

# Senior Design I Research Paper

Tobiah Bower      Matthew Morello      Morgan Snyder  
Electrical Engineering      Computer Engineering      Electrical Engineering

# FORWARD

Feedback Oriented Routing and Walker Assistance with Responsive Direction



Review Committee: Dr. Wasfy Mikhael, Dr. Chinwendu Enyioha, and Dr. George Atia

# Table of Contents

<b>1</b>	<b>Executive Summary</b>	<b>1</b>
<b>2</b>	<b>Project Description</b>	<b>2</b>
2.1	Project Motivations . . . . .	2
2.2	Project Objectives and Goals . . . . .	3
2.3	Project Requirement Specifications . . . . .	5
2.4	House of Quality . . . . .	6
2.5	Project Block Diagram . . . . .	8
<b>3</b>	<b>Research</b>	<b>10</b>
3.1	Existing Products and Projects . . . . .	10
3.1.1	Current Walker Sensing Applications . . . . .	11
3.1.2	Current Walker Stability Applications . . . . .	12
3.1.3	Current Computer Vision Object Detection Applications . . . . .	12
3.1.4	Current Audio Feedback Applications/Technologies . . . . .	14
3.1.5	Motor and Steering Applications . . . . .	14
3.2	Relevant Technologies . . . . .	15
3.2.1	Sensor Ranging . . . . .	15
3.2.2	Walker Stability . . . . .	17
3.2.3	Computer Vision Object Detection . . . . .	18
3.2.4	Current Audio Feedback Technologies . . . . .	18
3.2.5	Motor Shield/Driver . . . . .	20
3.2.6	Speed Control . . . . .	21
3.2.7	Steering and Braking Method . . . . .	21
3.2.8	Power Supply . . . . .	22
3.2.9	DC Motor Technology . . . . .	24
3.2.10	Haptic Motors . . . . .	25
3.2.11	Voltage Regulation . . . . .	26
3.2.12	Light Sensors . . . . .	27
3.3	Strategic Components . . . . .	27
3.3.1	Ultrasonic Sensors . . . . .	27
3.3.2	LiDAR Sensors . . . . .	28
3.3.3	Inertial Measurement Units . . . . .	29
3.3.4	Computer Vision/AI Image Processing Models . . . . .	29
3.3.5	Camera Technologies . . . . .	30
3.3.6	MCU Technologies . . . . .	31
3.3.7	Motor Controllers . . . . .	32
3.3.8	Motor Drivers . . . . .	34
3.4	Possible Architectures and Related Diagrams . . . . .	35
3.4.1	Proposed Sensor FOV Topology . . . . .	35
3.4.2	Euler Angles . . . . .	36
3.4.3	Velocity and Position Solution . . . . .	37
3.4.4	Kalman Filter . . . . .	37

3.4.5	Quaternions . . . . .	38
3.4.6	Typical CV camera setup . . . . .	38
3.4.7	Typical steering motor control wiring . . . . .	38
3.5	Part Selection . . . . .	38
<b>4</b>	<b>Requirements, Standards, and Constraints</b>	<b>45</b>
4.1	Related Standards . . . . .	45
4.1.1	Connection Standards . . . . .	45
4.1.2	Design Impact . . . . .	45
4.2	Economic Constraints . . . . .	46
4.3	Environmental Constraints . . . . .	47
4.4	Social and Political Constraints . . . . .	48
4.5	Ethical, Health, and Safety Constraints . . . . .	48
<b>5</b>	<b>Comparison of ChatGPT with Similar Platforms</b>	<b>50</b>
5.1	Example 1: Sonar vs. LiDAR . . . . .	50
5.2	Example 2: Power Supply to the MCU . . . . .	51
5.3	Example 3: . . . . .	52
<b>6</b>	<b>Hardware Design</b>	<b>53</b>
6.1	Rollator . . . . .	53
6.2	Electronics Chassis . . . . .	53
6.2.1	Location of Components . . . . .	53
6.2.2	Measurements of the Walker . . . . .	55
6.3	Arduino . . . . .	56
6.4	Detection Subsystem . . . . .	56
6.4.1	Sensor Orientation . . . . .	56
6.4.2	Incline and Decline Stability . . . . .	57
6.4.3	Sensor Fusion . . . . .	57
6.5	Identification Subsystem . . . . .	58
6.5.1	ESP32 Wireless Network . . . . .	58
6.6	Power Supply and Voltage Regulation . . . . .	58
6.7	Avoidance Subsystem . . . . .	59
6.7.1	Motor Control System . . . . .	59
6.7.2	Wheel Rotational Motion . . . . .	60
6.7.3	Turning Mechanics . . . . .	60
6.7.4	Motor Installation . . . . .	61
6.7.5	Emergency Braking . . . . .	62
6.7.6	Reconciling User Control and Automatic Guidance . . . . .	63
<b>7</b>	<b>Software Design</b>	<b>64</b>
7.1	Guidance, Navigation, and Control Software . . . . .	64
7.2	Computer Vision . . . . .	64
7.3	Serial Interface . . . . .	64
7.4	Motor Control Software . . . . .	64

7.5	Ranging Algorithms . . . . .	64
7.5.1	Range Reading Harmonization . . . . .	64
7.5.2	I2C Bus for Sensors . . . . .	66
7.6	Identification and Image Processing . . . . .	66
7.6.1	Training Object Recognition Models . . . . .	66
7.6.2	Predetermined Obstacles . . . . .	66
7.7	Avoidance Protocols . . . . .	66
7.7.1	Emergency Stop . . . . .	67
7.7.2	Stationary Obstacle . . . . .	67
7.7.3	Polite Response to Obstacle in Motion . . . . .	67
<b>8</b>	<b>Prototype Fabrication</b>	<b>69</b>
8.1	Printed Circuit Board Design . . . . .	69
<b>9</b>	<b>System Testing</b>	<b>71</b>
9.1	Subsystem Testing . . . . .	71
9.1.1	Detection FOV Threshold . . . . .	71
9.1.2	Identification Importance . . . . .	72
9.1.3	Control Feedback . . . . .	72
9.2	System Integration, Testing, and Evaluation . . . . .	73
<b>10</b>	<b>Administrative Content</b>	<b>74</b>
10.1	Project Milestones . . . . .	74
10.2	Project Budget . . . . .	76
<b>11</b>	<b>Conclusion</b>	<b>78</b>
<b>12 Appendix A - Permissions</b>		i
<b>13 Appendix B - References</b>		iii
<b>14 Appendix C - Chat GPT Outputs</b>		xiv

# List of Figures

1	Engineering Requirements . . . . .	6
2	House of Quality . . . . .	7
3	System Block Diagram . . . . .	9
4	"Rollator" with nine HC-SR04 sensors [1] . . . . .	11
5	2D Grid with Safe Region Generation . . . . .	13
6	Ultrasonic Directivity [20] . . . . .	16
7	Scanning LiDAR FOV [21] . . . . .	16
8	Bluetooth Spread-spectrum Frequency Hopping . . . . .	19
9	Pulse Width Modulation Duty Cycle Graph . . . . .	21
10	Proposed Sensor FOV (Range NOT to scale) . . . . .	36
11	Ultrasonic Sensor Options . . . . .	38
12	LiDAR Sensor Options . . . . .	39
13	IMU Sensor Options . . . . .	39
14	Comparison of MCU Options . . . . .	39
15	Comparison of Camera Modules for ESP32-based Applications . . . . .	40
16	Comparison of AI Image Processing Solutions . . . . .	40
17	Comparison of Headphone Options . . . . .	41
18	Motor Specifications . . . . .	41
19	Vibration Motor Specifications . . . . .	42
20	Motor Controller Specifications . . . . .	42
21	Haptic Motor Driver Specifications . . . . .	43
22	Wheel Motor Driver Specifications . . . . .	43
23	Comparison of Headlight Options . . . . .	43
24	Comparison of Battery Options . . . . .	44
25	ChatGPT compares sensing technologies . . . . .	51
26	Medline Premium Empower Medical Rollator . . . . .	53
27	Location of components on the walker . . . . .	55
28	Measurements of the walker . . . . .	55
29	Stability on Slopes . . . . .	57
30	Breadboard w/ Ultrasonics, and IMU & LiDAR I2C Bus . . . . .	58
31	Motor Control System Diagram . . . . .	59
32	Polite Obstacle Avoidance . . . . .	68
33	PCB Block Diagram . . . . .	69
34	PCB KiCAD Schematic . . . . .	70
35	Euler Angles Test . . . . .	72
36	Senior Design I Milestones . . . . .	74
37	Senior Design I Gantt Chart . . . . .	75
38	Senior Design II Milestones . . . . .	75
39	Senior Design II Gantt Chart . . . . .	76
40	Project Budget . . . . .	77

## **List of Tables**

# **1 Executive Summary**

FORWARD (Feedback Oriented Routing and Walker Assistance with Responsive Direction) is an assistive walker enhanced with obstacle avoidance and adaptive speed control, designed to extend the mobility and safety of its users. By harnessing the power of sensors, motors, and microprocessors, FORWARD brings the latest of electrical and computer technology to those who are in need, so that walkers can become more beneficial for not only the traditional user, but for those who are sensorially impaired.

## 2 Project Description

### Project Background

Walkers are a mobility aid commonly deployed in the environment of medical institutions such as hospitals and assisted living homes. They are also used daily by patients not just in the medical setting, but in neighborhoods, parks, shopping malls, and just about anywhere you can stroll. There is a sizeable market for these support tools. If you include other devices such as canes, the market valuation exceeds \$1 billion. There is a great need for these as the US elderly population continues to grow. Currently there are over 50 million people who are considered elderly, and some studies suggest that a quarter of these utilize walkers or canes. Additionally, there are 1 million people with blindness or severe visual impairment in the United States.

The goal of this project is to use the latest of electrical and computer engineering technologies to develop a solution that vastly improves the functionality of walkers and to improve their user experience. We want to implement functionality that will be useful for both users with physical injury and users with sensory impairments. For instance, a blind person will greatly benefit from audio feedback that warns them of hazards or obstacles ahead. Additionally, a deaf person will be blessed by haptic feedback for the same purpose. In short, FORWARD helps to keep people safe independently of the user's own spatial awareness.

### 2.1 Project Motivations

This project has the ability to help those who are physically impaired as a result of surgery recovery or have a more permanent hindrance such as blindness or deafness. This is also especially useful for people who both have a visual impairment and have also suffered a physical injury. In addition, FORWARD is a much cheaper option than a wheelchair so that the users have an affordable way to get around.

At the core, conventional walkers do little to assist the user outside of bearing their weight and providing a barrier between them and any obstacles. The user is still susceptible to tripping and falling because of an obstruction the walker collides with. This is especially harmful for those with sensory impairments because, if they are injured, they will not be able to have the same mobility as before. For example, people who are blind use a white cane to feel the ground in front of them while walking, which is not feasible to do when both hands are being used to support their weight.

It will be a great learning experience to implement a variety of different technologies

that we are not yet accustomed to, including computer vision, sensor fusion, and guidance systems. We will also be able to gain more practical experience to apply what we have learned in our classes about embedded systems, programming, and control systems. There are even aspects of linear circuits that we will be able to apply, such as power limitations between components and wiring a PCB.

With the technology available today, the opportunity exists to improve the quality of life and safety for walker users and enable them to have a faster and more secure lifestyle while traveling. Spend less time worrying about injury and more time enjoying the company of family and friends.

## 2.2 Project Objectives and Goals

Our goals can be divided into three categories: basic goals, advanced goals, and stretch goals. The basic goals for our project include object detection, obstacle identification, and obstacle avoidance, which will also define our major subsystems and work division. Below the objectives are listed, along with our advanced and stretch goals.

### Basic Goals - Objectives

Object Detection - FORWARD shall be able to recognize obstacles present and by using sensor fusion to resolve the measurements by the LiDAR and Sonar sensors, determine an accurate reading of the range to the obstacle. This ranging system must be able to work regardless of the material properties or nature of the obstacle, whether incline, decline, or freestanding object. The ranging subsystem should also transmit the LiDAR and Sonar sensor data to the MCU. This subsystem works hand-in-hand with identification and avoidance.

Obstacle Identification - FORWARD obstacle identification (CV) shall be able to implement AI Image processing and Computer Vision to correctly identify the current obstacle as well as the threat level presented to the user. The model shall take as an input a photo captured by the system camera and process this photo to correctly identify the item in the path of the user. The system shall classify the item into one of three categories: 1) Emergency Stop – meaning a continuance could put the user's life in danger, 2) A Reroute - meaning without guidance the user will run into the identified obstacle, and 3) Non-threatening - meaning the item can be ignored. The system will then send the needed information to the necessary outputs, such as guidance control and audio feedback.

Obstacle Avoidance - FORWARD must be able to avoid obstacles detected within the sensor range accurately and safely, finding another path for the walker to take when there is an obstacle in the way of the current path. Initially, the FORWARD system will be moving forward at a steady walking pace with the use of DC motors

all operating at a constant pace. Once an obstacle is both detected and identified, the speed will decrease on either the left or right DC motors, and the walker will steer toward the side in which the motors are running slower. Thus, once finding a safe path to avoid the obstacle, the FORWARD will go around the obstacle and then return to the normal walking pace. If the FORWARD is unable to safely go around the obstacle, instead the motors will slow down to a stop, indicating to the user that they need to stop as well. The way that the motors will be driven is by an MCU coupled with a motor shield, which will use data from the sensor system to decide the speed of each motor. When programming the MCU, it will be necessary to implement pulse width modulation (PWM) to adjust the motor speeds.

### **Advanced Goals - Objectives**

Headlights - As an advanced feature, FORWARD will also activate headlights in lowlight environments, fulfilling similar requirements to what is required by law for bicycles at night. We will use a photoresistor to detect the surrounding lighting conditions, so when darkness is detected for a certain duration, the LED headlights will illuminate the ground in front of the walker. This involves a simple reading and processing of the light input by the MCU and setting the output LED to on.

Affordability - FORWARD should be affordable. Currently, other smart walkers cost thousands of dollars. Oftentimes their physical footprint is obstructive, and they are laborious and heavy. Our system will provide a solution that is minimally noticeable and does not add an excessive amount of weight. It also will drastically reduce the cost by making more efficient use of the component technologies available.

Audio Feedback - FORWARD shall implement audio feedback to inform the user of the current surroundings and hazards. When a hazard is identified, the CV model will detect the hazard and transmit the object audibly over Bluetooth to the ambient hearing piece. The hearing piece will be in one ear only to maximize user hearing in our efforts to prioritize safety.

### **Stretch Goals - Objectives**

Depth Perception - By using a higher quality camera, an additional range reading can be supplied. Taking into account this different angle and the camera's unique perspective, it can be combined with the other range data from the sonar and LiDAR sensors in order to resolve an enhanced measurement. Artificial intelligence modeling and filters may be key in this instrumentation.

Tip-over Prevention - As a stretch requirement, we would like to implement tip-over prevention, which is a stabilization protocol. If the IMU detects the tilt limit is exceeded, thus indicating instability of the user, a motor command is sent that will turn the wheels to restabilize the walker, or an emergency brake activates to stop the wheels so that friction can allow the walker to support the falling user. So, whenever the user falls forward, there will be an attempt made by the walker to

prevent them from scraping their knees.

**Polite Obstacle Avoidance** Another stretch requirement describes the manner of response FORWARD takes to moving obstacles in its path. If, by the sensor and camera data, it intelligently knows that there is say, a person walking across the field of view, and it knows that person's direction of travel, the control software can veer to the opposite direction in order to greatly reduce the risk of collision.

**Incline and Decline Stabilization** Another use of the inertial measurement data would be to change the speed of the motors or activate braking if necessary while on an uphill or downhill slope. Take the case of the user letting go of the walker, and it rolling away down the hill and getting out of their reach. If a sharp increase in acceleration was detected, knowing the fact that the pitch was already not level, an emergency brake could be activated.

## 2.3 Project Requirement Specifications

The table below contains constraints for 1) hardware functionality, 2) software techniques, 3) system performance metrics, and 4) physical footprint. Some of these requirements will be further defined and derived in the longer research paper. The main constraint is time, as this project needs to be completed in the 8-month period concurrent with the senior design I & II courses. One other constraint is the use of a pre-built walker. We are not mechanically designing the walker frame itself.

1.1	FORWARD FOV (field of vision) object detection maximum range	3 meters 15 degrees aspect
1.3	FORWARD tilt instability detection	10 degrees
1.4	FORWARD Walker should support speeds within this range	0-6 MPH
1.5	FORWARD Walker shall be able to brake from max speeds to a complete stop within this time frame	<1 second
1.6	Battery full recharge time	<10 hours
1.7	FORWARD battery life	15 miles
2.1	Accuracy of the CV model identifying and classifying the hazards	>90%
2.2	The MCU will process sensor data through I2C (or SPI) with this refresh rate	> 1000 Hz (1millisecond)
3.1	Accuracy of the sensor ranging solution detecting hazards	>80%
3.2	Feedback latency	<100 milliseconds
4.1	FORWARD walker total weight	>20 lbs. <60 lbs.

*Figure 1: Engineering Requirements*

## 2.4 House of Quality

The figure below shows the weighted importance of the project deliverables and their relation to each other. The main marketing requirements are user mobility, user safety, tip-over stabilization, reliability, affordability, and assisted turn. Each of these features are discussed in the previous parts of this document. The main priorities of FORWARD are safety and mobility.

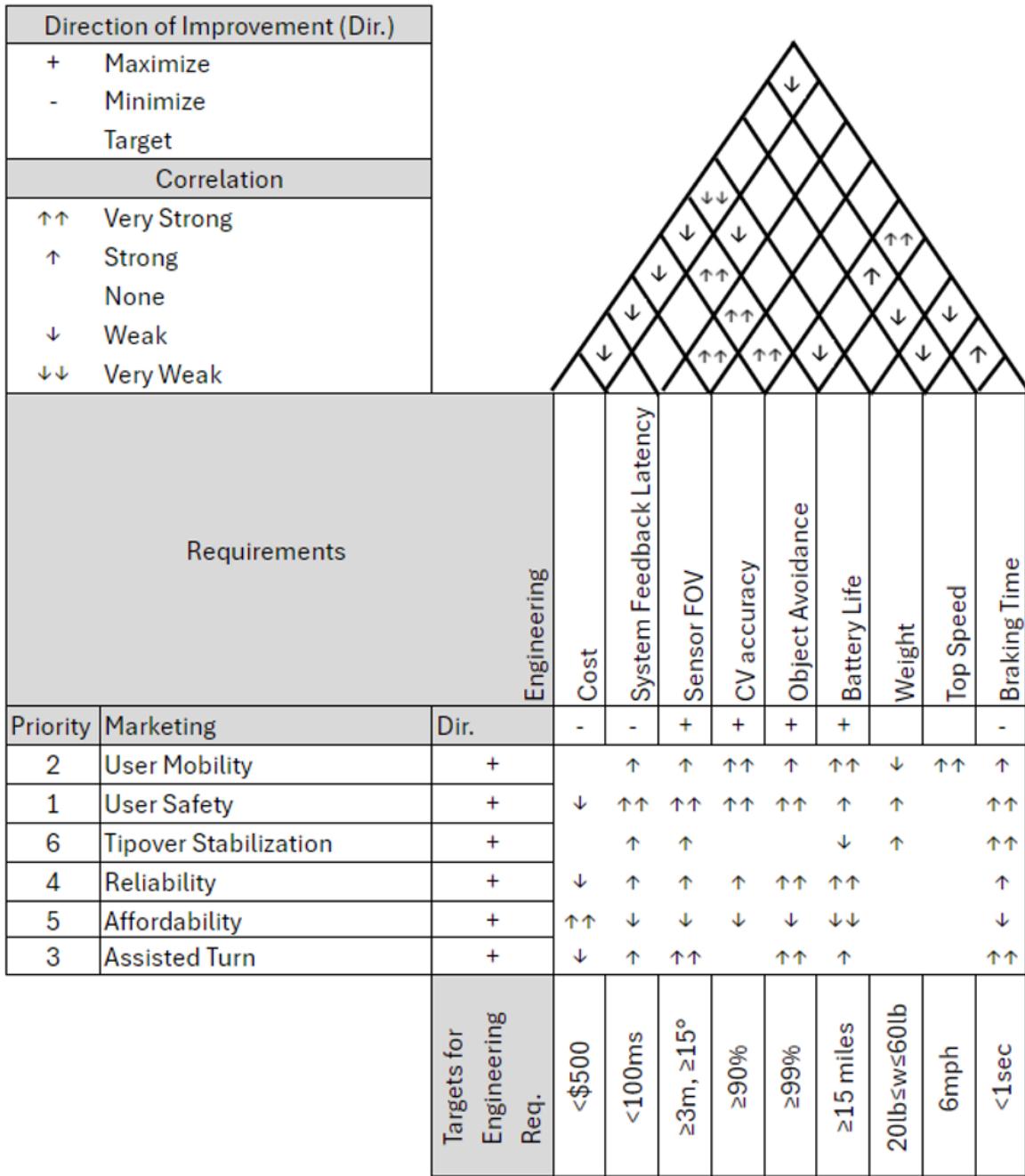


Figure 2: House of Quality

Note that the engineering requirements from Figure 1 are encapsulated on the house of quality as cost, system feedback latency (end-to-end, sensing to user feedback), sensor FOV, CV accuracy, object avoidance (primarily refers to steering protocols), battery life, weight, top speed, and braking time. The ability to efficiently reconcile the marketing requirements with these engineering requirements will spell a great product after design is completed.

## 2.5 Project Block Diagram

As indicated by color and work breakdown delegation, the three subsystems of obstacle detection, identification, and avoidance are shown. The peripherals, depicted in the diagram by circles, are functionally sensors and feedback for user guidance.

The microcontroller unit is central to system integration. It will receive and transmit data from the peripherals while also communicating with the motor controller to steer and drive. In turn, the position determination algorithm, coupled with the speed and steering control, comprise the object avoidance function. Computer vision and image processing are also encompassed by this obstacle identification subsystem. Headlights are an optional advanced requirement feature configured to turn on in lowlight environments. Finally, an implicit element of the diagram are the power inputs from the battery supply.

As seen below, each of the team members will be taking a lead role for different subsystems of the project. These roles were divided based on individual interests and skills, seeking to maximize overall productivity and effectiveness for the designs specified.

Tobiah, being an electrical engineering student with a focus in signal processing, will be covering the obstacle detection subsystem. This will involve research regarding the sensors and generating the range solution. The task at hand is then to give the walker vision of its surroundings without using cameras or any form of pre-planned pathing. FORWARD should be a reactive guidance system.

Morgan, being an electrical engineer interested in robotics and power, will be covering all subsystems under those categories. This includes the power supply as well as the more electromechanical components of the project such as the motors, headlights, and haptic feedback. The power supply will need to provide energy both to the MCU and to the different outputs. The MCU will then control these outputs, the headlights directly through the MCU and the motors for the wheels and haptic feedback using a motor controller. This will allow the system to functionally turn and avoid obstacles as well as vibrate to alert the user of obstacles.

As depicted by the blue shading, Matthew will be taking lead over most of the software related subsystems as well as the MCU. Since the camera will be primarily involved in transmitting video to the MCU for AI image processing – Matthew will be responsible for selecting the camera. The Audio Feedback Guidance will also involve heavy software support since it will be over Bluetooth, so this is also within Matthew's scope. The MCU will drive everything, facilitating all communication through embedded programming and so it is also within Matthew's scope.

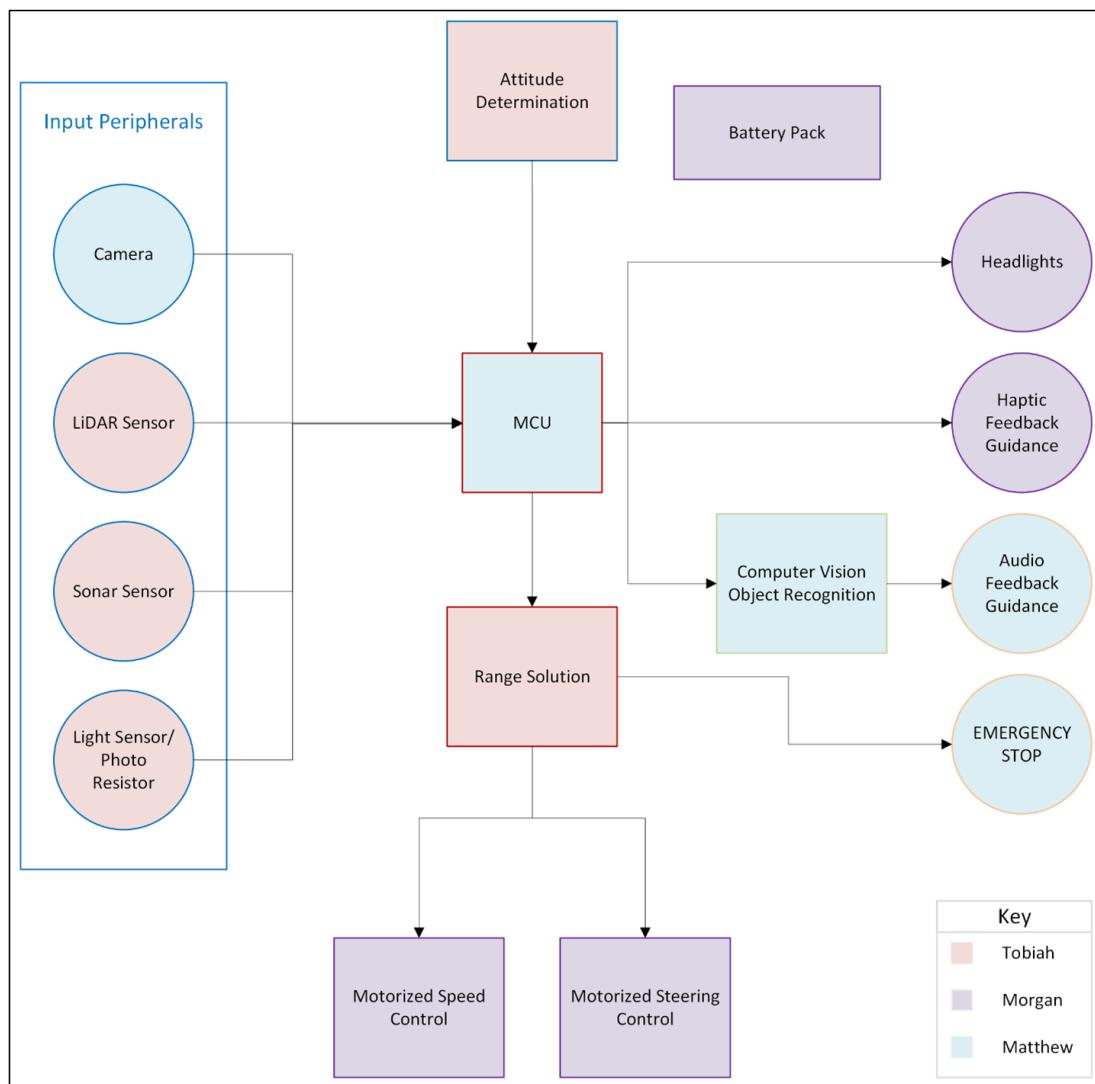


Figure 3: System Block Diagram

## 3 Research

There are many solutions for those that are sensorily impaired, helping them complete various tasks, of which autonomous navigation is one of the most complex, ambiguous, and challenging. Presently, the blind may use canes or guide dogs to travel and avoid obstacles; it is not only the fully blind who may rely on these trusted methods, but also the near or farsighted. In both cases, the system involves guidance in response to sensed information, followed by the person carrying out their course of travel appropriately. The environment itself may correct and guide them, for example, in tight spaces, where they can use railings or rely on memory of certain places where they have a mental picture of its layout. FORWARD seeks to create a universally applicable system based on these realistic cases which can be added as an addendum to any rollator, or even electric wheelchair for that matter. In the medical setting or as physical ailment is compounded onto visual inhibition, motorized and smart solutions are able to show their worth. When the user is less able to navigate on their own, an engineering solution can be formulated in the form of a control system, which informs them about the environment (obstacle detection and identification), and assists their journey while able to warn them about danger and create a smooth navigation feeling while pushing the rollator (avoidance). FORWARD is inherently, all about guidance, navigation, and control, and it borrows aspects from other fields such as robotics, autonomous driving technology, and more. The following section of this document is research of the existing similar products, technologies available, comparison of components to meet design requirements (specified in 2.3), and proposed architectures for system integration.

