

Automotive Utility Transport for Individuals: City Mobility

Senior Research 23-24

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Abstract

City environments are known for their cramped streets and impossible-to-find parking. The go-kart discussed in this paper is intended to be lightweight and have a minimized footprint of 25ft², making it the perfect vehicle to use in a city environment because of its usage of hub motors. Hub motors are motors that are embedded in the hubs of the wheels, combining many components required to provide power to the vehicle. These motors, when utilized in an electric go-kart with speed controllers, help to resolve issues that individuals have with current go-kart designs related to their size, weight, and maneuverability thanks to a four-wheel steering system. However, due to time constraints, the developed go-kart has a 25ft² footprint and operates with a two-wheel steering system. All research is intended to lead up to the use of four-wheel steering with slight modifications to the chassis.

Index Terms

Electric go-kart, four wheel-steering, personal vehicle, hub motor.

Nomenclature

CAD: computer aided design, in this case done using Fusion 360.

Hub motor: a motor for a vehicle that is built into the hub of the tire.

PWM: pulse width modulation, a digital signal used to control the average power delivered by an electric signal.

VESC: vedder electronic speed controller; a type of motor controller.

MATLAB: a programming software for engineers to analyze products digitally. Used in this project to simulate four-wheel steering on a go-kart.

Introduction

In cities, the desire for single-person transportation is unavoidable. Many people prefer driving personal vehicles over public transportation, but that only increases pollution concerns and further crowds city streets. To help counter this, we created an electric-powered go-kart with the following requirements:

- 25 ft² footprint
- Two-wheel steering system that mimics the steering of a standard car
- Capable of carrying a single person and a backpack to carry-on sized bag
- Operate at 15 mph without serious risk of causing damage to the driver

We created this go-kart with a four-wheel steering system in mind to allow for greater turning radius at lower speeds, increasing the maneuverability of the vehicle in a city environment, but were unable to implement the program due to time constraints.

Electric go-karts are often criticized for their size and weight, making them difficult to store and transport (Li, 2019). In response, we utilized aluminum to create the frame as it is lightweight and highly resistant to stress (Manasa & Kumar, 2022). To reduce the size of the go-kart, we shortened the aluminum extrusions for the frame while balancing safety concerns of the go-kart collapsing in on itself by further reinforcing the axles and cross-sections using stiffeners (Lin et al., 2021).

Further, consumers expressed concerns regarding the maneuverability of electric go-karts (Li, 2019). An effective steering system must be accurate and easy to handle, requiring minimal effort from the driver to turn the go-kart left and right (Khan et al., 2021). Standard go-karts and larger automobiles utilize a rack and pinion steering mechanism to achieve this. In rack and pinion steering, it takes the rotary motion from turning the steering wheel right and

left and turns it into translational motion, pushing the rack to the left or right. From there, the rack causes the tie rods to rotate about the kingpins, and the tires to pivot left or right, turning the go-kart (Khan et al., 2021).

However, this rack and pinion model is not effective for implementing four-wheel steering. As it creates a direct connection between the steering wheel and front axle, there isn't much that can be done to modify the rack and pinion steering model to control four wheels individually. So, to counter this, many four-wheel steering systems electronically connect the steering wheel to the four tires (Hidaka & Kunieda, 2023). Therefore, our go-kart utilizes hub motors instead of a fixed axle connected to a motor through the powertrain so the wheels can be controlled individually (Lin et al., 2021).

We created a four-wheel steering model in MATLAB to simulate it. In the future, four-wheel steering can be incorporated using an electronic four-wheel steering controller along with a speed sensor to control the direction and speed of the wheels. If the car is moving forward at a speed of 18 mph or less, the back wheels will turn in the opposite direction. However, if the car is moving backwards, all four wheels will turn in the same direction (Bhishikar et al., 2014). For a go-kart, the wheels should turn 45° when parking, allowing for the driver to park in a parallel parking spot without making multiple turns. To do this, a speed sensor must be connected to the four-wheel steering controller, feeding information to two angle sensors divided between the front and back halves of the go-kart. The rear wheel steering system would comprise of an electric motor, return spring, ball screw mechanism to convert rotational to linear motion, and the two sensors, one placed on one side of the motor alongside the return spring, and the other placed on the other side with the ball screw mechanism (Jamid, 2011).

