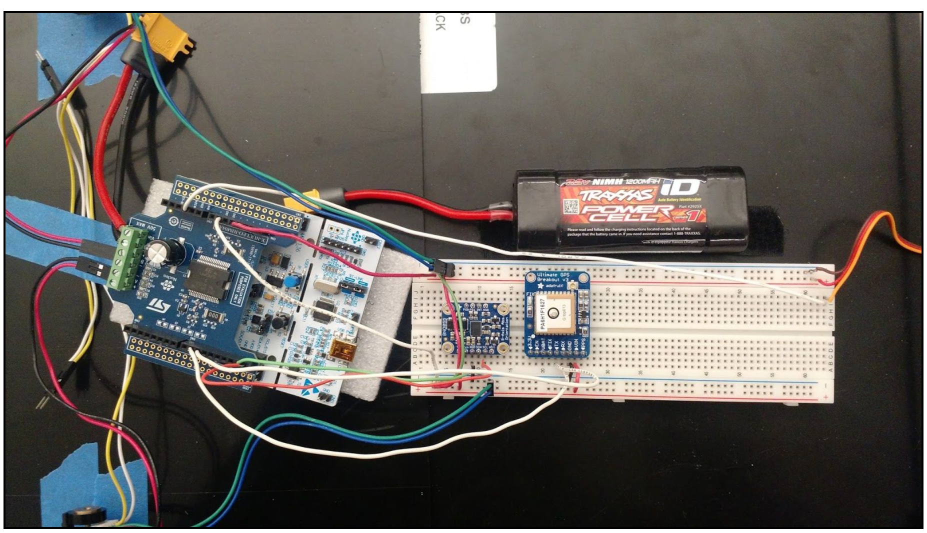


Figure 4.22 Test platform electronic component configuration.

4.7.1.2 - Configuring Sensors

Sensor configuration during system startup is limited to call response to ensure each sensor is functioning properly. If sensor values are outside expected norms or otherwise invalid they will be rejected and the sensor initialisation marked as failed. Later iterations of the project may be able to implement startup time sensor calibration using timed motions. However this is outside the scope of this iteration. According to tests on our physical model, full sensor initialisation requires only a few seconds. This puts our initial startup well within the specification of 10 minutes between tests.

4.7.2 - Enclosure Fabrication and Assembly Plan

The enclosure as a whole required very little actual machining to be done. Our design only two requires two components to be fabricated, and both of them are a relatively simple process. The primary part to be fabricated is the component mounting plate shown in Figure 4.23. We chose and Acetal plate for this part since it will allow us to use the Mustang 60 laser cutter for fabrication. Laser cutting the board will reduce our fabrication time as well as ensure an extremely high level of accuracy for the small electrical components holes. There is a risk that laser cutting our board will slightly melt the Acetal during the process, and cause some level of slop. However, we are not worried about this since once the holes have been located on the board by the initial laser cut we can refine their tolerances using a small drill press.

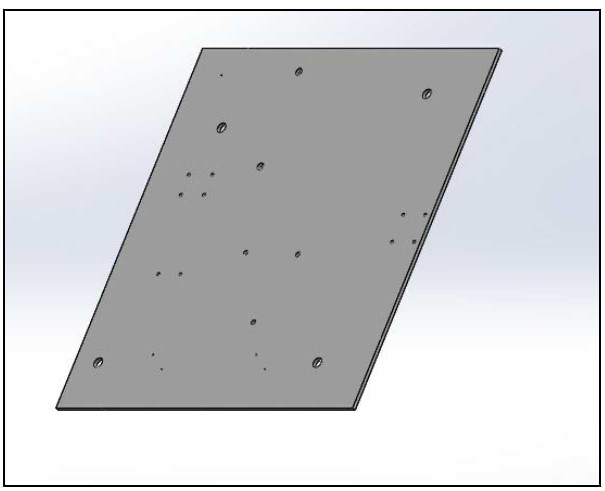


Figure 4.23 CAD model of component mounting plate.

The other part to be manufactured, is the battery wedge shown in Figure 4.24. This part will be used to hold our Turnigy LiPo battery in place while the vehicle is moving. The wedge will be placed up against the base of our battery, holding it on three sides. It will also serve as a way to attach a nylon strap which will run overtop of the battery and prevent it from lifting. Due to the simplicity of its design and the low stresses the part experiences, the wedge will be made of PLA filament using a Ultimaker 2 Extended+ 3D printer provided by the Cal Poly Innovation

Sandbox. It should be noted that the dimensions of the final Battery wedge will be slightly larger due to a recent change in battery selection.

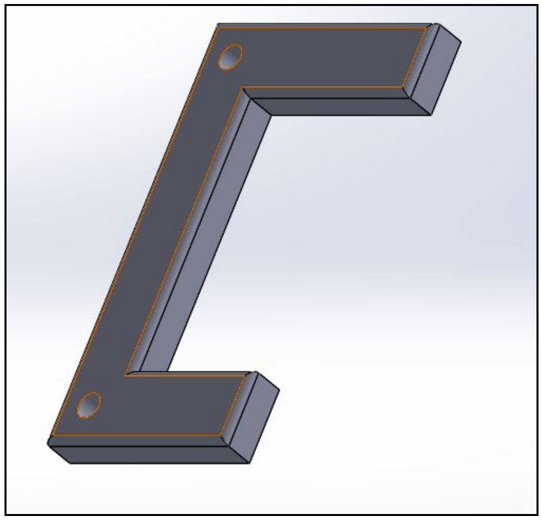


Figure 4.24 CAD model of battery wedge.

The rest of the parts which make up our final enclosure assembly are all of the shelf, from either manufacturing or electronics suppliers. All of our parts are fastened together using metric hex bolts, nylon spacers and nuts on the underside of the enclosure and mounting plate. We also included rubber bumpers on the bottom of the enclosure to avoid a metal on metal interface which could possibly damage our enclosure and cause unwanted vibration throughout the control system.

4.7.3 - Maintenance Considerations

The control system has no moving parts, and as such should not need significant maintenance. However the controls battery will need to be recharged daily under expected testing conditions. Some components may also need adjusting from time to time. To access the controls system the enclosure has a hinged lid. This will allow the battery to be removed and replaced as needed. For any more significant maintenance the enclosure is designed to be easily removable from the chassis. All internal components may be easily removed by unplugging the female headed ribbon cables and unscrewing from the enclosure via standard hex key. The power systems must be disconnected from the batteries before any maintenance. All power system components are easily accessible from nearly any side of the chassis.

4.8 - Safety Considerations

Although the control system hardware is relatively safe, there are a few potential safety hazards, to both humans and itself. The primary purpose of this project is to control a relatively heavy object travelling at high speeds. If the system is not tuned properly then relatively minor deviations from normal in our outputs could result in an unstable system which will cause the

system to act erratically and potentially injure humans or the system itself. The electronic components of this system will not be grounded to the earth in any significant way so, depending upon the voltages used, a minor internal short could induce electric burn dangers to human operators. A detailed list of potential failure mode effects can be found in Appendix H, which is our Failure Mode Effects Analysis document. Below we discuss two of the major systems that have the highest chance of injury.

4.8.1 - Batteries

The primary power source for the system is an array of three 12V batteries wired in series totalling 36V. Though these batteries are outside the scope of the control system they pose the highest risk and are therefore noted here. The batteries chosen are sealed lead acid batteries for automotive use. The batteries should be charged individually when completely separated from the system. The greatest risk when considering these batteries is a short across the terminals of any one, or series connected set. In the event of a short across any of these batteries they will dump current at their maximum capacity, will most certainly heat up due to internal resistance, and may fuse, melt, or vaporize whatever material induced the short. Under these conditions the batteries may burn humans nearby, may release hydrogen gas, and may leak strong acids.

An additional risk is a mechanical rupture in the battery casing. If a rupture occurs the batteries may leak acid. Additionally under conditions of great shock or mechanical pressure which would cause such a rupture the batteries may develop an internal short posing secondary problems. In order to be properly prepared for problems arising from the batteries, always have on hand chemical resistant rubber gloves, a chemical resistant bucket for disposal of the batteries, and a box of baking soda to neutralize any acid spills. Avoid direct skin contact with leaking batteries, and immediately wash any exposed skin with water to avoid chemical burns.

4.8.2 - Out of Control Vehicle

The second major risk is that of an out of control vehicle. Power calculations show the vehicle will be capable of rapid acceleration and may be capable of velocities exceeding 30 MPH. With this in mind the consequences of losing control of the vehicle are extremely high, potential harm to human operators and bystanders as well as damage to the system and other property may occur. To avoid this danger we have implemented a number of software and hardware safeguards. The program flow includes numerous checkpoints designed to ensure the vehicle is under control at all times. The system is designed to lock in an inert state with brakes fully locked in the event of any error. Similarly in the event of a controller loss there is a brake release servo is designed to fail closed. The primary safety feature to stop an out of control vehicle during testing is the user operated E-stop. The radio controller we have chosen has a minimum refresh rate of 50Hz. This gives a maximum time between the user triggering the E-stop on the radio, and the E-stop interrupt on the vehicle of only 20ms well within our specification of 100ms.

5 - Product Realization

The final stage of our senior project was to fabricate and assemble it based on the final design we had created. As with any first generation prototype, certain last minute modifications had to be made, and due to unexpected challenges, some features that were originally planned were not fully realized. Although our final project shown in figure 5.1, was not as fully featured as we originally anticipated, it has succeeded in setting the groundwork for future teams to build upon what we've learned and revise our design.

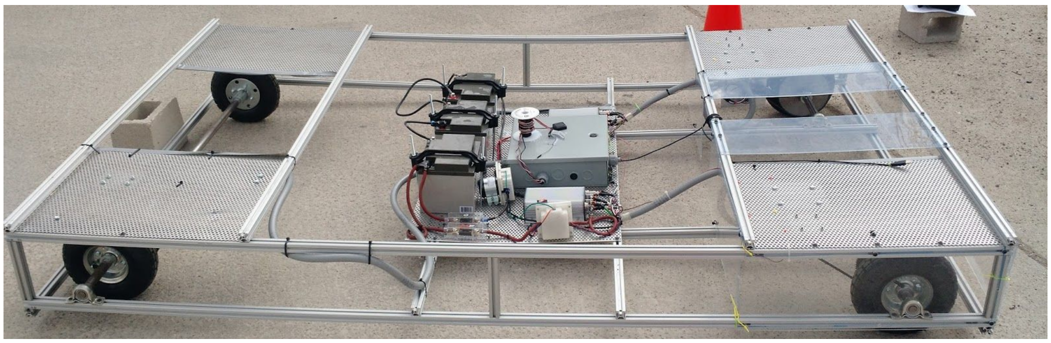


Figure 5.1 Final Guided Target Vehicle (control system in center)

5.1 - Manufacturing Process

Although the guided target control project had relatively few machined parts, a good portion of our effort was directed towards refining the physical system. Between the electrical and mechanical hardware we had to manufacture several mounting brackets and circuit boards, as well as establish the wiring for the entire system.

5.1.1 - Enclosure

The baseplate on which the electronics are mounted is made from Delrin which is electrically insulative. The delrin plate was laser cut to size and all holes for mounting screw were likewise machined. Most of the mounting holes were not used since some the components in the enclosure were changed or moved from the design of the mounting plate proposed in the critical design report. Electronic components were intended to be mounted on plastic spacers and bolted to the Delrin. The IMU, GPS receiver, and STM32 Nucleo were mounted in this way however some other components such as the SD card reader were never permanently affixed. The brake battery is secured with a velcro strip and a custom fitted support as intended in our final design. The enclosure knockouts were removed with a standard ball pein hammer. Plugs were later added to those knockouts which were no longer in use. The control electronics enclosure is mounted to the central electronics platform by the same four hex bolts which secure the baseplate to the enclosure.

5.1.2 - Wiring

Wiring within the controls enclosure served to connect the sensors to the Nucleo and conduct signals from the Nucleo to components outside the control electronics enclosure. To reduce the chance of wires coming loose we utilised ribbon cables wherever possible and grouped connections. This allowed for the ability to modify the design which wouldn't be as easily accomplished with a hardwired design.

Wiring outside the controls enclosure regularly required thick gauge wire and crimps. All power system wiring between the batteries fusing and main contractors was completed with 4 gauge cables suitable for the potentially high currents. After the main contactors we utilised six gauge wire to connect to the ESC and motors. The ESC's are connected to the motors using bolt through crimp connections.

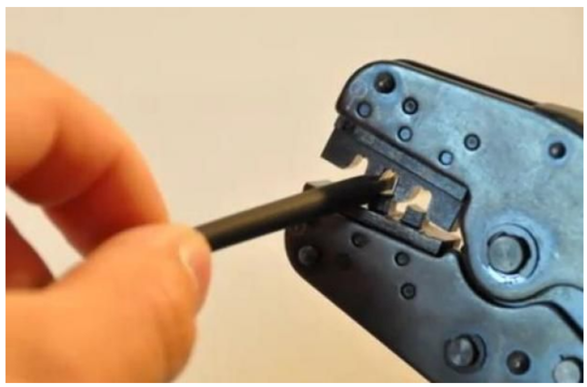


Figure 5.2 Crimping wires with crimping tool.

Each connection is encased in a removable shrink tube cover. Most wiring on the chassis is protected by watertight plastic conduit, but some exceptions to this. Wires which do not leave the central electronics platform are not shielded inside watertight conduit. The signal wires from the shaft encoders are also not shielded within the conduit which runs from the motors to the central housing. The hall effect sensors and shaft encoders are mounted alongside the motors and share power and ground wires. Power for these components is provided by a five volt supply built into the motor ESCs. As a protective measure against accidental shorts there is no chassis ground. All ground connections are made through shielded cables directly to the main batteries or central control electronics.

The radio receiver and GPS antenna both extend outside the electronics enclosure. In the event the soft target is covered in a radio reflective layer these components should be mounted outside the soft target to ensure the best possible radio and GPS connection. The radio cable includes a simple breakaway point to help protect the enclosure during impacts however the GPS does not have this feature. All impacts with the vehicle should be avoided for this iteration of the design.

5.1.3 - Printed Circuit Boards

To facilitate wiring we designed two printed circuit boards (PCB) using a PCB design software called EAGLE. The PCBs were machined using a small PCB mill called the Othermill, provided by the Innovation Sandbox. One board served to provide power for all sensors and connections simplify connections with the Nucleo (Figure 5.3) while the other allowed use of two digital to analog converters (DAC) used to communicate from the Nucleo to the motor electronic speed controllers. Since the boards were produced using a mill they do not have a solder mask layer, so we used Kapton tape to insulate the traces after manufacturing. Additionally we utilized two standard solder protoboards to mount the hall effect sensors near the motors.

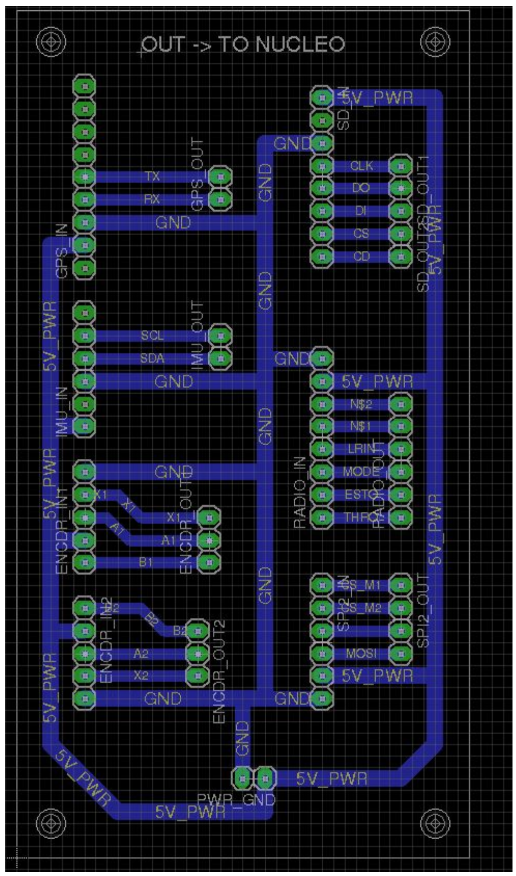


Figure 5.3 Board layout for connector board.

5.1.4 - 3D Printed Parts

Do to the availability of free 3D printing on campus provided by the Innovation Sandbox, we utilized a number of 3D printed components. The components that were 3D printed for our design were the bracket for the LiPo battery within the enclosure, shaft encoder mounts, hall effect sensor mounts, and caps to cover the main contactors for safety. Drawings of these parts can be found in Appendix H.

5.1.5 - Software

All of the software developed is under Git version control. Git was used since it allowed for easier management of files as well as simplifying software collaboration. The Git repository is accessible via a public GitHub account (https://github.com/jbarry510/slonav). The software used in the project is contained in the tests folder and is broken into folders for actuators, sensors, data collection, and full system. The actuator, sensor, and data collection folders contain a main file with test code, associated libraries, and a makefile which simplifies compiling the necessary code. The mBed development libraries, which provide drivers for the Nucleo hardware, are included in the repository and referenced by the make files. Two header files are provided in the mBed folder (pinout.h and pinout_model.h) which contain the pin names defined in the rest of the software. The full system folder contains test code that implements autonomous control loops as well as the radio control program and the makefiles for these programs reference libraries the required libraries from the other folders. When a program is compiled for the Nucleo using the make files a binary file is generated in the build folder. To flash the binary file on the Nucleo, copy the binary file to the file system that is mounted when the Nucleo is plugged into a computer via USB and wait until the status light finishes flashing red and green.

5.2 - Alterations from Planned Design

During the implementation of our design, some modifications were necessary to properly integrate our design with the full scale vehicle because of design oversights and incompatibilities between our design and the frame design.

5.2.1 - Hall Effect Sensors

In order to properly run the chosen motors using the our ESC's we needed three hall effect sensors mounted near each motor to detect the position of the rotor. The sensors are necessary for the ESC to properly commutate the motor as it is spinning. The sensors were not included in the original planned design due to late changes in the motor selection made by the frame team. These sensors look very similar to standard transistors but latch on when exposed to one pole of a magnet and latch off when exposed to the other side.

The hall effect sensors must be properly positioned so that they trigger when the back EMF of each motor phase crosses zero and wired so that there is a 120° electrical phase shift between the signals as the motor rotates. Since there are 10 pole pairs in the motors we used it was determined that physical spacing of 12°, or any multiple of 12°, between the sensors was necessary to achieve the proper electrical phase shift. The sensor mount was designed to be placed along a circle of a diameter that is 5 mm greater than the diameter of the motors (110 mm). The sensor mount has a 12.57 mm arc length between the sensors. To determine the proper orientation of the sensor bracket so that the motor poles aligned with the sensors we used an oscilloscope to measure the sensor output and back EMF of the motor while spinning it with a cordless drill. Figure 5.4 shows the setup used to find the orientation of the sensors and Figure 5.5 and Figure 5.6 show examples of the waveforms observed on the oscilloscope. In the

event that the motors begin to sound “grumbly”, especially at low speeds, it is likely the result of the Hall effect sensors having fallen slightly out of phase. This can also happen if the motors or sensors are wired incorrectly. Figure 5.7 shows the hall sensor mount model, the grooves help with placing the sensors at the proper spacing.

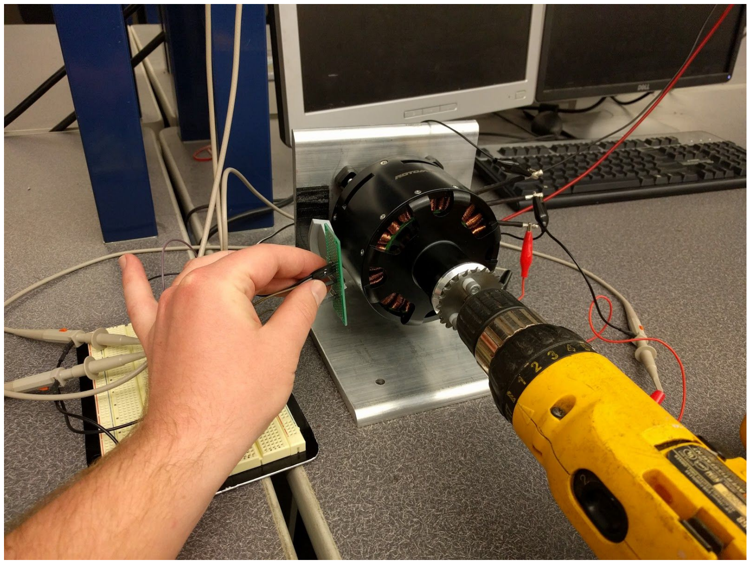


Figure 5.4 Hall effect sensor orientation setup.

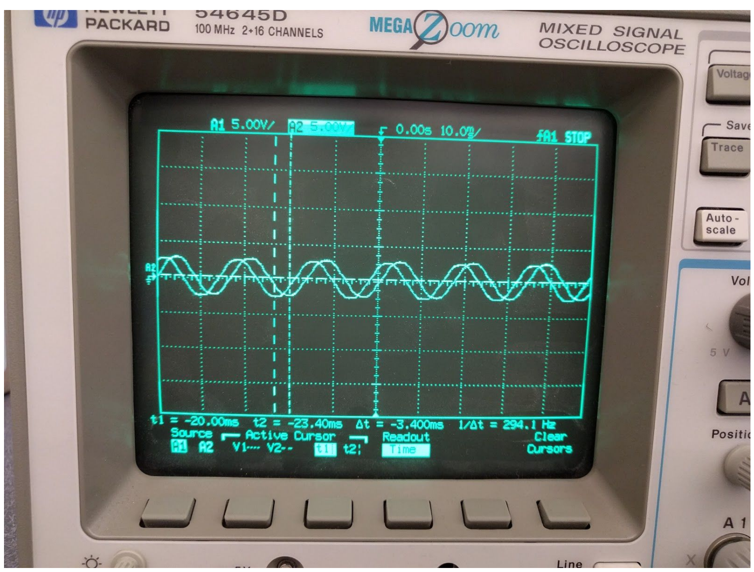


Figure 5.5 Example of waveform generated by observing two of the motor phases.

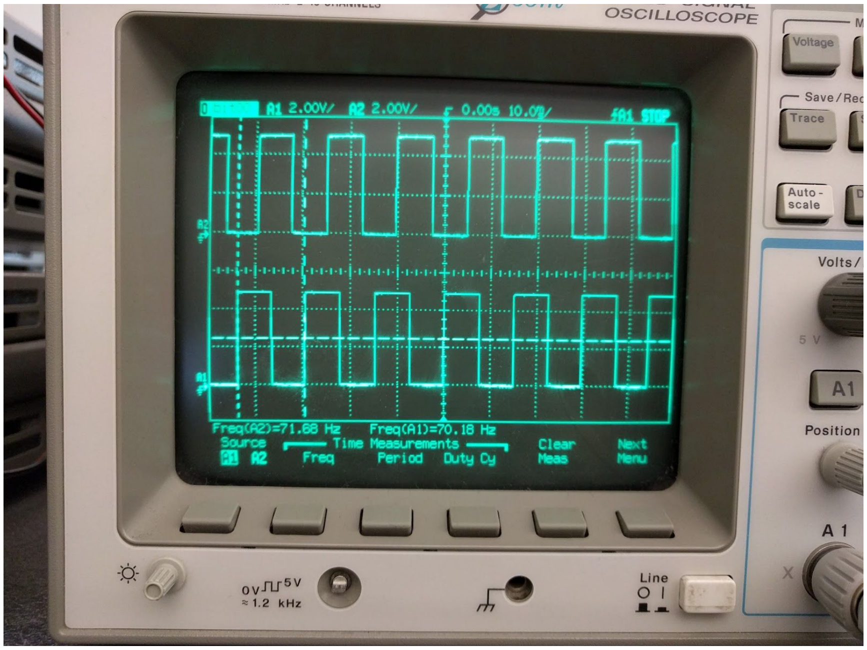


Figure 5.6 Example of waveform generated by hall effect sensors.

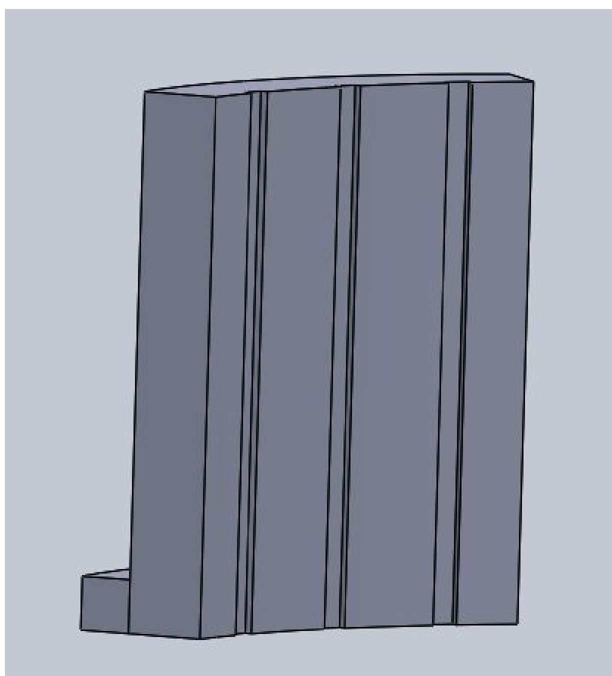


Figure 5.7 Hall sensor mounting bracket.

5.2.2 - Digital to Analog Converter Board

The digital to analog converter board allows the Nucleo to interface with the motor ESCs via their built in analog throttle and braking inputs. In the original design we planned on using the Nucleo's built-in DAC but we realized later that the Nucleo only has two DAC channels. It would have been possible to utilize the built-in DAC for just throttle input to each ESC but one of the

DAC channel pins conflicted with the pins used for interfacing with the SD card. This lead to us developing a DAC breakout board which provides four 12-bit DAC channels which provide the throttle and brake inputs. The DACs used are MCP4922-E/P produced by Microchip which each provide two channels.

The DAC board communicates with the Nucleo through SPI protocol and has a built in voltage level shifter (to assist in the transition from the Nucleo's 3.3V logic high and the DAC chips 5V logic high. The 5V logic of the DAC allows the Nucleo to utilize the full 0 to 5V range of the throttle and brake input since the Nucleo would have only provided 0 to 3.3V with it's built-in DAC. Figure 5.8 shows the wiring schematic for the DAC board and Figure 5.9 shows the board layout for the DAC PCB.

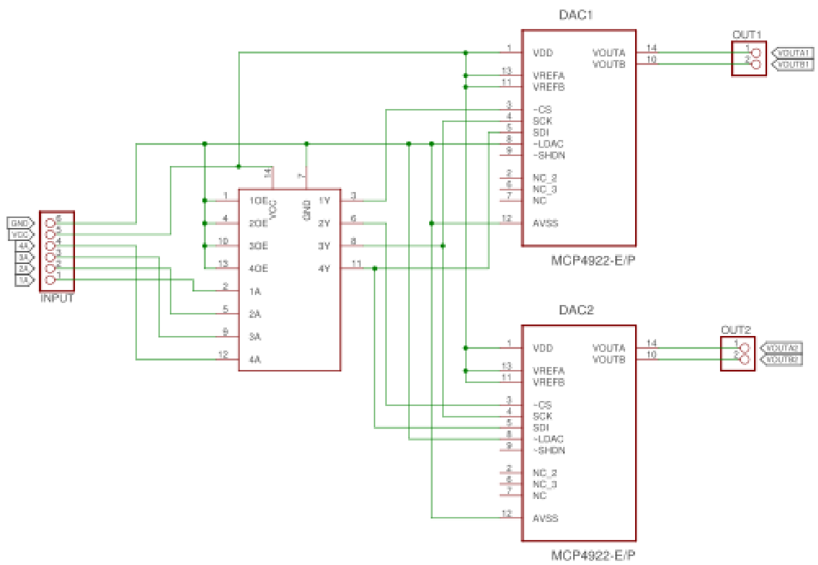


Figure 5.8 Wiring schematic for DAC breakout board.

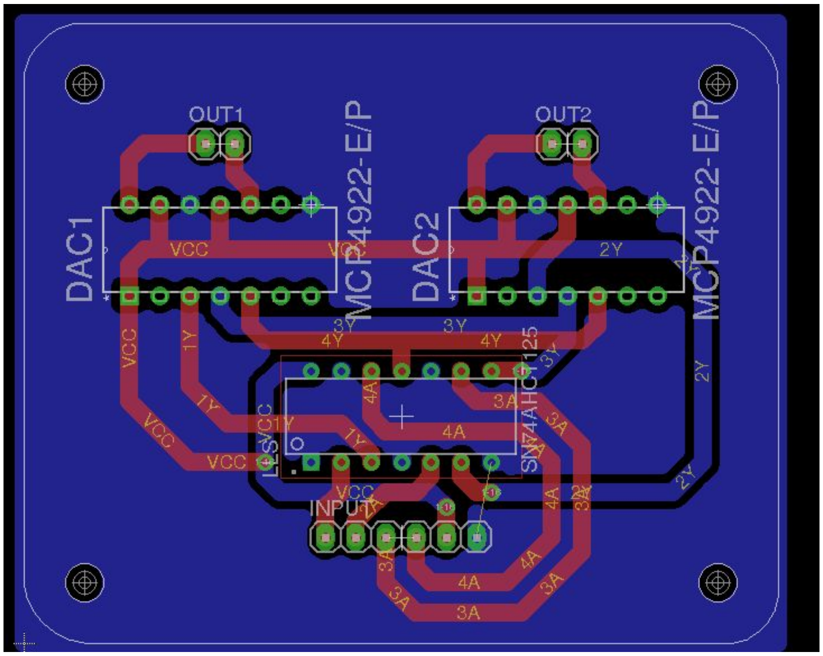


Figure 5.9 Board layout for DAC breakout board.

5.3 - Future Design Recommendations

Although our plans for this project were only created for the span of one senior project class, there are still many areas in which the vehicle control system can be improved. The three main areas of the project: control electronics, control software, and mechanical hardware each have ways in which they can be refined or reiterated to better meet the specifications originally designated by Daimler.

5.3.1 - Control Electronics Recommendations

In its current state, the vehicle hardware is fully capable of handling input from all our sensors as well as controlling the vehicle's motors and brakes. However, the wiring within the enclosure as well as throughout the frame could be substantially improved in terms of usability and simplicity. The enclosure currently has countless wires spread throughout it, connecting the Nucleo board to it's many inputs and outputs.

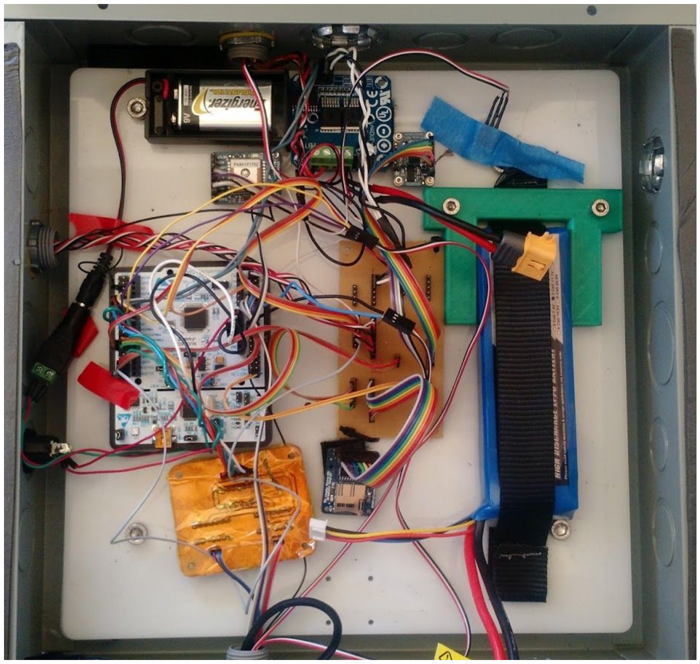


Figure 5.10 Final enclosure wiring.

As seen in Figure 5.10 these connections are made using standard ribbon cables and connectors. Although this type of connection allow for easy layout alteration and component addition, it is not secure enough to be completely reliable. During our testing we had several cases in which a wire came loose which caused an electrical failure in the field. Additionally, these failures were very difficult to diagnose and were often misattributed to software issues.

To solve the wiring issues within the enclosure, we recommend designing and manufacturing a large connector board or shield, which will plug directly into the chosen microcontroller. Unlike the connector board that we developed for our final system, this new board should also include secure mounts for each component included in the enclosure as well as all the appropriate pin connections. By securing everything to the board and minimizing how many loose ribbon cables are used, the overall reliability of the system should be greatly improved. If a connector board approach is not taken, we recommend improving the current wiring to either include proper labeling or a more consistent wire color coding scheme to improve the user interface as well as using latching connectors. Lastly, once the PCB designs have been validated we suggest having them manufactured by a PCB manufacturer so that they have a proper solder mask and silkscreen labels for components.

The wiring from the controller to the rest of the system could be improved with the addition of detachable wire connectors placed within the enclosure. Currently, we have several wires routed directly from the Nucleo through the conduit, to components outside the enclosure. Although these wires are well insulated and protected, they are not easily removed for maintenance. The addition of detachable connectors would allow the user to completely detach

the control board from the rest of the vehicle, thus improving user access and the modularity of the hardware.

We also faced issues during testing with the limited power provided by the 9V battery. Once everything was plugged in, the control system demanded approximately 4 Watts which resulted in a runtime of only a couple hours before the battery needed to be replaced. To resolve these issues we recommend replacing the current 9V battery power source with a different power source, with a more stable current flow.

Near the end of the project some inconsistencies were noticed when resetting the Nucleo hardware. These inconsistencies gave the impression that some of the variables used in the control code stored on the board of the board was not being reset properly. Moving forward, if these inconsistencies keep resurfacing then the root cause should be thoroughly investigated since it is a major safety concern since it could lead to erratic behavior of the vehicle.

