March 16, 2015

Dr. Andrew Rawicz
School of Engineering Science
Simon Fraser University
Burnaby, BC V5A 1S6

Re: ENSC 440W Design Specification for the Cart-Follow-X1 Capstone Project

Dear Dr. Rawicz,

The enclosed document is the design specification for our product Cart-Follow-X1 from TechAuto Inc. Our design goal is to provide our customers with the most convenient experience in cargo carrying. By designing an automated control system and integrating it with the mechanical system, our product will provide the option to make the process of carrying cargo effortless and hands free.

The design specification document provides an overview of the mechanical, hardware and software designs that will be implemented to meet the initial requirements of the Cart-Follow-X1. This document will also provide an explanation of our design process, system specifications, and procedures used to design the product. Finally, this document will also include a test plan to ensure the correct functionality of the Cart-Follow-X1.

TechAuto Inc. was founded by five senior computer and electronics engineering students from Simon Fraser University. The members include Evan Chen, Jeffrey Wang, Samin Semsarilar, Tom Weng, and James Zeng. If there are any questions or concerns, feel free to contact us at jawang@sfu.ca.

Sincerely,

Jeffrey Wang
Chief Operating Officer
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TECHAUTO

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ABSTRACT

This document will discuss the design specification for the Cart-Follow-X1 system, including the specifications for all mechanical and controlling components. The main objective of this document is to explain our design approach, and describe in detail our current and future implementation of the product.

Cart-Follow-X1 consists of two main systems:

- Control System - Raspberry Pi algorithms, tracking and collision detection (ultrasonic sensors), and motor control (DC drive)
- Mechanical System - Motor specifications, wheel transmission system, mounting and wiring considerations

The two main systems will each have its own section in this document with detailed description on its design logic, function and implementation. The specifications of each system and components will also demonstrate that all functional requirements are met according to the functional specification.

Finally, this document will conclude with a test plan that includes a set of test cases that will examine the functionality of the system and all its components. The test plan will be separated into two parts, individual component testing, as well as a system integration test plan.

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Glossary

Ah	Amp Hours
PWM	Pulse Width Modulation
RPM	Rotations Per Minute
Python	Programming Language

1 Introduction

The Cart-Follow-X1 is an automated four-wheel cargo carrying platform truck. This cart has the ability to follow it's user automatically as well as the ability to provide electrical motor assistance when operated manually. Our proposed project will address the problem of having to manually carry your belongings wherever you go, and also provide users with a “hands-free” experience. Cart-Follow-X1 is designed to be multi-purpose, so that the cart can be used both indoors and outdoors. Cart-Follow-X1 consists of two main systems. The first system is the control system, which includes three Raspberry Pi development boards, four ultrasonic sensors, and a DC drive. The second system is the mechanical system, which includes two 12V-24V motors, wheel transmission system, and the cart frame. The design specifications for each system, as well for all components used will be thoroughly explained in this document.

1.1 Scope

This document outlines the design of the Cart-Follow-X1, which includes the design approach, design logic, and potential modifications for future development. This document will also discuss the functional requirements that were previously established in the functional specification. Additionally, a test plan with a set of test cases is included for individual component testing as well as system integration to ensure the proper functionality of the overall system.

1.2 Intended Audience

This design specification is intended to be used by all members of TechAuto Inc. Throughout the development of the Cart-Follow-X1, the design team can consult this document as the main guideline for integrating and testing the product. Test engineers can also refer to this document to ensure that all pre-specified functions and design requirements are met.

2 System Overview

The Cart-Follow-X1 has two operating modes, “Follow” and “Assist” mode. In “Follow” mode, the user will be carrying a remote which contains an ultrasonic transmitter. The transmitter will start transmitting ultrasonic pulses once the “Follow” mode has been turned on. On the cart, two receivers are placed on two sides of the front of the cart to receive the ultrasonic pulses. User’ location relative to the cart can then be calculated through the pulse’s travelling time to each of the receiver. With information on the user’s location, the onboard microcontroller can then send out appropriate instructions to the DC motor drive to control the speed of each motor which will in turn, control the speed and steering of the cart. A collision detection system is also integrated to “Follow” mode to ensure safety in operation. A proximity sensor is placed in the lower front of the cart which will cause an emergency stop on the motors if it detects anything beyond the cart’s proximity limit. Figure 1 shows the main concept of “Follow” mode operation.

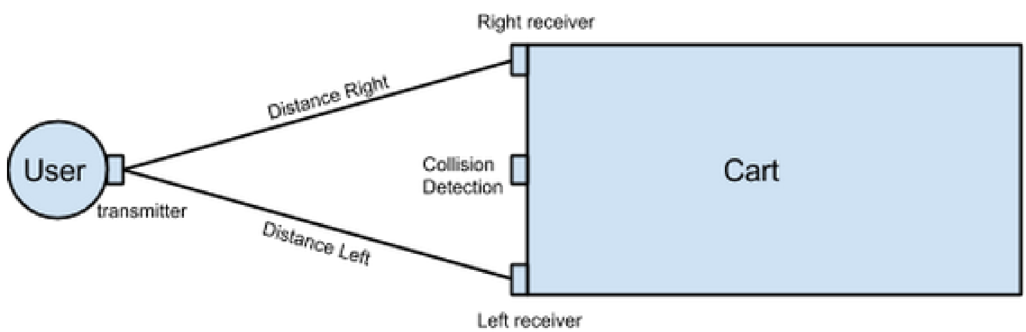

FIGURE 1: Follow Mode Operating Concept

In “Assist” Mode, the user will have full manual control over the cart with electric motor assistance for heavy loads. The electric motors can be controlled through a push button located on the handle of the cart for easy access. Releasing the push button applies full break on both motors which comes in handy if the user requires to stop the cart on ramps.

The prototype of Cart-Follow-X1 is powered by two 12V lead-acid batteries, which is responsible for supplying power to the DC drive, and two electric motors. Figure 2 shows the high level block diagram of the Cart-Follow-X1 system.