In general, the goal of this go-kart was to create a compact, maneuverable, single-person electric vehicle that is capable of carrying a backpack-sized bag to respond to concerns with the weight, size, and maneuverability of standard electric go-kart models. The ideal environment for this go-kart is in a city environment due to its capability for housing four-wheel steering and size that makes it able to fit in and move in cramped environments with ease. It is intended to be easy to operate to increase accessibility to a large variety of people, helping reduce gasoline-related emissions and crowding of city streets while providing users with the individual transportation they desire.

Body

Schedule

- Steering System Complete: 04/05
- Chassis Complete: 05/03
- MATLAB Completed: 05/12
- Electronics Complete: 05/13
- Assembly Complete: 05/14

Procedures

The go-kart was constructed from steel and aluminum rods, extrusions, and plates. The aluminum extrusions and steel and aluminum rods were cut to size using the horizontal bandsaw and later deburred and filed to remove sharp edges. To connect these pieces, we designed steel brackets in Fusion 360, cut them out using the water jet and fastened the brackets to the 1 inch aluminum extrusions used for the frame using nuts and bolts. While most go-karts have a chassis that is constructed out of welded steel pipes, due to their strength and relative light weight, we chose to build our frame with 1 inch extruded aluminum and a number of $\frac{1}{8}$ inch steel brackets due to the availability of the materials in the Prototyping Lab.

Prior to manufacturing the chassis, we created a fully parameterized model of the go-kart in Fusion 360. Once this CAD model was completed, we created a $\frac{1}{2}$ scale model of the go-kart out of balsa wood to ensure the pieces fit together correctly and were proportional to the components we were purchasing, such as the hub motors and kingpins. This model was critical when assembling the final go-kart, as it created an easy reference that could be utilized by any of the group members while assembling the individual aluminum extrusions for the chassis. See the Appendix section for the Go-Kart Assembly CAD. The balsa wood model did not, however, include the complex steering system, which was later developed and animated in Fusion 360 based on the measurements of the $\frac{1}{2}$ scale model. See the Appendix section for the Steering Assembly.

The steel brackets for the chassis were cut directly from the CAD model using the water jet. These brackets were later used to measure the placement of the holes that needed to be drilled on the aluminum extrusions to ensure they fit together and were square prior to assembly. The aluminum extrusions were cut using the horizontal bandsaw and loosely assembled on the ground with these brackets using the balsa wood model as a reference.

Where the balsa wood model and the final go-kart differed was in the seat. Originally, the plan was to make an upright section for the seat to attach to, but not only was this difficult to replicate in practice, it was impractical given the seat we were attempting to attach. In response, the seat was attached to the chassis using a series of aluminum extrusions and steel brackets that were bent using a bending break and the Ironworker. No sketches were made, nor

was a CAD model created in favor of taking measurements directly from the full-sized go-kart and marking the locations where the brackets would attach to the aluminum frame.

For the steering system, the components were constructed from steel and aluminum rods. We utilized a pre-made steering wheel and kingpins and assembled the steering system using nuts, bolts, and welds. The steering column was cut from an inch diameter solid steel rod to a length of 2.5 feet so the steering wheel, which was attached to the steering column using a single nut and bolt, fit comfortably between the driver's legs while allowing the wheel to turn freely.

The pinion was composed of two steel components cut using the water jet that were welded to the steering column to create a permanent joint. These parts were connected to the tie rods, which were two 16.25 inch long aluminum bars using bolts. This system was far simpler than the rack and pinion method utilized in larger automobiles, reducing the weight of the steering system while still allowing the go-kart the ability to turn left and right. The ends of the tie rods were bent $\sim 90^\circ$ using the iron worker so they would connect with the kingpins, allowing the turning motion of the steering wheel to translate to the kingpins and wheels.

