3/31/2023

Team 503: Hardware In Loop 1tenth Scale Automobile

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Abstract

The shift to autonomy is a primary focus for producers moving forward. Researchers are finding ways to make driverless cars while battling energy consumption. Our team aims to design a small-scale autonomous car that reduces energy losses by keeping a constant speed. Scaling down the project is beneficial to our goals. We can more easily deal with challenges that are hard to test with a larger model. We can also replicate a real environment with software that interacts with the scaled car. This is called hardware-in-the-loop. Hardware-in-the-loop is a testing technique that reproduces different environments based on physical signals. We split the project into two sides. These include the mechanical side of the project and the vision side. The two large sides of the project were broken even further into four parts. Looking at smaller parts of our project allows us to analyze the more complex design. The four parts include object detection, path planning, the steering, and the motor. Our team focuses on the mechanical side of the project while a separate team focuses on the vision side. Communication with the vision team is important to the success of the project. The mechanical side includes a steering design that rotates to a set angle. The angle is provided by the vision team, to adjust the direction the car is heading. The mechanical side also includes a motor design working to propel the car forward. The design should work without actions from a user. The path for the car goes from the back entrance of the Aero-Propulsion, Mechatronics and Energy Building to the B side entrance of the College of Engineering. The project will be successful when efficient power consumption is achieved. This will happen when less energy is lost from the car movement.

Keywords: Autonomy, Simulations, Discretion

Acknowledgement

We would like to acknowledge and give our warmest thanks to our project sponsor who made this work possible. The subject matter experts provided guidance and perspectives for our project that we would not have been able to provide ourselves.

We would also like to thank our sponsor, Camilo Ordonez. Without his knowledge and expertise in the subject matter, we would not have been able to progress in this project. We are especially grateful for our biweekly meetings which kept us accountable of the work that needed to be accomplished for a successful design.

Additionally, thank you to the faculty members who provided insight, comments, materials, and resources towards aspects of the project that are unfamiliar. Our sincerest thanks go towards Shayne McConomy, Patrick Hollis, Christian Hubicki, Keith Larson, Justin Pogge, and Wade Robinson.

Table of Contents

List of Tables

List of Figures

Notation

AAA	American Automobile Association
OEM	Original Equipment Manufacturers
SME	Subject Matter Expert
LiDAR	Light Detection and Ranging
IMU	Inertial Measurement Unit
FAMU	Florida Agricultural and Mechanical University
FSU	Florida State University
AME	Aero-Propulsions, Mechatronics and Energy Building
SBMPO	Sampling Based Model Predictive Optimization
MBPC	Model Based Predictive Control
PID	Proportional, Integral, and Derivative Control
ROS	Robot Operating System

Chapter One: EML 4551C

1.1 Project Scope

Project Description

The overall goal of the design experiment is to successfully develop a "hardware in loop" wheeled robot to optimize a path to maintain velocity and minimize inertial losses from accelerating and decelerating. The plan to do this is to create a control system for the vehicle's steering and acceleration. After discussing with the object detection team, a point of contact within the vehicle will be established where commands are sent to the control system. This should result in an autonomous vehicle, that optimizes its path and minimizes inertial losses.

Key Goals

The goals of the project will be defined so that, once met, the project functionality will match the project description.

The first goal of the project is to create a small-scale autonomous vehicle. To do so, the vehicle is expected to have sensors that allow for obstacle detection and light sensors that will detect if the vehicle is driving down a straight line.

The second goal of the project is to ensure the vehicle can maintain velocity. The assumption is that this design feature is like the cruise control feature found in cars, which utilizes acceleration and deceleration to control the speed of the car.

The final goal of the project is to minimize inertial losses from accelerating and decelerating. Inertial losses involve the energy needed to accelerate being proportional to the mass of the vehicle.

Assumptions

To successfully create a functioning design that meets all the key goals, assumptions had to be made. One assumption is that the obstacles the vehicle will come across will be static. Another assumption that will be made is that the road grade will be changing along the path. The third assumption is that there will be multiple possible paths from point A to point B, meaning it is up to our vehicles autonomy to choose the best one. To accomplish this, the vehicle should be able to utilize the features of object locating and tracking provided by team 504. Therefore, a feature of the design will include sensors, dynamic movement, and velocity changes to overcome the obstacles experienced when navigating an unknown terrain. The user is also assumed to be able to successfully operate the design, even though the design is intended to be autonomous.

The final assumption is regarding deliverable timing, where we expect the sponsor to want mechanical and software prototypes monthly once the design specifications are outlined.

Markets

In having our final design's functionality match the project description, the goal is to fulfill the requirements of the project sponsors, the Central Intelligence Agency (C.I.A.). The primary market includes C.I.A. teams and any counterterrorism teams in public and private government agencies. The secondary markets might consist of original equipment manufacturers (OEM), spyware enthusiasts, private search teams, and space exploration companies. Automobile companies can gain influence into autonomy and minimize inertial effects from our project and implement them on a larger scale. Spyware enthusiasts may find interest in the design to add to their collection. Space exploration and private search teams can use the small-scale vehicle to navigate with ease and collect information.

Stakeholders

Unlike markets, which depend on who will benefit from the final design, stakeholders are any party with active involvement in the project, which includes project sponsors, investors, advisors, and adjacent teams. For this project, the main stakeholders are the Central Intelligence Agency (C.I.A.), subject matter experts (SME), Dr. Shayne McConomy, Dr. Camilo Ordonez, and Team 504.

The C.I.A. sponsors the project and emphasizes control over the overall design as well as financing the design. As the project advisor, Dr. Camilo Ordonez will be contributing time and resources towards the design. The C.I.A. SME also contribute their time and knowledge to assist in design specifications. Dr. Shayne McConomy contributes his time by evaluating the project progression and helping the team by guiding the project in the right direction. Finally, Team 504 will be assisting in the visual mapping of the external surroundings.

1.2 Customer Needs

To gain a better understanding of the expectations from the customer, a series of questions was developed for the customer, sponsor, and advisor. The customer for this design is the CIA as they will ideally be able to use the developed product on missions to locate and track objects and/or targets of interest. The questions are primarily focused on design specifications and trying to learn what the customer is truly asking for. Once the statements were collected from the customer, interpretations of the design needs were formed. The questions, statements, and interpreted needs can be found in the table below.

Table 1: Customer Needs

Question/Prompt	Customer Statement	Interpreted Need
What is the estimated weight of the design?	Must be able to carry a payload without impacting maneuverability.	Focus primarily on a lightweight design to compensate for the extra weight that will be added.
Is the design based on the F1tenth competition requirements?	Yes, but improve on the design to gear towards the CIA requirements.	Follow F1tenth specifications but optimize being able to keep up with a tracked target.
What is the estimated cost of the design?	F1tenth bill of materials approximates $3500.	Work adjacent with team 504 to combine budgets and determine which team is financially capable of buying what items.
What is the general design of the obstacles?	min: 12x12x30cm max: 35x32x30cm LiDAR perceivable material	Design the obstacle out of cardboard to be detectable by LiDAR, starting at one of the size extremes.
Are the obstacles static or dynamic?	Both	Design for static obstacles first, then make the design more complex.
Define failure to avoid an obstacle?	The goal is to keep up with a target being tracked so, ideally, the design should not crash.	LiDAR specifications: detection range = 10 m scanning frequency = 40 Hz angular resolution = 0.25°
What speed is the vehicle operating at?	The average speed on a track is 35mph while the vehicle can go upwards of 70mph. Cornering and maneuverability affect speed.	Determine an optimal speed that does not sacrifice maneuverability. An even weight distribution can achieve an infinite critical velocity; however, acceleration will compromise weight distribution.

The table above is a breakdown of the questions, customer statements, and the interpreted needs for the project. The initial interaction with the customer yielded seven key questions that will increase the success of the project and satisfy the customer's needs. The questions include the design weight, cost, and speed. Additional questions were also the functionality of the design based on obstacles, the failure to avoid the obstacles, whether those obstacles were dynamic or static, and if the design should be based on within the F1Tenth competition.

The Model will be based on the F1Tenth competition design but will be augmented and optimized to be able to maintain position relative to a moving target. For the weight, speed, and cost of design, the focus will be to develop a lightweight model that can support specified weights that will not deter movement in any way. For the speed, the focus should be on monitoring various F1Tenth models in terms of track speed and total speed while ensuring no sacrifice in maneuverability and weight distribution. As for the cost, a budget of $3500 has been deemed necessary for the project's success, based on the cost of building a F1Tenth vehicle. The project objective of this team and team 504 are closely related and will hopefully work together during the final stages of the project completion. Based on this realization, the cost of parts should not reach the total budget because we can combine budgets. A crucial part of the customer's needs was the functionality of the design based on obstacles. Based on the specifications of the customer, various tests will be run by creating obstacles using LiDAR perceivable material with diverse sizes that can perceive both dynamic and static obstacles.

1.3 Functional Decomposition

After analyzing the project scope and the needs of the customer, the main functions of the design were formed. The main functions were heavily influenced by the key goals of the project because the success of the design is determined by how effective we are at accomplishing these key goals. Using functional decomposition, we were able to analyze a complex system and extract what individual components the system will be fulfilling. The main functions were broken down into subfunctions until there was an understanding of the physics required for a successful system.

