Maple Robotics

March 26, 2021

Dr. Craig Scratchley
Dr. Shervin Jannesar
School of Engineering Science
Simon Fraser University
Burnaby, British Columbia
V5A 1S6

Re: ENSC 405W/440 Design Specification for Lawnsweeper Mark I

Dear Dr. Scratchley and Dr. Jannesar,

The Lawnsweeper Mark I is a highly automated, robot-based collection system which combines obstacle avoidance, detection, and a rover-mounted collection system. The Lawnsweeper Mark I's objective is to ease the laborious task of collecting fallen leaves from residential yards. The purpose of the following Design Specification document is to discuss various stages of design and specifically, highlight the technical design decisions required to bring the proof of concept stage to fruition. A product background and overview are provided, along with a thorough explanation of design specifications relating to the Lawnsweeper Mark I's various subsystems.

In addition to the attached Design Specification document, a user interface appendix originally attached has been submitted prior. The appendix provides insight into the software and hardware components such as the mobile application, collection system, and the rover system that users may interact with.

The Maple Robotics team is composed of a diversified interdisciplinary team of computer engineers Daimon Gill, Haoming (Mark) Jing, Zi Zhou (John) Qu, Johnny Tsai, and Bin Xiong and systems engineer Ziniu Chen.

If any questions regarding the Lawnsweeper Mark I arise, please contact Chief Communications Officer, Daimon Gill, at daimong@sfu.ca. On behalf of the Maple Robotics team, we thank you for reviewing our Design Specification document.

Gratefully,

Daimon Gill
Chief Communication Officer
Maple Robotics

Maple Robotics

Design Specification

Lawnsweeper Mark I

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Issued Date: March 26, 2021

Abstract

This document describes the design specifications and outlines the design choices of the Lawnsweeper Mark I. The document contains a detailed look at specific design specifications and a complete analysis of the problems they aim to address. The design specifications will be supported with appropriate research and descriptions for each phase of our design, from the proof of concept prototype, engineering prototype and applicable production phase.

Our project, the Lawnsweeper Mark I comprises open source robotic components while utilizing the open source software, Android Studio for android application development. The application will include a UI that allows the user to remotely control the robot in addition to viewing its status all in one place. Thus, resulting in a seamless user friendly lawn care experience.

This document focuses on the technical analysis of software, physical, electrical and mechanical components along with the justifications for parts chosen and resulting design decisions. Additionally, a high-level test plan is included in the Appendix for comprehensively testing the various subsystems of the Lawnsweeper Mark I to ensure a fully functioning PoC. The proof of concept will be demoed during April 2021 while the beta phase will be further refined and optimized for consumers and by August 2021.

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Version History

Version #	Implemented By	Revision Date	Approved By	Approval Date	Reason
1.0	Company 19	3/26/2021	Company 19	03/26/2021	Final Submission

Glossary

CSA	Canadian Standards Association
EU	European Union
GND	Ground
I/O	Input/Output
IDE	Integrated Development Environment
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronics Engineers
IMU	Inertial Measurement Unit
ISO	International Organization for Standardization
LED	Light-Emitting Diode
OS	Operating System
PLA	Polylactic Acid
PoC	Proof of Concept
PWM	Pulse-Width Modulation
RPM	Revolution per minute
RoHS	Restriction of Hazardous Substances Directive
RX	Receive
TR	Technical Reports
TX	Transmit
UI	User Interface
UWB	Ultra Wideband
UX	User Experience

1. Introduction

1.1. Background

In a span of mere decades, the digital revolution has transformed the world through the widespread adoption and application of powerful and inexpensive integrated circuits. Leveraging their massive computation power and communication capabilities, engineers have been able to automate a myriad of tasks that were previously performed manually or with human supervision. Starting from scientific applications, the technology trickled down to industrial and home uses soon after. Around the turn of the century, autonomous household robots began appearing on the market. The modern robotic lawnmower was introduced in 1995 [1], followed by the robotic vacuum cleaner in 1997 [2].

Today, one area of home care has thus far escaped the attention of robotics companies: fallen leaf collection. Current solutions do not include a robotic option. Manual raking is too tiring for aged homeowners, and expensive if outsourced to professionals. Leaf blowers present a non-ideal result, since many municipalities consider leaf blowing a finable offense [3].

Maple Robotics offers the Lawnsweeper Mark I as a robotic solution to this problem while addressing the aforementioned shortcomings of existing solutions. Our product automates the task of leaf collection through a carefully designed collection mechanism mounted on a durable and mobile rover system. The robot is capable of completing the task autonomously or be controlled remotely via an easy-to-use Android application.

This project is inspired by existing robotic lawnmowers, which is a highly-mature and competitive market today. Virtually all current designs use a guide-wire based boundary detection system, and use random movement to navigate the working area much like Roomba designs. While they excel at their intended use, their small sizes exclude them from being able to perform leaf collection.

1.2. Product Intended Use

The Lawnsweeper Mark I is intended for home and personal use, for typical North American suburban single-detached households. Maple Robotics has made design decisions based on household research statistics [4] and the capabilities of the design team, in order to balance the features of this product versus design complexity and cost. The user of this product should consider the existing conditions of their lawn, paying particular attention to key factors such as area, slope, soil composition, shape, and level of maintenance. While the Lawnsweeper Mark I is designed to save labor and costs, it requires a suitable working environment and cannot automate the entire lawn care process. The goal of this product is to occupy a niche between small-scale manual methods and large-scale commercial alternatives. This is achieved by offering a solution that outcompetes commercial solutions on amortized cost, while being capable enough as an easy-to-use labour-saving lawn care appliance for a large portion of homeowners.

1.3. Document Target Audience

The target audience of this Design Specification document is, but not solely limited to, the ENSC 405W instructional team, led by Dr. Shervin Jannesar, Dr. Craig Scratchley, and Dr. Andrew Rawicz. As a technical document detailing the design of the Lawnsweeper Mark I, this document is also targeted at other engineers and business partners who are interested in the technical background of the design. Design decisions for all components of the product are listed in this document, including sections for physical, hardware, mechanical, electrical and software.
Additionally, investors and business partners interested in product development and design decisions of our project may find this document helpful.

1.4. Scope of Proof of Concept Stage

The proof of concept stage will be focused on the core functionality of a leaf collector robot. The PoC prototype will consist of the first iteration of the frame design, along with powered wheels to establish a base for the robot. The major subsystems to be tested and evaluated in this stage are the leaf collection system and the Bluetooth communication module onboard the robot. Preliminary testing will be conducted for both these subsystems near the end of ENSC 405W. The goal for the PoC stage for the collection system is to be able to gather leaves from the ground when turned on. For the Bluetooth module, the goal is to establish Bluetooth pairing between it and the Android phone, and transmit simple movement signals from the phone to the robot.

1.5. Design Classification

For consistency purposes, all requirements of this document will be written and follow the convention below:

Des {Domain Abbreviation}.{Requirement Number} - {Stage of Production}

The requirement classification of different stages is shown in the table below:

Table 1.1: The Convention Code of Each Stage

Stage of Production	Code
Proof of Concept (Alpha)	A
Prototype (Beta)	B

Table 1.2: Requirement Domain Abbreviation

Requirement Domain	**Abbreviation**
General	GE
Leaf Collection System	LC
Robotics System	RO
Mechanical System	ME
Microcontroller	MI
Motor Controller	MC
Sensor System	SE
Bluetooth Module	BM
Power Supply	PS
Battery	BA
Mobile Application	MA

2. Design Overview

The fundamental functionality of the Lawnsweeper Mark I is to navigate a residential yard and collect fallen leaves into a collection bag, thus, reducing the laborious work needed by homeowners concerned with the appearance of their yard. To accomplish this function, three dependent subsystems comprise the Lawnsweeper Mark I: mechanical, electrical, and software systems.

Development of the Lawnsweeper Mark I is divided into three stages: Proof of Concept, Prototype, and Final Product. The core functionality of simple robot movement and leaf collection will be implemented in the proof of concept phase. In later prototype and final product phases, obstacle avoidance, refined user experience, and improved product aesthetics shall be implemented. This document focuses on design decisions and procedures necessary to produce a working proof of concept.

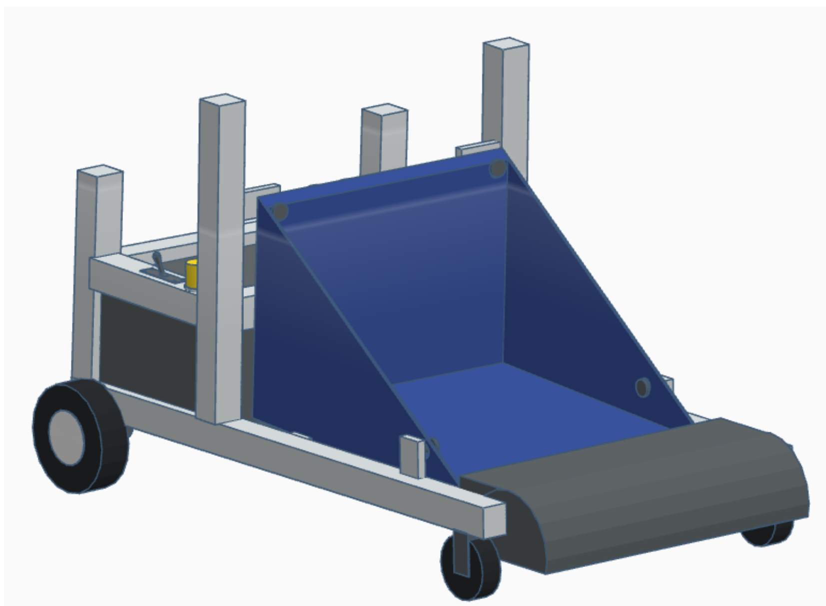

Figure 2.1: Concept Design of Lawnsweeper Mark I

A three-dimensional model of the Lawnsweeper Mark I used throughout Proof of Concept development.

All three of the Lawnsweeper Mark I's subsystems are vital to the core functionality of the product. Development of the Proof of Concept takes advantage of this modular design, and allows for independent testing of each subsystem prior to integration testing of the holistic system. Interactions between various components of the subsystems are illustrated in **Figure 2.2** below, with mechanical, electrical, and software subsystem components shown in yellow, blue, and green respectively.

