ECE 445 Final Report

Autonomous Golf Caddy

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Abstract

The autonomous golf caddy is an electrically powered motor vehicle which is designed to improve the golfing experience. The golf caddy uses an array of sensors to track a golfer's position and follow behind at a comfortable distance. The golf caddy is intended to allow the user to have the experience of walking the course without the strain of carrying or manually pushing their golf bag. This report outlines the initial research and development of a design based on modifications to a traditional golf push-cart. The findings of this report describe the results of the testing and verification processes for both individual components and system-level integration. The report is concluded with a discussion of future steps required to improve upon the design of the device.

Contents

1. Introduction

1.1 Objective

From a practical standpoint, the biggest obstacle in golf is transportation of the golf bag. The two most popular modes of bag transportation are putting it on a golf cart and driving the cart around the course or putting the bag on a pushcart and pushing it around the course. The problem with these is that golf carts cannot be driven anywhere on a course, forcing golfers to drive the cart to one location, and then walk some distance to their ball and then back to the cart. Pushcarts do not have this issue, but also require the golfer to physically push them around the course. Many golfers like to walk without pushing or carrying the bag. The most popular solution to this problem is to hire a caddie to carry the bag, which can cost upwards of $60 per round and is only available at certain country clubs. This can also ruin the sometimes-desired solidarity of a round of golf.

Our goal is to create an affordable autonomous pushcart that can be taken to any course and actively avoids obstacles. This allows the golfer to simply walk the course and have their clubs follow behind them without having to worry about their cart running into things.

1.2 Background

Current implementations of autonomous pushcarts are expensive ($1500+) and do not avoid obstacles [1]. This lack of obstacle avoidance can be rather detrimental to the operation of such devices as a person would not tend to simply step over small logs or other things on a golf course, whereas a cart does not have this ability. We chose to enable obstacle avoidance in our cart so it does not fail to operate when it encounters an obstacle, which would impose quite a bit of frustration in the golfer. Rather, our device will actively avoid obstacles by detecting them and maneuvering around them. Our device will also be much cheaper to produce and will also avoid obstacles such as trees, logs and other golfers.

2 Design

The high-level design of the Golf Caddy consists of 4 modules outlined below in Fig. 2.1.