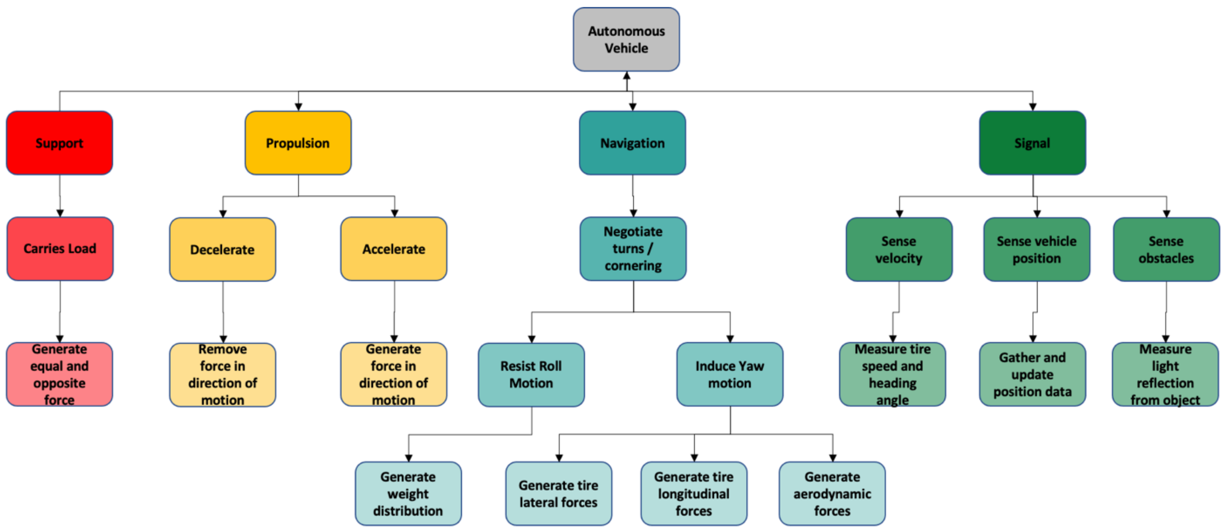


Figure 1: Functional Decomposition Hierarchy Chart

As stated previously, the main functions in the second row of Figure 1 were developed from the key goals of the project. The design is required to work adjacent with team 504 who is designing a system capable of tracking a target. This meant the design must be able to support the system coming from team 504. Specifically, it must be compatible with the tracking software developed by the team and must be able to hold the mechanical load of the system. To maintain a mechanical load on top of the design, there must be an equal and opposite force to counteract the force being applied by the mechanical load.

The design is also expected to be able to propel itself to successfully keep up with a tracked target and maneuver around a course. This is achieved through removing the force in the direction of motion to create deceleration and generating a force in the direction of motion to create acceleration.

The main function needed to maneuver around a course is navigation where the design must be effective in cornering to prevent collision with obstacles and the extremes of a track. The subsystems to achieve cornering involve resisting the roll motion in the longitudinal axis and inducing yaw motion in the vertical axis of the design. A weight distribution must be generated to counteract the roll motion expected in the design as its negotiation turns. There must also be longitudinal, lateral, and aerodynamic forces generated in the design to induce a yaw motion to negotiate turns. The vehicle must make turns as needed to follow a target or avoid obstacles in the way of its path. The signal main function was determined from the design having to operate autonomously. The design is meant to sense obstacles by measuring the reflection of light from the obstacle. The design must also be able to sense the speed at which it's moving through measuring the rotation of the tires and the heading angle. Finally, the design must be able to sense its position relative to a global frame.

The cross-reference table in Table 2 depicts how the customer needs are related to the main functions of the design. Each "X" indicates whether the need is affected by the main function. More than one "X" shows an overlap of influence that the need will have in the system. The table is meant to serve as an aid in prioritizing the main functions of the design.

Table 2: Functional Decomposition Cross-Reference Table

	Propulsion	Support	Signal	Navigation	Total
Generate force in direction of motion	X				1
Remove force in direction of motion	X				1
Generate Equal & Opposite Force		X			1
Generate Weight Distribution	X	X		X	3
Generate tire lateral forces				X	1
Generate tire longitudinal forces				X	1
Generate aerodynamic forces	X			X	2
Measure light Reflection from object			X		1
Measure tire speed and heading angle data			X		1
Measure and update position data			X		1
Total	4	2	3	4	

From the cross-reference table above, the systems that can be considered the most critical are the navigation and propulsion systems. These two systems have the most "X" values and navigation shares the most overlap with other systems. This leaves the signal and support systems which, while having less "X" values, serve to accomplish an integral part of the project.

The objective is to minimize inertial losses when accelerating and decelerating, so it would be assumed that the ability to change speeds and the movement through a course or around obstacles is a critical area of focus in the design. Therefore, the propulsion and navigation systems are favored by high priority. However, without any support, the design will lack the necessary weight distribution which will be detrimental to the performance when maintaining velocity while cornering. Signals are a major part of the navigation system because they will identify and interpret data from the environment.

Two of the minor functions listed in Table 2 overlap with multiple systems. The first function is to generate weight distribution, which falls under propulsion, support, and navigation. Maintaining an even weight distribution will help with resisting the roll motion, allowing for better acceleration, and will help determine the placement of the payload. The next function is to generate aerodynamic forces, which will also help with propulsion and navigation. In terms of navigation, aerodynamic forces will allow the vehicle to induce a yaw motion. For propulsion, generating aerodynamic forces can help with either acceleration or deceleration depending on how it is designed. These main functions will allow the team to develop targets and metrics to create a design that successfully fulfills the key goals outlined for the project.

1.4 Project Update 1

Upon further research, the initial scope for the project was adjusted. These adjustments include the following:

- size of the design
- will not fulfill F1tenth competition requirements
- constraints on the velocity
- Constraints on environment including various terrains, predetermined route, and inclines
- Heavier focus on minimizing inertial losses
- 3D engine to simulate robot and environment (Gazebo)
- Comparison between physical performance and simulated performance
- Functions including sensing weight since the payload is expected to vary

1.5 Target Summary

Propulsion

Considering the top speed that the design is aiming to achieve, a target was created for the Acceleration function. In modern performance cars, larger automotive manufacturers perform an acceleration test from 0 – 60 miles per hour, which is a third of the top speed of the vehicle. The design will be estimated to be performed at 1/3 of the expected top speed in a similar time frame of 4 seconds.

As for the deceleration function, data collected from sports cars that performed a stopping distance test in competitions showed that most were able to stop 7-8 times the length of the car's body. The length of the design is 52 inches or 1.32 meters. Based on the tests performed by the automotive manufacturers, the stopping distance should be approximately 10.6 meters.

Table 3: Propulsion Targets & Metrics

System	Function	Metric	Target
Acceleration	Generate Force	Time	0 - ($\frac{1}{3}$top speed) in 4 seconds
Deceleration	Remove Force	Distance	10.6 m

Support

Power wheel sized vehicles are designed to be used by children between the ages of one to seven years old. Therefore, the design should be able to accommodate children between the ages of four to eight years old. The impression is that children above the age of four should be knowledgeable enough to safely navigate the design. The Radio Flyer Tesla Model S was selected as a basis for the design. The Center for Disease Control and Prevention gathers data to produce growth charts that depict the height and weight of male and female children. Additional targets used to define the targeted heights and weights include the ages of children that are expected to operate the design.

After researching the 95th percentile and the 5th percentile of both boys and girls ages four and eight, extremes of potential users were identified. These values will represent the maximum and minimum weight of a payload the vehicle will have to carry, and the maximum and minimum amount of room allotted for the payload. The targets are defined in table 4.

Table 4: Support Targets & Metrics

System	Function	Metric	Target
Carries Load	Generate Equal & Opposite Force	Force (Weight)	≤ 36 kg (95th percentile 8-year-old girls)
Carries Load	Generate Equal & Opposite Force	Force (Weight)	≥12 kg (5th percentile 4-year-old girls)
Fits Load	Compensate stature	Height	137 cm (95th percentile 8-year-old boys)
Fits Load	Compensate stature	Height	88 cm (5th Percentile 4-year-girls)

To achieve the requirements outlined in the scope of the project, the chassis of the Radio Flyer Tesla Model S components will be altered to include the removal and replacement of components and compensation for the tracking payload provided by team 504. The curb weight of the original design was measured to be 18.37 kilograms, but with alterations to the chassis, the targeted weight for the design is estimated to be 22.68 kilograms.

Signal

Autonomy is an essential goal of design. It is important that the design has exteroceptive and proprioceptive sensors that are constantly feeding information to the vehicle about its current internal state and surrounding environment. The sensors will be selected to detect the current position, target, and optimal path. From this information, inverse kinematics can be applied to find the velocities of the wheels individually and the design. Knowing the vehicle's desired velocity will help find the desired wheel velocities where the tire speed can be measured.

Based on the general knowledge of robotics, IMU's can read data at a rate of 74 Hz. I The target the design is intended to hit is at least 80 readings a second, or 80 Hz.

Collection and testing of the object sensing will be done using "Simultaneous Localization and Mapping" or SLAM sensing. Visual SLAM uses multiple cameras to give the robot "eyes" and update what is in front of it, and LiDAR SLAM uses light detection and ranging to build a map of what is surrounding the robot. While the type of SLAM remains unknown, the robot surroundings should be updated at a rate of 15 Hertz to generate accurate decisions on obstacle detection and avoidance.

Table 5: Signal Targets & Metrics

System	Function	Metric	Target
Sense Velocity	Measure Tire Speed	Frequency	300 Pulses Per Revolution (PPR)
Sense Position	Gather & Update Position Data	Frequency	80 Hz
Sense Obstacles	Measure Light Reflections	Frequency	15 Hz

Navigation

For the design to be successful, the vehicle must be able to take corners with accuracy. If cornering is done with too much speed or an uneven ground, this may cause the vehicle to tip or roll over. Through analysis of energy and velocities, the rate of change for roll that will make the vehicle roll over was anything larger than $2\pi \frac{rad}{sec}$. This number was calculated using the track length and a situation where, after hitting uneven ground, one side of the car had an induced roll rate and the other side remained completely on the floor. The number calculated using this model is not extremely accurate, however, as more information is learned about the vehicle geometry, a threshold will be created through mechanical design that will allow for this target to be met. This parameter will be tested using one of the sensors that is within the vehicle. Using a gyroscope and accelerometer in the design, the roll rate can be easily calculated in the vehicles software.

As for yaw rate, the idea is to make a target based on how fast the design should make a full 360° turn. The desired period that was selected was 4 seconds. By doing some quick math, a 360° turn in 4 seconds, results in a yaw rate of $\frac{d\psi}{dt} = \frac{2\pi}{4} = \frac{\pi}{2}\frac{rad}{sec}$. This is the current target that was set; however, the yaw rate is a complex target to fully comprehend and will be adjusted in the coming weeks.