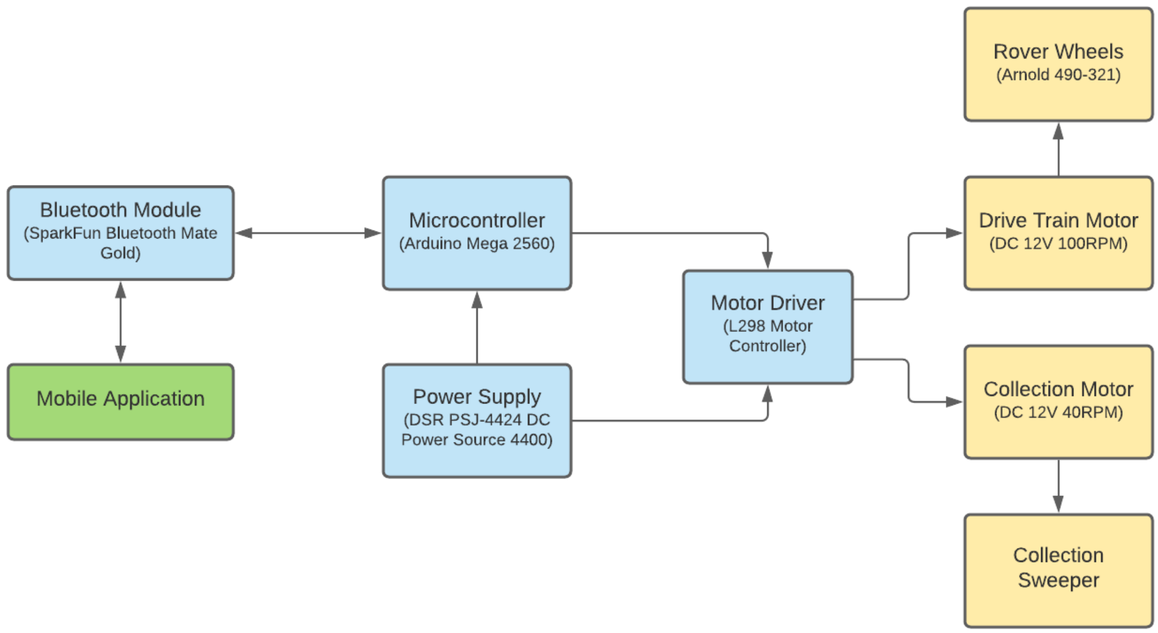

Figure 2.2: System Overview of Lawnsweeper Mark I

A system overview diagram highlighting interactions between various components of the three subsystems. It should be noted that the collection and rover subsystems compose the physical design, thus, are omitted from this diagram.

The mechanical subsystem is composed of the collection and rover subsystems, which makes up the physical design component of the Lawnsweeper Mark I. The rover subsystem is responsible for transporting the collection subsystem that's responsible for collecting and housing the fallen leaves. Both aforementioned subsystems are closely integrated with the electrical subsystem, which also makes up the physical structure of the product.

The electrical subsystem is responsible for supplying power to the various components such as the Bluetooth modules, motor drives, and the microcontroller. The electrical subsystem components will be housed within the rover subsystem once the subsystems are combined. **Figure 2.2** highlights the importance of proper functionality of the electrical subsystem, which serves as a connection between the software and mechanical subsystems.

In the Proof of Concept, the software subsystem serves as the primary method of user interaction with the Lawnsweeper Mark I through the use of a mobile Android application.

3. Design Specifications

3.1. Physical Design Specification

A fundamental subsystem required for the success of the Proof of Concept is the rover subsystem that comprises much of the physical design of the Lawnsweeper Mark I. **Figure 3.1.1** illustrates size specifications for the rover, as described by [Des RO.1 - A]. Moreover, the primary functionality of the rover subsystem is to provide the Lawnsweeper Mark I with movement, which results in the frame needing to support motors and wheels [Des RO.2 - A]. Since the collection system moves with the rover, it's important for the rover to support the collection system [Des RO.3 - A]; the frame design shown **Figure 3.1.1** possesses an open front-end to the frame, where it is intended to mount the collection system sweeper. Additionally, the electrical subsystem will be housed within the electronic compartment as shown in **Figure 3.1.2** [Des RO.4 - A].

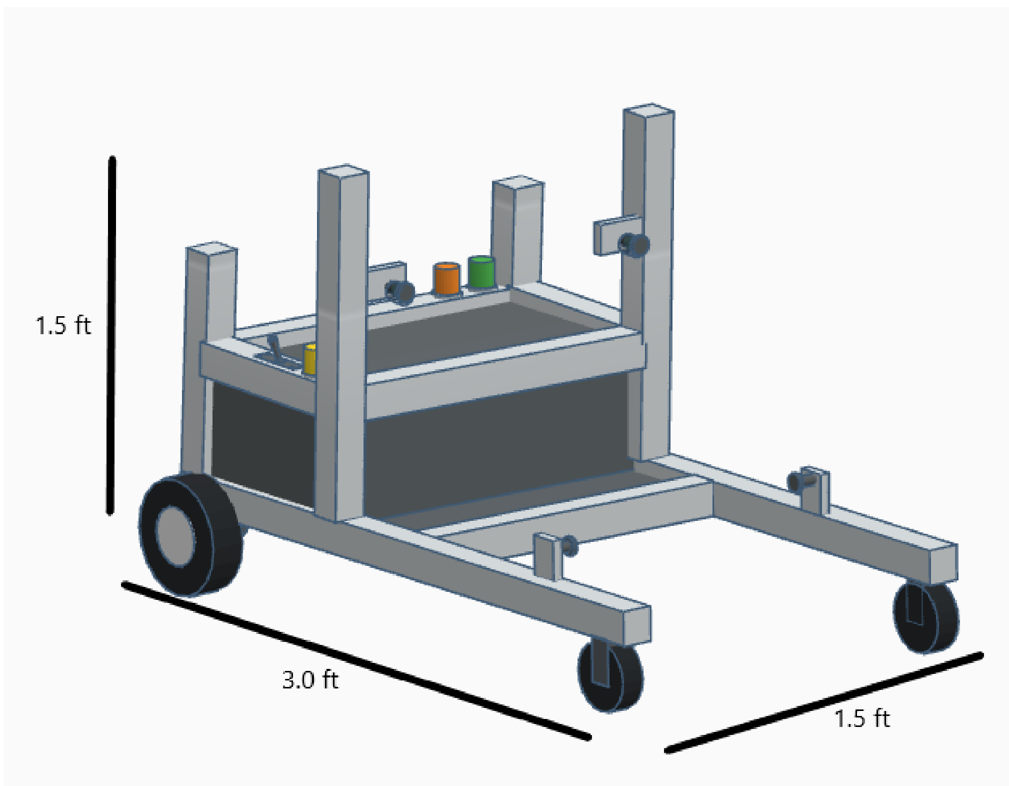

Figure 3.1.1: Dimensions of the Rover Frame

An illustration showcasing the 3.0ftx1.5ftx1.5ft physical dimensions of the Rover's Frame.

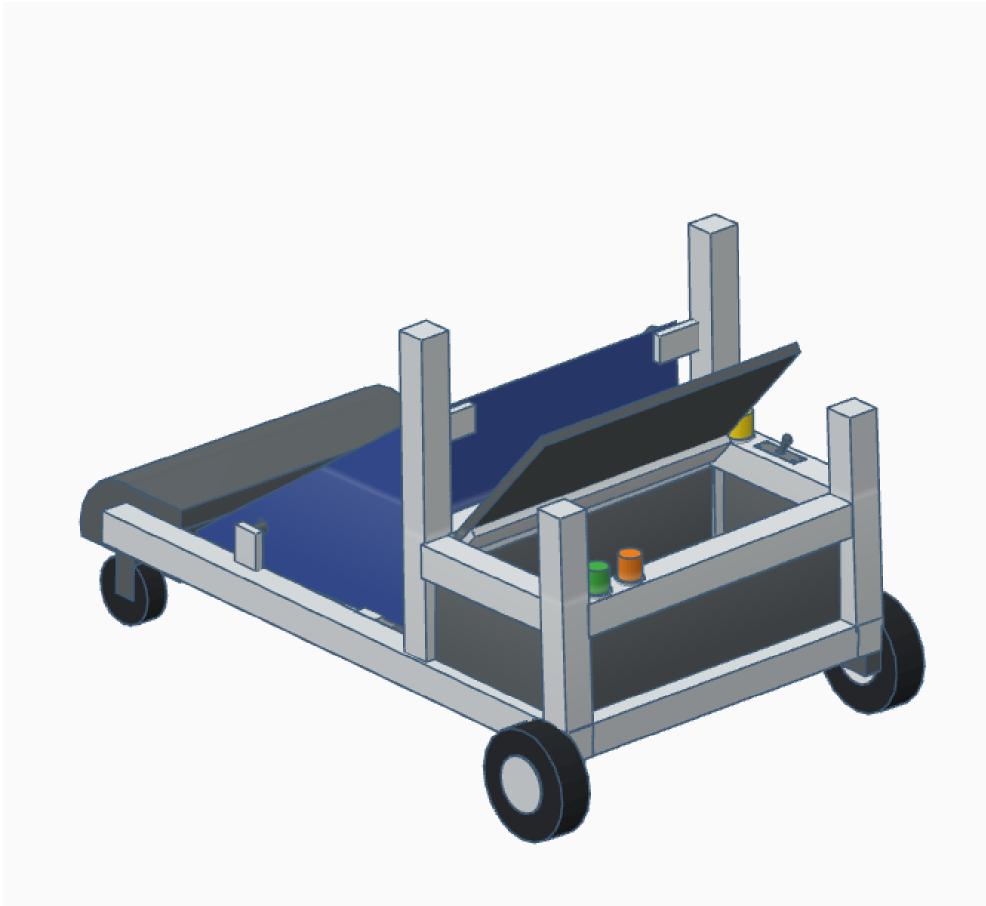

Figure 3.1.2: Electronic Compartment Housing
A three-dimensional model depicting how a user may access the internal components housed within the electronic compartment.

Design specifications relating to later iterations of the Lawnsweeper Mark I are also discussed. For example, the collection system utilizes a reusable polyethene bag to hold collected leaves. Consequently, to ensure the collection bag sits securely while also being easy to remove, pegs are attached to the frame to achieve this functionality [Des RO.5 - B]. Additionally, the electronics housing compartment should be sealed to provide water resistance capability [Des RO.6 - B]. The need for this arises as whether conditions may be unpredictable, and the Lawnsweeper Mark I may be subject to unanticipated rain.

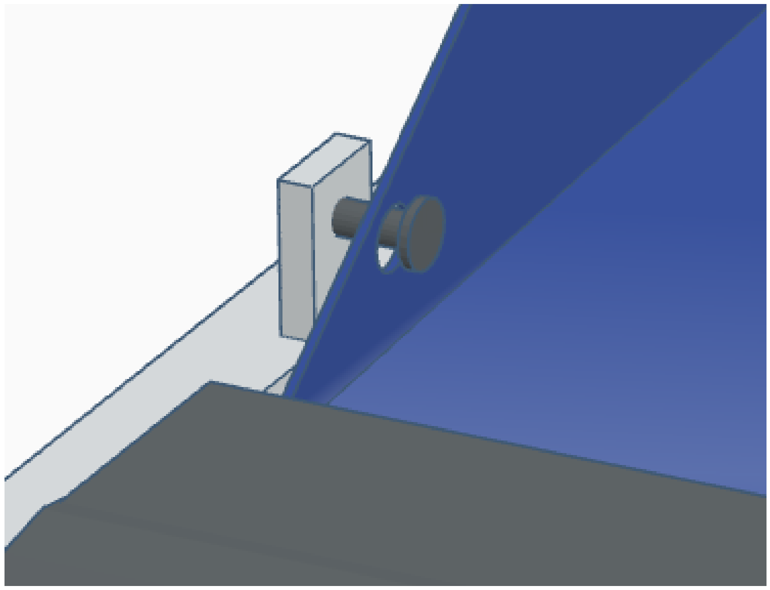

Figure 3.1.3: Collection Bag Mounting Pegs

A three-dimensional model depicting the mounting pegs used for the reusable collection bag.