### 3.1 Existing Products and Projects

There have been numerous efforts made by researchers to develop smart walkers using the available technologies. Perhaps the seminal work in this growing field of research and development is [2]. This group was the first to propose a smart walker project with localization, mobility control, and object avoidance. In the following sections we seek to analyze these technologies and methods in a way that identifies which of such will be most desired for our specific system, taking into consideration many factors, some of which being: cost, attainability, integration complexity, and performance. We also find hardware and software solutions to implement the strategies of design based on [2]. As we will see, these take the form of sensors, processors, and actuators - forming an integrated guidance and control system.

### 3.1.1 Current Walker Sensing Applications

Sensing is required to situate and guide the FORWARD walker safely. There are a plethora of technologies and methodologies available today, and we explore some of those.<sup>1</sup> In the smart walker prototype created in [1], nine HC-SR04 ultrasonic sensors are arrayed along the front of the walker. Seven face forward, while the remaining two point perpendicularly to the walker motion and opposite to each other. This setup provides a continuous reading of the walker's forward hemisphere with a detection range of 200cm. Our team aims to provide obstacle detection and notification, achieved with a more discrete array of sensors stowed onto the walker frame. We aim to maximize the operational FOV for ultrasonic sensors without requiring a large amount of them. We also anticipate that the introduction of supplemental LiDAR and camera technology will affect the ultrasonic approach. If it happens to be that obstacles have protruding edges, sensors at varying heights along the walker might be required. For instance, a highly directional sensor might miss a railing. For this reason, we also explore camera options later in this section to reinforce and prevent miss cases.



Figure 4: "Rollator" with nine HC-SR04 sensors [1]

Robotics are a popular use of LiDAR, often able to achieve feats such as autonomous delivery. However, many researchers have also introduced laser sensing methods and other waves near infrared in order to provide ranging data to mobile systems, which in our case is the walker. A senior design group at Michigan State University expanded on this [15]. Their approach to prototyping is beneficial for reference, as they utilized LiDAR Lite and HC-SR04 ultrasonic sensors, all encased with a housing mounted on the crossbar of the handles.

---

<sup>1</sup>This walker does not employ GPS technology. We are not looking primarily to track the location continuously. This technology has more of a place within the application of health monitoring and emergency alerts. Additionally, we are not using LiDAR environment mapping as many autonomously navigating delivery robots do. This requires what we believe, is an overabundant amount of processing which detracts from the dual nature of the FORWARD user control and guidance

This team maintained a discrete add-on to the walker, which is an advantageous feature for the users in their everyday life. It is also from this work that we obtain the incline and decline testing for the prototype, and this is a driving factor for including an IMU on-board the walker. In their topology, the sensors are angled downward so the FOV is more likely to detect ledges or divots; however, in the FORWARD system, we consider reducing this downward tilt to increase detection range, but it is a balance of ideal versus practical.

In [14], the group implements one of FORWARD’s stretch features with an unorthodox yet clever utilization of LiDAR and sensor fusion. In order to equip the walker with fall detection, both ultrasonic and laser sensors are installed near the footstep bay of the walker. They also add force sensors in the handlebars. The feedback provided by the sensing system is whether the user is walking uprightly. If the user began to fall, the laser sensors would reflect their feet moving out of view, and likely the force sensors would experience more pressure as the user reacted to a slip. Little inspiration is actually drawn from this source, but it is a good illustration of growing interest in smart rollators.

### **3.1.2 Current Walker Stability Applications**

The byACRE Ultralight Rollator [22] is among a few walkers to feature stability assistance. Initial analysis reveals that this is nothing more than smoothed turning via pneumatic control. The U-STEP Neuro [23] is another that features curb lifting, and it features speed control via mechanical configuration of the rolling resistance. The FORWARD group is considering the impact introducing an additional sensor to capture the attitude of the walker and provide data of its speed and turning movements. This technology is explored further in section 3.2.2. As we can predict, this sensor will be an inertial measurement unit.

### **3.1.3 Current Computer Vision Object Detection Applications**

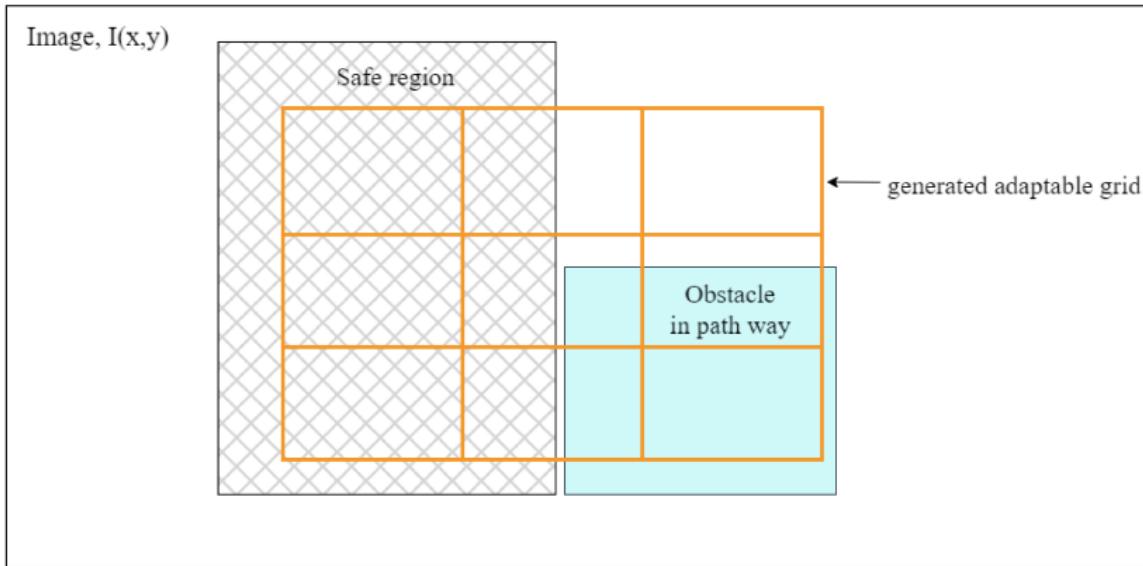
There are currently many attempts to develop an image processing/object detection system that, similar to our motivation, seeks to assist the millions of visually impaired people across the globe live normal daily lives. There have already been multiple attempts to exploit the current state of machine learning and AI to solve this problem. Many of the existing projects implement the YOLO model to develop their object detection algorithms. Many of these projects also implement an audio feedback system to alert the user of any upcoming hazards and important details of such. The following sections detail such research.

The project outlined in this paper [3] aims to provide guidance and navigation to the visually impaired using a user-worn chassis. A notable piece of hardware employed in the project is the high-performance Jetson Nano microcontroller unit

(MCU). The Jetson Nano features are further outlined in section 3.3.6.

The software aspect of this project is mainly comprised through an object classification system that uses the output of the YOLO5 model to classify the threat level of certain objects. By creating an "area of interest" represented by a 2D and 3D grid, they were able to perform calculations to achieve this.

The figure demonstrating this concept is show below:



*Figure 5: 2D Grid with Safe Region Generation*

Referring to the figure above, once the effective safe region is established, the MCU initiates calculations on the YOLO5 output to deliver accurate guidance to the system. Consequently, this group's approach, which integrates YOLO5 with carefully selected AI/ML-supporting hardware and applied mathematics, ensures precision and reliability for the user.

This project also implemented an audio feedback system. In order to interface to the user regarding the surroundings, there are typically two approaches: auditory and tactile feedback. This group decided to implement auditory feedback with a strategic design to target the use of dorsal and ventral processing, looking to engage the part of the brain created for processing visual cues for spatial awareness.

The project outlined in this paper [4] sought to design and implement a lightweight FPGA compatible obstacle detection AI model. This project took an approach similar to our scope in choosing a set of objects to train the model on, and look for based on user needs. This project also used a YOLO5 architecture to perform the object identification. This YOLO5 model is suitable for embedded and FPGA

devices, allowing for a lightweight AI model that is feasible for these applications.

This project seen in [6] seeks to implement a light weight and low cost object detection system using the ESP32 Cam Module. They trained the YOLO3 model on the COCO image data set. They then programmed the board using the ESP32 Cam library. Given this Cam module being connected to an ESP32 chip, they used the WiFi capability to transmit the photos to the laptop. The problem unsolved by this project is that the AI processing is done on a laptop, which has significantly more processing power than our MCU, but proves that this camera is suitable for our purposes of image capturing and transmission.

While the article above primarily addresses the camera solution, it references another article [7] that implements a camera solution that can perform the object classification processes as well. The Camera board is the *Realtek AMB82-Mini IoT AI* Camera Board, which contains many desired features for our purposes, all of which are outlined in section 3.3.5 (*Camera Technologies*). In the project referenced, they were able to successfully identify and detect 80 distinct objects of many different categories. They used the Arduino IDE to program the board and then demonstrated functionality. The board transmits the data fully over WiFi as well, which would minimize the overall footprint for our project but minimizing the need for wiring.

### **3.1.4 Current Audio Feedback Applications/Technologies**

There are currently many existing projects that exist to implement Bluetooth communication on a microcontroller (MCU). One of these projects [5] implements Bluetooth Low Energy (BLE) to send sensor data to an ESP32 MCU. Bluetooth devices use GATT stands for Generic Attributes and it defines a hierarchical data structure a hierarchical data structure (GATT) to define a standard communication protocol.

### **3.1.5 Motor and Steering Applications**

An electric scooter is a vehicle with similar technology and proportions that we plan to use for our FORWARD walker. Electric scooters also use a controller that is used to communicate between the sensors of the scooter and the motors. Similar to our design, electric scooters also implement safety features that require the actuators to respond given sensor feedback, for example, regenerative braking that responds to the handle brakes and electrical component temperature detection [30]. There are even some scooters that employ ultrasonic sensors to detect obstacles and come to a halt in response. An electric scooter that we found to have the capabilities to respond to obstacles uses an Arduino and RKL-1341 Motor driver to control an alarm and braking system [31]. The braking in this system is operated by a DC

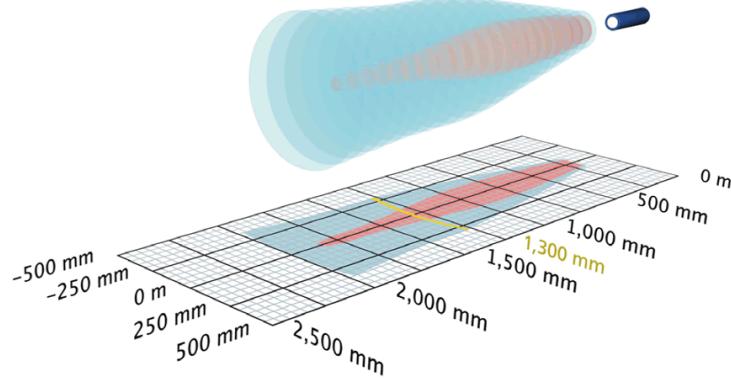
motor that pulls the brake lever, whereas in the scooter with regenerative braking, the DC motors go into reverse and slow down the scooter until it comes to a full stop. With this evaluation are examples of several different ways to implement technology for the same purpose on an equivalent device.

## 3.2 Relevant Technologies

### 3.2.1 Sensor Ranging

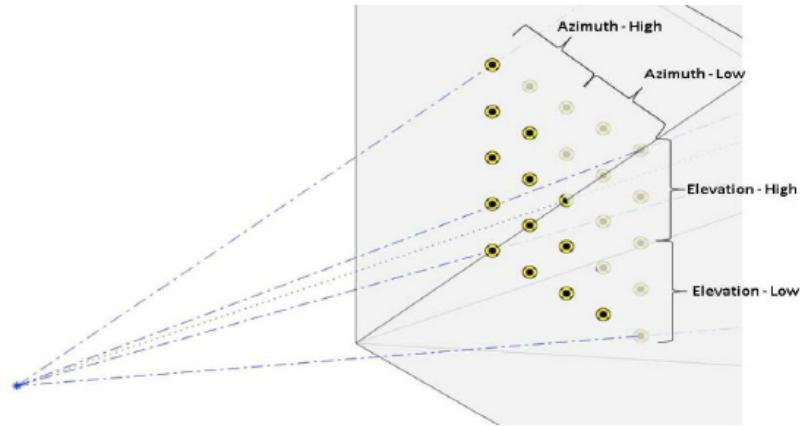
Ranging sensors are used to provide distance-to-obstacle information for a plethora of products today. They are popularly found in robotics, where they are able to provide awareness of the surroundings, vehicles, where they enable autonomous navigation, or for smart facility and home solutions, where they detect movement and are used to trigger various actions. FORWARD requires sensors to enable safe navigation and it is thus appropriate to examine the technologies available to determine which to install on the walker. The intent also is two-fold in that it is desired to gain knowledge of what is attainable, namely what information about the surroundings can we provide our processor and how accurate and insightful can that information be. Note that, FORWARD does not implement features of user health status or tracking and so we do not examine GPS as a relevant technology. FORWARD navigates autonomously, and it will do this by use of ***time-of-flight sensing***.

**Ultrasonic** There are differing variations of ultrasonic sensing technology, mainly varying by their 1) transmitting and receiving hardware, which can be realized as mono or multistatic, 2) emission and detection capability, which stipulates their active or passive status, and 3) their operating frequency [17]. As far as whether the hardware comes in the form of a multistatic setup or a single transceiver (emits and receives ultrasound), FORWARD's requirements do not necessarily rule out one or the other. Monostatic could be slightly more conducive to mounting on the walker legs and help retain a lower profile because of their smaller (2x) dimensions.



*Figure 6: Ultrasonic Directivity [20]*

LiDAR We deploy LiDAR in the context of this project as 1) oriented laterally, 2) topographic, and 3) using the scanning method fixed/solid-state (as opposed to swivel or rotating) without flash [16] (because we are not desiring to create maps). As designers, we must also consider that LiDAR reliability may be affected by the reflectivity of the target objects and ambient lighting of the surroundings. This is one of the primary reasons both sound and light sensing applications are under consideration. Note, figure 7 shows a scanning LiDAR. In this project, the azimuth and elevation difference are both negligible, as the light beam is single-point. Scanning would require another subsystem with servomotors, which is not in specification or budget. By utilizing both sonic and laser sensors however, we can cover a wider range of azimuth. As discussed earlier, the camera is able to cover more elevation for detection.



*Figure 7: Scanning LiDAR FOV [21]*

### 3.2.2 Walker Stability

Inertial Measurement Units are comprised of a magnetometer and accelerometer, which obtain the acceleration and body rate readings of the walker. This is traditionally done by reading a gyroscope rotation or looking at the magnetic field. It could be greatly beneficial to gain this data, not only for analytical use, but for functionality. Some of the stretch requirements include curb lifting, fall prevention, and incline decline adaptation. With an IMU on-board, the walker can respond appropriately to each scenario. For instance, when lifting over a curve, there can be a certain pitch angle limit imposed to prevent tipover. This is expanded in a similar fashion for fall prevention, where if the user leans too much on the handlebars and causes a tipover, the IMU data can inform the motors of a decision. Finally, the IMU angles are also useful when traversing over inclines or declines. The body rates may also be useful for stability while turning, smoothing the yaw maneuver.

Sonar vs. LiDAR for Detection As gleaned from [18], ultrasonic sensors are advantageous for their low cost, simple digital input and output, and wider FOV. However, they lack in their exposure to environment, slower response time, and larger physical size. LiDAR sensors on the other hand, are small and lightweight, and have a fast response time. However, they generally cost more and have a more narrow FOV because of their environmental seal and laser physics.

Balanced Sensor Informants When comparing the selling points of cameras and traditional sensing methods, we see that each have their advantages. Cameras allow for the most detailed information about the shape and size of the obstacle, but they rely on a lens that can become dirty. The camera may also not operate well in lowlight environments. By still including the ultrasonic and LiDAR, FORWARD can always sense obstacles and have multiple informants. Each sensing method covers the next. When ultrasonic may be affected by wind, the LiDAR is not. When the reflectivity of an object may obscure the LiDAR, the sound waves can still detect. [19].

Sensor Fusion Implementation of sensor fusion to converge on a most accurate range solution would not be beneficial derived from the ultrasonic and LiDAR outputs, because they should both give nearly identical readings, and thus, leaving no need for fusion. However, it could greatly enhance the computer vision by allowing it to not only identify and classify hazards, but also aid with range detection. The range given by the camera's depth perception could be fused with the more reliable range readings from the front of the walker to further confirm the presence and distance of obstacles. Additionally, the camera could inform the avoidance subsystem of ultrasonic and LiDAR range data to for any reason, ignore.

### 3.2.3 Computer Vision Object Detection

The Object Detection section of our system will be used to identify and alert the user of their surrounding environment. Because of this, we will need our system to be real-time and highly accurate. The main model used for this is known as YOLO. Many of the current object detection applications implement a YOLO model to process the image data. These algorithms works based on the following four steps: Residual blocks, Bounding box regression, Intersection Over Unions or IOU for short, and Non-Maximum Suppression. Residual blocks divide the image into an N by N grid, in which each section becomes a sub-problem. The algorithm then seeks to calculate a resulting vector through bounding box regression. The vector contains the confidence of an objects presence (pc), the image center (bx, by), and the area of the object (bh, bw), resulting in  $Y = [pc, bx, by, bh, bw, c1, c2]$ . c1 and c2 are the possible classifications. It's also worth noting the bh and bw can be greater than the size of the grid. The algorithm then uses intersection over unions and non-maximum suppression to determine what information has the greatest meaning, and thus, we have a prediction. It should also be said that the above describes how to model runs in real time applications, and operates on the assumption that the model has been trained, which in many cases, it has been trained on the MSCOCO data set.

### 3.2.4 Current Audio Feedback Technologies

The Audio Feedback portion of our project needs careful consideration given it's importance in providing the user with audio cues for their environment all the while still being implemented on an embedded MCU, which is likely to contain limited resources. The MCU's considered for this project all contain Bluetooth capabilities and so we will be diving into research for successful products for our application.

Bluetooth [10] is another key component to the success of our project. Before looking further into the audio feedback technologies, let us first explain how Bluetooth works and how it will be crucial for our system needs.

To successfully communicate important visual information to our user, we need to do so audibly; and to communicate audibly without interfering with the user with wires. Due to the target users being visually impaired, it is crucial to limit any possible hazards - thus creating a large need for Bluetooth technology. Bluetooth is a wireless communication protocol that transmits on a range centered at 2.45 GHz. Bluetooth is designed to connect clients of short distance, usually 0 to 30 feet, and can be on up to 79 channels. Bluetooth [11] also has two modes: classic and Bluetooth low energy (BLE). Classic is the standard Bluetooth we use daily but BLE is a newer technology which takes classic Bluetooth and makes it low power, which is optimized for close range applications and increased security. Bluetooth protocol allows for it to be very efficient through the concept of *spread-spectrum*

*frequency hopping*. This concept is pictured below in figure 8.

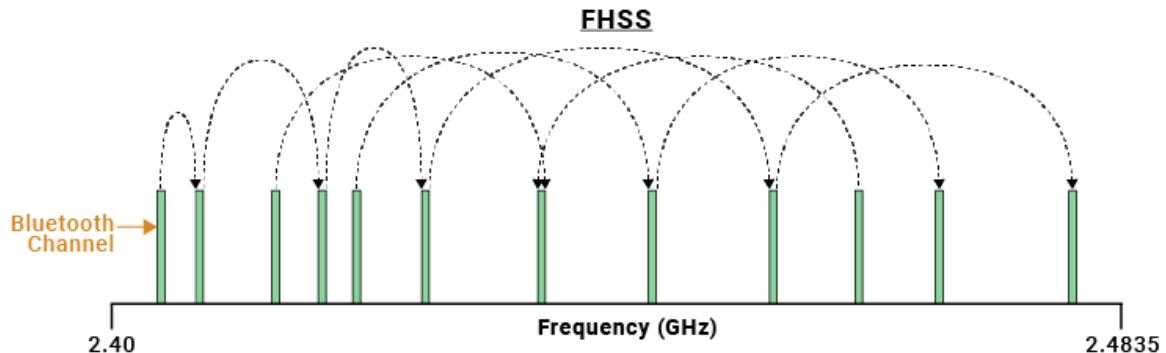


Figure 8: *Bluetooth Spread-spectrum Frequency Hopping*

Spread-spectrum frequency hopping is when two devices want to communicate, they look for a channel that is available by hopping frequencies. This concept also adds to the security and non-interfering capabilities of Bluetooth because many Bluetooth devices will do this up to thousands of times per second. Bluetooth is mainly used to connect electronics of close ranges, and is commonly used for audio applications - which will be our use as well.

Now, The first technology considered is based upon Bone Conduction technology [9]. Bone conduction technology allows users to perceive sound through the vibrations of the bones in the inner ear. One of the main benefits is that audio information can be received even if the ears canals are blocked, which allows for definite communication to the user. Conversely, it also addresses one of our biggest goals with this system by not obstructing the user's ears. The bone conduction technology ear pieces sit on the outside of the ear, providing complete freedom for the user's ear. Some secondary benefits of bone conduction are increased clarity and reduced background noise as well. While this technology is very advantageous for our goals, some health and comfort disadvantages exist. Prolonged and extraneous use of this technology has been seen to cause hearing loss, vertigo, and tinnitus. This technology can also become uncomfortable to wear for extended periods of time. On average, these headphones have 8 to 12 hours of play time and bluetooth capabilities.

The second technology considered is Ambient Sound Earbuds. In order to use a headphone that blocks the ear canal - it would require the use of ambient sound technology to still allow the sound from the outside world. The reason this is of importance is to allow the user to still maintain audible awareness of their immediate surroundings, which if hindered too much, can be severely hazardous. Albeit, even the current state of ambient sound technologies is not the greatest, and can introduce risk for the user having one or two of these earbuds in. The technical specifications for these products include - 5 to 8 hours of playtime. They

cost \$25 to \$50 which can be in our expected range and affordable.

The third technology considered is *Open Air Bluetooth Speakers*, coming directly from the chassis on the system. In general, bluetooth speakers are a highly developed technology, which means they are highly reliable with a wide variety of options for our needs. They can cost anywhere from \$20 to \$300, and can run 8 to 20 hours of battery life. The main downside though has public disturbance implications as it would impede on everyone's daily life around the user. The other downside is we introduce risk by not directly relaying the information to the user, such as in a loud room.

### 3.2.5 Motor Shield/Driver

FORWARD is a system that implements motors to accomplish complex movements, therefore it is required to have a motor driver to interface between the motors and the MCU. Motor drivers are electronic devices that provide the ability to control motors. For example, a DC motor is functional if simply connected to power and ground, however, reversing the direction would take a manual change in polarity and the speed would be constant. Using a motor driver will allow us to control the speed, direction, timing, and torque of the motors [33]. However, these controls do not all occur in one motor driver, but in several varieties of drivers (although can be combined in a motor controller as discussed below). To regulate the power, a motor driver could either use a linear regulator or a switching regulator [35]. To regulate the speed, there are motor drivers that implement pulse-width modulation (PWM). To control the direction and provide for braking, an H-bridge is used for a motor driver, which uses transistors as switches to change the polarity of the motors. When a positive voltage is applied across the motor, it will operate in the "forward" direction, if a negative voltage is applied to the motor, it will operate in the "reverse" direction, and if the voltage is shorted, the motor will "brake" by coming to a stop [35]. However, this short-circuiting may cause damage to components in the circuit [32]. Another reason why motor drivers are important in general is that the MCU cannot directly control the motors as they are a large load drawing much power [32].

Motor drivers are fairly simple devices, while there are also motor controllers, which are devices combining motor drivers that directly connect to an MCU and provide support for a hardware and software interface. Motor controllers typically provide more control than a motor driver because they receive feedback, correct for errors [32], power management and can use several motor drivers all at once, including H-bridge and PWM [34]. The motor controller also communicates easily with the MCU using serial communication (SPI, uART, etc.) and often includes libraries that simplify the process of programming the motors. However, motor controllers tend to be more expensive than motor drivers [32].

### 3.2.6 Speed Control

In order to control the speed of the motors, the technology behind this ability is what is known as Pulse Width Modulation (PWM). PWM is a method of allowing the motors to spin for a certain percentage of time within a given a time period. This means that voltage will be applied periodically for a certain duration and will alternate between “on” and “off” For a motor driver set to a duty cycle of 25%, power is applied to the motor for the first quarter of the period and remains off for the remainder of the period. Because the motor is only operating for a percentage of the time, the motor runs slower than a full duty cycle of 100%. Meanwhile, a duty cycle of 75% is a more average velocity between 25% and 100%. The figure below illustrates the difference between duty cycles. PWM is the technology used to control the speed of the motors, and is directly set and altered under the software controlling the motors. [35].