Table 6: Navigation Targets & Metrics

System	Function	Metric	Target
Navigation	**Resist Roll Motion**	Angular Velocity	$\leq 2\pi \frac{rad}{sec}$

Navigation	**Induced Yaw Rate**	Angular Velocity	$\approx \frac{\pi}{2} \frac{rad}{sec}$

Additional Targets and Metrics

The Tesla Model S Radio Flyer tops out at a maximum speed of about 2.68 m/s. After further insight, a top speed target of 4.47 m/s was devised as an optimization for the design. The test distance that the vehicle will take begins at the bus stop outside of the FAMU-FSU college of engineering and ends at the AME building. This distance is approximately 644 meters (about 2112.86 ft) and the requirement provided by the sponsors is to get from point A to point B in 5 minutes (300 seconds). By dividing the total distance by the time limit to get there a maintained velocity of about 2.17 m/s was calculated. These targets will be tested using the velocity sensor in the vehicle.

To determine the turn radius, comparisons were made based on cars in the current automotive market. Using the Tesla Model S, the Toyota Corolla, and the Volkswagen Jetta, the equation for steering angle was used $\delta = \frac{L}{R}$, using L as the length from front wheel to back wheel and R the turn radius to create a length to turn radius ratio. After using the equation for all three cars and taking the average of the values yielded, that data was set equal to the length of the project design vehicle over the turn radius of the project design vehicle, resulting in a 1.59 m turn radius. The turn radius can be tested by using simple mathematics, geometry, and physics.

After doing energy calculations, for a 22.8 kg vehicle going 4.47 m/s, it was deduced that roughly 226 Joules of energy is needed for the trip. To provide a buffer for the project, a battery that outputs around 350 Joules of energy to our system is desired, to power motors, sensors, and the microcomputer.

For this project simulations will be run before the start of the mechanical build of the vehicle. While simulations can be run until everything is "perfect," the simulations will never be able to fully represent what will happen in the real world. Since this is the case, a rough estimate of the number of simulations is desired to present a promising idea of what will happen, but without wasting too much time trying to perfect it. The number that was set was 50 simulations with different parameters.

Table 7: Additional Targets & Metrics

System	Function	Metric	Target
Additional	**Top Speed**	Velocity	4.47 m/s
Additional	Maintained Velocity	Velocity	2.17 m/s
Additional	Turning Radius	Distance	1.59 m
Additional	Battery Size	Energy	350 Joules
Additional	Simulation Runs	Iterations	50 Simulations

Critical Targets

The targets that were bolded in each individual table are critical targets to the project's success. The ones bolded were, Carries Load (Max), Resisting Roll Motion, Inducing Yaw Rate, and Top Speed.

Carries Load (Max) was considered a critical target as it sets limits on how heavy a load can be and still be carried by our design. In this case we went with 36 kg, which was the weight of a 95th percentile 8-year-old girl, which was the top end of the target demographic.

Next was to resist a roll motion, which was marked as critical because avoiding rollover is extremely important as a rollover would lead to failure in a time limit aspect. As stated by the sponsor, the design should reach the specified end point in 5 minutes or less which would not be achievable if rollover occurs.

Inducing a yaw rate is important because the car must be able to take tight corners. By reducing the amount of time spent on each mission of the vehicle, the inertial forces are then in turn reduced.

Lastly was the top speed, the top speed was marked as mission critical as there are a few other targets that were created based on the top speed target. Being able to achieve the top speed target will allow the design to be validated in other targets such as the acceleration target and the deceleration target.

1.6 Concept Generation

Concept generation is useful in the process of formulating and devising several solutions to solve the project objective. Multiple generation tools were utilized to create 100 design concepts to achieve the project goal.

Concept Generation Tools

Various techniques were utilized during the concept generation process to assist in reaching 100 design concepts. Among these techniques are the morphological chart, brainstorming, and biomimicry. Changes were made to strongly favor concepts along the generation process to better differentiate concepts as well as add other concepts.

Medium Fidelity Concepts

After reaching 100 concept ideas through the concept generation process, five concepts were chosen as medium fidelity concepts. These five concepts were chosen as medium fidelity concepts due to features that they include fitting for the project objective. Although these medium fidelity concepts are not being considered for upper-level prototyping, they are useful for creating certain design characteristics that are desirable in the eyes of the solution for the project. The medium fidelity concepts are shown below.

Table 8: Medium Fidelity Concepts

Concept Number	Concept Description
47	Omnidirectional ROS2 MBPC + PID Regenerative
50	Omnidirectional ROS2 SBMPO Regenerative
83	Modifying the frame of the vehicle for decreased drag
84	High roll centers (Suspension Design)
86	Completely even weight distribution

High Fidelity Concepts

From the 100 generated concepts three were chosen to be high fidelity concepts. For the high-fidelity concepts, the best and most desirable design characteristics and functions were chosen and combined to reach the best possible solutions for the project. The high-fidelity concepts are shown below.

Table 9: High Fidelity Concepts

Concept Number	Concept Description
28	Ackermann ROS2 MBPC + PID Resistive
29	Ackermann ROS2 MBPC + PID Regenerative
32	Ackermann ROS2 SBMPO Regenerative

1.7 Concept Selection

Pairwise Comparison and House of Quality

The CIA's needs and the medium and high-fidelity concepts from the previous section were examined using different methods to determine the ideal concept for the final design. A binary pairwise comparison was conducted for the customer needs chart in Table 10. The values in the left columns are compared to the corresponding values in the top row. A "1" indicates the former need is more important, and a "0" indicates it is less important. The results from the comparison chart were totaled for each row and column to show which needs have the highest relative importance for the final design.

Table 10: Binary Pairwise Comparison

Customer Need	1	2	3	4	5	6	7	8	9	Total
1) Optimized Pathing	-	1	0	0	1	1	0	0	0	3
2) Point A to B in 5 minutes	0	-	0	0	1	1	0	0	0	2
3) Autonomously Controlled	1	1	-	0	1	1	0	0	0	4
4) Reduce inertial losses	1	1	1	-	1	1	0	1	1	7
5) Carries Payload	0	0	0	0	-	1	0	0	0	1
6) Handles Road Grade	0	0	0	0	0	-	0	0	0	0
7) Simulated Environment	1	1	1	1	1	1	-	1	1	8
8) Maintaining optimal velocity	1	1	1	0	1	1	0	-	0	5
9) Fully Integrated with Team 504s Project	1	1	1	0	1	1	0	1	-	6
Total	5	6	4	1	7	8	0	3	2	n-1=8

After determining the relative importance of the customer needs, the engineering characteristics of our proposed design were then ranked in a House of Quality (HoQ) using the values from the pairwise comparison as weights. The HoQ indicates how the process of incorporating each engineering characteristic correlates with meeting the customer's needs. A “0” indicates no correlation, and “1”, “3”, and “9” indicate weak, medium, and strong correlation respectively. The improvement direction shows how the characteristics should be changed to improve design performance. The ranking from the HoQ shows that constant velocity and successful simulation testing are the most important characteristics, while resisting roll motion and carrying a payload are least important.

The Improvement Direction is a method in determining how our customer needs should be improved on providing an arrow in each column signifying whether the customer need should be decreased, increased, or blank no change. Finally, after assigning the correct weighted values, a relative weight can be developed from taking the combined value from the column and dividing that by the raw score. By sorting the relative weight percent from smallest value to largest and calculating the consecutive difference between points and developing a cutoff threshold.

Table 11: House of Quality

		Engineering Characteristics												
Improvement Direction		↑	↑	↓	↓	↓	↑	↑	↓	↑			↑	↓
Units		s	m	kg	cm	PPR	Hz	rad/s	rad/s	m/s	J	Iterations	m/s	m
Customer Requirements	Importance Weight Factor	Generates Force	Removes Force	Carries Payload	Fits Payload	Measure tire speed	Gather & Update position data	Resist roll motion	Induce yaw rate	Top speed	Battery size	Simulation runs	Maintained velocity	Turning radius
1) Optimized Pathing	3	3	3	0	0	3	9	0	3	3	9	9	3	9
2) Point A to B in 5 minutes	2	9	3	3	0	9	9	0	3	9	9	3	3	3
3) Autonomously Controlled	4	3	3	0	0	9	3	3	9	3	1	9	9	3
4) Reduce inertial losses	7	9	9	3	3	9	3	0	3	9	9	9	9	9
5) Carries Payload	1	9	9	9	9	0	0	3	1	0	3	0	9	1
6) Handles Road Grade	0	3	3	1	0	0	3	3	0	0	0	3	9	1
7) Simulated Environment	8	3	3	0	0	9	3	0	9	3	0	9	9	3
8) Maintaining optimal velocity	5	9	9	3	0	9	9	1	3	9	9	9	9	9
9) Fully Integrated with Team 504s Project	6	3	3	0	0	0	9	0	3	0	3	3	9	3
Raw Score	2213	198	186	51	30	243	201	20	178	171	178	267	294	196
Relative Weight %		8.947	8.405	2.305	1.356	10.981	9.083	0.904	8.043	7.727	8.043	12.065	13.285	8.857
Rank Order		5	7	10	11	3	4	12	8	9	8	2	1	6

Pugh Chart

Pugh charts are a way of design selection that uses our medium and high-fidelity concepts select and compares them to a datum. To initially begin we set our datum to an existing product that is the most identical to our goal design. This was chosen to be the F1tenth competitive race car because these automobiles are designed to maintain a velocity and race autonomously. It is imperative in the F1tenth competition that a path is optimized due to the car operating autonomously to reach the finish line.

Figure 2: F1tenth Model Car

Our engineering characteristics are referenced when comparing each design to the datum determining whether that target is better noted by a plus (+), not as good noted by a minus (-), or rather significantly the same noted by a (S). To achieve consistency within our results we eliminated designs that did not meet an efficient ratio. Once down to the last chart, the selected datum of even weight distribution, our final ratio proved once again that the Ackerman - Regenerative - MBPC + PID could be considered the best fidelity concept to pursue. The final Pugh chart is seen in Table 12.