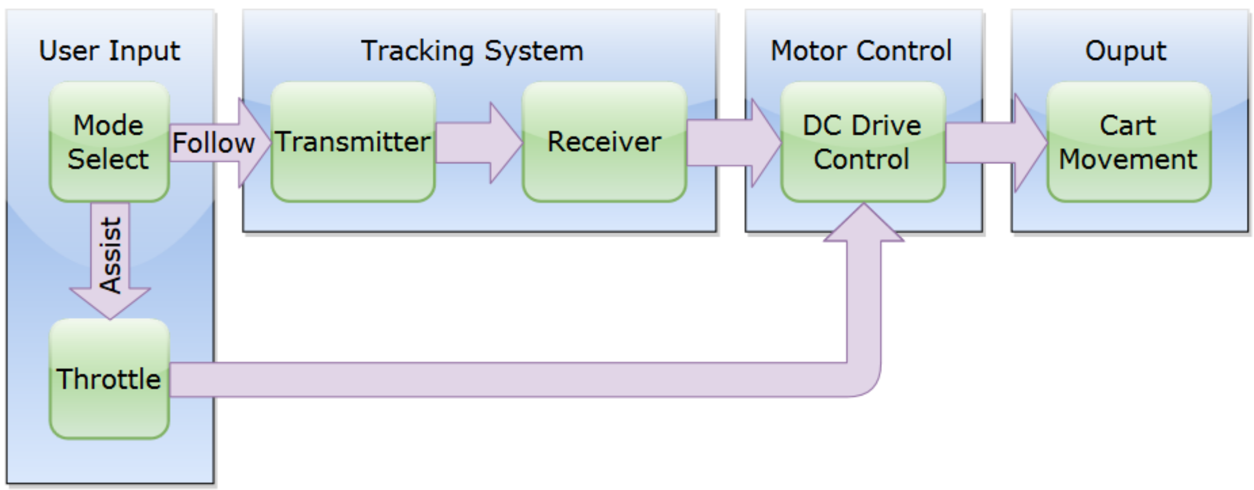

FIGURE 2: High Level Block Diagram of Cart-Follow-X1

The low level design of the Cart-Follow-X1 will be discussed more in-depth in the rest of the document.

3 Control System

The control system of the Cart-Follow-X1 prototype consists of three Raspberry Pi development boards, four ultrasonic sensors, and a DC motor drive. The meet the [R32-ii] requirement, all three development boards will have continuous power supply during the whole operation time to ensure stable operation. The first board is responsible for transmitting ultrasonic pulse to the board on the cart. The other two development boards on the cart will be responsible for distance calculation, and DC motor drive controls. A block diagram of the overall control system is shown in Figure 3.

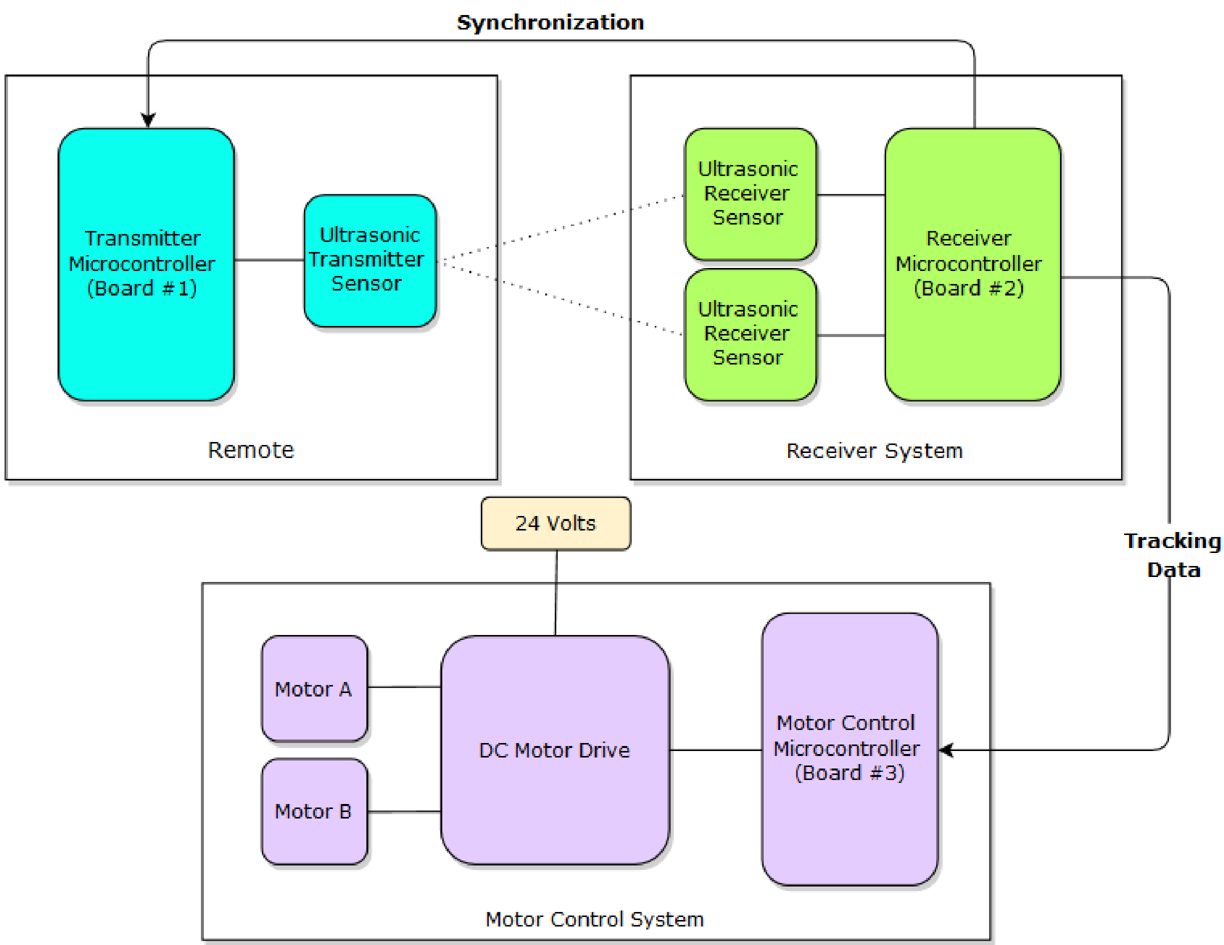

FIGURE 3: Control System Block Diagram

3.1 Component Specifications

3.1.1 Raspberry Pi B+ Development Board

To implement all the functions of Cart-Follow-X1, TechAuto decided to use the Raspberry Pi B+ for its strong computing power required. It`s Linux operating system makes implementation and development more convenient. Figure 4 describes the pin assignment of the Raspberry Pi B+ development board. The GPIO pins are used as the input and output pins for connections to other components.

