ECE445

Spring 2023 Senior Design Laboratory

Design Document

Personal Carrier Robot

Team No. 36

Okan Kocabalkanli
(okan2@illinois.edu)

Jirawatchara Tanthiptham
(jt20@illinois.edu)

Deniz Caglar
(dcaglar2@illinois.edu)

TA: Raman Singh
Professor: Viktor Gruev

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Abstract

This document is intended to provide a more detailed overview of the Personal Carrier Robot project compared to our proposal and request for approval (RFA). Provided within this document are the relevant high-level implementation details, requirements and safety considerations.

Contents

1 Introduction

1.1 Problem

The ability to carry objects is one that provides a great degree of convenience in our lives and is even crucial in many activities designed around their use. However, many experience difficulty or are entirely unable to carry items by themselves as a result of factors such as age, obesity, illness or injuries. Within the United States alone, studies estimate 1.6 million individuals living with limb loss as of 2005 with the number projected to double to 3.6 million individuals by 2050 [1]. This project aims to return the ability to live independently for such individuals by returning their ability to carry items for long distances such as while shopping or commuting.

1.2 Proposed Solution

Our solution is to create a path-finding robot that will follow the individual. A static mounted camera will be used to estimate the distance and bearing of the person of interest by tracking an article of clothing printed with QR code via OpenCV. Combining the obstacle and goal direction data, we will employ a path-finding/SLAM algorithm to direct and move the robot through terrain via a grid map as depicted in figure 1. The overall structure of the robot is depicted below in figures 2 and 3.

As an extension, we also plan to implement obstacle avoidance and non-line-of-sight pathfinding to the robot. We intend to achieve obstacle detection through a 360 degree lidar subsystem and avoidance through the usage of this data in the pathfinding map depicted in figure 1. In the event that the QR code is not visible, the robot will plot a path using the person of interests' phone's accelerometer and gyroscope sent via bluetooth. These extensions are covered in further detail in the addendum of this document.