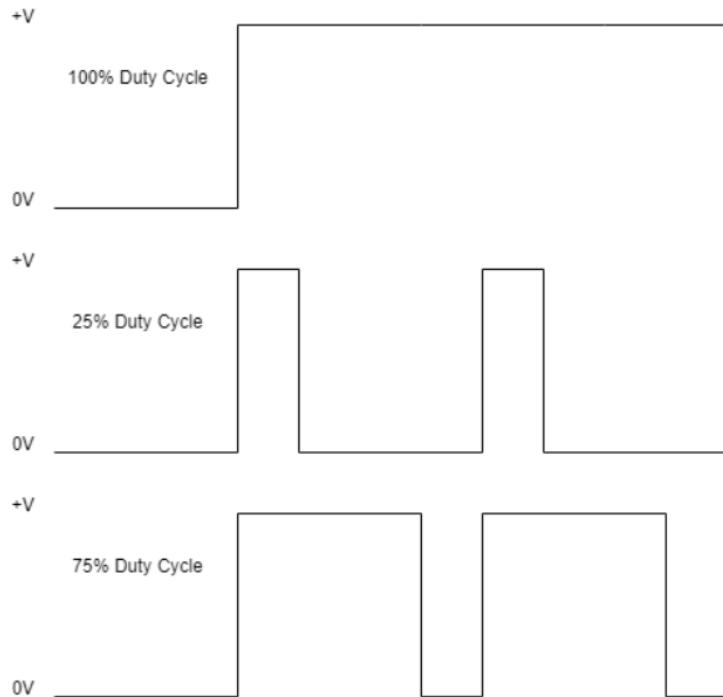


Figure 9: Pulse Width Modulation Duty Cycle Graph

### 3.2.7 Steering and Braking Method

One of the main functions of FORWARD is obstacle avoidance, meaning that after sensing and identifying obstacles, the walker must react. In order to dodge obstacles, the walker must steer out of the way of the obstacles, dependent on where the object is detected and the surroundings. One common method of steering, similar to a remote-controlled car, is to use a servo motor to turn an axle containing two of the wheels, at either the front or the back. However, we are using a rollator

and not a car. In order to reduce mechanical complexity, as we do not have axles, we will control the steering using individually controlled wheels. Two of the wheels of the walker (either the front two wheels or the rear two wheels) will each have a DC motor. The direction of the product can then be determined by the speed applied to each motor. To illustrate, if the walker detects an object straight ahead and sense that there is an open pathway to the right, it will veer right by keeping the velocity of the left motor constant while decreasing the velocity of the right motor proportional to the angle the walker is turning right. Likewise, if the walker needed to veer left to avoid the oncoming obstacle, the velocity of the left motor will decrease by lowering the duty cycle while the right motor remains at the same velocity.

Another aspect to obstacle avoidance is sometimes simply to break. There are instances where it is most beneficial for the walker to come to a complete stop, for example, if the sidewalk ends and leads into the road or if there is no room to pass an obstacle to the left or to the right. In order to accomplish this task, we again wanted to avoid mechanical complexity. A common solution to braking is to use hydraulic brakes that respond to a handle being squeezed. While it is certainly possible to implement hydraulic brakes into our design and automate them mechanically, we desired to exercise our learning in software design rather than mechanics. Thus, our method of applying brakes to our design is to slow down the DC motors driving the walker until the motors turn off and then reverse the direction of the motors until the walker comes to a complete stop. However, there may be a need for locking the wheels, similar to the emergency brake on a car, so that the walker does not roll away from the user when stopped [89].

### 3.2.8 Power Supply

In order for our FORWARD walker to operate, it needs to have a power source(battery) as well as a power supply to recharge this source. Power supplies are needed to first step down the voltage supplied by an AC source to the needed voltage, then to convert this AC power to DC power, reduce noise of the incoming voltage signal, and finally to regulate the voltage in charging the battery [69]. Since power sources only supply a certain rated voltage, in order to not damage any components, we need to step down our voltage and use a voltage regulator. For example, a 24V rechargeable battery used to power a 21.6V DC motor would need to be stepped down to match the motor at 21.6V, or else the motor could be damaged. The voltage would need to be regulated at this level as well so that the incoming voltage is a steady supply.

We need a battery pack (or multiple) that will be able to deliver enough power both to our motors, our MCU, and other peripherals. It is possible to supply all of these loads with only one battery pack, however, we must take care that the battery pack is suitable to meet the needs of each load. This includes regulating the voltage and current needed per load, accounting for noise (especially from the motors), and

using a common ground [45]. There is also the option of using a separate power supply per load, which would be much simpler in terms of catering to each specific need of the loads, however, it would be less streamlined and multiple battery packs would need to be recharged or changed. It would be more ideal to have one rechargeable battery pack that we can use to supply multiple loads, each with its own voltage regulation. This will also help to reduce the cost as we will not need to buy a battery for every load. However, since some of our components are very high voltage (12-24V, e.g. motors) and other components are lower voltage (3-5V, e.g. MCU [62]), we may have two separate power supplies, one for higher voltage components and one for lower voltage components. This is so that we need not drastically step down the voltage and more current/voltage can be supplied directly to the components with larger requirements. As we know from basic circuit theory, a power source supplying multiple loads will need to either divide the voltage (in series) or current (in parallel) between the loads. Thus, it would be beneficial to minimize the number of loads per power supply. Having a separate power supply for the lower voltage components would not be an extra burden of cost to our team since we could use a rechargeable phone battery pack to supply power.

When deciding upon a power source, necessary requirements to investigate are the voltage and capacity of the battery [88]. When supplying voltage to a load, the voltage supplied must be exact or somewhat lower than the voltage required by the components. This will not be much of an issue as we will regulate the voltage. Since our highest-voltage components are the DC motors driving the wheels, we should not need any voltage source exceeding this voltage. The DC motors decided upon under the parts comparison table have a rated voltage of 21.6V. Loads also draw current from the power source, and in general, the larger current that can be supplied the better. Loads will only draw the current that they are using from the power source, so the rated current requirements of components are minimums, not maximums. Battery capacity is measured in Amp\*Hours, meaning that there is a tradeoff between how much current a load can draw and how long the battery is able to supply such current. For example, a battery with 36Ah would be able to provide power to a load drawing 1 amp of current for 36 hours, or it could supply a load drawing 36 amps of current for just one hour. We specified as a constraint in our engineering requirements that FORWARD must be able to go up to 15 miles. Because the average walking speed of the average person is around 3 miles per hour, our product is required to have a battery life of up to 4 hours. Under the parts selection comparison, the motors that we decided to implement are rated to draw 11A of current, so the desired battery capacity needs to be at least  $1100\text{mA} * 5 \text{ hours} = 5500\text{mAh}$ . Of course, this is a minimum battery capacity; if the consumer of the product walks slower than 3mph or if the motors draw more current than expected under the data sheet, these factors may prevent the battery from lasting a full 15 miles.

### 3.2.9 DC Motor Technology

Our design for FORWARD involves obstacle avoidance, i.e. using motors to drive, steer, and stop the walker. However, there are many different electric motor technologies to choose from, including DC motors (shunt, series, PMDC, compound, brushless), AC motors (synchronous, induction), and other motors (stepper, servo, etc.) [36]. We will not be considering the use of stepper and servo motors since they are not designed to rotate 360 degrees [37], which we would need for the wheels to rotate and drive. We will also not be considering AC motors, seeing as they are powered by an AC source [38] and the FORWARD walker would need to operate with a portable power supply (battery), which supplies DC power. This leaves us with evaluating the different types of DC motors. DC motors operate with 3 basic parts: the stator, rotor, and commutator [39]. The stator is a stationary part that produces the magnetic field that rotates the rotor, while the commutator allows the motor to continue rotating.

Shunt DC motors are DC motors that include the DC power supply, shunt field, and armature all in parallel. Shunt motors are known for their ability to regulate their speed easily, and they can also increase in speed without the typical drawback of reducing torque by increasing current. These motors are most commonly used where a constant speed is desired, for example, a machine in an assembly line or a fan [40].

Series DC motors are DC motors that include the DC power supply, shunt field, and armature all in series rather than parallel. Because the circuit is one loop, each of these components use the same current and the current is not divided between components. This allows for a very strong magnetic field and thus a strong starting torque with a simple design. However, the series motor does not allow for very good speed regulation and there is a large tradeoff between speed and torque [41].

PMDC (Permanent Magnet DC) motors use a permanent magnet in order to generate the magnetic field. The circuit is very similar to a series DC motor, except the circuit components are the voltage supply, back emf, and armature resistance. PMDC motors are generally smaller and cheaper than other DC motors because they do not need windings, however, there is a capacity to the flux generated by these motors. These motors are most applicable where a smaller motor is needed, such as kitchen appliances and windshield wipers [42].

Compound motors combine shunt and series DC motors into one technology. The circuit combines the DC source in series with the shunt field and armature combined in parallel. This allows for the series advantage of a larger starting torque and the shunt advantage of good speed control. These motors are typically used in applications where a larger load is being driven, such as elevators [43].

*Brushless DC (BLDC)* motors are DC motors that use an electronic commutator to continue the motion of the motor rather than a physical commutator and brushes. The electronic commutator switches the voltage of the motor as the rotor rotates to a certain position so that the motor can rotate a full 360 degrees. BLDCs also use a permanent magnet that rotates along with the rotor that creates a magnetic field and is driven by the current. These motors are compatible to be controlled by microcontrollers, efficient, have minimal noise, and have high longevity, therefore they are used in a wide variety of applications, from transportation to everyday devices [44]. The main drawback to BLDC motors is that they tend to be less cost-effective than brushed motors because they are newer to manufacturing and use electronics [45]. Brushless DC motors therefore are much higher quality of motors, however, they will need to be compared with brushed DC motors to determine if there are motors of comparable price.

Power and speed will be necessary considerations as well in deciding which motors we need, as well as what we can afford in our budget. Given our constraints, the walker can weigh up to 60 lbs., plus the weight of the person leaning against the rollator can be up to 37% [47] their body weight (rollators are typically rated for 330lbs. [48]) and the wheels can be as small as 6". To achieve speeds of up to 6mph, the motors need to provide at least 336 rpm [46] Using a calculator, we found that for a 60lb electric bike, 122.1lb (37% \* 330lbs) rider load, and a frontal area of  $6.72\text{ft}^2$  (area of the walker plus the area of the person above the walker [50][51]) we would need 267W of power to achieve 6.0mph [49]. This calculator takes into consideration the effects of friction, air resistance, and the percent gradient for a hill. While a walker is not exactly the same as an electric bike, they both carry a rider and need to achieve a certain speed. The main differences between a bike and a walker are that a bike bears the full body weight of a person and bikes have much larger wheels than the walker. However, we already calculated the rider load to only be the percentage of the body weight that is bore by the walker, and smaller wheels actually require less power [52], providing a buffer so that it is possible the walker will need less than 267W of power. However, since we are using 2 motors, we can use 2 150W motors, which should add up to 300W of power [53].

### 3.2.10 Haptic Motors

In order for the FORWARD walker to more wholly provide an alert to the user of obstacles, we would like to implement haptic feedback. This means there will be small motors causing vibration in the handlebars when an obstacle is detected. Haptic motors, as well, need to be controlled using motor drivers [70], so this needs to be a consideration in determining a motor driver. Since haptic motors are simply used for vibration, they are typically much lower power motors, which tend to be cheaper.

There are three main varieties of haptic motors that are commonly used, including the Eccentric Rotating Mass (ERM), the Linear Resonant Actuator (LRA), and the Piezo Module [90]. The ERM is typically the most cost-effective variety, however,

also consumes the most power with the least response time. The LRA form of haptic motor is average in response time and cost, but has the lowest power consumption. The Piezo Module has medium power consumption and comes to a high cost, however has the best response time. The ERM haptic technology is preferable due to a low cost as well as operating as a brushless DC motor. It is more beneficial to use a brushless DC motor because it can easily be connected to most motor drivers. The ERM is also the only haptic technology that is operated using DC voltage as opposed to an AC waveform. The LRA is controlled by amplitude modification of the AC waveform, while the Piezo Module is controlled with a large bandwidth.

### 3.2.11 Voltage Regulation

Voltage regulation is an important technology that will allow us to provide the necessary amount of voltage for each component requiring power. This includes the MCU, each sensor, the motors, motor drivers, and the camera module. As each component requires a specific voltage, a voltage regulator will ensure that input voltage coming from the battery will not burn out any component. Voltage regulation will either step down or step up the input voltage and provide a constant, or regulated, output voltage. However, there are several different methods of voltage regulation available. In light of the below comparisons, a different method of voltage regulation may be needed depending on the component application.

Line Voltage Regulation is a method of voltage regulation that keeps the output voltage constant as the input voltage changes [91]. This type of regulation is crucial for when there is a variation of input power, for example, a dying battery or a wall outlet. If there are any sudden surges in power, or if the incoming voltage is simply noisy, this form of voltage regulation is necessary. This method is commonly used in uninterrupted power supplies, providing a smooth voltage to devices such as computers or monitors.

Load Voltage Regulation is a method of voltage regulation that keeps the output voltage constant as the load attached to the output voltage changes [91]. This technology would be most beneficial for loads that have a large variation in current drawn, a prime example being motors. Motors can draw different amounts of current depending on if the motor is first starting, the stress applied to the motor, and the heat dissipated by the motor.

Series Voltage Regulation is a method of voltage regulation where a variable resistor is connected to the load in series. The resistor varies in response to variance in input voltage[91].

Shunt Voltage Regulation is a method of voltage regulation where the extra current is dissipated by a circuit element, for example resistor, in parallel. This allows for a

constant output voltage with an excess of current[91].

### 3.2.12 Light Sensors

One of the advanced requirements for FORWARD is that headlights will activate when the surroundings of the walker are dark. The walker must use light sensors to be able to detect if headlights are needed. There are several different light sensing technologies available.

Photoresistors are resistors that vary their resistance in response to variations in light. These are common light sensors that are used to measure light intensity as the resistor either restricts or releases the flow of current. As the light intensity increases, the resistance decreases. Photoresistors are not as sensitive to light as photodiodes or phototransistors, however. [96] [95]

Photodiodes are diodes that are able to sense light as current is produced when the energy of photons exceeds the energy of the band gap. When this happens, electron-hole pairs are generated and the electrons can flow. Photodiodes are not only used as light sensors, but also used in optics and solar panels as they generate current. [97] [95]

Phototransistors are transistors that also can be used to detect and measure various forms of light, including visible, ultraviolet, and near-infrared light. Phototransistors produce a voltage as current is generated from light activating the base by forming electron-hole pairs. This technology is the most sensitive to light when compared to photodiodes and photoresistors. [98] [95]

## 3.3 Strategic Components

### 3.3.1 Ultrasonic Sensors

The range solution according to **time-of-flight sensing** is modeled by the simple equation, where  $d$  is distance,  $t$  is time to send and return an ultrasonic pulse, and  $v$  which is the speed of sound (340m/s):

$$d = 1/2 \times t \times v$$

HC-SR04 is probably the most popular ultrasonic sensor used by developers worldwide. Its ECHO pin outputs the time,  $t$ , taken by an emitted sound pulse (sent by a powered microcontroller) (TX) to return (RX). In practice, to continuously sense and report range, the microcontroller will repeatedly send 40kHz pulses to the sensor's TRIG pin, which are redirected by the transmitter as a beam. Using I2C, the microcontroller can read  $t$  and perform the range calculation.

HRLV-MaxSonar MB1000 This sensor features auto calibration, range filtering and many more output options: pulse width, analog voltage, ranging start/stop (real time), and serial output. The designers also claim that this higher quality sensor does not skew the range reading based on the target size as others do. To solve for range, either connect Pin 3 to an analog-to-digital converter and calculate:

$$d(\text{mm}) = \text{bits}_{\{0..1023\}} \times 5$$

Alternatively, Pin 4 gives options for real time range data based on its pull-up voltage. It can return a range on command by MCU or default to 2Hz filtered range data "based on recent ranges." Finally, Pin 5 is serial output in RS232 format, which sends in ASCII, the range in millimeters.

RCWL-1X0X sensors allow for the same solutions method as the HC-SR04 and MB1000. These models feature both UART and I2C serial outputs, in which the distance is read directly from the device using:

UART:  $\text{Distance} = ((\text{BYTE}_H \ll 16) + (\text{BYTE}_M \ll 8) + \text{BYTE}_L)/1000$

I2C:  $\text{Distance} = ((\text{BYTE}_H \& \text{It}; \& \text{It}; 16) + (\text{BYTE}_M \& \text{It} : \& \text{It}; 8) + \text{BYTE}_L)/1000$

During development, using libraries will likely circumvent the need to interact with the sensors at a low-level as shown above (bits and bytes). Later chapters will discuss methods used to test and begin to develop with the components once they are chosen.

H2KA150KA1CD00 operates at the high frequency of 150kHz. Unfortunately, the datasheet does not reveal much more about solving the range than the need to use a rectangular wavwdrive signal and a burst of 10 pulses. This returns an analog voltage output of the range. At a directivity angle of 8+/-2 degrees and a short range viability, this is not an ideal option for FORWARD.

### 3.3.2 LiDAR Sensors

LiDAR Lite V3 is an optical distance sensor manufactured by Garmin (known for the GPS solutions). The listing specifies this sensor is great for applications in robotics and drones. They call it "single-stripe" with its aperture of only 12.5mm. The procedure for obtaining the reading is as follows:

1. Write 0x04 to register 0x00.
2. Read register 0x01. Repeat until bit 0 (LSB) goes low.
3. Read two bytes from 0x8f (High byte 0x0f then low byte 0x10) to obtain the 16-bit measured distance in centimeters

XT-S1 is like the Garmin in that it is a more premium option at a higher price, but it does give a very long range of 30 meters. It allows for active continuous

measurement of range by reading start address  $0x00$ . Its output is hexadecimal, which is easily converted to a decimal reading in millimeters. XT-S1 is specified for autonomous navigation of automobiles and UAV avoidance.

TF Family LiDAR sensors allow continuous ranging and also read by command. Note these have a 20cm dead zone. The designers note the possibility of light shedding on two parts of a surface, at which the range reading could be any value inbetween. They advise avoiding this for reliability. In the greater FORWARD context, we can consider the lesser of the readings for safety, so this is not necessarily an issue.

### 3.3.3 Inertial Measurement Units

Because of the simplistic nature of the application of this technology in FORWARD, extensive research is not as necessary as with the range sensors. We consider two main options.

BNO055 is a 9-DOF (axis) IMU, meaning it contains a 3-axis accelerator, 3-axis gyroscope, and a 3-axis geomagnetic sensor. This device is said to run sensor fusion on-board to provide accurate attitude information. It runs on 2.4 – 3.6V and draws  $0.4mA$  of current when on its low power mode. It can be used in 3-axis only modes, meaning you can isolate the accelerator, gyroscope or magnetometer.

MPU-6050 is one of the most popular IMU devices. It is 6-DOF (no magnetometer), and runs a DMP (digital motion processor) for motion fusion algorithms. Essentially, it calibrates itself, and is said to reduce gyro drift by eliminating cross-axis alignment errors between the gyroscope and accelerator. It operates at  $3.6mA$  with a supply of 2.4 – 3.5V.

### 3.3.4 Computer Vision/AI Image Processing Models

Ultralytics YOLO (You only look once) is an open source AI driven image processing model. The Ultralytics YOLO platform provides an AI Image processing Architecture that is malleable to the users demands, and for our case, would process the input image to detect if one of the five hazards is present, as well as provide a confidence rating for these predictions. To implement the object detection functionality to our specifications, minimal training, as well as coding must be performed. The benefits of this solution for our image classification system include zero cost and easy configurability which are both important aspects for our desired solution. The negatives include the needed man hours to train and implement this model for our purposes and time to run (anywhere from 0.1 seconds to 3 seconds). It also has a relatively high memory footprint (a few hundred MB). The time to predict along with the memory footprint could potentially exclude this

from our options as we need to have classification under 1 second latency, ideally in the realm of a few hundred milliseconds and enough storage space for the model.

FOMO (Faster objects, More objects) is a machine learning image processing algorithm that seeks to solve the problem of running high complexity algorithms (such as neural networks) on MCU's. In the documents referenced [HERE], the Arduino Nicla board is used to classify the objects in frame at a rate of 33 microseconds (30 SPS). The objects can be classified and processed through multiple methods, but all of which would be applicable to our purposes. This system also minimizes the memory usage by needing only 256 KB of memory to run and store these algorithms. On the FOMO website, they claim that this algorithm is compatible with many of the MCU's that we are considering for this project, some of which being an ESP32, Arduino Nicla, Raspberry Pi, and others.

Edge Impulse is a website that is free to use and will allow for you to train models and then generate code for specific target devices. The way it works is, you upload your images for object detection, label and frame the objects, and then train the model. After this, you can choose your target device (Edge Impulse supports RaspberryPi, ESP32, Arduino, and more), and generate a zip file for a library of object detection code. This is a simple to use, low complexity option that supports all of our considered MCUs.

### 3.3.5 Camera Technologies

ESP 32 CAM Board is a ESP32 processor based camera module that can transmit video data at high resolutions, which can be processed by our CV/Image processing solution. The module also has WIFI connectivity that can connect to an MCU to wirelessly transmit the video stream. The module has a 32-bit CPU with a max clock frequency of 240 MHz and 520 KB of built-in SRAM with an external 4MB PSRAM. The board module also runs on FreeRTOS. The included camera, OV2640 camera, has a 2 MP resolution, up to 1600 x 1200 and interfaces the controller board over a 24 pin interface bus. A more advanced sister product to the OV2640 is the OV5640 camera. This camera has 5 MP resolution, up to 2592 x 1944. In order to achieve our stretch requirement of depth perception analysis for guidance and navigation, this camera could be advantageous.

Oak-D Lite is an AI robotics specific camera, capable of running AI models such as open CV. The camera is able to run on-board AI architectures to achieve object classification, edge detection, and feature tracking. This technology allow for high accuracy with object detection, and introduce the ability to implement edge detection as a means to depth perception, which can be used for routing in our GNC subsystem. The Oak-D Lite has a 13 MP RGB camera with auto-focus, as well a 60axis sensor using an accelerometer and gyroscope. It also uses USB2 and USB3 for power and communication, which is simple to interface to a

RaspberryPI. The camera can run 4K at 30 FPS or 1080P at 60 FPS.

*Realtek AMB82-Mini IoT AI Camera* is a lower cost option (\$25) to incorporate an AI object detection system within the camera and board. The specifications of the device are as follows: The MCU is an ARMv8M running up to 500 MHz, accompanied by an NPU with an Intelligent Engine capable of 0.4 TOPS. It features 128 MB of internal DDR2 memory. Connectivity options include dual-band Wi-Fi and Bluetooth 5.1. The audio code supports ADC/DAC/I2S, and the ISP/Video functionality includes both 1080p and 720p at 30FPS. The camera module is a JXF37 full HD CMOS image sensor with a resolution of 1920 x 1080 and a wide-view-angle FOV of 130°. The interface includes 1 microphone, 2 Micro USB B ports, 1 MicroSD card slot, and support for 3 UARTs, 2 SPIs, 1 I2C, 8 PWMs, 2 GDMA, and a maximum of 23 GPIOs. This solution would free up processing power on our MCU which could be of great value given the high workload placed on our MCU including sensor fusion, motor controlling, image processing, and other needed functionalities. Also, due to the high memory capacity (128 MB DDR2), we could implement a higher quality detection model.

### 3.3.6 MCU Technologies

The Embedded Processor/MCU for the project will be the "brains" of the system. It will bring together every other subsystem cohesively and run all necessary computations, while needing to maintain a minimal footprint in aspects such as power and physical size. We must also consider the cost effectiveness. It will also need I2C communication buses to interface the Sonar and LiDAR Sensors, Bluetooth to communicate with the audio feedback device, WiFi to communicate with the Camera, and UART/SPI/I2C to interface with the motor drivers/controllers. Given all of these needs and constraints, we will be looking into the current state of MCU products.

*The ESP32 MCU* is a small but powerful microcontroller with many features. These features include UART, SPI, and I2C communications, 4 MB - 8 MB of flash, with some PSRAM options. These boards also have WIFI and Bluetooth connectivity. The ESP32 series of MCU's range anywhere from \$9 to \$12. The current existing boards are ESP32-DevKitC-32E, ESP32-DevKitC-32UE, ESP32-DevKitCVE, ESP32-DevKitCVIE, and ESP32-DevKitCS1. The main difference between these boards are size and types of memory (4 MB - 8 MB and PSRAM/FLASH) along with antenna type (IPEX vs PCB). The ESP32 family also has a variety of products, such as camera modules, motor controllers, and others. The ESP32 is also easy to program as it is compatible with the Arduino IDE.

The final consideration for the ESP-32-WROOM DevKitC is which of the variation would best fit our purposes, the standard, U, or D series. The D contains a different PCB design relative to the standard which improves RF performance. The U is

optimized for wider range WiFi capabilities due to an external IPEX antenna. The cost is slightly different coming in at \$6.67, \$6.67, and \$7.50 respectively. The D is the best fit for our purposes given we don't need wide range WiFi since the system is within a cubic meter in size, but the RF performance improvement of the D would be helpful given we will be transmitting our camera data over WiFi.

The RaspberryPI 4 model B is a small computer with a 64-bit quad core processor running at 1.5GHz. The RaspberryPi has both dual-band 2.4GHz and 5GHz wireless LAN and Bluetooth 5.0/BLE. The Pi also has Ethernet capabilities along with a 40 pin GPIO header. It uses the Broadcom BCM2711 processor chip and comes with memory options of 1GB, 2GB, 4GB or 8GB LPDDR4-3200 SDRAM, as well as having a micro-SD slot for additional memory capabilities. The board also features many I/O ports, such as 2 USB 3.0 ports, 2 USB 2.0 ports, 2 HDMI ports, and a 2-lane MIPI CSI camera port. The board ranges from \$30 to \$50 and can be purchased online.

The Jetson Nano is a complex, high powered MCU designed for AI/ML applications. It is an NVIDIA product with a 128-core NVIDIA Maxwell™ GPU and a quad-core Arm® A57 CPU. It comes with 4 GB of 64-bit LPDDR4 memory and supports MicroSD storage. For power, it supports both 5 V, 4 A DC power and 5 V, 2 A via Micro-USB. In terms of connectivity, it offers a USB 3.0 Type-A port, a USB 2.0 Micro-B port, an HDMI/DisplayPort output, and Gigabit Ethernet. The board also includes various general-purpose input/output (GPIO) options, along with interfaces for I2C, I2S, SPI, UART, and a MIPI-CSI camera connector. These features make the Jetson Nano a robust solution for real-time processing tasks needed for guiding and navigating. This board is designed for running AI/ML applications. The MCU can cost anywhere from \$250 to \$500 depending on the model and specifications.