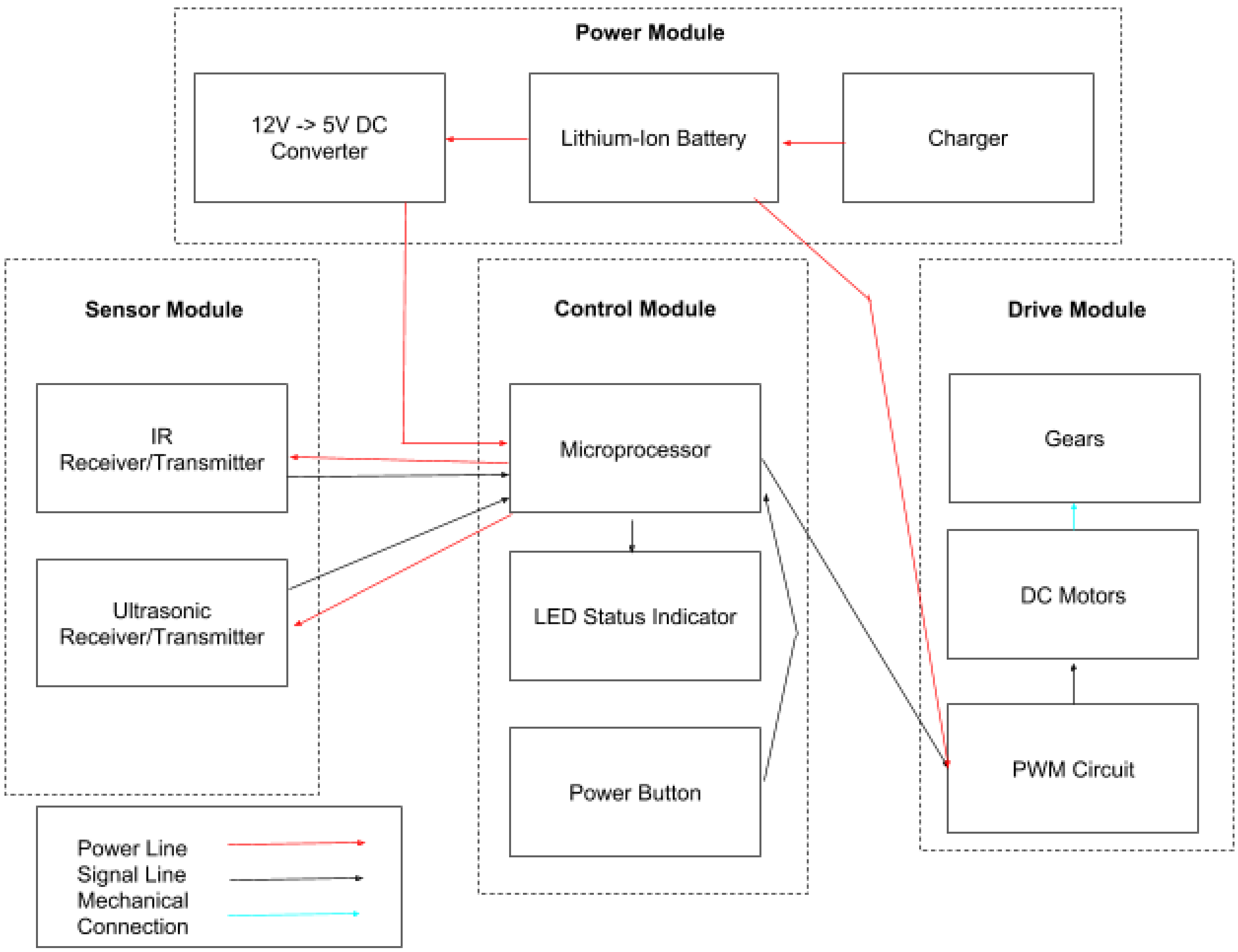

Figure 2.1

2.1 Power Module

The power module is responsible for providing energy to each component in the system at the required voltage levels.

2.1.1 Primary Power Source

The primary power source for the Golf Caddy is a rechargeable 12V 35Ah sealed lead acid battery (SLA) [2]. A battery was needed that could provide high-power output and respond quickly to changes in current demand. SLA was chosen to meet this general requirement. The battery provides power directly to both motors as well as a gate driver circuit. All other components are powered through an intermediary DC-DC converter.

2.1.2 Voltage Converters

The Golf Caddy features a 12V/5V step-down converter [3] and a 12V/3.3V step-down converter [4]. The output of the 5V converter provides power to the sensor array. The output of the 3.3V converted provides power to the system's microcontroller.

2.2 Drive Module

The drive module is responsible for providing acceleration and steering capability to the cart. It consists of two DC motors (one per front wheel), a PWM circuit to control and provide power to each motor, and two gears per side to interface between each motor and wheel. The rear wheels have a diameter of 10.5 inches. Our cart must be able to keep up with a golfer walking the ideal brisk walking pace of 5.72km/h (3.58 mph) [5]. We chose a max cart speed of 5 mph so that the cart is able to catch up to a golfer in case it needs to slow down temporarily to avoid an obstacle.

2.2.1 DC Motor

The DC motors physically turn the wheels of the pushcart. One motor is mounted near each wheel and drives the wheel with a gearing speed reduction. The motor we used is the "Mini CIM" from VEX robotics. It has a power rating of 215 watts and a a free speed of 5840 RPM [6]. This motor was chosen because it is relatively inexpensive and is compatible with many other parts on the VEX website, the most notable being various gears. Its power rating of 215 watts is more than required, as seen in Appendix B. The motor's input voltage of 12 volts gave us flexibility when choosing a battery. Since one of our primary concerns when choosing a motor was off-the-shelf gear compatibility, we did not find many suitable alternatives. The only alternative that was considered was the full-size CIM motor from VEX robotics. We chose the Mini version due to the extra power not being necessary and because the extra weight added by a larger motor would only complicate mounting each motor.

The motors were bolted to the frame via a custom mount. We also placed a diode in parallel with each motor in the orientation shown in Figure 2.2 to prevent back electromotive force from damaging our CPU. We did not implement this initially, and destroyed a CPU after turning off the motors.

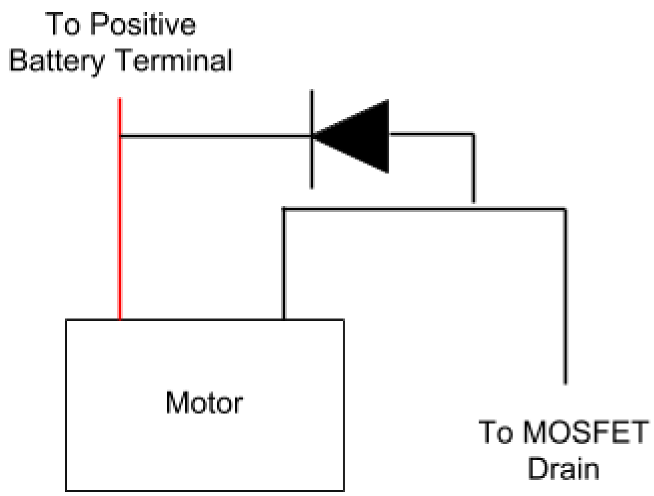

Figure 2.2

2.2.2 Gears

The gears are responsible for power transmission from the motors to the wheels. Our gearing ratio of motor speed to wheel speed is defined by two criteria: the ratio must allow the cart to reach a maximum speed of 5 mph (2.235 m/s) and must allow for maximum available torque at the lowest possible speed while still being able to reach the maximum speed. To satisfy these criteria, we matched the maximum wheel speed to the maximum motor speed. Using the wheel diameter of 10.5 inches [7], the motor speed of 5840 RPM and equation 2.1, this gives us a maximum wheel speed 160.0 RPM. Matching the maximum motor speed to the maximum wheel speed using equation 2.2 gives us a gearing ratio of 36.5:1. To ensure we do not hit the maximum motor speed, we will choose a gearing ratio that is lower than this. We decided to go with off-the-shelf gears from the VEX website, choosing a 72 tooth large gear [8] that will attach to the wheel and 11 tooth small gear [9] that will attach to the motor. To address efficiency concerns, our PWM control of the motors to allows the motors to produce different amounts of torque at the same motor speed. This allows near maximum efficiency at any motor speed.

$$\text{Linear speed} = \text{Diameter} * \text{Pi} * \text{RPM} \qquad \text{(Equation 2.1)}$$

$$\text{RPM}_1 * \text{Gearing Ratio}_{1:2} = \text{RPM}_2 \qquad \text{(Equation 2.2)}$$

2.2.3 PWM Circuit

The PWM circuit is responsible for controlling the speed of the motors. An internal PWM signal is produced by the microprocessor unit in response to the readings of the sensor. The PWM output of the microcontroller is fed into a gate driver circuit which increases the voltage of the signal from 2.5V to

10.5V. The gate drive circuit schematic is shown in figure 2.3. The gate drive circuit output is then used to gate a MOSFET which controls the motors directly [10].