1.3 Visual Aid

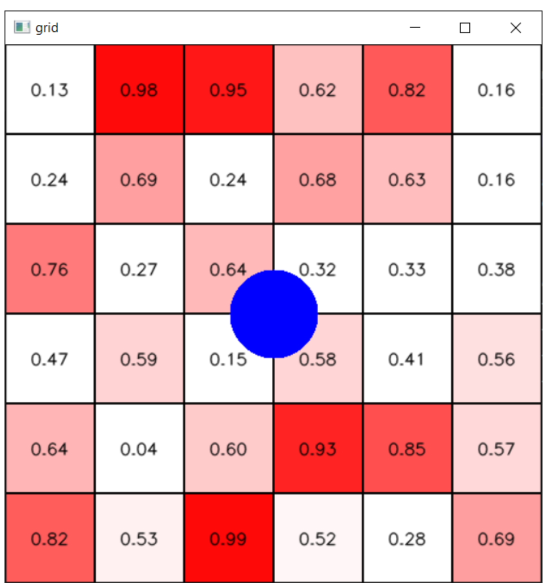


Figure 1: Sample OpenCV visualization of grid roadmap

[1] https://pubmed.ncbi.nlm.nih.gov/18295618/

Figure 2: Visual representation of the robot

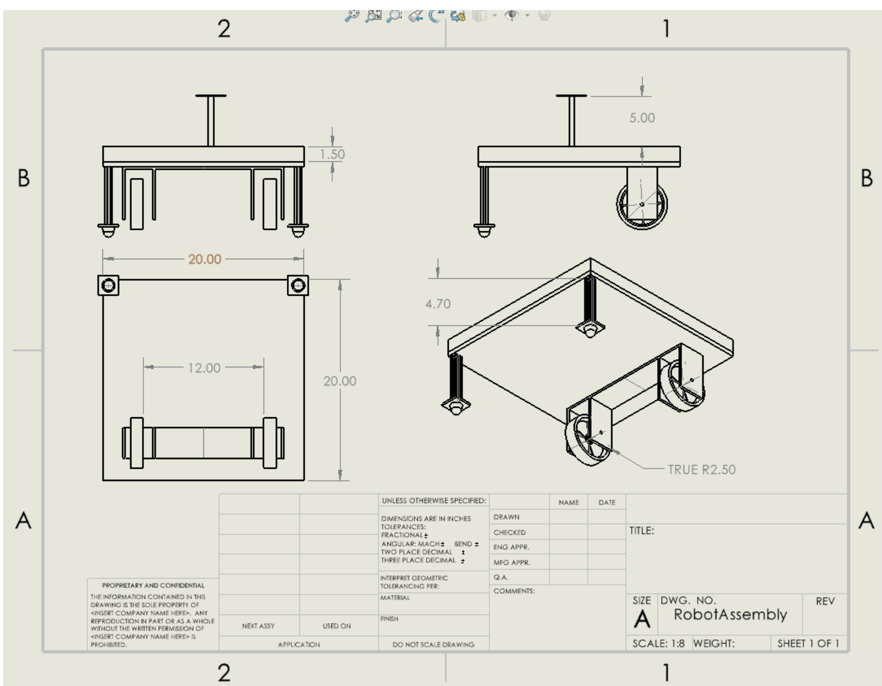


Figure 3: Robot frame dimensions

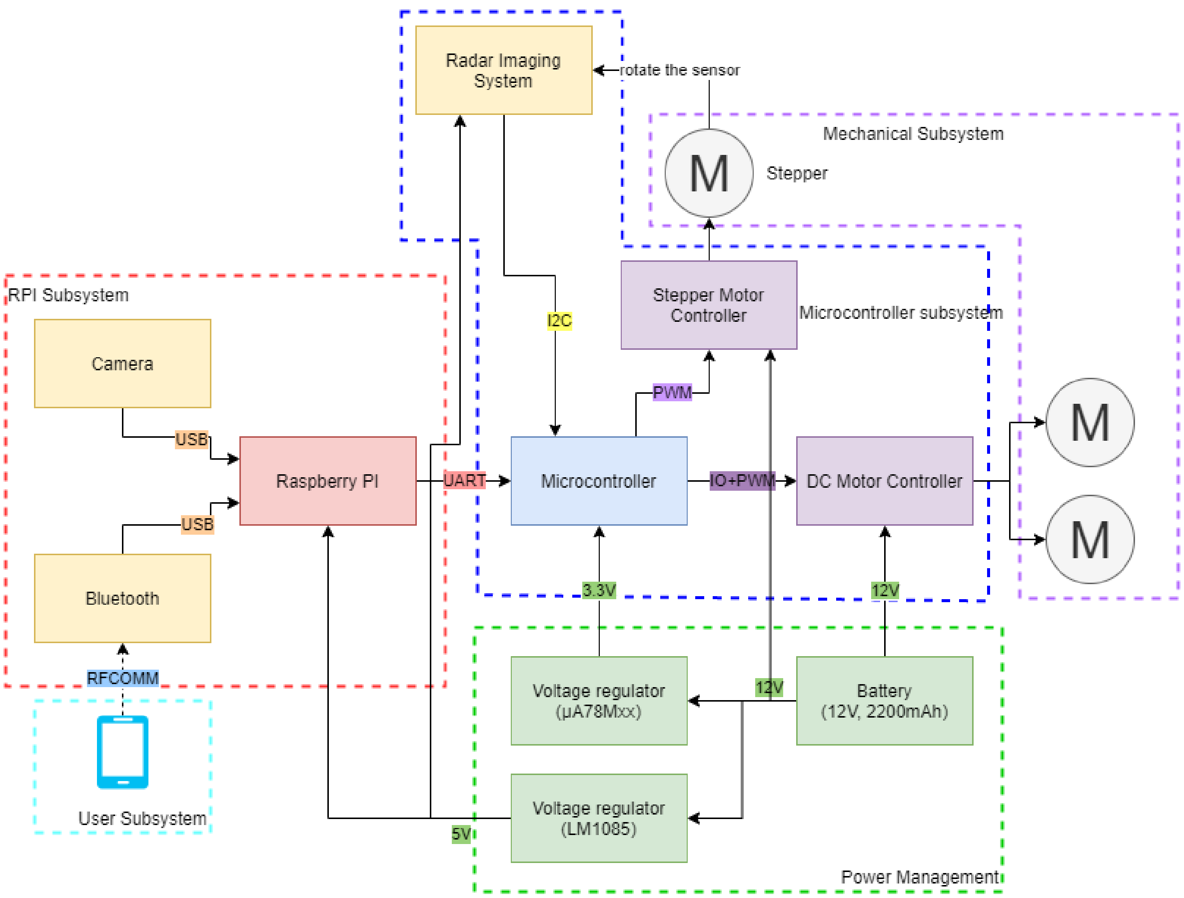
1.4 High-Level Requirements

To succeed, the robot must achieve the following criteria:

- The robot should be able to consistently follow the phone holder/color marker through flat terrain with static obstacles with a height of at least 30 cm
- The robot should also be able to carry a load of 3 kg over level ground
- The robot should be capable of moving at speeds of up to 0.5 miles per hour (0.8 km/h, 0.22 m/s)
- The robot will maintain a distance of 1-5 meters away from the person of interest

2 Design

2.1 Block diagram



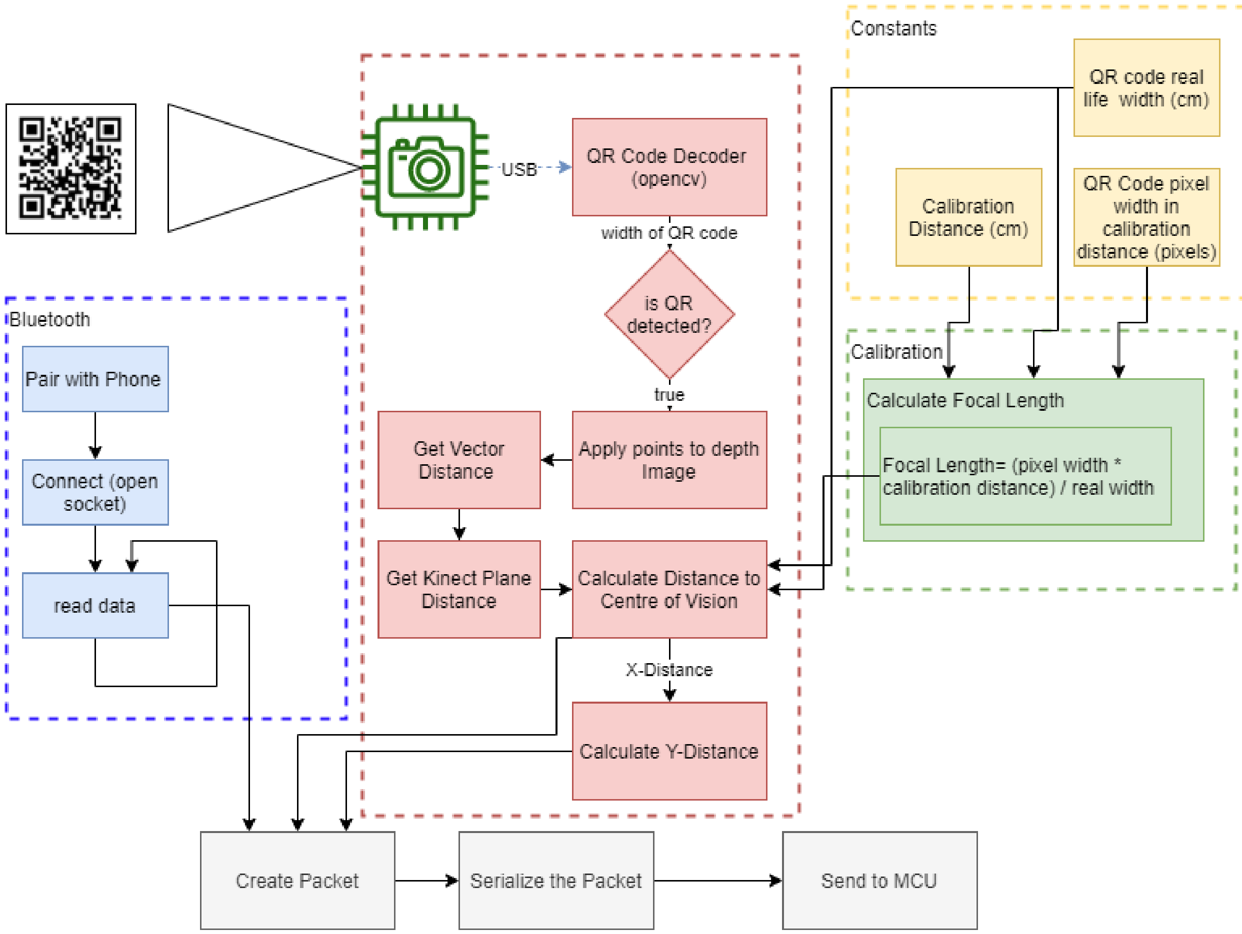
2.2 RPI Sensory Subsystem

2.2.1 Overview:

The Raspberry Pi subsystem's main goal is to provide information about the user, such as position, rotation, and heading. This subsystem has two main underlying components: a camera interface and, as an extension, a Bluetooth interface (see Addendum), as shown in Diagram #. The outputs of these two components are then stored in a packet and serialized, to be sent to the microcontroller over serial communication.