The success of the PoC design is heavily dependent on the design of the collection system. The collection system consists of a brush, driven by a DC motor, and a reusable collection bag. The core functionality of the rotating sweeper is to brush leaves in an upwards motion [Des RO.7 - A]. Additionally, a reusable polyethylene bag is used to collect leaves after they have been swept by the rotating sweeper [Des RO.8 - A].

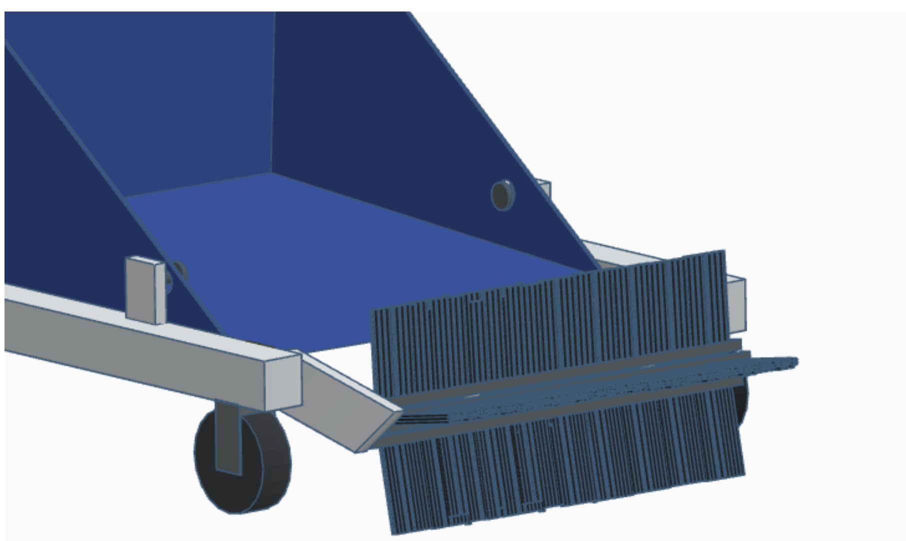

Figure 3.1.4: Collection System Sweeper

A three-dimensional model depicting the collection system sweeper, composed of 4-brushes mounted upon a cylinder the width of the frame.

Additionally, a core component to the collection system is the inclusion of a cover to guide the leaves along the curvature of the cover towards the collection bag as leaves will be swept in an upwards fashion [Des RO.10 - A].

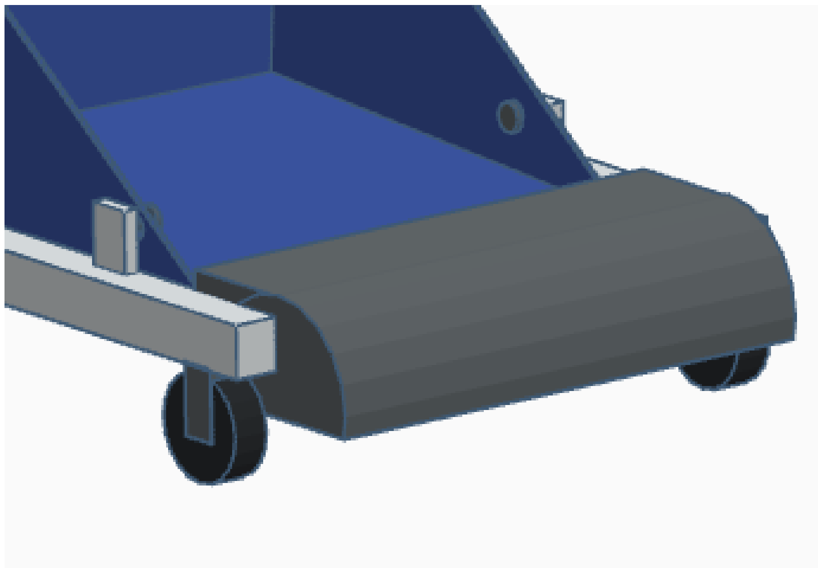

Figure 3.1.5: Collection System Cover

A three-dimensional model depicting the collection system cover used to direct swept leaves into the collection bag.

Table 3.1.1: Physical Design Specifications

Design Specification	Description	Corresponding Requirement/ Design Specification
Des RO.1 - A	The frame of the rover will be 3ft x 1.5ft x 1.5ft (LxWxH).	Req RO.7 - A
Des RO.2 - A	Wheels and motors will be able to be mounted to the frame of the rover.	Req RO.4 - A
Des RO.3 - A	The frame of the rover will hold the collection system.	Req GE.2 - A, Req GE.5 - A, Req LC.4 - A
Des RO.4 - A	The frame of the rover will house the electrical subsystem.	Req GE.1 - A, Req SE.1 - A
Des RO.5 - B	The frame of the rover will possess pegs to allow removal of the collection bag.	Req LC.4 - A
Des RO.6 - B	The electronic housing unit shall be water	Req RO.10 - F

	resistant.	
Des RO.7 - A	The collection system will possess a rotating sweeper powered by a DC 12V motor to sweep leaves upward.	Req LC.5 - A
Des RO.8 - A	The collection system will possess a reusable, polyethylene collection bag to hold fallen leaves.	Req LC.4 - A
Des RO.9 - A	The rotating sweeper and collection bag will work in conjunction to collect fallen leaves.	Req GE.2 - A
Des RO.10 - A	The collection system will be enclosed by a plastic cover to direct leaves into the collection bag.	Des RO.8 - A, Des RO.9 - A

3.2. Mechanical Design Specification

3.2.1. Mechanical Design Overview

In the following section, the mechanical components that are required to build a PoC prototype are introduced along with descriptions justifying the selection of each particular component. The following components are fundamental to realising a functional proof of concept, aiming to validate the feasibility of the Lawnsweeper Mark I's design while meeting requirements outlined in the Requirement Specification document.

3.2.2. Framing Material

The material used to construct the frame is aluminum U-channel (1/2' x 5/8' x 1/16'). When selecting which material to be used, shear limit, stiffness, density, and ease of use were considered. Price, however, was not a factor due to negligible difference between the materials considered. **Table 3.2.1** provides specifications pertaining to the selected building material and also showcases material specifications of the aluminum U-channel [5].

Table 3.2.1: Aluminum U-Channel Specifications

Aluminum U-Channel	Shear Limit (Two Bar)	Density	Stiffness
	1669 kg before severance	2700 kg/m^3	22,900 N/m

A principal requirement of the framing material was that it must satisfy weight constraints imposed by combined weight of the Lawnsweeper Mark I and the collected leaves that it will be carrying [Des ME.1 - A, Des RO.3 - A]. As such, **Equation 3.2.1** below shows the calculation on the shear limit of the Aluminum U-Channel, which defines the weight required to sever a piece of the framing material:

$$Aluminum\ Shear\ Strength = 207\ Mpa$$

$$\tau(one\ bar) = \frac{F}{A} = \frac{10Nx}{\frac{(0.15875 * 1.27)cm^2}{2}} = 248x\ kpa$$

$$\tau(two\ bar) = \frac{\tau(one\ bar)}{2} = 124x\ kpa$$

$$\therefore x = \frac{207 * 1000}{124} = 1669\ kg$$

Equation 3.2.1: Aluminum U-Channel Shear Limit Calculation

Consequently, we can conclude that our material would be able to withstand 1669kg before severance, far exceeding the requirements imposed on the Lawnsweeper Mark I.

In addition to the shear limit, the material's density is also considered as density correlates strongly to the weight of the material. Aluminum is considered low-density, thus, it offers a light-weight building material suitable for our needs [6]. Minimizing the weight of the framing material is paramount in drastically reducing the overall weight of the robot [Des ME.2 - A].

Another reason for selecting aluminum U-channel is its relative ease of use. Due to aluminum's low-density characteristics, this also allows for decreased difficulty when cutting the material during the fabrication process. Likewise, a U-channel design of material was selected opposed to aluminum rods or tubes as U-channel decreases the complexity when assembling the frame. L-brackets can be used with a piece of U-channel in a simplified manner as illustrated in **Figure 3.2.1 and 3.2.2**. Consequently, the combination of using U-channel and L-brackets vastly decreases the amount of drilling, cutting, and welding required when assembling joints of the rover's frame.

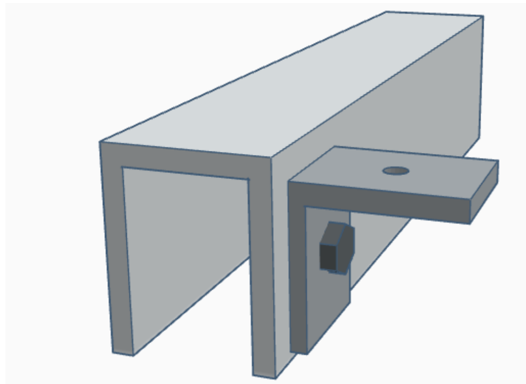

Figure 3.2.1: Aluminum U-Channel and L-Bracket
A three-dimensional model depicting the connection between an L-Bracket and the aluminum U-channel.

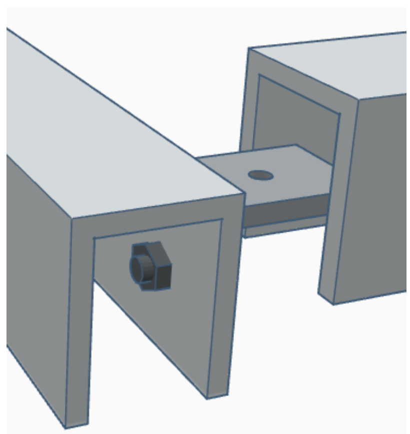

Figure 3.2.2: Aluminum U-Channel Connection
U-channel provides a simplified way to connect pieces of material when constructing the rover's frame.