See the Circuit Diagram for the Motors in the Appendix section for the electrical component setup. We utilized a 29.8 V battery to power the motor controller and motor. To power both of the motor controllers and motors with a single pedal and power source, we soldered the wires of the motor controllers together so they created a single wire. The motor controller we purchased required a PWM input, which required the single output of the pedal, which is a hall effect sensor, to be translated into a PWM using an Arduino Leonardo. The pedal and motor controller were both connected to the Arduino to translate the hall effect sensor's outputs into PWM. The three stage wires from the motor were connected to the motor controller's power output pins, and the sensory wires were connected to the digital input pins. This set-up allowed for both of the motors to theoretically receive power from the single battery and be controlled by the pedal.

Additionally, the motors we purchased had a built-in spot to attach brakes. There was a hexagonal pattern of 6 screw holes, each 44cm center to center from the hole opposite it, fitting a standard disc brake, which we purchased and installed onto the hub motor. The handles of the bicycle brakes were attached to the seat as a handbrake and connected to the motors using the cable of the bicycle brakes. These motors were attached to the frame using a series of extrusions put together in a rectangular shape. There were two steel brackets, one on each side of the motor, that held the motor in place with the help of a series of nuts and bolts. The motors were connected to the motor controllers, which were duct taped to the frame along with the Arduino Leonardo. The Arduino was connected to the pedal, which was screwed onto the front of the frame behind the tie rods.

Using the Kalman Filter on MATLAB, we created a simulation for some of the four-wheel steering results. The Kalman Filter is an optimal estimator that utilizes inaccurate, indirect, or uncertain data to infer parameters of interest. The closer this data is to a Gaussian distribution, which is graphically represented by a bell curve, this means there is less error within the simulation.

By creating a series of input values for the distance the go-kart is expected to travel in each direction when parking, the model simulated the possibilities of four-wheel steering in a city environment, where it would be useful to reduce the number of turns a driver would need to complete to parallel park on a cramped street. The simulation took the distances along the y-axis (the $\hat{y}$ distance) and x-axis (the $\hat{x}$ distance) to create a simple slope that would find the angles that each wheel needed to turn to allow for that movement. This movement was simulated for three different scenarios: one in which the vehicle drives as if it were front wheel drive, one where the wheels turn in opposite directions in order to increase turning radius and vehicle stability, and one in which all four wheels turned at the same angle, in other words parallel to each other, theoretically incurring a lateral displacement without tressturning.

Testing Methods

Prior to creating the physical go-kart, we performed stress tests in Fusion 360. As seen in the Appendix section under Fusion 360 Stress Testing, we tested the CAD model's strength by placing a force twice that of the average 200 lbs human against the bottom of the chassis, where the seat connects, as well as the force of a singular human against the two pillars that hold the seat upright. Across both tests there was less than 1.5 centimeters in displacement of the aluminum extrusion, well within a safe range for operation and longer term use.

Also using Fusion 360 we performed a crash test. Although we do not plan to test this with the final go-kart it is important we test the ability for the go-kart to sustain a collision given the fact it is intended to be used in a city environment. In this test we modeled the force of a 200-pound person driving 30 mph directly into a tree with the go-kart coming to a near instantaneous stop 0.1 seconds after impact. This created a massive pressure on the front of the go-kart, about 1.85 times the tensile strength of our aluminum extrusion, resulting in a 2 cm displacement followed by the aluminum breaking, as seen in the Fusion 360 Crash Testing image in the Appendix section. Although the aluminum broke, this result was satisfactory as the go-kart did not break in a way that presented an immediate risk to the driver because it was the front bumper that broke.

Later, we performed minor stress tests through various phases of assembling the go-kart. These tests included lifting the go-kart while a person sat in it to see whether or not the frame bent enough to be visibly apparent or even fell apart. Our physical stress tests were intended to put a lot of force on the weakest joints and welds, specifically on the connections between the hub motors and the frame and the kingpins and the frame.