### 3.3.7 Motor Controllers

When evaluating motor controllers, there are several factors to consider and are largely connected to our decision of motors. The voltage range of the selected motor controller must be able to provide voltage as low as 5V and as high as 21.6V as well as provide a current of at least 11A. This ensures that both types of motors we selected are able to function properly.

UMLIFE is a high voltage motor controller with a large rated current. This controller uses pulse width modulation to operate the motors and has a quick delivery time. However, it is only able to control one motor. In the design of our FORWARD product, we will need a total of four DC motors: two motors to drive and guide the wheels, and two motors to provide haptic feedback. Thus, it is desired that we select a motor controller or combination of motor drivers that are able to control all four motors.

MKSESP32FOC is a motor controller that allows for 2 DC motors to be operated at one time and can either utilize I2C or SPI communication. However, this controller only provides a limited voltage range of 12-24V and can only support a current draw of up to 6A per channel. The current draw is an issue because the DC motors that we selected have a maximum current draw of 11A. Likewise, because of our motor selection of haptic motors (3-5V), the MKSESP32FOC would not be able to support the haptic motors.

768861A\_Y1181 is a motor controller that operated in the range of 5-30V, ensuring that it can be utilized both for haptics motors and wheel-driving motors. This controller also provides 4 DC motors supplied with up to 10A of current per channel. This is less than the 11A maximum current drawn by the selected motors, however, upon examining the data sheet, this driver allows for somewhat larger current than the rated 10A to flow, with some degradation of the lifespan of the controller, as there was a graph labeled Life expectancy vs. Current of Load. If the motors draw up to 12A of current, the expected life expectancy according to this graph would be 80,000 operations. This should not be too much of an issue as the 11A drawn by the DC motors do not operate continually at 11A; it is simply a peak or maximum current. Although this may be seen as a reliability issue if used in industry, for our purposes, 80,000 operations should be far more than enough. Overall, this is the controller that would best fit our design as all of the motors can be controlled from one board, reducing the cost, and all of the motors are able to be driven within the correct voltage and current range.

ESP32FOC is a motor controller that provides plenty of current: 20A. However, this controller can only power one motor at a time, thus requiring a total of four motor controllers. This would greatly increase the cost. The voltage range of 12V-28V is also not suitable for controlling the haptic motors.

TB6612 is a motor controller that is lower voltage, with a range from 5-12V. This would work sufficiently for operating the haptic motors, however, not for operating the motors driving the wheels. This controller also only supplies 3A of current per channel, which again would be sufficient for the haptic motors, but the other motors draw too much current. The benefit of this controller would be that it can operate up to four motors at once.

For our purposes, at first glance, it would be ideal to invest in a motor controller. This is because a motor controller would be simpler to program and more risks are taken care of at the controller level. We also need to use multiple drivers since we will need to control a number of motors. However, one of the constraints for this course is significant PCB design. This means that we have a limit on the number of development boards that can be integrated into the PCB. Many motor controllers are development boards, meaning that they include an MCU already integrated into a pre-designed PCB. Thus, in order to meet the requirement of significant

PCB design, we need to evaluate if there is a suitable motor controller that does not use a development board. If we are unable to find such a motor controller, it will be necessary to implement the use of motor drivers and integrate them into our PCB design. After comparing our options, the motor controller that we found most suitable for the needs of the DC motors is the 76881A\_Y1181, which employs a development board. We are limited to the number of development boards and discouraged from using them unnecessarily, therefore, we plan to use motor drivers instead that will control each motor individually. In addition, the inclusion of another development board could increase complexity as it must communicate with the main ESP32 over Wi-fi.

### 3.3.8 Motor Drivers

Evaluating motor drivers is a very similar process to evaluating motor controllers. The main criteria we need to look at are a) voltage matching, b) minimum current, and c) number of motors controlled. However, for criteria c), it is most typical for motor drivers to only drive one motor at a time, so we will likely need to buy multiple motor drivers at a time. Also, since the haptic motors will be controlled separately from the wheel-driving motors, we can better match the voltage and current requirements to each motor.

B09P6D5TMV is a low voltage motor driver for the purpose of driving the haptic motors. This driver has a large range of 1.8-15V, well encompassing the 3-5V range of the haptic motors. This driver also supplies 2A of current, which is far above the necessary 15mA. However, there are less resources available for this driver compared to other drivers as it is less commonly used.

L298N is a very large voltage-range motor driver (from 5-35V) that will be able to allow for the haptic motors to be operated. 2A of current are supplied from this motor driver, which is sufficient for the haptic motors, and this driver also allows for two motors to be driven from the same driver. The L298N is also the most cost-effective option and the most widely used driver out of the haptic motor drivers, providing for plenty of documentations and resources.

DRV8871 is a motor driver that has a large voltage range of 6.5-45V, however, this is outside of the allowed range for our selected haptic motors. Although it supplies plenty of current for the haptic motors (3.6A), it is not enough for the wheel-driving motors and thus we cannot use this option for either type of motor. This driver is also least cost-effective haptic driver.

RRPDMSGSPC is a motor driver with a large voltage range of 12-40V, enveloping the necessary value of 21.6V for the selected DC motors. This option also supplies a maximum current of 10A, which may or may not be enough current supplied to the motors. If the motors draw their maximum current of 11A, it is

possible for this driver to be damaged. This driver also only controls one motor, so it is not the most cost-efficient.

BTS7960 is a motor driver that is rated or 27V, above our necessary 21.6V motor. Although this driver does not provide a range, typically the voltage range is centered around the rated voltage. When it comes to current, this driver provides the maximum amount of current out of any of the drivers. Although it comes at a slightly higher cost, the BTS7960 comes in a package of two, which is needed to provide for both motors and thus is net most cost-effective. Thus we decided to select this driver.

RR-6-90V-15A-PSC is a motor driver with the widest voltage range of 6-90V. This driver leaves no question if the 21.6V motors are able to be driven. The rated current for this driver also covers 15A of current, which is 4A above needed. However, this driver only comes in a package of one, and thus purchasing two drivers will come at double the price of \$9.99.

## 3.4 Possible Architectures and Related Diagrams

### 3.4.1 Proposed Sensor FOV Topology

A ranging apparatus comprised of four ultrasonic sensors, one central LiDAR sensor, and optionally, a camera with spatial AI, should provide ample ability to FORWARD's object detection feature. Two wide FOV ultrasonic sensors face forward: one on each walker leg. Two face sideways, also mounted on the bottom half of the legs. The LiDAR sensor is mounted centrally so its beam detects straight-on obstacles. The camera is also mounted centrally. Finally, we angle these downward to allow for detection of obstacles present at the knee down height level. Additionally, a zero energy return from the ultrasonics or LiDAR could constitute a drop-off or ledge or divot. This will be elaborated upon in obstacle classification and identification.

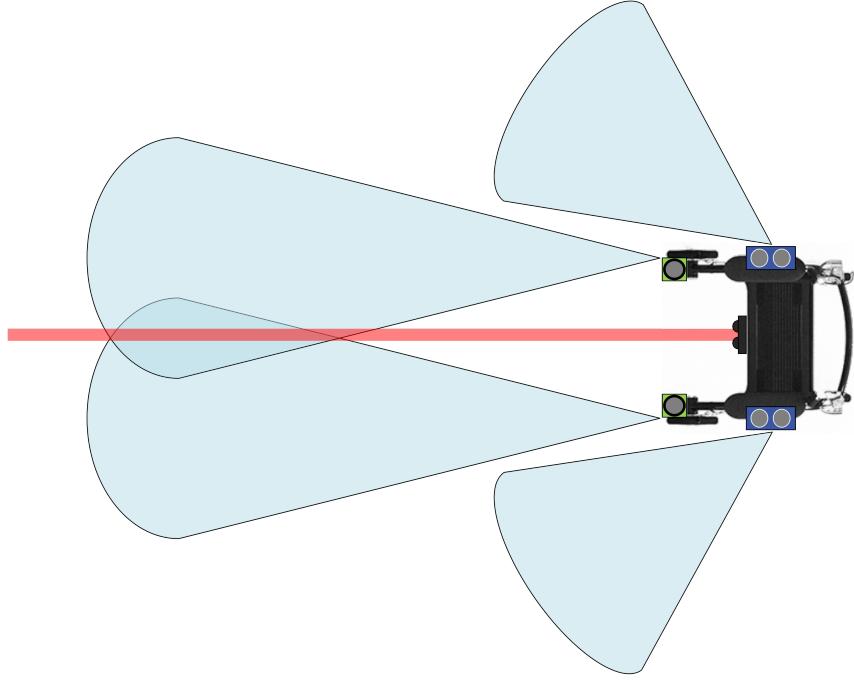


Figure 10: Proposed Sensor FOV (Range NOT to scale)

As mentioned in 2.2, the object detection data must work hand-in-hand with the identification and avoidance schemes. With identification, the range data is combined with any potential depth perception data generated by the camera. The closer the walker gets to the obstacle, the more urgently the system can respond. With avoidance, motor commands should be generated proportionately to the severity of the obstacle range-to-walker frame. Determining these specific plans of action is elaborated in later sections.

### 3.4.2 Euler Angles

Euler angles are one of our data streams that will inform FORWARD’s guidance commands. We define a body reference frame whose center is the center of gravity of the rollator (with chassis and power supply mounted already). From there, we can monitor the *attitude*  $[\psi, \theta, \phi]$ , or orientation, of the body frame, as represented by angles measured from the three major axes. The positive x-axis is defined as orthogonal to the front face of the rollator - in other words, forward looking-aft. Then, a positive rotation around this axis is defined as clockwise, or to the right, and results in a positive roll Euler angle,  $\psi$ . Next, we define the positive y-axis as perpendicular to the x-axis, using the right hand rule convention. A rotation about this axis is defined as positively clockwise, resulting in a positive pitch Euler angle,  $\theta$ . Finally, the positive z-axis is orthogonal to the xy-plane, and a positive rotation is rightwards. This results in a positive yaw Euler angle measurement  $\phi$ . We could theoretically define new reference frames, and perform coordinate

transformations into those frames in order to gain new insight into the rollator attitude, but that is not necessary for the scope of this senior design project. We will simply monitor these angles to ensure stability, and aid the guidance of the user.

### 3.4.3 Velocity and Position Solution

With the addition of the IMU as indicated in section 3.3, FORWARD is able to resolve its relative velocity and position based on a starting point by twice integrating the accelerometer data output. By tracking these updates, FORWARD can be more self-aware of its current traveling state. Not only is the IMU useful for tilt detection (identifying incline and decline), but it can also be used to verify and validate the range data output by the LiDAR and sonar sensors. For example, the software can have some condition where, if the range decreases under a predetermined threshold of danger, then the IMU data can reset and begin tracking position and velocity, with that initial point as the origin of the reference frame. This can allow for very precise geometric abstracted data visualization of the free space ahead and the trajectory of the walker.

### 3.4.4 Kalman Filter

As part of the project stretch requirement for depth perception using an upgraded camera, implementation of a typical sensor fusion algorithm will help to predict the walker's trajectory and provide counteractive insight to the guidance system. Implementation of a Kalman filter estimator would not be beneficial for the fusion of the LiDAR and Sonar data, because the delta between these should be small, and thus, would not provide any helpful insight to FORWARD. However, if obtaining a second range solution from AI depth perception, this data could be fused to choose how much credence is given to either the standard range solution or the computer vision. Essentially, this functionality would be able to minimize measurement noise originating from the information loss of the sensors, and to maximize the overall precision of obstacle avoidance. [25]

A Kalman Filter generates an estimation based on two measurements (that are likely noisy or deemed untrustworthy) by the following iterative algorithm:

1. Initialize the state estimate and error covariance.
2. Predict the next state and covariance based on previous states, covariance between successive measurements, and process noise (amount of credence given to either measurement).
3. Update the measurement based on the Kalman gain.

### 3.4.5 Quaternions

The BNO055 inertial measurement unit has a distinct advantage that involves a particularly interesting mathematical formulation. It is able to output quaternion data. Quaternions are a complex mathematical formulation which can be used as a replacement of sorts to *Euler Angles*, mainly addressing the gimbal lock issue of Euler Angles, which occurs when two torus of rotation align and thus reduce the degrees-of-freedom. Quaternions generally are able to all for a smoother representation of rotations, using four dimensions (three imaginary) to transcend the three. [24] FORWARD will likely not make use of these, but they are quintessential in the field of guidance, navigation, and control, and thus warrant a mention in this study. See the fundamental representation:

$$i^2 + j^2 + k^2 = ijk = -1$$

### 3.4.6 Typical CV camera setup

### 3.4.7 Typical steering motor control wiring

## 3.5 Part Selection

Model	HC-SR04	RCWL1XX5	RCWL1670	MB1000	H2KA	SEN0150
Type	Multi	XCVR	Multi	XCVR	XCVR	XCVR
Range (cm)	450	550	400	600	250	1000
Angle (deg)	+/-15	+/-30	+/-15	+/-20	8+/-2	+/-15
Accuracy	0.3 cm	+/-2%	+/-2%	1 inch	2 cm	1 cm
Protocol	I2C	I2C	I2C	?	?	UART
Freq. (kHZ)	40	40	40	42	150	49.5
Note		deadzone	waterproof			
Price	\$	\$	\$	\$\$	\$\$\$	\$\$\$

Figure 11: Ultrasonic Sensor Options

Taking into account all the specifications and overall fit with FORWARD requirements, the team selects two HC-SR04 for side-facing, and two RCWL1005's for forward-facing.

Model	SEN-14032	TFmini-S	TFmini Plus	TF-Luna	XT-S1
Type	Single	Single	Single	Single	Single
Range	40m-70% $\rho_\lambda$	0.1-12m	0.1-12m	0.2m 8m	0.3-30m
Angle (deg)	+/-0.5	+/-2	+/-2.3	+/-2	+/-1.5
Accuracy	<5m, +/-2cm	<6m, 1cm	1%-2%	+/-6cm	+/-0.1m
Note	nonlinearity <1m				
Price	\$\$\$	\$\$	\$\$	\$\$	\$\$

Figure 12: LiDAR Sensor Options

The FORWARD team selects the TF-Luna model. Its easy I2C and great range to price point make it a viable option.

Model	BNO055	MPU-6050
Axis	9-DOF	6-DOF
Sensitivity SF Tolerance	1%	3%
Nonlinearity	0.2%	0.5%
Sensor Fusion	Yes	Yes
Price	\$	\$

Figure 13: IMU Sensor Options

The FORWARD team select BNO055 IMU because of its slight advantages. This device is affordable and will enhance FORWARD stability.

Model	ESP32D	Raspberry Pi 4 B	Jetson Nano
Processor	Xtensa dual-core	Broadcom BCM2711	NVIDIA Maxwell GPU
Memory	4MB-8MB Flash/PSRAM	1GB-8GB LPDDR4	4GB LPDDR4
Connectivity	WIFI, Bluetooth	Wi-Fi, Bluetooth, Ethernet	Ethernet
I/O Ports	GPIO, UART, I2C, SPI	GPIO, 2 USB 3.0, 2 HDMI	USB 3.0, USB 2.0, HDMI
Power	5V (varies)	5V DC via USB or GPIO	5V 4A DC, 5V 2A Micro-USB
Price	\$5 - \$15	\$30 - \$50	\$250 - \$500

Figure 14: Comparison of MCU Options

The FORWARD team selects the ESP32 MCU because of it's affordability and I/O ports. This MCU achieves all of our needed functionality at a fraction of the cost of the other products.

Specification	ESP32 CAM	Oak-D Lite	AMB82-Mini
Resolution	2MP/5MP	13 MP (RGB)	1920 x 1080 (Full HD)
Frame Rate	1600x1200/2592x1944	4K@30FPS/1080P@60FPS	1080P/720P@30FPS
CPU/MCU	ESP32 @ 240 MHz	AI Engine, 6-axis sensor	ARMv8M (500 MHz/0.4 TOPS)
Memory	520 KB SRAM, 4 MB PSRAM	N/A	128 MB DDR2
Interface	Wi-Fi/24-pin Cam Bus	USB2/USB3	WiFi/BT/USB/GPIO
Price	\$10-15	\$199	\$25-\$30

*Figure 15: Comparison of Camera Modules for ESP32-based Applications*

The FORWARD team selects the Realtek AMB82-Mini IoT AI Camera because of it's ability to perform all necessary AI processes while still maintaining a cost effective price. It also is a noticeable image quality improvement over the ESP32 Cam.

A stretch requirement of our project is to implement a depth perception capability with our system. Due to the sensor fusion solution that we are taking (using the grid-like field of view described in figure 5) we have decided that we no longer need a high quality of camera to obtain the depth data.

Specification	Ultralytics YOLO	FOMO	Edge Impulse
Processing Time	6-100 ms	10-40 ms	10-50 ms
Memory Usage	Few hundred MB	256 KB	100 KB-1 MB
Supported Devices	ESP32, Raspberry Pi, GPU	ESP32, Raspberry Pi, GPU	ESP32, Raspberry Pi, GPU
Training Complexity	Moderate	Moderate	High
Cost	Free	Free	Free

*Figure 16: Comparison of AI Image Processing Solutions*

The FORWARD team selects to use the YOLO model family because of it's memory size flexibility from model to model as well as it's user friendly libraries to make integration simple.

Model	Suunto Wing	Shokz OpenRun Pro	YouthWhisper
Battery Life	6 hours (playtime)	10 hours	8 hours
Charging Time	1.5 hours	1 hour	2 hours
Water Resistance	IPX8	IP55	IPX6
Connectivity	Bluetooth 5.0	Bluetooth 5.1	Bluetooth 5.0
Weight	45 grams	29 grams	30 grams
Price	\$169	\$159	\$35

*Figure 17: Comparison of Headphone Options*

The FORWARD team selects to use the YouthWhisper Bone Conduction headphones due to their high affordability, solid battery life, and lighter weight.

Motor	Oumefar8r2gund350 [54]	775 DC Motor [55]	No. 14 [56]	SHABEAM A MOTOR [57]	P300 [58]	MBD65WI [71]	S55B-150 [77]
Voltage	12V	24V	18V	10.5V-21V	12V-24V	21.6V	21.6V
Current	0.32A	12A	8A starting	3.3A	7-13A	10A	11A (max tested)
Power	150W	200W	300W	300W	300W	150W	150W
Type	Brushed	Brushed	Brushless	Brushless	Brushless	Brushless	Brushless
RPM	15000	12000	Unlisted	31570	130000	Unlisted	Unlisted
Weight	0.77lbs	0.77lbs	1.23lbs	Unlisted	0.52lbs	0.62lbs	0.331lbs
Arrival Time	3 days	2 days	1-2 weeks	1-2 weeks	1-2 weeks	1-2 weeks	1-2 weeks
Price	\$19.49	\$12.99	\$28.03	\$20.01	\$42.46	\$13.83	\$10.57

*Figure 18: Motor Specifications*

When deciding on what DC motors that we wanted to use, our main concerns were power, current rating, motor type, and price. It was calculated that in order to meet the speed requirements, we needed a total of 300W or 150W per motor. All of the motors investigated thus are at least 150W. It was also preferable to use brushless DC motors, as they are higher in quality (longevity, efficiency, low noise) than brushed DC motors and are more widely compatible with motor drivers. To decide between the brushless DC motors, we mostly looked at price and found the most cost-effective motors, while also keeping in mind the current rating so that we can purchase motor drivers with a large enough current rating to supply the motors. Thus, we decided to use the S55B-150 DC motors.

The FORWARD team selects to use

Specification	B0B4SK8M1C [86]	A19090500ux0371 [85]	Vibration Motor [87]
Voltage	1.5-3.7V	4.5-12V	3-5V
Current	85mA	250mA	15mA
Type	DC	DC	DC
Arrival Time	4 days	4 days	1-3 weeks
Price (Qty)	\$5.99 (10)	\$10.99 (2)	\$9.21 (2)

Figure 19: Vibration Motor Specifications

Haptic motors are small DC motors that are used for vibration feedback in the handlebars of the walker. Because they are only used for the purpose of vibration, these motors are very small and do not draw much current. Our main concern with deciding which haptic motors to use is the voltage rating and price. In order to be compatible with most motor drivers, the motors should be able to be operated at both 5V and 3V. Although not the most cost-effective, we chose the "Vibration Motor" as it has the largest compatibility with motor drivers.

Model	UMLIFE	MKSESP32FOC	768861A_Y1181	ESP32FOC	TBB6612
Voltage	6-60V	12-24V	5-30V	12-28V	5-12V
Maximum Current	20A	12A (6A/ channel)	10A/channel	20A	3A/channel
# of DC Motors	1	2	4	1	4
Protocol	Unlisted	I2C, SPI	UART	UART, SPI, I2C	I2C
Speed Control	PWM	PWM	PWM	PWM	PWM
Library	General PWM Library	Simple FOC Library	Generic library; can use Simple FOC	Simple FOC library	B6612FNG_ESP32 Library
Arrival Time	4 days	1-3 weeks	1-2 weeks	1-2 weeks	Shipped within 2 weeks
Price	\$16.99	\$15.29	\$13.79	\$14.76	\$18.50

Figure 20: Motor Controller Specifications

After comparing multiple factors, we ultimately chose the 768861A\_Y1181 motor controller. This is because our main concern was supplying current to the motors and operating all 4 motors from the same controller. The motors that we chose to drive the wheels draw up to 11A of current, which the 768861A\_Y1181 would be able to handle, although it is rated for 10A, upon examining the data sheet. This motor controller also provides a wide voltage range of 5-30V, which is able to provide the correct voltage for both the wheel-driving motors and the haptic motors. The 768861A\_Y1181 also happens to be the most cost-effective of the motor controllers. [60] [67] [68] [75] [76] [62] [59] [61] [63] [64] [66] [78] [65]

Model	B09P6D5TMV	L298N	DRV8871
Motor	DC	DC	Brushed
Voltage	1.8-15V	5-35V	6.5-45V
Maximum Current	2A	2A	3.6A
# of DC Motors	1	2	1
MCU pins	GPIO/PWM	GPIO/PWM	GPIO/PWM
Arrival Time	3 days	3 days	3 days
Price (Qty)	\$6.99 (2)	\$5.99 (2)	\$15.49 (2)

*Figure 21: Haptic Motor Driver Specifications*

This table compares the different motor drivers available for use with haptic motors. We decided to use the L298N motor driver as this solution is simply the most cost-effective. All of the haptic motor driver options available have similar ratings in voltage and current. We were also able to find more documentation for the L298N [81] [83] [79].

Model	RRPDMSCSGSPC	BTS7960	RR-6-90V-15A-PSC
Motor	DC	DC	DC
Voltage	12V-40V	27V	6-90V
Maximum Current	10A	43A	15A
# of DC Motors	1	1	1
MCU pins	GPIO/PWM	GPIO/ PWM	GPIO
Arrival Time	4 days	3 days	3 days
Price (Qty)	\$9.99 (1)	\$12.57 (2)	\$9.99 (1)

*Figure 22: Wheel Motor Driver Specifications*

Comparing options, we decided upon using the BTS7960 motor driver. The BTS7960 is able to supply more than enough current to the DC motors driving the wheels. This option is also the most cost-effective as the price includes two motor drivers to be able to drive both motors [84] [82] [80].

Model	Vogely 500400240	Frdhee Headlight	StellarLights
Power	12-80V	12-80V, 18W	AAA (3)
Control	Wired	None	None
Mounting Ease	Difficult	Easy	Easy
Lumens	700	1200	300
Arrival Time	2-3 weeks	2 days	7 days
Price (Qty)	\$15.77 (1)	8.99 (1)	\$9.61 (1)

*Figure 23: Comparison of Headlight Options*

Comparing these different headlights that were originally intended for bicycles and motorcycles, we decided to use the Vogely 500400240. This is because these

are the only headlights of these options that are able to be controlled digitally. Headlights are only necessary in dark environments, so we must connect the headlights to a light sensor. [92] [93] [94]

Model	UB1245	SigmasTek	LiFePO4
Voltage	12V	12V	12V
Capacity	4.5Ah	5Ah	6Ah
Size	3.56" x 2.73" x 4"	3.54" x 2.76" x 3.98"	2.6" x 6" x 3.9"
Weight	3.12lb	3.5lb	2lb
Arrival Time	7-8 days	9 days	1 day
Price	\$18.26	\$15.99	\$19.99

*Figure 24: Comparison of Battery Options*

Comparing these different options for batteries, we decided upon using the SigmasTek battery. We evaluated 12V batteries since we ultimately decided on implementing 12V motors and these are our highest-voltage components. Comparing prices and capacity, we found that the SigmasTek battery was preferred because it provides the lowest cost for the needed battery capacity. [100] [101]

## 4 Requirements, Standards, and Constraints

Chapter 4 discusses the related standards and constraints for both hardware and software used by FORWARD during development and realization. The main consideration for standards is given to connections, medical rollators, and IEEE guidelines on Bluetooth, wireless networks, sensors, motors, and serial communications. In addition, we examine constraints through the lenses of economic, environmental, social, political, ethical, health, and safety.

### 4.1 Related Standards

FORWARD must comply with all IEEE-related standards relating to sensors, motors, computer vision, and image processing. Taking a brief look at the specifics, none are immediately seen as hindrances to the proceedings of FORWARD's research. Should an issue arise with IEEE-related standards later in the project, future documentation will indicate that.

The ADA (American Disabilities Act) also has stipulations for environments to make accommodations for these assistive vehicles including walkers and electric wheelchairs. However, none of these should affect our design process, given that our product is safe to operate around other people and in busy environments.

#### 4.1.1 Connection Standards

USB Type C is notably used to connect the ESP32 Camera module to the central processor. In addition, we utilized USB Type B to program the Arduino Uno for initial sensor interfacing. There are unique connectors for the DC brushless motors as well. The LiDAR sensor utilizes a 6-pin Japan Solderless Terminal (JST).

#### 4.1.2 Design Impact

The following is by far, not necessarily a finished list of design impacts that the technologies with standards attached have on FORWARD development. As the design process continues, this may be revised for the final documentation. The sensors, camera, and motor drivers all have a diverse method of connection, as far as hardware design goes. It will be necessary in the PCB design. This is discussed further in section 8.1.

*Design Impact of Digital Communication* Serial communication is what allows for the sending of bits over mediums, whether they be wires or through the air as electromagnetic waves. Microcontrollers have built-in support for GPIO pins and serial communication.

*Design Impact of I2C* Inter-integrated circuit (I2C) is a digital serial communication protocol commonly implemented between microcontrollers and sensor devices. It allows for fast and accurate transmission of data that can then be processed and operated upon. I2C is great for buses of sensors, especially as the number involved grows. FORWARD utilizes four ultrasonic sensors, one LiDAR, and one camera, and so this technology can greatly increase the ease of design implementation, were an I2C bus to be chosen.