The Camera component consists of Xbox 360 Kinect, and uses QR code detection and decoding to determine the distance between the robot and the user. It first searches the camera input for a QR code using OpenCV. The QR code contains a unique sha256 hash for each user. Upon finding the correct QR code, the coordinates of this QR code on the RGB image is applied to the depth image as a crop. The cropped depth image is flattened and the average is taken, giving us an average distance estimate of the QR code. This average distance is named as Vector Distance. The Vector Distance is converted to the same plane as the Kinect by taking the cosine of the tilt angle; this distance is named Kinect Plane Distance. Next, using the focal length of the camera and the pixel width of the found QR code, the distance between the QR Code and center of vision is calculated, named X-Distance. Using X-Distance, Kinect Plane Distance, and pythagorean theorem we calculate the Y-Distance. Y-Distance is the perpendicular distance between user and robot. The X-Distance and Y-Distance are sent to packet generation.

The Bluetooth component uses python to connect to the User's phone and receives sensory data such as accelerometer and gyroscope in fixed intervals. The system is using a bluetooth RFCOMM server which uses a callback function to process the data from JSON to a python dictionary. This data is processed to remove noise, then sent to packet generation, which then serializes the dictionary.



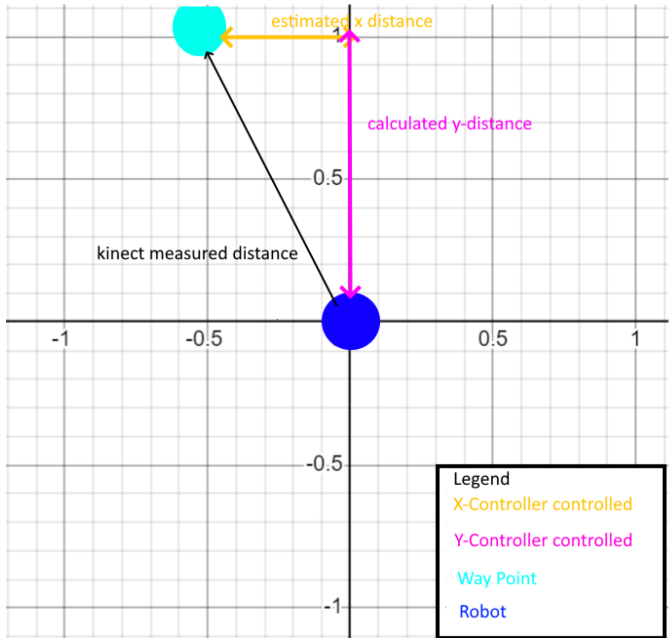
2.2.2: Requirements:

- Measure the distance to the user with a 5cm error rate in artificial lighting.
- Serialize measured and collected data, and transfer it to the microcontroller quickly with a Baud Rate of 115200.
- [Extension] Receive phone data via bluetooth