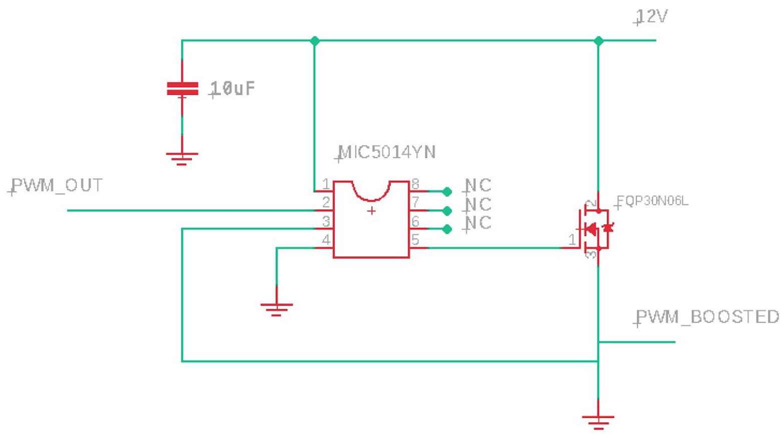

Figure 2.3

2.3 Sensor Module

The sensor module is responsible for gathering data from the environment which is then passed into the system's control module. All true distance measurements are taken through ultrasonic echolocation where all angular distance measurements are taken through infrared triangulation.

2.3.1 Ultrasonic Sensors

The Golf Caddy is equipped with three ultrasonic sensors. A single front-facing sensor is responsible for tracking the user's distance from the vehicle. Two additional sensors are mounted at a 45 degree offset in either direction from the front of the cart. These two sensors detect obstacles which may lie on the course.

Ultrasonic echolocation was chosen for obstacle detection over optical sensors given that assumptions cannot be made about the color of the obstacles or the ambient light conditions on a particular day. Ultrasonic echolocation was also chosen to track the user's true distance rather than extending the infrared sensor to calculate true distance as a function of infrared intensity. To justify this decision the following scenario was considered. In the case where the user was to turn their body such that the infrared emitter is not directly facing the infrared sensor the total intensity of infrared at the receiver drops. As a result the true distance calculation based on infrared intensity would incorrectly increase, although the angular distance would remain correct.

The Golf Caddy uses the HC-SR04 ultrasonic distance sensor [11]. The sensor provides both an ultrasonic emitter and ultrasonic detector. The control software periodically will send a signal to the sensor array to emit an ultrasonic burst. The ultrasonic burst travels through the air until it bounces off an object and returns to the sensor. At this point a return echo signal is sent to the control software. The sequence is illustrated in Fig. 2.4. The distance can be calculated as a function of time as shown in Eq. 2.3. A design challenge imposed by this method is the non-deterministic time at which the return echo is received. This challenge is addressed by the control software and an extended discussion can be found in section 2.5.1.

$$d = \frac{(echo-high-time) * 340\ (M/s)}{2} \qquad \text{(Equation 2.3)}$$

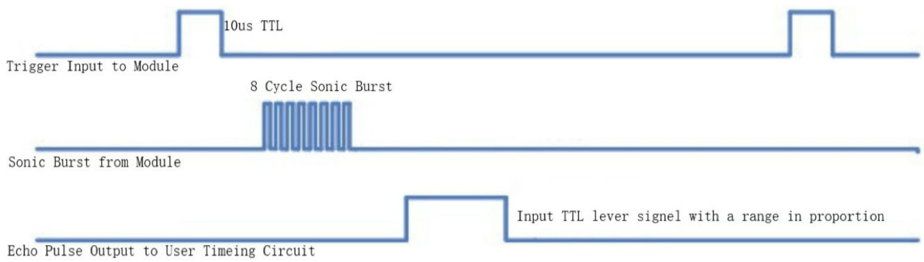

Figure 2.4

2.3.1 Infrared Sensor

The Golf Caddy features the IR Seeker V3 [12] which employs two infrared detectors offset by 37.5 degrees in either direction relative to the forward heading of the cart. The user is required to wear an ultrasonic emitter which can be affixed to a belt on the posterior of their body[15]. The infrared emitter-receiver pair has an operating frequency of 600Hz to minimize interference from ambient infrared light.