Table 12: Pugh Chart of Desired Datum

		Concepts		
Selection Criteria	86	28	29	47
Generates Force	Datum	S	+	+
Removes Force		S	+	+
Carries Payload		S	S	S
Fits Payload		S	S	S
Measure Tire Speed		S	S	-
Gather and Update Position Data		S	S	-
Resist Roll Motion		S	S	S
Induce Yaw Rate		+	+	-
Top Speed		S	-	-
Battery Size		S	+	+
Simulations		+	+	+
Maintain Velocity		+	+	-
Turning Radius		S	S	-
	# of Plus(+)	3	6	4
	# of Minus(-)	0	0	6

Analytical Hierarchy Process (AHP)

The Analytical Hierarchy Process (AHP) uses the top three concepts selected from the Pugh Charts to select the final design. Before comparing the concepts, the design team compared the selection criteria to each other in a Criteria Comparison Matrix to determine which of the engineering characteristics are the most critical to completion of the project. The criteria were listed as the rows and columns of the Criteria Comparison Matrix, and the rows were compared to the columns. Values were assigned on a scale of 1, 3, 5, 7, and 9. The values increase in significance with 1 being the least and 9 being the most significant. The inverse of these rankings was mirrored across the main diagonal. The columns were summed and used to normalize each column by dividing by the sum, and the average of the normalized row values were used to determine the Criteria Weights. If this is done correctly, both the sum down the columns should equal 1. Table 13 below shows the Normalized Criteria Comparison Matrix, and the original matrix can be found in Appendix E.

Table 13: Normalized Criteria Comparison Matrix

Normalized Criteria Comparison Matrix [NormC]										
Customer Need	1	2	3	4	5	6	7	8	9	Criteria Weights
1) Optimized Pathing	0.031	0.015	0.014	0.143	0.036	0.058	0.127	0.146	0.006	0.064
2) Point A to B in 5 minutes	0.215	0.102	0.291	0.184	0.108	0.058	0.228	0.204	0.204	0.177
3) Autonomously Controlled	0.092	0.015	0.042	0.102	0.046	0.042	0.127	0.087	0.041	0.066
4) Reduce inertial losses	0.004	0.011	0.008	0.020	0.036	0.032	0.025	0.010	0.008	0.017
5) Carries Payload	0.277	0.305	0.291	0.184	0.323	0.291	0.228	0.204	0.285	0.265
6) Handles Road Grade	0.154	0.508	0.291	0.184	0.323	0.291	0.228	0.087	0.122	0.243
7) Simulated Environment	0.006	0.011	0.008	0.020	0.036	0.032	0.025	0.087	0.285	0.057
8) Maintaining optimal velocity	0.006	0.015	0.014	0.061	0.046	0.097	0.008	0.029	0.008	0.032
9) Fully Integrated with Team 504s Project	0.215	0.020	0.042	0.102	0.046	0.097	0.004	0.146	0.041	0.079
Total	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000

To ensure that there was no bias in the weighting of the criteria, a consistency ratio was calculated for each of the criteria and must be less than 0.1. This check is shown in Appendix E. The results confirm that maintaining optimal velocity and reducing the inertial losses are the most important, while simulated environment and optimized pathing are close behind. With the criteria ranked, the concepts were rated using a similar process. The matrices and equations are the same except the concepts were compared against each other in each of the selection criteria. The specific matrices can be found in Appendix E. The former Criteria weights are now called Design Alternative Priorities, and these values were tabulated in a Final Rating Matrix, which shows how well each design did in each category; however, each category is not weighted equally so the final Alternative Value was calculated by multiplying the transpose of the Final Rating Matrix by the Criteria Weights. Table 14 shows the Alternative Values, and the intermediate steps are in Appendix E.

Table 14: Final Alternative Values

Concept	Alternate Value
# 28	1.64
# 29	1.68
# 47	1.02

Based on the values in Table 14, our Ackermann-ROS2-MBPC+PID-Regenerative design is the best alternative. This system uses an Ackermann style steering mechanism, along with a ROS2 operating system, which will allow communication between team 503 and 504's projects. Along with that this model uses a combination of Lateral and Longitudinal control in the form of MBPC + PID controllers (Model Based Predictive Controller), and a regenerative braking system. The regenerative braking system was an idea that was generated to go along with the reduces inertial loses requirement, which is why the regenerative braking beat the resistive braking system. Currently, there is uncertainty if the regenerative braking system will be a viable option, weight and cost-wise, however at this point in the design it theoretically fills most of the customer requirements and engineering criteria.

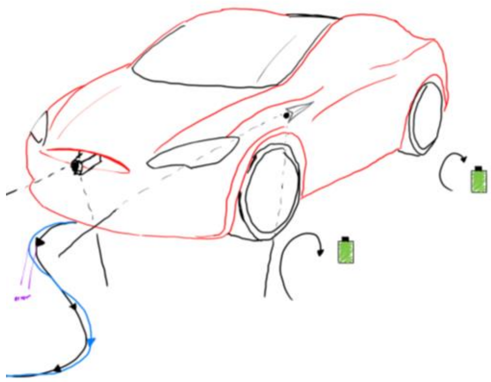


Figure 3: Selected Design

Chapter Two: EML 4552C

2.1 Spring Plan

The table 15 outlines the deliverables and calendar dates which will guide the remainder of our project progression. The idea behind the project plan was to give ourselves enough time to purchase, build, and validate our designs before presenting it to students and faculty on senior design day. The maximum lead time for parts was determined from the bill of materials found in Appendix G. In case our design failed or if we were unable to achieve the set targets, we needed to allocate time in case we needed to change some aspects of the design.

Table 15: Spring Project Plan

Task	**Deadline**	**Description**
Finalize Bill of Materials	January 3	Ensure all materials are itemized and confirm budget with sponsor.
Fulfill Purchase Orders	January 13	Order materials from BOM, especially those with long lead times
Testing Procedure Finalized	January 27	
Begin mechanical build	February 1	Mount sensors and connect RC system.
Collect data for model	February 6	Drive car and record data from the sensors, steering angle, etc.
Begin training model	February 8	Confirm output data from T504 to be decoded in controller
Design controller	February 8	Take in desired steering angle/steering command to output as PWM for motor rotations
Complete mechanical build	February 17	
Testing and Validation	March 1	
Final Product assembled	March 24	Integrate with T504
Integrated Product Tested	March 27	To ensure the projects work together
Engineering Design Day	April 6	PowerPoint and poster board presentations

2.2 Spring Project Updates

Due to the scope change a few months into the project, the design needed to be re-evaluated to break it down into systems and subsystems. The first subsystem involved steering actuation, seen in figure 4. This subsystem involves sending pulse width modulation signals to a direct current motor. In turn, this motor will move gears which moves the steering left and right. Initially, the design for the steering gears involved placing a gear on the steering wheel of the car. While this required little to no change to the chassis, it introduced safety issues. Specifically, if the car passenger attempted to grab the steering wheel and cut their fingers on the metal of the gears. The second design involved placing a rack and pinion directly onto the steering linkage. This does not work as a traditional rack and pinion assembly, rather as assisted steering for the user. The motor shaft is placed in the blue pinion in figure 5, whose rotation guides the steering direction.

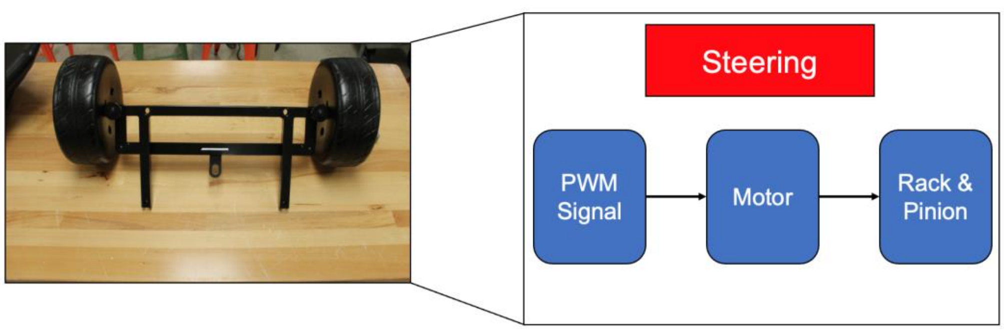


Figure 4: Steering Subsystem

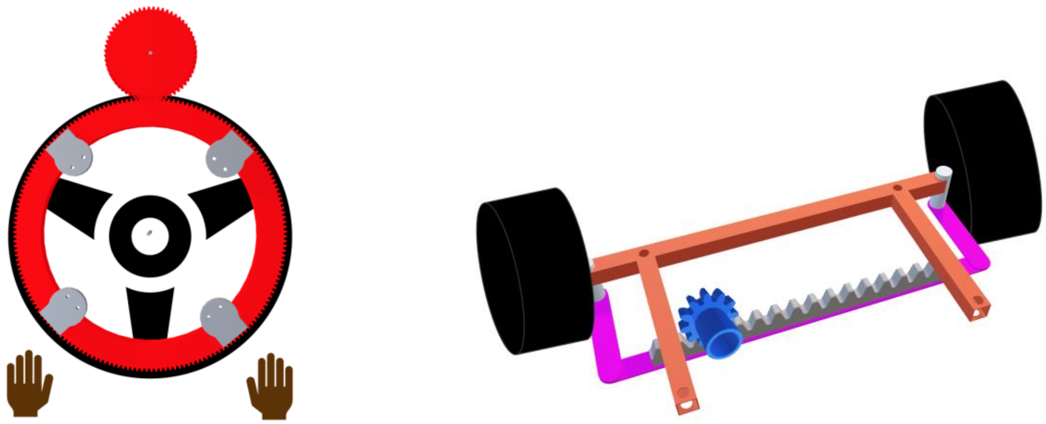


Figure 5: Initial v. Final Steering Designs

The second subsystem, outlined in figure 6, involves discretion of electrical components, wiring, and sensors. The sensor, an Intel RealSense depth camera, came from team 504, whose project integrated with our own. The electrical components from team 504 included an NVIDIA Jetson, power distributor, and buck module. Other electrical components included a Teensy microcontroller, motor drivers, and the motor with an encoder. The wiring had to be rerouted for power distribution and to allow us to be able to include emergency stops in our design. Team 504 camera had an initial design, like a phone case which allowed us to place the camera in the front bumper. However, the camera dimensions were larger than anticipated, and the camera alone was mounted to the front bumper.