5.3.2 - Control Software Recommendations

The software flow has been one of the main hurdles throughout this project. Currently the primary control loop is suited best for radio control and data gathering. To provide truly autonomous control we recommend the use of a more abstracted program flow. Options for this include but are not limited to utilizing a Real Time Operating System (RTOS) or schedule manager to handle system tasks, or implementing a simple API to allow the Nucleo to abstract the hardware away from a larger processor. Utilizing a scheduler would allow the implementation of much more complex tasks than can be reasonably allocated by a human. Moving forward a higher level of abstraction is the primary challenge.

During the preliminary testing the acceleration control loop, the behavior of the vehicle was erratic. It was determined that the likely cause of the behavior was related to the inherently noisy data from the accelerometer. The data retrieved would oscillate between large positive and negative numbers at times when the vehicle experienced quick movements. This suggests that using the accelerometer as feedback is not desirable and another more robust control scheme should be investigated. One possible replacement scheme would be to utilize a velocity setpoint controller which would provide a tracking setpoint to the motors and operate on the error produced by the desired velocity at the next trigger point minus the velocity needed to reach it based on the predicted time till arrival. A paper by Tsz-Chiu Au discussing this approach can be found in the 2012 IEEE International Conference publication [23].

Sensor fusion using an extended Kalman filter was researched and partially implemented for the final design but was not completed. The implementation was going to use the TinyEKF library (https://github.com/simondlevy/TinyEKF) which requires a measurement model, process model, the Jacobians of those models, and noise models. The library may require some modification since it implements the prediction and update steps as one function which may not be desirable for project. The state variables that were chosen were the longitudinal position, lateral position,

longitudinal velocity, longitudinal acceleration, and heading. The measurements that were chosen to be provided to the filter were longitudinal acceleration (IMU), lateral acceleration (IMU), heading (IMU), longitudinal position (GPS), lateral position (GPS), and longitudinal velocity (encoders). A thesis by Jonathan Webster at Virginia Polytechnic Institute was found to be helpful for developing the models need for the Kalman filter implementation [24]. The code that was developed is available within the GitHub repository for the project within the fusion folder.

5.3.3 - Mechanical Hardware Recommendations

Although the project does not have many physical parts, there are a few improvements that could be made for future iterations of the project.

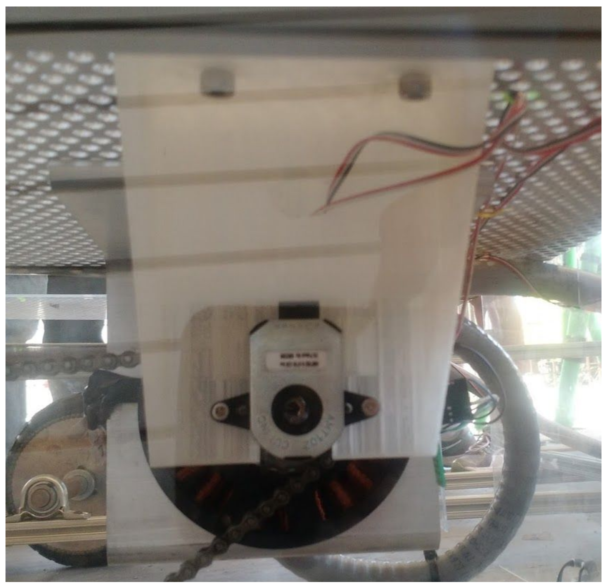


Figure 5.11 Encoder mount on full scale vehicle.

Primarily, the encoder mounts shown in figure 5.11 that are currently in place, served primarily as a rapid prototype to test if we could get readings from the shaft encoder while the vehicle was running. The mounts are both 3D prints made from PLA plastic, and are therefore not highly durable. Although they are reinforced and completely functional, if the motor shaft ever shifted out of alignment, it could easily rip apart the plastic. As a result we recommended that that mounts be redesigned to be made from a more durable and stiff material in future versions of the project.

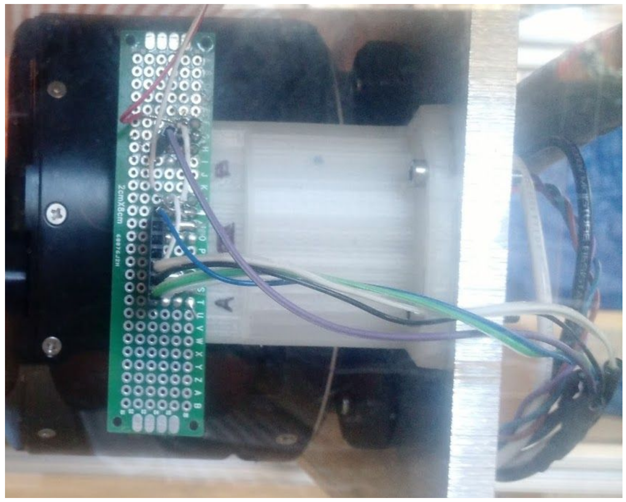


Figure 5.12 Hall effect sensor mount on full scale vehicle.

We recommend future additions include a more robust mounting system for the hall effect sensors compared to those shown in Figure 5.12. At the moment they have a tendency to fall out of alignment under heavy vibrations which is not suitable for long term testing.

6 - Design Verification Testing

During the design stages of our project, we developed a multi-stage test plan to validate our system design against our specifications. These tests were separated into three phases, the first phase involved testing the scale model, the next phase was to test the integration with the frame design, and the last phase was full functional system testing, running the vehicle in a secure location. All of these tests and the evaluation criteria are documented in our design verification plan and report which can be found as Appendix I. Unfortunately, due to the time constraints imposed by the senior project class, as well as a few unforeseen complications from the other teams, much of our testing had to be revised and several of our test plan milestones were not met.

6.1 - Planned Scaled System Validation

Early in the initial planning phase, it was decided that we would need to develop a test platform to enable us to test our control system without relying on the completion of the other autonomous target projects. We designed the platform to be a 1:5 scale model of the final vehicle with the hope of being able to scale our vehicle dynamic controls. However, after some discussion with Dr. Birdsong, it was determined that due to the high number of variables in the driving mechanics we would use the test platform mainly for sensor, software, and control system validation. The scaled system is discussed in detail in Section 5.7.1.

6.1.1 - Sensor Testing

Using the test platform, we developed drivers necessary to communicate with the different sensors. With our driver integration mostly complete we were then able to begin testing control loops and integration without waiting for the full scale components. We were able to collect data from the sensors over time which were used to check the performance of the sensors as well as evaluate the impulse response of the chassis and the latency of our control loops.

For the inertial measurement unit (IMU) we focussed on determining the accuracy of the heading orientation, and sensor latency. Testing the heading angle was done by comparing the angle to a known reference, and rotating it to see if it accurately determines the difference in angular orientation. Our preliminary IMU tests were sufficient to allow the development of a successful PID based heading control algorithm.

For the GPS focussed on the positional accuracy and sensory latency. To determine the positional accuracy we intended to take readings at different points in an open area where we could measure the distance between those points. The measurements were to be compared against the GPS readings to determine the accuracy. The sensor latency was be determined in a similar manner as the IMU. Unfortunately we had considerable difficulty obtaining a GPS lock and it was not until late in the project that we had the ability to take these measurements

For the motor encoders we focussed on the accuracy of reading pulses. To determine the accuracy of pulses we connected the encoder to a shaft and had it complete a full rotation while measuring the number of pulses generated. We were able to confirm in this method the proper functioning of our shaft encoders.

6.1.2 - Sensor Integration Testing

The next step in testing the sensors will involve testing the accuracy of our heading orientation, position, velocity readings, and latency after implementing the extended Kalman filter. The orientation and position tests will be conducted similarly to the IMU and GPS tests. The velocity verification will be done by having the test platform travel at a set velocity while measuring the time it takes to move between two marked points. We intended to compare this data versus the output from the filter to determine the velocity accuracy. The latency would be determined similar to the method described in the previous section.

6.1.3 - Control System Testing

The last step in testing with the scale test platform will be to validate the control schemes. For all software deployed to the final vehicle there was an analogous piece which we tested on the scale platform. For any team moving forward this scale platform testing will be essential to ensure safety of both systems and personnel. The first step in testing the control systems will be to determine the gains for the PID controllers. This should be done by using a relay method [25], where you replace the controller with a relay which produces a set of positive or negative control

outputs depending on the value of the process variable versus the setpoint. The period and amplitude of this relay output should be measured to give the ultimate period and amplitude of the system. This can then be used to calculate the PID gains based on various methods such as Ziegler Nicholas, Cohen Coon, etc. This full testing remains to be completed for the autonomous control algorithms.

The validation of the steering system was intended to done by conducting a chalk line test. A piece of chalk will be attached to the vehicle and it will try to follow a marked straight line. The difference between the straight line and the chalk marks will be used to determine the accuracy of following the straight line. We also intended to use this test to fine tune our controller gains. These tests were not completed do to time constraints.

The validation of the acceleration control system will involve marking trigger points along a linear path and loading a velocity profile that contains an acceleration, constant velocity, and deceleration section. At each point we would measure the time from the previous point and with these measurement we can determine the velocity profile. The data from the sensors should also be compared against the test readings.This test was not implemented in the final control scheme.

6.1.4 - Safety System Testing

The emergency braking system and radio control systems were tested for latency and range. The range was tested by measuring the distance from the test platform the radio controller could be before the microcontroller no longer registers its inputs. We found this to be well over a mile and was still operable through multiple concrete walls.The latency of the system was of continuous concern throughout the project as we found there was often a noticeable or significant delay between actuation of the E-Stop and activation of the brakes.

6.2 - Integration with Frame Design

Due to considerations of scale time and resources the scale model was inherently unlike the final chassis in many respects. Because of this difference, interfacing the controls system with the final chassis required significant additional testing. To ensure the controls system is properly calibrated, and all safety measures are effective we integrated the controls system with the frame using a series of comprehensive full scale tests. Each component was tested to ensure it was at the same level of operability as on the small scale test vehicle. The only component which has not been thoroughly tested in this manner is the main powered break which was not mounted on the chassis until the last days of the project.

6.2.1 - Motor Controller Testing

To ensure that the final motor controller will integrated successfully with the software we developed using the scale model we tested the motor controller with one of the drive motors before mounting to the chassis. It will also be necessary to characterize the motor which we have not had time to complete. For this purpose connect one motor at a time, independent of

the chassis or any gearing and test the motor at numerous speeds, for torque, accuracy, and power draw. Motor speed will be determined both by the shaft encoders and by timed strobe light. These tests should be repeated at various battery levels to determine any deviation in the motor controllers to changes in voltage.

6.2.2 - Sensor Accuracy

When the control system is integrated with the frame and the soft target there is the possibly we will lose some of the accuracy of our sensor readings. The soft target team is using material that attempts accurately match the signature of a vehicle on the road and which will likely affect our radio transmission and GPS sensor. To determine the accuracy of the vehicle after integrating with other designs, we planned to conduct similar sensor tests as described in Section 6.1.1 and 6.1.4. We also planned to ensure that the encoders accurately read the velocity of the final drive motors. To check the encoders we intended to mount the encoders with the frame lifted off the ground and then use the motor controller to set the speed and we will determine the velocity based on the encoder pulses. This testing was partially complete when the project ran out of time

6.2.3 - Braking Actuator Control

To begin determining control variables for the braking system we disconnected the motors (for safety) and performed a series of tests using external power to move the vehicle. While the vehicle was moving applied various levels of braking to determine variables such as braking force, time to stop, and braking control precision.

6.3 - Planned Track Day Testing

The culmination of all the testing done in the previous sections was intended to be the testing of the fully integrated system at a test track in a nearby town. The main focus of these tests was to verifying that the safety systems work and verifying the performance of our final design. Unfortunately neither we nor the other Daimler Teams were fully ready for original track day so it was cancelled. A later track day was scheduled and hardware issues arose during testing that prevented us from testing the full scale vehicle.

6.3.1 - Safety Systems

For safety, full scale testing began with tests of all individual components to ensure everything was operating in good order. Controls system safety testing began by checking the decision making with simulated input, and by stress testing the error checking algorithms for the map, radio, and GPS failsafes. Sensors were tested primarily through the use of impulse testing and some unpowered motion. Again interference from the chassis and soft target may prove hazardous in the future.

For a full system safety checklist pleases see the pre-test checklist included with this report.

Testing of power system fusing and circuit protection must be conducted with the motor controllers disconnected and fully removed from the chassis. This will be a series of destructive tests designed to burn out every fuse in the power system. Replacement fuses as well as a class C fire extinguisher should be kept on hand. If the circuit protection works as designed the fuses will fail safely and individually without affecting the others. These tests should be done at least once before any high speed operation of the vehicle is attempted.

6.3.2 - Control Systems

Testing of the final control system was very similar in nature to testing on the scale model. We intended to begin with determining the values of the controller gains using the relay method described in Section 6.1.3. However, The acceleration and steering control systems were not ready for testing in the same manner as described in Section 6.1.3.

6.3.3 - Track Day Safety

The inherently dangerous nature of a high powered system traveling under its own control at high velocities requires a number of stringent safety precautions be taken during testing. The following safety guidelines are recommended for all track day personnel and all tests.

1) Never stand directly in front or behind the vehicle
2) The E-stop shall be under operator control whenever the batteries are connected.
3) Regardless of time saved no personnel should be stationed at the far end of a test. Or within the GPS defined map of the track.
4) At all times a class 2A 10BC (universal) fire extinguisher shall be present at both ends of the track.
5) A battery safety and disposal bucket should be placed at both ends of the track.
6) Battery Safety guidelines described in the safety section shall be followed
7) When the main batteries are installed and the main breaker closed no persons shall make physical contact in any way with the system. All adjustments must be performed before the system is powered on. This excluded powering down the system by pushing the main breaker.
8) The control system should always be powered on before the power system.
9) Sections of the code designed to prevent tampering with the system or unsafe operation shall not be altered on track day. If there is a significant program bug it should be fixed and fully tested prior to track day.

For further safety measures and track day procedure please see the attached documents Track day test protocol and pre-test checklist (Appendix J).

6.4 Test Results

Due to delays in manufacturing the full scale vehicle resulting from shipping, design oversights, and issues on our track testing day many of the tests were unable to be completed to the level that was planned. This section covers the tests that were formally completed and analyzed.

6.4.1 Test Code

When developing and integrating drivers for the various actuators and sensors in the system, test code was written to verify the operation of the devices. The test code for each device is available on the GitHub repository within the folders relating to the devices. Many of these tests were evaluated qualitatively based on serial output from the Nucleo. The tests can be used to further evaluate the hardware by future teams, if desired.

6.4.2 Frame Resonance

Upon noticing that the frame is extremely flexible and acts as a damped mass spring system when loaded with the main batteries we conducted a series of resonance tests utilising the onboard IMU. We set the chassis on a flat level surface fully loaded with all final components including batteries motors and controls systems. We applied impulse to the frame to induce resonance and recorded the resulting acceleration using the controls system IMU. Impulse was applied in all directions and from all sides of the vehicle. Magnitude of the impulses applied was also varied so as to reveal as much of the frames underlying natural and forced response as possible. The goal of these tests was to identify frequencies which we should expect and be able to filter out of IMU data for autonomous control.

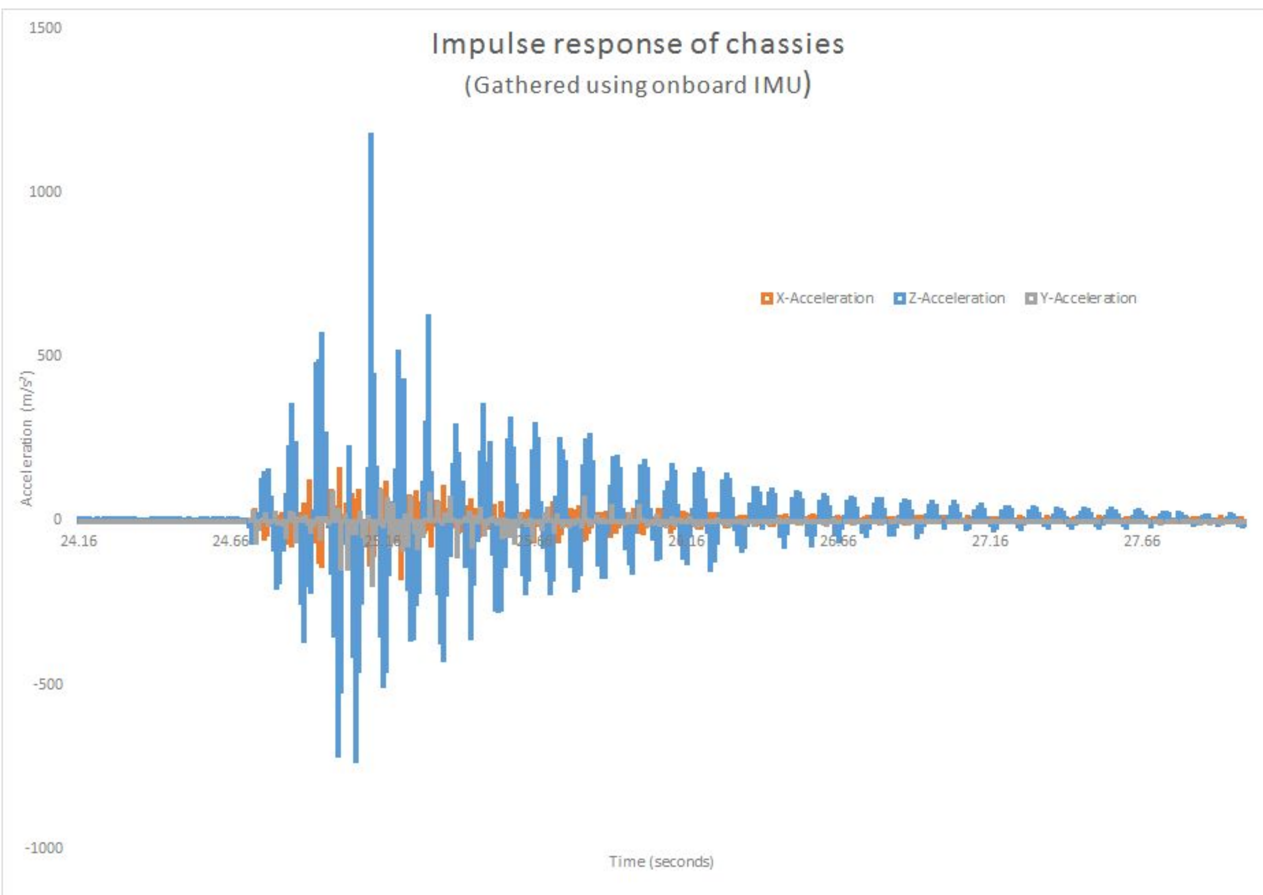


Figure 6.1 Data gathered from impulse testing by IMU.

According to our analysis of the data recorded, which involved correlating the IMU readings with the system latency and GPS timestamps, the chassis has a primary resonant frequency on the Z axis of approximately 2.8Hz. This resonant frequency has very limited damping, with a standard damping coefficient as low as 0.18. The result is a dramatic flexing of the vehicle on the XY plane under nearly any applied impulse. Less dramatic resonances were found on the X and Y axis of the vehicle however these were much higher frequency and had much higher levels of damping. These axis should not be a significant concern in the operation of the vehicle. The Z axis however should be monitored closely to ensure the center of the chassis does not oscillate sufficiently to make contact with the ground.

6.4.3 Steering Control

To evaluate the feasibility of using a heading based steering control loop, the sensor development platform was used to perform a basic test. The test compared a heading angle change over a 16 ft distance of steering control implementation, with a proportional gain of 5, versus the uncontrolled system. The test was also used to determine the drift of the system over that distance by using a marker attached to the back of the vehicle while it drove over a long piece of paper. Figure 6.2 is a picture of the test setup.

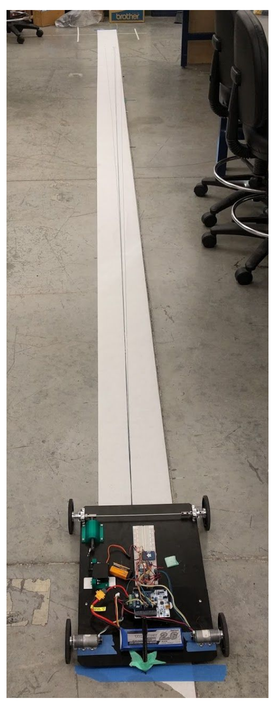


Figure 6.2 Picture of the steering control test setup.

For measuring the heading angle change we used the readings from the IMU which are summarized by Figure 6.3.

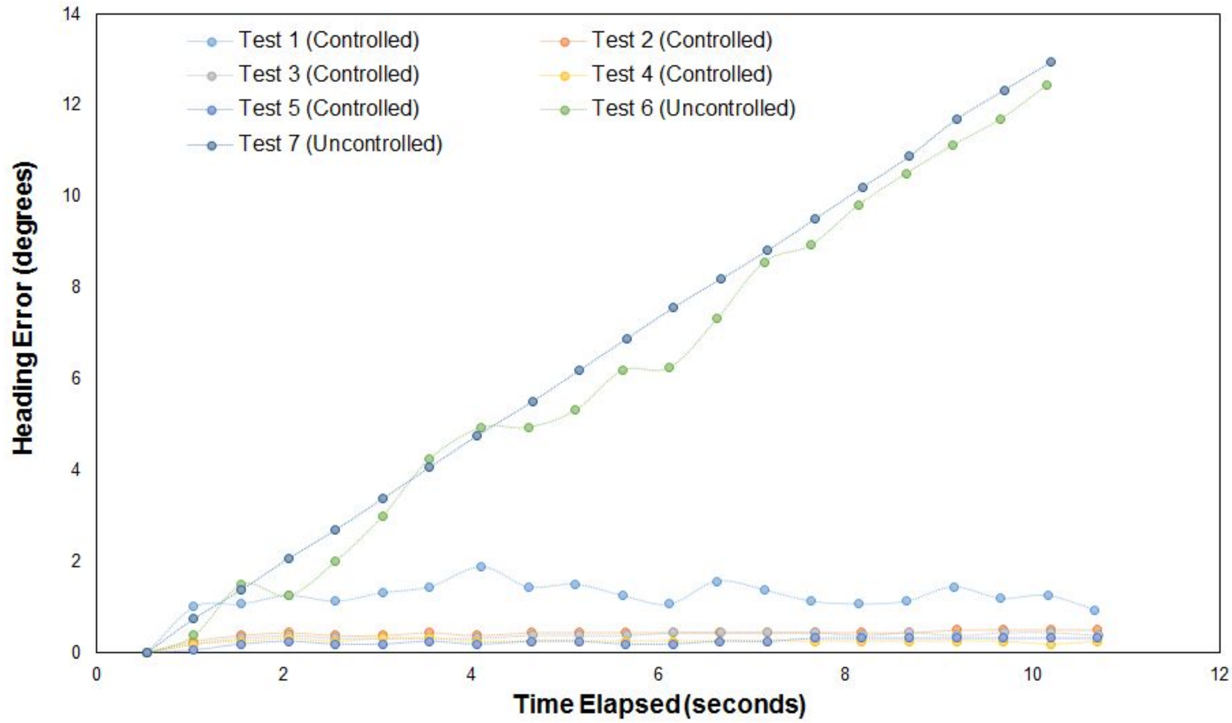


Figure 6.3 Heading angle error over time. Tests were conducted with the sensor platform traveling a distance of approximately 16ft. Maximum heading error of the controlled platform was approximately 1.5°. The controlled tests used a proportional gain of 5 and no integral or derivative gain.

From the test we were also able to determine that the vehicle would drift from the straight line by approximately 3 in over 16 ft (approximately 1.5%) when controlled. This test proves that the heading based steering control is feasible for the final design but further testing and tuning of the hardware on the full scale vehicle would need to be done to implement the control loop.

6.4.4 Acceleration Control

A preliminary test to determine the feasibility of the acceleration control scheme was conducted on the sensor platform. The tests quickly made it apparent that acceleration control based on the IMU accelerometer values would not work well. The noisy nature of the accelerometer measurement lead to erratic unstable behavior of the vehicle. The response was improved when a simple low pass filter was implemented by averaging four readings prior to closing the control loop. Figure 6.4 shows an example of the data produced by the IMU during one of the acceleration test runs.

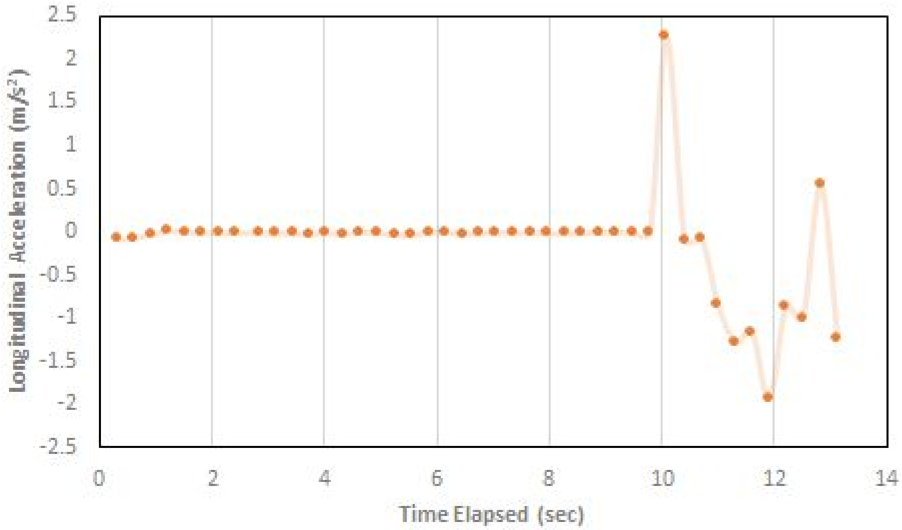


Figure 6.4 Example of acceleration control data. Test was conducted with a proportional gain of 1.0 and no integral or derivative gain. The response of the system was unstable because of large and fast magnitude changes.

Since the car was only using a proportional gain it needed an initial bump to start accelerating. The sensor platform was programmed to accelerate to 0.25 m/s over 0.25 m distance, then hold that velocity for another 0.25 m, and then decelerate to 0 m/s at 0.75 m.

7 - Conclusion and Recommendations

The autonomous test target is designed and intended to reduce human testing error, increase testing accuracy, and remove danger to the human operators. Our controls system is a fundamental component of this larger vehicle. The controls system as designed has the capacity to maneuver our vehicle in a straight line through a series of precise acceleration profiles over nearly two miles of track. The controls system is also designed to be sufficiently adaptable and modular that it can be used by future students as a platform for further autonomous test target development. If properly constructed and calibrated we predict our controls system will provide a safe and effective alternative to the human driven testing currently in use.

7.1 - Recommendations for Future Improvement

At the completion of our senior project, there are many steps that still need to be taken to fully realize Daimler's original vision for the final Guided Target Vehicle. On the controls side of the project, we have produced the hardware and software capable of operating the target frame remotely, but not autonomously. In its current state, the navigation system is able to take user remote control input to drive, steer, and brake, as well as make corrective action using IMU data

when veered off course. However, none of these features have been fully refined and have much room for improvement.

The next steps for this project will be to reiterate the hardware layout to a more compact form, to better accommodate Daimler’s future plans to be able to drive over the frame. However, the primary focus for future control system teams will be to build upon the existing vehicle control to implement autonomous driving capabilities. To enable autonomy, the system will need a more refined method of acceleration control, as well as complete sensor fusion.

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Appendices

Appendix A - QFD Spreadsheet

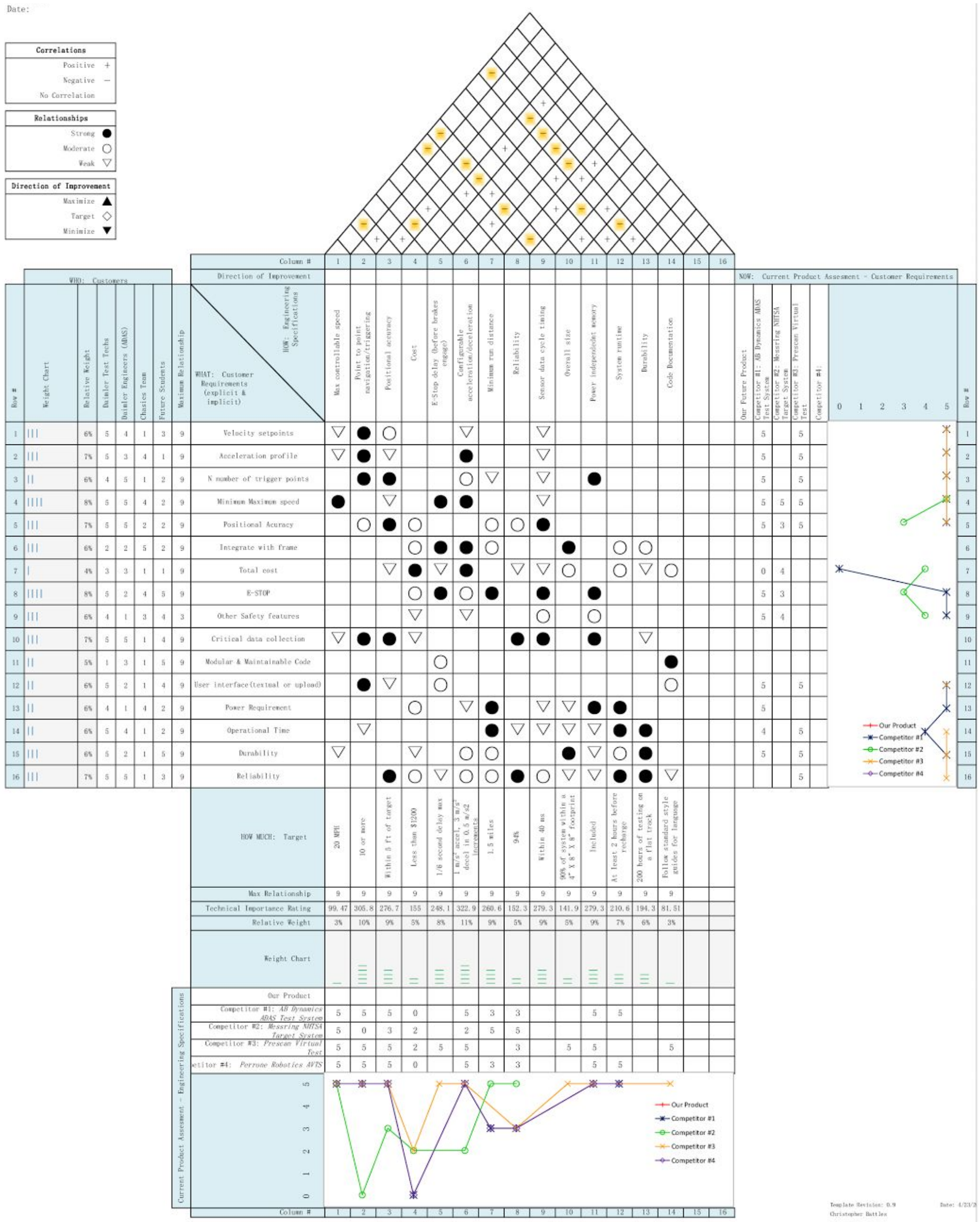
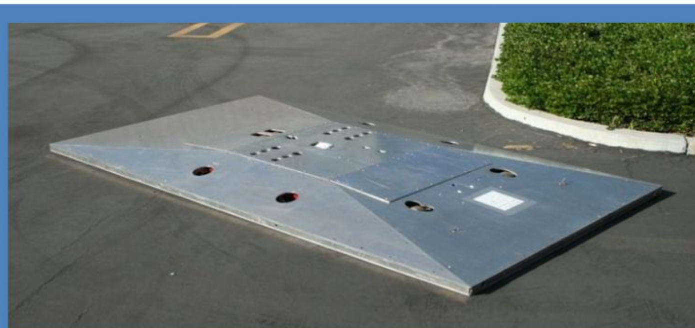


Figure A1. Original Quality function deployment spreadsheet to analyze our customer requirements and create our engineering specifications. Some specifications have been changed based on sponsor and advisor feedback.

Appendix B - Competitor Specification Sheets

Low profile driverless vehicle for dynamic interactions and high-speed impacts with other vehicles

The ABD Guided Soft Target Vehicle (GSTV) is designed for use in the testing of vehicle Advanced Driver Assistance Systems (ADAS), and is particularly suited to the testing of vehicle collision detection and crash mitigation systems. The GSTV is the result of collaboration between ABD and Dynamic Research Inc. of Torrance, California, (DRI), with ABD being primarily responsible for the control system and software and DRI primarily responsible for the chassis. The GSTV is designed to enable high-speed collisions to be carried out without causing significant damage to the test vehicle. It consists of a Low-Profile Chassis (LPC), which can be driven over, and a separate foam panel body (or other suitable payload). When the low-profile vehicle is driven over, the wheels of the vehicle retract into the chassis to protect the suspension of the LPC and to provide the minimum possible shock input to the test vehicle's suspension.



The Low-Profile Chassis (LPC)

The LPC uses electric motors with on-board batteries to propel the vehicle, and houses a control system which can accurately guide the vehicle along a pre-programmed course at a defined speed. The batteries used to power the system will provide sufficient power for a typical 2 hour session. Additionally, they can be recharged between tests by quick connection to a suitable supply at the track.

The controller uses position feedback from a high-precision, GPS-corrected, inertial navigation system to allow accurate path-following control to be achieved. The time signal from the GPS unit is used to ensure the precise millisecond synchronisation that is necessary to generate accurate and repeatable crash and close-passing scenarios. The control system and software is based on the systems used by ABD's standard in-vehicle robots, so that users already familiar with them will find using the GSTV easy. The GSTV is controlled via radio from the same remote base-station that is used by ABD's standard driverless testing system. The common software and hardware platform allows the GSTV and other vehicles driven by ABD's robots to be easily used together to create complex multi-vehicle tests.