To track angular distance optical light was chosen due to the availability of low-cost sensors which can measure intensity. The pair of infrared sensors in this design each measure the intensity of light and calculate the angle of the user based on relative intensity between them.The relative intensity is calculated as shown in Eq. 2.4. A graphical view of this calculation can be seen in Fig. 2.5. All data transfer is handled over I2C protocol.

$$\varphi = \frac{75 \times (r_{left} + r_{right})}{200}\ degrees \qquad \text{(Equation 2.4)}$$

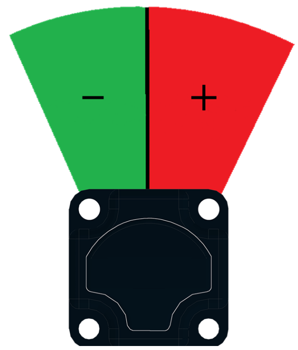

Figure 2.5

2.4 Control Module

The control module is the intermediary between sensor input and motor output. The control module receives the raw sensor data and calculates the speed and heading necessary to properly follow the user. The control module additionally handles all interactions through the user interface and safety protocol. The control module schematic is shown in Fig. 2.6.

2.4.1 Microprocessor Unit

The primary component of the control module is the LPC804 ARM Cortex M0+ [13] microcontroller unit (MCU). The LPC804 was chosen as a low-profile, low power consumption MCU. The LPC804 is capable of handling I2C protocol, PWM output and analog-to-digital conversion.

2.4.2 User Interface

The Golf Caddy employs a simple user user interface. All user input is handled by a pair of switches [14]. A run/pause switch is used to toggle the operation mode between normal operation (follower) mode and a stationary pause state. A power switch is used to turn the device on or off. A pair of LEDs is used to indicate the state of the device. The pause LED is illuminated when the device is put into the pause state. The power LED is illuminated anytime the device is powered on.

The control software does not gather any data that would be of direct use to the user. As a result, the user interface does not provide any additional information to the user beyond the operating state of the device.

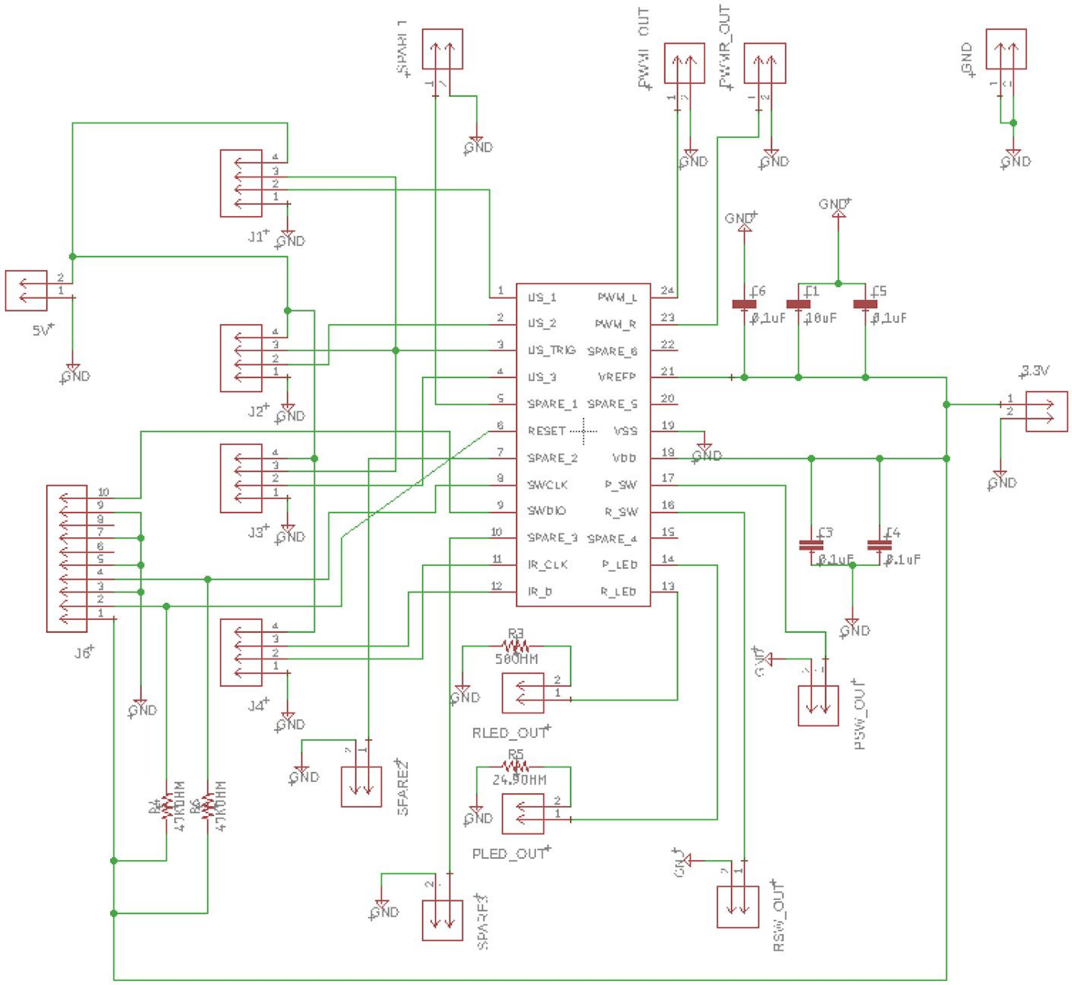

Figure 2.6

2.5 Software

2.5.1 PID Control

The MCU used Proportional-Integral-Derivative (PID) control to decide how how fast to turn each motor in order to control the cart. The two inputs to this control algorithm are the cart's current distance from the user and the cart's current angle relative to the user. Its outputs are duty cycles for the PWM signal sent to each motor There are a total of six gains in our implementation: a proportional gain, integral gain, and derivative gain for the distance to the user, and a set of three more PID gains for the angle. The distance gains are applied to both motors and the angle gains are applied to one motor based on the sign of the angle.