Testing the electronics was a long process of trial and error. As the wire colors were not standardized between electrical components, we created a table of possible wire combinations until something worked. The motor controller, motor itself, and pedal needed to be tested individually before being integrated into a system together. We first tried to establish the functionality of the motor controller using a motor that we already knew worked. We did so by connecting our motor controller to an Arduino Leonardo with a PWM output in an attempt to get the motor to spin. This was unsuccessful so we did some further research into the motor controller and found VESC software, which was designed specifically with our use case in mind and would allow us to calibrate the motor controller along with our actual motor. Once calibrated, the motor spun, indicating both the motor and motor controller were functioning as expected; however, the motor was uncontrollable without the pedal. After multiple trials, the motor was first controllable using a remote controller, and later wired to the pedal once the VESC software proved to be functional with the remote controller. To determine the output frequencies of the remote controller, we utilized a spectrum analyzer and changed our PWM range in our Arduino code to 45-140 to match the working controller. Reading the values given off by our hall effect sensor pedal, we got a range from 180-650, which we mapped to 45-140, which allowed us to control the motor with the pedal.

Results

We were able to fully assemble the go-kart using the procedures described in the previous sections. Most importantly, we made a stable go-kart with a frame that was able to hold the weight of a person and a backpack without warping or breaking apart. The motors were receiving power and the steering system functioned so the front wheels could turn the go-kart left and right while it was rolling. However, the go-kart was unable to power itself as the hub motors were not spinning in tandem with each other, making us uneasy with testing the go-kart's ability to drive due to general safety concerns.

Discussion

While assembling the go-kart, there were several instances where the frame nearly shook itself apart. As we utilized a series of brackets held together by nuts and bolts instead of using welds to secure the pieces of the frame together, any sort of force that caused the frame to vibrate would loosen these bolts and lead to the potential of the frame completely falling apart. For the final assembly, we applied Loctite to each bolt in hopes that it would stop the nuts from rattling off of the bolts with use, but this could have been avoided entirely if the entire frame had either been made of steel or aluminum. The Prototyping Lab did not have an abundance of steel piping as it did aluminum extrusions, explaining why we initially didn't choose to weld together the frame components, but the Lab also had materials that could be used to weld aluminum pieces together, which would have resulted in far stronger bonds

between the aluminum extrusions. Additionally, this would have made it so the go-kart would only need to be assembled once, reducing the time spent on taking apart and reassembling the go-kart for a variety of reasons.

The original design was created with brackets surrounding the entire hub motors. This is not conducive for a go-kart with four-wheel steering capabilities. A four-wheel steering system requires all wheels to be independent and given the necessary room for mobility. These brackets constrict the radius of movement of the wheels, reducing the mobility of the rear wheels and therefore making the impact of four-wheel steering less noticeable. However, this design was necessary for the hub motors we utilized, as there was no solid axle between them and they had mounting screws on both sides of the motor because they were originally intended for use on an electric scooter. Given this information we now know, we should have either spent more time working on ways to reduce the number of attachment points the motors needed or invested in motors that were intended to have a single attachment point and be used for go-karts or other similar vehicles.

This same need to have spent more time researching the hub motors we purchased should have been put into all of the electrical components. The final assembly of the go-kart was delayed by about a month from its original goal date of early April. This was partially due to shipping times for electronic components, but also due to a lack of experience and knowledge with the electronics systems. As we hadn't spent as much time as we should have researching the electronic components and referencing the work other people had done to make similar motors spin, the development of the go-kart slowed down once we reached that point. Although we were able to make relatively quick improvements with the help of our lab directors, this effect could have been minimized had more research been done prior to the electrical components arriving.

Originally, the intention was to use MATLAB to calculate forces that may occur using four-wheel steering to help us understand the maximum amount a wheel could turn for a given speed in a given direction. We decided instead to use MATLAB for the simpler purpose of measuring how far the car would turn for a given change in wheel angle. This decision was made due to a lack of experience with MATLAB along with the fact that the Kalman Filter was not given accurate data to the model we created. Since we did not have enough time to test the go-kart prior to submission, we did not collect data from the go-kart to use in the Kalman Filter. Because of this, the four-wheel steering model would not be completely accurate to our go-kart. However, it still could have provided useful information for simulating the lateral and rotational movements and velocities of a go-kart based on the wheel rotational velocities and angles they were turned at. In the future, more focus should be placed on this MATLAB simulation to properly establish the kinematic models we would use in our simulink.