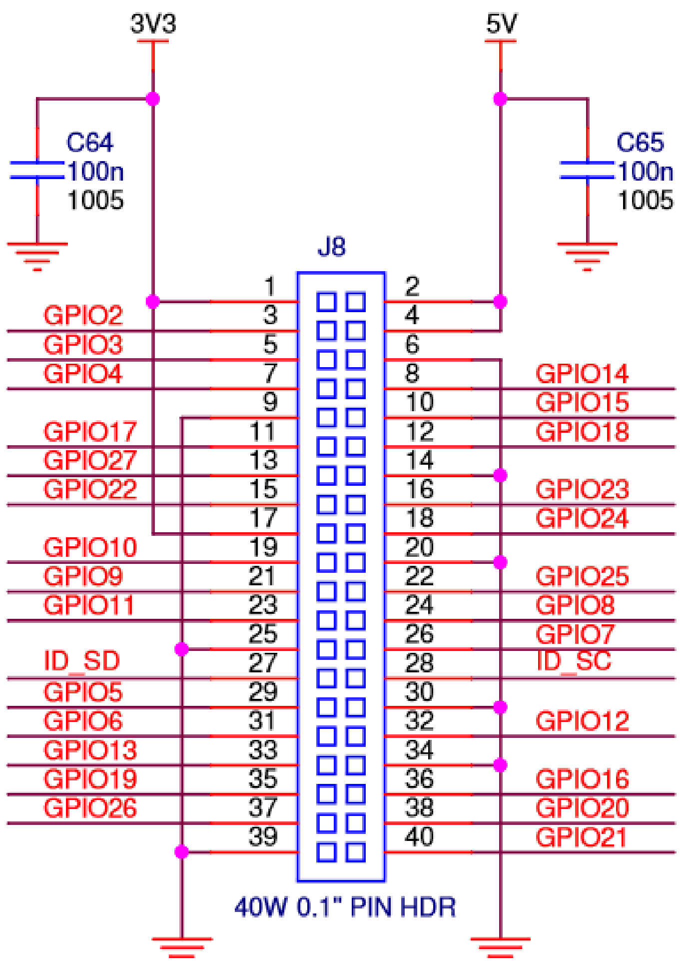

FIGURE 4: Raspberry Pi B+ Pin Assignment [1]

3.1.2 HC-SR04 Ultrasonic Sensors

To meet the functional requirements [R50-i], [R60-i], [R61-i], and [R62-i], regarding the sensor requirements, TechAuto has chosen to use the HC-SR04 ultrasonic sensors. As shown in Table 1, the electric parameters of these sensors will be sufficient to perform the necessary functions that the Cart-Follow-X1 requires.

FIGURE 5: HC-SR04 Ultrasonic Sensor[2]

TABLE 1: Electric Parameters of the HC-SR04 [2]

Working Voltage	DC 5 V
Working Current	15mA
Working Frequency	40Hz
Max Range	4m
Min Range	2cm
MeasuringAngle	15 degree
Trigger Input Signal	10uS TTL pulse
Echo Output Signal	Input TTL lever signal and the range in proportion
Dimension	45*20*15mm

Since the input pin for the Raspberry Pi B+ is rated at 3.3V [3], we used a voltage divider to convert the 5V output from the ultrasonic sensor to a workable 3.3V (Figure 6).

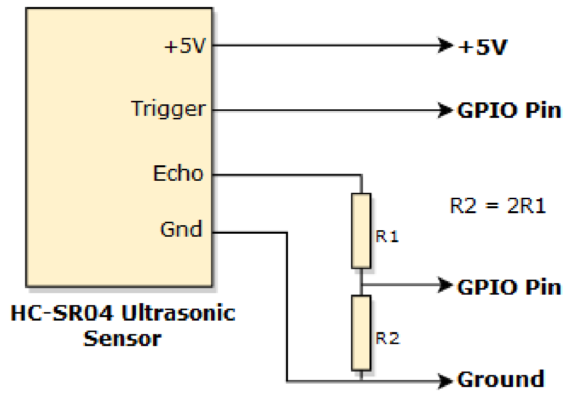

FIGURE 6: Voltage Divider Applied to the Sensor

Figure 7 shows the operation timing diagram of the HC-SR04 ultrasonic sensors.

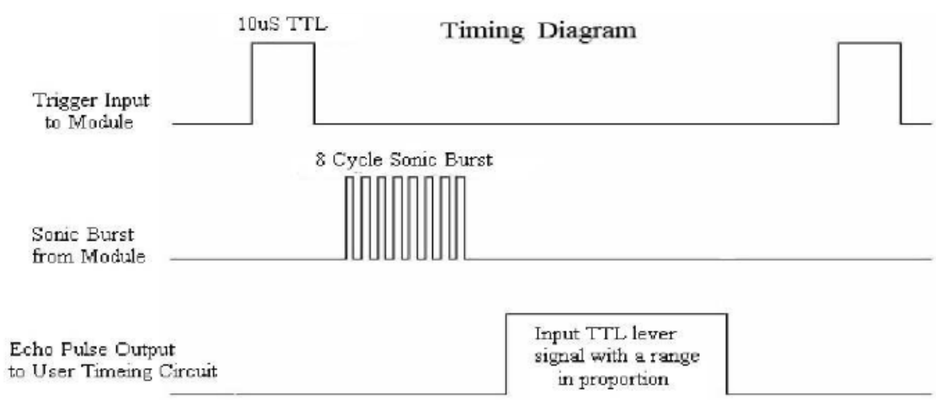

FIGURE 7: HC-SR04 Operation Timing [2]

For the purposes of distance tracking, the ultrasonic sensors can be used in the following way. First, the Trigger pin of the sensor receives a 10 us pulse. Then an 8 cycle sonic burst is emitted from the transmitter of the sensor. Once the burst is sent, the Echo pin goes to high. The code timestamps the moment before Echo goes high, signifying the very moment that the ultrasonic pulse is sent from the transmitter. Echo goes to low once the receiver on the HC-SR04 picks up the ultrasonic pulse after it has bounced off of something and back. Another timestamp is placed when Echo goes to low. Subtracting the end time and the start time gives the amount of time that Echo was high, or the pulse duration. This value is divided by 2 to remove the bounce back distance, and then multiplied by the speed of sound (343 m/s) which converts the time into a distance.

3.1.3 Sabertooth Dual 12A 6V-24V Regenerative Motor Driver

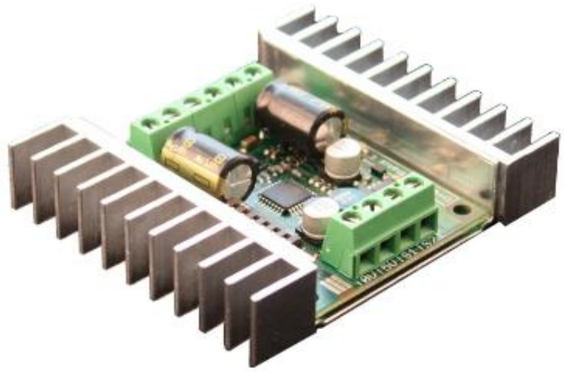

FIGURE 8: Sabertooth Dual 12A 6V-24V Regenerative Motor Driver [4]

The two motors on the Cart-Follow-X1 is controlled using the Sabertooth Dual 12A DC motor drive. Each motor is being controlled from S1 and S2 input respectively. To reverse the motor, S1 and S2 inputs are set to below 2.5V with 0V at highest reverse RPM. Similarly, for forward motor operation, S1 and S2 inputs are set to above 2.5V with 5V at highest forward RPM [4].

3.2 Mode Selection

The cart's operation mode can be selected through a selection switch. Selecting "Assist" mode will grant user full control over motor operation and therefore bypassing the whole tracking system. Selecting "Follow" mode gives the tracking system full control over motor operation.