Summary of GSTV features

- Aluminium chassis - wheels retract into chassis when LPC is driven over
- Electric drive system with belt drive transmission
- Electrically-actuated steering system
- Lithium Iron Phosphate battery pack for good power to weight ratio
- 4-disc hydraulic braking system with failsafe emergency braking
- Uses ABD's proven driverless control system, with hardware mounted in water-resistant casing
- Position feedback from Inertial Navigation System with GPS correction
- Accurate path-following and speed control capability
- Control software for operation of Guided Soft Target Vehicle allows coordinated motion with other vehicles (either driven manually or equipped with ABD's driving robots)
- LPC has Low radar signature to minimise "visibility" to car's sensors

GSTV fitted with foam panel body

Reassembly of foam body takes 10 minutes

Anticipated Performance / Dimensions	
Typical Maximum speed	**70 km/h (depending upon aerodynamic drag)**
Maximum acceleration	**0.3g**
Maximum deceleration	**0.9g**
Maximum lateral acceleration	**0.4 – 0.5g**
Foam panel car body mass	**60kg**
Low profile vehicle mass	**260kg**
LPC Length	**2800mm**
LPC Width	**1520mm**
LPC Height (suspension retracted into chassis)	**125mm**
LPC Height (suspension at full rebound and set to maximum ride height)	**155mm**
LPC Edge height	**40mm**
LPC Wheelbase	**1400mm**
LPC Front track	**660mm**
Max ground clearance, set to max ride height	**30mm**
Testing duration	**Estimated 2 hours before battery recharge required**
Path-following accuracy	**Dependent upon motion pack (2cm *1SD RMS* typical maximum)**

For more detailed information on this and other related products contact:

Email: info@abd.uk.com
Tel: +44 (0)1225 860200

ABD has representatives throughout the world.
For details please refer to our website:
www.abd.uk.com

"This product may be covered by one or more of the following US Patents: 8,428,864; 8,447,509; and 8,457,877. Patents pending."

avts target robots

safe, accurate, and repeatable testing of collisions with adas, partial, and fully automated vehicles.

The Automated Vehicle Test System (AVTS) target robots are low profile mobile autonomous ground vehicle platforms that allow safe run-over by vehicles. Atop of the target robot platforms, "soft targets" such as balloon, foam, or other soft materials representing other ***vehicles***, ***pedestrians***, or ***cyclists*** may be placed. As such,the AVTS target robots allow for the programmable plotting of repeatable routes that are engaged by ADAS-equipped, partial, or fully autonomous vehicles.

The AVTS TRV is an AVTS Target Robot capable of carrying a 230 lb. soft target representative of a vehicle while exhibiting high speed vehicle dynamics and behavior. The TRV supports testing and safe collisions at highway speeds and can be used within indoor, covered, and outdoor test facilities alike.

The TRV was developed based on requirements from the Insurance Institute for Highway Safety (IIHS) for the execution of their current and future tests of ADAS-equipped, partial, and eventual fully automated vehicles. Additionally, support for tests outlined by other agencies is supported by the TRV including NHTSA Forward Collision Warning (FCW), NHTSA Crash-Imminent Braking (CIB), NHTSA Dynamic Brake Support (DBS), Euro NCAP Autonomous Emergency Braking (AEB), among others.

TRV key features include:

- Programmable autonomous navigation of routes, trajectories, and maneuvers
- Acceleration, steering, and braking dynamics similar to a passenger car
- Carry payloads up to 230 lbs
- Passenger car footprint of 12 feet long x 5.5 feet wide
- Run-over height of 5 inches
- Speeds of 0 to 55 mph in 8 seconds or less
- Braking up to 1g
- Tele-operated control as well as autonomous

target robot base

The Target Robot base is a low-profile robotic platform designed to carry "crashable" soft targets representing passenger cars, trucks, cyclists, and pedestrians. If the safety system of the vehicle under test fails to prevent a collision, the test vehicle runs over the base and collides with the soft target, which can be quickly retrieved and reassembled on top of the Target Robot base. All Target Robot bases are designed to sustain run-over from SUVs and some for run-over by tractor trailers. The base of each Target Robot is 3" to 5" high (tractor trailer bases vary).

control and navigation

The Target Robot can be remotely controlled or configured for autonomous navigation of test profiles in software. A sophisticated and highly programmable set of maneuvers can be configured to yield a wide range of automotive test procedures and scenarios. The Target Robot includes sensors for position, heading, and speed as well as a ruggedized computer with software for navigation and control. The Target Robot is can be used with any preferred GPS system. The AVTS Target Robots have also been integrated with the Locata local positioning system enabling more precise positioning as well as use for indoor or covered track environments.

Built using the ***MAX™ general purpose robotics and automated vehicle operating system (https://perronerobotics.squarespace.com/max)***, the TRV and AVTS Target Robots inherit a long legacy of sophisticated fully autonomous robotics functions, maneuvers, and programmable behaviors.

e-stop system

The AVTS Target Robot includes a robust E-Stop system for stopping and powering down in the event of unsafe conditions. A Target Robot can be manually stopped and powered off at any time with a handheld remote E-Stop unit. A Target Robot also monitors communications and navigation systems to automatically shut down and stop based upon sensor or system failures. A watchdog inside of the Target Robot performs fail-safe monitoring of signals and information. The Watchdog responds to fail-safe signals from remote E-Stop units and passively monitors information from the Target Robot computers and sensors. Upon any E-Stop trigger, the Target Robot will immediately perform safety critical responses inclusive of controlled braking, emergency fail-safe braking, drive system cut-off, and power cut-off.

Setting the standard in automotive testing

RT2000

Cost-effective GNSS/INS for vehicle dynamics testing

The RT2000 family of inertial navigation systems from Oxford Technical Solutions combine high-grade gyros and accelerometers with cost-effective GNSS technology to deliver a complete dynamics solution on a budget.

>> Key features

>>RT2002 v2

- 1 cm position accuracy
- 0.2° slip angle

>>RT2500/RT2502

- 50 cm position accuracy
- Single or dual antenna

>>RT2000 common features

- High accuracy orientation
- GLONASS option
- Optional CAN acquisition
- OxTS gx/ix performance technology
- Multiple slip points
- Driving robot interface
- Tightly coupled GNSS/INS
- ISO 17025 calibration available

>> Applications

- Vehicle dynamics analysis
- ADAS validation
- NHTSA regulation testing
- Tyre testing
- Driving robot control
- Acceleration testing
- Electronic power steering tests
- Slip angle measurement

>> Experts in GNSS and inertial technology

Advanced algorithms in the RT2000 seamlessly blend the inertial and GNSS data to provide smooth, robust, real-time outputs. Even in poor GNSS environments the RT2000 remains accurate with low latency outputs of position, velocity, orientation and more. Now with OxTS gx/ix technology, we have improved position, velocity and orientation measurements making the performance even better than ever before.

>> One box, turnkey solution

Combining GNSS receivers, an inertial measurement unit, internal storage and a real-time on-board processor all in one compact box, the RT2000 delivers everything you need for a complete dynamics solution. The optional CAN acquisition upgrade eliminates the need for 3rd party acquisition systems making the RT2000 a true one-box solution for vehicle test engineers. All cables and antennas are included, and the RT2000 comes with an extensive software suite so you can post-process and plot your data at no additional cost.

>> Simple, flexible, reliable

With secure mounting options available and simple software wizards, installing and using the RT2000 is quick and easy. Data can be output at up to 250 Hz over Ethernet, serial or CAN in a range of formats. Packed with features to improve performance and functionality, including wheel speed input, driving robot interface, and heading lock, the RT2000 ensures reliable performance in all situations.

>> Worldwide standard

OxTS inertial navigation systems are recognised as a symbol of precision and performance around the globe. With a large number of systems in operation wordwide, you can be sure of the quality to expect from the RT2000. Now with ISO 17025 calibration available, our inertial measurements are traceable to national standards.

>> RT2000 models

100 Hz model	RT2500	RT2502	RT2002 v2
250 Hz model[1]	RT2500-250	RT2502-250	RT2002-250 v2

>> Performance[2]

Positioning	GPS L1 GLONASS[1] L1	GPS L1 GLONASS[1] L1	GPS L1, L2 GLONASS[1] L1, L2
Position accuracy (CEP)			
SPS	2.0 m	2.0 m	1.5 m
SBAS	1.0 m	1.0 m	0.6 m
DGPS	0.5 m	0.5 m	0.4 m
RTK			0.01 m
Velocity accuracy (RMS)	0.1 km/h	0.1 km/h	0.1 km/h
Roll/pitch accuracy (1σ)	0.05°	0.05°	0.05°
Heading accuracy (1σ)	0.2°	0.15°[3]	0.1°
Track angle accuracy (1σ)[4]	0.15°	0.15°	0.1°
Slip angle accuracy (1σ)[4]	0.3°	0.25°	0.2°
Dual antenna	x	✓	x

>> Interfaces

- Ethernet
- Serial
- CAN
- Digital I/O:
  - Odometer input
  - Event input trigger
  - 1PPS output
  - Odometer simulation output
  - IMU sync output

>> Hardware

Dimensions	234 x 120 x 76 mm
Mass	2.3 kg (RT250_) 2.4 kg (RT200_)
Input voltage	10–25 V dc
Power consumption	15 W
Operating temperature	-10° to 50° C
Vibration	0.1 g^2/Hz, 5–500 Hz
Shock survival	100 g, 11 ms
Internal storage	2 GB

>> Sensors

Type	Accelerometers	Gyros
Technology	MEMS	MEMS
Range	10 g	100°/s
Optional	30 g	300°/s
Bias stability	5 µg	3°/hr
Linearity	0.01%	0.05%[5]
Scale factor	0.1%	0.1%
Random walk	0.005 m/s/√hr	0.2°/√hr
Axis alignment	<0.05°	<0.05°

[1] Optional upgrade.
[2] Valid for open sky conditions.
[3] 2 m antenna separation. Wider separation will improve accuracy. Supports up to 5 m separation.
[4] At 50 km/h.
[5] With SuperCAL adjustment.

Document version: 140613. Specifications subject to change without notice.

OXTS Inertial+GPS
77 Heyford Park, Upper Heyford, Oxfordshire, OX25 5HD, UK
Tel: +44 1869 238 015 Email: sales@oxts.com Web: www.oxts.com

Appendix C - Bill of Materials

**"Part Ref. Number" based on the part number in the parts list and drawings

Table C1. Final Bill of Materials. The P column refers to if the item was purchased, R refers to if the item was received, and U refers to if the item was used in the final project. Green implies that the column is true and red means it is false.

Part Category	Part Type	Selected Part	Part Ref. Number	Vendor Item Number	Vendor	Qty	Unit Cost	Cost	P?	R?	U?
Central Control	MCU	STM32 Nucleo-64 F446RE	10	3A991A2	ST	1	$13	$13			
	Battery	Turnegy Lipo Battery	7	T2650.3S.20	Turnegy	1	$11.02	$11.02			
	9V Holder	9V Enclosed Battery Holder W/Switch	49	VUPN7826	Amazon	1	$2.95	$2.95			
	9V Battery	Duracell CopperTop - 9V Size - Alkaline Battery	50	MN1604B2Z	Amazon	1	$3.20	$3.20			
	Battery Charger	Turnigy 12v 2-3S Basic Balance Charger	22	Turnigy-3S	Turnegy	1	$4.81	$4.81			
	IMU	BNO055 Absolute Orientation Sensor	9	2472	Adafruit	1	$34.95	$34.95			
	GPS	Ultimate GPS Breakout 66 channel w/ 10Hz updates	8	724	Adafruit	1	$39.95	$39.95			
	Radio Comms	AR610 (pairs with DX6e)	23	SPM6650	Horizon Hobby	1	(included transmitter)	0			
	Power Conditioner	Ferrite Bead	24	32121703	Amazon	1	$6.25	$6.25			

	Opto Isolators	Sparkfun optoisolator breakout	11	BOB-09118	Sparkfun	5	$4.95	$24.75			
	SD Card Breakout	Micro SD card breakout (part 254)	12	254	Adafruit	1	$7.50	$7.50			
Frame Interface	Motor ESC	KBL BLDC MOTOR SPEED CONTROLLER		KBL48301X	Kelly Motor Controls	2	$319.00	$638.00			
	Proximity Startup E-stop	Adjustable PIR Motion Sensor	26	RB-Ite-116	RobotShop	4	$2.62	$10.48			
	Thermal Breaker	Hi-Amp Surface Mount Circuit Breakers	27	77082	Del City	1	$44.29	$44.29			
	Reverse polarity protection Solenoid	SPST 48V 200A Grounded Intermittent Solenoid	28	MJZ-200D	Golf Cart Parts Outlet	2	$51.43	$102.86			
	Braking Motor Driver	VNH5019 Motor Driver Carrier	29	1451	Polulu	1	$24.95	$24.95			
	Motor Encoder	CUI Inc. AMT102-V	39	102-1307-ND	Digikey	2	$23.63	$47.26			
Enclosure	Enclosure	Electrical enclosure with knockouts	2	75065K59	McMaster-Carr	1	$41.22	$41.22			
	Enclosure Fastener plate	Delrin® Acetal Resin Sheets	6	8573K285	McMaster-Carr	1	$12.30	$12.30			
	Spacers	Nylon Unthreaded Nucleo Spacers	13	93657A021	McMaster-Carr	3	$1.09	$3.27			

		Nylon Unthreaded Sensor Spacers	14	93657A212	McMaster-Carr	10	$1.02	$10.20			
		Nylon Unthreaded Plate Spacers	3	94639A862	McMaster-Carr	1	$8.51	$8.51			
	Screws	M2 Stainless Steel Socket Head Screw	16	91292A835	McMaster-Carr	1	$3.86	$3.86			
		M3 Stainless Steel Socket Head Screw	17	91292A123	McMaster-Carr	1	$6.00	$6.00			
		M5 Stainless Steel Socket Head Screw	18	91292A127	McMaster-Carr	1	$7.78	$7.78			
		M6 Stainless Steel Socket Head Screw	4	91292A144	McMaster-Carr	1	$7.76	$7.76			
	Nuts	M2 Medium-Strength Steel Thin Hex Nut	19	90695A025	McMaster-Carr	1	$3.64	$3.64			
		M3 Zinc-Plated Steel Hex Nut	20	90591A250	McMaster-Carr	1	$2.06	$2.06			
		M5 Zinc-Plated Steel Hex Nut	21	90591A260	McMaster-Carr	1	$2.61	$2.61			
		M6 High-Strength Steel Hex Nut	5	99899A211	McMaster-Carr	1	$7.53	$7.53			

	Hall Effect Sensors	Discrete 3 pin hall effect sensors	51		Digikey	6	$0.57	$1.71		
	Rubber Bumpers	Adhesive round back bumpers	30	8771K82	McMaster-Carr	1	$5.67	$5.67		
	Rubber damper for enclosure lid	Weatherproof window insulation	54	5602-32-AFC	HomeDepot	1	$2.12	$2.12		
	Conduit	1/2 in. x 100 ft. Flexible Aluminum Conduit	31	5602-30-AFC	HomeDepot	1	$32.37	$32.37		
	Radio Antenna	Spectrum DX6e	32	SPM6650	Horizon Hoby	1	$179.00	$179.00		
	SD card Reader	IOGEAR micro SD reader	33	GFR204SD	Amazon	1	$4.69	$4.69		
External	GPS antenna	SMA external antenna	34	960	adafruit	1	$12.92	$12.92		
	Controls interface connectors	HIGHROCK Automotive Connectors	35	HRD-PN-79121989	Amazon	1	7.99	7.99		
	Power systems connectors	8AWG Battery Lugs	36	33461	Pilotshop	20	1	20		
	Controls power Switch	Toggle Switch and Cover	37	COM-11310	Sparkfun	1	2.95	2.95		
	GPS Antenna adapter	SMA adapter	38	851	adafruit	1	$3.95	$3.95		
							Total	$1,406		

Appendix D - Gantt Chart

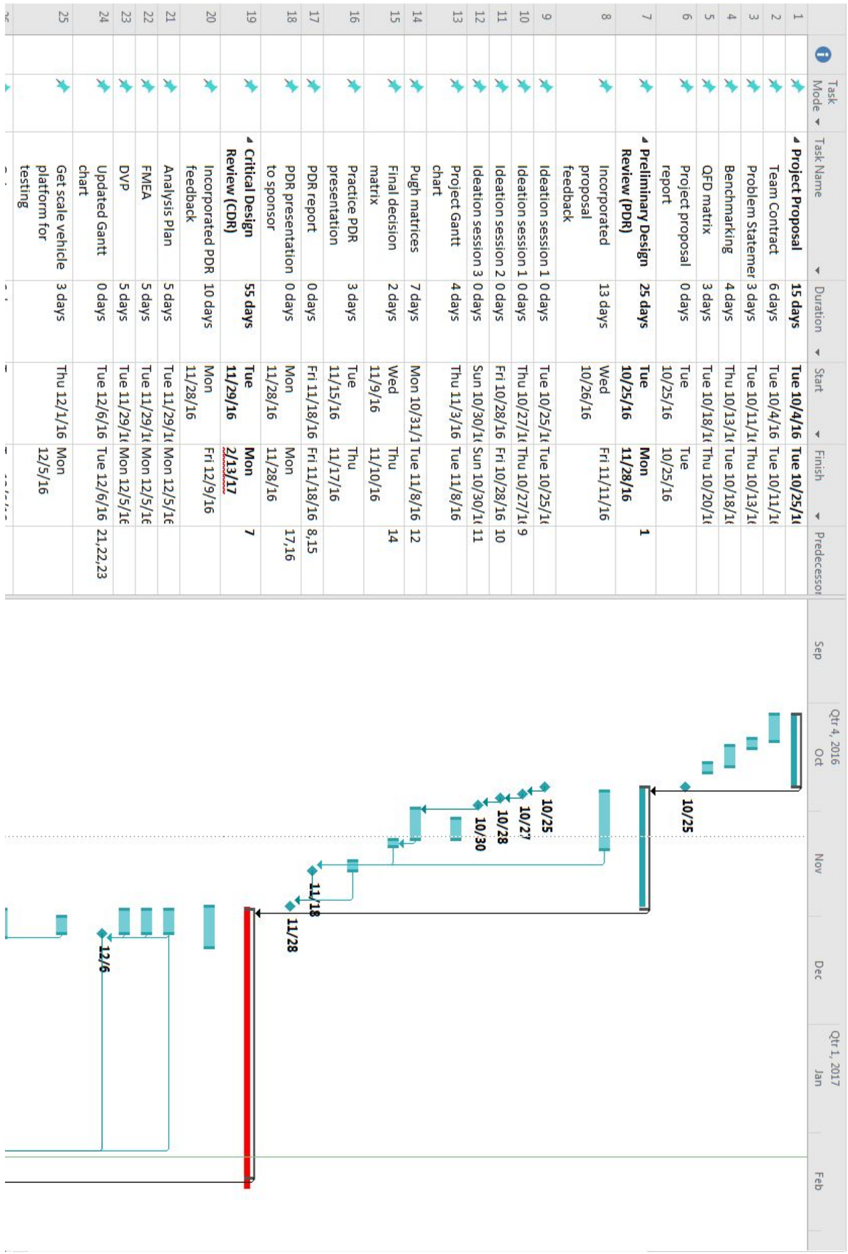


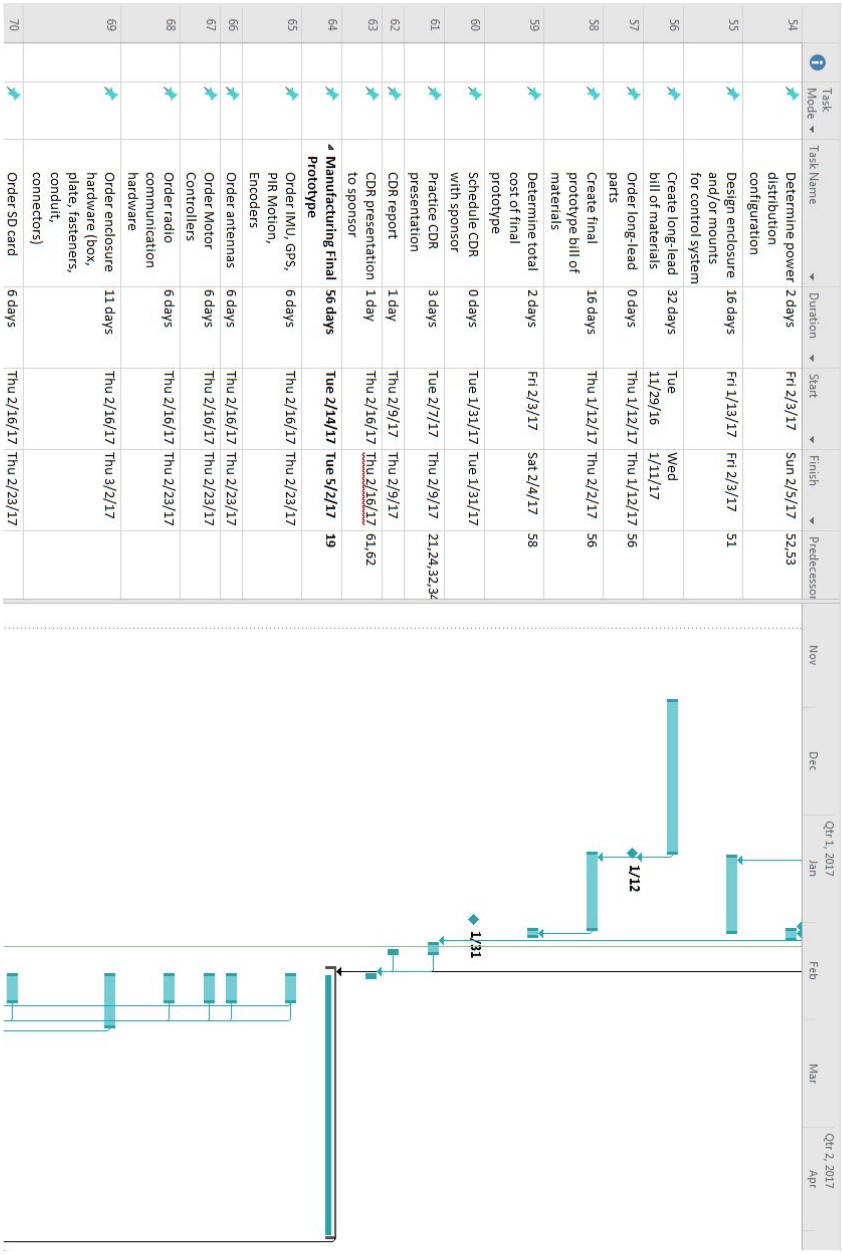
Figure D.1 Gantt Chart showing major milestones and tasks in project timeline. Part 1 of 7.

	Task Mode	Task Name	Duration	Start	Finish	Predecessors
26		Get microcontroller board	6 days	Tue 11/29/16	Tue 12/6/16	
27		Get motor drivers for scale vehicle	5 days	Tue 12/6/16	Mon 12/12/16	25
28		Get GPS module for testing	5 days	Tue 11/29/16	Mon 12/5/16	
29		Get IMU module for testing	5 days	Tue 11/29/16	Mon 12/5/16	
30		Write IMU driver for test platform	23 days	Tue 12/6/16	Thu 1/5/17	29
31		Write GPS driver for test platform	23 days	Tue 12/6/16	Thu 1/5/17	28
32		Determine sensor fusion algorithm (IMU + GPS)	7 days	Fri 1/6/17	Mon 1/16/17	30,31
33		Determine latency of sensor fusion data	6 days	Tue 1/17/17	Tue 1/24/17	32
34		Choose IMU to use in final prototype	8 days	Sat 1/21/17	Tue 1/31/17	30,32
35		Choose GPS to use in final prototype	8 days	Sat 1/21/17	Tue 1/31/17	31,32
36		Determine motor type for final design	13 days	Tue 11/29/16	Thu 12/15/16	
37		Develop motor model	20 days	Fri 12/16/16	Thu 1/12/17	36
38		Develop preliminary motor driver code	23 days	Tue 12/13/16	Thu 1/12/17	27
39		Verify motor model with scale system	5 days	Fri 1/13/17	Thu 1/19/17	37,38
40		Determine motor control system algorithm	5 days	Fri 1/20/17	Thu 1/26/17	39
41		Choose motor	3 days	Fri 1/27/17	Tue 1/31/17	40

Figure D.2 Gantt Chart showing major milestones and tasks in project timeline. Part 2 of 7.

	Task Mode	Task Name	Duration	Start	Finish	Predecessor
41		Choose motor driver for final prototype	3 days	Fri 1/27/17	Tue 1/31/17	40
42		Determine braking system components	28 days	Tue 11/29/16	Thu 1/5/17	
43		Develop braking model	5 days	Fri 1/6/17	Thu 1/12/17	42
44		Develop braking system scale model	2 days	Fri 1/13/17	Mon 1/16/17	
45		Verify braking model with scale system	5 days	Tue 1/17/17	Mon 1/23/17	43,44
46		Determine braking control system algorithm	3 days	Tue 1/24/17	Thu 1/26/17	45
47		Choose control components for braking system	3 days	Fri 1/27/17	Tue 1/31/17	46
48		Determine high level structure of software	38 days	Tue 11/29/16	Thu 1/19/17	
49		Create diagrams of software control flow	5 days	Fri 1/20/17	Thu 1/26/17	48
50		Develop framework for final system	6 days	Fri 1/27/17	Fri 2/3/17	48,49
51		Determine physical interface with frame	33 days	Tue 11/29/16	Thu 1/12/17	
52		Determine electrical interface with frame	34 days	Tue 11/29/16	Fri 1/13/17	
53		Determine power requirements for system	2 days	Wed 2/1/17	Thu 2/2/17	34,35,41,4
54		Determine power	2 days	Fri 2/3/17	Sun 2/5/17	52,53

Figure D.3 Gantt Chart showing major milestones and tasks in project timeline. Part 3 of 7.



	Task Mode	Task Name	Duration	Start	Finish	Predecessors
54		Determine power distribution configuration	2 days	Fri 2/3/17	Sun 2/5/17	52,53
55		Design enclosure and/or mounts for control system	16 days	Fri 1/13/17	Fri 2/3/17	51
56		Create long-lead bill of materials	32 days	Tue 11/29/16	Wed 1/11/17	
57		Order long-lead parts	0 days	Thu 1/12/17	Thu 1/12/17	56
58		Create final prototype bill of materials	16 days	Thu 1/12/17	Thu 2/2/17	56
59		Determine total cost of final prototype	2 days	Fri 2/3/17	Sat 2/4/17	58
60		Schedule CDR with sponsor	0 days	Tue 1/31/17	Tue 1/31/17	
61		Practice CDR presentation	3 days	Tue 2/7/17	Thu 2/9/17	21,24,32,34
62		CDR report	1 day	Thu 2/9/17	Thu 2/9/17	
63		CDR presentation to sponsor	1 day	Thu 2/16/17	Thu 2/16/17	61,62
64		**Manufacturing Final Prototype**	**56 days**	**Tue 2/14/17**	**Tue 5/2/17**	**19**
65		Order IMU, GPS, PIR Motion, Encoders	6 days	Thu 2/16/17	Thu 2/23/17	
66		Order antennas	6 days	Thu 2/16/17	Thu 2/23/17	
67		Order Motor Controllers	6 days	Thu 2/16/17	Thu 2/23/17	
68		Order radio communication hardware	6 days	Thu 2/16/17	Thu 2/23/17	
69		Order enclosure hardware (box, plate, fasteners, conduit, connectors)	11 days	Thu 2/16/17	Thu 3/2/17	
70		Order SD card	6 days	Thu 2/16/17	Thu 2/23/17	

Figure D.4 Gantt Chart showing major milestones and tasks in project timeline. Part 4 of 7.

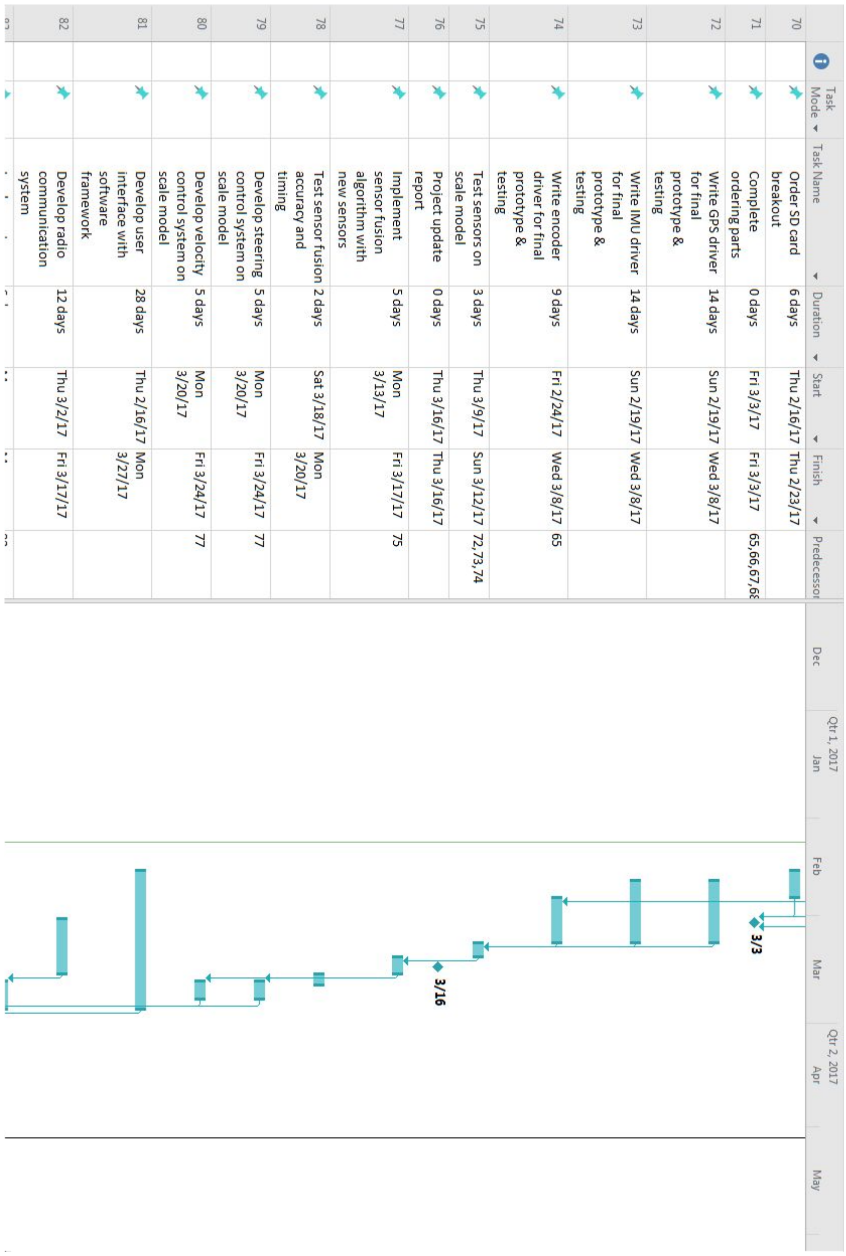
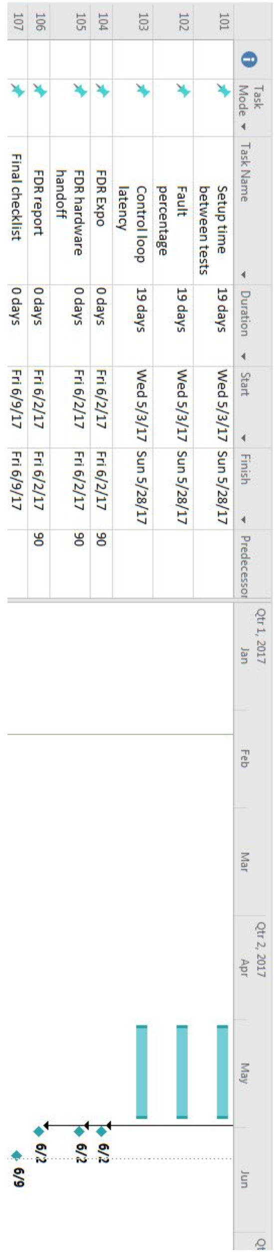


Figure D.5 Gantt Chart showing major milestones and tasks in project timeline. Part 5 of 7.

	Task Mode	Task Name	Duration	Start	Finish	Predecessors
83		Implement emergency stop and safety systems	6 days	Mon 3/20/17	Mon 3/27/17	82
84		Write motor controller driver for final prototype & testing	18 days	Thu 3/2/17	Mon 3/27/17	
85		Begin integration with frame design	19 days	Tue 3/28/17	Fri 4/21/17	84,79,80,81
86		Conduct integration tests	7 days	Sat 4/22/17	Mon 5/1/17	85
87		Hardware/Safety demo	0 days	Tue 5/2/17	Tue 5/2/17	
88		**Final Design Review (FDR)**	**23 days**	**Wed 5/3/17**	**Fri 6/2/17**	**64**
89		Track Day Testing	1 day	Wed 5/10/1:	Wed 5/10/1:	
90		**Specification Evaluation**	**19 days**	**Wed 5/3/17**	**Sun 5/28/17**	
91		Max speed	19 days	Wed 5/3/17	Sun 5/28/17	
92		Speed increments	19 days	Wed 5/3/17	Sun 5/28/17	
93		Speed accuracy	19 days	Wed 5/3/17	Sun 5/28/17	
94		Number of trigger points	19 days	Wed 5/3/17	Sun 5/28/17	
95		Positional accuracy	19 days	Wed 5/3/17	Sun 5/28/17	
96		Straight line accuracy	19 days	Wed 5/3/17	Sun 5/28/17	
97		E-Stop signal latency	19 days	Wed 5/3/17	Sun 5/28/17	
98		Max acceleration	19 days	Wed 5/3/17	Sun 5/28/17	
99		Max deceleration	19 days	Wed 5/3/17	Sun 5/28/17	
100		Acceleration/Dı increments	19 days	Wed 5/3/17	Sun 5/28/17	
101		Setup time between tests	19 days	Wed 5/3/17	Sun 5/28/17	

Figure D.6 Gantt Chart showing major milestones and tasks in project timeline. Part 6 of 7.