In our attempted MATLAB simulation we modeled the car as if it operated on two wheels in line with the center of gravity and the actual locations of the wheels. We would use a series of kinematic equations (Wang & Qi, 2001):

$$\begin{aligned}\dot{X} &= v(\cos(\psi + c)) \\ \dot{Y} &= v(\sin(\psi + \beta)) \\ \dot{\psi} &= \frac{v(\cos(\beta))(\tan(\delta_f) + \tan(\delta_r))}{l_f + l_r}\end{aligned}$$

Where

$$\begin{aligned}\beta &= \arctan \frac{l_f(\tan(\delta_r)) + l_r(\tan(\delta_f))}{l_f + l_r} \\ v &= \frac{v_f(\cos(\delta_f)) + v_r(\cos(\delta_r))}{2(\cos(\beta))}\end{aligned}$$

β is the angle the whole go-kart turns, ψ is the heading angle, and δ is the angle the front and rear “wheel” turn, and l is the y component of displacement from the center of mass.

Conclusion

The purpose of this project was to create an electric go-kart with a functioning four-wheel steering model in MATLAB. The physical go-kart needed to have a two-wheel steering system that mimics the steering of a standard car, have a 25 ft² footprint, carry a person and a backpack-sized bag, and operate at 15 mph without putting the driver at serious risk. Overall, we were mostly successful with achieving these objectives, creating a MATLAB model for four-wheel steering and assembling a go-kart of the required footprint, carrying capacity, and steering system.

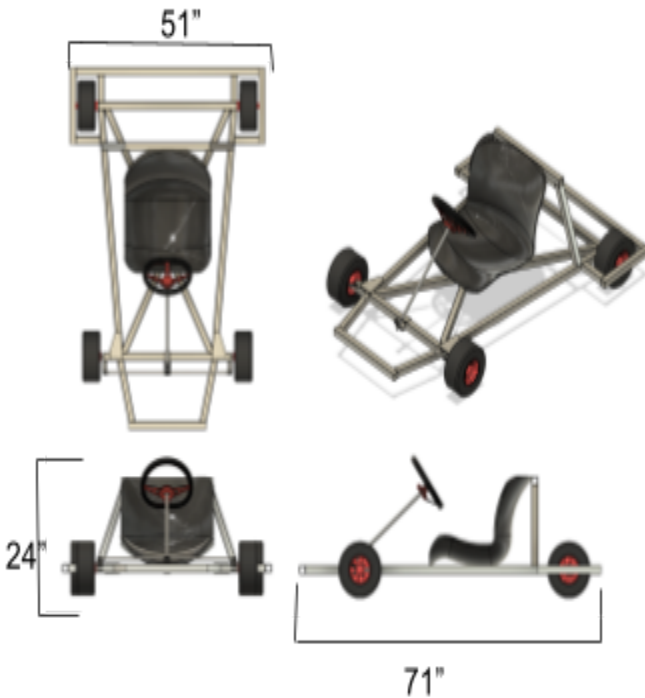
In the future, research should be done to improve the MATLAB model and implement it. Specifically, getting the motors to spin in tandem needs to be a priority for future research. As each motor controller could only be programmed to one motor, the motors need to be connected to a single battery despite this or separate batteries need to be connected to each motor. Either way, as this was not a focus of this project, this is something that needs to be focused on in the future. Once this issue is resolved, the current go-kart will be in a much better place to continue researching how to better attach the hub motors and implement the four-wheel steering system as designed in MATLAB.