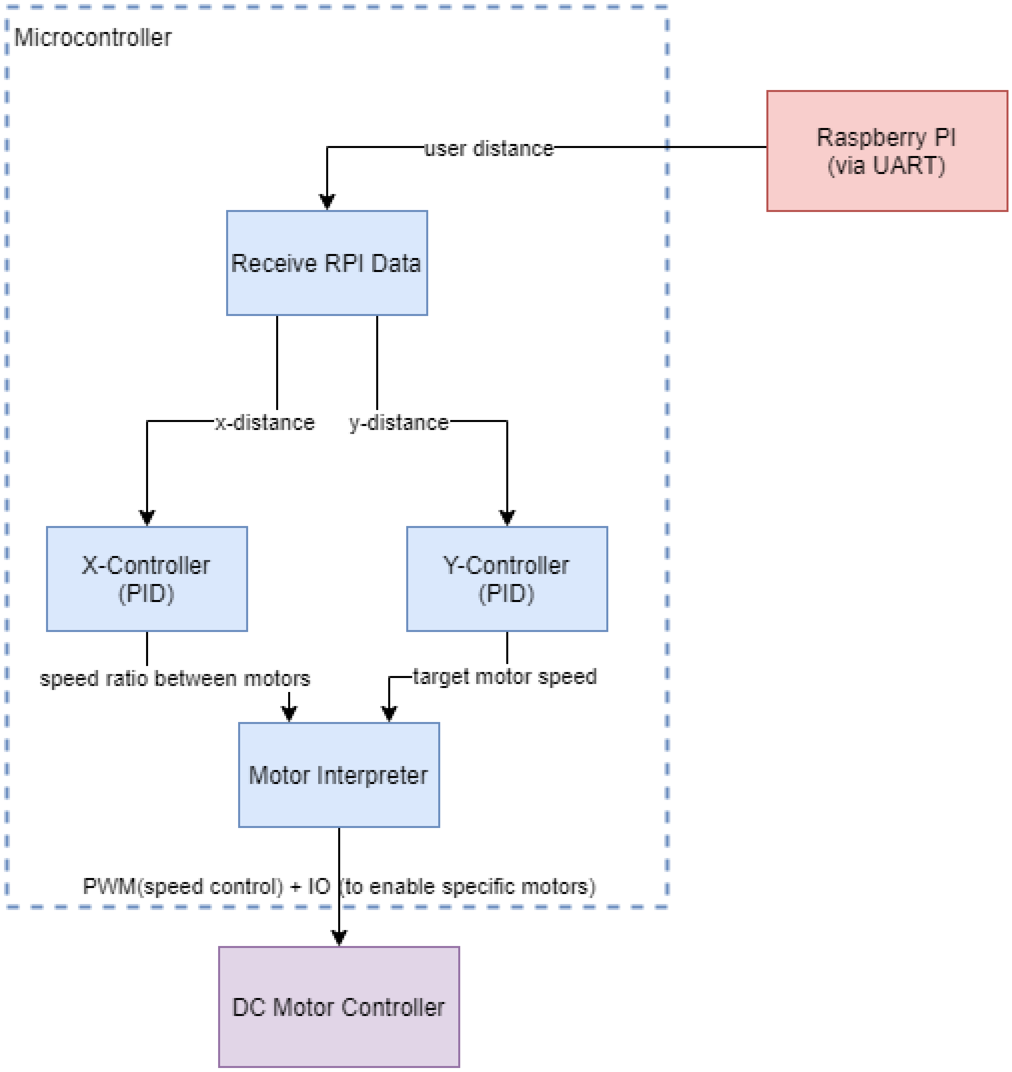
2.3 Microcontroller Subsystem

2.3.1 Overview:

The Microcontroller Subsystem consists of two main parts; the pathfinding system and driving subsystem. As an extension, the microcontroller subsystem may also incorporate a LIDAR based obstacle detection system (See addendum). These three components work together to detect obstacles, find the path, and control the motor to follow that path.



The Driving Subsystem is responsible for guiding the robot along a given path. It receives a list of waypoints and uses them as targets for two PID controllers. The first controller governs the y-axis, representing the distance between the robot and its target. When avoiding obstacles, the steady state is set to 0. However, without obstacle avoidance, this steady state value represents the desired follow distance. The controller adjusts the motor speed to reach and maintain this distance. The second controller governs the robot's lateral movement along the x-axis, adjusting the robot's tilt based on the ratio of motor speeds. Its steady state is set to 0, representing the center of the robot's vision. Its primary objective is to keep the person in the center of the robot's vision at all times by controlling the robot's tilt. By using these two controllers together, the Driving Subsystem ensures that the robot stays on course and follows its intended path while maintaining a safe distance from the person it is following.



2.3.2 Requirements:

- PID controllers can follow waypoints with 70% accuracy

2.4 Power Management

2.4.1 Overview:

For the power system we will be using a 12V, 5000mAh lead acid battery alongside a uA78Mxx and LM1085 voltage regulators. From the battery, the system will supply 12V, 2.2A to the drive motors. Via the uA78Mxx voltage regulator, the system will supply 5V, 2.5A to the RPI subsystem and via the LM1085 voltage regulator, the system will supply 3.3V, <0.5A to the microcontroller subsystem. Due to safety considerations, charging of the battery component of the subsystem will be accomplished by removing the battery from the subsystem and charging separately from the robot using a separate battery charger.

2.4.2 Requirements:

- System is able to provide sufficient voltage and current for all components
- System is able to step down voltage to safe levels for all components
- System is able to provide sufficient power for the required run-time
- Battery component of the subsystem is able to be removed and replaced in a safe and easy manner not requiring any specialized tools.

2.5 Tolerance Analysis

The subsystem is primarily limited by the operating requirements of the lithium polymer battery and the voltage regulator ICs.

The LM1085 voltage regulator ICs are rated for a maximum input-output voltage differential of 27V and temperature ranges of -40 to 150C. The uA78Mxx voltage regulator ICs are rated for a maximum input voltage of 35V and temperature ranges of -65 to 150C. From the output voltage of the battery, the maximum voltage differential is unlikely to be a concern given the 12V output of the battery. However, in continuous operation heating, particularly in hot settings with poor airflow, may be a concern. To mitigate this, the IC and battery components of the subsystem will be mounted in a porous enclosure to allow for cooling via airflow.