*Design Impact of UART* The Universal Asynchronous Receiver-Transmitter (UART) is a lower-speed digital communication protocol. It sends 8-bit data packets, essentially forming a bitstream that follows a clock signal. UART is advantageous for its ease of implementation and accuracy for accessing data from single devices. UART can also be used in simplex, half-duplex, or full-duplex mode. In the context of FORWARD, the sensors selected for the most part will support UART, so that it will be an option available.

*Design Impact of Bluetooth* Bluetooth is a short-range wireless digital communication protocol that is commonly utilized in audio systems. It makes use of frequency hopping (see Figure 8) in order to avoid interference and jamming. Bluetooth will help the FORWARD designers easily relay audio feedback to the user in a way that is not invasive to mobility and accessibility, which is possible because of the wireless capability. Wired headphones would inevitably become a safety hazard and a nuisance. To maintain the pledge of autonomous navigation and responsive direction, Bluetooth must make an essential design impact.

*Design Impact of Wifi* FORWARD's potential inclusion of its own wireless network could open new possibilities for unified response to obstacles. Essentially, the network will allow the range data as well as image recognition classification data to be collected and centralized.

*Design Impact of Embedded Software* Embedded programming in the C language gives great low-level control over registers containing the FORWARD sensor readings as well as allowing the computer vision to interact with the feedback and velocity control by the motors. As noted in later sections however, Arduino is the preferred development tool.

## 4.2 Economic Constraints

One of the main constraints for our project FORWARD is economic constraints. Our project is self-funded, which means that we can spend as little or as much as we wanted, but given the current state of our teams financial situation, this was limited to \$250 to \$400. We also needed to conserve 10% to 20% of our budget for back up components and extra PCB boards. Due to this, our already

limited budget is now cut down even more, which will in turn, limit the quality and efficiency of the components we can afford.

Due to the high cost of AI hardware, selecting the chip/MCU that will run the object detection models was one of our main constraints. Much of the GPU hardware is far too expensive and out of scope for this project, leaving us to look into the current state of AI focused embedded MCU hardware. Many of the preexisting products implement hardware that can cost anywhere from \$250 to \$500, which is well outside of our budget - in fact, some of which would consume our entire budget. In order to work within this constraint, we were able to find a low cost MCU driven camera board which had a MCU capable of running light weight AI models. The downside to this board is a lower camera quality, which could make certain stretch requirements such as depth perception more difficult. It also limits the quality of the object detection models that we can run.

The motor system was also part of the economic constraints for our project. The motor drivers/shield board and the motors for similar applications (i.e electric scooters, vacuum cleaners, other walkers) can cost upwards to around \$50 each. To limit the cost of such, we needed to implement a walker solution with only two motors (front wheel drive). The limitation decrease the control we can have over the walker as well as will cause for faster deterioration of the front wheels over time.

Another aspect of our projects economic constraints is the power system. Our system runs on 21.6 V and many of the power supply's can cost upwards to \$70 each for our purposes. For this aspect of the project, there isn't much we can do to avoid this cost, which means we must spend extra time in research for the part we will use, and everything else will be limited as an effect.

Overall, the constraints listed above can be very limiting for our project and create possible issues later on. In an effort to avoid this, we are taking extra precaution to maximize our budget through extensive research. We can also always extend our budget later on, but that is undesired.

### 4.3 Environmental Constraints

It is known that battery manufacturing and disposal is often horrid for the cleanliness of the environment, so the FORWARD project is utilizing rechargeable power banks to avoid burning through batteries. A more pressing concern environmentally is would the conversion of yet another "smart" device be invasive to the enjoyment of public facilities such as nature trails or parks. The answer to that is a no because of how minimalistic the FORWARD system addition to a standard non-enhanced rollator is. The introduction of the electronics chassis, sensors, and bluetooth earpiece should not deter or distract users from enjoying their stroll

through nature. Being the motor control is electric, there are no carbon emissions to worry about, and being that the user can abandon the earpiece and rely solely on the haptic feedback for guidance means that there is no risk of not hearing the surroundings at a crucial time because of distraction. Finally, FORWARD not only enhances the viability of safely taking medical rollators out into the environment, but also their viability in the indoor setting. It can be operated in any ambient lighting setting and does not necessitate constant reliance on an external network. Therein lies its passive guidance solely utilizing the range sensors and haptics. The obstacle identification will transmit over Wi-Fi, so it would not be reliable in areas with no network connection. Similarly, the Bluetooth earpiece is limited by its battery life, but that is no environmental or design concern of ours. Increased safety and reduction of collisions due to rollators is an immense benefit to the environment in the respects that it applies to.

#### **4.4 Social and Political Constraints**

FORWARD is an assistive technology. It is not classified as a wearable one however and it is simply an enhancement made to an existing tool available to the physically impaired, extended to the spatially impaired. This should be viewed by most as a positive advancement, allowing for more participation and mobility in places with obstacles that previously would be difficult for walker users. Given that this is empowering to groups who may or may not have been previously ostracized, FORWARD has a positive impact socially. The main social constraint institutes that FORWARD should help prevent collisions. Such would be a nuisance (if caused by FORWARD's mistake)! Politically, FORWARD does not seem constrained in a considerable amount.

#### **4.5 Ethical, Health, and Safety Constraints**

The FORWARD walker is primarily to be used as a tool to help people who have various kinds of impairments and/or disabilities. Since the walker is intended to physically support the user, there are many considerations for ethics, health and safety. As it relates to safety, we must not hinder the structural stability of the walker. The chassis must be strong enough to uphold the user and stable enough not to tip. These considerations led to a few of our design constraints, including a minimum weight requirement of 20 pounds and instability tilt detection of 10 degrees. Whenever the walker detects tilting over 10 degrees, this will provide feedback to the DC motors driving the wheels in order that the motors can vary in speed to correct for the instability, depending on the side the walker is leaning towards. These constraints are intended to keep the user from falling if their weight is not distributed properly across the walker or if there is something causing the walker to tip. The majority of the remaining design constraints also relate to

safety, but in regard to the motion and feedback of the walker. The FORWARD field of vision, CV model accuracy, and sensor accuracy all are necessary to detect obstacles in the path of the walker. If obstacles are not correctly detected and identified, then the user could be injured. For instance, if the walker does not correctly identify a curb, the user could trip and fall. Another safety constraint is response time. FORWARD must be able to brake to a complete stop within 1 second in case an object encountered that is very close to the walker. If the motors do not brake in time, the walker may collide with an object. Our requirement of feedback latency also relates to safety as the user needs to be aware of their surroundings and how the walker is moving in order to respond appropriately. Too long of a delay in the haptic and audio feedback could cause confusion or disorientation to the user, which may cause them to stumble. Apart from our product, there are ways in which a generic rollator or walker must be operated. Oxford Health has an encompassing pamphlet that describes the safe operation of a generic walker, including how to sit, how to apply the brakes, where to place your feet behind the rollator, and how to proceed upon encountering a curb [89].

Health is another important constraint to our design. FORWARD is being developed to assist people with various physical medical conditions, including sensory impairment, blindness, deafness, injury, issues with balance, etc. There is a plethora of purposes for FORWARD as the walker can aid in injury recovery, allow users to gain awareness to their surroundings, and provide stability to the user. Rollators in general can be intended as a means of physical therapy [89], and our design simply expands upon this purpose.

Ethics are essential throughout our design in meeting the design constraints and not compromising on the safety of the users. There could be serious ramifications if a larger object, such as a vehicle, is not detected, identified, and avoided accurately. There is therefore a great responsibility required from us to employ the best practices possible to ensure safety. If we choose to forego these constraints or do not utilize quality parts, this product could be a danger both to the user and the people surrounding them.

## 5 Comparison of ChatGPT with Similar Platforms

ChatGPT and the realm of search engine AI's were particularly useful in this research process for identifying the different types of technologies currently available, given the market observable on the internet. However, the LLM tended to struggle with providing accurate and specifications from datasheets, requiring the researchers to sift through and locate them. Additionally, ChatGPT was useful for preparing references for sources, but even in this it sometimes struggled to gather the correct article or paper title, although it was strong in being able to provide them in most formats including the IEEE reference style.

### 5.1 Example 1: Sonar vs. LiDAR

One specific example of ChatGPT aiding the research process is by providing a concise explanation of the comparison between the Sonar and LiDAR sensing methods. It is able to be objective and pull from all knowledge of these technologies to best inform our decisions.

**1. Enhanced Object Detection and Classification:**

- LIDAR provides high-resolution 3D data, allowing for precise object detection, mapping, and distance measurement. It is excellent for detecting objects with well-defined edges and surfaces.
- Sonar can detect objects that are difficult for LIDAR to handle, such as transparent, reflective, or soft objects (e.g., plastic wraps, foam, or cloth). It's also less affected by dust and debris, which can sometimes interfere with LIDAR.

Benefit: By fusing the data from both sensors, the system can accurately detect and classify a wider variety of objects on the conveyor, improving overall reliability.

**2. Improved Obstacle Detection and Collision Avoidance:**

- LIDAR provides detailed spatial information and can detect potential obstacles at longer distances.
- Sonar can supplement this by providing additional data at shorter ranges, especially in scenarios where LIDAR data might be less reliable (e.g., close to reflective surfaces or low contrast objects).

Benefit: The combined data can lead to more reliable obstacle detection, reducing the risk of collisions and ensuring smooth operation even in complex environments.

**3. Robustness in Challenging Environments:**

- In environments with high dust levels, varying lighting conditions, or reflective surfaces, LIDAR performance can degrade.
- Sonar sensors, which are less affected by these environmental factors, can provide critical supplementary data.

Benefit: Sensor fusion enhances the robustness of the system, allowing it to maintain accurate operation in a broader range of environmental conditions.

**4. Redundancy and Fault Tolerance:**

- By using both LIDAR and sonar, the system can be more fault-tolerant. If one sensor type fails or provides unreliable data, the other can compensate.

Benefit: Increased reliability and uptime for conveyor systems, reducing the risk of operational disruptions.

**5. Cost-Effectiveness in Specific Applications:**

- LIDAR sensors are more expensive than sonar sensors. By strategically combining both, the system can leverage the cost-effectiveness of sonar for simple detection tasks while reserving LIDAR for more complex operations.

Benefit: Optimized sensor costs while still achieving high-performance detection and navigation.

*Figure 25: ChatGPT compares sensing technologies*

## 5.2 Example 2: Power Supply to the MCU

ChatGPT proved to be very useful for the sake of research, particularly when there were specific concerns. In this example, we used ChatGPT to answer a question of compatibility in order to determine how many power sources were necessary to purchase. The response both clearly and concisely answered the question with several conditions to keep in mind. Thus, one of the main advantages to generative AI is that it provides a direct answer to a specific question, automatically sifting through information that is irrelevant. Very often, a simple Google search will draw only a certain sentence or paragraph from a website that relates to the query, while the rest of the website may or may not be relevant. ChatGPT instead combines several sources with almost all relevant information so that less investigating is required. However, one advantage to a Google search is that you are able to see the source of the answer and understand the surrounding context. For example, you may create a query asking how a motor driver works, meanwhile you do not know how DC motors work in general. A Google search may provide a website that provides preliminary information on the functionality of DC motors before diving into the functionality of motor drivers themselves. On the contrary,

ChatGPT only would have provided information on motor drivers themselves. This is advantageous when you are unsure where to start researching or "don't know what you don't know."

Prompt: Can you power microcontroller and motors with the same battery pack?

Response from ChatGPT:

Yes, you can power a microcontroller and motors with the same battery pack, but there are a few considerations to keep in mind:

**Voltage Compatibility:** Ensure that the battery pack provides a voltage compatible with both the microcontroller and the motors. For example, if the microcontroller operates at 5V and the motors require 6V, you'll need a way to regulate the voltage for the microcontroller.

**Current Requirements:** Motors can draw significantly more current than microcontrollers. Make sure the battery pack can supply enough current for both without causing voltage drops that might reset the microcontroller.

**Noise and Interference:** Motors can introduce electrical noise, especially when they start or change speed. It's a good idea to use decoupling capacitors near the microcontroller and possibly include a separate power supply or filtering for sensitive components.

**Power Management:** If the microcontroller is in sleep mode or only occasionally active, consider using a power management system to optimize battery life.

**Common Ground:** Make sure that both the microcontroller and motors share a common ground to avoid potential issues with signal integrity.

By keeping these factors in mind, you can successfully power both components from the same battery pack!

### **5.3 Example 3:**

## 6 Hardware Design

### 6.1 Rollator

The most clear option for the choice of walker frame, to be outfitted with motors and the electronics system, is a standard medical rollator, available on common online commercial marketplaces. The model of choice is the Medline Premium Empower Rollator. The steel frame remains at a weight under 20 pounds, and its dimensions are given as 23.8"D x 11"W x 22"H. It comes with a seat, storage compartment, and pneumatically actuated brakes. The FORWARD team plans to remove the seat and storage compartment to replace with the electronics housing, change the braking system to velocity control, and to dismount the wheels to install the DC motors. The wheels are also 8 inch diameter, which we anticipate will provide enough torque for the adaptive velocity control and steering enacted by the motor shield.



*Figure 26: Medline Premium Empower Medical Rollator*

There are many other variants of rollators available - some with enlarged front wheels and some with only three wheels altogether. There seem to be two main shapes of frame: A and what we can call  $\lambda$ . We estimate that, the A frame is more appropriate for our purposes. FORWARD velocity control and electric braking also requires four wheels.

### 6.2 Electronics Chassis

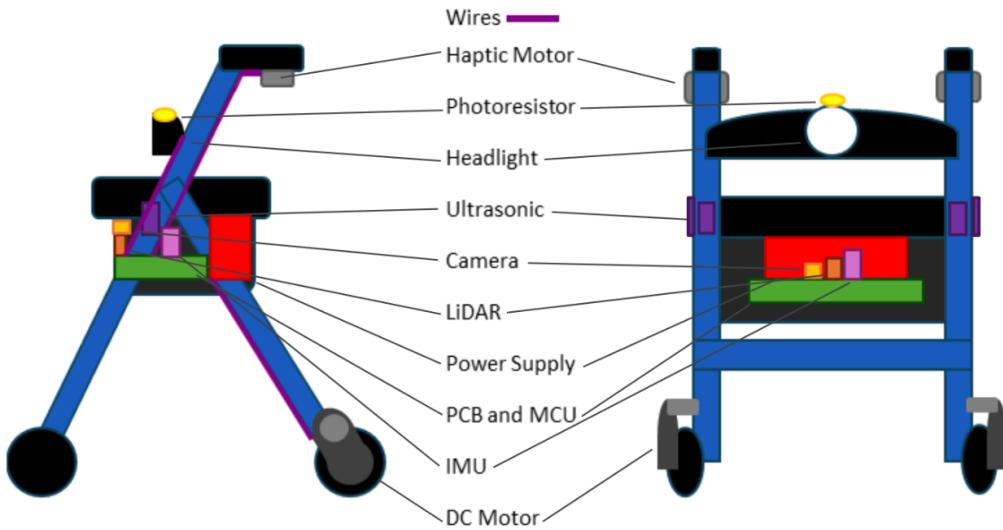
#### 6.2.1 Location of Components

The diagram below depicts the physical location of the components as attached to the walker. Several components, including the power supply, PCB, IMU, and LiDAR will be housed within a hard casing, most likely made of metal or wood. They will be encased so that they are stable and not exposed to the elements. The LiDAR and IMU, both of which are mounted to the PCB, should not be allowed

to change position. In particular, the IMU measures the angle of the walker and needs to be level. If the IMU is not level, it will give incorrect readings. It is also undesirable for the PCB to be unstable or mounted loose beneath the seat because it would be easy for connections to loosen or for vibration to damage sensitive parts. We will use screws to mount the internal components to this casing so that all of the units are fixed in place. All of the other components will need to have wires running to this casing. These wires will be organized and mounted against the walker using wire clips so that there are no dangling wires, which could be a tripping hazard to the user and would appear unprofessional.

For the components installed apart from the electronics case, we will use different methods of mounting depending on the nature of the component. The haptic motors will be located underneath the handlebars so that the user's hands are able to clearly sense the pattern of vibration. Each motor will be attached using a mounting bracket. This bracket will need to use tension or compression in order to secure the motors in place as the motors do not come with holes to mount to the back of the seat with screws. The headlight will be mounted on top of the backing of the walker seat. This location was chosen because it is the highest point of mounting for which the light can shine unobstructedly. It comes with a mounting bracket that will need to be attached to the walker using screws. The photoresistor may be attached to the headlight, out of the way of shadows, using a clip. There are four ultrasonic sensors that we will mount to the legs of the walker. Two will appear facing the front of the walker and the other two will appear on the side, angled toward front. The ultrasonic sensors contain small holes at each corner for mounting, however, it would be difficult to drill into the metal structure of the walker. We could use fishing rod clips to attach to the walker and mount the sensors to the clips.

The most difficult components to mount will likely be the DC motors driving the wheels. We must attach the motors in such a way that the wheel rotates as the rotor attached to the gearbox rotates. We also must ensure that the manual braking system is not eradicated, which limits our options to not mount the motor directly above the wheels. For example, we could detach the wheels from the hub and attach them directly to the motors whereas the motors are mounted to the walker. However, this would remove the braking mechanism from the wheels. Thus, we will mount the motor (using a connector piece screwed into the gearbox and the rim of the wheel) to the outside of the wheel and simply use a custom metal bracket to attach the motor to the leg of the walker. We will mount the two motors to the two rear wheels of the walker, as they are fixed, while the front two wheels swivel.



*Figure 27: Location of components on the walker*

### 6.2.2 Measurements of the Walker

Upon purchasing the rollator chassis, we took measurements in order to design the placement of components on the walker. This is especially essential for obtaining the correct length of wires. We would like to have organized wires flush against the walker running from the PCB to different components, which requires precise measurements of the length of wires to appear professional. For example, we measured the distance from the wheel to the seat of the walker and will need to later add the measurement from the seat to the PCB housing underneath the seat. For Senior Design II, we will need the measurements for the PCB before we can start ordering the correct length of wires.

Measurement of Walker	Inches
Comprehensive height of the walker	39"
Height from the ground to the top of the backseat of the walker	33"
Height from the ground to the bottom of the seat	23"
Length of the walker	20"
Height of the seat	2"
Length of the seat	16"
Width of the seat	13.75"
Diameter of wheels	8"
Distance from the wheel to the seat	22"
Distance from the haptic motors to the seat	23"

*Figure 28: Measurements of the walker*

Discuss psychical location of all elements and components on the walker frame and

explain the reason. explain plans for wiring and attachment (tape, glue, screws etc).

discuss positioning of sensors on the walker, wiring; need for IMU to be level. installation of haptics. implementation of earpiece being available to user. braking, motor speed control. physical object avoidance margins. obstacle classifications.

sensor housing, surface mount IMU (on PCB), surface mount LiDAR? (on PCB), PCB centrally mounted, bluetooth module centrally mounted?

headlights? curb assist? tipover prevention with motors explained

## 6.3 Arduino

Initial interfacing to the sensors was performed using the Arduino integrated development environment. Because of its ease of access and abstraction, this has become the preferred programming tool for the FORWARD system. The Arduino IDE can

## 6.4 Detection Subsystem

Recall the requirements of the detection subsystem. It should be able to detect objects at least 3 meters away and within a 15 degree aspect angle. It also should detect walker instability up to 10 degrees in pitch angle. It should detect hazards with an accuracy of at least 80%. Finally, feedback latency should not exceed 100 milliseconds to keep the user safe.

Let us also define the input and output of the obstacle detection subsystem. The input is energy return from the environment, supplied to 5 different points on the walker frame, as well as accelerometer and magnetometer data outputs describing the attitude of the walker itself. The output is somewhat joint with the obstacle identification system, as it helps to generate velocity motor commands for both speed and turn angle. Detection and identification are the FORWARD system inputs, and avoidance is the output.

### 6.4.1 Sensor Orientation

The range sensors are mounted on the frame perpendicularly to obstacles. In other words, the direction of the energy transmitted is perpendicular to the ground. However, the question of maximizing capability of detecting obstacles at the wheel level, and to prevent ignorance of more dangerous and deceptive hazards such as ledges or step-downs is raised. The monostatic ones will be mounted on the legs near the wheels, front-facing. These

#### 6.4.2 Incline and Decline Stability

The simple function fulfilled by the inclusion and integration of the IMU is stability. By monitoring the pitch angle of the walker, we know whether the user is at risk of falling over.

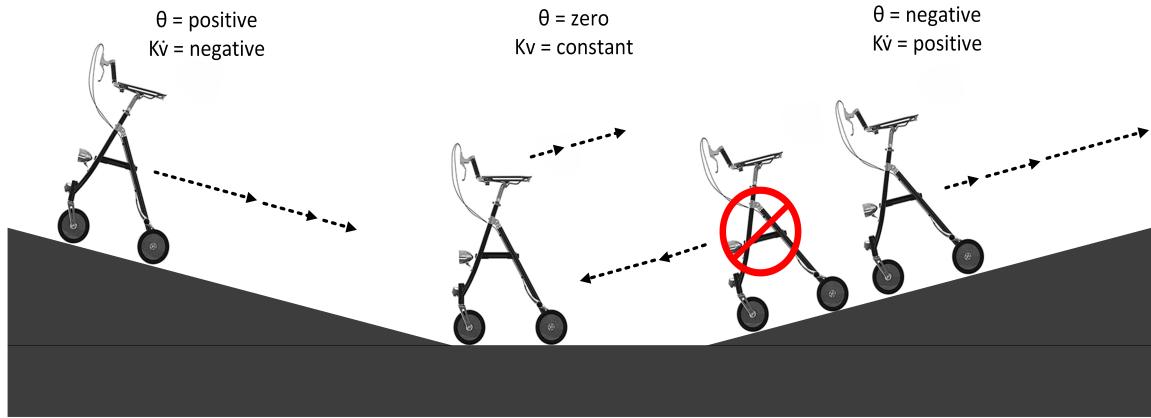


Figure 29: Stability on Slopes

#### 6.4.3 Sensor Fusion

How do we make sense of the range detection made at all five points of the front-face of the walker? How do we combine that with pixel data of the corners of an object detection made by the camera? We can generally perceive depth by averaging the 4 coordinates, where closer is a higher average. We also know whether an obstacle is on the left or right side ahead based on which ranges are lower the maximum. We have to take into account the dead zones. With all of this information available on the network, we can build algorithms to guide the way forward, as discussed in the following chapter.

As noted, the ESP32 development board supports all the sensors and the camera simultaneously without the need of multiplexing. The setup pictured below in figure 30 has the IMU and LiDAR on an I2C bus, and the ultrasonic sensors routed to GPIO pins. A table of the varying assignments, labels, and voltage requirements would be provided for the topology in figure 30, but it is forbidden by the UCF ECE guidelines. Suffice it to say, the IMU requires 3.3V, the TFLuna LiDAR requires 5V, and both variants of the ultrasonic can support either voltage.

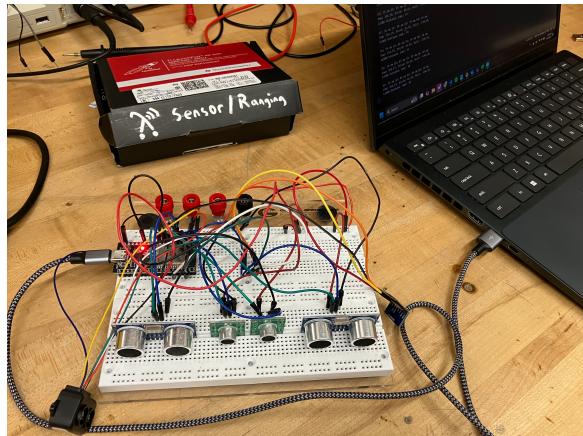


Figure 30: Breadboard w/ Ultrasonics, and IMU & LiDAR I2C Bus

## 6.5 Identification Subsystem

### 6.5.1 ESP32 Wireless Network

Antenna?

## 6.6 Power Supply and Voltage Regulation

Each component of the FORWARD walker requires a specific amount of voltage. In order to cater to each of these needs, we will first need to have separate power supplies. The motors driving the wheels as well as the headlight both demand 12V, so they will require a larger power supply that only outputs 12V. The remainder of the components, contrarily, all use a much smaller power supply. Thus, we will utilize a large power supply and a small power supply (both of which are rechargeable).

For the smaller power supply, we will need to employ voltage regulation to provide the correct amount of voltage between the different units. The microcontroller and accompanying sensors all require one voltage supplied to the MCU and distributed to the sensors. The ESP32 is rated as a 3.3V device[106] and powers the sensors using the GPIO pins. However, the haptic motors require a separate power supply from the MCU as they are operated using a motor driver rated for 5V. The camera module is also powered separately from the MCU with a supply of 5V. In order to deliver enough voltage for both the MCU, the camera module, and the haptic motors, we will use a 5V battery pack (originally designed to charge phones) and from there add voltage regulation circuits to the PCB. The haptic motors and the camera module will accept the simple output of the battery pack at 5V, however, the MCU and its sensors will need this voltage to be stepped down 3.3V. This circuit will be implemented within the PCB.

## 6.7 Avoidance Subsystem

This subsystem is dedicated to the movement of the walker as pertains to the motors and mechanics. FORWARD has a prescribed method of steering and braking that will be expanded upon. There have also been changes to the design throughout the project affecting our choice and application of the motors to be discussed.

### 6.7.1 Motor Control System

In order for the motors to rotate, they must be controlled by a control system. Once the user initiates FORWARD by powering it on, there will be a dial (potentiometer) that the user has can spin in order to select the starting speed. This dial will have divots or braille for the user to feel to determine if they are selecting a slower or faster speed. This constant will then be sent by the potentiometer to the MCU (controller), which will process the input and send commands to the motor driver. The motor driver will receive the commands from the MCU and apply the correct voltage and PWM signal to the motors, which are the actuators performing the action of spinning the wheels. As the walker drives forward, the sensors will be continually reading data and providing feedback to the MCU. When an obstacle is encountered, the MCU transmits new commands to the motor driver in accordance with the sensors and camera. The motor driver will then alter the PWM signal and the motors will change direction or apply brakes accordingly.

The other components of feedback operate in a similar closed loop. The haptic motors use the same diagram, except their speed is not dependent on the potentiometer and only activate when an obstacle is detected by the sensors and camera. In addition, the output of the haptic motors is vibration instead of motion. The audio feedback follows a similar process, however, it is ideally controlled directly by the MCU (although may have need of another circuit to act as a driver) and the output is playing back audio files of the objects detected by the camera.