	Task Mode	Task Name	Duration	Start	Finish	Predecessors
101		Setup time between tests	19 days	Wed 5/3/17	Sun 5/28/17	
102		Fault percentage	19 days	Wed 5/3/17	Sun 5/28/17	
103		Control loop latency	19 days	Wed 5/3/17	Sun 5/28/17	
104		FDR Expo	0 days	Fri 6/2/17	Fri 6/2/17	90
105		FDR hardware handoff	0 days	Fri 6/2/17	Fri 6/2/17	90
106		FDR report	0 days	Fri 6/2/17	Fri 6/2/17	90
107		Final checklist	0 days	Fri 6/9/17	Fri 6/9/17	

Figure D.7 Gantt Chart showing major milestones and tasks in project timeline. Part 7 of 7.

Appendix E - Design Ideation Sessions and Brainstorming

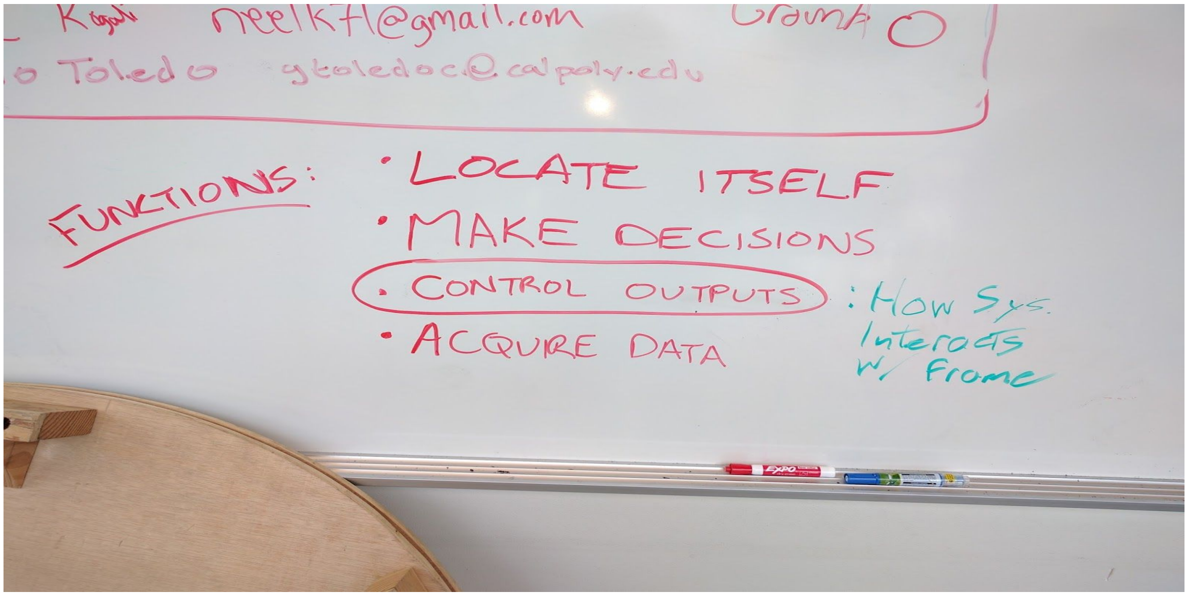


Figure E.1 Ideation session list

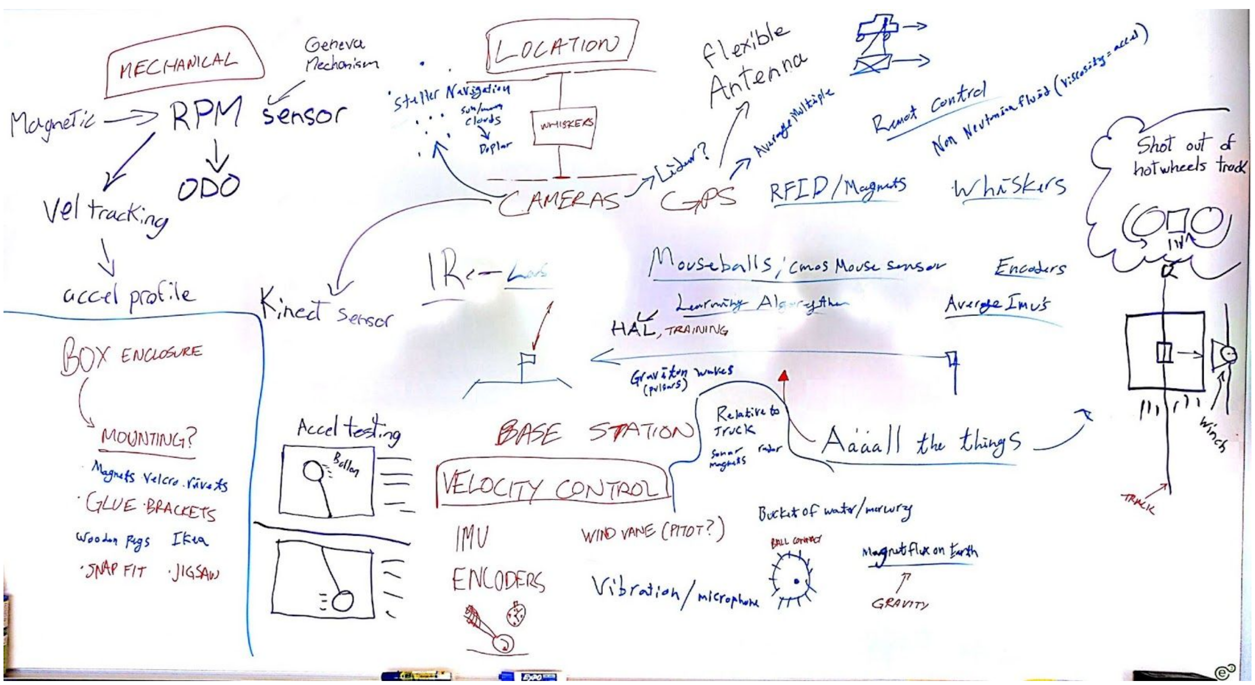
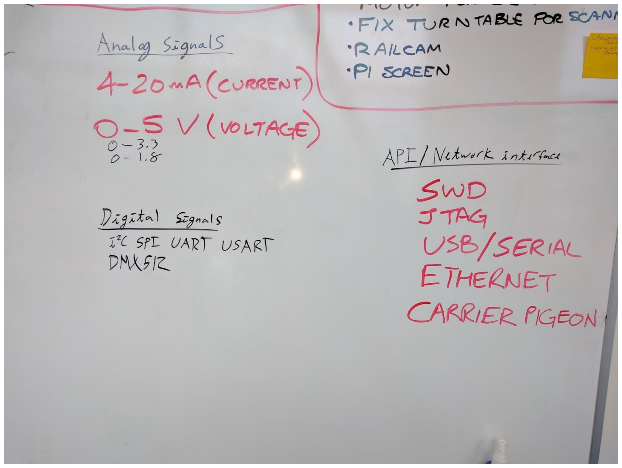
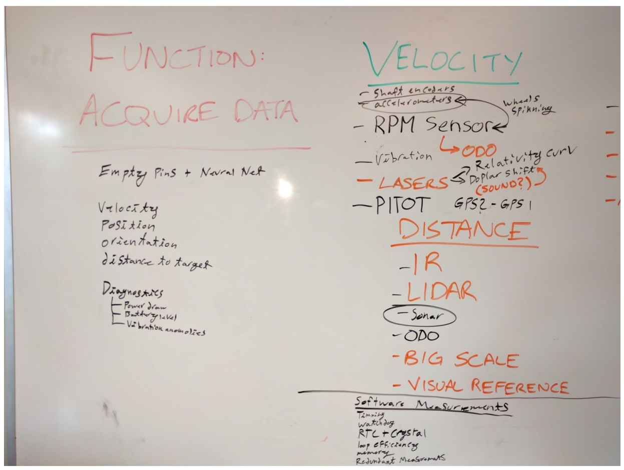


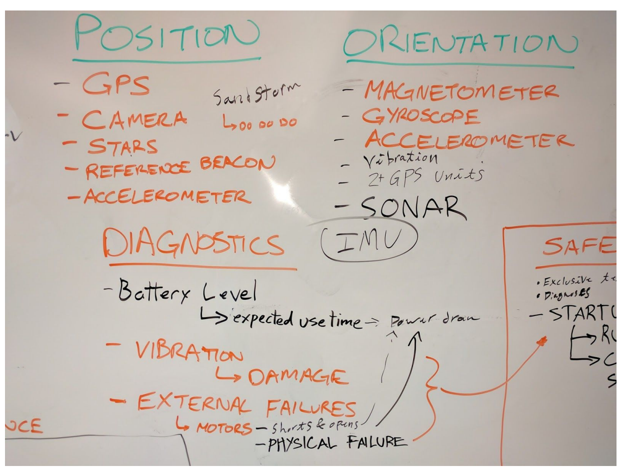
Figure E.2 Locate itself ideation session



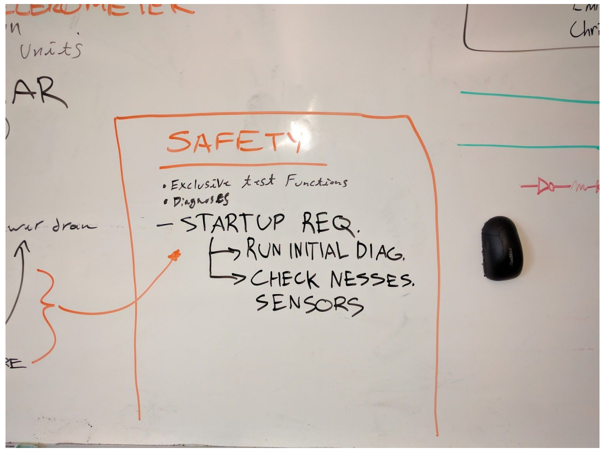
Analog Signals
4-20mA (CURRENT)
0-5 V (VOLTAGE)
0-3.3
0-1.8
Digital Signals
I2C SPI UART USART
DMX512
•FIX TURNTABLE FOR SCAN
•RAILCAM
•PI SCREEN
API/Network interface
SWD
JTAG
USB/SERIAL
ETHERNET
CARRIER PIGEON



FUNCTION:
ACQUIRE DATA
Empty Pins + Neural Net
Velocity
Position
orientation
distance to target
Diagnostics
Power draw
Battery level
Vibration anomalies
VELOCITY
- Shaft encoders
- accelerometers
wheels spinning
- RPM Sensor
↳ODO
- Vibration
Relativity curv
Doplar shift
- LASERS
(SOUND?)
- PITOT
GPS2 - GPS1
DISTANCE
- IR
- LIDAR
- Sonar
- ODO
- BIG SCALE
- VISUAL REFERENCE
Software Measurements
Timing
watchdog
RTC + Crystal
loop efficiency
memory
Redundant Measurements



POSITION
- GPS
Sand Storm
- CAMERA
↳oo oo oo
- STARS
- REFERENCE BEACON
- ACCELEROMETER
ORIENTATION
- MAGNETOMETER
- GYROSCOPE
- ACCELEROMETER
- Vibration
- 2+ GPS Units
- SONAR
IMU
DIAGNOSTICS
- Battery Level
↳ expected use time ⇒ Power draw
- VIBRATION
↳ DAMAGE
- EXTERNAL FAILURES
↳ MOTORS - shorts & opens
- PHYSICAL FAILURE
SAFE
• Exclusive
• Diagnoses
- START



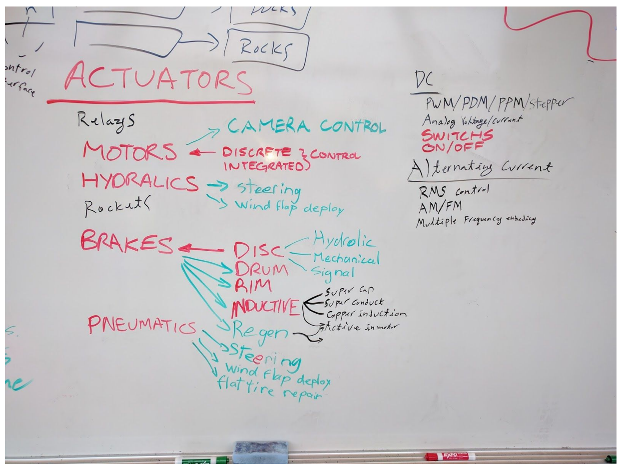


Figure E.3 Sensor and actuator ideation sessions.

Appendix F - Detailed Supporting Analysis

Steering Simulation Matlab Script
test_vehicle_model.m

Script contains variable declarations and loads data necessary to execute the test vehicle Simulink model (test_vehicle_model.slx)

```
% Developed by: SloNav (John Barry, Zach Eagan, Ryan Mackintosh)
% Date Created: Jan. 19, 2017
% License: MIT
```

Clears workspace, command window, and closes windows

```
clear all
close all
clc
```

Controller

```
% Setpoints and disturbances
look_ahead = 1;        % Look ahead carrot point [ft]
disturb_time = 5;      % Time of disturbance [sec]
disturb_val = 30;      % Intensity of disturbance [lb]
speed_sp = 30;         % 2 * Speed of motors [%FS]

% PID Controller coefficients for steering system
steer_P = 1;
steer_I = 0.15;
steer_D = 0.2;
steer_N = 100;
```

Inputs

Variables that define the initial conditions and length of simulation

```
u_start = 0.01;   % Starting speed of the vehicle [ft/s]
t_start = 0;      % Simulation start time [s]
t_stop = 70;      % Simulation stop time [s]
```

Motor variable declarations

Variables are used for both motors

```
% Motor variables
k_motor = 167;         % Motor gain (Kv) [RPM/V]
t_motor = 0.025;       % Motor time constant [1/sec]
gear_ratio = 1/4.1;    % Gearing after motor [RPM/RPM]
```

Vehicle dynamics variable declarations

Geometry

```
B = 5;          % Track width [ft]
L = 7;          % Length between axles [ft]
a = 3.75;       % Distance from center of gravity to solid axle [ft]
b = L - a;      % Distance from center of gravity to motors [ft]
m = 300/32.2;           % Mass of vehicle [lb]
I = 210000/(12^2); % Moment of inertia of vehicle [lb*ft^2]

% Tire properties
R = 4/12;       % Wheel radius [ft]
Kx = 2150;      % Longitudial slip stiffness [lb/rad]
Ka = 2150;      % Cornering stiffness [lb/rad]
```

Runs Simulink model

Executes the test_vehicle_model.slx

```
sim('test_vehicle_model');
figure(1);
plot(pos(:,1),pos(:,2));
xlabel('X Position');
ylabel('Y Position');
```

Appendix G - Failure Mode Effects Analysis (FMEA)

*See the following pages

Item / Function	Potential Failure Mode	Potential Effect(s) of Failure	Severity (0 - 10)	Potential Cause(s) / Mechanism(s) of Failure	Occur (0 - 10)	Critical (0 - 100)	Recommended Action(s)	Responsibility & Target Completion Date	Actions Taken
System Element: Power									
		System Moves Too Fast	8	Over Voltage	6	48	Remove Power source and allow energy disipation. In the design add voltage independent limiting to the motor controllers so that as long as the voltage is within parameters the speed will be voltage independent and so that the system will not power on at voltages outside system specs.	Zach / March 16th, 2017	Motor controllers chosen have overvoltage detection and shutoff protocol
			9	Unexpected Stored Charge	2	18	Power down system and use resistor to ground to reduce stored charge. locate cause of stored charge and fix. In the design avoid use of unprotected power storage eliments such as large capacitors or inductors with exposed wires	Ryan / March 16th 2017	Flyback diode on main contactor and fusing handle issue
		Motor Burnout	6	Over Voltage	7	42	Remove Power source and allow energy disipation. In the design add voltage limmiting protections to the motor drivers and avoid any unregulated power lines which connect directly from the power source to the motors OR between any two motors.	Zach / March 16th, 2017	Motor controllers chosen have overvoltage detection and shutoff protocol
			6	Major Short	8	48	power down system, locate short, and remove cause. In the design recomend high quality motors and protection to motors from unnessisary physical shocks or conductive debri.	Solution Required upon error, no immediate fix	Fuses handle over current and control software detects if there is discrepency between motor output and motor operation via encoders.

Electronics Failure	6	Over Voltage	7	42	Remove Power source and allow energy disipation. In the design include passive voltage protection for each major component. Pay special attention to locations where conducting lines enter and leave our scope. Whenever possible isolate these locations electrically fromother components using opto-isolators, voltage following buffers and fuses.	Zach / March 16th, 2017	Motor controllers are optoisolated from main control electronics.
	6	Major Short	6	36	power down system , locate short, and remove cause. In the design avoid exposed wires or unnessisarily large solder joints. whenever possible coat finished components in epoxy or other insulator to prevent shorts from conductive particles or moisture. AVOID LEADLESS SOLDER.	Solution Required upon error, no immediate fix	Frame team implementing a dead man switch on emergency brake
	5	Unexpected Stored Charge	4	20	Power down system and use resistor to ground to reduce stored charge. locate cause of stored charge and fix. In the design avoid unnescisary use of capacitive an inductive eliments.	Ryan / March 16th 2017	Flyback diode on main contactor and fusing handle issue
	5	Reversed Polarity	7	35	Power down, remove power source, reorient and replace. If power source is not the problem use electrical schematics and multimeter to locate the reveresed wiring and fix. In the design utilise physically polarised connectors and use passive circuit protection to handle inevitable mistakes.	Zach / March 16th, 2017	Main contactor and fusing handle issue
	4	Transients in Supply	5	20	Power down, if first time retry, if problem persists add additional filtering to design. At all connections between major components utilise basic noise filters. At all locations where power enters or leaves our scope impliment complex filters or isolators where possible.	Zach / March 16th, 2017	Motor controllers are optoisolated and controller is powered by seperate battery

Electric Shock	8	Over Voltage	3	24	Remove Power source and allow energy disipation. In the design utilise a chassies ground to prevent electric problems from extending outside the chassies.	Zach / March 16th, 2017	Motor controllers chosen have overvoltage detection and shutoff protocol
	9	Unexpected Stored Charge	4	36	Power down system and use resistor to ground to reduce stored charge. locate cause of stored charge and fix. In the design avoid unnessisary ungrounded storage components.	Ryan / March 16th 2017	Flyback diode on main contactor and fusing handle issue
 Martin Short	6	Over Voltage	6	36	Remove Power source and allow energy disipation. In the design, avoid voltages high enough to arc through a reasonable airgap.	Solution Required upon error, no immediate fix	Motor controllers chosen have overvoltage detection and shutoff protocol
	4	Unexpected Stored Charge	4	16	Power down system and use resistor to ground to reduce stored charge. locate cause of stored charge and fix. In the design avoid storage of high voltages, additionaly add flyback diods whenever possible to any inductors expected to undergo digital voltage changes.	Ryan / March 16th 2017	Flyback diode on main contactor and fusing handle issue
Electronics Brown Out	3	Under Voltage	9	27	power down and charge power source. In the design include voltage monitors and automatic shutoff when voltage falls bellow threashold.	John / March 10th, 2017	Initialization routines turn off power to all actuators
	5	Martin Short	6	30	power down system , locate short, and remove cause. In the design avoid any design where systems expected behavior will draw more power than is available to the system.	Solution Required upon error, no immediate fix	Main contactor and fusing handle issue
System Moves	3	Under Voltage	9	27	power down and charge power source. in the design include voltage monitors and automatic shutoff when voltage falls bellow threashold.	Solution Required upon error, no immediate fix	Motor controllers have undervoltage protection

Power System / Provide Steady and Predictable Power to Actuators, Controllers, Electronics, and Sensors	Provides Incorect or Unsteady power	Slowly	5	Martin Short	6	30	power down system , locate short, and remove cause. in the design avoid any component which draws more power than available to the whole system.	Solution Required upon error, no immediate fix	Main contactor and fusing handle issue
		Unpredictable Motion	8	Under Voltage	9	72	power down and charge power source. in the design include voltage monitors and automatic shutoff when voltage falls bellow threashold.	Solution Required upon error, no immediate fix	Motor controllers have undervoltage protection
			8	Loss of Ground	7	56	Power down system. Locate open in the ground line and repair. In the design. In the design, use only connectors which are tested to handle continuous vibration and long term stress in the expected automotive range.	Solution Required upon error, no immediate fix	No precaution taken
			7	Electronics Communications Failure	6	42	In the design use parity bits and checksum to ensure acurate communication and include software solutions to loss of a component including but not limited to full shutdown or alternate control algorythms.	John / March 10th, 2017	Developing error handling code
			6	Bad Sensor Data	8	48	Power down, locate cause of sensor malfunction, fix if possible. If sensor malfunction is result of external circumstances such as satiligte orbits simply try again under different conditions. In the design use parity bits and checksum to ensure acurate communication and include software solutions to loss of a component including but not limited to full shutdown or alternate control algorythms.	Solution Required upon error, no immediate fix	Developing error handling code

		8	Unexpected Stored Charge	4	32	Power down system and use resistor to ground to reduce stored charge. locate cause of stored charge and fix. In the design avoid large capacitors near the motor controllers, and analog DC voltage sensor outputs.	Ryan / March 16th 2017	Flyback diode on main contactor and fusing handle issue
		8	Reversed Polarity	9	72	Power down, remove power source, reorient and replace. If power source is not the problem use electrical schematics and multimeter to locate the reveresed wiring and fix.	Solution Required upon error, no immediate fix	Flyback diode on main contactor and fusing handle issue
	Overheating / Fire	9	Martin Short	6	54	power down system , locate short, and remove cause. Include power sutoff failsafes for between every major component. These can be as simple as a fuse or as complex as a voltage buffer controlled by the CPU but should always cut power when higher than expected current is detected.	Ryan / March 10th, 2017	Flyback diode on main contactor and fusing handle issue
	Loss of Power	5	Martin Short	6	30	power down system , locate short, and remove cause. Include power sutoff failsafes for between every major component. These can be as simple as a fuse or as complex as a voltage buffer controlled by the CPU but should always cut power when higher than expected current is detected.	John / March 10th, 2017	Flyback diode on main contactor and fusing handle issue
		3	Loss of Ground	4	12	Power down system. Locate open in the ground line and repair. In the design. In the design, use only connectors which are tested to handle continuous vibration and long term stress in the expected automotive range.	Ryan / March 10th, 2017	No precaution taken
	Battery Overheat / Explosion	9	Martin Short	8	72	power down system , locate short, and remove cause. In the design recomend motorcycle grade batteries. Consider a battery edjection system. Consider aditional batery monitoring such as thermocupples.	Ryan / March 10th, 2017	Flyback diode on main contactor and fusing handle issue

Over Voltage	6	Transients in Supply	4	24	Power down, if first time retry, if problem persists add additional filtering to design. Include power supply conditioner at the primary power input.	Zach / March 16th, 2017	Motor controllers are optoisolated and controller is powered by seperate battery
Electronics Communication Failure	6	Loss of Ground	4	24	Power down system. Locate open in the ground line and repair. In the design. In the design, use only connectors which are tested to handle continuous vibration and long term stress in the expected automotive range. Additionally include logic to handle loss of communication in any or all components in the system.	Ryan / March 10th, 2017	No precaution taken
	6	Unexpected Stored Charge	4	24	Power down system and use resistor to ground to reduce stored charge. locate cause of stored charge and fix. In the design avoid ungrounded charge storage near intercomponent communications connections.	John / March 10th, 2017	Flyback diode on main contactor and fusing handle issue
	6	Transients in Supply	6	36	Power down, if first time retry, if problem persists add additional filtering to design. In the design use power conditioners on the input power lines to each component.	Ryan / March 10th, 2017	Motor controllers are optoisolated and controller is powered by seperate battery
Reversed Polarity	6	Unexpected Stored Charge	8	48	Power down system and use resistor to ground to reduce stored charge. locate cause of stored charge and fix. In the design avoid ungrounded capacitors and inductors.	John / March 10th, 2019	Flyback diode on main contactor and fusing handle issue

		Failure to Power Down	7	Unexpected Stored Charge	3	21	Power down system and use resistor to ground to reduce stored charge. locate cause of stored charge and fix. In the design avoid extraneus charge storage eliments such as large capacitors and batteries. Include power off logic in software as well as hardware so no action will be taken by the system in the event that the hardware does not shut down.	John / March 10th, 2017	Main contactor and fusing handle issue
System Element: Microcontroller									
		Fails to recieve E-Stop	9			0	In the design the E-stop should be a dead-man signal, wherin the system will physicaly power down in the event of loss of the carrier signal and will trigger a software powerdown in the event the E-stop watchdog starves.	Zach / March 16th, 2017	EStop signal is required to be toggled when starting to ensure it is detected. EStop is checked during autonomous operation for signal integrity

Process communication between user and vehicle	Incorectly proccessed communication	Corrupt or nonexistent node map	6	The transfer of the node mape from human to storage to executable program may become corrupted. This could result from a bas storage medium or a glitch durring coppying. Additionally Human error may result in a valid node map which is unsafe. Finally a blank node map could be inserted if the storage device is reformated.	9		In the node-map specifications should be included two forms of checksum, the first is a standard data checksum to ensure the data itself is correct. The second is a check for human understanding wherin the node-map must be acompanied by a simple set of constraint points which define the space in which the vehical may operate. If any node, or the strait line between two nodes with device precision considered falls outside the constraint map the software will assume human error and will not execute the Node-Map. Recomend also including a check for the maximum number of times or a time window durring which a node-map may be run without re-upload. this would be to ensure the wrong map is not selected under conditions which would make it unsafe even though all parameters are otherwise acceptable.	Ryan / March 10th, 2017	Developing error handling code
		Fails to recieve "Go"	2	Radio problem	4		Recomend no action. Device is safest when inert		Developing error handling code
Handle all sensor data	Fails to process one or more sensor datum	vehicle veers off course damaging itself or others		Sensor could fail or an algorithm could fail or communications between components could fail		0	In the design the behavior of the vehicle should be defined to be full stop when any sensor exhibits unexpected behavior or the sensor data presents an improbable curve (look for acute angles in the position data or accelerations beyond the capabilities of the vehicle)		Developing error handling code

	sensor datum	vehicle spins out of control	8	Sensor data evaluated in conflicting vectors suggesting multiple simultaneus actions	7		In the software design regardless of algorithms used for evaluating indevidual sensors, the final output vector should be defined to be consistent and a smooth curve over time, space, and all output controls.	Zach / March 16th, 2017	Developing error handling code
Provide control outputs to actuators	Does not provide appropriet control to actuators	Vehical moves in unpredictable or unexpected ways	9			0		Zach / March 16th, 2017	Test code extensively to determine appropriate control gains
System Element: Sensors									
Track absolute vehicle location	Lose track of vehicle location	vehicle veers off course damaging itself or others	10	GPS receiver power loss	1	10	power down motors when GPS power loss detected	Zach / March 16th, 2017	Developing error handling code
				GPS reciever signal loss	4	40	Power down motors when GPS signal loss for extened period of time	Zach / March 16th, 2017	Developing error handling code
				delayed processor cycle	2	20	continue vehicle opperation until delay causes a divergence from set path	John / March 10th, 2017	Developing error handling code
		crash test vehicle collides with vehicles being tested	10	GPS receiver power loss	1	10	power down motors when GPS power loss detected	Zach / March 16th, 2017	Developing error handling code
				GPS reciever signal loss	4	40	Power down motors when GPS signal loss for extened period of time	Zach / March 16th, 2017	Developing error handling code
				delayed processor cycle	2	20	continue vehicle opperation until delay causes a divergence from set path	John / March 10th, 2017	Developing error handling code
		test data collected becomes useless	5	GPS reciever signal loss	4	20	Power down motors when GPS signal loss for extened period of time	Zach / March 16th, 2017	Developing error handling code
		test vehicle drives erratically	8	GPS receiver power loss	1	8	power down motors when GPS power loss detected	Zach / March 16th, 2017	Developing error handling code
				GPS reciever signal loss	4	32	Power down motors when GPS signal loss for extened period of time	Zach / March 16th, 2017	Developing error handling code
				delayed processor cycle	2	16	continue vehicle opperation until delay causes a divergence from set path	John / March 10th, 2017	Developing error handling code
		Test vehicle could come to a sudden stop, potentially damaging components	7	delayed processor cycle	2	14	continue vehicle opperation until delay causes a divergence from set path	John / March 10th, 2017	Developing error handling code

Report vehicle kinematic data	Report incorrect kinematic data	entire dataset unusable	4	sensor malfunctions	2	8	cease vehicle opperations, notify user of the malfunction	Ryan / March 10th, 2017	Developing error handling code
				system power loss during testing	1	4	cease vehicle opperations	Ryan / March 10th, 2017	No precautions able to be taken
				error in data processing	1	4	notify user of error	Ryan / March 10th, 2017	No precautions taken
		test engineer must to re-run test	4	data collected become corrupted upon transfer	1	4	replace memory storage device	Solution Required upon error, no immediate fix	Safe file operations used in code
				system power loss during testing	1	4	cease vehicle opperations	Ryan / March 10th, 2017	No precautions taken
				error in data processing	1	4	notify user of error	Ryan / March 10th, 2017	No precautions taken
		vehicle accelerates/decelerates unexpectedly	9	sensor malfunction	2	18	cease vehicle opperations, notify user of the malfunction	Ryan / March 10th, 2017	Developing error handling code
Check correct vehicle orientation and ground placement	Ignore vehicle orientation and placement	vehicle operates when not right side up	9	sensor malfunction	2	18	cease vehicle opperations, notify user of the malfunction	Ryan / March 10th, 2017	Developing error handling code
				failure to run safety check	1	9	enable safety check safeguard	Zach / March 16th, 2017	Developing error handling code
		vehicle operates when being picked up	10	sensor malfunction	2	20	cease vehicle opperations, notify user of the malfunction	Ryan / March 10th, 2017	Developing error handling code
				failure to run safety check	1	10	enable safety check safeguard	Zach / March 16th, 2017	Developing error handling code
		vehicle operates while being transported	9	sensor malfunction	2	18	cease vehicle opperations, notify user of the malfunction	Ryan / March 10th, 2017	Developing error handling code
				failure to run safety check	1	9	enable safety check safeguard	Zach / March 16th, 2017	Developing error handling code
System Element: Communications									
				Wire disconnected	4	24	Ensure wiring is mounted properly (no stress on wires and rigidly connected at ends)	Zach / March 16th, 2017	Wires inside control box will be connected with ribbon cables and developing error handling code

	Lose communication with IMU	Vehicle unable to steer	6	Noise on communication line	3	18	Include appropriate filtering for communication lines	John / March 16th, 2017	Motor controllers are optoisolated and controller is powered by seperate battery
				Code error	5	30	Test IMU communication code extensively and include appropriate error handling	Ryan / March 16th, 2017	Developing error handling code
				IMU broken	2	12	Replace IMU	Solution Required upon error, no immediate fix	Developing error handling code
		Control loop blocks	8	Wire disconnected	4	32	Ensure wiring is mounted properly (no stress on wires and rigidly connected at ends)	Zach / March 16th, 2017	Wires inside control box will be connected with ribbon cables and developing error handling code
				Noise on communication line	3	24	Include appropriate filtering for communication lines	John / March 16th, 2017	Motor controllers are optoisolated and controller is powered by seperate battery
				Code error	5	40	Test IMU communication code extensively and include appropriate error handling	Ryan / March 16th, 2017	Developing error handling code
				IMU broken	2	16	Replace IMU	Solution Required upon error, no immediate fix	Developing error handling code
		Vehical drifts off course	6	Wire disconnected	4	24	Ensure wiring is mounted properly (no stress on wires and rigidly connected at ends)	Zach / March 16th, 2017	Wires inside control box will be connected with ribbon cables and developing error handling code
				Noise on communication line	3	18	Include appropriate filtering for communication lines	John / March 16th, 2017	Motor controllers are optoisolated and controller is powered by seperate battery
				Code error	5	30	Test GPS communication code extensively and include appropriate error handling	Ryan / March 16th, 2017	Developing error handling code

Relay information between microcontroller and sensors	Lose communication with GPS			GPS broken	2	12	Replace GPS	Solution Required upon error, no immediate fix	Developing error handling code
		Control loop blocks	6	Wire disconnected	4	24	Ensure wiring is mounted properly (no stress on wires and rigidly connected at ends)	Zach / March 16th, 2017	Wires inside control box will be connected with ribbon cables and developing error handling code
				Noise on communication line	3	18	Include appropriate filtering for communication lines	John / March 16th, 2017	Motor controllers are optoisolated and controller is powered by seperate battery
				Code error	5	30	Test GPS communication code extensively and include appropriate error handling	Ryan / March 16th, 2017	Developing error handling code
				GPS broken	2	12	Replace GPS	Solution Required upon error, no immediate fix	Developing error handling code
		Vehicle unable to steer	6	Wire disconnected	4	24	Ensure wiring is mounted properly (no stress on wires and rigidly connected at ends)	Zach / March 16th, 2017	Wires inside control box will be connected with ribbon cables and developing error handling code
				Noise on communication line	3	18	Include appropriate filtering for communication lines	John / March 16th, 2017	Motor controllers are optoisolated and controller is powered by seperate battery
				Code error	5	30	Test IMU and GPS communication code extensively and include appropriate error handling	Zach / March 16th, 2017	Developing error handling code
				GPS broken	2	12	Replace GPS	Solution Required upon error, no immediate fix	Developing error handling code
				IMU broken	2	12	Replace IMU	Solution Required upon error, no immediate fix	Developing error handling code

	Lose communication with IMU and GPS	Vehical drifts off course	6	Wire disconnected	4	24	Ensure wiring is mounted properly (no stress on wires and rigidly connected at ends)	Zach / March 16th, 2017	Wires inside control box will be connected with ribbon cables and developing error handling code
				Noise on communication line	3	18	Include appropriate filtering for communication lines	John / March 16th, 2017	Motor controllers are optoisolated and controller is powered by seperate battery
				Code error	5	30	Test IMU and GPS communication code extensively and include appropriate error handling	Ryan / March 16th, 2017	Developing error handling code
				GPS broken	2	12	Replace GPS	Solution Required upon error, no immediate fix	Developing error handling code
				IMU broken	2	12	Replace IMU	Solution Required upon error, no immediate fix	Developing error handling code
		Control loop blocks	8	Wire disconnected	4	32	Ensure wiring is mounted properly (no stress on wires and rigidly connected at ends)	Zach / March 16th, 2017	Wires inside control box will be connected with ribbon cables and developing error handling code
				Noise on communication line	3	24	Include appropriate filtering for communication lines	John / March 16th, 2017	Motor controllers are optoisolated and controller is powered by seperate battery
				Code error	5	40	Test IMU and GPS communication code extensively and include appropriate error handling	Ryan / March 16th, 2017	Developing error handling code
				GPS broken	2	16	Replace GPS	Solution Required upon error, no immediate fix	Developing error handling code
				IMU broken	2	16	Replace IMU	Solution Required upon error, no immediate fix	Developing error handling code