Table 3.2.2: Framing Material Specifications

Design Specification	Description	Corresponding Requirement/ Design Specification
Des ME.1 - A	Material will provide adequate structural support up to 30kg for system components and collected leaves.	Req GE.4 - A, Req GE.5 - A
Des ME.2 - A	Material will limit the frame's weight to 5kgs.	Req GE.4 - A
Des ME.3 - A	Enough material will be purchased to account for 19 feet of material required for the frame.	Des ME.1 - A

3.2.3. Wheels

Figure 3.2.3: Side-View of Rear Wheel

Figure 3.2.4: Overall View of Rear Wheel

Table 3.2.3: Mechanical Design Specification for Rear Wheel

Design Specification	Description	Corresponding Requirement/ Design Specification
Des ME.7 - A	The base of the chassis will have a 2 inch clearance from the ground.	Req RO.6 - A
Des ME.8 - A	The rear wheels will be driven by motors.	Req RO.4 -A
Des ME.9 - A	The rear wheels will provide enough traction with the grass.	Des ME.14 - A

After careful movement options for the Lawnsweeper Mark I, wheels were chosen instead of tracks as its pros far outweighs the cons, mainly due to minimizing the sheer number of parts as the deciding factor. To satisfy the requirement of 2 inches of clearance from the bottom of the chassis with the ground, **Figure 3.2.3** illustrates the wheel chosen having an outer diameter of 7 inches with an inner diameter of 0.5 inches, resulting in a 3 inch clearance exceeding the original requirement. [Des ME.7 - A]. The two rear wheels are attached to individual gearbox motors that provide power to the wheels [Des ME.8 - A]. The rubber wheels are 1.5 inches wide with deep treads shown in **Figure 3.2.4** to maximize traction with the ground, providing adequate torque for robot movement [Des ME.9 - A].

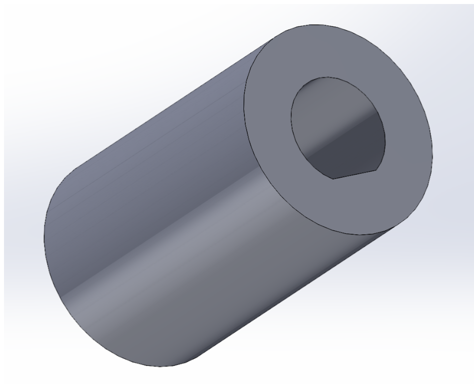

Figure 3.2.5: Overall View of Adapter Between Wheel and Motor

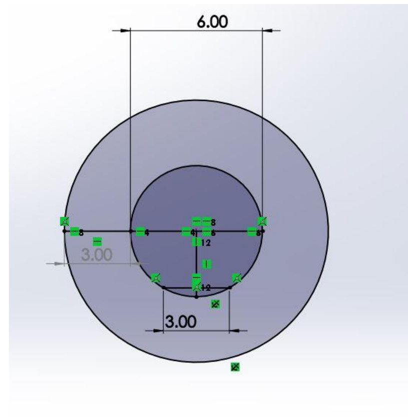

Figure 3.2.6: Cross Section View of Adapter Between Wheel and Motor

Table 3.2.4: Mechanical Design Specification for Adapter Between Wheel and Motor

Design Specification	Description	Corresponding Requirement Specification
Des ME.10 - A	The wheels have to directly connected with motors	Req RO.1 - A
Des ME.11 - A	The adapter has to withstand the weight of the rover.	Req RO.9 - B

Figure 3.2.5 and **Figure 3.2.6** show the dimensions of the adapter required to connect the wheels to the motors due to the mismatching diameter of the wheel and the motor's transmission shafts. [Des ME.10 - A] As the adapter piece is uniquely shaped and not found in store, it will be 3D-printed with PLA material that provides sufficient strength [Des ME.11 - A] with a outer dimension of 12mm or 0.5 inches that will fit snugly in the wheel axis cavity.

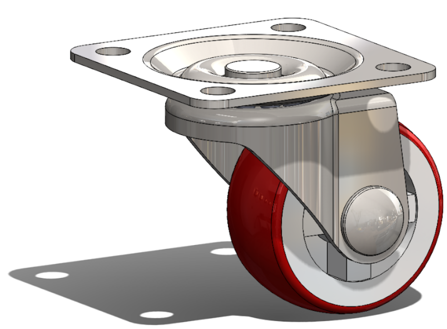

Figure 3.2.7: Overall View of the Caster Wheel

Table 3.2.5: Mechanical Design Specification for Caster Wheels

Design Specification	Description	Corresponding Requirement Specification
Des ME.12 - A	The front wheels will be rotating on the z-axis.	Req RO.8 - B
Des ME.13 - A	The front wheels will have to stand the weight of the rover.	Req RO.9 - B

As **Figure 3.2.7** shows, the caster wheel can freely rotate along the Z axis [Des ME.12 - A]. Since the caster wheel's components are made up with steels, it's capable of withstanding the weight of our rover [Des ME.13 - A].

3.2.4. Motors

3.2.4.1. Drivetrain Motors

As the Lawnsweeper Mark I possesses an electric power supply, electrically driven geared motors are selected for our project for the drivetrain motors [Des ME.16 - A]. Each individual rear wheel will have its own separate drivetrain motor [Des ME.15 - A]. The internals mechanism of the gearboxes can be seen in **Figure 3.2.8 and 3.2.9**, with the overview as observed in **Figure 3.2.10**.

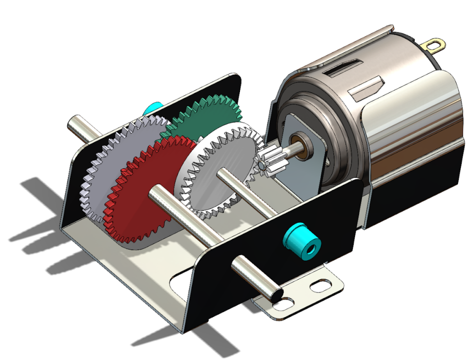

Figure 3.2.8: Internal Overview of Reduction Motor Mechanism

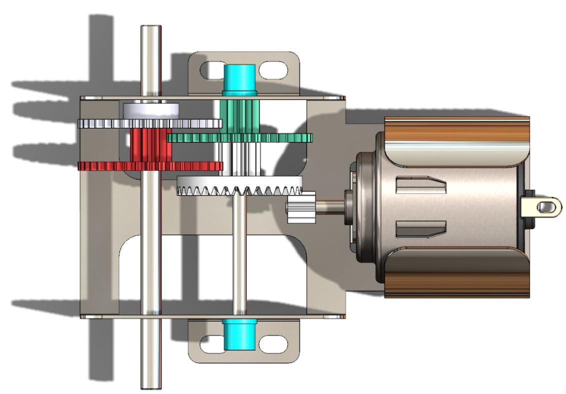

Figure 3.2.9: Top-Down View of Internal Reduction Motor Mechanism

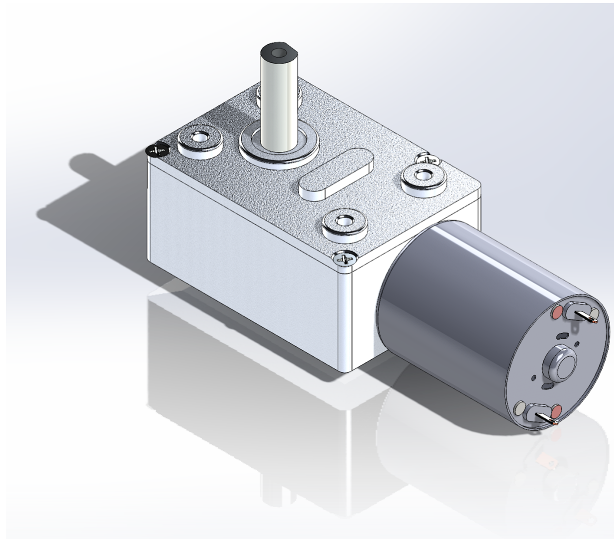

Figure 3.2.10: Overall View of Reduction Motor

Table 3.2.6: Mechanical Design Specification for Drivetrain Motors

Design Specification	Description	Corresponding Requirement Specification
Des ME.14 - A	The drive-motors will provide adequate torque with a top speed of 0.8 m/s	Req RO.1 - A
Des ME.15 - A	The rover will have two drive-motors.	Req RO.4 - A
Des ME.16 - A	It will be powered by a 12V power supply.	Req RO.2 - A
Des ME.17 - A	The motor will withstand the weight of the rover.	Req RO.9 - B

The gearbox reduces the rotational speed providing additional torque and stability [Des ME.14 - A]. **Figure 3.2.9** highlights that changing the radius of the red and green gears can affect the final RPM of the motor. The motors casing and shaft construction are made of steel, as illustrated in **Figure 3.2.10**, providing enough structural integrity to be mounted beneath the chassis of the robot [Des ME.17 - A].

Equation 3.2.2 below shows calculation of the motor's torque while satisfying the requirement of adequate top speed of 0.8 m/s [Des ME.14 - A].

$$Assume\ no\ slipping\ between\ wheel\ and\ grass.$$

$$\mu_y = 0.2\ \mu_{rover} = 10kg\ \ \varphi = Friction\ Coeffecient\ \ r_{wheel} = 9cm$$

$$v_{rover} = 0.8\frac{m}{s}\ \omega_{rover} = 1.41\frac{rad}{s} = 13\ RPM\ \omega_{motor} = 100\ RPM = \frac{10}{3}\pi\frac{rad}{s}$$

$$f = \mu_y * m * g = 20N$$

$$\tau_{required} = f * r_{wheel} = 1.8\ N * m$$

$$P_{Input\ Motor} = \tau_{motor} * \omega_{motor}$$

$$12V * 2A = \tau_{motor} * \frac{10}{3}\pi\frac{rad}{s} \rightarrow \tau_{motor} = 2.3\ N * m$$

$$\therefore\ \tau_{motor} > \tau_{required}$$

Equation 3.2.2: Motor Torque Justification

3.2.4.2. Collection System Motor

Table 3.2.7: Mechanical Design Specification for Collection System Motor

Design Specification	Description	Corresponding Requirement Specification
Des ME.18 - A	The collection system will have a motor to rotate brushes.	Req LC.5 - A
Des ME.19 - A	The motor will be powered by a 12V power supply.	Req LC.3 - A

The collection system will be powered by a motor that operates at 200 RPM but will also be connected to the same 12V battery supply [Des ME.18 - A, Des ME.19 - A].

3.2.5. Collection System

3.2.5.1. Brush Component

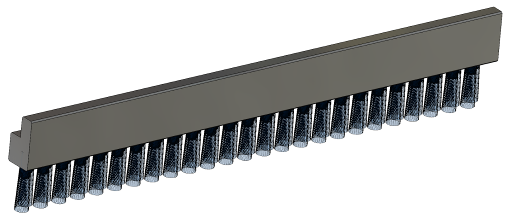

Figure 3.2.11: 3D Model of Single Brush

Table 3.2.8: Mechanical Design Specification for Brushes

Design Specification	Description	Corresponding Requirement Specification
Des ME.19 - A	The brush will be rigid enough to sweep leaves.	Req LC.5 - A

Figure 3.2.11 illustrates one for four brushes from the rotating sweeper of the collection system that possesses a highly dense and rigid set of bristles to minimize bending when sweeping leaves [Des ME.19 - A].