2.5.2 User Interface

The software handles both switches as interrupt requests. For the safety of the user, it is vital that the cart can be put into both the pause and off state regardless of the current point in program execution. Handling the switch inputs as interrupts provides this guarantee.

The LEDs are simply driven directly by output ports of the MCU. The power LED is illuminated during the device startup sequence. The pause LED is illuminated during the run/pause interrupt service routine.

2.6 Cart Assembly

The cart assembly houses all other components and modules as well as the golf bag.

2.6.1 Cart Base

The pushcart base in our design is the Caddymatic Continental 3. We chose this model for its tubed metal construction and its independent rear axles. The metal tubing allows for simple mounting and modification and the independent axles allow the rear wheels to be driven separately, enabling the cart to turn.

2.6.2 Cart Modifications

Various modifications were made to the cart base to accommodate various components in other subsections. The most notable are the motor mounts, which were cut from aluminum using a an angle grinder, drill and a hole saw to allow each motor to be mounted in an optimal location relative to each wheel. Other modifications include a shelf to hold the battery, converters and large MOSFETs, and a caster wheel in the front to allow for better turning than the non-pivoting wheel that was preinstalled on the cart. //todo: add pictures of mods?

3. Design Verification

The full requirements and verification (RV) table can be found in Appendix A.

3.1 Power Module

Requirement No.1 (Appendix A): The system shall provide reliable 12V, 5V and 3.3V power.

While cart was in operation mode each supply voltage was measured using a digital multimeter. The results are shown in Fig. 3.1.

Expected Voltage (V)	Measured Voltage (V)	Error (%)
12	12.7	5.8
5	5.09	1.8
3.3	3.31	0.3

Figure 3.1

Requirement No. 14 (Appendix A): The cart shall last an entire round of golf

The average length of a round of golf is four hours. For the sake of ensuring this requirement be fulfilled an additional 50% tolerance is added to account for extreme course conditions. Thus, our cart shall be able to last six hours in operation mode. To calculate power consumption a factor of 0.5 was considered to conservatively account for motor off-time and expected average duty cycle (50%). Equation XX was then used to calculate the expected battery life of the Golf Caddy.

The typical current draw for each motor was measured to be 3A using a digital multimeter. The current draw of the sensors and MCU are assumed to be negligible. Thus, the average current draw of the system was found to be 6A. By Eq. 3.1 the Golf Caddy is expected to maintain a charge for 1.94 rounds of golf.

$$\frac{35Ah}{\frac{6h}{round} \cdot 6A \cdot 0.5} = 1.94\ rounds \qquad \text{(Equation 3.1)}$$

The results indicate that the power module met each of its requirements. This aspect of the design will be carried forward through the next iteration of the golf .

3.2 Drive Module

Requirement No. 2 (Appendix A) : Gears must allow motors to drive cart at maximum speed of 5 mph

The drive module did not meet this requirement. This was due to the cart's inability to drive in a straight line which prevented us from running the test outlined in our RV table. This is due to both one motor being run backward and a friction imbalance between the two wheels. This causes the same PWM signal to run each motor at different speed. Ideally we would simply add an offset or proportional gain to one motor in order to rectify this, but the poor granularity of our PWM outputs does not allow this to work well. While we were not able to run the test outlined in our RV table, the goal of the maximum speed requirement is to ensure that the cart was able to keep up with a user that walks briskly. We often had to break into a jog to catch the runaway cart during testing. The cart seems quick enough qualitatively, but we had difficulty quantifying these results.

Requirement No. 3 (Appendix A): Current draw must not exceed 80% of MOSFET's rated value

This requirement was not fulfilled as we destroyed multiple MOSFETs, including one the day of our demonstration. We cannot test the current draw directly as none of the lab equipment is able to measure currents near 15 A, but based on these results it is safe to assume we did not stay within 80% of the rated current of the MOSFET.

3.3 Sensor Module

Requirement No. 7 (Appendix A) Ultrasonic transmitter/receiver must be able to detect objects within 2.5m in front of the receiver

This requirement is not fulfilled as the ultrasonic sensors are only able to detect an object within 1 meter of the cart. We want to note that this requirement was satisfied when detecting a wall when the sensor connected to an Arduino (seen in Table 3.1), but failed when detecting other objects when connected to our microprocessor.

Requirement No. 8 (Appendix A) Distance data shall have a granularity of 5cm or better:

This requirement is only fulfilled to a distance of about 90cm, as seen in Fig. 3.2. For distances smaller or equal to 90cm, the measured distance is within 4cm of the true value. For distances greater than 90cm, the error is greater than 5cm and does not meet our granularity requirement.

Expected	5	10	15	20	25	30	35	40	45	50
Measured	6	10	16	21	25	32	34	43	46	52
Expected	55	60	65	70	75	80	85	90	95	100

Measured	58	61	67	73	79	82	86	92	101	104
Expected	110	120	130	140	150	160	170	180	190	200
Measured	117	127	132	149	161	166	182	182	194	224

Measured vs. Actual Distances of an ultrasonic sensors using an arduino
Figure 3.2

Requirement No. 9 (Appendix A) IR receiver can detect transmitter within 2.5 meters of the cart within 150 degree field of view relative to the front of the cart:

The infrared sensor provided the required field of view. However, the readings were sporadic and provided little granularity.