Send start/stop signals wirelessly	Lose communication with wireless transmitter	Unable to start test program	1	Broken reciever	2	2	Replace wireless reciever	Solution Required upon error, no immediate fix	Developing error handling code
				Wireless interference	5	5	Determine what is causing interferance and remove it	Solution Required upon error, no immediate fix	No precaution taken
				Code error	5	5	Test wireless communication code extensively and include appropriate error handling	Zach / March 16th, 2017	Developing error handling code
		Unable to stop vehicle remotely	9	Broken reciever	2	18	Replace wireless reciever, ensure vehicle stops if wireless signal is not recieved	Solution Required upon error, no immediate fix	Developing error handling code
				Wireless interference	5	45	Ensure vehicle stops if wireless signal is not recieved	Zach / March 16th, 2017	No precaution taken
				Code error	5	45	Test wireless communication code extensively and include appropriate error handling	Zach / March 16th, 2017	Developing error handling code
System Element: External Memory									
Upload user created test route to vehicle microcontroller	Fails to upload test route to vehicle	Vehicle does not begin test	5	GPS unable to locate itself	7	35	restart the GPS	Solution Required upon error, no immediate fix	Developing error handling code
				Loss of power	1	5	restart the GPS	Solution Required upon error, no immediate fix	Developing error handling code
				Control System caught in loop	1	5	restart the system	Solution Required upon error, no immediate fix	Developing error handling code
		vehicle runs previous test route	8	User didn't upload new route properly	2	16	retry uploading route	Solution Required upon error, no immediate fix	Developing error handling code
				system did not register new route	1	8	retry uploading route	Solution Required upon error, no immediate fix	Developing error handling code
		Vehicle runs a misinterpreted test run	9	system did not register route properly	1	9	retry uploading route	Solution Required upon error, no immediate fix	Developing error handling code
Record correct testing kinematic data	Fails to record kinematic data porperly	test engineer must re-run test	4	sensor malfunction	2	8	restart system and rerun test	Solution Required upon error, no immediate fix	Developing error handling code
				corrupted memory device	1	4	replace memory device	Solution Required upon error, no immediate fix	Developing error handling code
		test engineer is given incorrect data	5	sensor malfunction	2	10	restart system and rerun test	Solution Required upon error, no immediate fix	Developing error handling code
				data mishandled by algorithms	1	5	restart system and rerun test, if problem fixed perform debugging procedure	Solution Required upon error, no immediate fix	Developing error handling code

Download test run kinematic data to user device	Fails to download kinematic data	test engineer must re-run test	4	corrupted memory device	1	4	replace memory device	Solution Required upon error, no immediate fix	Developing error handling code
		test engineer must	2	corrupted memory device	1	2	replace memory device	Solution Required upon error, no immediate fix	Developing error handling code
System Element: Acutation Control									
Interpret control ouput to provide correct power output to drive system	Lose drive system power	Vehicle slows down to a stop	1	Wire disconnects	4	4	Ensure wiring is mounted properly (no stress on wires and rigidly connected at ends)	Zach / March 16th, 2017	Wire outside of control box will be routed through flexible conduit. Wires inside control box will be connected with ribbon cables. Power connections use lugs.
				Battery runs out	6	6	Recharge system	Solution Required upon error, no immediate fix	No precautions taken
	Drive system breaks	Vehicle slows down to a stop	4	Wiring breaks	3	12	Ensure wiring is mounted properly (no stress on wires and rigidly connected at ends)	Zach / March 16th, 2017	Wire outside of control box will be routed through flexible conduit. Wires inside control box will be connected with ribbon cables. Power connections use lugs.
				Motors burn out	2	8	Replace motors	Solution Required upon error, no immediate fix	Error handling discrepency between motor output and encoder readings
	Drive system controller breaks	Vehicle slows down to a stop	2	Motor driver overvolt	3	6	Replace driver board	Solution Required upon error, no immediate fix	Error handling discrepency between motor output and encoder readings
				Motor pulls too much current	4	0	Replace driver board	Solution Required upon error, no immediate fix	Error handling discrepency between motor output and encoder readings

		Vehicle acclerates to max speed	10	Driver code error	5	50	Test motor driver code extensively and include appropriate error handling	Ryan / March 16th, 2017	Developing error handling code
	Drive system controller malfunctions	Vehicle slows down to a stop	1	Driver code error	5	5	Test motor driver code extensively and include appropriate error handling	Ryan / March 16th, 2017	Developing error handling code
		Vehicle acclerates to max speed	9	Driver code error	5	45	Test motor driver code extensively and include appropriate error handling	Ryan / March 16th, 2017	Developing error handling code
	Lose braking system power	Vehicle runs into a person	9	Wire disconnects	4	36	Ensure wiring is mounted properly (no stress on wires and rigidly connected at ends)	Zach / March 16th, 2017	Wire outside of control box will be routed through flexible conduit. Wires inside control box will be connected with ribbon cables. Power connections use lugs.
				Battery runs out	6	54	Include brake failsafe mechanism (applies brake when power is lost)	John / March 16th, 2017	Dead man switch on braking system developed by frame team
		Vehicle runs into a obstacale	6	Wire disconnects	4	24	Ensure wiring is mounted properly (no stress on wires and rigidly connected at ends)	Zach / March 16th, 2017	Wire outside of control box will be routed through flexible conduit. Wires inside control box will be connected with ribbon cables. Power connections use lugs.
				Battery runs out	6	36	Include brake failsafe mechanism (applies brake when power is lost)	John / March 16th, 2017	Dead man switch on braking system developed by frame team

		Vehicle misses trigger points	2	Wire disconnects	4	8	Ensure wiring is mounted properly (no stress on wires and rigidly connected at ends)	Zach / March 16th, 2017	Wire outside of control box will be routed through flexible conduit. Wires inside control box will be connected with ribbon cables. Power connections use lugs.
				Battery runs out	6	12	Include brake failsafe mechanism (applies brake when power is lost)	John / March 16th, 2017	Dead man switch on braking system developed by frame team
Interpret control ouput to provide correct power output to braking system	Braking system breaks	Vehicle runs into a person	10	Wiring breaks	4	40	Ensure wiring is mounted properly (no stress on wires and rigidly connected at ends)	Zach / March 16th, 2017	Wire outside of control box will be routed through flexible conduit. Wires inside control box will be connected with ribbon cables. Power connections use lugs.
				Acuator breaks	2	20	Include brake failsafe mechanism (applies brake when actuator doesn't respond is lost)	John / March 16th, 2017	No precaution taken
		Vehicle runs into a obstacale	7	Wiring breaks	4	28	Ensure wiring is mounted properly (no stress on wires and rigidly connected at ends)	Zach / March 16th, 2017	Wire outside of control box will be routed through flexible conduit. Wires inside control box will be connected with ribbon cables. Power connections use lugs.
				Acuator breaks	2	14	Include brake failsafe mechanism (applies brake when actuator doesn't respond is lost)	Zach / March 16th, 2017	No precaution taken

		Vehicle misses trigger points	2	Wiring breaks	4	8	Ensure wiring is mounted properly (no stress on wires and rigidly connected at ends)	Zach / March 16th, 2017	Wire outside of control box will be routed through flexible conduit. Wires inside control box will be connected with ribbon cables. Power connections use lugs.
				Acuator breaks	2	4	Include brake failsafe mechanism (applies brake when actuator doesn't respond is lost)	John / March 16th, 2017	No precaution taken
	Braking system controller breaks	Vehicle runs into a person	10	Acutator driver overvolt	3	30	Include brake failsafe mechanism (applies brake when actuator doesn't respond is lost)	John / March 16th, 2017	Wire outside of control box will be routed through flexible conduit. Wires inside control box will be connected with ribbon cables. Power connections use lugs.
				Acutator pulls too much current	4	40	Include brake failsafe mechanism (applies brake when actuator doesn't respond is lost)	Zach / March 16th, 2017	Dead man switch on braking system developed by frame team
		Vehicle runs into a obstacale	7	Acutator driver overvolt	3	21	Include brake failsafe mechanism (applies brake when actuator doesn't respond is lost)	John / March 16th, 2017	Dead man switch on braking system developed by frame team
				Acutator pulls too much current	4	28	Include brake failsafe mechanism (applies brake when actuator doesn't respond is lost)	John / March 16th, 2017	Dead man switch on braking system developed by frame team
		Vehicle misses trigger points	2	Acutator driver overvolt	3	6	Include brake failsafe mechanism (applies brake when actuator doesn't respond is lost)	John / March 16th, 2017	Dead man switch on braking system developed by frame team
				Acutator pulls too much current	4	8	Include brake failsafe mechanism (applies brake when actuator doesn't respond is lost)	Zach / March 16th, 2017	Dead man switch on braking system developed by frame team

				Driver code error	5	10	Test brake driver code extensively and include appropriate error handling	Ryan / March 16th, 2017	Developing error handling code
	Braking system controller malfunctions	Vehicle runs into a person	9	Driver code error	5	45	Test brake driver code extensively and include appropriate error handling	Ryan / March 16th, 2017	Developing error handling code
		Vehicle runs into a obstacale	6	Driver code error	5	30	Test brake driver code extensively and include appropriate error handling	Zach / March 16th, 2017	Developing error handling code
		Vehicle misses trigger points	2	Driver code error	5	10	Test brake driver code extensively and include appropriate error handling	Ryan / March 16th, 2017	Developing error handling code

Appendix H - Parts List and Part Drawings

*Read index as, 1. = drawing #100, 1.2 = drawing #120, 1.2.3 = drawing #123
**BOM reference number listed in (_parentheses_)

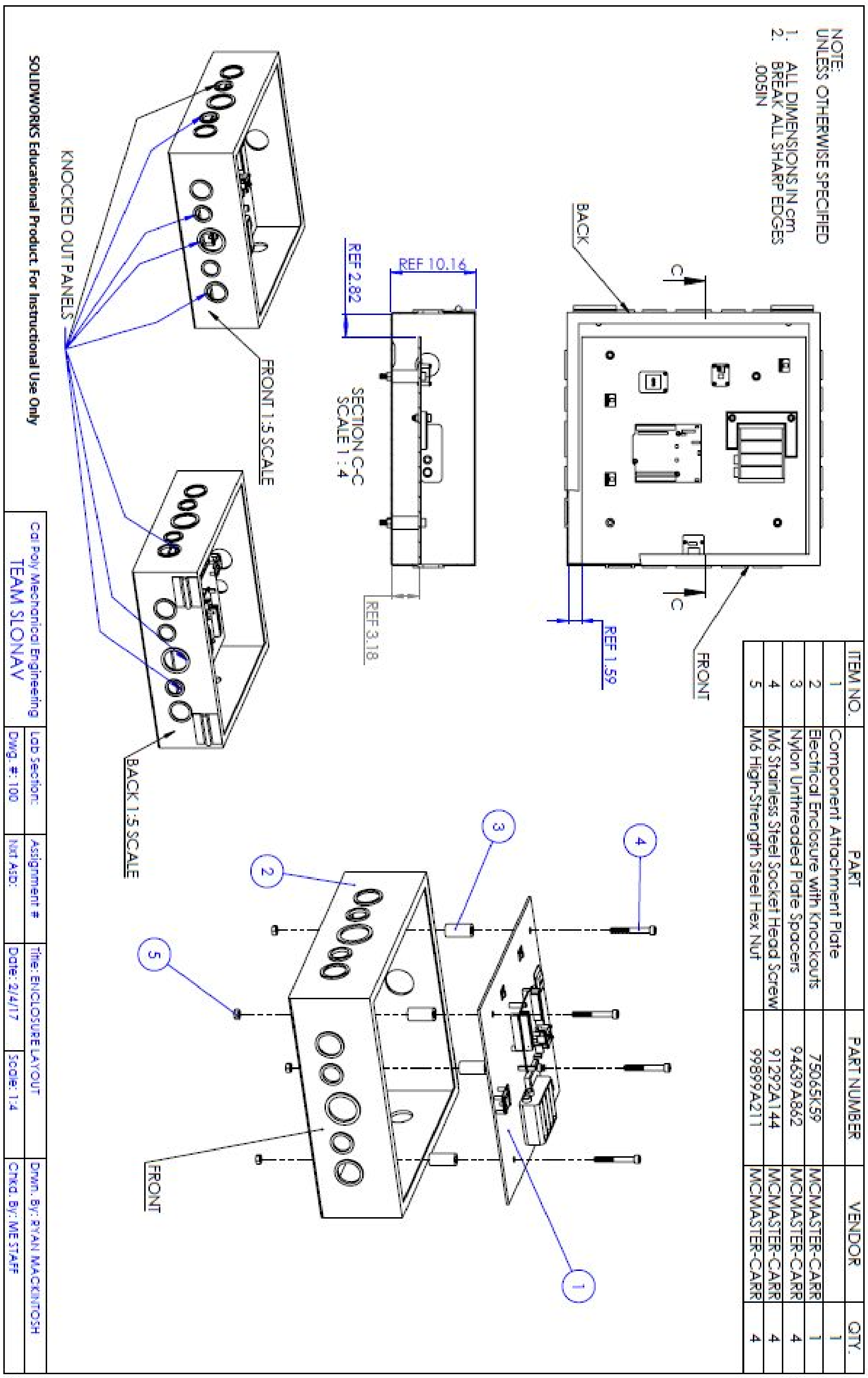
1. Enclosure Layout
- **1.1.** Electrical Enclosure with Knockouts (2)
- **1.2.** M6 Stainless Steel Socket Head Screw (4)
- **1.3.** M6 High-Strength Steel Hex Nut (5)

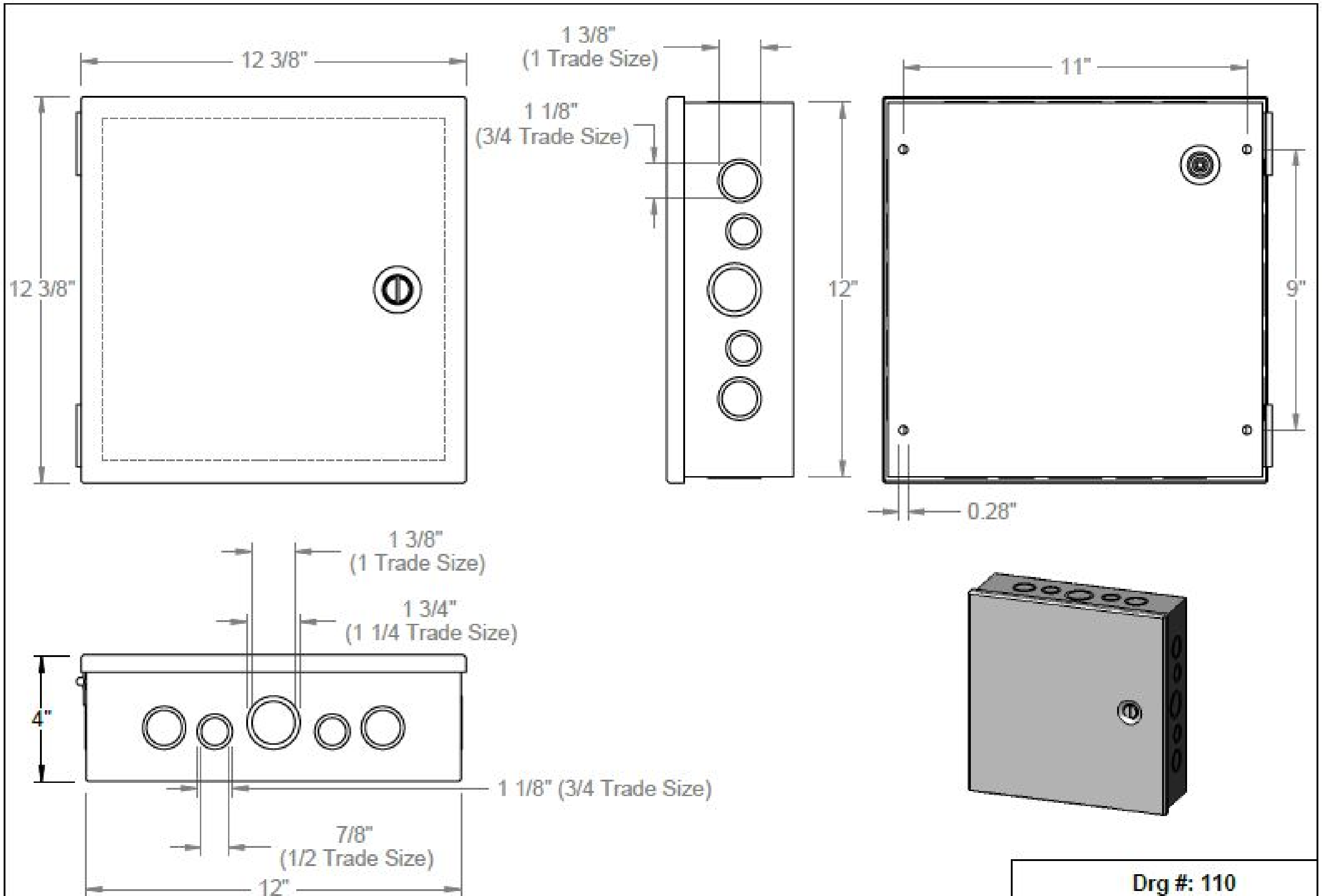
2. Component Plate Layout (1)
- **2.1.** Component Plate (6)
- **2.2.** Additional Parts
  - **2.2.1.** Nylon Unthreaded Plate Spacers (3)
  - **2.2.2.** Nylon Unthreaded Nucleo Spacers (13)
  - **2.2.3.** Nylon Unthreaded Sensor Spacers (14)
  - **2.2.4.** Battery Wedge (15)
- **2.3.** M2 Stainless Steel Socket Head Screw (16)
- **2.4.** M3 Stainless Steel Socket Head Screw (17)
- **2.5.** M5 Stainless Steel Socket Head Screw (18)
- **2.6.** M2 Medium-Strength Steel Thin Hex Nut (19)
- **2.7.** M3 Zinc-Plated Steel Hex Nut (20)
- **2.8.** M5 Zinc-Plated Steel Hex Nut (21)

3. Central Control
- **3.1.** Lipo Battery (7)
- **3.2.** 10 Hz 66 Channel GPS (8)
- **3.3.** BNO055 IMU (9)
- **3.4.** STM32 Nucleo-64 F446RE (10)
- **3.5.** Basic Balance Charger (22)
- **3.6.** AR610 Radio Comms (23)
- **3.7.** Micro SD Card Breakout (12)

4. Frame Interfacing
- **4.1.** KBL BLDC Motor Speed Controller (25)
- **4.2.** **Part number not used**
- **4.3.** **Part number not used**
- **4.4.** Grounded Intermittent Solenoid (28)
- **4.5.** Brake Motor Driver (29)
- **4.6.** Encoder Bracket (38)
- **4.7.** Shaft Encoders (39)
- **4.8.** Hall Effect Sensor Bracket

1) Enclosure Drawings



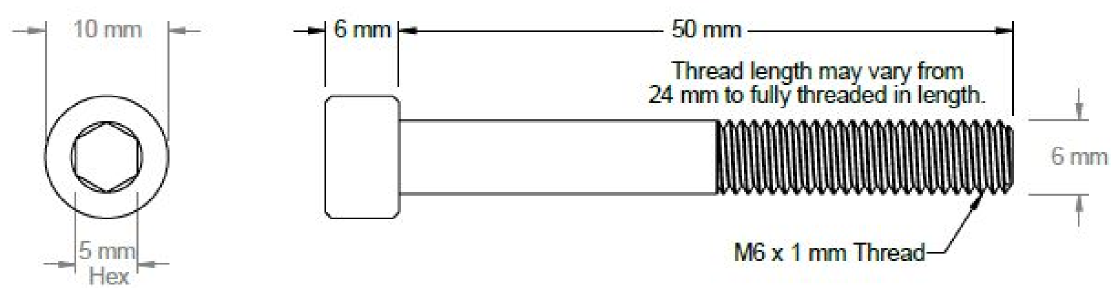


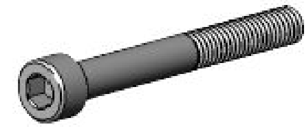
SOLIDWORKS Educational Product. For Instructional Use Only

16-ga Steel (0.0598")

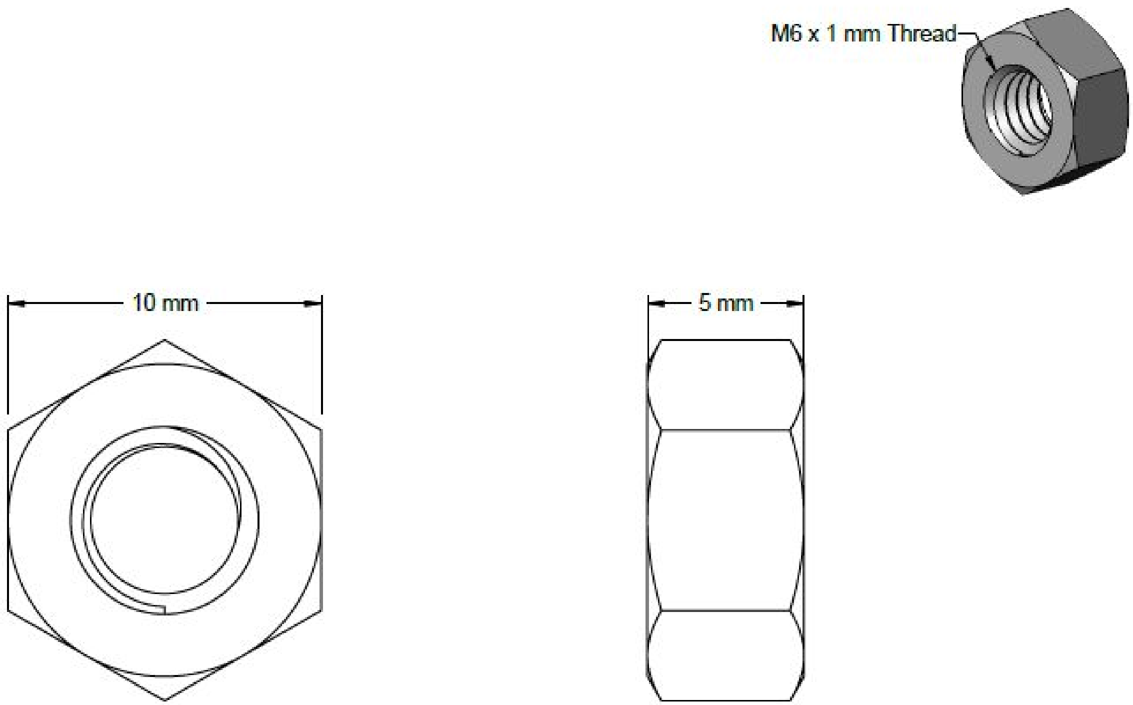
Approximate Internal Dimensions: Ht. 10 7/8", Wd. 10 7/8", Dp. 3 7/8"

	Drg #: 110
McMASTER-CARR® CAD	PART NUMBER 75065K59
http://www.mcmaster.com Information in this drawing is provided for reference only.	Indoor Steel Enclosure with Knockouts





	Drg #: 120
McMASTER-CARR® CAD	PART NUMBER 91292A144
http://www.mcmaster.com © 2014 McMaster-Carr Supply Company Information in this drawing is provided for reference only.	Stainless Steel Socket Head Cap Screw



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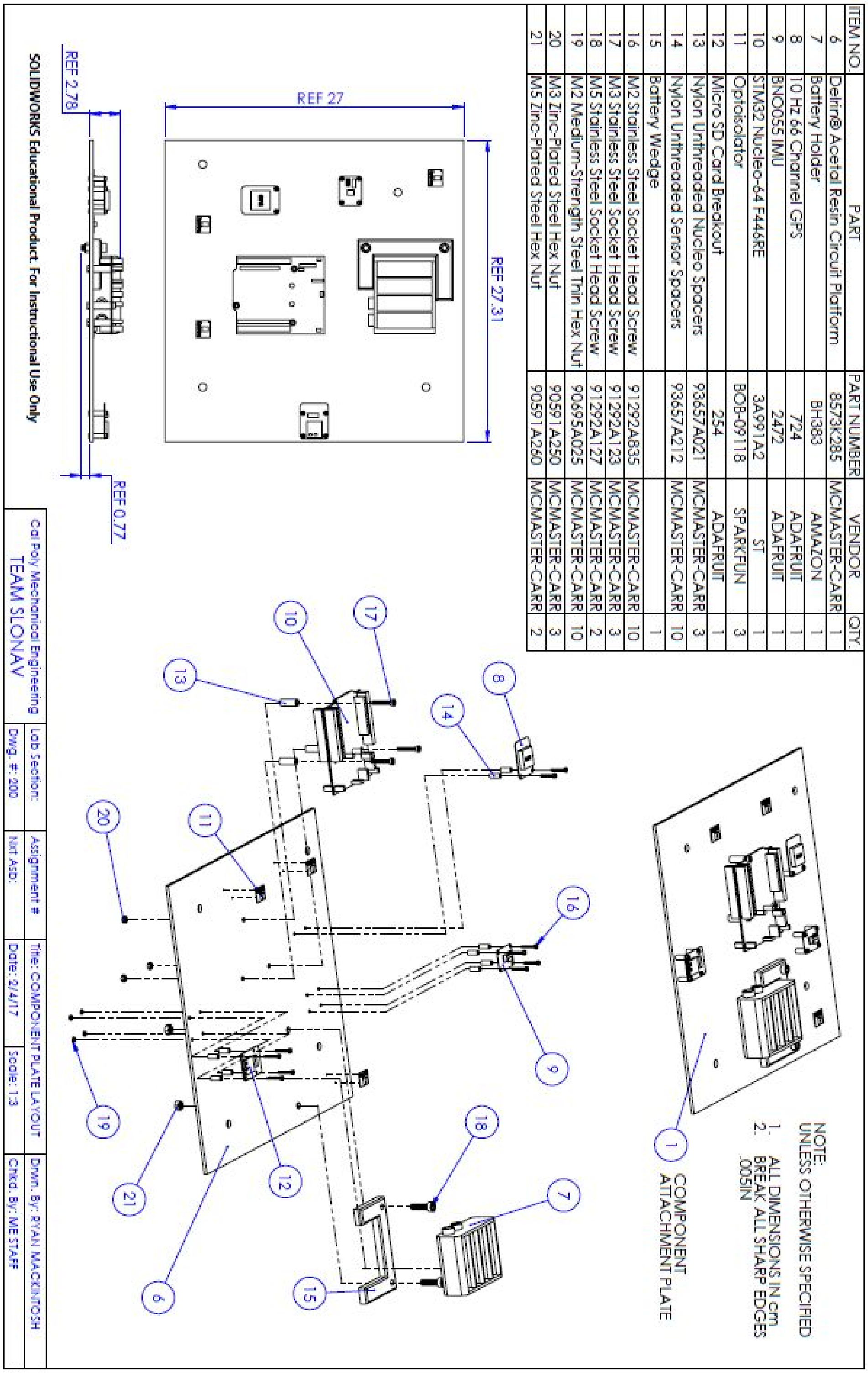
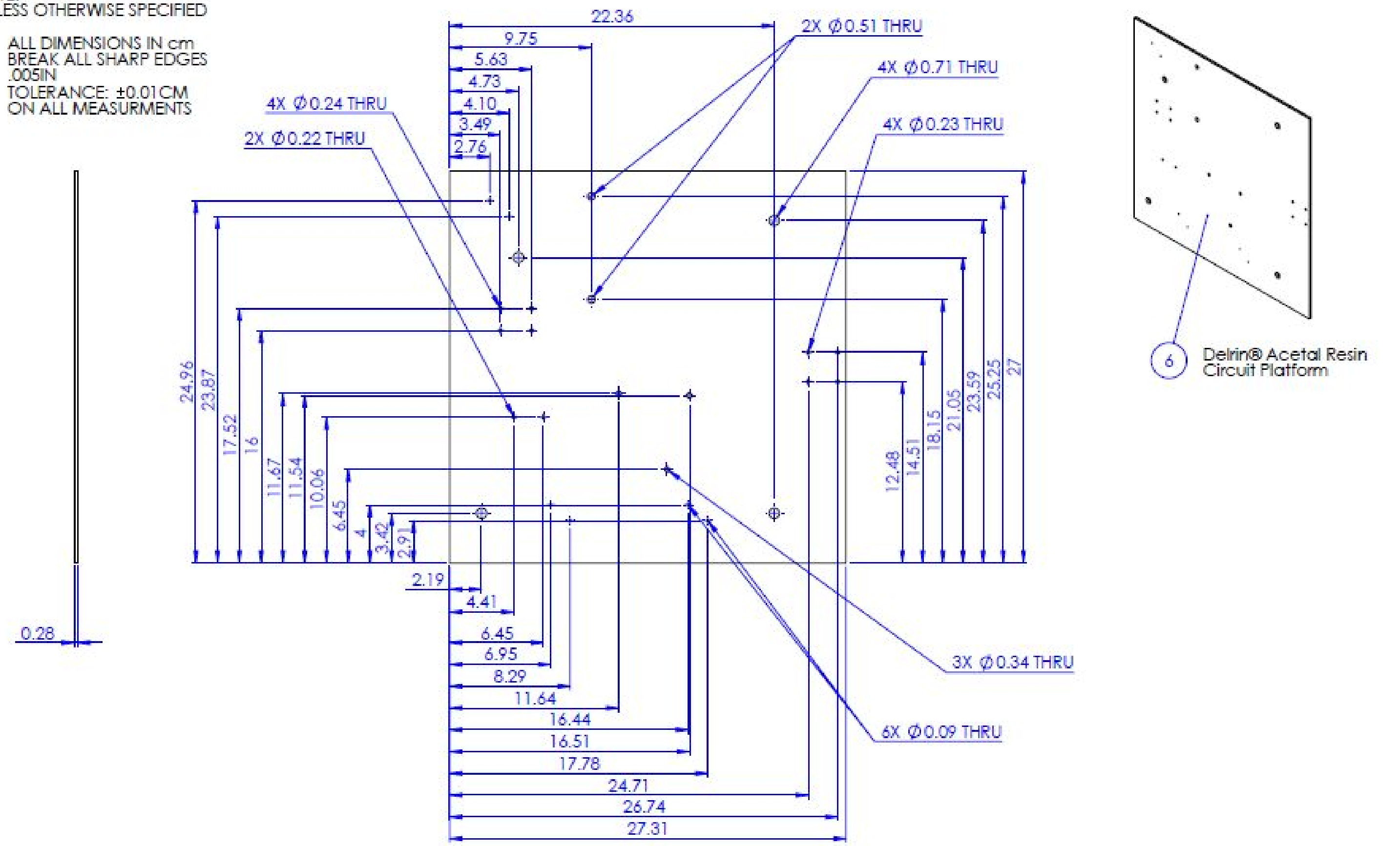
McMASTER-CARR® CAD	Drg #: 130
http://www.mcmaster.com	PART NUMBER 99899A211
© 2015 McMaster-Carr Supply Company	Metric
Information in this drawing is provided for reference only.	Hex Nut

2) Component Plate Layout



NOTE:
UNLESS OTHERWISE SPECIFIED

1. ALL DIMENSIONS IN cm
2. BREAK ALL SHARP EDGES .005IN
3. TOLERANCE: ±0.01CM ON ALL MEASURMENTS



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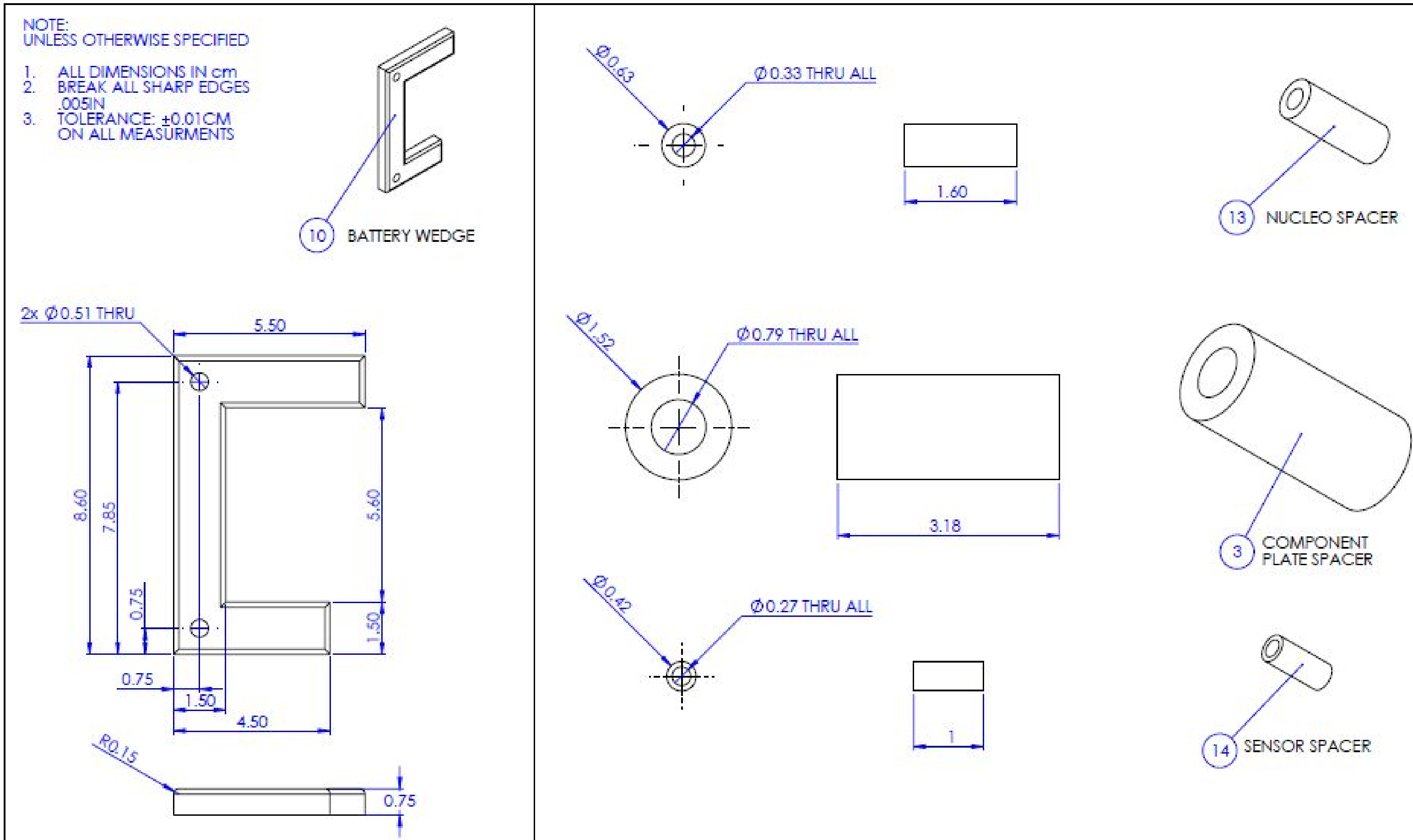
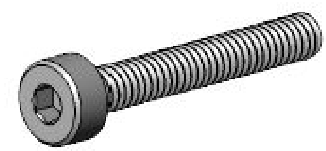
Cal Poly Mechanical Engineering TEAM SLONAV	Lab Section:	Assignment #	Title: COMPONENT PLATE		Drwn. By: RYAN MACKINTOSH
	Dwg. #: 210	Nxt Asb:	Date: 2/4/17	Scale: 2:5	Chkd. By: ME STAFF