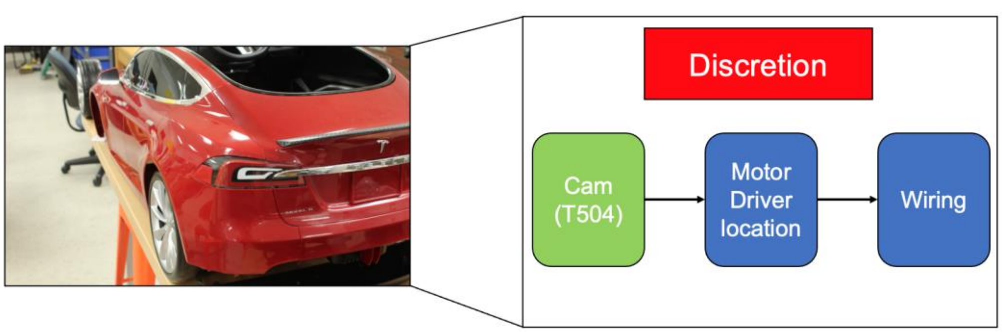


Figure 6: Discretion Subsystem

Figure 7: Camera Discretion Initial v. Final Design

The last subsystem involves propelling the vehicle forward, as seen in figure 8. After sensing the surrounding environment, the NVIDIA Jetson computes and outputs the necessary steering angle and velocity for transport. The Teensy microcontroller then uses the velocity output to send pulse width modulation signals to the motor drivers to control speed.

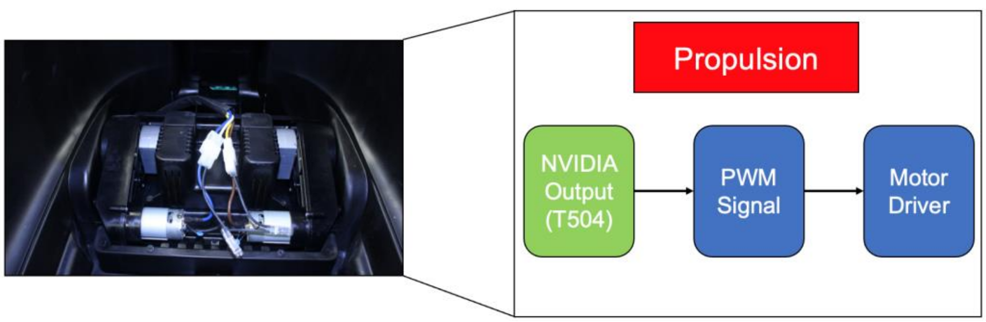


Figure 8: Propulsion Subsystem

The vehicle's maneuverability was studied by simulating its movement through a slalom path that was in the shape of a sinusoidal sweep. The simulation used a control system for the dynamics and behavior of the car. As the project progressed, the simulation was used as a base for the control system that was implemented into the steering system.

Appendices

Appendix A: Code of Conduct

Mission Statement

The team will conduct a successful design experiment with a level of professionalism expected by a future employer. Each member will contribute to the design experiment by completing all responsibilities listed in the code of conduct. This includes, but is not limited to, submitting assignments on time, communicating effectively, demonstrating respect for all members, and providing honest progress reports each week. The overall goal of the design experiment is to successfully develop hardware in loop wheeled automobile to optimize a path to maintain velocity and minimize inertial losses from accelerating and decelerating.

Team Roles

Any duties not outlined in the team roles will be split among each team member. Factors that will determine which member obtains the duties include the member's availability/workload as well as their specialties/strengths. The team must come to a consensus before distributing duties to each member.

Design Engineer - Richard Allen

Responsible for generation of CAD models and mechanical prototypes. This will be essential to the creation of the engineering drawings needed for the manufacturing.

Controls Engineer - Nicholas Muoio

Responsible for bridging the gap between software and hardware. Making sure the system is calibrated to respond in the way expected when prompted by the software. Expected to work closely with Design, Test, and Software Engineers to create a coherent final product.

Hardware Engineer - David Gordon

Responsible for determining the components required for the system as well as the component implementation. Expected to work closely with the software engineer to conduct tests and analyze system behavior during simulation.

Software Engineer - Chet Iwuagwu

Responsible for developing scripts to maintain the environment and working on embedded systems that control the automated equipment. Expected to work closely with the hardware engineer.

Research/Test Engineer - Kathleen Bodden

Responsible for developing a process to successfully test the functionality of the experiment. Also responsible for finding the optimal design for the experiment to obtain accurate results needed to understand the experiment.

Structural Engineer - Micah Hilliard

Responsible for materials and the basic structure for the design. Could include drafting and creating drawings for the design as well as finding and picking the best materials for the optimal design.

Communication

The primary forms of communication will be electronic mail (email), Microsoft Teams, and text messaging. Meeting invitations, formal communication, and any communication between the members and sponsor will occur through email. Any progress reports, information requests, projects and group documents, or important information will go through Microsoft Teams. Additionally, each member is required to submit a progress report every Friday. Informal communication such as notifications and deadlines will occur through both Microsoft Teams and text messaging.

Meetings and Attendance

Formal meetings will occur in-person and through Microsoft Teams if an in-person meeting is not possible. All members are required to attend and take notes

Failure to attend a meeting with no prior notice will result in a strike against the members' record. Each member is allowed 3 excused absences if they communicate 24 hours before the scheduled meeting; otherwise, the absence will not be excused, and the member will receive a strike on their record.

Meeting times will be determined after the first meeting. During the first meeting, each member is required to specify any obligations they have outside of being an engineering student. Each member's schedule will also be posted on Microsoft Teams to avoid conflict when scheduling meetings. Meetings should be scheduled at least 72 hours (about 3 days) in advance of the meeting and must be agreed upon by all members. Meetings may be scheduled by any member of the group.

Conflicts and Consequences

For the first strike occurrences, there will be discussion among the group members about the conflict/issue. If a member were to receive 3 strikes on their record, immediate mediation is required between the group and Professor McConomy. Additionally, any conflict that cannot be resolved within the group will require mediation by Professor McConomy. Any discussion regarding a member's record or conflicts must occur through a meeting with all members present.

Dress Code

Each class and team meeting will require a casual dress code. Advisor and sponsor meetings will be business professional. Presentations will have a business casual dress code with a team consensus on the specific style and colors depending on the availability of each team member 72 hours before the presentation.

Amendments to Code of Conduct

Amendments made to the Code of Conduct require a meeting with all members and a majority vote will be needed to enact that amendment.

Statement of Understanding

By signing this document, all members agree to adhere to the guidelines set forth by the Code of Conduct. Failure to abide by this document will result in the consequences outlined by this Code of Conduct and the course.

DocuSigned by:
Kathleen Bodden
38B379CE6C5A4FC...

9/8/2022 | 4:47 PM EDT

Team Member 1 — Date

DocuSigned by:
[illegible]
07F4ACD89F7C414...

9/8/2022 | 4:54 PM EDT

Team Member 2 — Date

DocuSigned by:
[illegible]
2601B3D5EC6A40E...

9/8/2022 | 4:53 PM EDT

Team Member 3 — Date

DocuSigned by:
Micah Hilliard
AC923D58B8E1418...

9/8/2022 | 4:52 PM EDT

Team Member 4 — Date

DocuSigned by:
Chet Iwuagwu
15F5C63CCAE2468...

9/8/2022 | 10:04 PM EDT

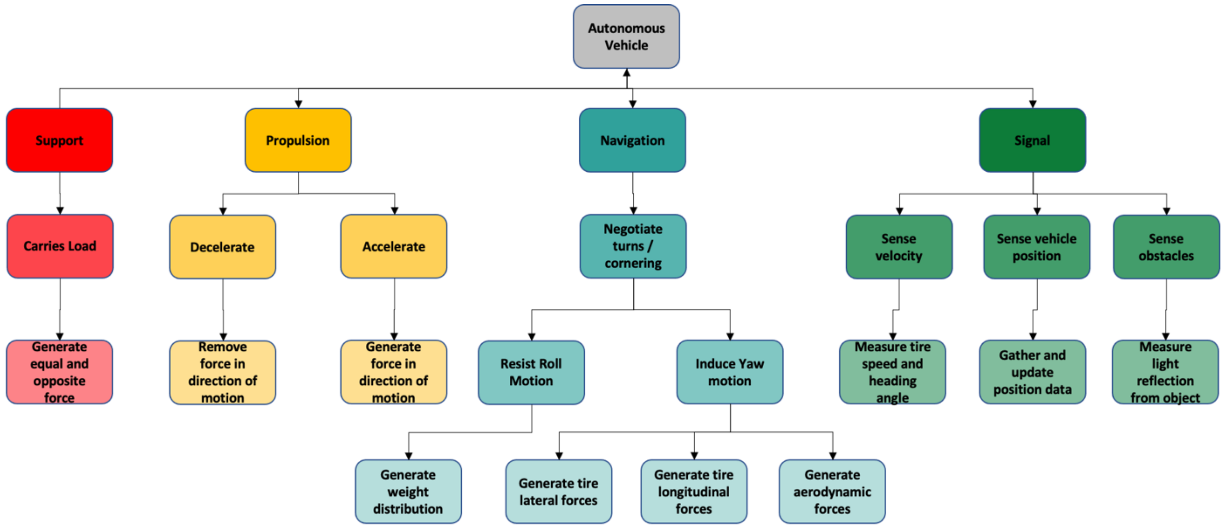
Team Member 5 — Date

DocuSigned by:
David Gordon
F1BB48645FA34D2...