3.4 Control Module

Requirement No. 12 (Appendix A) MCU can provide PWM signal to gate the speed controller MOSFET

Initially, the MCU output pins were found to be incapable of providing a voltage large enough to open the drain-source channel in the speed controller MOSFET. The introduction of an isolated gate driver circuit (Section 2.2.3) increased the voltage of the PWM signal from 2.5V to 10.5V which provided a high enough voltage to meet this requirement. Waveform captures are shown below in Fig. 3.3 and Fig. 3.4.

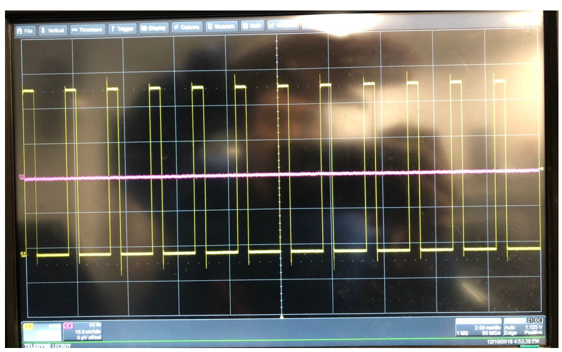

Figure 3.3

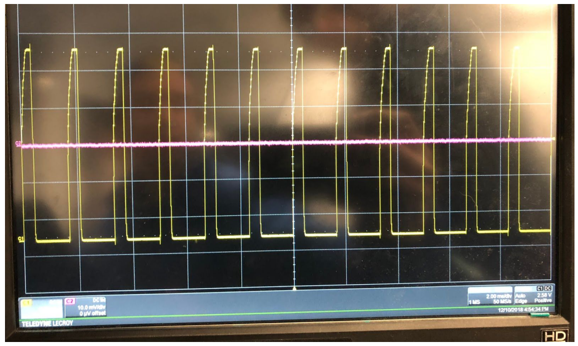

Figure 3.4

Requirement No. 4 (Appendix A) LED can be seen from a distance of 10 meters

The LED was observed from a distance of 15m and was visible to the human eye. This test was performed in a well-lit environment. While trivial, this requirement was met.

Requirement No. 5 (Appendix A) Buttons function properly

The buttons were successfully integrated into the final design. The push buttons were used to control the run/pause state of the device. This requirement was met.

Requirement No. 6 (Appendix A) Button must turn the system on when the system is off

The button itself functions and the control module raised the correct interrupt. However, the functionality to disconnect and connect the power to the motor using the button was not implemented. This requirement was not met.

3.5 Software

Requirement No. 10 (Appendix A): The cart shall transition to the pause state when the user is more than 2.5 m away

As a result of the ultrasonic sensors losing accuracy distances greater than 1m (Section 3.3) this requirement was not met. Over the course of 15 trials, the motors only turned off within 10% of 2.5m five times. A 33.3% success rate is not acceptable for this requirement.

Requirement No. 13 (Appendix A): The cart shall follow .5-2 meters behind the user

As a result of the failure in the drive system to operate in the expected manner this requirement is assumed as failed.

3.6 Cart Assembly

The cart assembly was not subject to any specific requirements. Nevertheless the chosen cart lacked the sturdiness that is required to be modified to the specifications of this design.

3.6.1 Cart Base

At a basic functional level the cart provided the expected function. However, the mounting mechanism of the wheels into the axle receptacle allows the wheel to tilt from side to side when the cart is moving. This mechanism also caused the distance between the wheel gear and the motor gear to increase when weight is added to the car. This causes undesired friction between the gear. A future iteration of this project would need to use a cart where the axles are in a more fixed position, independent of the weight the cart is carrying.