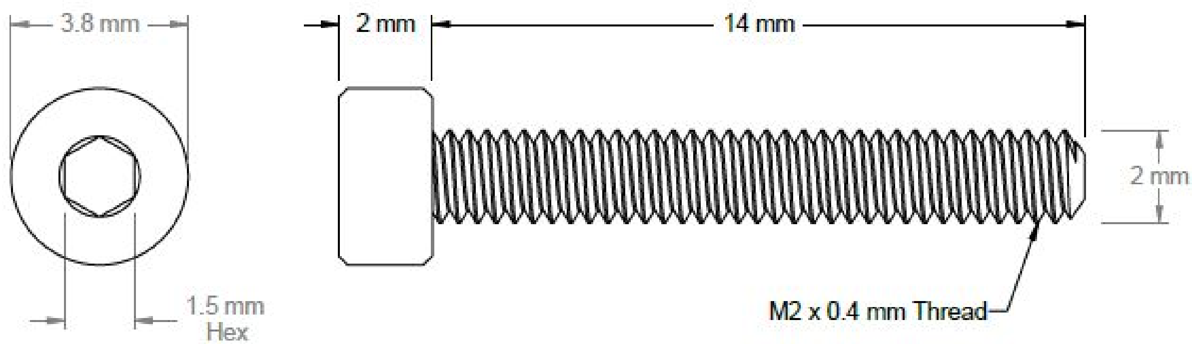
NOTE:
UNLESS OTHERWISE SPECIFIED

1. ALL DIMENSIONS IN cm
2. BREAK ALL SHARP EDGES .005IN
3. TOLERANCE: ±0.01CM ON ALL MEASURMENTS

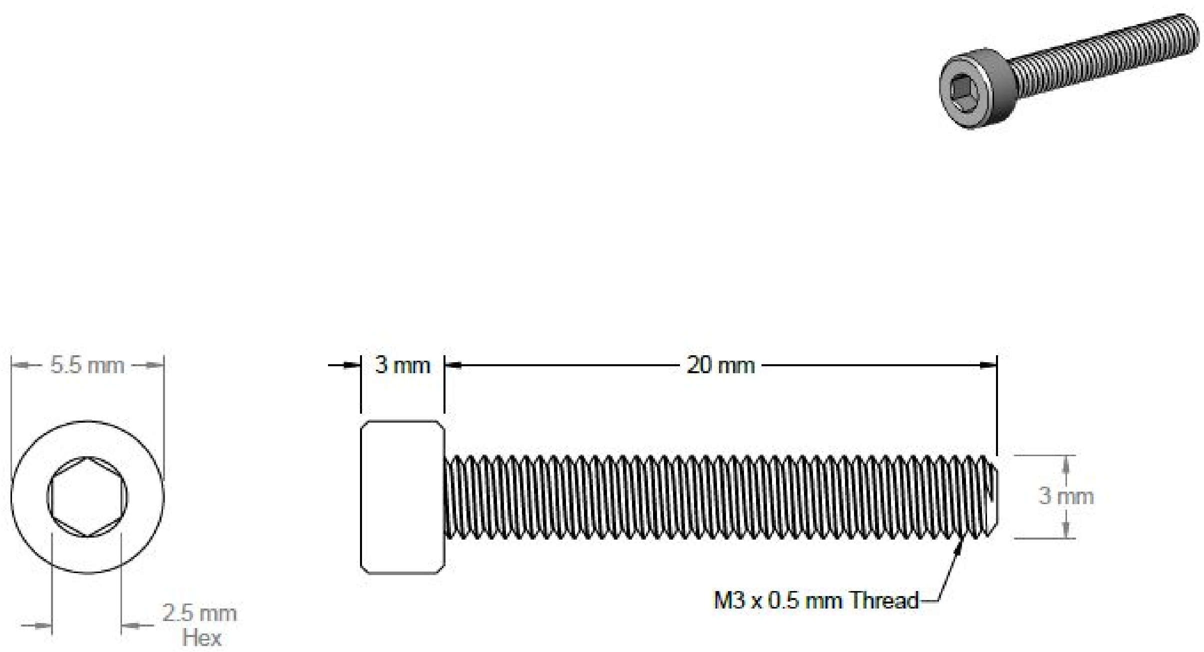


Cal Poly Mechanical Engineering TEAM SLONAV	Lab Section:	Assignment #	Title: ADDITIONAL FAB PARTS		Drwn. By: RYAN MACKINTOSH
	Dwg. #: 220	Nxt Asb:	Date: 2/5/17	Scale: 1:1 / 2:1	Chkd. By: ME STAFF

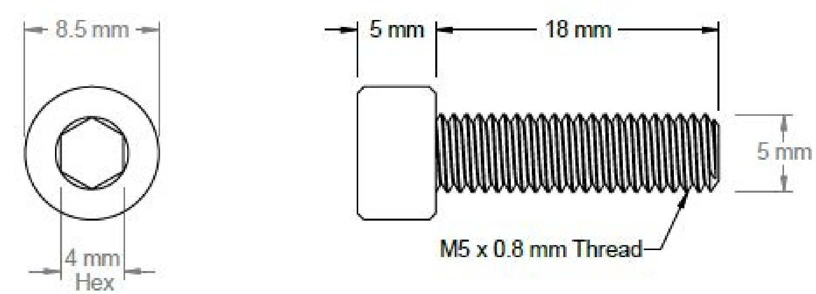


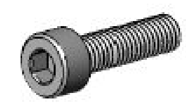


	Drg #: 230
McMASTER-CARR® CAD	PART NUMBER 91292A835
http://www.mcmaster.com © 2014 McMaster-Carr Supply Company Information in this drawing is provided for reference only.	Stainless Steel Socket Head Cap Screw

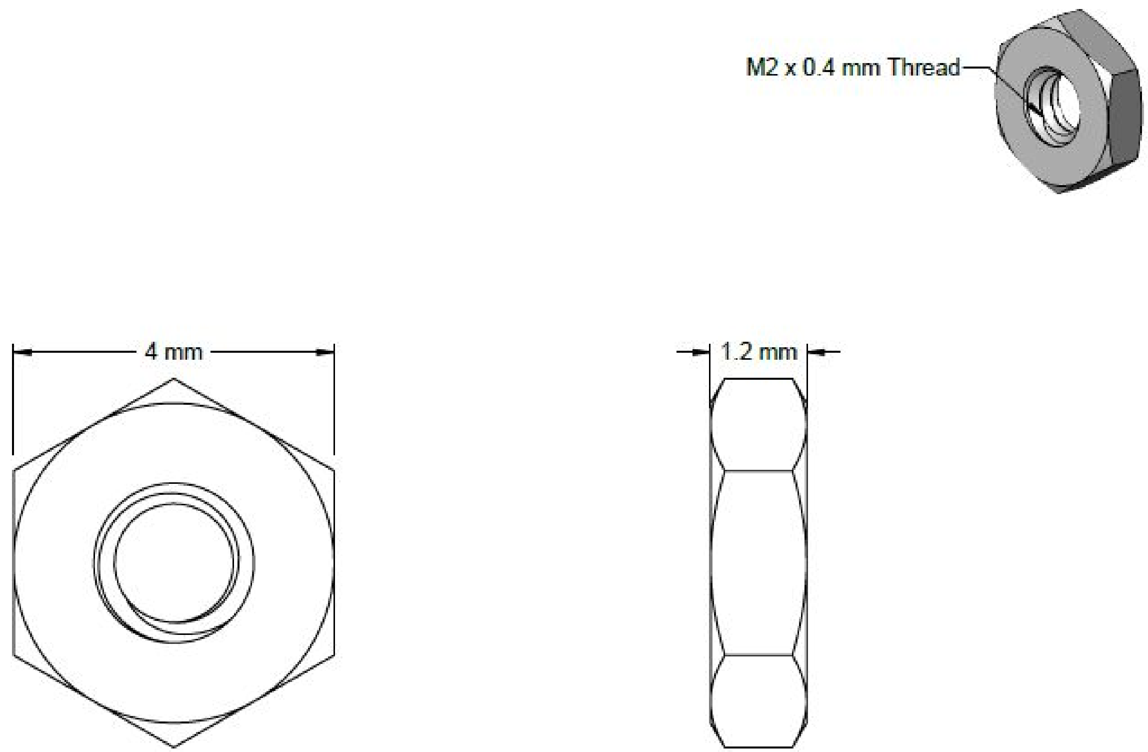


	Drg #: 240
McMASTER-CARR® CAD	PART NUMBER 91292A123
http://www.mcmaster.com © 2014 McMaster-Carr Supply Company Information in this drawing is provided for reference only.	Stainless Steel Socket Head Cap Screw

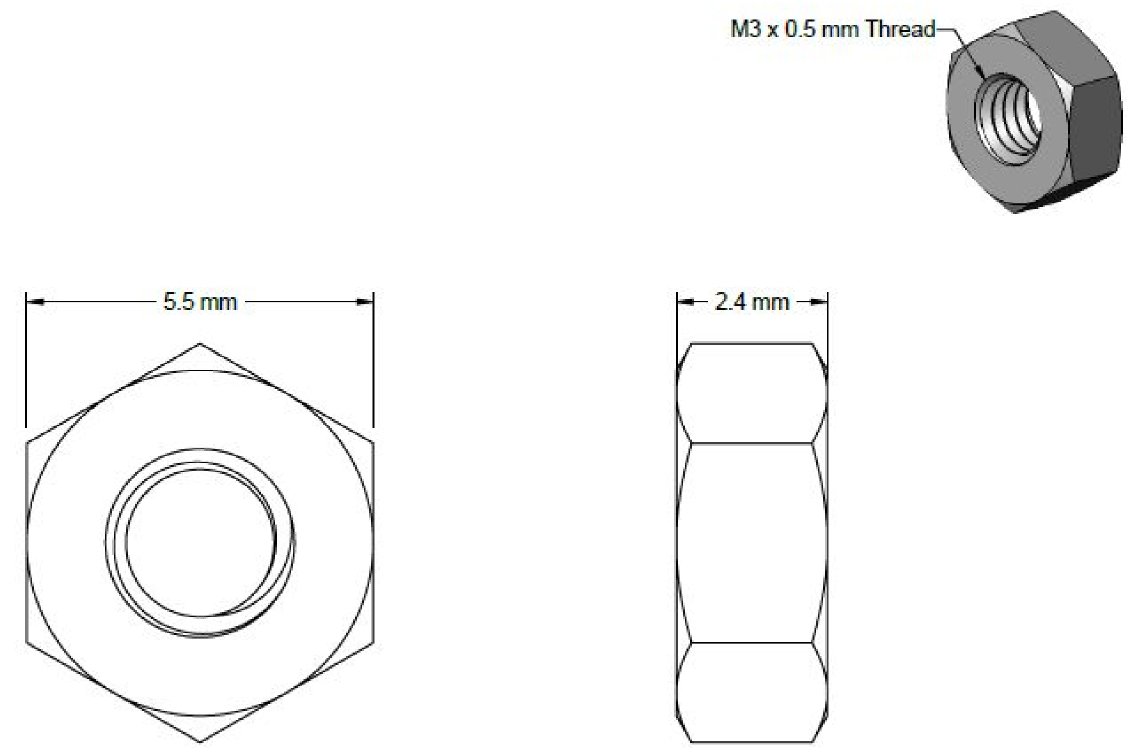




	Drg #: 250
McMASTER-CARR® CAD	PART NUMBER 91292A127
http://www.mcmaster.com © 2014 McMaster-Carr Supply Company Information in this drawing is provided for reference only.	Stainless Steel Socket Head Cap Screw



	Drg #: 260
McMASTER-CARR® CAD	PART NUMBER **90695A025**
http://www.mcmaster.com © 2015 McMaster-Carr Supply Company Information in this drawing is provided for reference only.	Metric Thin Hex Nut — DIN 439B



SOLIDWORKS Educational Product. For Instructional Use Only

McMASTER-CARR CAD

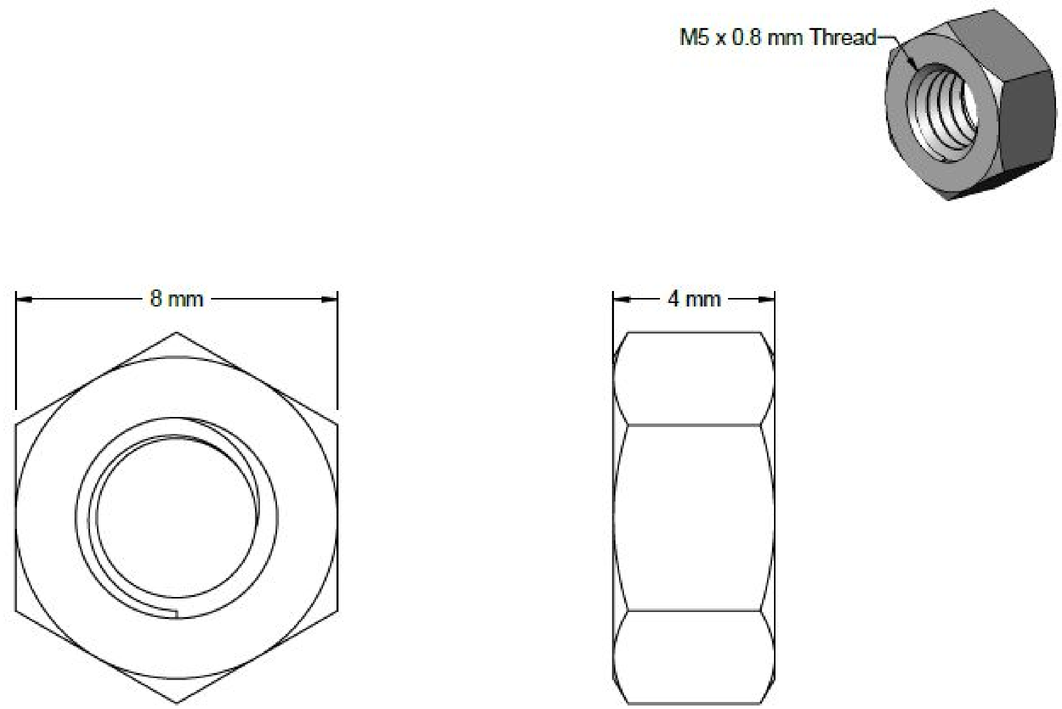
http://www.mcmaster.com

Information in this drawing is provided for reference only.

Drg #: 270

PART NUMBER **90591A250**

Metric
Hex Nut



McMASTER-CARR® CAD

http://www.mcmaster.com

Drg #: 280

PART NUMBER 90591A260

Metric

Hex Nut

3) Central Control

Turnigy 2650mAh 3S 20C Lipo Pack | Drg #: 310

Turnigy batteries are known the world over for performance, reliability and price. It's no surprise to us that Turnigy Lipoly packs are the go-to pack for those in the know. Turnigy batteries deliver the full rated capacity at a price everyo...
More >

$13.12

STOCK: IN STOCK

Weight: 309g Quantity: 1

Rate: SKU: T2650.3S.20

BUY NOW!

Wish List | Issue | Price War

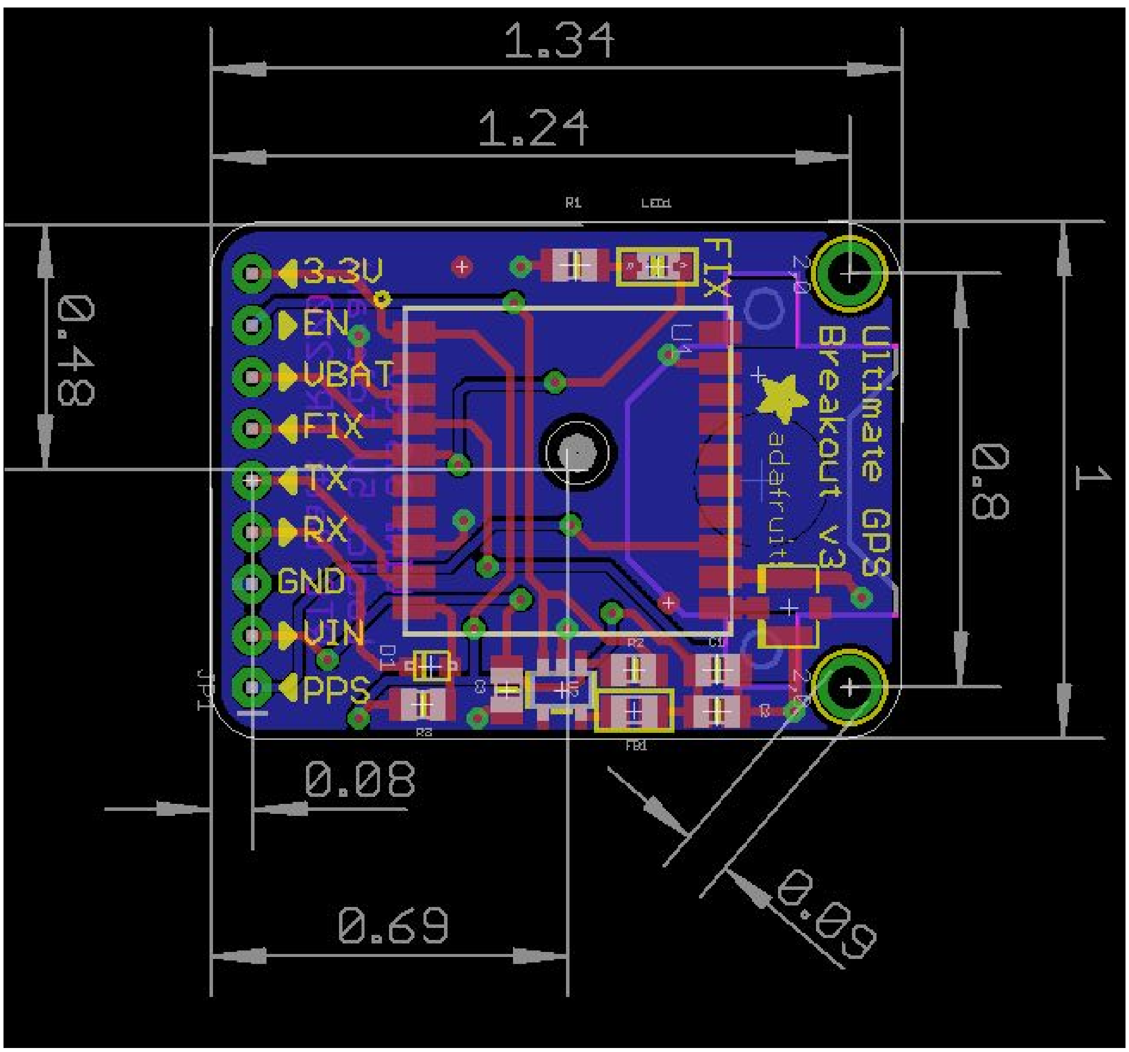
Overview | Specs | Discussion | Reviews | Video | File

Blade Count:	N/A	Speed (Sec/60deg):	No
Kv(rpm/v)	No	Torque(kg)(min. 0.01kg)	No
Diameter X(Inch):	No	Max Currents (A):	No
Power (W)	No	A(mm)	No
B(mm):	No	Length B (mm):	No
C(mm)	No	Can Length D(mm)	No
Max Voltage(V):	No	D(mm):	No
Shaft A(mm)	No	E(mm)	No
F(mm):	No	Diameter C(mm):	No
Total Length E(mm)	No	SKU	T2650.3S.20
Weight(g):	309.00	Length:	140.00
Width	17.00	Height	45.00
Capacity (mAh):	2650.00	Discharge(c):	20.00
Length-A(mm)	137.00	Height-B(mm)	43.00
Width-C(mm):	17.00	Unit Weight (g):	213
Max Charge Rate(C)	2.00	Watt Hour	29.00

TECHNICAL DETAILS

Drg #: 320

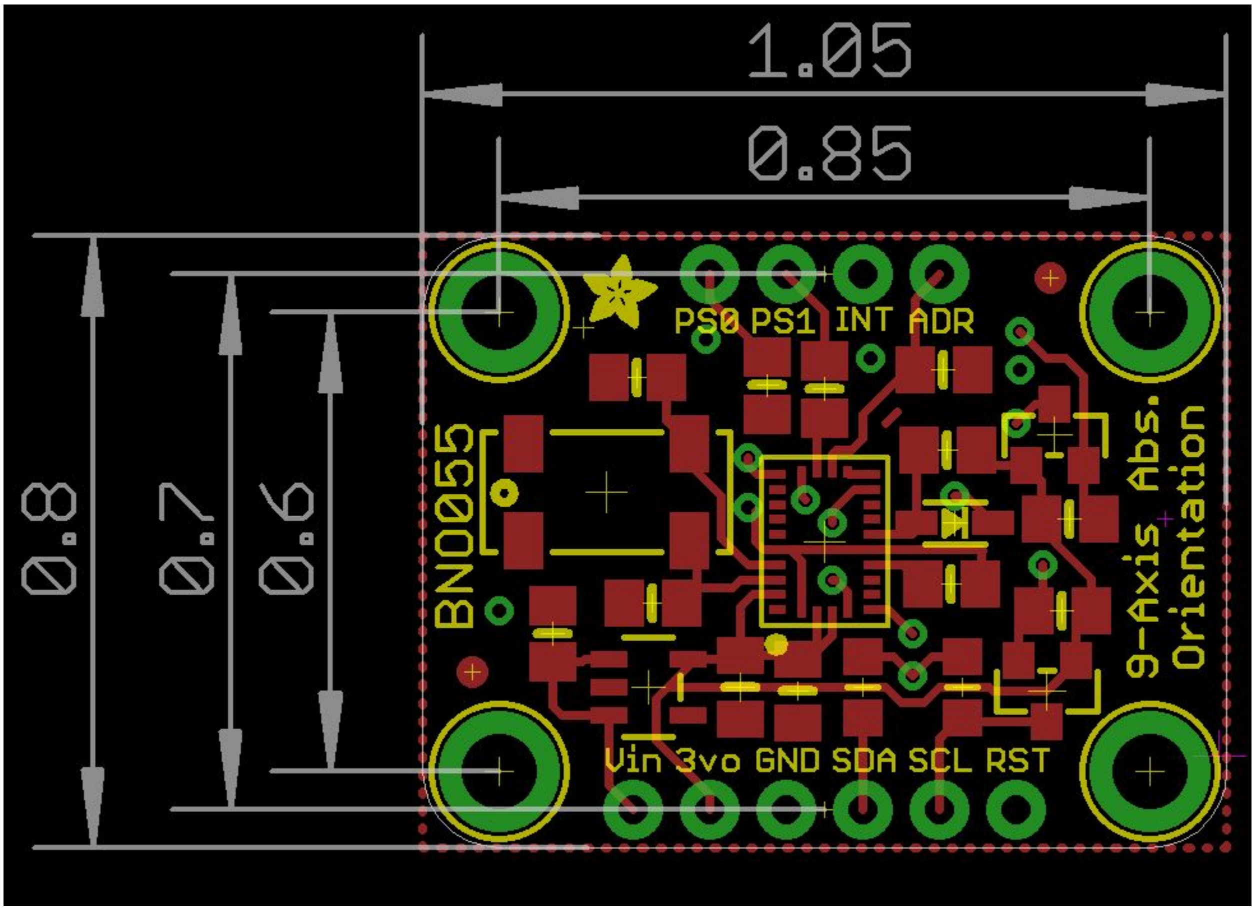
- Satellites: 22 tracking, 66 searching
- Patch Antenna Size: 15mm x 15mm x 4mm
- Update rate: 1 to 10 Hz
- Position Accuracy: < 3 meters (all GPS technology has about 3m accuracy)
- Velocity Accuracy: 0.1 meters/s
- Warm/cold start: 34 seconds
- Acquisition sensitivity: -145 dBm
- Tracking sensitivity: -165 dBm
- Maximum Velocity: 515m/s
- Vin range: 3.0-5.5VDC
- MTK3339 Operating current: 25mA tracking, 20 mA current draw during navigation
- Output: NMEA 0183, 9600 baud default
- DGPS/WAAS/EGNOS supported
- FCC E911 compliance and AGPS support (Offline mode : EPO valid up to 14 days)
- Up to 210 PRN channels
- Jammer detection and reduction
- Multi-path detection and compensation



TECHNICAL DETAILS

Drg #: 330

- Dimensions: 20mm x 27mm x 4mm / 0.8" x 1.1" x 0.2"
- Header holes begin 4mm from the mounting holes
- Mounting Hole dimensions: 20mm x 12mm apart
- Uses I2C address 0x28 (default) or 0x29
- Weight: 3g
- Datasheet, EagleCAD PCB files, and Fritzing available in the product tutorial



life.augmented

Drg #: 340

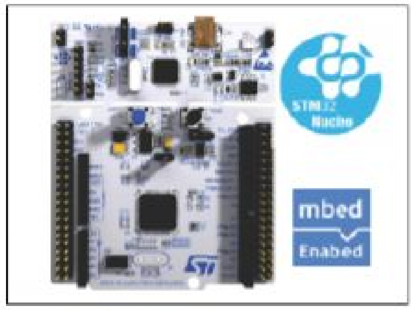
NUCLEO-XXXXRX

STM32 Nucleo-64 boards

Data brief

Features

- STM32 microcontroller with LQFP64 package
- Two types of extension resources
  – Arduino Uno Revision 3 connectivity
  – STMicroelectronics Morpho extension pin headers for full access to all STM32 I/Os
- mbed-enabled (http://mbed.org)
- On-board ST-LINK/V2-1 debugger/programmer with SWD connector
  – selection-mode switch to use the kit as a standalone ST-LINK/V2-1
- Flexible board power supply
  – USB VBUS or external source (3.3 V, 5 V, 7 - 12 V)
  – Power management access point
- Three LEDs
  – USB communication (LD1), user LED (LD2), power LED (LD3)
- Two push buttons: USER and RESET
- USB re-enumeration capability: three different interfaces supported on USB
  – Virtual Com port
  – Mass storage
  – Debug port
- Supported by wide choice of Integrated Development Environments (IDEs) including IAR™, Keil®, GCC-based IDEs



1. Picture not contractual

Description

The STM32 Nucleo board provides an affordable and flexible way for users to try out new ideas and build prototypes with any STM32 microcontroller line, choosing from the various combinations of performance, power consumption and features. The Arduino™ connectivity support and ST Morpho headers make it easy to expand the functionality of the STM32 Nucleo open development platform with a wide choice of specialized shields. The STM32 Nucleo board does not require any separate probe as it integrates the ST-LINK/V2-1 debugger and programmer. The STM32 Nucleo board comes with the STM32 comprehensive software HAL library together with various packaged software examples, as well as direct access to mbed online resources.

Table 1. Device summary

Reference	Part number
NUCLEO-XXXXRX	NUCLEO-F030R8, NUCLEO-F070RB, NUCLEO-F072RB, NUCLEO-F091RC, NUCLEO-F103RB, NUCLEO-F302R8, NUCLEO-F303RE, NUCLEO-F334R8, NUCLEO-F401RE, NUCLEO-F410RB, NUCLEO-F411RE, NUCLEO-F446RE, NUCLEO-L053R8, NUCLEO-L073RZ, NUCLEO-L152RE, NUCLEO-L476RG

Turnigy 12v 2-3S Basic Balance Charger Drg #: 350

This Turnigy balance charger is simple to use, reliable and safe for any modeler. It features a smart charge protection to ensure the batteries are not overcharged and has real time monitoring increasing the cycle life of your battery packs. It ca...

More >

$4.81

STOCK: IN STOCK

Weight: 99g Quantity: 1

Rate: SKU: Turnigy-3S

BUY NOW!

Wish List | Issue | Price War

Overview | Specs | Discussion | Reviews | Video | File

Blade Count:	N/A	Diameter X(Inch):	No
SKU	Turnigy-3S	Watt Hour	0.00
Weight(g):	99.00	Length:	90.00
Width	27.00	Height	62.00

DX6e 6-Channel DSMX Transmitter with AR610 (SPM6650)

SPEKTRUM ☆☆☆☆☆ Be the first to write a review

Drg #: 360

Share Print

Free Shipping on orders over 99. Learn More*

Quantity 1

~~$206.99~~ **$179.99**

as low as $16/mo with Affirm

Add to Cart | Add to Wish List +

THIS PRODUCT IS IN STOCK

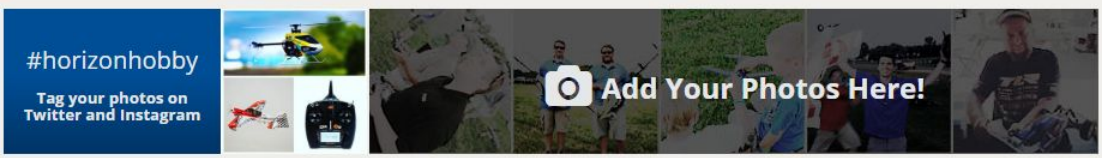
The DX6e gives you more than you ever thought possible from a 6-channel radio under $200. Four model types, 250-model memory, wireless trainer link – you get it all and more. You can even share model setups with users of other Spektrum transmitters.

Quick Support

- Parts and Upgrades
- Question and Answers
- Manuals

Share Your Photos with the Community

View Gallery › Add a Photo › Powered by Olapic



You Might Also Consider

Spektrum field towel ☆☆☆☆☆ $9.99

Single Aircraft Transmitter Case ★★★★★ $74.99

DX6e 6-Channel DSMX Transmitter Only ★★★★★ $149.99

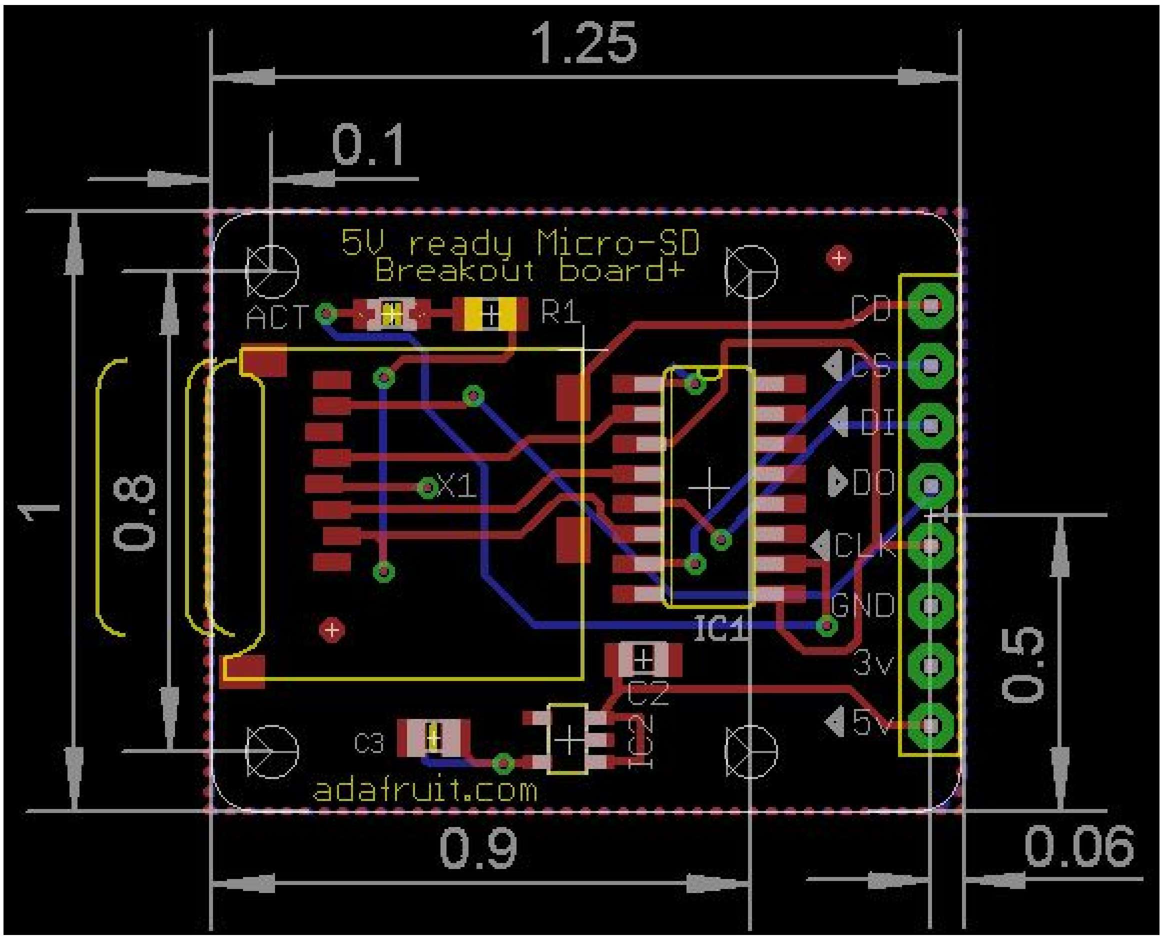
Overview | Specs | Reviews | Parts & Accessories | Manuals & Support | Q & A

Band:	2.4GHz
Channels:	6
Model Memory:	250
Model Type:	Airplane/Helicopter/Sailplane
Modes:	User Selectable Mode 1-4
Modulation:	DSMX,DSM2
Range:	Full
Receiver:	AR610
Telemetry:	Compatible
Transmitter (Tx) Battery Type:	AA

Not just a simple breakout board, this microSD adapter goes the extra mile - designed for ease of use.