9/9/2022 | 2:22 PM EDT

Team Member 6 — Date

Appendix B: Functional Decomposition



	Propulsion	Support	Signal	Navigation
Generate force in direction of motion	X			
Remove force in direction of motion	X			
Generate Equal & Opposite Force		X		
Generate Weight Distribution	X	X		X
Generate tire lateral forces				X
Generate tire longitudinal forces				X
Generate aerodynamic forces	X			X
Measure light Reflection from object			X	X
Measure tire speed and heading angle data			X	
Measure and update position data			X	

Appendix C: Target Catalog

System	Function	Metric	Target
Acceleration	Generate Force	Time	0 - (top speed) in 4 seconds
Deceleration	Remove Force	Distance	10.6 m

System	Function	Metric	Target
Carries Load	Generate Equal & Opposite Force	Force (Weight)	≤ 36 kg (95th percentile 8-year-old girls)
Carries Load	Generate Equal & Opposite Force	Force (Weight)	≥12 kg (5th percentile 4-year-old girls)
Fits Load	Compensate stature	Height	137 cm (95th percentile 8-year-old boys)
Fits Load	Compensate stature	Height	88 cm (5th Percentile 4-year-girls)

System	Function	Metric	Target
Sense Velocity	Measure Tire Speed	Frequency	300 Pulses Per Revolution (PPR)
Sense Position	Gather & Update Position Data	Frequency	80 Hz
Sense Obstacles	Measure Light Reflections	Frequency	15 Hz

System	Function	Metric	Target
Navigation	Resist Roll Motion	Angular Velocity	$\leq 2\pi \frac{rad}{sec}$
Navigation	Induced Yaw Rate	Angular Velocity	$\approx \frac{\pi}{2} \frac{rad}{sec}$

System	Function	Metric	Target
Additional	Top Speed	Velocity	4.47 m/s
Additional	Maintained Velocity	Velocity	2.17 m/s
Additional	Turning Radius	Distance	1.59 m
Additional	Battery Size	Energy	350 Joules
Additional	Simulation Runs	Iterations	50 Simulations

Appendix D: Concept Generation

Ideas generated from Morphological chart

1. Ackermann-ROS1-MBPC + PID-Resistive
2. Ackermann-ROS1-MBPC + PID-Regenerative
3. Ackermann-ROS1-MBPC + PID-Reverse
4. Ackermann-ROS1-SBMPO-Resistive
5. Ackermann-ROS1-SBMPO-Regenerative
6. Ackermann-ROS1-SBMPO-Reverse
7. Ackermann-ROS1-Selekwa-Resistive
8. Ackermann-ROS1-Selekwa-Regenerative
9. Ackermann-ROS1-Selekwa-Reverse
10. Differential-ROS1-MBPC + PID-Resistive
11. Differential-ROS1-MBPC + PID-Regenerative
12. Differential-ROS1-MBPC + PID-Reverse
13. Differential-ROS1-SBMPO-Resistive
14. Differential-ROS1-SBMPO-Regenerative
15. Differential-ROS1-SBMPO-Reverse
16. Differential-ROS1-Selekwa-Resistive
17. Differential-ROS1-Selekwa-Regenerative
18. Differential-ROS1-Selekwa-Reverse
19. Omnidirectional-ROS1-MBPC + PID-Resistive

20. Omnidirectional -ROS1-MBPC + PID-Regenerative
21. Omnidirectional -ROS1-MBPC + PID-Reverse
22. Omnidirectional -ROS1-SBMPO-Resistive
23. Omnidirectional -ROS1-SBMPO-Regenerative
24. Omnidirectional -ROS1-SBMPO-Reverse
25. Omnidirectional -ROS1-Selekwa-Resistive
26. Omnidirectional -ROS1-Selekwa-Regenerative
27. Omnidirectional -ROS1-Selekwa-Reverse
28. Ackermann-ROS2-MBPC + PID-Resistive
29. Ackermann-ROS2-MBPC + PID-Regenerative
30. Ackermann-ROS2-MBPC + PID-Reverse
31. Ackermann-ROS2-SBMPO-Resistive
32. Ackermann-ROS2-SBMPO-Regenerative
33. Ackermann-ROS2-SBMPO-Reverse
34. Ackermann-ROS2-Selekwa-Resistive
35. Ackermann-ROS2-Selekwa-Regenerative
36. Ackermann-ROS2-Selekwa-Reverse
37. Differential-ROS2-MBPC + PID-Resistive
38. Differential-ROS2-MBPC + PID-Regenerative
39. Differential-ROS2-MBPC + PID-Reverse
40. Differential-ROS2-SBMPO-Resistive
41. Differential-ROS2-SBMPO-Regenerative

42. Differential-ROS2-SBMPO-Reverse
43. Differential-ROS2-Selekwa-Resistive
44. Differential-ROS2-Selekwa-Regenerative
45. Differential-ROS2-Selekwa-Reverse
46. Omnidirectional-ROS2-MBPC + PID-Resistive
47. Omnidirectional -ROS2-MBPC + PID-Regenerative
48. Omnidirectional -ROS2-MBPC + PID-Reverse
49. Omnidirectional -ROS2-SBMPO-Resistive
50. Omnidirectional -ROS2-SBMPO-Regenerative
51. Omnidirectional-ROS2-SBMPO-Reverse
52. Omnidirectional -ROS2-Selekwa-Resistive
53. Omnidirectional -ROS2-Selekwa-Regenerative
54. Omnidirectional -ROS2-Selekwa-Reverse

Other ideas (Sensors Placement)

55. Infrared camera part of sensors / Night vision
56. 360 View camera
57. Cameras in headlights
58. Cameras in bumpers
59. Cameras in mirrors
60. Lidar mounted underneath the car
61. Sensors mounted on helmet that are wearable by passenger
62. Microphone sensor for voice recognition

63. Spinning camera

64. Telescoping camera from hood

65. Reflection Sensors

66. Cameras in the doors

67. Sensors attached to balloon/kite that floats above the car

68. Cameras stacked on top of each other 90 degrees apart

69. Cameras inside the wheel well

70. Cameras attached to steering wheel

71. Camera on the dash

Other ideas (Programs)

72. Autonomous control + User control via controller ~

73. Object classification to network server

74. Face recognition and person remembering

75. Text-to-speech (if microphone)

76. Object velocity tracking

77. Voice recognition

78. Person characteristics recognition and storage

79. Object Location in 3D space ~

80. GPS mapping software

81. Data to SQL Server ~

Other ideas (Mechanical)

82. Spoiler for increased aerodynamic force

83. Modifying the frame of the vehicle for decreased drag
84. High roll centers (Suspension Design)
85. Low roll centers (Suspension Design)
86. Completely even weight distribution
87. Forward heavy weight distribution
88. Rear end heavy weight distribution
89. Left side heavy weight distribution
90. Right Side heavy weight distribution
91. Lengthen wheelbase to increase efficiency (a to CG length)
92. Brake regeneration for max. Power consumption

Other ideas (Control)

93. Coupled longitudinal and lateral control systems
94. Uncoupled longitudinal and lateral control systems
95. PI Longitudinal controller
96. PD Longitudinal Controller
97. Pure pursuit object avoidance
98. Reinforcement learning object avoidance
99. Genta Model (Path following)
100. Machine Learning via Human Interaction
101. Using a bumper for obstacle avoidance

Appendix E: Concept Selection

Binary Piecewise Comparison

Customer Need	1	2	3	4	5	6	7	8	9	Total
1) Optimized Pathing	-	1	0	0	1	1	0	0	0	3
2) Point A to B in 5 minutes	0	-	0	0	1	1	0	0	0	2
3) Autonomously Controlled	1	1	-	0	1	1	0	0	0	4
4) Reduce inertial losses	1	1	1	-	1	1	0	1	1	7
5) Carries Payload	0	0	0	0	-	1	0	0	0	1
6) Handles Road Grade	0	0	0	0	0	-	0	0	0	0
7) Simulated Environment	1	1	1	1	1	1	-	1	1	8
8) Maintaining optimal velocity	1	1	1	0	1	1	0	-	0	5
9) Fully Integrated with Team 504s Project	1	1	1	0	1	1	0	1	-	6
Total	5	6	4	1	7	8	0	3	2	n-1=8

House of Quality

		Engineering Characteristics												
Improvement Direction		↑	↑	↓	↓	↓	↑	↑	↓	↑			↑	↓
Units		s	m	kg	cm	PPR	Hz	rad/s	rad/s	m/s	J	Iterations	m/s	m
Customer Requirements	Importance Weight Factor	Generates Force	Removes Force	Carries Payload	Fits Payload	Measure tire speed	Gather & Update position	Resist roll motion	Induce yaw rate	Top speed	Battery size	Simulation runs	Maintained velocity	Turning radius
1) Optimized Pathing	3	3	3	0	0	3	9	0	3	3	9	9	3	9
2) Point A to B in 5 minutes	2	9	3	3	0	9	9	0	3	9	9	3	3	3
3) Autonomously Controlled	4	3	3	0	0	9	3	3	9	3	1	9	9	3

4) Reduce inertial losses	7	9	9	3	3	9	3	0	3	9	9	9	9	9
5) Carries Payload	1	9	9	9	9	0	0	3	1	0	3	0	9	1
6) Handles Road Grade	0	3	3	1	0	0	3	3	0	0	0	3	9	1
7) Simulated Environment	8	3	3	0	0	9	3	0	9	3	0	9	9	3
8) Maintaining optimal velocity	5	9	9	3	0	9	9	1	3	9	9	9	9	9
9) Fully Integrated with Team 504s Project	6	3	3	0	0	0	9	0	3	0	3	3	9	3
Raw Score	2213	198	186	51	30	243	201	20	178	171	178	267	294	196
Relative Weight %		8.947	8.405	2.305	1.356	10.981	9.083	0.904	8.043	7.727	8.043	12.065	13.285	8.857
Rank Order		5	7	10	11	3	4	12	8	9	8	2	1	6

Pugh Charts

		Concepts							
Selection Criteria	F1Tenth	28	29	50	47	86	84	83	32
Generates Force	Datum	-	-	-	-	-	-	-	-
Removes Force		+	S	S	S	+	+	+	S
Carries Payload		+	+	+	+	+	+	+	+
Fits Payload		+	+	+	+	+	+	+	+
Measure Tire Speed		+	+	+	+	+	+	+	+
Gather and Update Position Data		+	+	+	+	+	+	+	+
Resist Roll Motion		+	+	+	+	+	+	+	+
Induce Yaw Rate		S	S	-	-	-	-	-	S
Top Speed		-	-	-	-	-	-	-	-
Battery Size		+	+	+	+	+	+	+	+
Simulations		S	S	S	S	S	S	S	S
Maintain Velocity		S	S	S	S	+	S	+	S
Turning Radius		+	+	+	+	+	+	+	+
	# of Plus(+)	8	7	7	7	9	8	9	7
	# of Minus(-)	2	2	3	3	3	3	3	3