3.3 User Tracking System

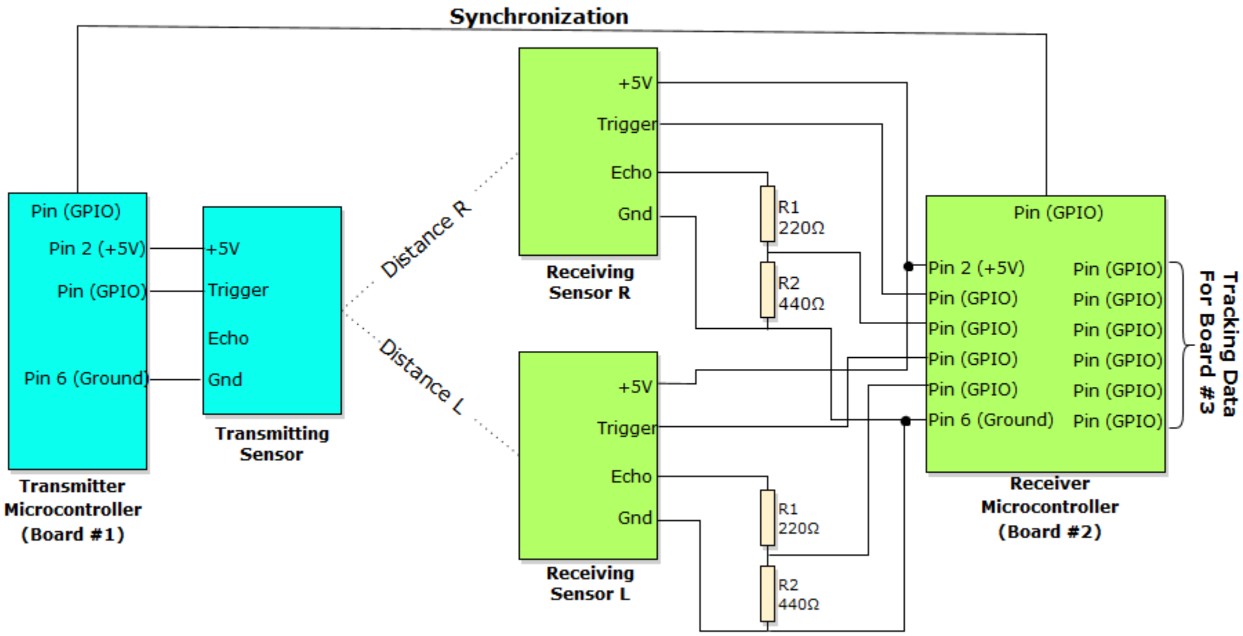

FIGURE 9: Tracking System Block Diagram

Our tracking system utilizes three ultrasonic sensors to collect information on user's position. Board #1 will be used to trigger one of the ultrasonic sensor to send out ultrasonic pulses and Board #2 will be used to calculate the distance between the transmitter and board#2 which is used for 2 receivers. Distance measurements between the transmitter and 2 receivers locates the user's position relative to the cart. based on that information, Board #3 will send instructions to the DC drive to control the two DC motors to follow the user.

3.3.1 Transmitter

The transmitter's task is to transmit a synchronized ultrasonic pulse to the receiver. The pulse can be sent by sending a trigger signal through the Trigger pin on the ultrasonic sensor through Board #1. By sending an ultrasonic pulse along with a synchronization signal, the receiver will have the information on the exact time that the transmission happened. With that information, the receiver will be able to calculate the travelling time of the pulse signal. The synchronization was done with a single wired connection between Board #1 and Board #2 (Figure 10).

When the synchronization pin is set to high by the receiver, the transmitter will send a pulse.

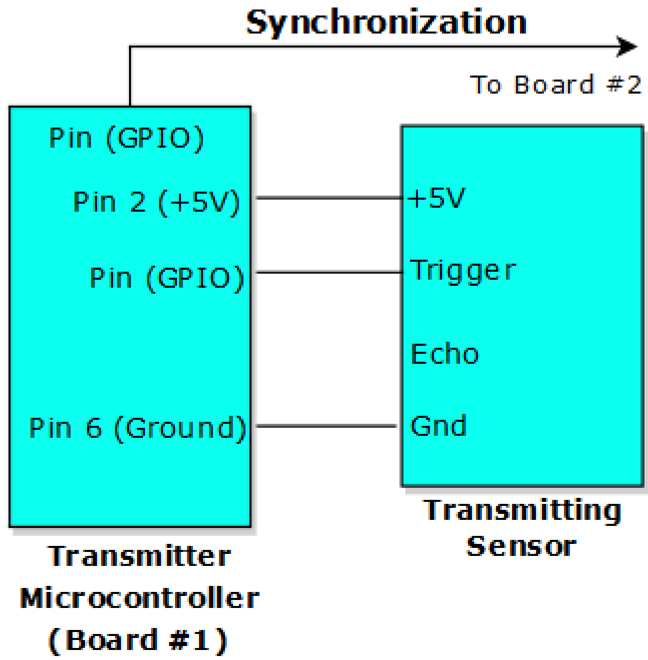

FIGURE 10: Synchronization Between Board #1 and Board #2

3.3.2 Receiver

The Receiver utilizes two ultrasonic sensors through Board #2 (Figure 11).