- Onboard 5v->3v regulator provides 150mA for power-hungry cards
- 3v level shifting means you can use this with ease on either 3v or 5v systems
- Uses a proper level shifting chip, not resistors: less problems, and faster read/write access
- Use 3 or 4 digital pins to read and write 2Gb+ of storage!
- Activity LED lights up when the SD card is being read or written
- Four #2 mounting holes
- Push-push socket with card slightly over the edge of the PCB so its easy to insert and remove
- Comes with 0.1" header (unattached) so you can get it on a breadboard or use wires - your choice
- Tested and assembled here at the Adafruit factory
- Works great with Arduino, with tons of example code and wiring diagrams

Drg #: 370



4) Frame Interfacing

KBL48301X,24V-48V,300A,BLDC CONTROLLER/WITH REGEN Drg #: 410

KBL48301X,24V-48V,300A,BLDC CONTROLLER/WITH REGEN

Price : $319.00

Weight: 4.20 lbs

In stock

CAN Bus: Unselected

High Speed Motor Option: Unselected

Ultra High Speed Motor Option: Unselected

Quantity : 1 Add to Cart

DESCRIPTION

Kelly KBL Controllers User Manual

KBL BLDC MOTOR SPEED CONTROLLER

Kelly KBL programmable BLDC motor controller provides efficient, smooth and quiet controls for golf cart, go-cart, electric motorcycle, forklift, hybrid vehicle, electrical vehicle, electric boat, as well as industry motor speed or torque control. Motor speed controller uses high power MOSFET, PWM to achieve efficiency 99% in most cases. Powerful microprocessor brings in comprehensive and precise control to BLDC motor controllers. This programmable brushless motor controller also allows users to set parameters, conduct tests, and obtain diagnostic information quickly and easily.

Features:
- Intelligence with powerful microprocessor.
- Synchronous rectification, ultra low drop and fast PWM to achieve very high efficiency.
- Electronic reversing.
- Voltage monitoring on 3 motor phases, bus, and power supply.
- Voltage monitoring on voltage source 12V and 5V.
- Current sense on all 3 motor phases.
- Current control loop.
- Hardware over current protection.
- Hardware over voltage protection.
- Support torque mode, speed mode, and balanced mode operation.
- Configurable limit for motor current and battery current.
- Low EMC.
- LED fault code.
- Battery protection: current cutback, warning and shutdown at configurable high and low battery voltage.
- Rugged aluminum housing for maximum heat dissipation and harsh environment.
- Rugged high current terminals, and rugged aviation connectors for small signal.
- Thermal protection: current cut back, warning and shutdown on high temperature.
- Configurable 60 degree or 120 degree hall position sensors.
- Support motors with any number of poles.
- Up to 40,000 electric RPM standard. Optional high speed 70,000 ERPM, and ultra high speed 100,000 ERPM. (Electric RPM = mechanical RPM * motor pole pairs).
- Support three modes of regenerative braking: brake switch regen, release throttle regen, 0-5V analog signal variable regen.
- Configurable high pedal protection: the controller will not work if high throttle is detected at power on.
- Current multiplication: Take less current from battery, output more current to motor.
- Easy installation: 3 wire potentiometer can work.
- PWMable reverse alarm output.
- Remove fault code LED driver.
- Current meter output.
- Standard PC/Laptop computer to do programming. No special tools needed.
- User program provided. Easy to use. No cost to customers.

General Specifications:
- Controller supply voltage range, PWR, 18V-90V.
- Frequency of Operation: 16.6kHz.
- Standby Battery Current: < 0.5mA.
- 5V Sensor Supply Current: 40mA.
- Configurable battery voltage range, B+,18V-60V.
- Analog Brake and Throttle Input: 0-5 Volts. Producing 0-5V signal with 3-wire pot.
- Reverse Alarm, Main Contactor Coil Driver, Meter.
- Full Power Operating Temperature Range: 0°C to 50 °C (controller case temperature).
- Operating Temperature Range:-30°C to 90 °C, 100°C shutdown (controller case temperature).
- Boost Current, 10 seconds: 350A.
- Motor Current Limit, 1 minute: 300A.
- Motor Current Limit, continuous: 140A.
- Max Battery Current : Configurable.

Solenoid 24V4P 586 Series

Email to a Friend

Be the first to review this product

Availability: In stock

$79.98 **Drg #: 440**

Qty: 1 **Add to Cart**

-OR- **PayPal Check out**

The safer, easier way to pay

Double click on above image to view full picture

SMAKN

SMAKN® Double Bts7960b 43a Motor Driver High-power Module/smart Car Driver Arduino

9 customer reviews

Price: $22.60 & **FREE Shipping** on orders over $25. Details

In Stock.

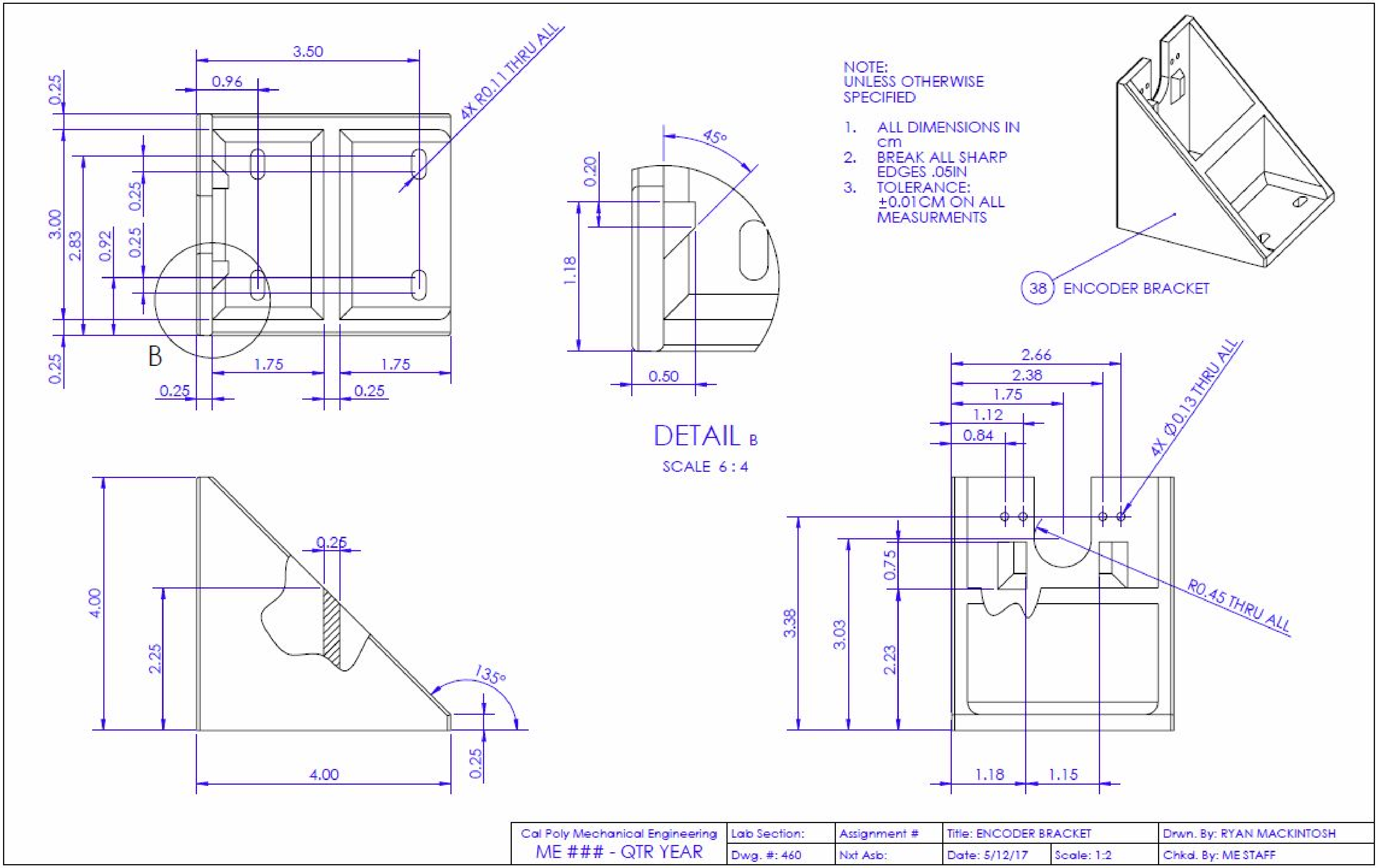
Want it Wednesday, June 7? Order within 24 mins and choose **Two-Day Shipping** at checkout. Details

Sold by SMAKN and Fulfilled by Amazon. Gift-wrap available.

- 5V isolate with MCU, and effectively protect MCU; 5V power indicator on board;
- voltage indication of motor driver output end; can solder heat sink;
- Just need four lines from MCU to driver module (GND. 5V. PWM1. PWM2); isolation chip 5 V power supply (can share with MCU 5 V);
- Able to reverse the motor forward, two PWM input frequency up to 25kHZ; two heat flow passing through an error signal output;
- Isolated chip 5V power supply (can be shared with the MCU 5V), can also use the on-board 5V supply; the supply voltage 5.5V to 27V

New (1) from $22.60 & FREE shipping on orders over $25.00. Details

Drg #: 450



NOTE:
UNLESS OTHERWISE SPECIFIED
1. ALL DIMENSIONS IN cm
2. BREAK ALL SHARP EDGES .05IN
3. TOLERANCE: ±0.01CM ON ALL MEASURMENTS
4X R0.11 THRU ALL
B
DETAIL B
SCALE 6 : 4
38 ENCODER BRACKET
4X Ø0.13 THRU ALL
R0.45 THRU ALL
3.50
0.96
0.25
3.00
2.83
0.92
1.75
0.20
1.18
0.50
45°
135°
4.00
2.25
2.66
2.38
1.12
0.84
3.38
3.03
0.75
2.23
1.15
Cal Poly Mechanical Engineering
ME ### - QTR YEAR
Lab Section:
Dwg. #: 460
Assignment #
Nxt Asb:
Title: ENCODER BRACKET
Date: 5/12/17
Scale: 1:2
Drwn. By: RYAN MACKINTOSH
Chkd. By: ME STAFF

Product Overview	
Digi-Key Part Number	102-1307-ND
Quantity Available	**4,075** Can ship immediately
Manufacturer	CUI Inc.
Manufacturer Part Number	AMT102-V
Description	ENCODER PROG 16RES SW TTL RADIAL
Lead Free Status / RoHS Status	Lead free / RoHS Compliant
Moisture Sensitivity Level (MSL)	1 (Unlimited)
Manufacturer Standard Lead Time	8 Weeks

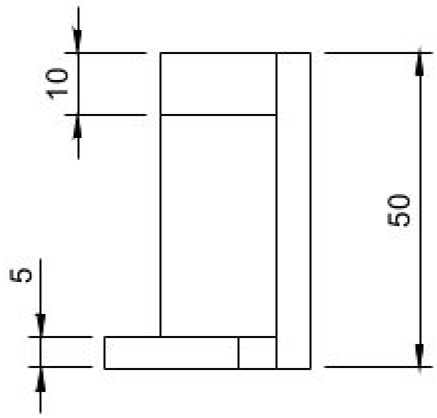
Drg #: 470

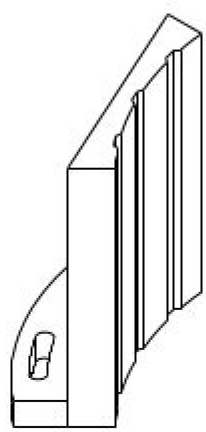
Documents & Media	
Datasheets	AMT10 Series
Product Training Modules	Capacitive Modular Encoders AMT10 and AMT11 Series
Video File	CUI Inc AMT Encoder Series – Another Geek Moment Mounting CUI's AMT10 Modular Encoder Series Mounting the AMT11, AMT20 and AMT31 Modular Encoder Series
RoHS Information	AMT10x-V KIT Cert of Compliance
Design Resources	Development Tool Selector
Featured Product	AMT Series
3D Model	AMT102-V KIT
Online Catalog	AMT10 Series Kits

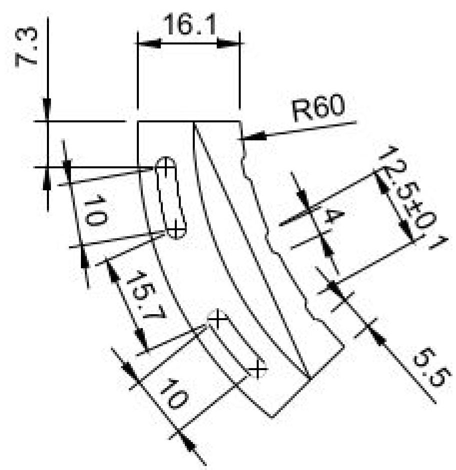
Product Attributes		Select All
Categories	Sensors, Transducers Encoders	
Manufacturer	CUI Inc.	
Series	AMT10X	
Part Status	Active	
Encoder Type	Capacitive	
Output Type	Quadrature with Index (Incremental)	
Pulses per Revolution	Programmable	
Voltage - Supply	3.6 V ~ 5.5 V	
Actuator Type	2mm ~ 8mm Open Center	
Detent	No	
Built in Switch	No	
Mounting Type	Chassis Mount, Motors	
Orientation	Vertical	
Termination Style	Terminal Pins	

NOTE:
UNLESS OTHERWISE SPECIFIED

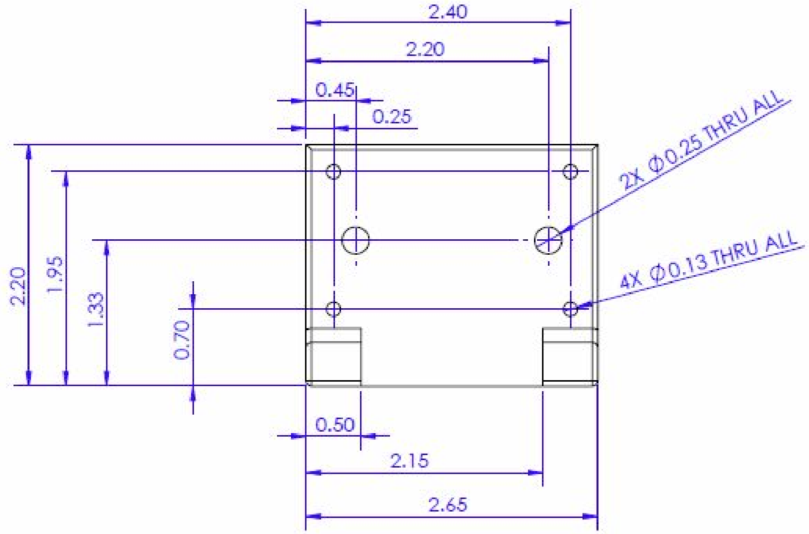
1. ALL DIMENSIONS IN mm
2. BREAK ALL SHARP EDGES
3. TOLERANCES:
    1. = ±1 mm
    0.1 = ±0.5 mm





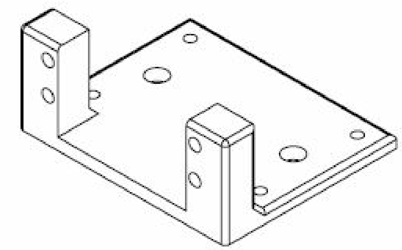


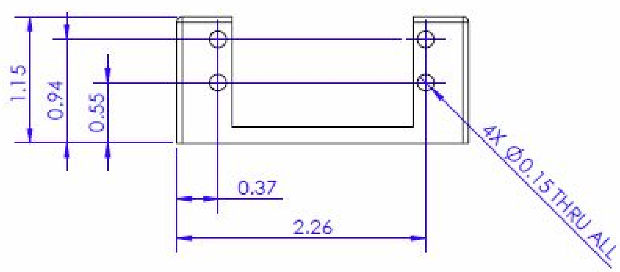
Dept.	Technical reference	Created by		Approved by	
MECH ENGR	SLONAV	John Barry	6/5/2017	N/A	N/A
		Document type: DRAWING		Document status	
		Title: Sensor Bracket		DWG No.: #480	
				Rev.: v2	Date of issue: 6/4/17 · Sheet: 1/1

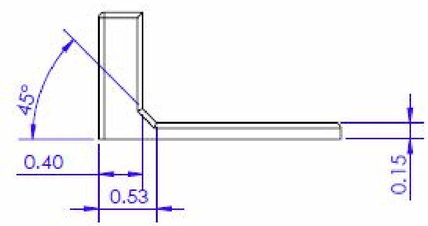


NOTE:
UNLESS OTHERWISE SPECIFIED

1. ALL DIMENSIONS IN cm
2. BREAK ALL SHARP EDGES .05IN
3. TOLERANCE: ±0.01CM ON ALL MEASURMENTS







Cal Poly Mechanical Engineering ME ### - QTR YEAR	Lab Section:	Assignment #	Title: BRAKE SERVO MOUNT	Drwn. By: RYAN MACKINTOSH
	Dwg. #: 490	Nxt Asb:	Date: 5/28/17 Scale: 1:1	Chkd. By: ME STAFF

5) External Enclosure Components

Model # 6002-22-00 Internet #202286718 Store SKU #610198

Drg #: 520

AFC Cable Systems

1/2 x 25 ft. Non-Metallic Liquidtight Conduit

★★★★½ (2) Write a Review Questions & Answers (16)

- Sunlight and oil resistant
- Suitable for exposed and concealed locations use
- Sunlight and oil resistant

$10.37 /each

Drg #: 550

Ceramic Path Specification:

Operating Frequency	T1 1575.42±1.023 MHz
Output Impedance	50 ohms
Polarization	R.H.C.P.
Bandwidth	10 MHz min. @S11<=-10 dB
Gain at 10° elevation	-1 dBic Typ.
Axial Ratio	3.0 dB Typ.

General specification:

Dimensions	L 41.2xW38.5xH13.3 mm
Mount	Magnetic Antenna
Antenna Color	Black
Coaxial Cable	RG174 Length=5M (Option)
Cable Connector	SMA MALE (Option)
Operating Temperature	-30°C to +85°C
Storage Temperature	-40°C to +90°C

Product Overview

Digi-Key Part Number	480-3310-ND
Quantity Available	870 Can ship immediately
Manufacturer	Honeywell Sensing and Productivity Solutions
Manufacturer Part Number	SS461C
Description	MAGNETIC SWITCH LATCH TO92-3
Expanded Description	Digital Switch Latch Open Collector Hall Effect TO-92-3
Lead Free Status / RoHS Status	Lead free / RoHS Compliant
Moisture Sensitivity Level (MSL)	1 (Unlimited)
Manufacturer Standard Lead Time	14 Weeks

Price & Procurement

Quantity 1

480-3310-ND

Customer Reference

Add to Cart

All prices are in USD.

Price Break	Unit Price	Extended Price
1	1.14000	1.14
10	0.70700	7.07
25	0.63240	15.81
50	0.57480	28.74
100	0.51720	51.72
500	0.45724	228.62
1,000	0.42840	428.40
5,000	0.39396	1,969.80

Submit a request for quotation on quantities greater than those displayed.

Drg #: 560

Documents & Media

Datasheets	SS361CT, 461C Datasheet SS361CT, 461C Install Instr
Design Resources	Development Tool Selector Sensor Selector Industrial Automation Product Selector
PCN Assembly/Origin	Hall Effect Magnetic Sensor 03/Feb/2016 Multiple Devices 07/Mar/2016
Online Catalog	SS361CT and SS461C Series

Product Attributes

Select All

Categories	Sensors, Transducers Magnetic Sensors - Switches (Solid State)
Manufacturer	Honeywell Sensing and Productivity Solutions
Series	-
Packaging	Bulk
Part Status	Active
Function	Latch
Technology	Hall Effect
Polarization	South Pole
Sensing Range	9.5mT Trip, -9.5mT Release
Test Condition	-40°C ~ 125°C
Voltage - Supply	4 V ~ 24 V
Current - Supply (Max)	8mA
Current - Output (Max)	20mA
Output Type	Open Collector
Features	-

Drg #: 570

AMP® BATTERY TERMINALS

(Click image for a larger view)

See Below for Parts, Pricing, and Ordering

From $0.74 to $7.50

★★★★★ (0) review this

Current Sub-total: $0.00

Rocker Switch - SPST (round)

COM-11138 ROHS✔

★★★★☆ 2

Drg #: 580

Description: This little round on/off toggle switch is rated up to 10A at 125VAC and can be panel mounted in a 20mm diameter hole. It'll also look pretty slick in your project.

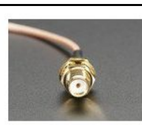
Documents:

- Dimensional Drawing

$0.50

ADD TO CART

1	quantity
	250+ in stock
$0.50	1+ units
$0.48	25+ units
$0.45	100+ units



Drg #: 590

SMA to uFL/u.FL/IPX/IPEX RF Adapter Cable

PRODUCT ID: 851

$3.95

IN STOCK

1 ADD TO CART

QTY	DISCOUNT
1-9	$3.95
10-99	$3.56
100+	$3.16

ADD TO WISHLIST

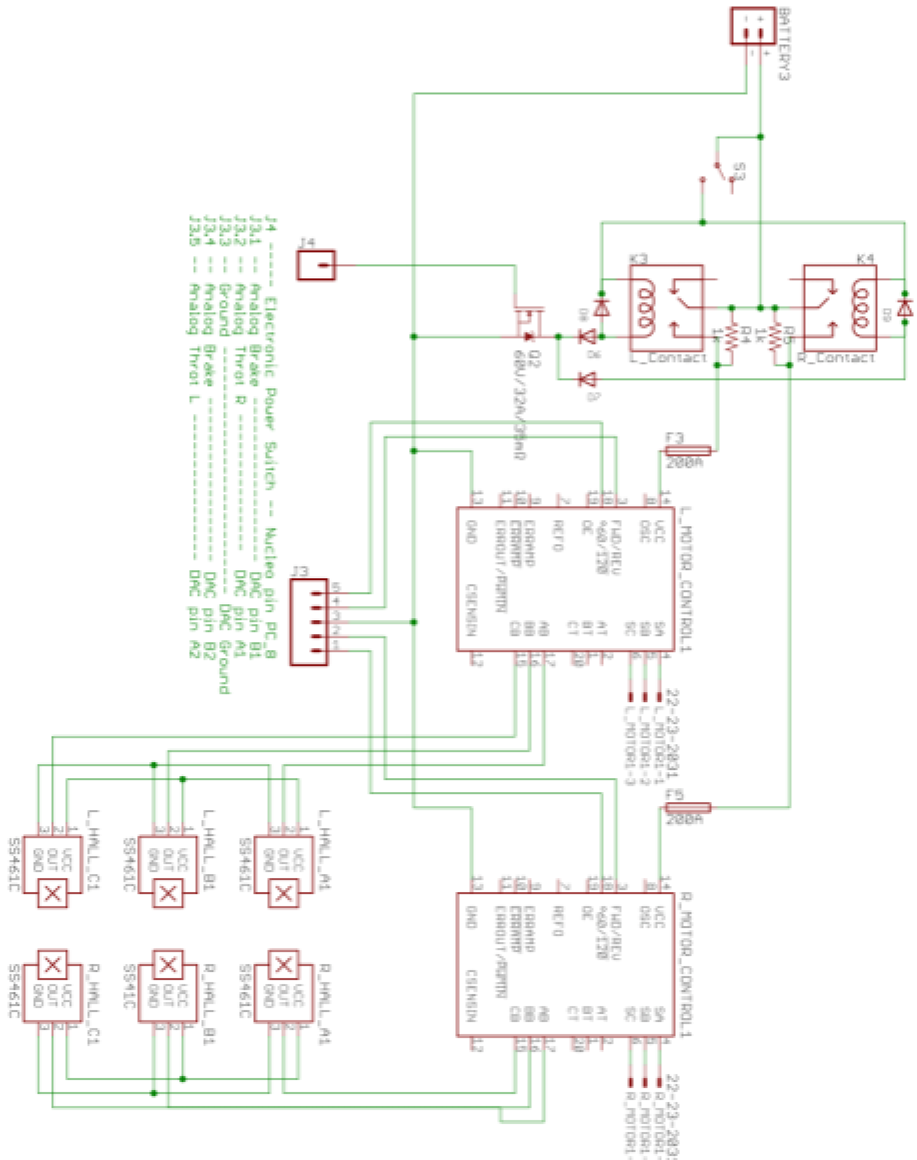
DESCRIPTION

This RF adapter cable is super handy for anyone doing RF work. Often times, small electronics save space by having a pick-and-placeable u.FL connector (also called uFL, IPEX, IPAX, IPX, MHF, and AM). But most antennas have SMA or RP-SMA connectors on them. This little cable will bridge the two!

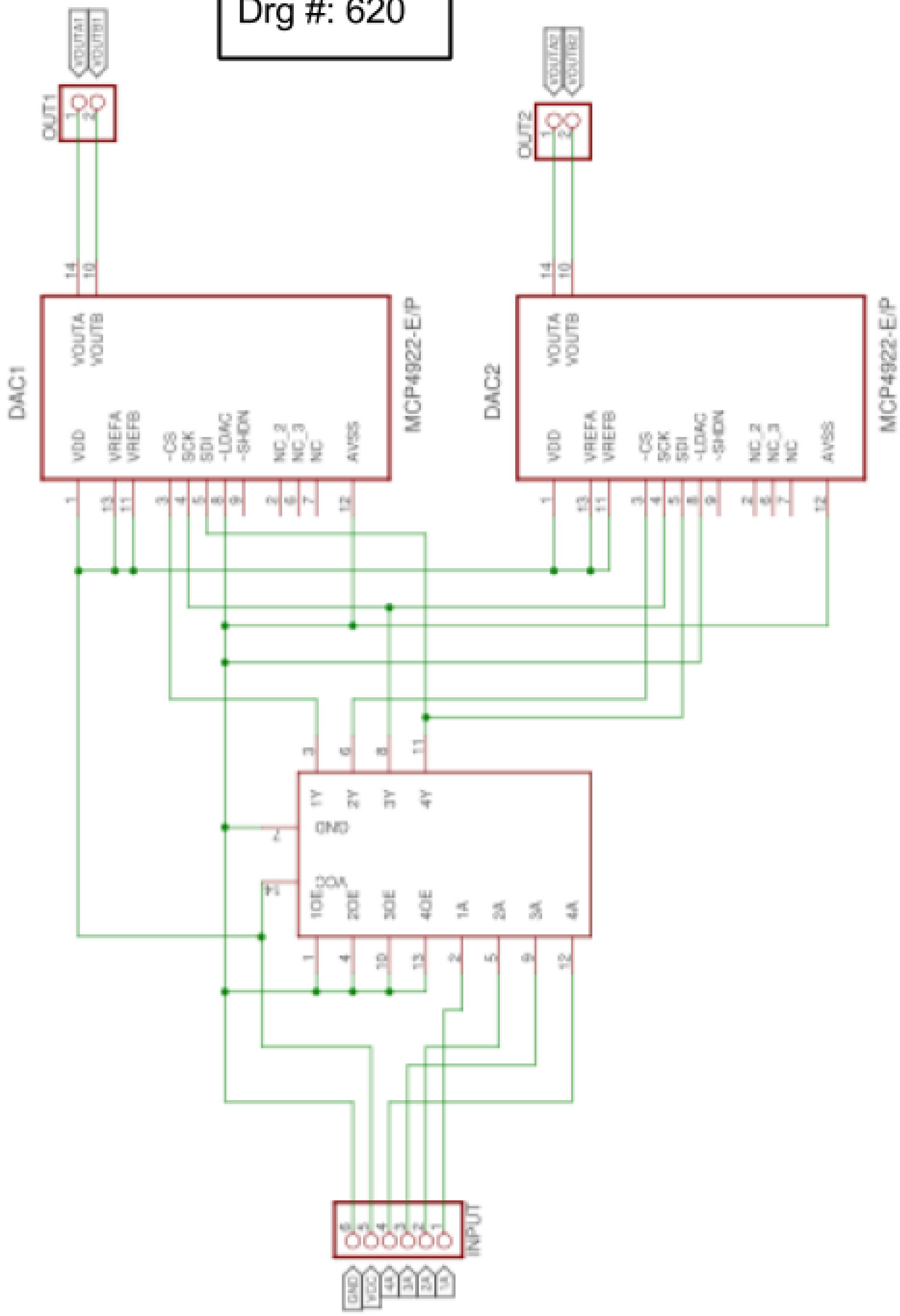
This cable is RG178 and is 15cm (5.9") long not including the SMA connector. It has a panel-mount **SMA** connector on the end, often used for GPS and cellular connections. Most WiFi devices/routers that have a connector use RP-SMA. Check the antenna you want to connect, and the close up image above to verify if you need RP-SMA or SMA as they are not compatible!