3.2.5.2. Collection Bag Component

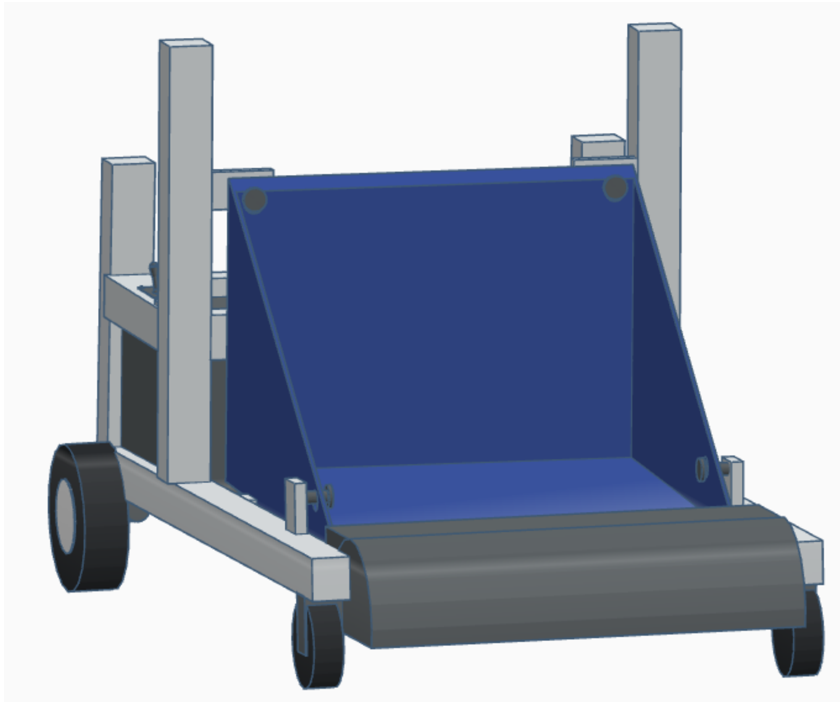

Figure 3.2.12: View of Mounted Collection Bag

As a reusable collection bag is required, a durable polyethene bag is chosen due to its ability to withstand frequent removal and reattachment without tearing. The bag and the mounting system can be seen in **Figure 3.2.12**, but is also discussed previously in section 3.1 [Des ME.20 - A].

Table 3.2.9: Mechanical Design Specification for Collection Bag

Design Specification	Description	Corresponding Requirement Specification
Des ME.20 - A	The reusable collection bag will be strong enough to hold collected leaves.	Req LC.4 - A

3.3. Electrical Design Specification

3.3.1. Electrical Design Specification Overview

In this section, the electrical components required to build a PoC prototype are discussed in detail. The purpose of the electrical design is to build a working electrical circuit to demonstrate and validate the critical components as outlined in the requirement specification document. The Arduino Mega, the chosen microcontroller, is the core of the system that controls the motor driver with digital data and PWM signals, and processes incoming and outgoing data from the Bluetooth module. Additionally, in later prototypes, it will receive and process data from proximity sensors, calculating movement decisions to be conducted by the robot. The electric system can be viewed in **Figure 3.3.1**.

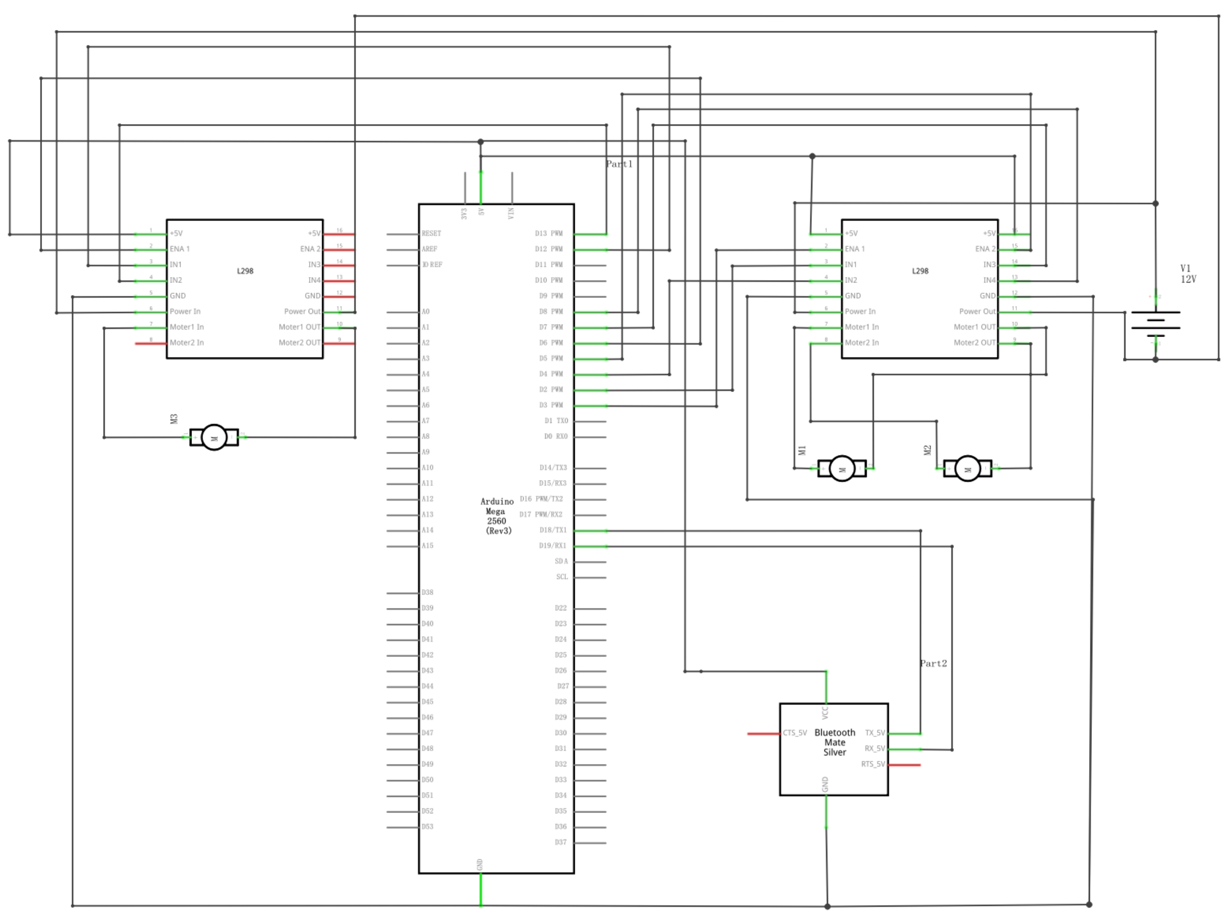

Figure 3.3.1: Electric Schematic Overview of The Lawnsweeper Mark I

Table 3.3.1: Pin Setup for Arduino Mega

Pin Type	Pin Name	Description
Power	5V, GND	5V: Regulated power supply which powers the microcontroller and other components on the board. GND: Ground for other components on the board.
Digital (including digital PWM)	2 to 8, 12, 13	Provides digital signal and pulse-width signal to the motor controller which controls motor direction and speed.
Serial	TX-I, RX-I	Transmits and receives data from the Bluetooth module.

Among 9 digital pins, 3 will output PWM signals in order to control the speed of the motors. The serial pins are used to transmit and receive serial data via Bluetooth through TX-I and RX-I ports respectively. Connection to the Bluetooth module can be observed in **Table 3.3.3** below.

Table 3.3.2: Pin Setup for L298 Motor Controller

Pin Type	Pin Name	Description
Power	5V, GND, Power In, Power Out, Motor1 In, Motor1 Out, Motor2 In, Motor2 Out	5V: Receives regulated power from Arduino Mega, only for powering the logical processing. GND: Calibrates ground level voltage with Arduino Mega, only for powering the logical processing. Power In, Power Out: Connects with the positive/negative side of the power source, 12V battery, which transmits power to the motor. Motor1 In, Motor1 Out: Connects with the motors and provides 12V power, obtained from Power In/Out, to motor 1. Motor2 In, Motor2 Out: Connects with the motors and provides 12V power, obtained from Power In/Out, to motor 2.
Digital	ENA1, IN1, IN2	Receives digital signal and pulse-width signal from microcontroller to control motor 1’s direction and speed.

Digital (PWM)	ENA2, IN3, IN4	Receives digital signal and pulse-width signal from microcontroller to control motor 2's direction and speed.

The product will contain two motor controllers to decode the digital command signals sent from the Arduino Mega. The motor driver on the left of **Figure 3.3.1** is the motor controller responsible for the sweeper rotation, while the motor driver on the right is responsible for rear wheel direction and speed.

The digital input pins connected to IN ports will transmit 0 or 1 to enable the H-bridge connection in the motor controller. Further, the digital PWM signal will be assigned different duty cycle percentages to vary speeds. Setting a higher duty will represent faster moving speed.

Table 3.3.3: Pin Setup for Bluetooth Module (Sparkfun Mate Gold)

Pin Type	**Pin Name**	**Description**
Power	VCC, GND	VCC: Receives 5V regulated power from the Arduino Mega. GND: Calibrates ground level voltage with Arduino Mega.
Serial	TX, RX	Receives and transmits data with the Arduino Mega.

3.3.2. Microcontroller

There are plenty of microcontrollers on the market, the Arduino Mega 2560 in **Figure 3.3.2** was chosen due to the high number of ports, sufficient memory size, simple programming language, and its relatively low price. Development on the Arduino Mega will be done using Arduino code and stored in the non-volatile memory to ensure the program runs when it powers up.

Figure 3.3.2: Picture of Arduino Mega

Table 3.3.4: Electrical Design Specification for Microcontroller

Design Specification	Description	Corresponding Requirement Specification
Des MI.1 - A	The microcontroller will have 9 digital pins to transmit data including 6 pins to control directions and 3 pins to control speed.	Req LC.2 - A Req RO.5 - A
Des MI.2 - B	The microcontroller will have sufficient ports for later design iterations to include additional pin requirements.	Req GE.7 - B
Des MI.3 - B	The microcontroller will have enough memory to store code required robot operation.	Req RO.8 - B

Figure 3.3.1 indicates that each motor needs three pins, one PWM pin to control the speed of the robot and two signal pins to change the directional status. Thus, the three motors lead to 9 digital pins in total on the microcontroller for the PoC [Des MI.1 - A]. The system will add more sensors in the Beta phase for the implementation of additional functionality such as obstacle detection and pathfinding. Which means the chosen microcontroller should have enough ports and memory size to support various demands. As a result, Arduino Mega with 54 digital input/output pins in total and 14 available as PWM outputs along with 256K flash memory and 8K SRAM is chosen and will be adequate [Des MI.2 - B, Des MI.3 - B].