As a whole, the robot demands a maximum current load of 2.34A. Of this total, 0.15A is drawn from the LIDAR, 0.64A from the DC drive motors, 1.2A from the Raspberry Pi and 0.35A from the stepper motors with the required current for other ICs being negligible.

$$Time\ (hours) = (mAh\ rating) / (mA\ current)$$
$$1\ h = 2200\ mAh / 2200\ mA$$
$$0.94\ h = 2200\ mAh / 2340\ mA$$

The battery selected for this project is rated for a capacity of 2200 mAh with a discharge rate of 50C. This allows the battery to supply a 2.2A current for 1 hour or a maximum of 110A for 1.2 minutes. Thus, at peak current demand of 2.34A, the robot can be expected to remain operational for 56.4 minutes under ideal conditions as detailed in the above calculations. As a whole, the robot remains capable of performing under peak demands for an acceptable period of time. Detailed below are the peak current values of relevant components.

Battery Discharge: 50 C
Battery Capacity: 2200 mAh

LIDAR Current = 0.15A
DC Motor Current = 0.32x2 = 0.64A
RPI Current: 0.5 to 1.2A
Stepper Motor Current = 0.35A
Microcontroller Current = Negligible
Motor Controller Current = Negligible *
Voltage Controller Current = Negligible

* Outputted to controlled motors

3 Cost and Schedule

3.1 Cost Analysis

3.1.1 Labor Costs

As of 2021, the average annual starting salary (excluding bonuses) for a UIUC graduate is $80,296 for an electrical engineer and $105,352 for a computer engineer[2]. Assuming a 40 hour work week and 52 work weeks per year, these work out to $38.60 and $50.65 per hour respectively. As a whole, we plan to work on the project for roughly 30 hours per week each for a total project period of 9 weeks. With two computer engineers and one electrical engineer, the total engineering labor costs for this project is 113,319 USD.

$$Labor\ Cost\ =\ (Total\ Man\ Hours)\ \times\ (Total\ Hourly\ Wage)$$
$$Labor\ Cost\ =\ (3\ \times\ 30\ \times\ 9)\ \times\ (38.60\ +\ 2\ \times\ 50.65)\ =\ 113,319\ USD$$

In addition to this, the ECE Machine Shop has quoted 32 hours of labor for the final assembly of the robot including the Chassis-Rotating Tower assembly and motor mount. The UIUC Facilities and Services quotes a billable hourly rate of $90.22 for machinists[3], resulting in a total machine shop cost of 2887.04 USD.

Accounting for all currently known costs, the total cost of this project is 116,686.10 USD.

$$Total\ Cost\ =\ Engineering\ Cost\ +\ Machining\ Cost\ +\ Part\ Cost$$
$$Total\ Cost\ =\ 113,319\ +\ 2,887.04\ +\ 480.06\ =\ 116686.10\ USD$$

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[2] https://ece.illinois.edu/admissions/why-ece/salary-averages
[3] https://fs.illinois.edu/services/f-s-service-rates

3.1.2 Parts Costs

All costs below are in units of U.S. dollars from listed pricing at time of purchase

Description	Manufacturer	Part #	Quant.	Total Cost	Link
Chassis	Machine Shop	n/a	1	100.00	n/a
Pulley	Machine Shop	n/a	1	4.00	n/a
Rotating Tower	Machine Shop	n/a	1	15.00	n/a
Lazy Susan	McMaster Carr	6031K16	1	3.55	Link
Slip Ring	Comidox	CP164	1	11.93	Link
Circuit Housing	Siebel Center 3D Printed	n/a	1	3.00	n/a
Geared Brushed DC Motor w/ Encoder 12V 100RPM	Walfront	Walfrontz6k1co4w2a-05	2	32.20	Link
DC Motor Cont. Board Module w/ L298N IC	HiLetgo	3-01-0032-4PCS	4	11.49	Link
Stepper Motor Cont.	Pololu	TB67S128FTG	2	33.9	Link
Nema 17 Stepper Motor	STEPPERONLINE	17HS16-2004S1	2	27.98	Link
PCB	PCBway	n/a	2	TBD	Link
Connectors	TBD	TBD	TBD	TBD	TBD
LIDAR Laser Ranging Module	Pulsed Light	LL-905-PIN-01	1	48.97	Link
Devboard	STMicroelectronics	NUCLEO-F767ZI	1	23.00	Link
Microcontroller Unit	STMicroelectronics	STM32F767ZIT6	2	42.98	Link
Raspberry Pi 4 Model B	Raspberry Pi	DEV-15447	1	55.00	Link
XBox360 Kinect	Microsoft	5KG-00001	1	40.97	Link
Voltage Regulator 5V	STMicroelectronics	LM1085	2	3.36	Link
Voltage Regulator 3.3V	Texas Instruments	UA78M33QDCYRG4Q1	2	1.74	Link
Voltage Regulator 12V	NTE Electronics, Inc	NTE966	2	3.00	Link
Lead Acid Battery 12V	MightyMax	ML5-12 SLA	1	17.99	Link
Battery Charger	TBD	TBD	1	TBD	TBD