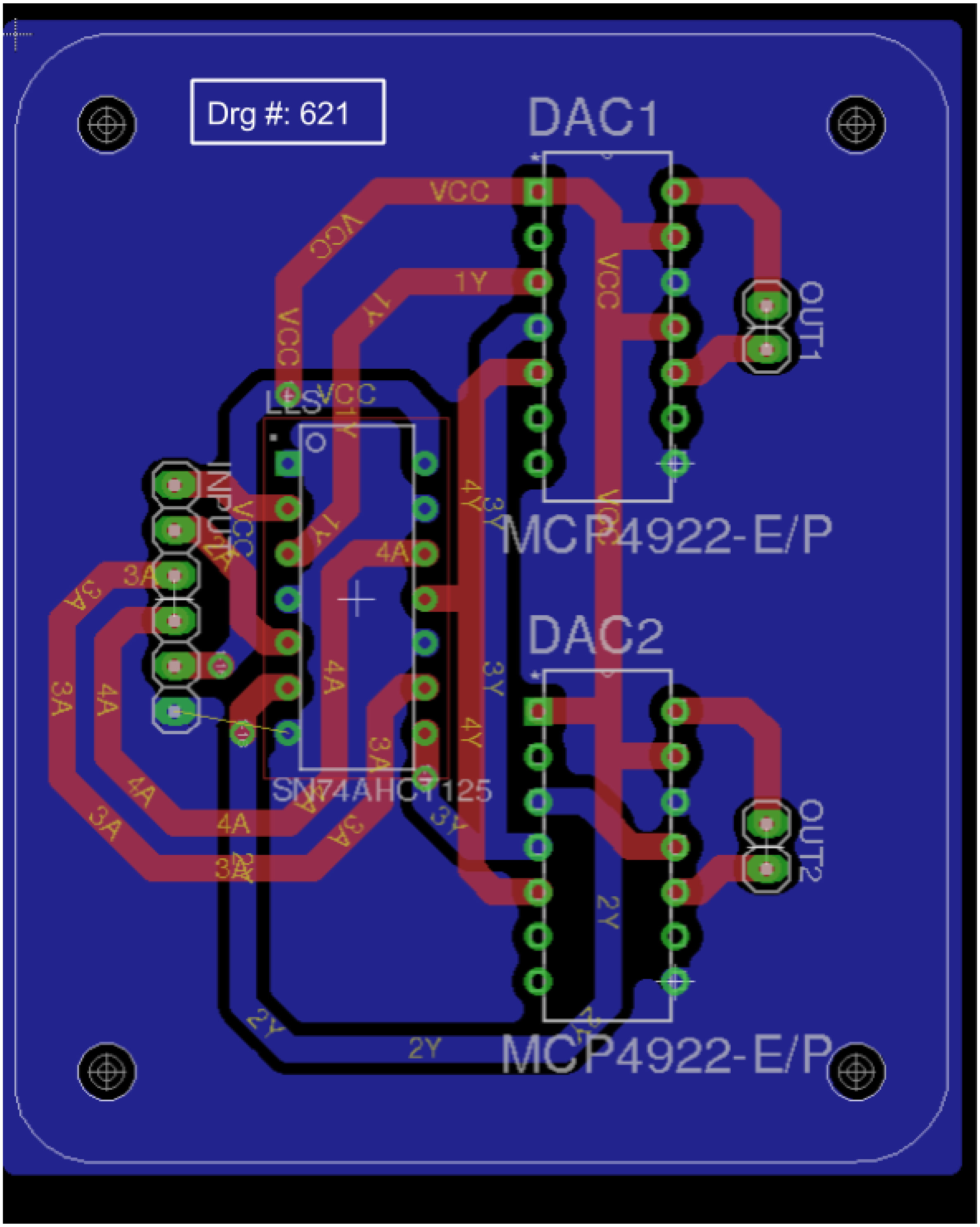
6) Electrical Schematics and PCB Layouts

Drg #: 610

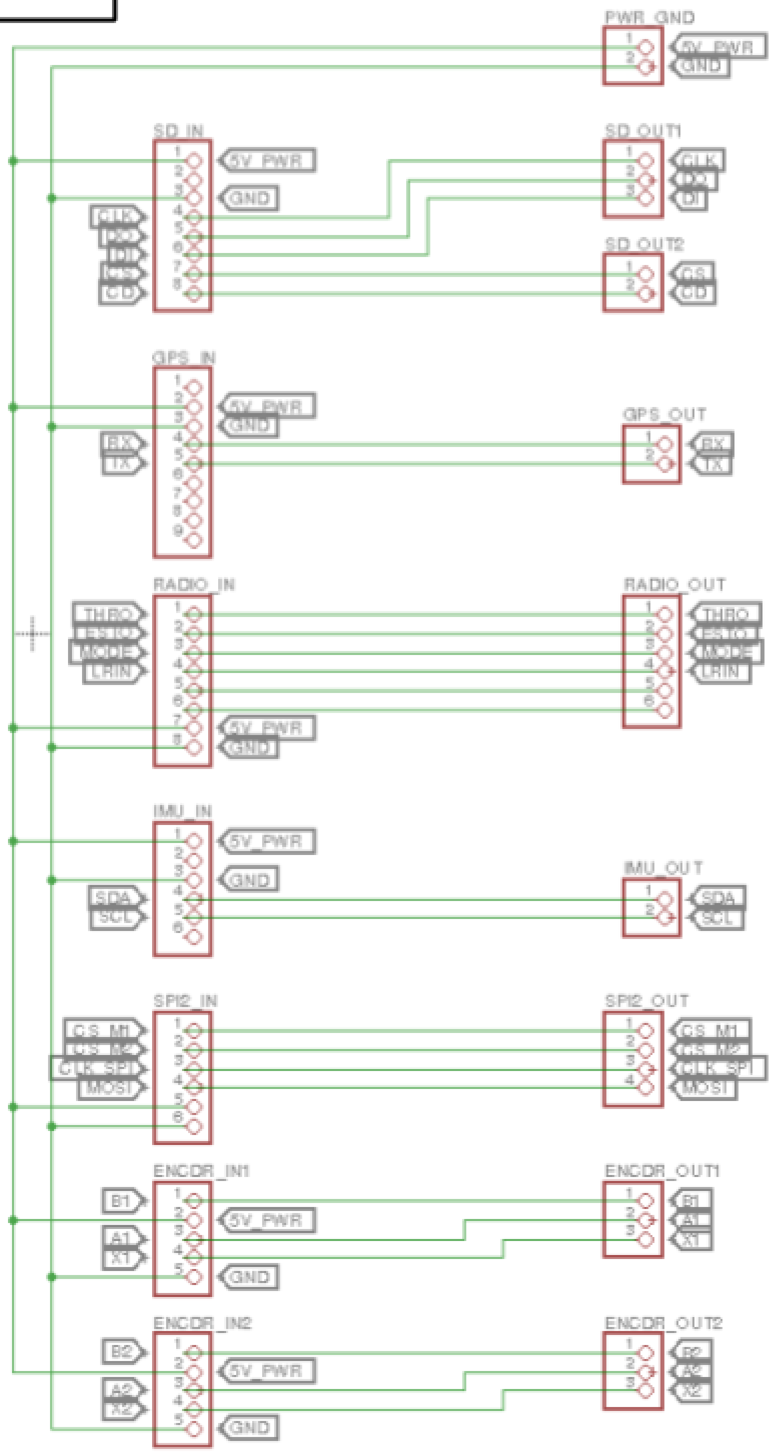


Drg #: 620

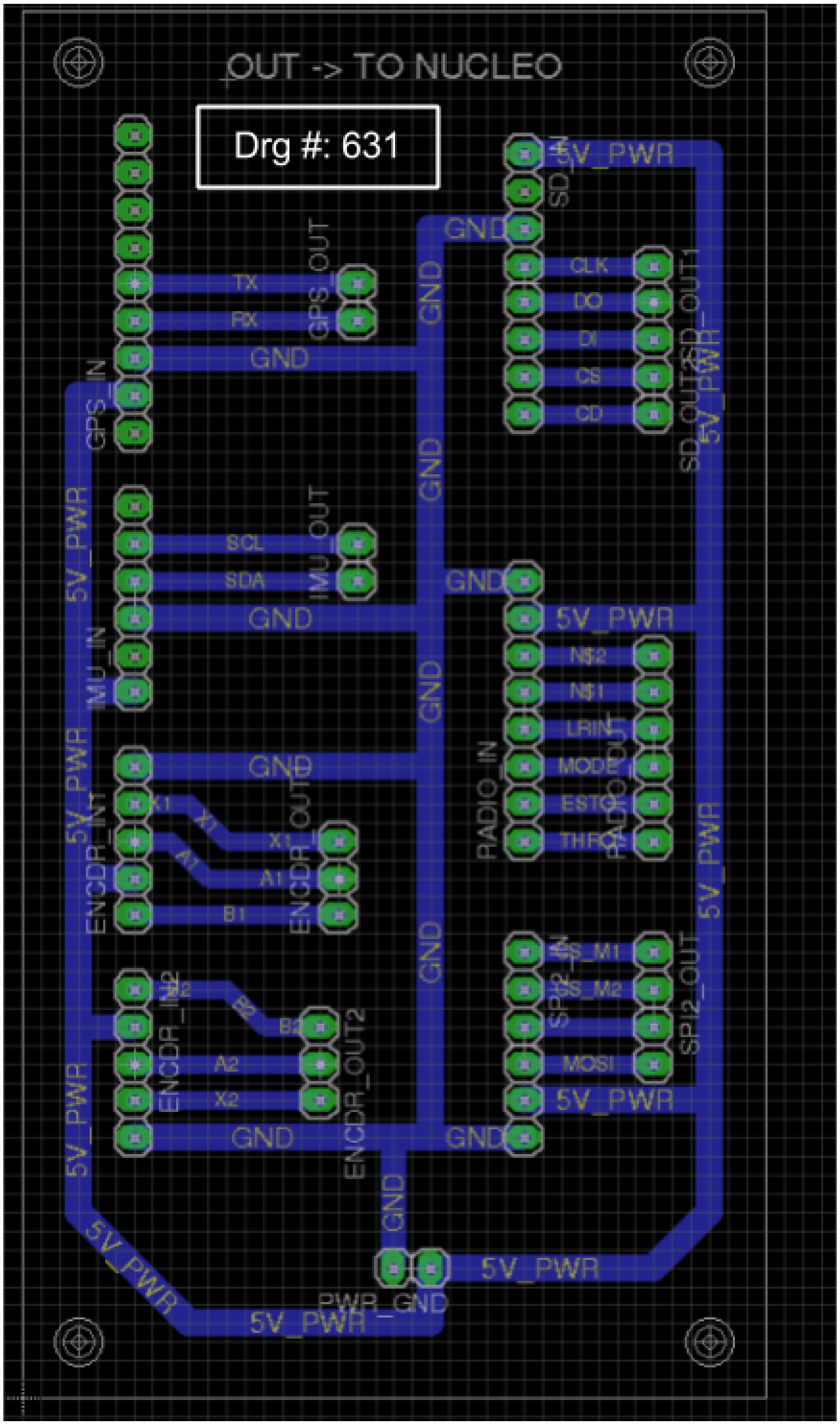

OUT1
OUT2
DAC1
DAC2
MCP4922-E/P
MCP4922-E/P
VOUTA
VOUTB
VDD
VREFA
VREFB
~CS
SCK
SDI
~LDAC
~SHDN
NC_2
NC_3
NC
AVSS
1Y
2Y
3Y
4Y
GND
VCC
1OE
2OE
3OE
4OE
1A
2A
3A
4A
INPUT


Drg #: 621
DAC1
MCP4922-E/P
DAC2
MCP4922-E/P
SN74AHCT125
OUT1
OUT2
INPUT
VCC
1Y
2Y
3Y
4Y
3A
4A

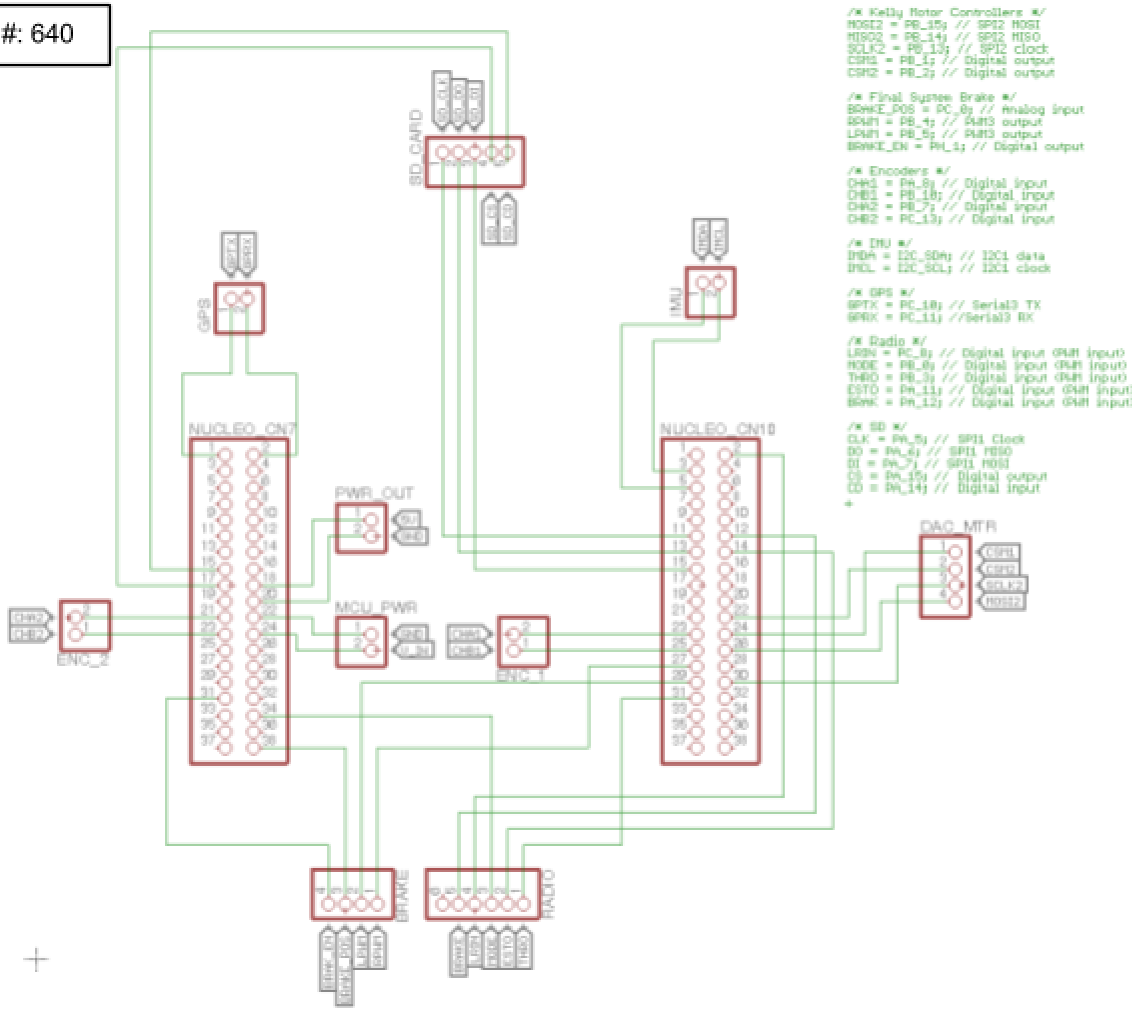
Drg #: 630



PWR_GND
5V_PWR
GND
SD_IN
SD_OUT1
CLK
DO
DI
SD_OUT2
CS
CD
GPS_IN
GPS_OUT
RX
TX
RADIO_IN
RADIO_OUT
THRO
ESTO
MODE
LRIN
IMU_IN
IMU_OUT
SDA
SCL
SPI2_IN
SPI2_OUT
CS_M1
CS_M2
CLK_SPI
MOSI
ENCDR_IN1
ENCDR_OUT1
B1
A1
X1
ENCDR_IN2
ENCDR_OUT2
B2
A2
X2


OUT -> TO NUCLEO
Drg #: 631
GPS_IN
GPS_OUT
TX
RX
GND
5V_PWR
IMU_IN
IMU_OUT
SCL
SDA
ENCDR_IN1
ENCDR_OUT1
X1
A1
B1
ENCDR_IN2
ENCDR_OUT2
B2
A2
X2
SD_IN
SD_OUT1
SD_OUT2
CLK
DO
DI
CS
CD
RADIO_IN
RADIO_OUT
N$2
N$1
LRIN
MODE
ESTO
THRO
SPI2_IN
SPI2_OUT
SS_M1
SS_M2
MOSI
PWR_GND

Drg #: 640



/* Kelly Motor Controllers */
MOSI2 = PB_15; // SPI2 MOSI
MISO2 = PB_14; // SPI2 MISO
SCLK2 = PB_13; // SPI2 clock
CSM1 = PB_1; // Digital output
CSM2 = PB_2; // Digital output
/* Final System Brake */
BRAKE_POS = PC_0; // Analog input
RPWM = PB_4; // PWM3 output
LPWM = PB_5; // PWM3 output
BRAKE_EN = PA_1; // Digital output
/* Encoders */
CHA1 = PA_8; // Digital input
CHB1 = PB_10; // Digital input
CHA2 = PB_7; // Digital input
CHB2 = PC_13; // Digital input
/* IMU */
IMDA = I2C_SDA; // I2C1 data
IMCL = I2C_SCL; // I2C1 clock
/* GPS */
GPTX = PC_10; // Serial3 TX
GPRX = PC_11; //Serial3 RX
/* Radio */
LRSN = PC_8; // Digital input (PWM input)
MODE = PB_8; // Digital input (PWM input)
THRO = PB_3; // Digital input (PWM input)
ESTO = PA_11; // Digital input (PWM input)
BRAK = PA_12; // Digital input (PWM input)
/* SD */
CLK = PA_5; // SPI1 Clock
DO = PA_6; // SPI1 MISO
DI = PA_7; // SPI1 MOSI
CS = PA_15; // Digital output
CD = PA_14; // Digital input
SD_CARD
GPS
IMU
NUCLEO_CN7
NUCLEO_CN10
PWR_OUT
MCU_PWR
DAC_MTR
ENC_1
ENC_2
BRAKE
RADIO
CHA2
CHB2
CHA1
CHB1
GND
CSM1
CSM2
SCLK2
MOSI2

Appendix I - Design Verification Plan and Report (DVP&R)

Table J1 DVP&R Test Plan.

DVP&R									
Date: 6/2/17			Daimler Trucks		Guided Target Control System	Dr. Birdsong			
TEST PLAN					TEST REPORT				
Item No	Specification or Clause Reference	Test Description	Acceptance Criteria	Test Responsibility	TEST RESULTS			NOTES
					Test Result	Quantity Pass	Quantity Fail	
1	Controllable Speed	Test Max Speed	Reach at least 32.2 kph	Ryan	N/A	N/A	N/A	Did not perform test
2		Test Speed Increments	Speed set in 1 kph increments	Ryan	N/A	N/A	N/A	Did not perform test
3		Test Speed Accuracy	Speed accurate to within 0.5 kph	Ryan	N/A	N/A	N/A	Did not perform test
4	Number of Trigger Points	Upload and run a large test map	Map has >= 10 points	Zach	N/A	N/A	N/A	Did not perform test
5	Positional Accuracy(with regard to trigger points)	Full stop at each spatial location allowing time to verify position	Vehicle stops within 1.5 meters of each center point	Zach	N/A	N/A	N/A	Did not perform test
6		Run Map dragging chalk or other temporary marker to verify path	Marked Path deviates no more than 1.5 meters from any	Zach	N/A	N/A	N/A	Did not perform test

			position point					
7		Comparison of actual path with retrieved sensor data	Retrieved data deviates no more than 0.5 meters from verified path	Zach	N/A	N/A	N/A	Did not perform test
8	Positional Accuracy (with regards to straight line between defined points)	Run Map dragging chalk or other temporary marker to verify path	Marked Path deviates no more than 0.5 meters from the straight line between two points	Zach	N/A	N/A	N/A	Did not perform test
9		Comparison of actual path with retrieved sensor data	Retrieved data deviates no more than 0.5 meters from verified path	Zach	N/A	N/A	N/A	Did not perform test
10	E-Stop signal Latency	Synchronise clocks and compare log of E-stop push to actuation occurrence	100ms	John	N/A	N/A	N/A	Did not perform test
11	Acceleration	Starting at 0, 3, and 6 meters per second measure the time for the vehicle to travel to a point 4.5, 13.5, and 22.5 meters	Δt <= 3s	John	N/A	N/A	N/A	Did not perform test

		away respectively.						
12	Deceleration	Starting at 0, 3, and 6 meters per second measure the time for the vehicle to come to a full and complete stop.	Δt <= 3s, 6s, 9s	John	N/A	N/A	N/A	Did not perform test
15	Acceleration / Deceleration	Starting at 0 m/s run several tests of accelerations at multiples of 0.25m/s^2. Mark a distance 20 meters down the track and measure the time for the vehicle to reach this point. Do this test again at 3 and 6 m/s starting to ensure the control holds through the full range of vehicle velocities.	Control of acceleratio n is accurate to within 0.25m/s^2 over the full range of the velocity and acceleratio n.	John	N/A	N/A	N/A	Did not perform test

16	Initial Setup Time	Starting with the vehicle as separate major components (chassis, control, soft target) time the assembly of the vehicle and loading of the first map using four or fewer persons	Δt <= 30 minutes	Ryan	Pass	2	0	26 min setup time
17	Setup time Between Tests	Time the reset time between several different runs. Time from the time the last run ends to the time the vehicle is ready to go waiting only for the start button.	Δt <= 10 minutes	Ryan	Pass	1	0	5 min setup time
18	Percentage of successful tests conducted without control system fault	Mark each test and note failures and causes. Keep a rolling average of testing problems	94% success rate for control system	John	Fail	0	1	~50%

19	Latency for control loop feedback	include counter in the code which notes each full cycle completion and the elapsed time since the end of the last full cycle. Include this data in the final system test output	$\Delta t <= 28ms$ for full control loop	Zach	N/A	N/A	N/A	Did not perform test
20	Size	Measure by approximate volume the size of the control system	90% of the volume of the control system is contained within a single 16in X 16in X 4in box	John	Pass	1	0	
21	Cost of control system/data acquisition hardware	At the end of the project calculate the final BOM total cost	Cost <= $1200	Zach	Fail	0	1	Over budget
22	Code documentation	Have three programmers with no prior knowledge of our code read the documentation and make a successful modification or develop a new function.	Time for major modification <= 2 hours	Zach	N/A	N/A	N/A	Did not perform test

Appendix J - Pre-Test Safety Checklist and Test Procedures

SLONAV Pre-Test Checklist

Note 1: Team SLONAV, Daimler Trucks, and CalPoly take no responsibility for injuries incurred during testing of the autonomous test target system. We strongly recommend you utilize other test equipment whenever possible.

Note 2: Refraining from performing any check in full or ignoring a failure for any reason will likely cause serious injury or death

Note 3: Read all safety checks, instructions, manuals, and related documentation before beginning any test.

Note 4: Before Activation of system have on hand one or more Battery safety kits. These kits should consist at minimum of the following items:

1. PVC or Neoprene rubber gloves designed for handling battery acid of 30-70% dilute sulfuric acid.
2. PVC bucket at least large enough to hold one standard size car battery in the event of a slow leak.
3. A large box of Sodium Bicarbonate (Baking Soda) for use neutralizing small spills of battery acid.
4. Fire Extinguisher Class ABC for putting out small fires
5. A set of MSDS for all batteries
6. Phone numbers for local chemical spill and hazardous materials authorities

Note 5: For any problems which cannot be handled by the above battery safety kit please call local Police/Fire/Emergency services at “911”
Note 6: For those testing outside the USA please confirm the emergency phone number for your local Police/Fire/Emergency services prior to beginning a test as it may be different from the number listed in *NOTE 5.*

ID	1.000 Physical Checks	Pass	Fail
1.100	Perform the following checks with batteries in place but not electrically connected		
1.200	With the exception of the Wheels, the Frame is no lower than 1.5 inches off the ground at any point.		
1.300	The tires are between 25 and 30 PSI		
1.400	No loose bolts		
1.411	No loose bolts (Back Left section)		
1.412	No loose bolts (Back Right section)		
1.413	No loose bolts (Front Left section)		
1.414	No loose bolts (Front Right section)		
1.421	No loose bolts (Center Frame section)		
1.431	No loose bolts (Electronics Enclosure)		
1.441	No loose bolts (Battery Tie-Downs)		
1.500	No loose wires		
1.511	No loose wires (Back Left Motor)		
1.512	No loose wires (Back Left Hall Effect Sensor)		
1.513	No loose wires (Back Left Shaft Encoder)		
1.514	No loose wires (Back Left Conduit)		
1.521	No loose wires (Back Right Motor)		
1.522	No loose wires (Back Right Hall Effect Sensor)		
1.523	No loose wires (Back Right Shaft Encoder)		
1.524	No loose wires (Back Right Conduit)		

1.531	No loose wires (Front Axle E-Brake)		
1.532	No loose wires (Front Axle Main Brake)		
1.533	No loose wires (Front Axle Conduit)		
1.541	Radio Wire Safely Tied Down		
1.551	GPS wire Safely Tied Down		
1.561	No loose wires or connectors in central electronics mounting		
1.600	Both Fuses Intact		
1.700	No Apparent Burns or abrasions on chassis or electronics		
1.800	E-Brake is in the closed position		
1.900	Front wheels will not turn and vehicle is difficult to move		

ID	2.000 Battery Power Checks	Pass	Fail
2.100	The three main batteries do not appear damaged or leaking		
2.200	The three main batteries each have a voltage between 11v and 13v when measured by accurate multi-meter		
2.300	The three main batteries have their original bolts and washers		
2.400	The Brake Battery does not appear damaged or leaking		
2.500	The Brake Battery has a voltage between 11v and 13v when measured by accurate multi-meter		
2.600	The Nucleo Battery does not appear damaged or leaking		
2.700	The Nucleo Battery has a voltage between 8v and 10v when measured by accurate multi-meter		

2.800	When powered on the Radio shows full power		

ID	3.000 Wheel Alignment Checks	Pass	Fail
3.000	Support the rear wheels off the ground		
3.111	Left Wheel Alignment is square		
3.112	Right Wheel Alignment is square		
3.211	Left Wheel Chain is taut but not ridged		
3.212	Right Wheel Chain is taut but not ridged		
3.311	There is no debris in Left chain, gear, or motor		
3.312	There is no debris in Right chain, gear, or motor		
3.411	Left wheel assembly turns smoothly without grinding		
3.412	Right wheel assembly turns smoothly without grinding		
3.500	Return Back Wheels to ground		

ID	4.000 E-Brake Checks	Pass	Fail
4.000	Ensure Main Batteries are disconnected.		
4.100	Connect the Brake Battery		
4.200	Connect the Nucleo Battery and power on Nucleo		
4.300	Power on Radio		
4.400	Toggle the radio E-Stop		
4.410	E-Brake toggles with radio E-Stop		
4.500	With E-Stop Engaged Power Down Nucleo		
ID	**5.000 Power Up Procedure**	**Pass**	**Fail**
5.001	Brake Battery is connected		

5.002	Nucleo power is off		
5.003	Nucleo Battery is connected		
5.004	Main Batteries are disconnected		
5.005	Main Power Switch is OFF		
5.006	All Previous Checks Passed		
5.100	Load Map File and insert SD card into onboard reader		
5.200	Clear Non-Essential Personnel from track		
5.300	Connect Main Batteries		
5.310	No solenoid actuation click was audible		
5.400	Power on Remote Control		
5.410	Ensure all switches and controls are in the default arrangement. Most importantly the E-Stop should be engaged, the Mode Select should be at position 2 and the Throttle should be at zero		
5.500	Flip Main Power Switch to ON		
5.510	No solenoid actuation click was audible		
5.500	Stand to the Left side of the Vehicle		
5.600	Flip Nucleo Power Switch to ON		
5.610	No solenoid actuation click was audible		
5.700	Back away at least ten feet from the vehicle. Do not stand behind or in front of the vehicle.		
5.710	Call “Vehicle Enabled Clear Track!”		
5.800	Disengage E-stop.		
5.810	Solenoid Actuation Was Audible		
5.900	Begin Test		

ID	**6.000 Power-Down Procedure**	Pass	Fail
6.000	Engage E-Stop		
6.100	Wait for vehicle to come to a complete stop		
6.200	Approach vehicle cautiously from the side.		
6.300	Flip Main Power to OFF		
6.400	Flip Nucleo Power to OFF		
6.500	Open Controls Box and remove SD card for review		
6.600	The Following Steps can be skipped in the event of repeating a test within the next ten minutes.		
6.700	Disconnect Main Batteries		
6.800	Disconnect Nucleo Battery and Brake Battery. Power Down Radio.		
6.900	Store Vehicle in a cool dry location out of Direct sunlight.		

SLONav Full Scale Test Plan

Test Date:
Conducted By:
Conducted At:

Reliability

- Throughout testing keep track of number of resets done and number of successful tests

  # of scheduled resets:
  # of unscheduled resets:
  # of successful tests:

Initial Startup

- Start stopwatch
- Conduct full safety checklist (See SLONav Checklist)
- Stop stopwatch when vehicle is awaiting user input

  Goal: 30 mins
  Actual:

  Notes:

Reset Procedure for Radio Control Mode

  - Ensure Estop is engaged
  - Approach vehicle from left side.
  - Turn off main power
  - Turn off Nucleo power
  - Remove SD card
  - Retrieve data and load new map file
  - Insert SD card
  - Ensure Brake power is connected
  - Turn on main power
  - Turn on Nucleo power

- Should not hear an audible solenoid click
- If solenoid click audible turn off main power

Reset Time Test

- Start stopwatch
- Conduct reset procedure for radio control mode
- Stop stopwatch when vehicle is awaiting user input

Goal: 10 mins

Actual:

Notes:

Radio Range

- Put car on block so that wheels are not touching ground with power off
- Start car in radio control mode
- Move away from vehicle in 25 ft increments until range exceeds boundary of testing area
- At each increment, slowly increase throttle until wheel visibly turn. Then return throttle to low
- Testing at extreme range may require a spotter to stay with the vehicle, in contact with the operator by phone or walkie-talkie
- Finish by engaging emergency brake
- Initiate standard power down procedure

Goal: 1 Mile

Actual:

Notes:

Standard Radio Control Test

- ○ Ensure Vehicle is powered down
- ○ Ensure standard pre-test checklist complete
- ○ Load valid map file to SD card.
- ○ Place vehicle on blocks so that tires do not touch the ground
- ○ Insert SD card
- ○ Ensure Brake power is connected
- ○ Power up radio
- ○ Switch main power to ON
- ○ Switch nucleo power to ON
- ○ Disengage radio E-stop
- ○ Listen for audible solenoid click
- ○ Power down and abort test if no “click” heard
- ○ Switch mode select to radio control
- ○ Confirm main break activates with right joystick
- ○ Confirm wheel spin when throttle is brought up
- ○ Confirm wheel speed ratio changes when left joystick is moved left and right
- ○ Engage E-stop
- ○ Wait for system to stop moving
- ○ Shut off main power
- ○ Shut off Nucleo power
- ○ Remove SD card
- ○ Review DATA

Goal: Safe control of vehicle

Actual:

Notes:

Test Upload and Data Collection

- SD card detect
    - Ensure Vehicle is powered down
    - Remove SD card
    - Initiate standard radio control test (Do not reinsert SD card)
    - Vehicle should not respond to user input
    - Power down
- Map check
    - Load a completely blank SD card into vehicle.
    - Attempt radio control test.
    - Vehicle should not respond to user input.
    - Power down.

- Map invalid check
    - Ensure Vehicle is powered down
    - Alter a valid map file so it is invalid in one or more ways.
    - Initiate standard radio control test (use the invalid map file)
    - Vehicle should not respond to user input.
    - Power down

Goal: Vehical non-responsive for all tests

Actual:

Notes:

Sensor Verification

IMU

- Orientation
    - Mark points in front of vehicle corresponding to every 15 degrees of a circle with center at center of vehicle rear axle.
    - Start vehicle in radio control mode with motor power manually shut off
    - Manually move vehicle front end to each marked angle.
    - Pause at each angle for at least five seconds
    - Return vehicle to original orientation

- Power down vehicle
- Ensure data gathered matches 15 degree increments as marked on track

- Acceleration
    - Warning! Begin tests at slowest possible speeds. Run multiple tests at higher speed only after lower speeds are confirmed controllable and safe.

  - Mark start and stop point on track exactly 20ft apart
  - Mark emergency points on track 20 ft beyond the start and stop marks
  - Place vehicle at the start mark oriented so it will drive toward the stop
  - Move all personnel behind and to the sides of the vehicle
  - Ready one or more persons with stop-watches.
  - Ready one person as the caller. This person's job is to call start and stop when the vehicle crosses the start and stop lines.
  - Start vehicle in radio control mode
  - Use radio to accelerate the vehicle to a constant speed maintain speed until reaching the stop mark. REduce throttle to zero and engage brake. Engage E-stop if vehicle reaches the emergency mark.
  - Start stopwatch when vehicle begins moving
  - Stop stopwatch when vehicle crosses stop point.
  - Analyze data by comparing acceleration to average acceleration calculated
  - For additional data gathering position a radar gun to the rear and side of the vehicle and record velocity from this.
- Deceleration
    - Warning! Begin tests at slowest possible speeds. Run multiple tests at higher speed only after lower speeds are confirmed controllable and safe.
  - Mark start and stop point on track exactly 20ft apart
  - Mark emergency points on track 20 ft beyond the start and stop marks
  - Place vehicle at the emergency mark beyond the start mark oriented so it will drive toward the stop mark
  - Move all personnel behind and to the sides of the vehicle
  - Ready one or more persons with stop-watches.
  - Ready one person as the caller. This person's job is to call start and stop when the vehicle crosses the start and stop lines.

- Start vehicle in radio control mode
- Use radio to accelerate the vehicle to a constant speed maintain speed until reaching the start mark. Reduce throttle to zero and engage brake. Engage E-stop if vehicle reaches the emergency mark.
- Start stopwatch when vehicle reaches start mark
- Stop stopwatch when vehicle crosses stop point.
- For additional data gathering position a radar gun to the rear and side of the vehicle and record velocity from this.

Encoders

- Velocity
  - Analyze data from IMU tests by comparing encoder readings to IMU readings, distance of travel, stop watch readings and radar gun readings.

GPS

- Location
  - Ensure Vehicle is unpowered
  - Move vehicle to start mark
  - Connect Computer to vehicle and initiate serial read of GPS data.
  - Wait for GPS to lock
  - Confirm GPS value with known good value from phone or dedicated module
  - Move GPS to stop mark reconfirm vGPS output
  - Power down
- Time
  - Ensure Vehicle is unpowered
  - Move vehicle to start mark
  - Connect Computer to vehicle and initiate serial read of GPS data.
  - Wait for GPS to lock
  - Confirm GPS time with known good value from phone or dedicated module
  - Move GPS to stop mark reconfirm GPS time output
  - Power down

Goal: GPS matches known good values to within 0.5 meters. Time to within 1 second

Actual:

Notes:

Emergency Stop

- Place Vehicle on blocks.
- Conduct standard radio control test
- Time latency between E-stop engaged and E-brake engaged.

Goal: 100ms latency on brake engagement

Actual: 25% -
50% -
75% -

NOTE: Do not conduct this test until it is confirmed that the E-stop is sufficiently powerful to slow the vehicle. Test this by pushing the vehicle unpowered with E-Stop engaged.

- Mark start and stop point on track exactly 20ft apart
- Mark emergency points on track 20 ft beyond the start and stop marks
- Place vehicle at the start mark oriented so it will drive toward the stop
- Clear Track
- Start Vehicle in radio control mode
- Accelerate vehicle to ¼ throttle
- Engage E-Stop when vehicle reaches the stop mark
- Start Stop Watch when E-stop is engaged.
- Stop Stop watch when vehicle is completely stopped.

Vehicle Dynamics

- Put vehicle in radio control mode
- Perform various vehicle maneuvers
- Accelerate then decelerate to stop
- Lane change
- Max turning radius
- Save and analyze data for future use

Notes:

Other Tests Performed

Notes:

Appendix K - Operator's Manual

Operator Manual

SLONav Senior Project 2017

Summary

This manual serves as a guide to the standard operation of the guided target control system developed by the SLONav team for Daimler North America as a Mechanical Engineering senior project (2016-2017).

Startup

1. Generate a map data file that contains the boundary of the track, positions of trigger points, and desired velocities at those points using the template file.
2. Load the map data file to an SD card and insert the SD card into the appropriate port in the control system enclosure.
3. Turn on power to the control system and vehicle
4. Wait for GPS to obtain a fix and status lights are green.
    a. **Note:** For first time startup in a new location this could take as long as half an hour. Normal time for GPS lock is 5-10 minutes
5. With all status lights green and radio controller off, flip the main power switch to ON
6. From this point onward stand clear of the vehicle by at least 5 meters unless powering down the vehicle.

Operation

1. With all switches set to default settings power on the radio controller. Ensure the E-STOP is switch is set to stop.
    a. **Note:** E-STOP switch is the toggle switch furthest back on the top left of the controller.
2. Watch for the vehicle status light to blink off for one second every five seconds. This confirms radio control.
3. Clear all remaining personnel from test track. Ensure no one is within 5 meters of the vehicle.

Autonomous Test

1. Flip the mode switch on the remote control to autonomous.
    a. **Note:** Mode switch is the three position toggle switch on the right side above the left joystick.
2. To start test flip the E-STOP switch to run.
3. To prematurely end the test flip the E-STOP switch to stop.

Manual Test

1. Flip the mode switch on the remote control to manual.
2. To start test flip the E-STOP switch to run.
3. To end the test flip the E-STOP switch to stop.
4. Use the right joystick to control braking and the left joystick to control throttle and steering.

Shutdown

1. Make sure the vehicle has stopped moving and engage the E-STOP.
2. One person may then approach the vehicle and manually power down the the main power system by flipping the main switch to off.
3. With the vehicle powered down switch the controls system switch to OFF.
4. When the controls system has powered down, indicated by an unlit indicator light, remove the SD card.
5. Once the SD card has been removed, review test data via any common spreadsheet viewer.