		Concepts						
Selection Criteria	50	28	29	47	86	84	83	32
Generates Force	Datum	S	S	S	+	S	+	S
Removes Force		+	+	S	+	+	+	S
Carries Payload		S	S	S	+	S	S	S
Fits Payload		S	S	S	S	S	+	S
Measure Tire Speed		S	S	S	S	S	S	S
Gather and Update Position Data		+	+	S	-	-	-	S
Resist Roll Motion		S	S	S	+	+	S	S
Induce Yaw Rate		+	+	S	-	+	-	S
Top Speed		+	S	S	+	+	+	S
Battery Size		-	S	S	-	-	-	S
Simulations		+	+	+	-	-	-	S
Maintain Velocity		S	S	S	+	S	+	S
Turning Radius		S	S	S	S	+	S	S
	# of Plus(+)	5	4	1	6	5	5	0
	# of Minus(-)	1	0	0	4	3	4	0

		Concepts		
Selection Criteria	86	28	29	47
Generates Force	Datum	S	+	+
Removes Force		S	+	+
Carries Payload		S	S	S
Fits Payload		S	S	S
Measure Tire Speed		S	S	-
Gather and Update Position Data		S	S	-
Resist Roll Motion		S	S	S
Induce Yaw Rate		+	+	-
Top Speed		S	-	-
Battery Size		S	+	+
Simulations		+	+	+
Maintain Velocity		+	+	-
Turning Radius		S	S	-
	# of Plus(+)	3	6	4
	# of Minus(-)	0	0	6

Analytical Hierarchy Process

Criteria Comparison Matrix [C]									
Customer Need	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
1) Optimized Pathing	1.0	0.1	0.3	7.0	0.1	0.2	5.0	5.0	0.1
2) Point A to B in 5 minutes	7.0	1.0	7.0	9.0	0.3	0.2	9.0	7.0	5.0
3) Autonomously Controlled	3.0	0.1	1.0	5.0	0.1	0.1	5.0	3.0	1.0
4) Reduce inertial losses	0.1	0.1	0.2	1.0	0.1	0.1	1.0	0.3	0.2
5) Carries Payload	9.0	3.0	7.0	9.0	1.0	1.0	9.0	7.0	7.0
6) Handles Road Grade	5.0	5.0	7.0	9.0	1.0	1.0	9.0	3.0	3.0
7) Simulated Environment	0.2	0.1	0.2	1.0	0.1	0.1	1.0	3.0	7.0
8) Maintaining optimal velocity	0.2	0.1	0.3	3.0	0.1	0.3	0.3	1.0	0.2
9) Fully Integrated with Team 504s Project	7.0	0.2	1.0	5.0	0.1	0.3	0.1	5.0	1.0
Total	32.5	9.9	24.1	49.0	3.1	3.4	39.5	34.3	24.5

Normalized Criteria Comparison Matrix [NormC]										
Customer Need	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	Criteria Weights
1) Optimized Pathing	0.03	0.01	0.01	0.14	0.04	0.06	0.13	0.15	0.01	0.06
2) Point A to B in 5 minutes	0.22	0.10	0.29	0.18	0.11	0.06	0.23	0.20	0.20	0.18
3) Autonomously Controlled	0.09	0.01	0.04	0.10	0.05	0.04	0.13	0.09	0.04	0.07
4) Reduce inertial losses	0.00	0.01	0.01	0.02	0.04	0.03	0.03	0.01	0.01	0.02
5) Carries Payload	0.28	0.30	0.29	0.18	0.32	0.29	0.23	0.20	0.29	0.27
6) Handles Road Grade	0.15	0.51	0.29	0.18	0.32	0.29	0.23	0.09	0.12	0.24
7) Simulated Environment	0.01	0.01	0.01	0.02	0.04	0.03	0.03	0.09	0.29	0.06
8) Maintaining optimal velocity	0.01	0.01	0.01	0.06	0.05	0.10	0.01	0.03	0.01	0.03
9) Fully Integrated with Team 504s Project	0.22	0.02	0.04	0.10	0.05	0.10	0.00	0.15	0.04	0.08
Total	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00

Weighted Sum Vector	Criteria Weights	Consistency Vector	
0.76	0.06	11.98	
2.51	0.18	14.17	
0.90	0.07	13.67	
0.20	0.02	11.49	
3.52	0.27	13.26	
3.17	0.24	13.06	
0.83	0.06	14.50	
0.30	0.03	9.40	
1.00	0.08	12.62	
		12.68	AVG (λ)
Consistency Index:	0.460		
Consistency Ratio:	0.318		

Alternative Comparisons

	Generates Force			
Concepts	# 28	# 29	# 47	Avg
# 28	1	1	9	3.666667
# 29	1.00	1	9	3.666667
# 47	0.11	0.11	1	0.407407
Total	2.111111	2.111111	19	

	Normalized Generates Force			
Concepts	# 28	# 29	# 47	Critical Weight
# 28	0.473684	0.473684	0.473684211	0.473684211
# 29	0.473684	0.473684	0.473684211	0.473684211
# 47	0.052632	0.052632	0.052631579	0.052631579
Total	1	1	1	1

	Removes Force			
Concepts	# 28	# 29	# 47	Avg
# 28	1	1	7	3

	Normalized Removes Force			
Concepts	# 28	# 29	# 47	Critical Weight
# 28	0.466667	0.466667	0.466666667	0.466666667

# 29	1	1	7	3
# 47	0.142857	0.142857	1	0.428571
Total	2.142857	2.142857	15	

# 29	0.466667	0.466667	0.466666667	0.466666667
# 47	0.066667	0.066667	0.066666667	0.066666667
Total	1	1	1	1

	Carries Payload			
Concepts	**# 28**	**# 29**	**# 47**	**Avg**
# 28	1	1	0.2	0.733333
# 29	1.00	1	0.142857	0.714286
# 47	5.00	7.00	1	4.333333
Total	7	9	1.342857	

	Normalized Carries Payload			
Concepts	**# 28**	**# 29**	**# 47**	**Critical Weight**
# 28	0.142857	0.111111	0.14893617	0.134301475
# 29	0.142857	0.111111	0.106382979	0.120117078
# 47	0.714286	0.777778	0.744680851	0.745581448
Total	1	1	1	1

	Fits Payload			
Concepts	**# 28**	**# 29**	**# 47**	**Avg**
# 28	1.00	1.00	1.00	1
# 29	1.00	1.00	1.00	1
# 47	1.00	1.00	1.00	1
Total	3	3	3	

	Normalized Fits Payload			
Concepts	**# 28**	**# 29**	**# 47**	**Critical Weight**
# 28	0.333333	0.333333	0.333333333	0.333333333
# 29	0.333333	0.333333	0.333333333	0.333333333
# 47	0.333333	0.333333	0.333333333	0.333333333
Total	1	1	1	1

	Measure Tire Speed			
Concepts	**# 28**	**# 29**	**# 47**	**Avg**
# 28	1	1	7	3
# 29	1	1	7	3
# 47	0.142857	0.142857	1	0.428571

	Normalized Measure Tire Speed			
Concepts	**# 28**	**# 29**	**# 47**	**Critical Weight**
# 28	0.466667	0.466667	0.466666667	0.466666667
# 29	0.466667	0.466667	0.466666667	0.466666667
# 47	0.066667	0.066667	0.066666667	0.066666667

Total	2.142857	2.142857	15	

Total	1	1	1	1

	Gather Position Data			
Concepts	# 28	# 29	# 47	Avg
# 28	1.00	1.00	0.33	0.777778
# 29	1.00	1.00	3.00	1.666667
# 47	3.00	0.33	1.00	1.444444
Total	5	2.333333	4.333333	

	Normalized Gather Position Data			
Concepts	# 28	# 29	# 47	Critical Weight
# 28	0.2	0.428571	0.076923077	0.235164835
# 29	0.2	0.428571	0.692307692	0.44029304
# 47	0.6	0.142857	0.230769231	0.324542125
Total	1	1	1	1

	Resist Roll			
Concepts	# 28	# 29	# 47	Avg
# 28	1	1	1	1
# 29	1	1	1	1
# 47	1	1	1	1
Total	3	3	3	

	Normalized Resist Roll			
Concepts	# 28	# 29	# 47	Critical Weight
# 28	0.333333	0.333333	0.333333333	0.333333333
# 29	0.333333	0.333333	0.333333333	0.333333333
# 47	0.333333	0.333333	0.333333333	0.333333333
Total	1	1	1	1

	Induce Yaw			
Concepts	# 28	# 29	# 47	Avg
# 28	1	1	5	2.333333
# 29	1	1	5	2.333333
# 47	0.2	0.20	1	0.466667
Total	2.2	2.2	11	

	Normalized Induce Yaw			
Concepts	# 28	# 29	# 47	Critical Weight
# 28	0.454545	0.454545	0.454545455	0.454545455
# 29	0.454545	0.454545	0.454545455	0.454545455
# 47	0.090909	0.090909	0.090909091	0.090909091
Total	1	1	1	1

	Top Speed			
Concepts	# 28	# 29	# 47	Avg
# 28	1	3	7	3.666667
# 29	0.333333	1	3	1.444444
# 47	0.142857	0.333333	1	0.492063
Total	1.47619	4.333333	11	

	Normalized Top Speed			
Concepts	# 28	# 29	# 47	Critical Weight
# 28	0.677419	0.692308	0.636363636	0.668696895
# 29	0.225806	0.230769	0.272727273	0.243100985
# 47	0.096774	0.076923	0.090909091	0.08820212
Total	1	1	1	1

	Battery Size			
Concepts	# 28	# 29	# 47	Avg
# 28	1	0.2	0.2	0.466667
# 29	5	1	1	2.333333
# 47	5.00	1	1	2.333333
Total	11	2.2	2.2	

	Normalized Battery Sized			
Concepts	# 28	# 29	# 47	Critical Weight
# 28	0.090909	0.090909	0.090909091	0.090909091
# 29	0.454545	0.454545	0.454545455	0.454545455
# 47	0.454545	0.454545	0.454545455	0.454545455
Total	1	1	1	1

	Simulation Runs			
Concepts	# 28	# 29	# 47	Avg
# 28	1	1	1	1
# 29	1	1	1	1
# 47	1	1	1	1
Total	3	3	3	