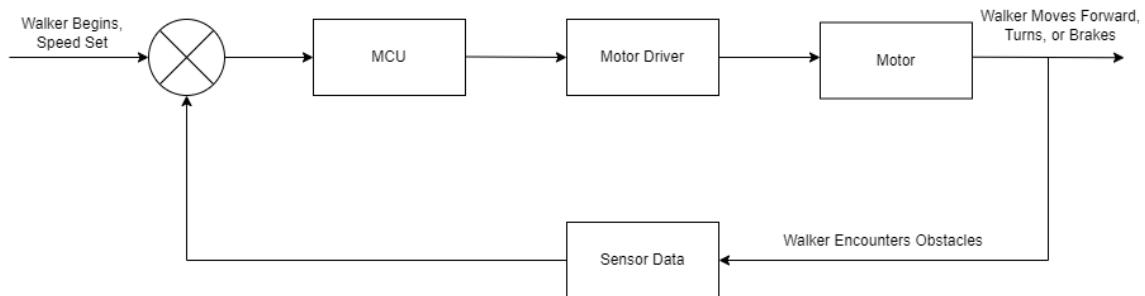


Figure 31: Motor Control System Diagram

### 6.7.2 Wheel Rotational Motion

The rollator wheels will dictate the way by which turning can be achieved. There are four wheels. We call the distance in between the front wheels  $axel_f$  and the distance in between the rear wheels  $axel_r$ . Upon initial inspection of the rollator once acquired, we see that  $axel_f > axel_r$ . The measurements are as follows:

[TABLE HERE OF MEASUREMENTS]

From a top view, the rear two wheels can be viewed as simple points. They do not swivel, and thus can rotate in place but cannot do horizontal translation, stipulated by friction and attachment to the rollator frame. Of course, they can also roll and move forward.

In addition, the front wheels are on a  $360^\circ$  swivel. They can also be modeled as points in a sense; however, their orientation changes.

Case 1 (extreme): Both wheels rotate. The front wheels translate.

Case 2 (extreme): One wheel rotates, the other stationary. The front wheels revolve.

Case 3 Veering. motor speeds may not have to change. User can veer based on feedback, and gentle guidance provided by FORWARD.

### 6.7.3 Turning Mechanics

A major question pertaining to obstacle avoidance is our mechanism of steering. As mentioned previously in section 3.2.7, we wish to rely solely on the DC motors for steering control in order to minimize mechanical complexity. To refresh, rather than using a servo motor or other apparatus to turn an axle that steers the wheels, we will use two separately controlled DC motors with no axle. Because each of these motors are controlled independently, each will assume a different speed in order to steer the wheels, else remain at equal speeds to move forward in a straight line. The angle of the turn is determined by the drop in speed of the motor adjacent to the turning direction. As an example, if the walker needs to veer very sharply to the left, the left motor will either halt rotating or rotate very slowly compared to the right motor. On the contrary, if simply a slight turn is needed to avoid an obstacle, both motors will drive at comparable speeds with one motor slightly decreased in speed. One potential issue with this strategy is that FORWARD can only move in a straight line if both motors are rotating at exactly the same speed; otherwise, the walker may drift toward one side or the other, as opposed to an axle that is driving the wheels symmetrically. However, we are using identical motors from the same manufacturer and applying the same amount of voltage. It is possible that there

will still be some amount of drift due to manufacturing errors, wire resistance, or other unknown factors. Nonetheless, we do not anticipate drift to be much of an issue as the walker can also correct itself upon straying from the path, as it will detect an obstacle, whether the obstacle is a curb, the grass, the road, etc.

#### 6.7.4 Motor Installation

##### Calibration

Our initial selection for DC motors driving the wheels were the S55B-150 motors from Chapter 3. However, there were several factors that we did not account for in purchasing these motors. To begin with, these motors are brushless three-phase DC motors. After discussing with Dr. Weeks, one of our coordinators for Senior Design, we learned that in order to program these motors to function properly, each of the phases needs to be aligned within the programming. This would be a very difficult process, especially considering that there is hardly any documentation given for the S55B-150 given by the seller. In considering this advice, we purchased instead [104]. Although these motors are only 40-50W, they nonetheless provide plenty of torque to drive the walker due to the gearbox increasing torque. We will eventually need to test the speed of the walker to see if it will be able to achieve one of our requirements of 6mph. The motors with no load can rotate up to 30,000rpm, which with 8" diameter wheels translates to over 700mph [105]. However, this number will drastically change as up to 60lbs plus the weight of the user's body leaning against the walker acts as a large load. We will simply need to test the speed of the walker in Senior Design II and keep in mind that speed may not be a requirement that is met.

##### Vibrating Handlebars via Haptics

Our design for haptic feedback includes small ERM motors that will spin at a rapid rate with no load. Attached underneath the handlebars to the walker, the rapid spinning will cause a vibration noticeable to the user. This is a vital portion of guidance to the user, as our desire with this project is to provide a solution for people with a broad range of sensory disorders. If the user has issues with using the audio feedback or is unable to hear, the haptic motors provide similar directions describing the surroundings and motion of the walker. When our FORWARD walker detects and identifies obstacles, the user must be aware that an obstacle has been detected, what the obstacle or danger level is, and what steps the walker will take in order to avoid the obstacle. Otherwise, the user may act contrary to the walker or stumble in response to the sudden change in movement. For example, if FORWARD approaches a wall and comes to a stop, the user, who is walking with the walker, could run into the walker or be lunged forward by inertia apart from feedback.

The haptic motors are being controlled by a motor driver communicating with

the ESP32. This motor driver receives commands from the ESP32, which also combines input from the various sensors, and sends commands to the motors that vibrate accordingly. When an obstacle is initially detected, the motor on the side in which the obstacle is detected will vibrate in pulses until it is time for FORWARD to either steer or brake to avoid the obstacle if needed. If the walker needs to veer to the right or to the left in response to the obstacle, the handlebar in the direction the walker is steering toward will vibrate for the duration of the turn. The ERM motors will vibrate in pulses while the walker is turning, with the period of the pulses dependent on the steering angle. If FORWARD needs to take a sharp turn, the haptics will vibrate more often with shorter pulses, whereas a slight turn will vibrate with longer pulses. If FORWARD is coming to a stop, both haptic motors will vibrate simultaneously until the walker has come to a complete stop. After a short delay, perhaps around five seconds, if the obstacle passes, both of the haptic motors will vibrate twice for around one second per pulse to indicate the walker will move forward again. The motion will begin after this warning is given to the user. If the obstacle does not pass but instead FORWARD needs to turn away from the obstacle after coming to a complete stop, one haptic motor will vibrate twice for around one second per pulse on the side in which the walker is turning toward.

Considering the data captured and processed by the camera, we also need a way for the user to distinguish between different obstacles. The system of haptic feedback will accomplish this using pulse width modulation (PWM). PWM is a method of speed control discussed in section 3.2.6 where voltage is applied for a percentage of a period. When the high voltage pulses are wider (the motors are spinning at a faster rate), the haptic motors vibrate louder, whereas a shorter voltage pulse results in weaker vibration. Because a louder vibration draws more attention, a sense of urgency is conveyed. Thus, we will use the speed of vibration to indicate the danger of the approaching obstacle. We will first classify each of our recognized obstacles with a danger level (for example, a vehicle most dangerous, then a human, and grass least dangerous) and set the speed of the motors accordingly.

### 6.7.5 Emergency Braking

FORWARD of necessity must also be able to respond to obstacles by braking. The chassis we have chosen to use already contains a manual braking system. There are pneumatic triggers beneath the handlebars that apply the brakes upon compression. We would like to preserve these manual brakes for the sake of safety in case any electrical or software issues arise. However, we also need FORWARD to brake automatically in response to obstacles. We will accomplish this by programming the motors to first slow down their speed to a stop and then reverse the direction of the motors until the entire walker is no longer in motion. This is known as dynamic braking[102]. We will need to test the braking

to determine the correct timing of when the walker comes to a complete stop so that we know when to stop the motors after reversing. If we are unable to correctly time the motors, we may need a way to sense when the walker has come to a complete halt. This may be possible using the camera or a motion sensor [103].

### **6.7.6 Reconciling User Control and Automatic Guidance**

There is also an issue of user error that must be considered. Our design is intended for the walker to lead the user, not for the user to lead the walker. This is not much of an issue with braking as there should not be any safety issues in the user applying manual brakes when not needed. Although this may wear down the motors over time as the rotor is prevented from rotating, we do not foresee any major consequences. However, the user may try to steer the walker in the wrong direction when not directed by the walker. This could cause a serious issue in the safety of the user if they steer the walker into an obstacle. Currently, if the user tried to steer the walker, the walker would automatically correct itself upon encountering an obstacle and warn the user of the obstacle. A more advanced solution could be pressure sensors that detect the body weight of the user and can sense if the user is leaning a particular way. However, this is outside the scope of our project, although in production this issue would certainly need to be addressed.

## 7 Software Design

### 7.1 Guidance, Navigation, and Control Software

GNC situation, tilt (attitude) using IMU, (incline decline), velocity and position solutions, ESP32 source code GitHub (`hc-sr04.c` `luna.c` `haptic.c` `audio.c` `motor.c` `ip.c` `avoid.c`), motor commands calculation

[UML CLASS DIAGRAM HERE]

### 7.2 Computer Vision

### 7.3 Serial Interface

### 7.4 Motor Control Software

### 7.5 Ranging Algorithms

Instructing FORWARD where to guide the user is a solution that the detection and identification systems generate. Various scenarios are described in the system testing chapter. It will be a matter of solving an adaptive geometrical situation and relaying the results to the processor.

#### 7.5.1 Range Reading Harmonization

There are more outputs the inertial measurement unit can provide besides the angles. One of most interesting ones is the accelerations. This would be the rate that the velocity of the rollator body is changing with respect to time. From a control standpoint, we can think of a state-space representation. FORWARD is a multi-input, multi-output system (MIMO). Let's define the states  $X = [x_1, x_2, x_3, x_4, x_5, x_6, x_7]^T$ :

$$x_1 = \psi, x_2 = \theta, x_3 = \phi$$

$$x_4 = a_x, x_5 = a_y, x_6 = a_z$$

$$x_7 = \phi_c$$

The inputs  $U = [u_1, u_2, u_3, u_4, u_5, u_6, u_7]^T$  are as follows. Notice roll is not dealt with because  $\psi$  is static.

$u_1$  : incline angle

$u_2$  : user steering force

$u_3$  : motor commands

$u_4 : S1, u_5 : S2, u_6 : S3, u_7 : S4, u_8 : L1$

The state equations:

$$\ddot{X} = AX + BU$$

$$Y = CX + DU$$

, where D=0 because there is no direct transmission. We then can define the 11x11 state transition matrix:

$$A = \begin{bmatrix} \alpha_1 & 0 & 0 & \beta_1 & 0 & 0 & 0 \\ 0 & \alpha_2 & 0 & 0 & \beta_2 & 0 & 0 \\ 0 & 0 & \alpha_3 & 0 & 0 & \beta_3 & 0 \\ 0 & 0 & 0 & \zeta_1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & \zeta_2 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & \zeta_3 & 0 \\ 0 & 0 & \gamma_1 & \gamma_2 & \gamma_3 & 0 & 0 \end{bmatrix}$$

The control influence matrix is a 3x11 which describes the relationship of the inputs to the states:

$$B = \begin{bmatrix} \omega_1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & \omega_2 & 0 & 0 & 0 & 0 & 0 \\ 0 & \omega_3 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & \lambda_1 & \lambda_2 & \lambda_3 & \lambda_4 & \lambda_5 \end{bmatrix}$$

By this, we see that the state of the euler angles and accelerations are interdependent in some axes and that the yaw steering command is dependent on the yaw angle and x and y accelerations. To ensure stability, we must either minimize acceleration or maximize the range readings.

One important note to consider is interference of the ultrasonic pulses. Being that FORWARD uses four of them, it is important to make sure the receivers do not receive each others emitted energy reflections. Ultrasonics are directional, so by pointing the multistatic sensors to the left and right sides of the rollator to monitor passing or approaching obstacles, we decouple them from the monostatic. However, the front-facing sensors are only separated by the length of the axel, meaning these will need to be triggered sequentially to avoid interference. This can be implemented simply in Arduino by separate digital write statements.

This is also where a state estimator is useful. There is not a need nor a call for a mathematical definition of a Kalman filter for the scope of this project. However, we can make a general remark on the nature of the inputs and states. The sensor readings are all continuous, but can experience near instantaneous changes due to sudden appearances of obstacles or disturbances in the environment. For example, a fast moving obstacle can quickly enter the field of view, which may cause range sensor readings to drop quickly, while the amount of objects identified by the camera may change quickly as well. Therefore, an estimator is useful in the

event of actively avoiding an obstacle present, in that it can help smooth response to commands and provide the best advice on where to veer toward, but it would be disrupted by the volatile environment.

### **7.5.2 I2C Bus for Sensors**

The utilization of four ultrasonic sensors and one LiDAR to supply a feed of information to FORWARD's central processor can be integrated and realized through a wiring bus with the I2C digital communication protocol. This I2C scheme will use a synchronous clock signal provided to the sensors by the MCU. It will operate always in half-duplex, meaning data will be transmitted in only one direction at a time - from the MCU to the sensors and from the sensors back to the MCU in successive time steps. Additionally, the sensors will be accessed by their unique addresses and send packets of information as a sequence, taking turns. FORWARD does not require the use of a multiplexer device, as accessing the sensor data is done by address over the two common wires.

## **7.6 Identification and Image Processing**

FORWARD uses neural network technology to classify obstacles within the field of vision of the camera module.

### **7.6.1 Training Object Recognition Models**

### **7.6.2 Predetermined Obstacles**

## **7.7 Avoidance Protocols**

With the presence of telemetry and range detection data from the sensors, and the obstacles classified and their movement tracked by the camera and the neural networks, FORWARD can proceed to generate guidance feedback and motor commands to steer the rollator and to keep the user safe from collisions. Avoidance protocols may take the form of: emergency stop, right or left hand turn, or veering. The form these protocols will take is primarily cooperative feedback through haptic handlebar vibration and spatial audio over Bluetooth bone conduction headphones. There is also the emergency stop maneuver and polite obstacle avoidance. Stability is also taken into consideration because after veering away from an obstacle, FORWARD should re-orient itself to travel straight once again.

### **7.7.1 Emergency Stop**

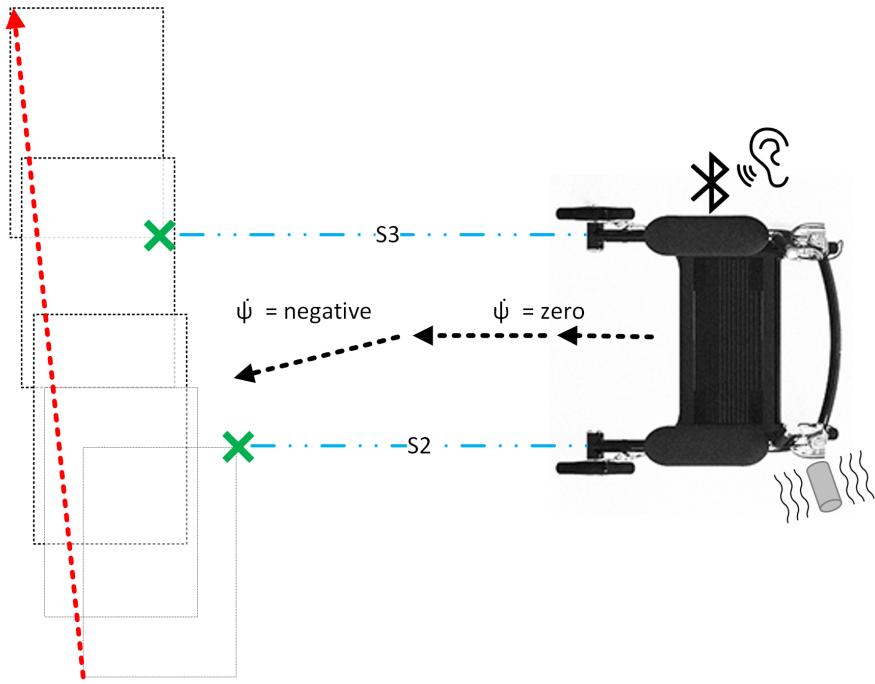
An emergency stop would take place if a road is detected ( $> 2$  cars detected) or if there is a drop off (cliff). It would also occur when the rollator acceleration increases rapidly, indicating it is fleeing the user down a decline.

### **7.7.2 Stationary Obstacle**

A stationary obstacle such as a wall or staircase would require a complete pivot, either preceding or following an emergency stop. The order would depend on the speed of the user and how much margin there is for guidance.

### **7.7.3 Polite Response to Obstacle in Motion**

Polite obstacle avoidance is a veering-moded response to moving obstacles, namely people, pets, and vehicles. The inspiration was drawn from real world experiences, where an obstacle will non-intelligently obstruct fluid travel straight ahead. If there is for example, a person walking from left to right (rollator frame of reference) across the camera field of vision, we can track the coordinates of its detection square, and form some abstract calculation of its velocity. We also have some idea of how fast this might be traveling based on other environmental data obtained by the camera; however, methods beyond the scope of this project would likely be required to harness this and improve avoidance strategies. Nevertheless, knowing the direction of travel of the obstacle means FORWARD can veer the user in the opposite direction. Being opposite is paramount because traveling behind the forward path of the obstacle will vastly decrease the chance of collision, and it will not infringe on either party's convenience or safety. The effects of collision for a stationary object are less severe compared to the likes of a running person or God forbid, a car. FORWARD will be able to confidently halt the user from these dangerous situations, and strategically navigate around them in a seamless manner.



*Figure 32: Polite Obstacle Avoidance*

In figure 32, the red dotted line is the assumed constant velocity of an obstacle, represented by the dotted rectangle, crossing from left (S2) to right (S3). An initial deadset detection is made at the lower green X, when the obstacle passes into sensor S2's own field of view. The second green X above indicates the last moment (MCU refresh frame) when the obstacle is considered to be "in the way." After passing by, S3 will return to max range reading, indicating the dormant navigation mode can be re-entered, assuming no other obstacles have come into view. The pulsed blue line is the ultrasonic energy path of transmission and reception. The black dotted line is the direction of the rollator velocity, which is also shown to change to move forward (in the direction of negative a yaw angle), politely behind the moving obstacle. Also pictured is both audio and haptic feedback being activated and actuated.

# 8 Prototype Fabrication

## 8.1 Printed Circuit Board Design

It is advantageous to use the 5V configuration for ESP32 UART bridge. In development, we used a development board to program the MCU but in practice must implement a UART bridge on the PCB to communicate with the MCU for flashing the memory and sending serial data out.

For voltage regulation, it could be expedient to, instead of using Texas Instruments Webench to design circuits for the PCB, use a 1/3 voltage divider for the ultrasonic ECHO pins. This is necessary because the ESP32 operates on 3.3V while the ultrasonic sensors use 5V, even though they are 3.3V compatible. This can be easily implemented by a  $1\text{k}\Omega$  and  $2\text{k}\Omega$  resistor in series.

One other consideration are the PCB traces. We intend to use 20mil (0.5mm) isolations and traces. The PCB does not use RF signals.

Motor controllers are more sensitive components and should be implemented on an independent PCB. These are considered as optically isolated motor drivers in order to minimize back EMI/F. In this case, one would bias an LED to turn the controller on.

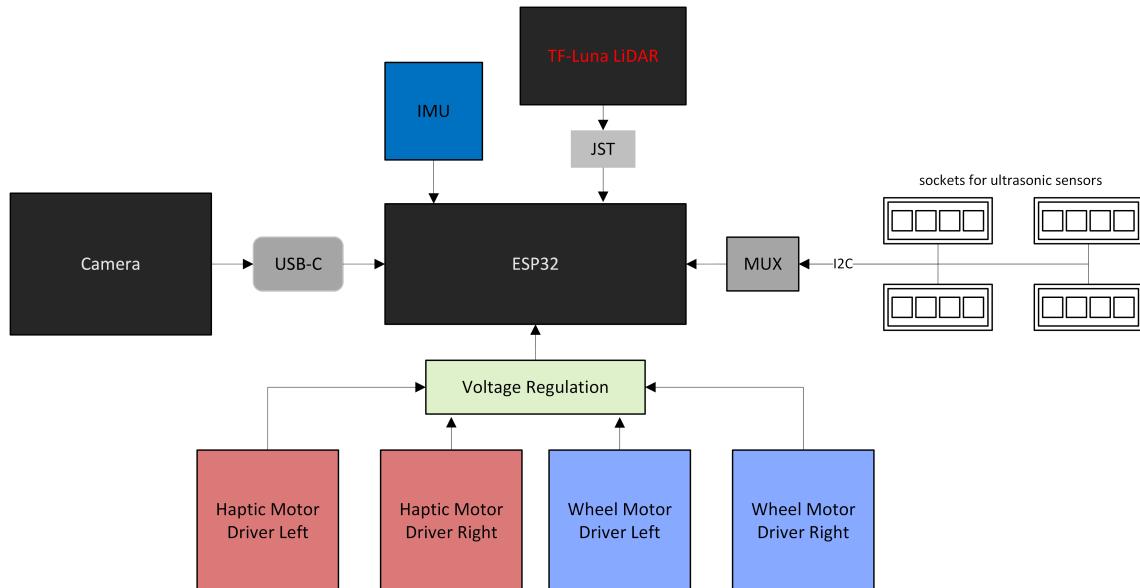


Figure 33: PCB Block Diagram

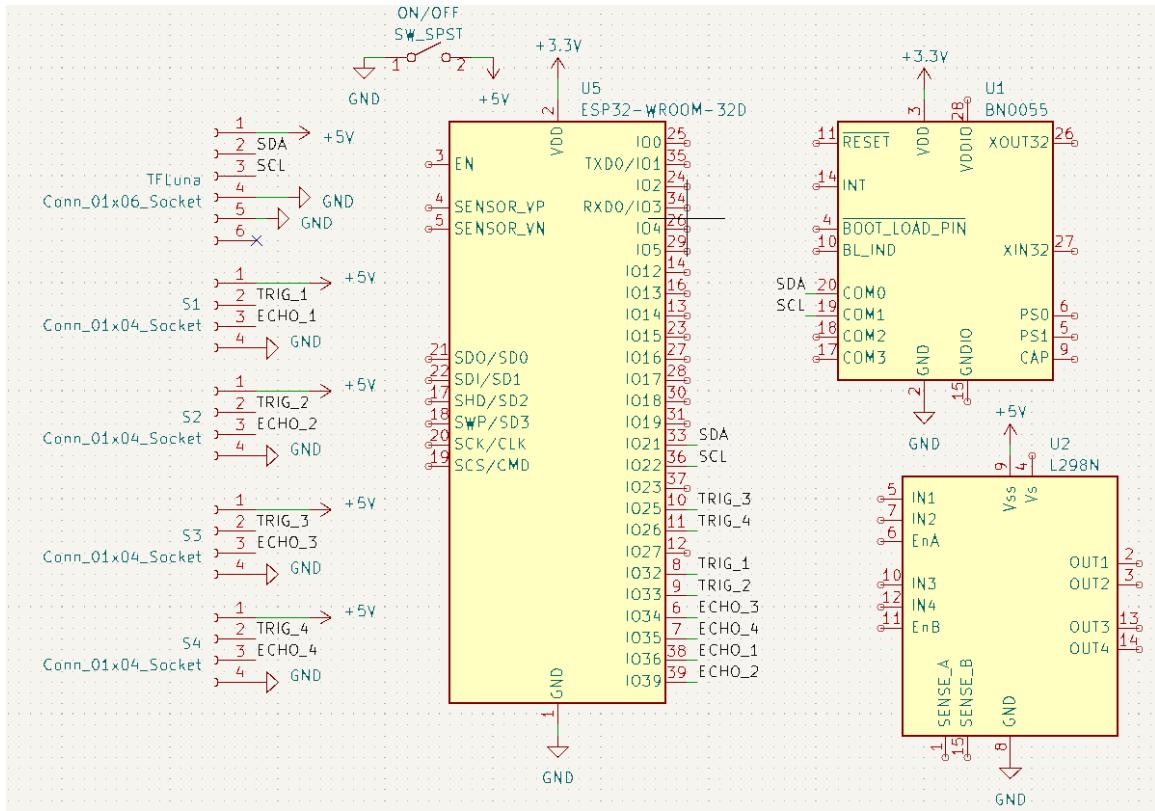


Figure 34: PCB KiCAD Schematic

# 9 System Testing

## 9.1 Subsystem Testing

### 9.1.1 Detection FOV Threshold

The first test for the obstacle detection subsystem is straightforward. It will consist of the sensor readings code uploaded to the microcontroller, connected to a laptop which rests on the seat of the rollator. The serial plotter will be open and we aim to observe changes to pitch and yaw angles as well as sensor ranges all simultaneously. This will provide a visual indication and verification that the proper decisions based on detections can be created in the Senior Design II course. This test should work regardless of surface material and orientation of the obstacle. Therefore, it will be tested indoors in a hallway and open forum environment, outdoors in a neighborhood. The indoor test environments resemble that which FORWARD might be deployed in the medical hospital or assisted living facility, while it may also be driven around in lower calamity settings. Regardless, we will verify that ranging is independent of the environment.