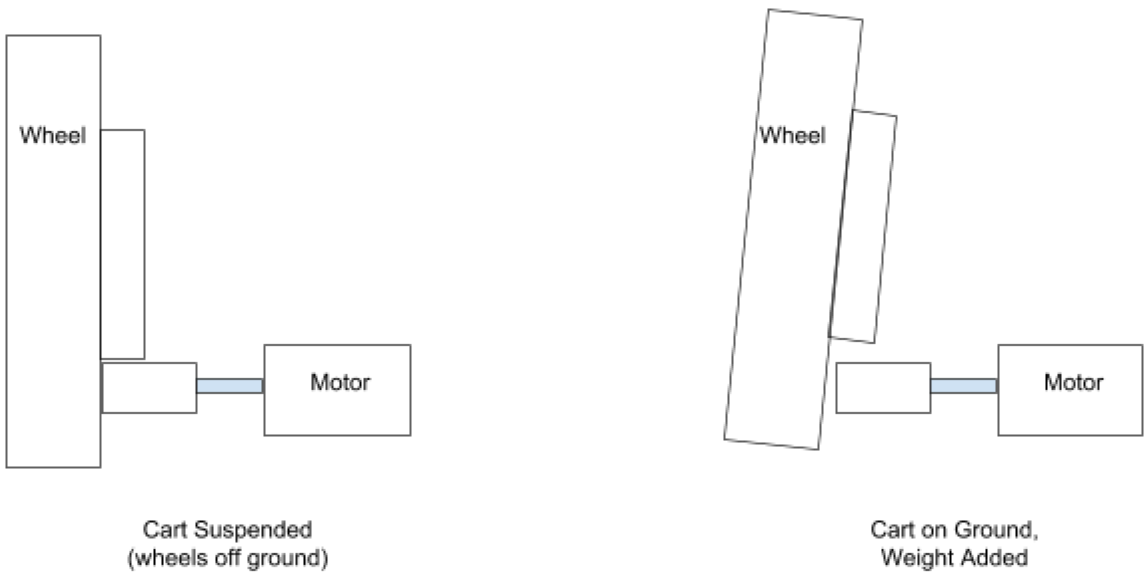

Figure 3.5

3.6.2 Cart Modifications

The modifications to the cart work well, and meet their responsibilities of housing other components. However, our motor mounts are not adjustable enough to properly compensate for the wheel tilt shown in figure x. The cart works properly most of the time, but the gears occasionally become dislodged and must be put back in place. If our design were more adjustable, this would not be an issue. Additional adjustability could be implemented using a hinging motor mount that also has screw channels to allow different mounting locations along an axis.

The wheels also had different rolling resistances due to modification inconsistencies. The cart base has a brake on side which even after being cut and filed still caused additional rolling resistance on the wheel mounted on that side. A solution to this is to simply file the break further in order to reduce the contact area between the gear and the brake. However, we did not have access to the necessary tools in the lab to do this.

4. Costs

4.1 Parts

Figure 4.1 Parts Costs

Part	Manufacturer	Retail Cost ($)	Bulk Purchase Cost ($)	Actual Cost ($) (Shipping Included)
Mini CIM DC Motor (x2)	VEX Robotics	29.99	29.99	71.46
72T Aluminium Spur Gear (x2)	VEX Robotics	29.99	29.99	71.46
11T Steel Spur Gear (x2)	VEX Robotics	9.99	9.99	31.46
Continental 3 Cart	Caddymatic	84.99	84.99	84.99
1x8 Wooden Plank (8 ft)	Do It Best	7.99	5.92	7.99
IR Seeker V3	Modern Robotics	34.99	N/A	42.98
SLA Battery (w/ Charger)	Interstate Battery	134.99	N/A	134.99
Circuit Components	Various	24.11	12.05	32.10
Printed Circuit Board	PCBWay	5.00	0.69	5.00
Total		**362.04**	**173.62**	**482.43**

4.2 Labor

Over the course of the 16 week semester, we averaged about 12 hours per week each developing this cart. We estimate that we would need another 10 weeks to have a finished product. Our hourly labor costs are estimated to be $43 / hour / partner based on salary data of recent Computer Engineering graduates from UIUC.

$43 / Hour * 12 Hours / Week * 2 partners * 26 Weeks * 2.5 = $67,080

5. Conclusion

5.1 Accomplishments

Although the final product of the first iteration of design did not meet many of the stated requirements there were successful aspects of the project.

The root point of failure of the project was the inability to control the speed of the motors with high enough precision to drive the cart at a comfortable pace. Nonetheless the system was able to receive input from the sensor and adjust the motor speed depending on the values. The user interface was also implemented such that a user was able to toggle the system between the run/pause states.

The power source for the system was also a success and will move into the next design iteration without any adjustments. Likewise, the control module will move forward into the next iteration as it indeed provided the intended functionally.

5.2 Ethical considerations

Potential hazards and overall safety are a concern in our design process as this is noted in the IEEE Code of Ethics, #1: "to hold paramount the safety, health, and welfare of the public" [16]. As designers, we must ensure that this code is upheld by minimizing potential hazards associated with our device and informing end users of these hazards. We will include safety literature outlining potential hazards with our device should it ever be distributed.

There are a few potential safety hazards with our device. The most notable is a runaway pushcart, which could potentially run into a person if some sort failure arises in the control module. This is mitigated by handling error cases very carefully in our software and having a kill switch on the cart. The speed of the device is also limited to a brisk walking pace (5 mph) so that in the case of a collision, damage is minimal.

Other potential hazards are a result of our device being a prototype and not a finished product ready for distribution. These include sharp edges, exposed wiring and lack of waterproofing that could cause cuts, electric shocks, or the entire device to fail. In the event that we distribute this product, these would be addressed by adequately in a final product by properly securing and covering all wires and connections from both rain and from user contact as well as filing and sanding all sharp edges. Another safety concern is electrical failure due to moisture, since golf courses can often be wet in the morning or during rainy weather. We would also need to cover the motors adequately to protect from both rain and small puddles. Our device will not be waterproof in cases of submersion, but will be able to operate in rainy weather or a fairly wet course.

The other ethics concern with our device is to adhere to the IEEE Code of Ethics #3, "to be honest and realistic in stating claims or estimates based on available data" [16] by being realistic about the capabilities of our device. Overselling the device or embellishing features it would not align with this code and can be tempting to do at times, as this is seen in many consumer product descriptions. Even in a regulated market such pharmaceutical sales, more than half of evaluated products make misleading claims [17].

5.3 Future work

A future iteration of this project will require many design changes to improve upon the current state of the design. The primary issue that will need to be addressed is the drive system. The gearing ratio of the wheels must be increased in order to provide a larger range of duty cycles which provide useful output. Additionally, the motors must be replaced with motors that are rated for higher torque and have a lower natural operating frequency. This will provide the cart with a considerable lower minimum speed. The speed controller also must be upgraded to contain more resilient components that are less prone to thermal damage and can handle higher switching frequencies.