3.3.3. Motor Controller

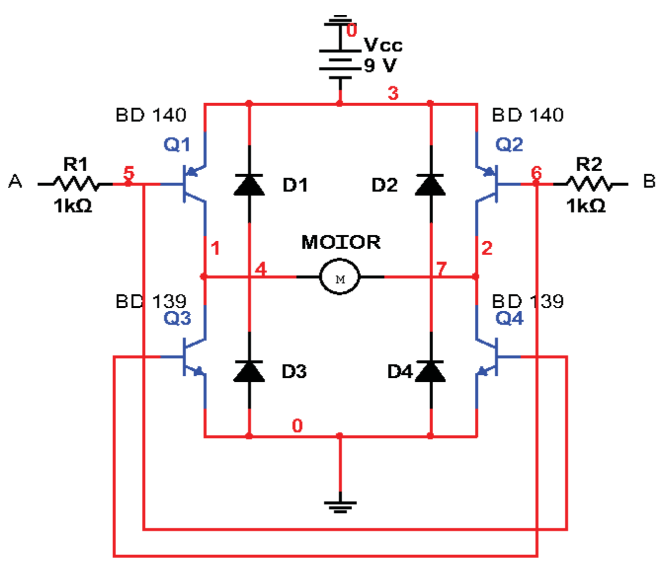

Figure 3.3.3: H-Bridge Motor Controller Using 2 Inputs to Control Motor Rotation Direction [7]

Figure 3.3.3 shows a sample of the 2 inputs single channel H-bridge motor controller circuit. For instance, when A inputs 1 and B inputs 0, the logic gates Q1 and Q4 will be closed and current will flow out from the power source, through Q1, motor and Q4 to the GND. By swapping the value of A and B inputs, the current will run from the other direction, which leads to an opposite rotation direction. Since we are using 12V DC motors in our design, the motor controller should be able to drive the motors with 12V power source at a moderate speed, which depends on the resolution of the motor at 12V and the duty cycle of the PWM input signal. **Figure 3.3.4** is a picture of the controller board, L298 2-Channel H-Bridge Motor Driver used in this project.

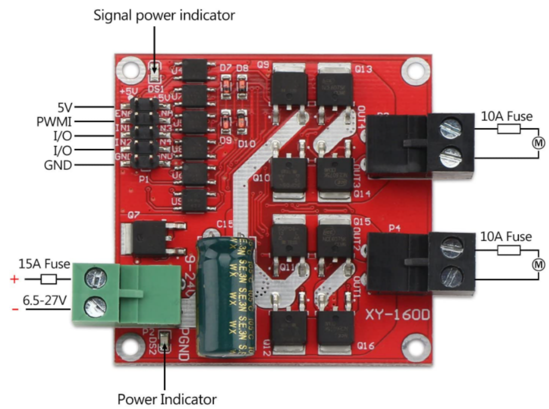

Figure 3.3.4: L298 2-Channel H-Bridge Motor Driver [8]

Table 3.3.5: Electrical Design Specification for Motor Controller

Design Specification	Description	Corresponding Requirement Specification
Des MC.1 - A	The motor driver will provide adjusted power for the motor to spin and sweep leaves up.	Req LC.5 - A
Des MC.2 - A	The motor driver will provide adequate power for motors to move at a top speed of 0.8 meter per second on the lawn on a slope no greater than 30 degrees.	Req RO.1 - A
Des MC.3 - A	The motor driver will control the motors' rotation speed and direction.	Req RO.3 - A

As shown in **Figure 3.1.2 and Figure 3.1.4**, the collection system will use a motor to rotate the brush to sweep leaves upward, while the rover will be driven with two motors. The system will require two high current and high voltage motor controllers, one for the drivetrain motors and one for the collection system motor. The L298 2-channel H-Bridge motor controller can drive a motor up to 12V and 7A at each channel, and provide 160W power in total, meeting the requirements by the previously described collection system and drivetrain motors [Des MC.1 -

A, Des MC.2 - A]. Additionally, the motor controller must control speed and direction [Des MC.3 - A].

Table 3.3.6: Motor Interface Control Signal Logic

IN1	IN2	ENA1	IN3	IN4	ENA2	Status
0	0	0	0	0	0	Stop
1	0	PWM	1	0	PWM	Forward
1	0	PWM	0	0	0	Right
0	0	0	1	0	PWM	Left
0	1	PWM	0	1	PWM	Backward

Table 3.3.6 shows how our team designs the signal logic to control the robot. It describes the motor status with two inputs pins labeled *IN*, and one speed control input, *ENA* (Enable). As mentioned, *IN1* and *IN2* are the direction control inputs for motor 1, and *ENA1* is the speed control input for motor 1. Likewise for motor 2 it includes *IN3*, *IN4* and *ENA2*. The directions of the DC motors are entirely determined by the current flow direction.

3.3.4. Bluetooth Module

In order to facilitate communication with an Android smartphone, an Arduino Mega compatible module, the Mate Gold Bluetooth Module, has been selected. The Mate Gold Bluetooth module offers simple wiring, good documentation, wide communication range, and stable data transfer.

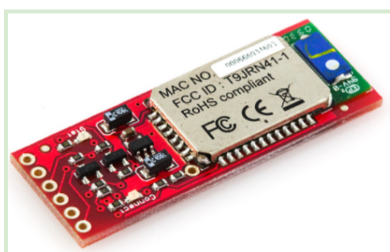

Figure 3.3.5: SparkFun Bluetooth Mate Gold Module

Table 3.3.7: Electrical Design Specification for Sparkfun Mate Gold Bluetooth Module

Design Specification	Description	Corresponding Requirement Specification
Des BM.1 - A	The system will connect to a mobile application which provides basic control functionality regarding to control the moving direction and change the working status.	Req GE.6 - A

Des BM.2 - A	The Bluetooth module operates at greater than 20m range.	Req SE.1 - A

Table 3.3.7 represents requirements for connecting to the mobile application. The chosen Bluetooth module operates at a wide range of approximately 100 meters, therefore enabling the microcontroller to connect with an Android device outdoors [Des BM.1 - A, Des BM.2 - A].

3.3.5. Battery

The power supply, a battery, is a fundamental component as it provides power to the entire robot. Our company opted for a KMG Lead Calcium battery as the power supply in the robot system. **Figure 3.3.6** shows the actual battery as below:

Figure 3.3.6: KMG Lead Calcium Battery [9]

As shown in **Figure 3.3.1**, the battery will power three 12V motors, two motor controllers, one Arduino Mega board, and one Bluetooth module. The power supply is able to provide continuous power to all system components for approximately 30 minutes. The KMG battery provides 12V voltage with 9.5 Ah capacity. The power consumption for each component has been outlined in **Table 3.3.8** below:

Table 3.3.8: Power Consumption for Various Components

Component	Power Consumption
Arduino Mega	73.19mA at 9V
3 X Motor	3 X 5A at 12V
2 X Motor Controller	2 X 36mA at 5V
Bluetooth	25mA at 5V

The three motors are the primary contributors to power consumption; we can approximately calculate the maximum total power consumption which is about 15.17A at 12V. Therefore, the battery with 9.5Ah capacity will support the system working for 37 minutes as calculated in

Equation 3.3.1 [Des BA.1 - A]. The battery is rechargeable and meets the Beta phase requirement as well [Des BA.2 - B].

$$Time = \frac{Power\ Capacity}{Power\ Consumption} = \frac{9.5Ah}{15.17A} = 0.626\ hours = \ 37\ mins$$

Equation 3.3.1: Battery Runtime Calculation

Table 3.3.9: Electrical Design Specification for Battery

Design Specification	Description	Corresponding Requirement Specification
Des BA.1 - A	The battery will provide 12V voltage with sufficient power for the system to operate at least 30 minutes.	Req PS.1 - A
Des BA.2 - B	The battery will be rechargeable.	Req PS.3 - B

3.4. Software Design Specification

3.4.1. Front-end Design

Lawnsweeper Mark I's software system for the PoC phase mainly comprises the application component that sends simple control commands for the rover's microcontrollers to execute [Des MA.1 - A, Des MA.2 - A]. Additionally, status information will be displayed for a more friendly user experience. To accomplish this, the application will be developed in Android Studio using Java.

Table 3.4.1: Software Design Specifications for the Mobile Application

Design Specification	Description	Corresponding Requirement/ Design Specification
Des MA.1 - A	The application will be able to pair with the robot via Bluetooth.	Req MA.1 - A
Des MA.2 - A	The application shall be able to communicate with the robot	Des BM.1 - A

3.4.2. Bluetooth

Connection of the microcontroller's Bluetooth module to the application on the mobile Android device is critical. **Figure 3.4.1** and **Figure 3.4.2** below illustrate toggling on and off Bluetooth functionality on the Android system and the device discovery along with pairing to the Bluetooth module respectively.

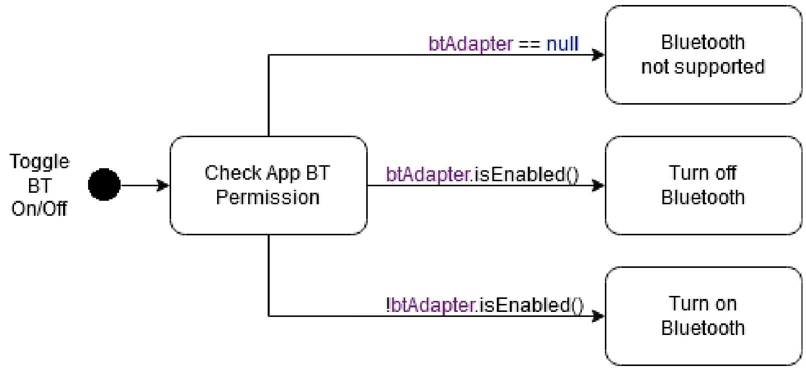

Figure 3.4.1: Diagram for Turning Bluetooth On/Off

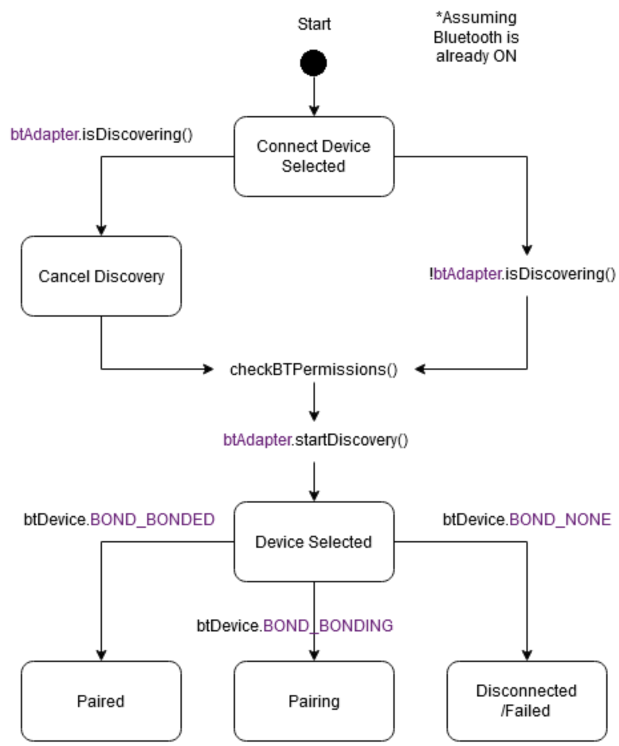

Figure 3.4.2: Diagram for Device Discovery and Pairing

4. Conclusion

Design specification document outlines the design decisions made to fulfill the goals stated in the Requirement Specification document while considering factors such as performance, pricing, and availability. This document also highlights the development aspect as we incorporate the core functionality into the PoC prototype, in addition to design changes and improvements made as we move into the beta phase of the product's life cycle.