Sensors must be integrated on the Medline rollator in their assigned positions, continuously transmitting the data to the microcontroller. The secondary goal will be to then connect the Arduino COM port to Matlab in order to generate a polar plot showcasing the field of vision of the rollator when outfitted with purely the range sensors. The three tiers of requirements for passing the test are as follows:

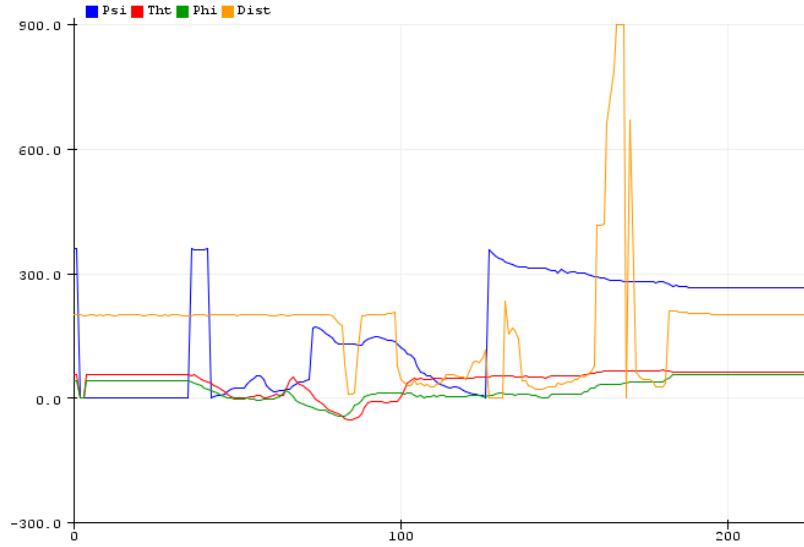
1. **Basic:** Successfully detect face-on obstacles at 0.500, 2.000, 7.000 meters. Range decreases and increases as the rollator is driven by the user.
2. **Stretch:** Successfully detect obstacles at distance, at angles  $\pm 15^\circ$ ,  $\pm 30^\circ$ ,  $\pm 90^\circ$  and sub-intervals depending on rollator attitude (degrees). Instantaneous delta in range measurement is observed when obstacle passes out of  $S_x$  field of view
3. **Advanced:** Alert the network "surrounded" or "hallway dead end" if all sensor ranges are below the 0.5 meter threshold.

where a detection is defined by an instantaneous delta in the sensor readings, resulting in a less-than-maximum range. The distances are defined by radial distance from the center of mass of the rollator. The angles are defined in a polar manner, where the origin is also the center of mass. The coordinates  $(x, y)$  of an obstacle  $X_x$ , detected by sensor  $x$  at range  $S_x$  and angle  $\theta$  whose positive increase is counterclockwise in this frame is then given by:

$$X_x = S_x(\cos(\theta), \sin(\theta)) = (x, y)$$

As known, there are minor dead zones in the range sensors. Therefore, to determine a safe zone range threshold, it would need to exceed the range of dead

sensing. Now, there could be a way to determine that FORWARD is reading the dead zone and coordinate emergency stops based on that (although it is also important to note that an emergency stop for low range may only be necessary if S2 and S3 front-facing are dead). The detection threshold can then be hard-coded into the GNC software, say 0.25 meters.



*Figure 35: Euler Angles Test*

It follows then, that we can define a range grid in polar coordinates where the maximum range detected is plotted versus yaw angle of the rollator. In this plot, we can also see precisely when there is an obstacle that causes a reduction in range.

### 9.1.2 Identification Importance

The tiers of testing goals are:

1. **Basic:** Alert the network there is a certain type of obstacle present (i.e. person, dog, car).
2. **Stretch:** Alert the network that if two or more cars are present, "road ahead." If two or more people are present, "crowd ahead"
3. **Advanced:** If range sensors return low but no obstacles classified, alert the network "wall." This is a placeholder code for any static solid obstacle.

### 9.1.3 Control Feedback

A successful control feedback test is defined by:

1. **Basic:** Successfully vibrate the rollator handlebars via the haptic motors attached.
2. **Stretch:** Increase the frequency of vibration as range reading decreases.
3. **Advanced:** Spatially aware haptic feedback - left and right handlebars indicate the location of the obstacle.

## 9.2 System Integration, Testing, and Evaluation

System integration was already incorporated to some extent into the subsystem testing described in the previous subsection. However, there will be further concerns and scrutiny the FORWARD system must be subjected to as a whole. Among basic properties such as secure mounting and housing in the electronics chassis (discussed in section 6.2), it is good to consider waterproofing, temperature, viability with low battery/power supply, and configurations with sensors on, camera off, or vice versa. This should be done in order to ensure a reliable product is brought to the user.

*PCB Assembly and Testing* As mentioned, the printed circuit board should be tested with varying levels of battery life remaining.

*Autonomous Navigation with Cooperative User* With motors installed on the rollator, which is also equipped with GNC software, there should be decision-making in the main code to distinguish how FORWARD adapts based on the environment. Some scenarios that come to mind are:

1. Evasive mode. FORWARD takes full control (i.e. emergency stop)
2. Cooperative navigation mode. FORWARD guides the user in a way does not infringe on their free movement.
3. Dormant mode. User has full control of direction.

*Free Roam Evaluation* The final phase of testing is done when FORWARD integration is complete, and this is called the free roam evaluation. Essentially, the walker will be driven out in public for a pre-determined period of time, and the team will note mishaps and incidents that the guidance, navigation, and control protocols fail to prevent. These would be noted for future improvements for future endeavors and projects or products. This evaluation method will truly test and determine the successful or unsuccessful implementation of FORWARD from the beginning specifications and requirements listed. Multi-obstacle scenarios, mixtures of incline and decline territories, and mild levels of danger will be encountered. If requirements are met, design is up to specification, and all previous tests have been passed, we are confident FORWARD evaluation will be a success.

# 10 Administrative Content

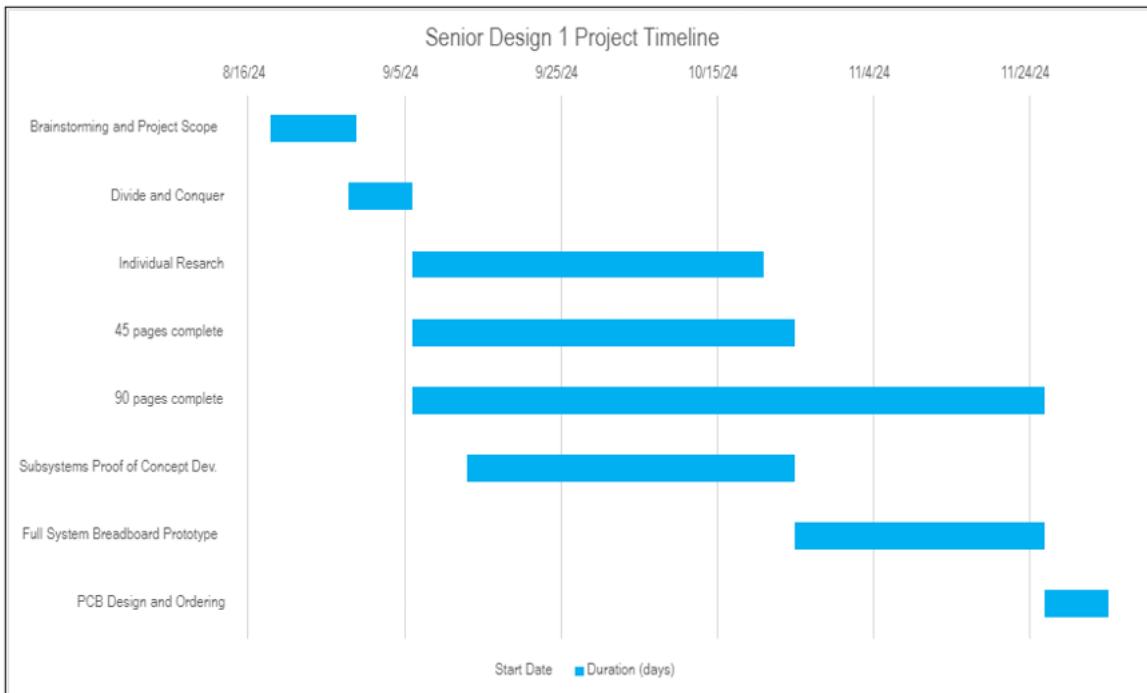
FORWARD is an extensive project that integrates both software and hardware. The following section outlines the development milestones this team is complying to, as well as the allocated budget. At the time of writing this, many of the components have already been ordered, and so section 10.2 provides an analysis of how the team is saving money or also being required to spend more. Mainly, the cost of surface mount components for the printed circuit design was somewhat overlooked during the development of the budget, but it should not be a problem due to saving money on the sensors.

## 10.1 Project Milestones

The figures below show various project milestones with their estimated start and end dates. The duration is given in days. There is also a Gantt chart generated by this data. The paper should be incrementally completed throughout the first semester, progressing towards a subsystem demo before an official full system prototype is made on a breadboard. After that is done, the printed circuit board will be ordered and the entirety of the second semester will be dedicated to integration and final testing and assembly.

	Start Date	End Date	Duration (days)	Duration (weeks)
Brainstorming and Project Scope	8/19	8/30	11	1.6
Divide and <u>Conquer</u>	8/29	9/6	8	1.1
Individual Research	9/6	10/21	45	6.4
45 pages complete	9/6	10/25	49	7
90 pages complete	9/6	11/26	81	11.6
Subsystems Proof of Concept Dev.	9/13	10/25	42	6
Full System Breadboard Prototype	10/25	11/26	32	4.6
PCB Design and Ordering	11/26	12/6	10	1.4

Figure 36: Senior Design I Milestones

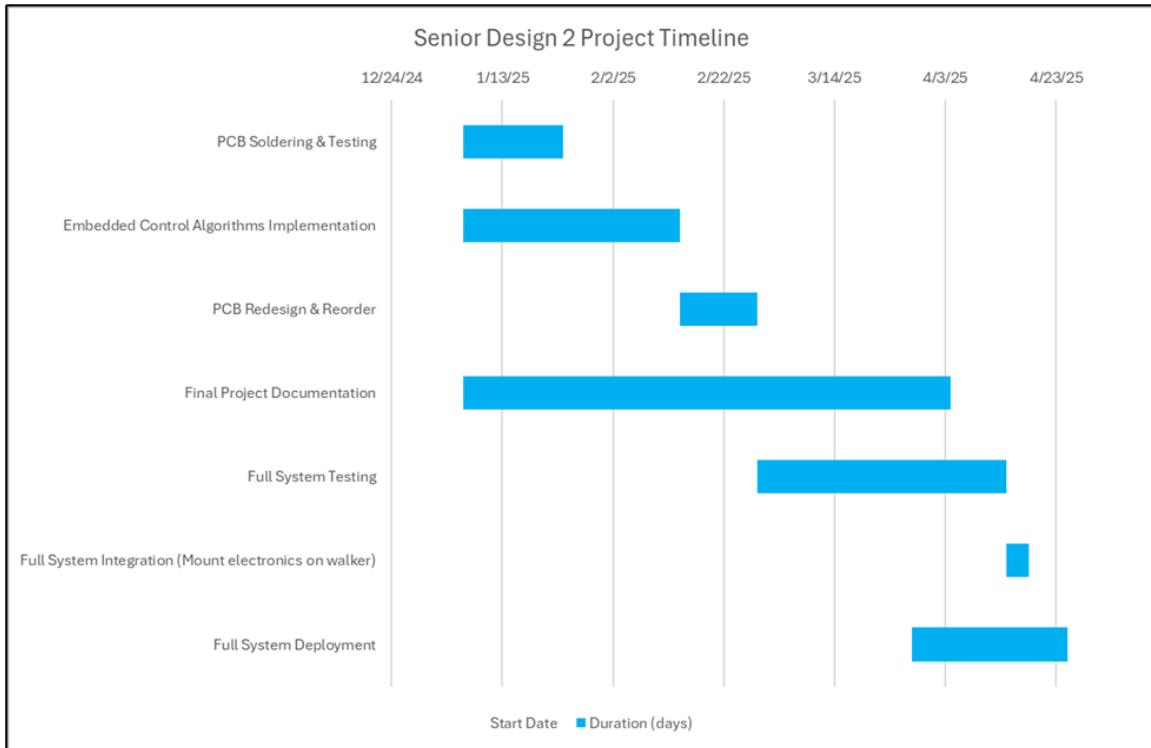


*Figure 37: Senior Design I Gantt Chart*

Senior Design II takes place during the second semester of the project, and is mainly dedicated to system integration and testing. There is a time allotted for PCB reordering, assuming that there might be problems the first time around. Much of the time will also be spent marketing and presenting the results of the project, and showcasing the hardware and software capabilities within the engineering department here at UCF.

	Start Date	End Date	Duration (days)	Duration (weeks)
PCB Soldering & Testing	1/6	1/24	18	2.6
Embedded Control Algorithms Implementation	1/6	2/14	39	5.6
PCB Redesign & Reorder	2/14	2/28	14	2
Final Project Documentation	1/6	4/4	88	12.6
Full System Testing	2/28	4/14	45	6.4
Full System Integration (Mount electronics on walker)	4/14	4/18	4	0.6
Full System Deployment	3/28	4/25	28	4

*Figure 38: Senior Design II Milestones*



*Figure 39: Senior Design II Gantt Chart*

## 10.2 Project Budget

The table above shows the budget for FORWARD. As we continue to research and develop, there will likely be changes made to this table. The project will require a pre-built walker as well as 5 peripheral components, 2 motors, and 2 controllers, as well as wiring and PCB housing.

<b>Component</b>	<b>Type</b>	<b>Total</b>
Walker	housing	\$60
All-Terrain Wheels (4)	housing	\$48
LiDAR sensor	peripheral	\$40
Ultrasonic sensor	peripheral	\$5
CV Camera	peripheral	\$15
IMU	peripheral	\$15
DC Motors (2)	motor	\$52
Motor shield	controller	\$18
MCU	controller	\$20
Wires (4)	wiring	\$8
PCB	housing	\$25
Audio feedback	feedback	\$40
Vibrating disk (4)	feedback	\$8
<b>Total:</b>		<b>\$346</b>

*Figure 40: Project Budget*

Up to this point, the budget for sensors, processors, and motors has been successfully upheld. As advised by Dr. Wei early on to search Craig's List for a rollator, so we did and have found a great deal by a local close to UCF!

## **11 Conclusion**

## 12 Appendix A - Permissions

Dear Mr. Bower

Thank you for your enquiry and your interest in our products.

With this e-mail I confirm that the use of the content available on our website is permitted.

I would like to ask you in return to send me resp. my colleague, Melanie Harke, information about your final work for internal use.

Feel free to contact me if you have further questions.

Kind regards

i. A. Valerias Schneider

Discover our ultra-agile [cube](#).

**microsonic GmbH**

Phoenixseestraße 7 / 44263 Dortmund / Germany

T +49 231 97 51 51-55 / F +49 231 97 51 51 51 / E [valerias.schneider@microsonic.de](mailto:valerias.schneider@microsonic.de) / W [microsonic.de](http://microsonic.de)

Geschäftsführer: Dipl.-Ing. Johannes Schulte / Handelsregister: HRB Dortmund 9342

### Request for Ultrasonic Directivity from Microsonic



Tobiah Bower • 11:13 AM

Hi Bogdan,

I am a senior electrical engineering student at UCF. I am contacting you to ask for permission to use a figure you show in the following paper: APPLICATION OF A LASER RANGEFINDER.

Regards!



Bogdan Udrea • 11:14 AM

Aloha Tobiah. Sure thing, please feel free to use the figure. Which one is of interest to you?



Tobiah Bower • 12:53 PM

it's the one showing a lidar sensor azimuth. i can send it when i get home if you want to confirm  
and thank you!



Bogdan Udrea • 3:01 PM

Thanks for letting me know. There's no need to email me the figure. I remember it

### Request for LiDAR Azimuth Figure

Good morning,

Thank you for your Medline inquiry. I forwarded your email onto our Product Support manager for approval to use the Medline product photo. You should be hearing from in a timely manner. Thank you for your patience.

\*\*\*Medline Industries will be **CLOSED** Thursday 11.28 and Friday 11.29 in observance of the Thanksgiving Holiday.  
Thank you and have a good day.



We make  
healthcare  
run better.™

AtHome Team  
[AtHome.Medline.com](http://AtHome.Medline.com)

Sales Service Center  
Medline Industries, LP  
[www.medline.com](http://www.medline.com)

☎ 855-441-8737 (Customer Service)  
✉ [athome@medline.com](mailto:athome@medline.com) MTEE

## Request for Medline Empower Image

## 13 Appendix B - References

### References

- [1] Mostafa N, Feltner C, Fullin K, Guilbe J, Zehtabian S, Bacanlı SS, Bölöni L, Turgut D. A Smart Walker for People with Both Visual and Mobility Impairment. Sensors. 2021; 21(10):3488. <https://doi.org/10.3390/s21103488>
- [2] S. Dubowsky et al., "PAMM - a robotic aid to the elderly for mobility assistance and monitoring: a 'helping-hand' for the elderly," Proceedings 2000 ICRA. Millennium Conference. IEEE International Conference on Robotics and Automation. Symposia Proceedings (Cat. No.00CH37065), San Francisco, CA, USA, 2000, pp. 570-576 vol.1, doi:10.1109/ROBOT.2000.844114
- [3] B. K. Asiedu Asante and H. Imamura, "Towards Robust Obstacle Avoidance for the Visually Impaired Person Using Stereo Cameras," Technologies, vol. 11, no. 6, p. 168, 2023. doi:10.3390/technologies11060168
- [4] A. B. Atitallah, Y. Said, M. A. B. Atitallah, M. Albekairi, K. Kaaniche, and S. Boubaker, "An effective obstacle detection system using deep learning advantages to aid blind and visually impaired navigation," Ain Shams Engineering Journal, vol. 15, no. 2, p. 102387, 2024. doi:10.1016/j.asej.2023.102387
- [5] Rui Santos, "ESP32 BLE Server – Environmental Sensing Service (ESP-IDF)," Random Nerd Tutorials, 6 October 2022. [Online]. Available: <https://randomnerdtutorials.com/esp32-ble-server-environmental-sensing-service/>. [Accessed: Oct. 29, 2024].
- [6] How2Electronics, "ESP32-CAM based object detection & identification with OpenCV," How2Electronics. [Online]. Available: <https://how2electronics.com/esp32-cam-based-object-detection-identification-with-opencv/>. [Accessed: Oct. 9, 2024].
- [7] How To Electronics, "Object Detection & Identification with AMB82 Mini AI Camera," How2Electronics. Available: <https://how2electronics.com/object-detection-identification-with-amb82-mini-ai-camera/>. [Accessed: Oct. 9, 2024].
- [8] R. Kumar, "YOLO Object Detection Explained," DataCamp, <https://www.datacamp.com/blog/yolo-object-detection-explained>. (accessed Oct. 24, 2024).
- [9] Soundscape HQ, "Unlock Sound Through Bones: Understanding Bone Conduction," Soundscape HQ, 2024. [Online]. Available: <https://soundscapehq.com/what-is-bone-conduction/>. [Accessed: Oct. 15, 2024].

- [10] Bluetooth Technology, "Tech Overview," Bluetooth.com, <https://www.bluetooth.com/learn-about-bluetooth/tech-overview/>. (accessed Oct. 24, 2024).
- [11] C. Woodford, "How Bluetooth Works," Explain That Stuff, <https://www.explainthatstuff.com/howbluetoothworks.html>. (accessed Oct. 24, 2024).
- [12] YouthWhisper Bone Conduction Headphones Bluetooth, Wireless Open-Ear Headset with Microphones, Titanium Lightweight Sweat Resistant, Answer Phone Sports Earphones for Running Hiking Bicycling Black <https://www.walmart.com/ip/YouthWhisper-Bone-Conduction-Headphones-Bluetooth-Wireless-Open-Ear-Headset-Microphones-Titanium-Lightweight-Sweat-Resistant-Answer-Phone-Sports-Earp/278825770>
- [13] JLab Wireless Bluetooth Charging Multipoint Earbuds, Ambient Sound Mode. <https://www.amazon.com/JLab-Wireless-Bluetooth-Charging-Multipoint/dp/B0CC772D37>
- [14] D. -M. Ding, Y. -G. Wang, W. Zhang and Q. Chen, "Fall Detection System on Smart Walker Based on Multisensor Data Fusion and SPRT Method," in IEEE Access, vol. 10, pp. 80932-80948, 2022. doi:10.1109/ACCESS.2022.3195674
- [15] T. Dirheimer, J. Hancock, D. Hill, Y. Kochubievsky, and S. Moore, Smart Walker Design: Final Report, ECE 480, Michigan State University, April 29, 2015.
- [16] ThinkAutonomous. "Types of LiDAR: What's the difference? | Think Autonomous," ThinkAutonomous.ai, [Online]. Available: <https://www.thinkautonomous.ai/blog/types-of-lidar/>. Accessed: Sep. 15, 2024.
- [17] M. Toa and A. Whitehead, "Ultrasonic Sensing Basics," Texas Instruments, Application Report SLAA907D, Dec. 2021. [Online]. Available: <https://www.ti.com/lit/an/slaa907d/slaa907d.pdf>. Accessed: Sep. 15, 2024.
- [18] "Laser vs Ultrasonic Distance Sensor Tests," DroneBot Workshop, Sep. 29, 2019. [Online]. Available: <https://dronebotworkshop.com/laser-vs-ultrasonic-distance-sensor-tests/>. [Accessed: Sep. 10, 2024].
- [19] "Pros and cons of camera, LiDAR, RADAR, and ultrasonic detection technologies in AV," ResearchGate. [Online]. Available: [https://www.researchgate.net/figure/Pros-and-cons-of-camera-LiDAR-RADAR-and-ultrasonic-detection-technologies-in-AV\\_tbl](https://www.researchgate.net/figure/Pros-and-cons-of-camera-LiDAR-RADAR-and-ultrasonic-detection-technologies-in-AV_tbl). [Accessed: Sep. 15, 2024].
- [20] Microsonic, "Detection Zones," Microsonic, [Online]. Available: <https://www.microsonic.de/en/support/ultrasonic-technology/detection-zones.htm>. [Accessed: 15-Sep-2024].

- [21] R. M. [Last Name], "FOV Definition: Optical axis of scanning LIDAR (Black dotted line)," ResearchGate, [Online]. Available: [https://www.researchgate.net/figure/FOV-Definition-Optical-axis-of-scanning-LIDAR-Black-dotted-line\\_fig1\\_280132809](https://www.researchgate.net/figure/FOV-Definition-Optical-axis-of-scanning-LIDAR-Black-dotted-line_fig1_280132809). [Accessed: 15-Sep-2024].
- [22] byACRE, "Carbon Ultralight Rollator," byACRE, [Online]. Available: <https://shop.byacre.com/us/carbon-ultralight-rollator.html>. [Accessed: 16-Sep-2024].
- [23] uStep, "Standard Model," uStep, Available: <https://www.ustep.com/product/standard-model>.
- [24] E. W. Weisstein, "Quaternion," MathWorld—A Wolfram Web Resource. [Online]. Available: <https://mathworld.wolfram.com/Quaternion.html>.
- [25] R. E. Kalman, "A new approach to linear filtering and prediction problems," Journal of Basic Engineering, vol. 82, no. 1, pp. 35-45, Mar. 1960. [Online]. Available: <https://www.cs.unc.edu/welch/kalman/media/pdf/Kalman1960.pdf>.
- [26] Brain, M. (n.d.). How brakes work. HowStuffWorks. <https://auto.howstuffworks.com/auto-parts/brakes/brake-types/brake.htm>
- [27] Calculator Academy. (n.d.). Battery run time calculator. Calculator Academy. <https://calculator.academy/battery-run-time-calculator/>
- [28] Grand View Research. (2024). Assisted walking devices market size, share & trends analysis report by product type (Canes, Crutches, Walkers, Gait Trainers), by region, and segment forecasts, 2022 - 2030. Grand View Research. <https://www.grandviewresearch.com/industry-analysis/assisted-walking-device-market>
- [29] Mallard Perez. (n.d.). What the Florida law says about bicycle lights. Mallard Perez. <https://www.mallardperez.com/faqs/what-the-florida-law-says-about-bicycle-lights.cfm>.
- [30] Apollo Scooters, "Understanding Electric Scooter Controllers," Apollo Scooters, [Online]. Available: <https://apolloscooters.co/blogs/news/understanding-electric-scooter-controllers>. [Accessed: Oct. 24, 2024].
- [31] J. S. Hwang, S. Y. Kim, and H. M. Kim, "A Study on the Design of the Control Algorithm for the Electric Scooter," *IEEE Access*, vol. 8, pp. 146207-146215, 2020. <https://ieeexplore.ieee.org/document/9137951>. [Accessed: Oct. 24, 2024].
- [32] Core Electronics, "Motor Drivers vs. Motor Controllers," Core Electronics, [Online]. Available: <https://core-electronics.com.au/guides/motor-drivers-vs-motor-controllers/>. [Accessed: Oct. 24, 2024].

- [33] Thingbits, "Motor Drivers," Thingbits, [Online]. Available: <https://www.thingbits.in/t/categories/motors-and-drivers/motor-drivers>. [Accessed: Oct. 24, 2024].
- [34] Power Electronics News, "Learning the Basics of Motor Control," Power Electronics News, [Online]. Available: <https://www.powerelectronicsnews.com/learning-the-basics-of-motor-control/>. [Accessed: Oct. 24, 2024].
- [35] Etech Sparks, "DC Motor Controller: Working Principle & Definition," Etech Sparks, [Online]. Available: <https://etechsparks.com/dc-motor-controller-working-principle-definition/>. [Accessed: Oct. 24, 2024].
- [36] Elprocus, "Different Types of Electric Motors," Elprocus, [Online]. Available: <https://www.elprocus.com/different-types-of-electric-motors/>. [Accessed: Oct. 24, 2024].
- [37] The Pi Hut, "What's the Difference Between DC, Servo & Stepper Motors?" The Pi Hut, [Online]. Available: <https://thepihut.com/blogs/raspberry-pi-tutorials/whats-the-difference-between-dc-servo-amp-stepper-motors>. [Accessed: Oct. 24, 2024].
- [38] Power Electric, "AC Motors vs. DC Motors," Power Electric, [Online]. Available: <https://www.powerelectric.com/motor-blog/ac-motors-vs-dc-motors>. [Accessed: Oct. 24, 2024].
- [39] Elprocus, "DC Motor: Basics, Types, and Applications," Elprocus, [Online]. Available: <https://www.elprocus.com/dc-motor-basics-types-application/>. [Accessed: Oct. 24, 2024].
- [40] Elprocus, "DC Shunt Motor: Construction, Working Principle, and Circuit Diagram," Elprocus, [Online]. Available: <https://www.elprocus.com/dc-shunt-motor-construction-working-principle-circuit-diagram/>. [Accessed: Oct. 24, 2024].
- [41] Elprocus, "DC Series Motor: Components, Circuit Diagram, and Applications," Elprocus, [Online]. Available: <https://www.elprocus.com/dc-series-motor-components-circuit-diagram-applications/>. [Accessed: Oct. 24, 2024].
- [42] Elprocus, "PMDC (Permanent Magnetic DC) Motor: Construction and Working," Elprocus, [Online]. Available: <https://www.elprocus.com/pmdc-permanent-magnetic-dc-motor-construction-working/>. [Accessed: Oct. 24, 2024].
- [43] Linquip, "Compound DC Motors," Linquip, [Online]. Available: <https://www.linquip.com/blog/compound-dc-motors/>. [Accessed: Oct. 24, 2024].