Appendix

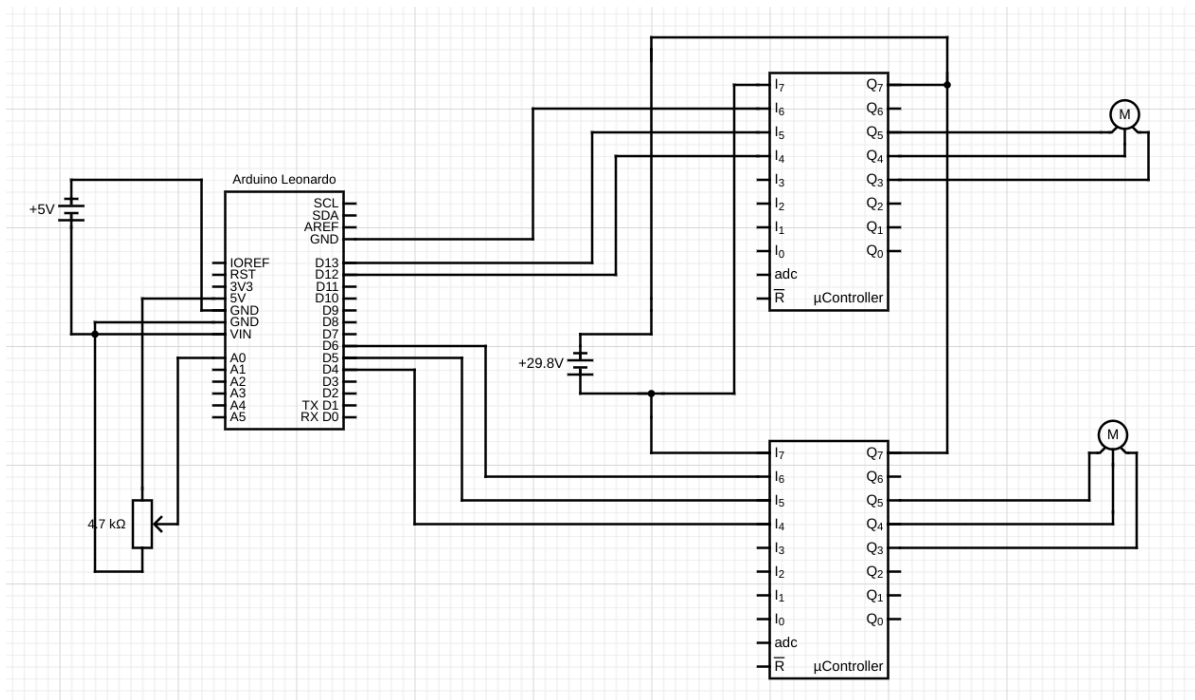
Original Designs, CAD Drawings, and Sketches