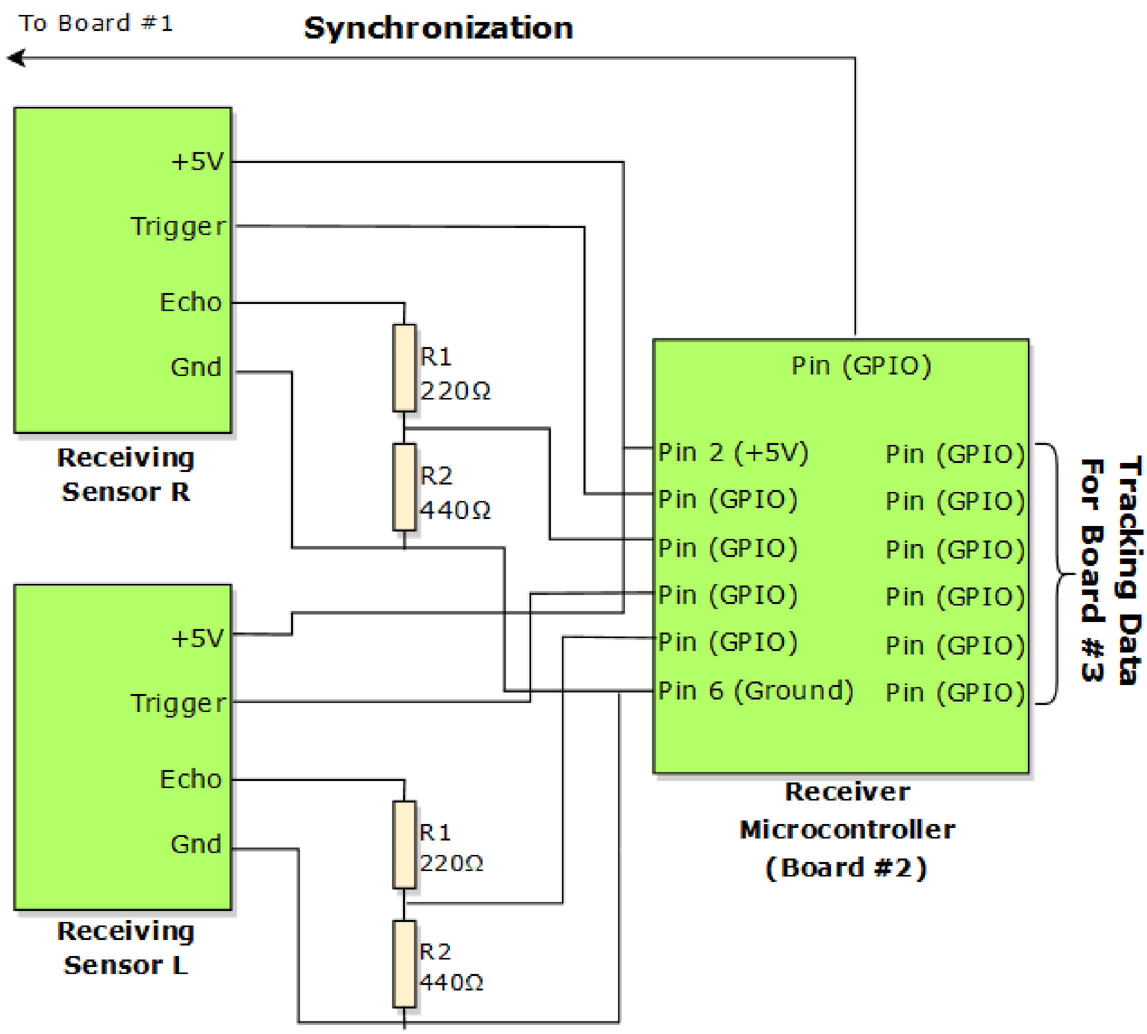

FIGURE 11: Receiving Sensors and Microcontroller

To receive the pulse sent from the transmitter, the receiving sensors need to be triggered at the same time as the transmitting sensor on the transmitter. This is achieved by setting the synchronization pin to high at the time of trigger and setting it back to low after the trigger. In order to ensure that the receivers only receives pulses from the transmitter and not its own, the transmitter component of the sensor has been taken out (Figure 12).

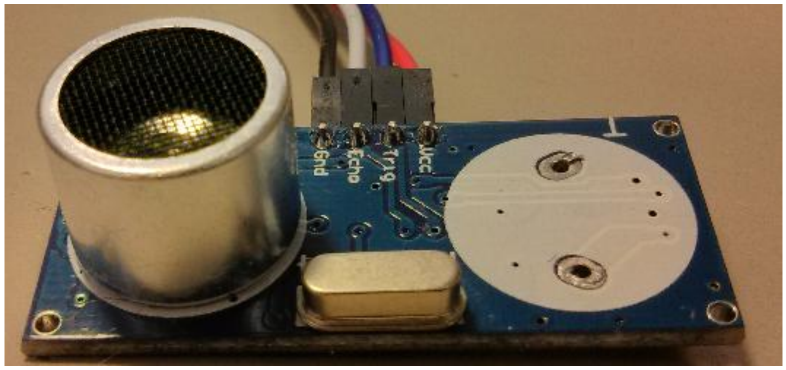

FIGURE 12: Receiver Sensors

The original algorithm for distance calculation needs to be multiplied by 2 because the ultrasonic pulse received was sent directly from the transmitter and has therefore traveled only half the distance compare to its original application. To obtain more accurate and consistent result, all measurements are taken as the average of every 5 readings. The following is an example code for pulse detection for the left receiving sensor:

```
start==1
counter==0
while start==1:
      for x in range(0,5): ##runs 5 times to take average value
            time.sleep(0.001)
            Sync == 1 ##Send the synchronization signal
            GPIO.output(TRIG_R, False)
            GPIO.output(TRIG_R, True)
            time.sleep(0.00001)
            GPIO.output(TRIG_R, False)
      ##Triggers the Left Sensor

            while GPIO.input(ECHO_R)==0:
                  pulse_start_R = time.time()
                  ##Timestamps when transmitter transmits the pulse
                  counter = counter+1
                  if counter > 1000 :
                        counter = 0
                        break
                  ## Anti-freeze algorithm, this statement will break
            out of the loop if the sensor fails to receive the
            Trigger signal

            while GPIO.input(ECHO_R)==1:
                  pulse_end_R = time.time()
                  ##Timestamps when receiver receives the pulse
```

The following is the algorithm to calculate sensor distance:

```
distance_R = round(pulse_duration_R * 17150*2, 2)
distance_L = round(pulse_duration_L * 17150*2, 2)
##Distance calculation for both left and right sensors.
 Multiplied by two because the pulse only traveled one
 way instead of two
```

3.4 Motor Control System

Distance information transmitted from Board #2 to Board #3 is used to determine the proper motor instruction. Board #3 will convert these instructions into duty cycle values which will be passed through the PWM to analog filter to generate analog signals which is required by the DC motor drive. The block diagram of the motor control is shown in Figure 13.

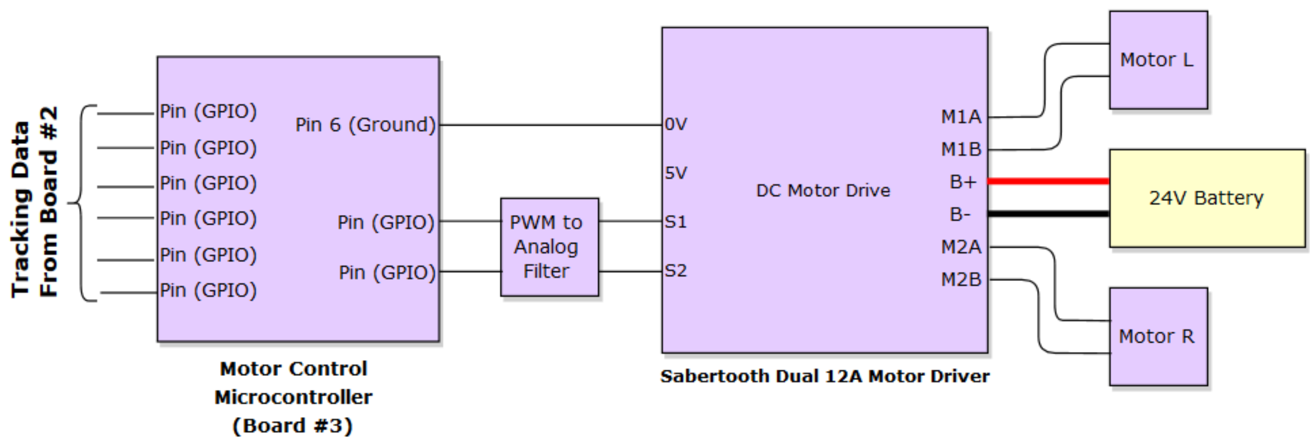

FIGURE 13: Motor Control System Block Diagram

3.4.1 Speed Control

The DC motor drive control input S1 and S2 requires analog voltage signal from 0V to 5V to control the motor, therefore a PWM to analog filter is required. A RC circuit is recommended by the DC motor drive's user manual [5] for the filter (Figure 14). Through this filter, input voltage of S1 and S2 can be changed by varying the PWM signal's duty cycle and therefore varying the motor's RPM [5].