- [44] Elprocus, "Brushless DC Motor: Advantages, Applications, and Control," Elprocus, [Online]. Available: <https://www.elprocus.com/brushless-dc-motor-advantages-applications-and-control/>. [Accessed: Oct. 24, 2024].
- [45] Monolithic Power Systems, "Brushless vs. Brushed DC Motors," Monolithic Power Systems, [Online]. Available: <https://www.monolithicpower.com/en/learning/resources/brushless-vs-brushed-dc-motors>. [Accessed: Oct. 24, 2024].
- [46] Spike VM, "RPM to MPH Calculator," Spike VM, [Online]. Available: [https://www.spikevm.com/calculators/fuel\\_distance/rpm-mpm.php](https://www.spikevm.com/calculators/fuel_distance/rpm-mpm.php). [Accessed: Oct. 24, 2024].
- [47] J. Lee, J. Kim, and H. Kim, "A Study on the Efficiency of Electric Motors," *Nat. Sci. Rep.*, vol. 9, no. 1, pp. 1-11, 2019. [Online]. Available: <https://www.ncbi.nlm.nih.gov/pmc/articles/PMC6353162/>. [Accessed: Oct. 24, 2024].
- [48] Trionic, "How Much Weight Can the Rollator Hold," Trionic, [Online]. Available: <https://www.trionic.us/en/knowledge/135-how-much-weight-can-the-rollator-hold>. [Accessed: Oct. 24, 2024].
- [49] Gribble, "Cycling Power vs. Speed Calculator," Gribble, [Online]. Available: [https://www.gribble.org/cycling/power\\_v\\_speed.html?units=metric&rp\\_wr=74.843&rp\\_wb=17&rp\\_a=0.509&rp\\_cd=0.63&rp\\_dtl=1&ep\\_crr=0.04&ep\\_rho=1.22601&ep\\_g=8&ep\\_headwind=0&p2v=200&v2p=35.41](https://www.gribble.org/cycling/power_v_speed.html?units=metric&rp_wr=74.843&rp_wb=17&rp_a=0.509&rp_cd=0.63&rp_dtl=1&ep_crr=0.04&ep_rho=1.22601&ep_g=8&ep_headwind=0&p2v=200&v2p=35.41). [Accessed: Oct. 24, 2024].
- [50] Drive Medical, "Drive Medical Rollator with Removable Back Support," Amazon, [Online]. Available: <https://www.amazon.com/Drive-Medical-Rollator-Removable-Support/dp/B00NFJX0PU>. [Accessed: Oct. 24, 2024].
- [51] XConvert, "Square Inches to Square Feet Converter," XConvert, [Online]. Available: <https://www.xconvert.com/unit-converter/square-inches-to-square-feet>. [Accessed: Oct. 24, 2024].
- [52] Ox Wheels, "Does Tyre Size Affect Car Performance?" Ox Wheels, [Online]. Available: <https://www.oxwheels.com.au/Does-tyre-size-affect-car-performance>. [Accessed: Oct. 24, 2024].
- [53] E-Bikes Forum, "Does a 750 Front and a 750 Rear Add Up to 1500 Watts?" E-Bikes Forum, [Online]. Available: <https://ebikesforum.com/threads/does-a-750-front-and-a-750-rear-add-up-to-1500-watts.5464/>. [Accessed: Oct. 24, 2024].
- [54] YZL, "150W Brushless DC Motor Replacement Cylindrical 13000-15000RPM," Amazon, [Online]. Available: <https://www.amazon.com/>

Brushless-Cylindrical-13000-15000RPM-Propulsion-Specific/dp/B09NCJ24W6. [Accessed: Oct. 24, 2024].

- [55] Citpho, "775 6000-12000RPM Electric Brushless Motor," Amazon. [Online]. Available: <https://www.amazon.com/Citpho-775-6000-12000RPM-Electric-Electrical/dp/B0CMXM1N94>. [Accessed: Oct. 24, 2024].
- [56] AliExpress, "Electric Brushless Motor," AliExpress. [Online]. Available: <https://www.aliexpress.us/item/3256807288642417.html>. [Accessed: Oct. 24, 2024].
- [57] AliExpress, "Brushless Motor," AliExpress. [Online]. Available: <https://www.aliexpress.us/item/3256804436743610.html>. [Accessed: Oct. 24, 2024].
- [58] AliExpress, "DC Brushless Motor," AliExpress. [Online]. Available: <https://www.aliexpress.us/item/3256802991206296.html>. [Accessed: Oct. 24, 2024].
- [59] AliExpress, "High Torque Brushless Motor," AliExpress. [Online]. Available: <https://www.aliexpress.us/item/3256807195926102.html>. [Accessed: Oct. 24, 2024].
- [60] UMLIFE, "300W Three Phase Brushless Motor Controller," Amazon. [Online]. Available: <https://www.amazon.com/UMLIFE-Three-Phase-Brushless-Controller-Control/dp/B09BHXLGW6>. [Accessed: Oct. 24, 2024].
- [61] C. Burgess, "Quad Motor Servo Shield for ESP32 Project Board," Tindie. [Online]. Available: <https://www.tindie.com/products/cburgess129/quad-motor-servo-shield-for-esp32-project-board/>. [Accessed: Oct. 24, 2024].
- [62] Espressif Systems, "ESP32-WROOM-32 Datasheet," Espressif. [Online]. Available: [https://www.espressif.com/sites/default/files/documentation/esp32-wroom-32\\_datasheet\\_en.pdf](https://www.espressif.com/sites/default/files/documentation/esp32-wroom-32_datasheet_en.pdf). [Accessed: Oct. 24, 2024].
- [63] Random Nerd Tutorials, "Installing the ESP32 Board in Arduino IDE (Windows Instructions)," Random Nerd Tutorials. [Online]. Available: <https://randomnerdtutorials.com/installing-the-esp32-board-in-arduino-ide-windows-instructions/>. [Accessed: Oct. 24, 2024].
- [64] Espressif Systems, "MCPWM API Reference," Espressif. [Online]. Available: <https://docs.espressif.com/projects/esp-idf/en/v4.4.2/esp32/api-reference/peripherals/mcpwm.html>. [Accessed: Oct. 24, 2024].

- [65] P. Peza, "TB6612FNG\_ESP32," GitHub. [Online]. Available: [https://github.com/pablopeza/TB6612FNG\\_ESP32](https://github.com/pablopeza/TB6612FNG_ESP32). [Accessed: Oct. 24, 2024].
- [66] SimpleFOC, "Installation Guide," SimpleFOC. [Online]. Available: <https://docs.simplefoc.com/installation>. [Accessed: Oct. 24, 2024].
- [67] AliExpress, "DC Brushless Motor," AliExpress. [Online]. Available: <https://www.aliexpress.us/item/3256805324882671.html>. [Accessed: Oct. 24, 2024].
- [68] Makerbase Motor, "MKS ESP32 FOC V1.0 Manual," GitHub. [Online]. Available: <https://github.com/makerbase-motor/MKS-ESP32FOC/blob/master/User%20Manual/MKS%20ESP32%20FOC%20V1.0%20Manual.pdf>. [Accessed: Oct. 24, 2024].
- [69] Act Power, "What Is a Power Supply and How Does It Work?" Act Power. [Online]. Available: <https://www.actpower.com/blog/what-is-a-power-supply-and-how-does-it-work/>. [Accessed: Oct. 24, 2024].
- [70] RC Beacon, "Power Supply Units (PSUs): General Information," RC Beacon. [Online]. Available: [https://rcbeacon.com/pmb/psu\\_general\\_1.htm](https://rcbeacon.com/pmb/psu_general_1.htm). [Accessed: Oct. 24, 2024].
- [71] Precision Microdrives, "AB-001: Discrete Driver Circuits for Vibration Motors," Precision Microdrives. [Online]. Available: <https://www.precisionmicrodrives.com/ab-001-discrete-driver-circuits-for-vibration-motors>. [Accessed: Oct. 24, 2024].
- [72] AliExpress, "High Torque Brushless Motor," AliExpress. [Online]. Available: <https://www.aliexpress.us/item/3256803905606674.html>. [Accessed: Oct. 24, 2024].
- [73] Stack Exchange, "What is the safe amount of current I can apply to a DC motor?" Stack Exchange. [Online]. Available: <https://electronics.stackexchange.com/questions/301233/what-is-the-safe-amount-of-current-i-can-apply-to-a-dc-motor>. [Accessed: Oct. 24, 2024].
- [74] Arduino Forum, "Stall Current vs. Rated Current," Arduino Forum. [Online]. Available: <https://forum.arduino.cc/t/stall-current-vs-rated-current/1004977>. [Accessed: Oct. 24, 2024].
- [75] AliExpress, "High-Speed Brushless Motor," AliExpress. [Online]. Available: <https://www.aliexpress.us/item/3256805089628613.html>. [Accessed: Oct. 24, 2024].

- [76] Circuit Basics, "SRD-05VDC-SL-C Relay Datasheet," Circuit Basics. [Online]. Available: <https://www.circuitbasics.com/wp-content/uploads/2015/11/SRD-05VDC-SL-C-Datasheet.pdf>. [Accessed: Oct. 24, 2024].
- [77] AliExpress, "Brushless Motor Controller," AliExpress. [Online]. Available: <https://www.aliexpress.us/item/3256806182053704.html>. [Accessed: Oct. 24, 2024].
- [78] SimpleFOC, "Supported Microcontrollers," SimpleFOC. [Online]. Available: <https://docs.simplefoc.com/microcontrollers>. [Accessed: Oct. 24, 2024].
- [79] HiLetgo, "DRV8871 H-Bridge Motor Driver Breakout Board," Amazon. [Online]. Available: <https://www.amazon.com/HiLetgo-DRV8871-H-Bridge-Breakout-6-5V-45V/dp/B0CDWW7FZ8>. [Accessed: Oct. 24, 2024].
- [80] "Hobbywing QuicRun 1060 Brushed ESC," Amazon. [Online]. Available: <https://www.amazon.com/dp/B00F839VNQ>. [Accessed: Oct. 24, 2024].
- [81] BOJACK, "DC Motor Speed Controller, Adjustable Voltage Regulator," Amazon. [Online]. Available: <https://www.amazon.com/BOJACK-Voltage-Controller-Adjustable-Driver/dp/B09P6D5TMV>. [Accessed: Oct. 24, 2024].
- [82] "Gikfun L298N Dual H Bridge Motor Driver," Amazon. [Online]. Available: <https://www.amazon.com/gp/product/B09HXXG3DM>. [Accessed: Oct. 24, 2024].
- [83] "BEEYDC 12V 24V 36V 48V DC Motor Speed Controller," Amazon. [Online]. Available: <https://www.amazon.com/gp/product/B0CR6BX5QL>. [Accessed: Oct. 24, 2024].
- [84] RioRand, "DC Motor Controller, High Efficiency, Reversible, with Overcurrent Protection," Amazon. [Online]. Available: <https://www.amazon.com/RioRand-Controller-Efficiency-Generating-Protection/dp/B007TH4EN6>. [Accessed: Oct. 24, 2024].
- [85] "uxcell 5V Vibration Motor, Electric Vibrating Massager," Amazon. [Online]. Available: <https://www.amazon.com/uxcell-Vibration-Vibrating-Electric-Massager/dp/B08265KJLY>. [Accessed: Oct. 24, 2024].
- [86] DIANN, "Vibration Button Type Switch, 10mm x 2.7mm," Amazon. [Online]. Available: <https://www.amazon.com/DIANN-Vibration-Button-Type-10mmx2-7mm-Appliances/dp/B0B4SK8M1C>. [Accessed: Oct. 24, 2024].

- [87] "Electric DC Motor 12V 550," eBay. [Online]. Available: <https://www.ebay.com/itm/125600353141>. [Accessed: Oct. 24, 2024].
- [88] "How to Match Battery with Motor," I Need Motors. [Online]. Available: <https://www.inneedmotors.com/news/how-to-match-battery-with-motor-69783315.html>. [Accessed: Oct. 24, 2024]
- [89] Oxford Health NHS Foundation Trust, "Safety information leaflet: four-wheeled rollators," 2014. [Online]. Available: <https://www.oxfordhealth.nhs.uk/wp-content/uploads/2014/08/OP-101-15-Safety-information-leaflet-four-wheeled-rollators.pdf>. [Accessed: Oct. 28, 2024].
- [90] NFPMotor, "Vibrating Vibrator Vibration Motors," NFP-Motor, [Online]. Available: <https://www.nfpmotor.com/Vibrating-vibrator-vibration-motors.html#:~:text=Haptics%20Motor%20-%20by%20the%20definition,through%20the%20use%20of%20vibrations>. [Accessed: 7-Nov-2024].
- [91] GeeksforGeeks, "Voltage Regulation," GeeksforGeeks, [Online]. Available: <https://www.geeksforgeeks.org/voltage-regulation/>. [Accessed: 7-Nov-2024].
- [92] Vogely, *Vogely Universal 12V Electric Headlight for Bike, Motorcycle, Waterproof*, Amazon, [Online]. Available: <https://www.amazon.com/Vogely-Universal-Headlight-Electric-Waterproof/dp/B0CHKP8899>. [Accessed: Nov. 12, 2024].
- [93] Frdhee, *Frdhee Motorcycle LED Headlight, High Brightness Conversion, Waterproof*, Amazon, [Online]. Available: [https://www.amazon.com/Frdhee-Motorcycle-Brightness-Headlights-Conversion/dp/B0DGQD1DXF/ref=sr\\_1\\_23?crid=2TBUAGBXRIDAA&dib=eyJ2IjoiMSJ9.Bw0hUngN\\_FfXnbyiQmIjag9aXvRcQFYMiMTow34zag4NBh8VQS8BZaf3-UQFMqJoK3aamzn4C57wci8yY7IQfqihA9MmaFPauWfw9xndDkhS0sD\\_ggo6-ab\\_3LF1QRN4\\_UQTGV\\_z2C\\_Rw8Bqr\\_ZxJwnENlyS6PgU4heHzIAQt0ADL91fZnKFP-4Xe2I10jaCwKMLCN\\_XHR9gdTbBi-e-tnIRWYhKFivX5PiulPRAJ8zCc-7IEMR2Tc9w9c\\_p9-VMTMCLUITbqk\\_BVBtnS0wzbr2c9zk.Jj7GE6TTNpy0wI9oH1BiHZ9zulinaG8pXcY5n13zmBA&dib\\_tag=se&keywords=electric%2Bheadlight&qid=1731384528&sprefix=electric%2Bheadlight%2Caps%2C174&sr=8-23&th=1&psc=1](https://www.amazon.com/Frdhee-Motorcycle-Brightness-Headlights-Conversion/dp/B0DGQD1DXF/ref=sr_1_23?crid=2TBUAGBXRIDAA&dib=eyJ2IjoiMSJ9.Bw0hUngN_FfXnbyiQmIjag9aXvRcQFYMiMTow34zag4NBh8VQS8BZaf3-UQFMqJoK3aamzn4C57wci8yY7IQfqihA9MmaFPauWfw9xndDkhS0sD_ggo6-ab_3LF1QRN4_UQTGV_z2C_Rw8Bqr_ZxJwnENlyS6PgU4heHzIAQt0ADL91fZnKFP-4Xe2I10jaCwKMLCN_XHR9gdTbBi-e-tnIRWYhKFivX5PiulPRAJ8zCc-7IEMR2Tc9w9c_p9-VMTMCLUITbqk_BVBtnS0wzbr2c9zk.Jj7GE6TTNpy0wI9oH1BiHZ9zulinaG8pXcY5n13zmBA&dib_tag=se&keywords=electric%2Bheadlight&qid=1731384528&sprefix=electric%2Bheadlight%2Caps%2C174&sr=8-23&th=1&psc=1). [Accessed: Nov. 12, 2024].
- [94] StellarLights, *StellarLights 1600 Lumen LED Bicycle Headlight, Wide-Angle Beam, Waterproof*, Amazon, [Online]. Available: [https://www.amazon.com/StellarLights-Lumen-Bicycle-Headlight-Wide-Angle/dp/B019E81TMQ/ref=sr\\_1\\_87?crid=SI26K5INHEXE&dib=eyJ2IjoiMSJ9.cqbZnnB2T83LvSKMugRXgkCScs4XZvBSRQrTcKrPa2\\_](https://www.amazon.com/StellarLights-Lumen-Bicycle-Headlight-Wide-Angle/dp/B019E81TMQ/ref=sr_1_87?crid=SI26K5INHEXE&dib=eyJ2IjoiMSJ9.cqbZnnB2T83LvSKMugRXgkCScs4XZvBSRQrTcKrPa2_)

xFRcY61JRfXKEV0SpM-1g2BJpvtquHGCTYiH0oCgQRtDhDYq5xFpaeD1vqb0taZD2oSPrqrJDYdTbR  
 Svz7VbI\_-WMTunymyCZQEgeyn7X41B\_0EriQTwhLzY\_  
 YDT4h-yyoJLx3xo3bAaGRERdkcORArGZxuZJqVAN7hQ0jF\_  
 xMR6WpaRXkdDpmLv0Lkge7z3v-aoEI.Qb\_wRFvKZ2dMDIrIF7m76dWFgSyvk1VCvZUErT8qVAw&  
 dib\_tag=se&keywords=bike%2Bheadlight&qid=1731383790&refinements=  
 p\_36%3A-1200&rnid=386589011&sprefix=bike%2Bheadlight%2Caps%2C271&  
 sr=8-87&th=1. [Accessed: Nov. 12, 2024].

- [95] Analog Devices, *Light Sensor Glossary*, [Online]. Available: <https://www.analog.com/en/resources/glossary/light-sensor.html#:~:text=Common%20types%20of%20light%20sensors,proximity%20sensors%2C%20and%20renewable%20energy>. [Accessed: Nov. 12, 2024].
- [96] EE Power, *Photoresistor Guide*, [Online]. Available: <https://eepower.com/resistor-guide/resistor-types/photo-resistor/#.> [Accessed: Nov. 12, 2024].
- [97] Byju's, *Photodiodes and Their Applications*, [Online]. Available: <https://byjus.com/physics/photodiodes-applications/#:~:text=Photodiodes%20are%20used%20in%20safety,used%20in%20solar%20cell%20panels>. [Accessed: Nov. 12, 2024].
- [98] GlobalSpec, *Phototransistors and Their Applications*, [Online]. Available: [https://www.globalspec.com/learnmore/optics\\_optical\\_components/optoelectronics/phototransistors#:~:text=Phototransistors%20are%20used%20in%20almost,are%20more%20sensitive%20than%20photodiodes](https://www.globalspec.com/learnmore/optics_optical_components/optoelectronics/phototransistors#:~:text=Phototransistors%20are%20used%20in%20almost,are%20more%20sensitive%20than%20photodiodes). [Accessed: Nov. 12, 2024].
- [99] UB1245, *UB1245 SLA1250 12V 4.5AH Sealed Lead Acid (SLA) Battery for Medical Devices*, Amazon, [Online]. Available: [https://www.amazon.com/UB1245-SLA1250-Battery-12V4-5AH-Medical/dp/B0B2F8VQW2/ref=sr\\_1\\_25?crid=3PMYZZNW7UKXA&dib=eyJ2IjoiMSJ9.X8csgQtFQoACxgT9yTB45Z5\\_XNgff2P3aeaAebGcw8z6P4-eN0V3XgAgzRNe8sjImjrQMCnsy00itfNrBdQ4d0qunFwFGExxoD6KeoLtxiYj6E42m874N9g2zgNdwRqCrPQmlQBhHv-j3EXFC6j7rqQ5rHqF9iKJ2YpELkjaw\\_gzTP3vquUVh-pSs.posU3ZC8nx8\\_nnF1\\_b0zplxdYj9tW-yGgYzC0uSfLg&dib\\_tag=se&keywords=12v+5ah+battery&qid=1731528204&refinements=p\\_36%3A-2000&rnid=386636011&suffix=12v+5ah+battery%2Caps%2C156&sr=8-25](https://www.amazon.com/UB1245-SLA1250-Battery-12V4-5AH-Medical/dp/B0B2F8VQW2/ref=sr_1_25?crid=3PMYZZNW7UKXA&dib=eyJ2IjoiMSJ9.X8csgQtFQoACxgT9yTB45Z5_XNgff2P3aeaAebGcw8z6P4-eN0V3XgAgzRNe8sjImjrQMCnsy00itfNrBdQ4d0qunFwFGExxoD6KeoLtxiYj6E42m874N9g2zgNdwRqCrPQmlQBhHv-j3EXFC6j7rqQ5rHqF9iKJ2YpELkjaw_gzTP3vquUVh-pSs.posU3ZC8nx8_nnF1_b0zplxdYj9tW-yGgYzC0uSfLg&dib_tag=se&keywords=12v+5ah+battery&qid=1731528204&refinements=p_36%3A-2000&rnid=386636011&suffix=12v+5ah+battery%2Caps%2C156&sr=8-25). [Accessed: Nov. 12, 2024].
- [100] LiftMaster, *LiftMaster 485LM Replacement Battery by SigmasTek for Garage Door Openers*, Amazon, [Online]. Available: [https://www.amazon.com/Liftmaster-485LM-Replacement-Battery-SigmasTek/dp/B07DLBQMTG/ref=sr\\_1\\_37?crid=3PMYZZNW7UKXA&dib=eyJ2IjoiMSJ9.X8csgQtFQoACxgT9yTB45Z5\\_XNgff2P3aeaAebGcw8z6P4-eN0V3XgAgzRNe8sjImjrQMCnsy00itfNrBdQ4d0qunFwFGExxoD6KeoLtxiYj6E42m874N9g2zgNdwRqCrPQmlQBhHv-j3EXFC6j7rqQ5rHqF9iKJ2YpELkjaw\\_gzTP3vquUVh-pSs.posU3ZC8nx8\\_nnF1\\_b0zplxdYj9tW-yGgYzC0uSfLg&dib\\_tag=se&keywords=12v+5ah+battery&qid=1731528204&refinements=p\\_36%3A-2000&rnid=386636011&suffix=12v+5ah+battery%2Caps%2C156&sr=8-25](https://www.amazon.com/Liftmaster-485LM-Replacement-Battery-SigmasTek/dp/B07DLBQMTG/ref=sr_1_37?crid=3PMYZZNW7UKXA&dib=eyJ2IjoiMSJ9.X8csgQtFQoACxgT9yTB45Z5_XNgff2P3aeaAebGcw8z6P4-eN0V3XgAgzRNe8sjImjrQMCnsy00itfNrBdQ4d0qunFwFGExxoD6KeoLtxiYj6E42m874N9g2zgNdwRqCrPQmlQBhHv-j3EXFC6j7rqQ5rHqF9iKJ2YpELkjaw_gzTP3vquUVh-pSs.posU3ZC8nx8_nnF1_b0zplxdYj9tW-yGgYzC0uSfLg&dib_tag=se&keywords=12v+5ah+battery&qid=1731528204&refinements=p_36%3A-2000&rnid=386636011&suffix=12v+5ah+battery%2Caps%2C156&sr=8-25)

tag=se&keywords=12v+5ah+battery&qid=1731528204&refinements=p\_36%3A-2000&rnid=386636011&sprefix=12v+5ah+battery%2Caps%2C156&sr=8-37. [Accessed: Nov. 12, 2024].

- [101] NewtiPower, *LiFePO4 12V 6Ah Lithium Iron Phosphate Battery for Overland Applications*, Amazon, [Online]. Available: [https://www.amazon.com/LiFePO4-NewtiPower-Phosphate-Overland-Applications/dp/B0CLKGZTVL/ref=sr\\_1\\_18?crid=1DAII15KD4DBK&dib=eyJ2IjoiMSJ9.T3TrHc9NiW58k6jEHCpoMKuKZCcqC0YPbQCeu4rFfpkq9r1p2srjiWz7701jal6fi8BDZdNschSdNbAx58Px5rVydRHi-kwz4femr4vV9081Fk3v-NpF1KgH0EOJh5WLUWHatXKhHJEZrmQbGzt06DcU1Y02IU.9ylGtRMVS9G6wKECoMuzAZHcP04XTQGrIza42Jt-WVg&dib\\_tag=se&keywords=12v+6ah+battery&qid=1731529264&refinements=p\\_36%3A-2700&rnid=386419011&suffix=12v+ah+battery%2Caps%2C177&sr=8-18](https://www.amazon.com/LiFePO4-NewtiPower-Phosphate-Overland-Applications/dp/B0CLKGZTVL/ref=sr_1_18?crid=1DAII15KD4DBK&dib=eyJ2IjoiMSJ9.T3TrHc9NiW58k6jEHCpoMKuKZCcqC0YPbQCeu4rFfpkq9r1p2srjiWz7701jal6fi8BDZdNschSdNbAx58Px5rVydRHi-kwz4femr4vV9081Fk3v-NpF1KgH0EOJh5WLUWHatXKhHJEZrmQbGzt06DcU1Y02IU.9ylGtRMVS9G6wKECoMuzAZHcP04XTQGrIza42Jt-WVg&dib_tag=se&keywords=12v+6ah+battery&qid=1731529264&refinements=p_36%3A-2700&rnid=386419011&suffix=12v+ah+battery%2Caps%2C177&sr=8-18). [Accessed: Nov. 12, 2024].
- [102] ElectricalEasy, "Electric Braking of DC Motors," 2014. [Online]. Available: <https://www.electricaleasy.com/2014/01/electric-braking-of-dc-motors.html#:~:text=Braking%20effect%20is%20controlled%20by,rheostat%20is%20connected%20in%20series>. [Accessed: Nov. 16, 2024].
- [103] Bay Alarm, "How Do Motion Sensors Work? A Guide," 2024. [Online]. Available: <https://www.bayalarm.com/blog/how-do-motion-sensors-work-a-guide/#:~:text=A%20motion%20sensor%2C%20or%20motion,right%20to%20your%20mobile%20phone>. [Accessed: Nov. 16, 2024].
- [104] Amazon, "550 30000RPM Gearbox with 12V Motor for Power Wheels, RS550 12 Volt DC Motor High Speed Match Children Powered Ride On Car," [Online]. Available: [https://www.amazon.com/dp/B072F7QWBQ?ref=ppx\\_yo2ov\\_dt\\_b\\_fed\\_asin\\_title](https://www.amazon.com/dp/B072F7QWBQ?ref=ppx_yo2ov_dt_b_fed_asin_title). [Accessed: Nov. 16, 2024].
- [105] Lucidar, "Revolution Per Minute to Miles Per Hour Converter," [Online]. Available: <https://lucidar.me/en/unit-converter/revolution-per-minute-to-miles-per-hour/>. [Accessed: Nov. 16, 2024].
- [106] SparkFun, "ESP32 Thing Hookup Guide - Hardware Overview," [Online]. Available: <https://learn.sparkfun.com/tutorials/esp32-thing-hookup-guide/hardware-overview#:~:text=The%20ESP32's%20operating%20voltage%20range,pins%20are%20not%205V%2Dtolerant!>. [Accessed: Nov. 16, 2024].

## **14 Appendix C - Chat GPT Outputs**