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Appendix A Requirement and Verification Table

Requirement No.	Requirement	Verification	Status (Y/N)
1	The system shall provide reliable 12V, 5V and 3.3V power.	Ensure all voltage sources are within 10% of expected rating • Determine by measuring output voltage of converter with a voltmeter	Y
2	Gears must allow motors to drive cart at maximum speed of 5 mph	Test that cart can reach a speed of at least 5 mph (2.32 m/s) • Walk 1 meter from cart and walk at a brisk pace • Time how long it takes the cart to travel 5 meters after it reaches steady speed • Verify that this time is under 2.24 seconds	Y
3	Current draw cannot be allowed to exceed 80% of rated MOSFET tolerance	MOSFETs are rated at 80 A, maximum current draw is 15 A, far lower than 80 amps. See battery verification for more info.	Y
4	LED can be seen from a distance of 10 meters	Turn LED on in lab with lab equipment, walk 10 meters away, and ensure that LED is visible	Y
5	Button functions properly	Test button contacts using a digital multimeter in continuity mode. Verify the expected behavior in operational mode.	Y
6	Button must turn the system on when the system is off	Ensure that the the system turns on when the button is pressed while in the off state	N
7	Ultrasonic transmitter/receiver must be able to detect objects within 2.5m in front of the receiver	Test the output of each transmitter/receiver to ensure that it signals a large change whenever an object is placed within 2.5 meters of the front of the receiver	N
8	Distance data shall have a granularity of 5cm or better	Using serial output measure object at 5cm intervals within the full range of ultrasonic detection	Y

9	IR receiver can detect transmitter within 2.5 meters of the cart within 150 degree field of view relative to the front of the cart	Test the edges of the cone shape these requirements create and ensure the distance is within +/- 10% of the true distance and the angle is within the 2.57 degrees of the true angle, as discussed in our tolerance analysis. This can be done with a simple Arduino program or with our debugger	N
10	The cart shall transition to the pause state when the user is more than 2.5 m away	The cart will not transition from the PAUSE state to the RUN state unless the user location is known The cart will transition from the RUN state to the PAUSE state whenever user location becomes unknown	N
11	The cart shall stop in less than 2.5 meters	The cart shall stop in less than 2.5 meters from a full speed. Run cart at full speed, cut power to motors and test how far it takes to stop.	Y
12	ARM chip can properly send PWM gate signals to the MOSFET	Use test program to show 0 - 100% duty cycle square waves on oscilloscope from gate pin	Y
13	The cart shall follow .5-2 meters behind the user	Put the cart in the run state, walk around, and ensure that the cart does not violate this distance requirement	N
14	The cart shall last an entire round of golf	Our battery is rated at 35 amp hours at 12v. Because we run our motors at a maximum of 50% duty cycle, their max current draw will be 7.5a each. We assume that the golfer will be walking for 2 hours or less during the 4 hour round, so we multiply 7.5 by 2 motors and 2 hours and we get 30 Ah as our theoretical maximum power draw, less than the battery's rated storage.	Y

Appendix B Required Motor Power Derivation

We can roughly calculate necessary motor power based on the weight of the cart and the time in which we want to reach maximum speed. Because we want to maintain a maximum follow-behind distance of 2.5 meters (defined by IR sensor) so that the cart does not lose track of the golfer. To give us a bit of an extra buffer, we would like our motors to be able to accelerate the cart quickly enough to maintain a maximum follow-behind distance of 2 meters. If we assume an initial distance of 1 meter between the golfer and the cart, this means that the cart must accelerate fast enough to allow a maximum additional gap of 1 meter to form when the golfer starts walking. Assuming linear acceleration (not true, but close enough for small times), negligible friction and rolling resistance, and near immediate acceleration of the golfer to a very brisk 5 mph (far above the ideal pace, but we must prepare for edge cases), we derive the following equations for the distance gap:

$$d_{golfer} = 2.23 * t \quad \text{(Equation B.1)}$$

$$d_{cart} = 1 * a * t^2 \text{ [18]} \quad \text{(Equation B.2)}$$

$$\text{Distance gap} = d_{golfer} - d_{cart} = 2.23 * t - .5 * a * t^2 \quad \text{(Equation B.3)}$$

Since we assumed constant acceleration, we know that the gap will be largest when the cart reaches the same speed as the golfer, and that the cart will have traveled at an average velocity equal to half that of the golfer (also evident in the $½ * a * t^2$ term in Equations B.2 and B.3). This is described by the following equation, where t is the time it takes the cart to reach the speed of the golfer (2.23 m/s):

$$\text{Maximum gap} = .5 * t * 2.23 + d_i \quad \text{(Equation B.4)}$$

$$1 = .5 * t * 2.23$$
$$t = .897 \text{ seconds}$$

Assuming the cart will have a maximum estimated mass of about 35 kg (highly dependent on the mass of the golf bag, which will vary) , we can then calculate the required power rating for the two motors combined:

$$\text{Kinetic Energy} = .5 * m * v^2 = .5 * 35 * 2.23^2 = 87.02 \text{ Joules} \quad \text{(Equation B.5)}$$

$$\text{Power} = KE/s = 87.02 / .897 = 97.0 \text{ watts} = 48.5 \text{ watts per motor} \quad \text{(Equation B.6)}$$