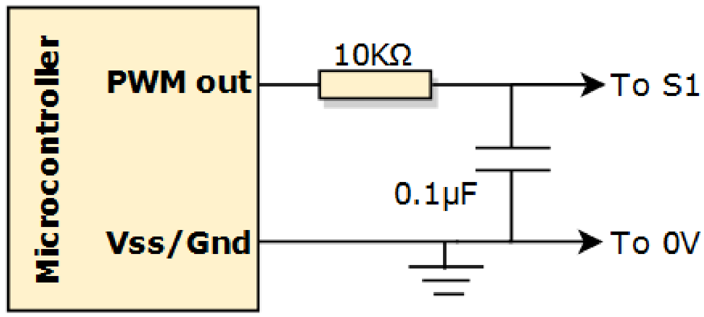

FIGURE 14: PWM RC Low Pass Filter

3.4.2 Steering Control

The Cart-Follow-X1 uses motor speed differential as steering method. The cart will be steered by varying the turning speed of the two wheels. When the RPM of the left wheel is greater than the right wheel, the cart turns right. Similarly, if the RPM of right wheel is greater, the cart turns left. Using the user location information sent from Board #2, the duty cycle of the PWM signal to each motor control can be varied accordingly to steer the cart to follow its user.

3.4.3 Assist Mode Motor Control

The onboard throttle control for assist mode is connected directly to Board #3. The throttle push button is only functional in assist mode. Board #3 will instruct the cart to move forward if throttle button is pushed and will apply motor break otherwise.

3.5 Collision Detection System

The Cart-Follow-X1 has a collision detection sensor placed in the lower front of the cart. Whenever an object falls between the cart and the user, an emergency stop on the motors will be activated. The response time of the collision detection system is programmed to ensure that the Cart-Follow-X1 meets the [R62-i] requirement.

4 Mechanical System

The mechanical system grants Cart-Follow-X1 the ability to move by motor power. This section of the document will outline the design of the mechanical system. The specifications of the mechanical components, transmission system, and design in mounting and wiring will be discussed.

4.1 Component Specifications

4.1.1 M27-150-P Motors

Cart-Follow-X1 uses two 24V, 150W rated Electric DC motor for movement. Motor's performance chart can be seen in Figure X

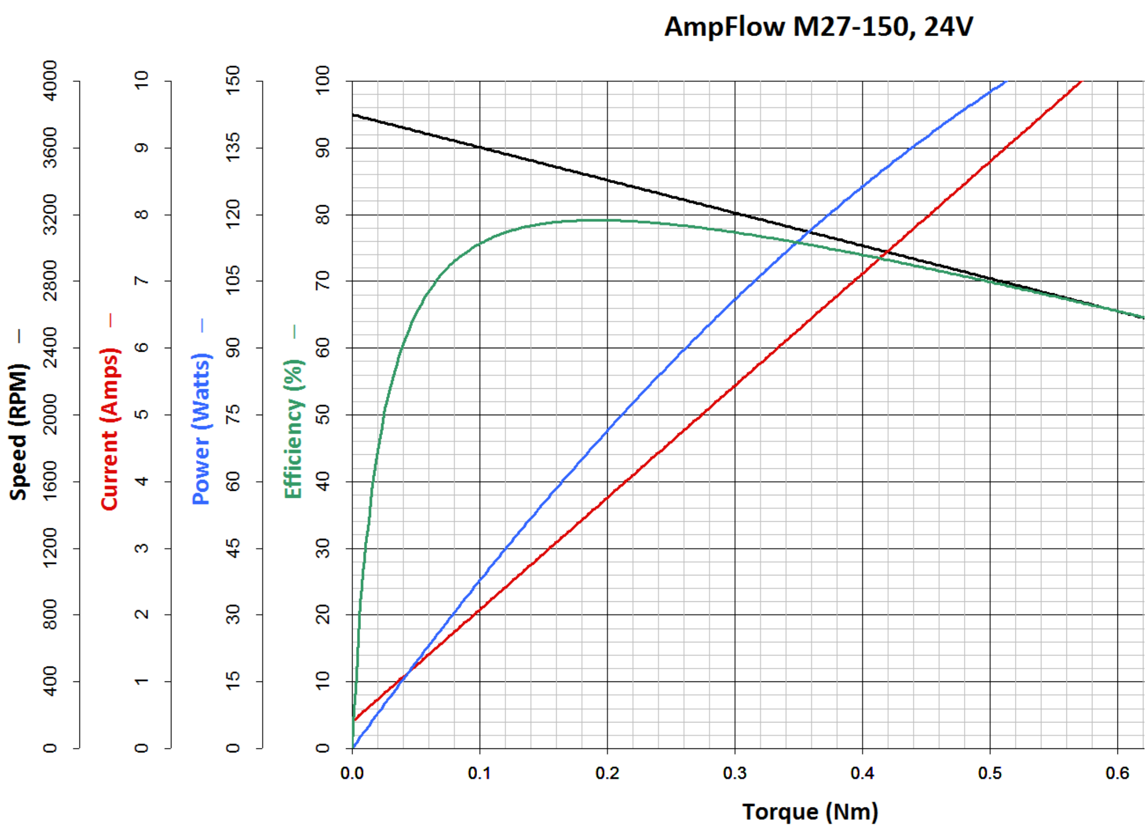

FIGURE 15: Performance Chart of the M27-150-P Motor [5]

To meet requirement [R23-iii], the motor shall not exceed 50% of its maximum power output during normal operation, therefore limiting its maximum continuous current draw to a combined 10 Amps.

4.1.2 IT5-12 INFINITY Battery

According to [R54-ii], the Cart-Follow-X1 uses two 12V, 5Ah lead-acid batteries to power our system. The two batteries are connected in series to provide 24V power required by the motors.

FIGURE 16: Rechargeable Sealed Lead Acid (VRLA) Battery [6]

The battery requires a continuous current with a minimum voltage of 14.40 V for recharge. Figure 17 shows the recharge voltage specification.