Go-Kart Assembly CAD

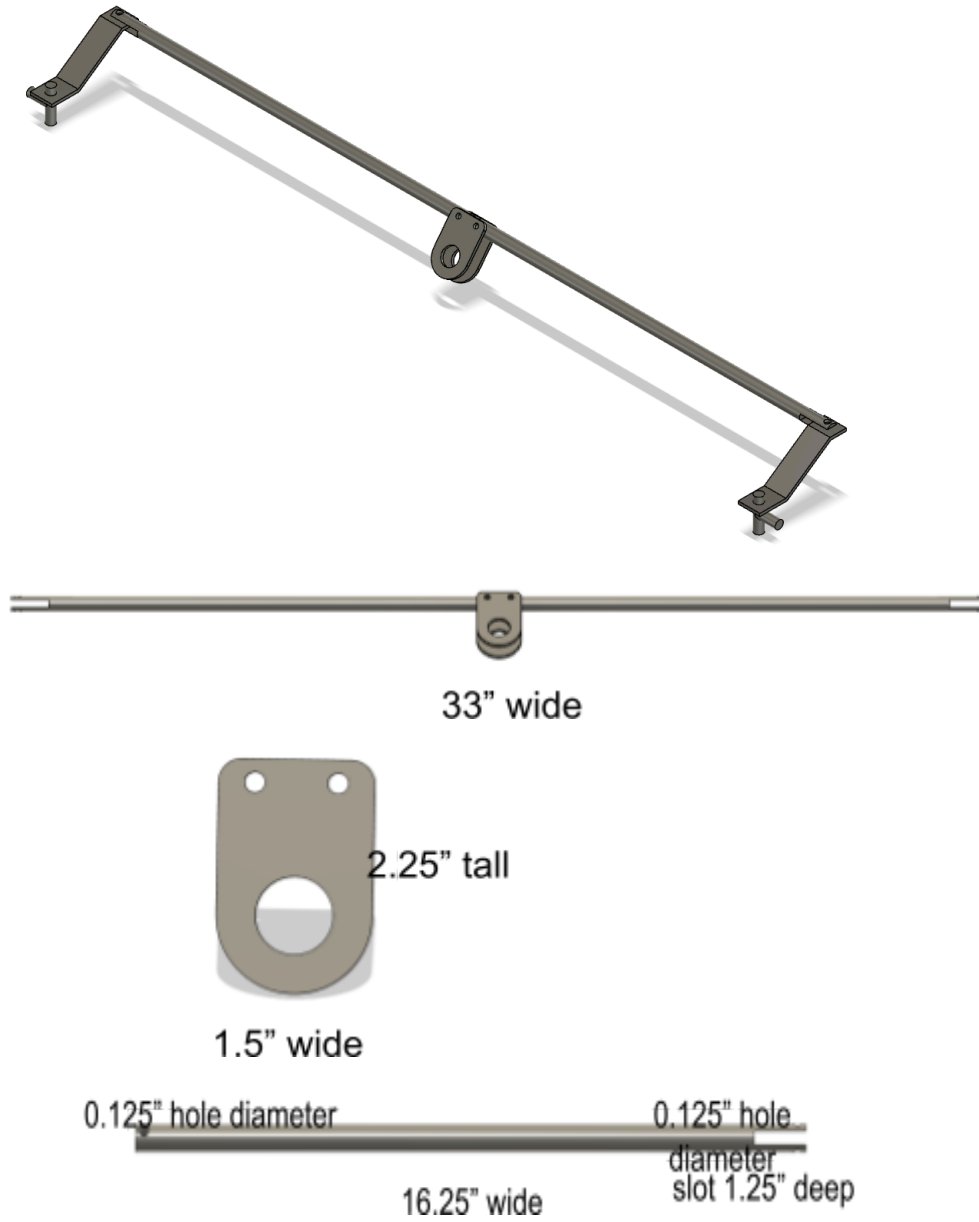
Go-Kart Assembly CAD



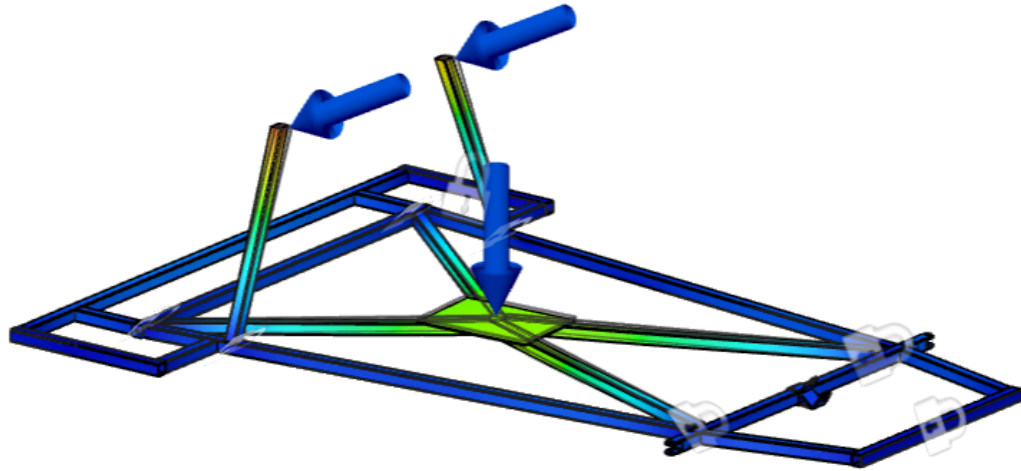
Circuit Diagram for the Motors



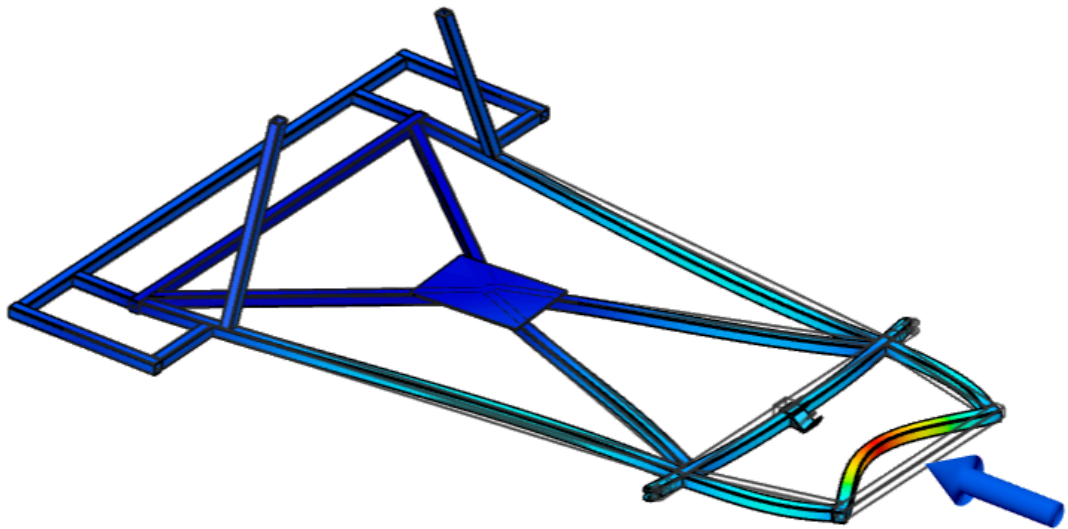
Steering Assembly (including pinions and steering rods)



Additional Images
Fusion 360 Stress Testing



Fusion 360 Crash Testing



Final Go-Kart Assembly



Bill of Materials

Material	Quantity	Cost
1/8th inch Steel Sheet	1	\$64
Steel Rod (3/16 in x 48 in)	1	\$4
Steering Wheel	1	\$23
Tires	4	\$120
Hub Motor	2	\$168
29.4V Battery	1	\$48
72 inch 1010 Aluminum	5	\$120
Kingpin	2	\$120
Aluminum Rod	1	\$11
Seat	1	\$50
Pedal Potentiometer	1	\$13
Motor Controller	2	\$160
Disc Brakes	1	\$20
TOTAL:		\$921

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We would like to thank our Engineering lab directors, specifically Mr. Clinton Behling, Dr. Daniel Parilla, and Mr. Jared Seyler for helping us manufacture the go-kart chassis and . Without their support and expertise, this project would not have been possible.

Additionally, we would like to thank our parents for their support and fellow senior Sebastian Toro for soldering the electronics at the last minute when we did not have the confidence or expertise to do so.

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Biographies



Carter Ellis

Carter, a senior at the Thomas Jefferson High School for Science and Technology, will be pursuing a degree in mechanical engineering from the University of Delaware. A former member of Project Caelus, his interest in designing and manufacturing ideas from start to finish translated cleanly to the go-kart and Engineering Research Lab as a whole.

Liam Harmon

Liam, currently a senior at the Thomas Jefferson High School for Science and Technology, will be majoring in mechanical engineering at Northeastern University. His experience in circuitry, machining, and assembly was needed throughout the development of the go-kart.



Leilani Harris

Leilani, a senior at the Thomas Jefferson High School for Science and Technology, will be attending the United States Air Force Academy with hopes to pursue aviation. A Captain of the Thomas Jefferson Rocketry Club and previous member of the Automotive Engineering Club, her experience with go-karts brought her in as a last-minute addition to the team.

Aditya Jain

Aditya, currently a senior at the Thomas Jefferson High School for Science and Technology, will be pursuing a Bachelors in Mechanical Engineering at Drexel University. President of the Thomas Jefferson Automotive Engineering Club, his expertise with go-karts and other vehicles was put to great use during the development of this project.