	Normalized Sim Runs			
Concepts	# 28	# 29	# 47	Critical Weight
# 28	0.333333	0.333333	0.333333333	0.333333333
# 29	0.333333	0.333333	0.333333333	0.333333333
# 47	0.333333	0.333333	0.333333333	0.333333333
Total	1	1	1	1

	Maintained Velocity			
Concepts	# 28	# 29	# 47	Avg
# 28	1	1	5	2.333333

	Normalized Maintained Velocity			
Concepts	# 28	# 29	# 47	Critical Weight
# 28	0.454545	0.454545	0.454545455	0.454545455

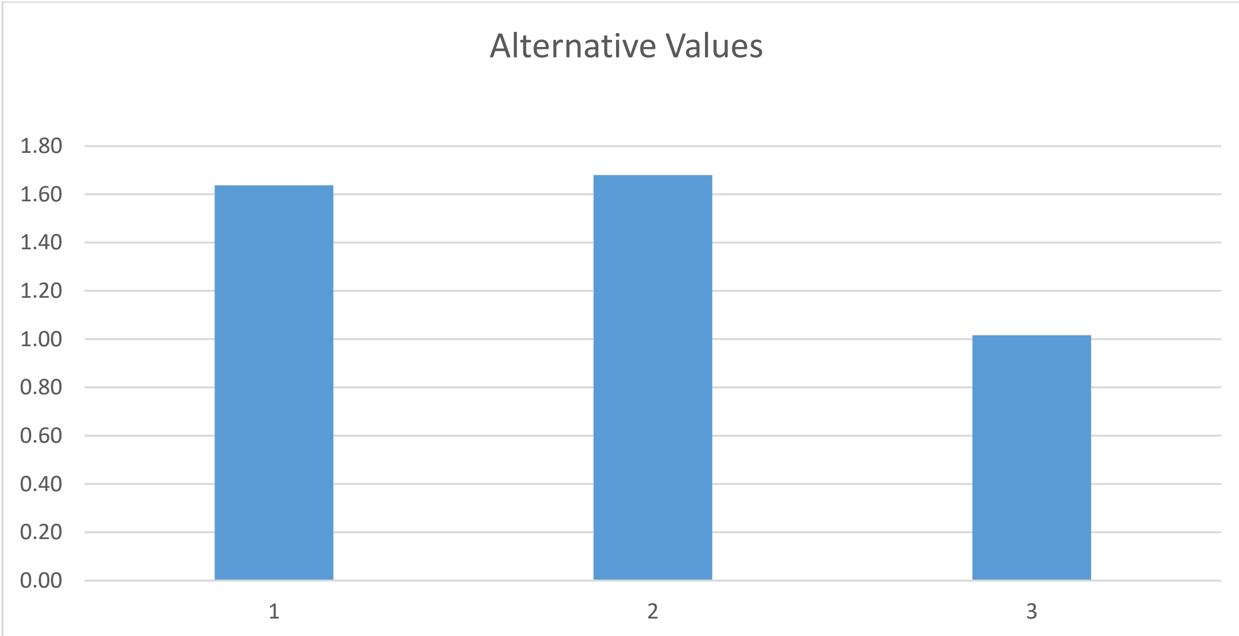
# 29	1	1	5	2.333333
# 47	0.2	0.2	1	0.466667
Total	2.2	2.2	11	

# 29	0.454545	0.454545	0.454545455	0.454545455
# 47	0.090909	0.090909	0.090909091	0.090909091
Total	1	1	1	1

	Turning Radius			
Concepts	**# 28**	**# 29**	**# 47**	**Avg**
# 28	1	1	7	3
# 29	1	1	7	3
# 47	0.142857	0.142857	1	0.428571
Total	2.142857	2.142857	15	

	Normalized Turning Radius			
Concepts	**# 28**	**# 29**	**# 47**	**Critical Weight**
# 28	0.466667	0.466667	0.466666667	0.466666667
# 29	0.466667	0.466667	0.466666667	0.466666667
# 47	0.066667	0.066667	0.066666667	0.066666667
Total	1	1	1	1

Concept	Alternate Value
# 28	1.64
# 29	1.68
# 47	1.02



Alternative Values
1.80
1.60
1.40
1.20
1.00
0.80
0.60
0.40
0.20
0.00
1
2
3

Appendix F: Work Breakdown Structure

WBS#	Deliverable	Work Package	Owner	Status
1	Sponsor Meeting			
1.1		Set up Meeting with sponsor	Kathleen	Complete
1.2		Create Questions	All	In Progress
1.3		Record Meeting Minutes in OneNote	Micah	
1.4		Submit Meeting Minutes	Richard	
2	Project Scope			
2.1		Project Brief	Micah	
2.2		Key Goals	Kathleen	
2.3		Markets	David	
2.4		Assumptions	Richard	
2.5		Stakeholders	Nicholas	
3	Customer Needs			
3.1		Listen to customer	All	
3.2		Ask questions to customer	Chet	
3.3		Clarify Statements customer	Micah	
3.4		synthesize data	David	
3.5		organize needs	Kathleen	
3.6		establish relative importance	Micah	
3.7		reflect and synthesize	All	
4	Functional Decomposition			
4.1		Breakdown system into smaller parts	Richard	
4.2		Identify the overall function of each sub-group	David	
4.3		Describe Physical Action	Kathleen	
4.4		Describe Outcome	Nicholas	
5	VDR1			
5.2		Project Scope	Richard	
5.3		Customer Needs	Chet	
5.4		Functional Decomposition	Nicholas	
6	Targets & Metrics			
6.1		Decide how we want to validate a function	Nicholas	
6.2		Find 3 - 5 competitors, that we can benchmark off of (Maybe Kits?)	Kathleen	
6.3		Consumer & Technical Specs	David	
6.4		Use physics to estmate what you want to accomplish	Richard	
7	Concept Generation			
7.1		Morphological Chart	Nicholas	
7.2		Biomimetic Design	Kathleen	
7.3		Brainstorming	Micah	
7.4		Synectics	Chet	
7.5		Random Input Technique	Richard	
7.6		Generate 100 Concepts	All	
7.7		Medium Fidelity Concepts	Kathleen	
7.8		High Fidelity Concepts	Micah	
8	Concept Selection			
8.1		House of Quality	Micah	
8.2		Pugh Chart	Kathleen	
8.3		Analytical Heirarchy Process	Nicholas	
8.4		Select final concept	All	
9	Risk Assessment			
9.1		Safety Expectations	All	
9.2		Project hazard assessment	All	
9.3		Project Control	All	
10	Bill of Materials			
10.1		Line Items	Richard	
10.2		Order Needs	Chet	
10.3		Vendor Identification	Kathleen	
10.4		Line Item Maturity	David	
10.5		Project Maturity	Micah	
10.6		Project Cost	Chet	
10.7		Unit Cost	Richard	
10.8		Labor Cost	Kathleen	
11	Spring Project Plan			
11.1		Document timeline working backwards (graduation, finals, design day)	All	
12	VDR2			
12.1		Targets & Metrics	David	
12.2		Concept Generation	Kathleen	
12.3		Concept Selection	Micah	
13	Build Plan		Micah	
14	Testing		Richard	
15	Analysis		Kathleen	
16	Results		David	
17	Discussion		All	
18	Conclusion		David	
19	Future Work		Micah	

Appendix G: Bill of Materials

Line Item	Vendor	Part No.	Part Name	Quantity	Amount
1	Radio Flyer		Tesla	1	$ 1,000.00
2	McMaster-Carr	5174T11	Metal Gear Rack	1	$ 56.86
3	McMaster-Carr	5172T61	Metal Gear	2	$ 31.85
4	Amazon	B07JZ2GQJF	DC Buck Module w/ LED Display	2	$ 13.99
5	Amazon	B06XGD5SCB	DC Jack Power Cable (x10)	1	$ 9.09
6	Amazon	B07C7VSRBG	Remote Emergency Stop	1	$ 23.99
7	Amazon	B0899M5Z8D	DC Motor Driver L298 Dual H Bridge	2	$ 15.78
8	McMaster-Carr	8382K261	Emergency Stop Panel Mount Switch	1	$ 46.85
9	Pololu	4846	75:1 Metal Gearmotor 25Dx69L mm HP 12V with 48 CPR Encoder	1	$ 48.95
10	Amazon	B07B9VBG6G	Pololu 25D mm Metal Gearmotor Bracket Pair	1	$ 15.90
11	Intel		10 Pin Electrical Wire connector	1	$ 17.99
12	Pololu	2676	Intel Realsense D555 Depth Camera	2	$ 419.00
13	Pololu	1075	Machine Screw: M3, 5mm Length, Phillips (25-pack)	1	$ 1.39
14	Grainger	6JHY0	Multipurpose Grease: Lithium, White, 16 oz, NLGI Grade 2, 120°F Max. Op Temp.	1	$ 21.86
15	McMaster	1346K11	1566Carbon Steel, 3/8" Diameter, 12" Long	1	$ 9.41
16	McMaster	94355A146	18-8 Stainless Steel Flat-Tip Set Screws 6-32 Thread, 3/8" Long	1	$ 3.55
17	McMaster	92785A118	18-8 Stainless Steel Cone-Point Set Screws 4-40 Thread, 3/8" Long	1	$ 7.70
18	Amazon	B06ZZN8L9S	100pcs Male Header Pins	1	$ 10.99
19	Amazon	B088JY7P2H	PJRC Teensy 4.1 ARM Cortex-M7 Processor	1	$ 35.29
20	Amazon	B08QVSX2LW	USB Cable	1	$ 7.50
21	Amazon	B002L3RUVG	Dremel 4000	1	$ 74.50
22	Pololu	2828	DC Motor w/ Encoder	1	$ 51.95
23	Grainger	26X626	CONDOR Ear Muffs	3	$ 64.41
24	Pololu	1084	DC Motor Brackets	1	$ 9.95
25	Amazon	B088JVVS1Z	Odometer and Speedometer	1	$ 29.99
26	Amazon	B07W7H121C	Suction camera mount	1	$ 17.99
27	Amazon	B00HB0Y0Z8	Adjustable Bike Helmet	1	$ 30.08

References

There are no sources in the current document.