Cyclic Application Recharge Voltage (77°F / 25°C)			
Minimum	**Recommended**	Maximum	
14.40	14.55	14.70	Volts D.C.
2.40	2.425	2.45	Per Cell
Temperature Coefficient: -2.8mV / °F / Cell (- 5mV / °C / Cell)			
Standby Application Recharge Voltage (77°F / 25°C)			
Minimum	**Recommended**	Maximum	
13.50	13.65	13.80	Volts D.C.
2.25	2.275	2.30	Per Cell
Temperature Coefficient: -1.7mV / °F / Cell (- 3mV / °C / Cell)			

FIGURE 17: Battery Charging Specification [6]

4.1.3 Cart Frame

The Cart frame of the prototype is based off Steel-Tough™ 400 3 in 1 Engineered Nylon Hand Truck [7] (Figure 18).

FIGURE 18: Original Cart

4.2 Transmission System

Cart-Follow-X1 uses a V-Belt Pulley system as its transmission system (Figure 19).

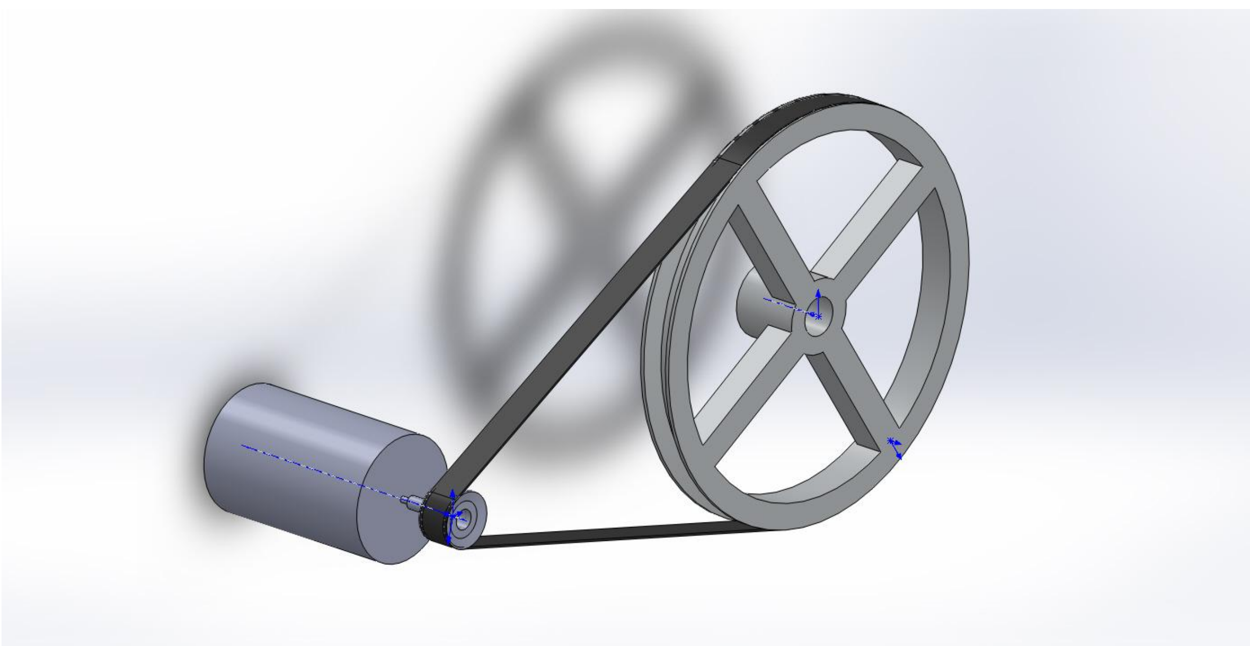

FIGURE 19: V-Belt Pulley System

The transmission ratio of this system is 1:5, which reduces speed and increases torque of the cart. The system is mounted on the cart as in Figure 20.

FIGURE 20: Actual Mounting of the Transmission System

4.3 Mounting & Wiring

All the components will be mounted onto the cart as required by [R37-ii]. The bottom of the cart is covered with wooden board with holes for zip ties and wiring. Mounting Layout are shown in Figure 21 and Figure 22.