3.2 Schedule

Week	Task	Person
Feb 20st-26	RPI Kinect control	Deniz
	Bluetooth control with App	Okan
	RPI MCU communication w UART	Okan
	Stepper Control with MCU (Extension)	Okan
	First PCB Design & Pass Review	Alex
	LIDAR Communication w MCU (Extension)	Deniz & Okan
	Design Document	Everyone
Feb 27th-March 5th	Sensor processing on MCU	Okan
	Stepper Motor Control with RPI sensor Data (Extension)	Okan
	DC Motor Control Prototyping	Alex
	Design Review with Machine Shop	Deniz
	PCB Revisions & Pass Audit	Alex
March 6th - 12th	PID Controller Training and Parameter Tuning	Okan & Alex
	Roadmap Grid Generation (Extension)	Okan & Deniz
	First Experiment (without Obstacle Detection)	Everyone
	LIDAR obstacle processing	Deniz
	First PCBway Orders March 7th	Alex
March 13th - 19th (Spring Break)	*Grid Pathfinding (Extension)*	Deniz
	Extended Kalman filtering (Extension)	Okan
	Build the PCB	Everyone
	PCB Design Revisions	Alex
Match 20th - 26th	**Second Experiment (with static obstacles)**	Everyone
	Second PCB Design and Pass Audit	Alex

	Fix Existing Bugs	Everyone
March 27th - April 2nd	**Second PCBway Orders 3/28**	Alex
	Build the PCB	Everyone
	Finalize Assembly	Everyone
	Fix Existing Bugs	Everyone
April 3rd - 9nd	Fix Existing Bugs	Everyone
	Fine tune the system	Everyone
April 10th - 16th	Fix Existing Bugs	Everyone
	Finalize plans for demo	Everyone
April 17th - 23rd	Mock Demo	Everyone
	Fix issues identified in demo	Everyone
April 24th - 30th	Final Demo	Everyone
May 1st - May 7th	Final Presentation	Everyone
	Final Papers	Everyone

4 Ethics & Safety

Regarding the ethical considerations of this project, our team intends to hold ourselves to the highest ethical standards through adherence to the IEEE Code of Ethics. Outlined below are the relevant safety, ethical and regulatory concerns we have identified as well as the means through which we intend to alleviate these issues.

1.) As the power management subsystem only makes use of a single battery while charging intended to not occur during use, the subsystem does not include a battery management system (BMS) circuit. Having discussed the matter with a teaching assistant, the absence of BMS in a single battery system should not pose any issues given the intended discharge-only use of the battery. Thus, to avoid the risk of battery failure or fires, we have designed the robot to require the battery to be charged separately from the rest of the system.
    - a.) Additionally we will follow best practices for battery safety by storing the battery in a cool well-ventilated area and insulating the battery terminals to prevent conductive materials from coming in contact.
    - b.) Given the inherent fire hazard of lithium-based batteries, we have elected to use a spill-resistant sealed lead-acid (SLA) battery to reduce the risk of fire and leaks.
    - c.) Each team member will be informed on how to use a battery spill kit and the Safety Data Sheet instructions in case of a spill.

d.) Each team member will become familiarized with the ML5-12 SLA battery's Material Safety Data Sheet (MSDS)[4].

2.) Regarding the user subsystem, we will ensure that only necessary user data is obtained and transmitted. The data, transferred via Bluetooth, shall only be transferred between the user's phone and the robot, shall not be used for any purpose other than the pathfinding of the robot and shall not be retained by any system of the project when not in active use.
3.) We will ensure that our project follows any relevant licensing terms and conditions for all software and parts used in the project.
4.) To prevent any harm to people or materials around the robot due to collisions we will implement PID controllers to ensure that the robot does not accelerate at an alarming rate. In addition to this, plan to include a kill-switch on the robot to stop operation in case of an emergency.

5 Addendum

The following section will describe the extensions to our project that we intend to fulfill should time permit.