The Lawnsweeper Mark I's design comprises three main subsystems. The physical design consists of the hardware that makes up the robot, such as wheels, chassis, and sweeper. The electrical design encompassing microcontroller, motor drivers, and Bluetooth modules. Lastly the software system that provides an interface for end users to interact with the robot. Design choices and decisions for each of the chosen components are explained in greater detail in the preceding sections.

Between the requirement specification document, progress review meeting #2, feedback from the instructional team and this document, the team believes pathfinding utilizing localization of the robot using UWB beacon technology added unnecessary complexity. Further discussion and consideration brought forth the idea of using a combination of optical encoders combined with IMU or even simplistic bump sensors. Further design choices regarding pathfinding of the robot will be considered more thoroughly in the beta phase of the project.

In order to achieve a smooth product life cycle, a separate Appendix submitted prior entails a detailed user feedback form for both internal members and end users to indicate their satisfaction level from UI, UX and the physical product. Invaluable feedback will guide our team and provide insight for subsequent design phases.

At Maple Robotics, we strive to bring simplicity and ease of use to home and lawn owners. Our product Lawnsweeper Mark I aims to bridge the gap between manual labour-intensive methods and commercial grade equipment for leave collection.This document details our design choices throughout the phases of our project, but may be subject to changes as new challenges are faced and improvements are made.

Appendix A: Supporting Test Plans

Test Purpose: This acceptance test plan is a checklist that may be used to demonstrate that the Proof of Concept prototype meets the requirements for the ENSC 405W demo.

Test Condition: Testing should be done in a controlled environment with minimal obstacles or deviation from a relatively flat and well groomed lawn in dry weather conditions.

To verify the PoC's functionality, individual subsystems can be tested prior to system integration, allowing concurrent development and testing of each as outlined in the Test Sheet below. Once the subsystems have been tested, the leaf collection test will be done again as the metric to identify if the proof of concept operates as intended.

Test Sheet		
		Date:
Hardware Requirements		
1. Leaf Collection System		Note/Comments:
The leaf collection system is able to collect leaves from the ground into the collection bag.	❏ Pass ❏ Fail	
2. Robotic System		Note/Comments:
The motors are able to power the wheel and move the entire system 5 meters.	❏ Pass ❏ Fail	
The rover is able to drive in a forward direction unassisted.	❏ Pass ❏ Fail	
The rover is capable of carrying the load of battery and leaf collection system.	❏ Pass ❏ Fail	
Electrical Requirements		
1. Power Supply		Note/Comments:
Power supply is able to provide power to the system for at least 30 minutes.	❏ Pass ❏ Fail	

2. Bluetooth		Note/Comments:
The Bluetooth module operates at greater than 20m range.	❏ Pass ❏ Fail	
The Bluetooth module maintains a connection through walls and can receive status from the robot.	❏ Pass ❏ Fail	
Software Requirements		
1. Mobile Application		Note/Comments:
The app can relay commands to start and stop the leaf collection system.	❏ Pass ❏ Fail	
The app can relay commands for the rover to move straight and stop.	❏ Pass ❏ Fail	
The application can toggle Android's Bluetooth system on and off.	❏ Pass ❏ Fail	

Appendix B: Supporting Design Options

B.1 Mechanical Specification Alternatives

B.1.1 Framing Material

An alternative to the aluminum U-channel framing material chosen for this design and discussed in **section 3.2.2** was perforated steel square tube, the specifications of which is listed below in **Table B.1**. The criteria used when selecting which material to be used considered shear limit, stiffness, density, and ease of use.

Table B.1: Perforated Steel Square Tube Material Specifications [5]

Perforated Steel Square Tube	Shear Limit (Two Bar)	Density	Stiffness
	6116 kg before severance	7800 kg/m^3	22,650 N/m

As highlighted by **Equation B.1**, both framing materials possess similar qualities in terms of shear limit, both far exceeding the required specifications of the Lawnsweeper Mark I. However, a principal factor governing the decision to use aluminum U-channel rather than steel square tubes due to the large discrepancy in density between the two materials. Steel possesses a higher density, resulting in a significantly higher weight. As previously described, minimizing the weight of the framing material is critical.

$$Steel\ Shear\ Strength = 379\ Mpa$$

$$\tau(one\ bar) = \frac{F}{A} = \frac{10Nx}{\frac{(0.317 * 1.27)cm^2}{2}} = 124x\ kpa$$

$$\tau(two\ bar) = \frac{\tau(one\ bar)}{2} = 62x\ kpa$$

$$\therefore x = \frac{379 * 1000}{62} = 6116\ kg$$

Equation B.1: Steel Shear Strength Calculation

Additionally, aluminum U-channel is a far easier material to work with. As steel possesses a higher density, this may result in problems when shaping and cutting the material during the fabrication process. Furthermore, a square-like material also creates problems when creating joints in the Lawnsweeper Mark I’s frame; the need for welding may arise during assembly of the frame.

Consequently, as illustrated here and thoroughly explained in **section 3.2.2**, aluminum U-channel was selected as the framing material as it met the criteria better than the steel square tube.

B.2 Electronic Component Alternatives

B.2.1 Microcontroller

Based on our requirements, the microcontroller needs a high number of ports, reasonable size of memory, low power demand, simple programming language, and a low price. Those specifications are shown in **Table B.2** below.

Table B.2: Microcontroller Choices

Option	Memory	Power Demand (Watts)	Programming Language	Price	Pin Port
Raspberry Pi 4	Up to 2GB of RAM	15 W	C++/C, Python, Java, and more	47.45 CAD	27 I/O ports
Arduino Mega 2560 Rev3	Memory 256 KB and SRAM 8 KB	5 W	Arduino Code	49.99 CAD	Digital I/O pins 54 and analog input pins 16

The Raspberry Pi was one of the microcontroller options. Compared to the Arduino Mega 2560 Rev3, the Raspberry Pi 4 far exceeds the performance required, as the Raspberry Pi 4 is considered a computer. It has high memory size, enough I/O ports and strong computational performance. Additionally, Raspberry Pi 4 already has integrated Bluetooth and would not work well with 3rd-party Bluetooth modules that satisfy the robot’s range requirements. Furthermore, the Bluetooth module (SparkFun Mate Gold) intended to be used in our project has compatibility issues with the Raspberry Pi.

As motors will consume a large portion of current from the battery, decreasing power consumption of the microcontroller is crucial. The Arduino Mega 2560 Rev3 offers significantly lower power consumption than the Raspberry Pi 4. Due to the factors above, the Raspberry Pi 4 was eliminated in favor of the Arduino Mega 2560 Rev3 as the chosen microcontroller.

B.2.2 Wireless Module

The communication range and signal stability are of great importance when evaluation and considering potential wireless modules.

Table B.3: Wireless Module Choices

Option	Communication Range
HC-06	10 Meters approximately transmission range in open space
SparkFun Bluetooth Mate Gold	106 meters transmission range in open space
ESP 8266	300 meters transmission range in open space

Considering the working environment of the Lawnsweeper Mark I, Bluetooth was considered for the transfer of data. Compared to WI-FI modules such as the ESP 8266, Bluetooth can exchange data directly with the phone without the use of agents in between. As this is designed for outdoor use, wi-fi signals may not be reliable and depend on the modem's position, resulting in weaker signals through walls.

Regarding Bluetooth modules, ensuring reasonable communication with the robot while in monitorable sight is considered. The Sparkfun Mate Gold provides a much larger communication range than the HC-06, being able to transmit and receive data up to 100 meters. As a result, the SparkFun Bluetooth Mate Gold was selected over the HC-06 and ESP 8266 communication modules as it met the selection criteria better.

B.2.3 Power Supply

Many power supply options were considered, from gas to electrically powered. However, gas powered alternatives were quickly eliminated due to complexity, weight, cost, and environmental concerns, leaving only electrical alternatives. Electrical systems not only allow renewable and reusable, it also allows for the independent control of each motor.

Table B.4: Power Supply Choices

Option	Key Characteristics
KMG motorcycle battery (Lead Calcium)	Capacity: 9.5 Ah. 12 Volts output without current limitation.
TalentCell power bank (Lithium ion)	Capacity: 11.1V/6Ah. Output limit is 12V 3A.

Serial connected AA batteries (Alkaline)	Based on numbers of batteries in the circuit. One battery is 1.5 Volts

KMG motorcycle battery provides a large capacity with an adequate output power limit. The TalentCell power bank outputs 12V at 3A which isn't sufficient to power the entire robot. Lastly, using AA batteries connected in serial is unsafe and would require a control system. Therefore, KMG Lead Calcium battery was chosen.

B.3 Mobile Application Alternatives

B.3.1 Mobile OS Platform

The Apple iOS mobile operating system for the iPad and iPhone devices is another obvious choice of target OS for our mobile application. With nearly 80 million iPhone devices sold in Q4 2020 [10] alone, it is the second most popular mobile operating system in the world after Android, with a significant market share in North America [11].

Many of our team members have prior experience working with iOS application development, mainly from previous coursework experience. Development would be done using Apple's proprietary IDE application Xcode, available exclusively on MacOS workstations.

We ultimately did not choose to develop our mobile application for iOS due to a lack of MacOS and iOS devices currently owned by our team members. Whereas previously SFU campus offered readily available MacOS workstations, it is no longer the case due to certain current events. The alternative of purchasing MacOS workstations solely for the purpose of this project is extremely uneconomical as it would easily increase our budget beyond reason.

B.3.2 Development Language

For a long time, the Android operating system was developed in the Java language, this changed in 2019 when Google announced a new language Kotlin, which would become the official language of Android moving forward [12]. Kotlin aims to cut down on the boilerplate code repetition that is emblematic to Java, with an emphasis on code brevity.

Due to the relatively young age of Kotlin, its community and user base are both smaller than that of Java. Of particular interest to us is the fact that the supporting software libraries for our Arduino Bluetooth module are all written in Java instead of Kotlin. Furthermore, none of our team members have any prior experience with either Java or Kotlin, so we will be relying on existing software and community to guide much of our own application development. In this aspect the advantage of Java is enough to convince us to use it as the sole development language for our application.

Appendix C: User Interface and Appearance Design

C.1 Introduction

As a largely-autonomous robotic product, the majority of user experience (UX) and interaction of our product, Lawnsweeper Mark I, will be through the Android application. The application will be a means of receiving status updates and providing instructions to the robot via Bluetooth. As our product targets upper-middle class homeowners, it is paramount to consider the demographic and technology-savviness of our target market when designing our product.