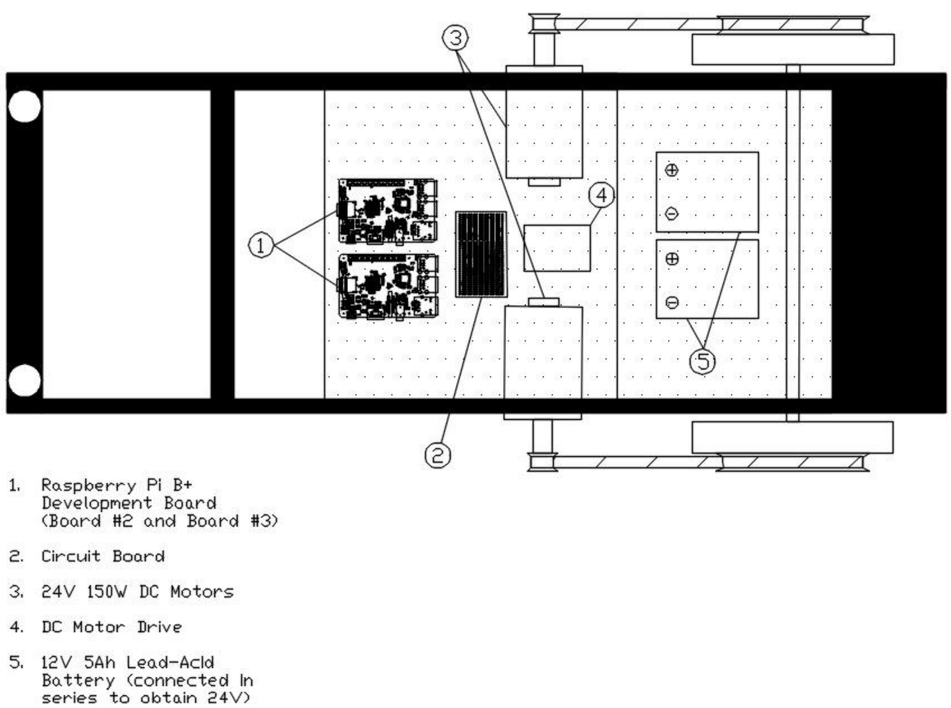

FIGURE 21: Top View of the Mounted Cart

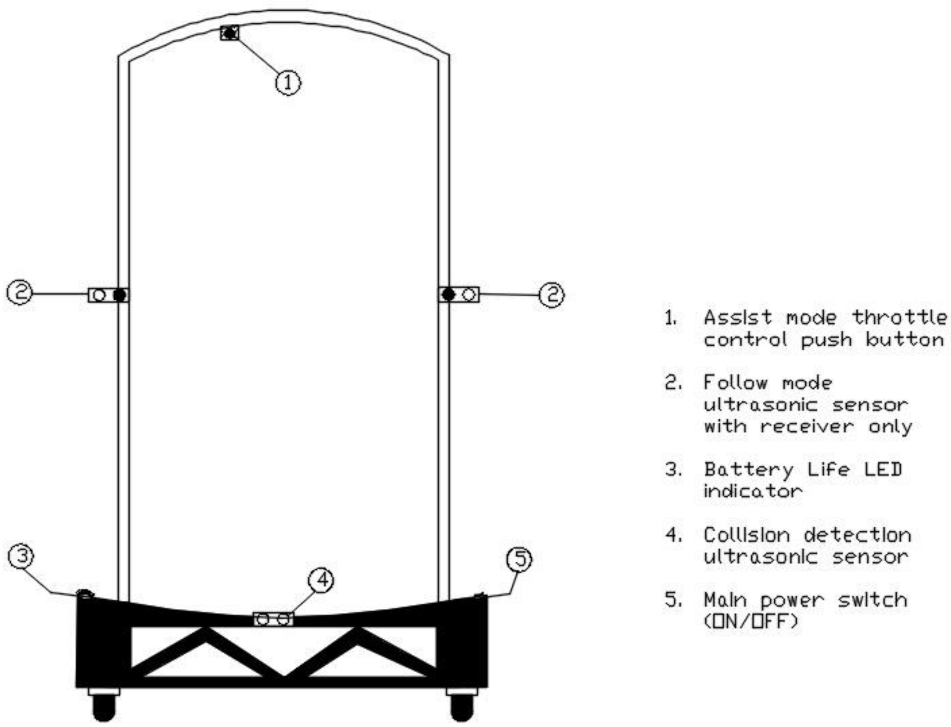

FIGURE 22: Front View of the Mounted Cart

5 USER INTERFACE

The user interface of our system is designed to give the user sufficient control of the Cart-Follow-X1. By utilizing switches and push buttons, the user will have control over operation of the cart. [R11-i] and [R63-i].

To summarize, user interface contains the following components:

- LED battery indicator: indicate battery status [R11-i]
- System Power Switch: Main power switch that turns on and off the whole system [R7-i]
- Mode selection Switch: Selects between "Follow" and "Assist" mode [R10-i]
- Assist Mode Throttle Control : Applies motor power in "Assist" mode [R8-i]

6 Test Plan

The following test plan is created to ensure that our final product meets the requirements of our function specifications. We are going to test our product with various type of testing. Tests will be divided into different stages. First, we will conduct tests on each of our individual components. Afterwards, we will perform post-integration testing on the final prototype.

6.1 Component Testing

6.1.1 Ultrasonic Sensors

Ultrasonic Sensors Testing Item #1: Accuracy and detection range

Testing Method: Move an object in front of the sensor between the range of 2m to 4m.

Expecting Outcome: As required by [R56-i] and [R57-i], the sensor should have a reading between 2m to 4m with an error within the range of +/- 5cm.

Ultrasonic Sensors Testing Item #2: Interference between sensors

Testing Method: Put two sensors besides each other and place an object far from one of the sensors and another object close to the other sensor.

Expecting Outcome: Both sensors should give correct readings. And according to[R58-i], the ultrasonic waves from the sensors should not interfere with one and another.

6.1.2 Motor

Motor Testing Item #1: Motor power

Testing Method: Apply a load weighing 150kg on the cart and attempt to move at a constant speed

Expecting Outcome: As required by [R41-ii], the cart should manage to move at a constant speed of 4km/h with 150kg of weight on it.

Motor Testing Item #2: Breaking

Testing Method: Run the cart with 150kg load at full speed and suddenly shut off the power to the motors.

Expecting Outcome: As required by [R40-ii], the cart should come to a complete halt within 1 second.

6.1.3 Battery

Battery Testing Item #1: Battery life

Testing Method: Hook up the fully charged batteries to our final integrated circuit and let the system run.
Expecting Outcome: As required by [R19-ii], [R23-iii], the system should run for 5 hours without the need of external power.

Battery Testing Item #2: Charging Speed and Functionality

Testing Method: Hook up the fully drained batteries to a power source and apply a charging voltage of 13.65V and a charging current of 2.275A.
Expecting Outcome: As required by [R6-ii], [R17-i], [R20-ii] the battery will be fully charged within 5 hours

6.1.4 Raspberry Pi Board

Raspberry Pi Testing Item: Functionality

Testing Method: Run a sample code on the board and connect a multimeter to the analog pins in order to measure the pin values.
Expecting Outcome: The code should be able to run correctly. The voltage measured from the GPIO output pins should be between 0V and 3.3V.

6.1.5 Motor Control

Motor Controller Testing Item: Functionality

Testing Method: Connect the controller with the Raspberry Pi and the motors. Then run code which will perform motor control by setting and changing duty cycles
Expecting Outcome: The motor speed will change according to the instructions of the code

6.1.6 Switches

Switches Testing Item: Functionality

Testing Method: Connect switches between the battery and the motors for safety and testing purposes.
Expecting Outcome: The motor should not be turning when the switch is off and should be turning if the switch is on.

6.2 Integration System Testing

6.2.1 Tracking System

Tracking System Testing Item: Functionality in a straight line

Testing Method: Place the module at one point and carry the remote away from the point, making sure that the receiving sensors on the module maintain line of sight of the transmitting sensor on the remote when moving in a straight line.

Expecting Outcome: As required by [R61-i] and [R41-ii] The cart should stop if the remote is too close (50cm), the cart should move faster if the sensor is further away (150cm) and at steady speed (4km/hr) otherwise. As required by [R60-i], the cart should be able to track the user at a maximum distance of 4m.

Tracking System Testing Item: Functionality when turning

Testing Method: Place the module at one point and carry the remote away from the point, turning the remote away from the receiving sensors enough to create a large enough difference between the distance from the left and right sensors to the remote.

Expecting Outcome: The tracking system recognizes that the user carrying the remote is turning either left or right. The motor on the right should turn faster than the motor on the left if the user is turning left. The motor on the left should turn faster than the motor on the right is the user is turning right

6.2.2 Collision Detection System

Collision Detection System Testing Item: Functioning

Testing Method: While the module is moving normally, place an object that blocks the line of sight from the remote and the receivers.

Expecting Outcome: As required by [R9-i] and [R40-ii], the cart should come to a complete halt within 1 second.

6.2.3 Mode Switching

Mode Switching Testing Item: Functionality

Testing Method: Change the cart function mode from Follow Mode to Assist Mode and vice versa by pressing the Mode Switch Push Button

Expecting Outcome: When the Mode Switch Push Button is pressed, the cart changes modes.

6.2.4 Assist Mode

Assist mode Testing Item: Functionality

Testing Method: While in assist mode, the user pushes the throttle button on the handle of the cart

Expecting Outcome: The cart will move forward at the user's walking speed while the throttle button is being held down

7 Conclusion

This document has specified all the details of the design specification, design logic and technical details of the Cart-Follow-X1. The corresponding functional specifications for each system has also been discussed throughout the document. We have also provided a list of test plans for quality assurance purposes. This document will be used as a guideline to approach our final product. We are confident about the completion of our final product at early April-2015.

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