5.1 Bluetooth & App Subsystem

5.1.1 Overview

For the user subsystem, we are using react native to create a mobile app that sends sensory packets via Bluetooth to RPI subsystem via a USB Bluetooth Adapter connected to the Raspberry Pi. The mobile app will transfer the user's gyroscope and accelerometer data to assist the robot in pathfinding, particularly when the user is not in line of sight.

5.1.2 Requirements:

- System is able to reliably deliver data from the user within the required 1-5 m distance from the person of interest

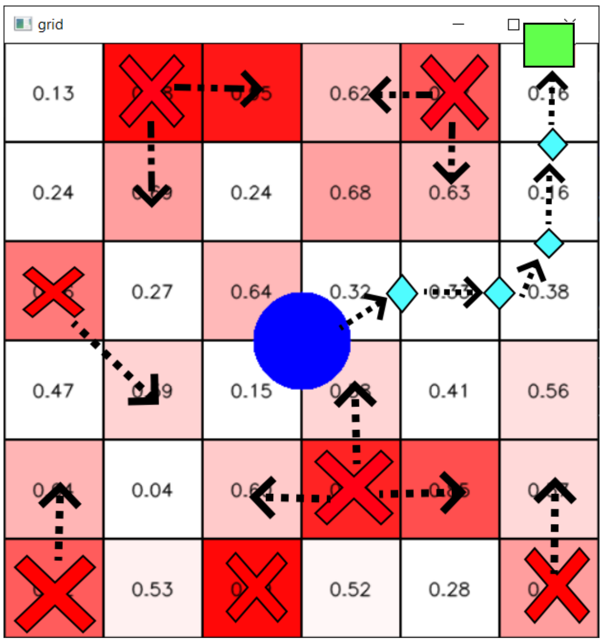
5.2 Obstacle Detection Subsystem

5.2.1 Overview

The path decision system is the main computation in this project. This system uses data from radar imaging sensors to generate obstacle objects. These objects are then fed into a Kalman Filter (EKF). The Kalman Filter returns as with estimated trajectories of these obstacles. Next, the system generates a grid based on fixed cell size and max distance as bounds. Using the estimated trajectories the cells are assigned a collision probability. The grid is a two-dimensional array; the visualization of this grid can be seen in Figure #. After the grid is generated, the microcontroller uses the A* algorithm to find the shortest and safest path. For the A*, the heuristic will be based on the lowest collision probability and shortest Manhattan distance. The heuristic will be weighted in favor of minimum collision probability. Finally, after the path is determined it is sent through an encoder which turns these points into motor instructions.

[4] https://mans.io/files/viewer/1693682/1

Radar imaging for this subsystem is implemented using a single Lidar sensor and a stepper motor to turn the sensor 360 degrees, generating a 2d distance map. The stepper motor is controlled by a controller which is controlled by a PWM from the microcontroller. The frequency of the PWM controls the speed of the microcontroller. This speed is adjusted by the distance to the user provided by the RPI to optimize imaging resolution.



Legend:

- Green Square: User
- Cyan Diamonds: Waypoint generated
- Red Crosses: Obstacles
- Dashed Arrows: Possible Movement of the object

5.2.2 Requirements

- System is able to detect obstacles within 1-2 meters, with an accuracy of 80%.
- System is able to predict trajectories for those obstacles with a collision rate of 10% or less.
- System is able to generate a probability grid based on obstacle data
- System can generate a path using the probability grid.

6 Citation

[1] Ziegler-Graham K;MacKenzie EJ;Ephraim PL;Travison TG;Brookmeyer R; “Estimating the prevalence of limb loss in the United States: 2005 to 2050,” *Archives of physical medicine and rehabilitation*. [Online]. Available: https://pubmed.ncbi.nlm.nih.gov/18295618/. [Accessed: 23-Feb-2023].

[2] Grainger Engineering Office of Marketing and Communications, “Salary averages,” *Electrical & Computer Engineering | UIUC*. [Online]. Available: https://ece.illinois.edu/admissions/why-ece/salary-averages. [Accessed: 23-Feb-2023].

[3] “University of Illinois facilities and services,” *Facilities and Services University of Illinois Urbana Champaign*. [Online]. Available: https://fs.illinois.edu/services/f-s-service-rates. [Accessed: 23-Feb-2023].

[4] “Mighty max battery ML5-12 [3/8] 8. exposure controls ... - mans.io.” [Online]. Available: https://mans.io/files/viewer/1693682/3. [Accessed: 23-Feb-2023].