By referring to Don Norman's book, The Design of Everyday Things [13], we paid careful attention to the seven key criterias: discoverability, feedback, conceptual models, affordances, signifiers, mappings, and constraints, to construct a product that provides an easy to learn and pleasant user experience. Critical interactions with the fundamental functionalities of the robot such as powering on/off, and detaching and reattaching collection bags frequently are designed and tested with this goal in mind.

C.2 Purpose

This appendix will illustrate both hardware and software user interactable components of our project, the Lawnsweeper Mark I. This document will explain the reason for specific design choices of the Proof of Concept.

C.3 Scope

This document will discuss the following: user analysis, technical analysis, graphical representation, engineering standards, analytical usability testing, and empirical usability testing.

C.4 User Analysis

The target audience of the Lawnsweeper Mark I are lawn owners that face the frequent task of collecting fallen leaves and are interested in a convenient, effort-saving alternative. Currently, the most common solution for lawn owners to collect leaves is by using hand tools such as rakes, brushes, and manual push lawn sweepers. Maple Robotics offers the Lawnsweeper Mark I as an intuitive labor-saving solution.

Furthermore, we have designed our product for people who have exposure to similar product concepts such as roombas or manually pushed lawn sweepers. To provide a simplistic design for the end-users, we minimize the number of physical switches and buttons on the robot. The Lawnsweeper Mark I consists of only one toggle switch that turns the robot on and off. To manually control the robot, users will need to download an Android-based mobile application designed to pair via Bluetooth. The app displays the status of the system in addition to controlling the robot. Therefore, users with knowledge of smartphone operation will be able to use and operate the Lawnsweeper Mark I.

C.5 Technical Analysis

Don Norman's Book "The Design of Everyday Things" discusses the 7 fundamental design principles for a more efficient and effective product. The following section summarizes how these 7 design principles are considered and applied to our product's design.

C.5.1 Discoverability

Discoverability aims to ensure the user can easily identify the basic functionalities or features of the product. To provide a product with good discoverability we incorporated various LEDs on the robot to display the status of the system. For example, users can clearly identify the status of the robot power, Bluetooth connectivity, and sweeper movement via respective LEDs. For user's convenience, the system status will also be displayed on the Android application under the home screen. The application will display four direction buttons under the manual driving screen that allows users to easily control the robot.

Main actions for users to perform:

1. The product must be easy to turn on and off.
2. Users can use the mobile application to connect the Bluetooth to the Lawnsweeper Mark I.
3. Users can drive the robot manually through the application.
4. Users can easily attach and detach the collection bag.

To achieve these actions:

1. A toggle switch will be placed on the rear of the robot accompanied by a green-colored LED to indicate power status of the system.
2. The Android application will have a simple and easy user interface to allow users to intuitively discover the functionalities of our application.
3. The collection bag is attached to the frame via four pegs in four corners of the collection bag.

C.5.2 Feedback

Feedback refers to responses generated based on user inputs that serve to reassure users that their input has been received, in addition to informing the user of notifications generated by the system. The mobile application will serve as the centralized interface for both these purposes. Furthermore, the user will receive additional feedback in the form of LEDs from the robot regarding system status.

User inputs such as presses are to be acknowledged with tactile, visual, and aural feedback. If the phone is not in mute, every registered press should be accompanied by a slight vibration, a change of color on the pressed button, and the playback of a sound. This maximizes feedback to the user, to ensure the input feedback can be reliably given even if their sensory abilities are impaired in any way.

Notifications through Android OS convey various important information such as the status of the robot, as well as the end of a cleaning session. These feedback messages are designed to be sent to the user when the application is not open, thus requiring extra audiovisual cues to alert the user. The application will use a combination of ringtones and text for this purpose.

Additionally, LEDs are apart of the robot circuitry to provide users with visual feedback:

- Orange (*solid*): Collection system is moving
- Orange (*off*): Collection system is stopped
- Green (*solid*): Successful bluetooth connection
- Green (*off*) No bluetooth connection
- Yellow (*solid*): Robot powered on
- Yellow (*off*): Robot powered off

C.5.3 Conceptual Models

A conceptual model explains the functionality of the system, and how it is controlled. For our application, the UI must match their mental model of how each feature should work. In other words, the controls must feel intuitive to the user by matching to their conceptual models of how our application should work. This means creating intuition of control through clever use of textual and iconographic prompts to convey the functionality of each button. This includes all buttons seen in the app, such as the switch for the sweeper, and controls for manual driving of the robot.

C.5.4 Affordances

Affordance gives the user clues to the usage of a control. In our UI design, we take inspiration from common and successful existing designs to ensure our application's appearance clearly conveys the action afforded by each control and minimize incorrect interpretations. Signifiers and mapping considerations are also used to enhance the affordance of our UI controls.

C.5.5 Signifiers

Signifiers inform the user which control performs which kinds of action. Our application uses visual cues to signify the meaning of the on-screen controls as well as text and labels matching appropriate actions. A green color is used to signify a control that is currently in the “on” state, while a grey color is used to signify an “off” state. On the robot, LEDs will signify its operational status; various LEDs will indicate status such as power on and collection system operation. Additionally, each LED will be labeled with its corresponding functionality.

C.5.6 Mappings

Mappings describe the correspondence between controls and their effects. In terms of physical controls, it is advisable to place them near or on the object being controlled. All of the physical controls on the robot, such as the on/off switch, satisfy this criteria.

C.5.7 Constraints

Constraints limit the amount of information presented to the user at any single time to avoid overwhelming the user with excessive information. Instead, many layers of menus are used to present information in a piecewise, sequential manner. This reduces the density of information to be processed by the user when using the application, and helps enforce an order of decisions to be made which will help the user to learn patterns for commonly used actions. In our mobile application, constraints are implemented via limiting the number of on screen controls to 4 or less in any screen.

C.6 Graphical Representation

Figures C.6.1 - C.6.6 illustrate various ways an individual would interact with the Lawnsweeper Mark I robot. Various LEDs on the rear of the robot, methods for collection bag removal, power switch placement, and access to inner components are shown.

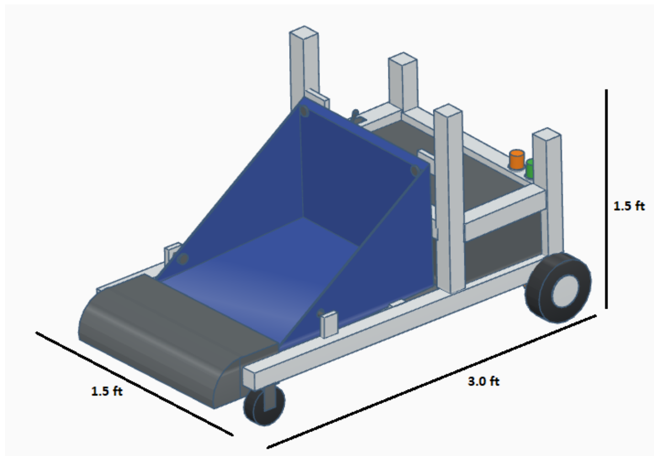

Figure C.6.1: Physical dimensions of Lawnsweeper Mark I

The Lawnsweeper Mark I provides a simple and intuitive user-feedback system located on the rear of the robot's frame. By viewing three LEDs, a user can interpret the status of the collection system, bluetooth connectivity, and power.

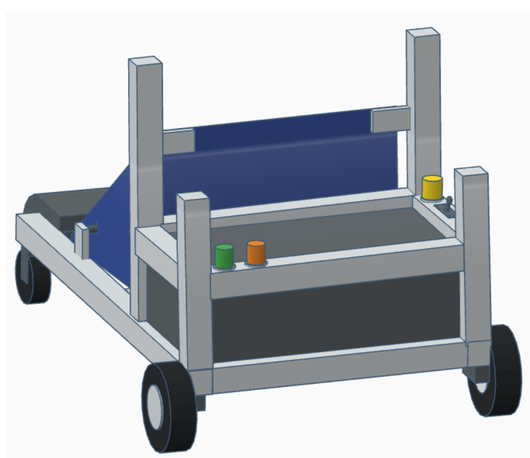

Figure C.6.2: Rear status LED view of Lawnsweeper Mark I

The orange-colored LED will emit light when the robot's collection system is moving, while the green-colored LED will emit light when the robot is successfully paired with a mobile device.

Users are required to physically turn the Lawnsweeper Mark I on and off. A toggle switch has been placed on the rear of the robot accompanied by a yellow-colored LED to indicate power status of the system. The power-control system can be viewed in **Figure C.6.3**.

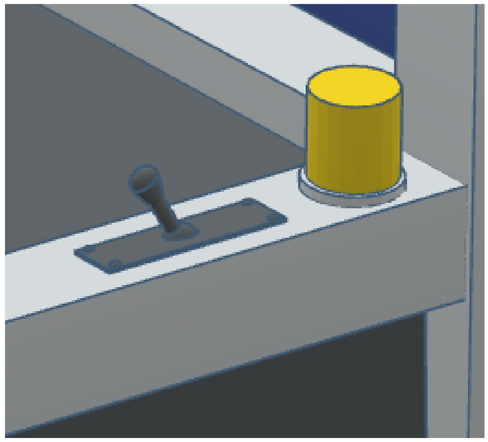

Figure C.6.3: Power status LED

A third LED is a part of the toggle switch used for the power system of the Lawnsweeper Mark I. The yellow-colored LED emits light when the robot is powered on.

A principal interaction that a user will have with the Lawnsweeper Mark I is removing the full collection bag, emptying the bag, and securing the bag to the robot again. To reduce complexity, the bag is only secured in four locations, as shown in **Figure C.6.4**. Moreover, at each point of connection between the frame and collection bag, intuitive pegs are used so that the collection bag can be easily removed and resecured as shown in **Figure C.6.5**.

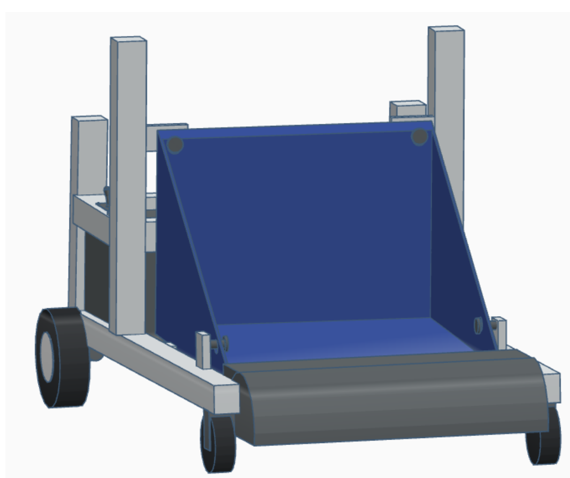

Figure C.6.4: Overview of Mounted Collection Bag

The collection bag of the robot is secured to the frame via four pegs in four corners of the collection bag.

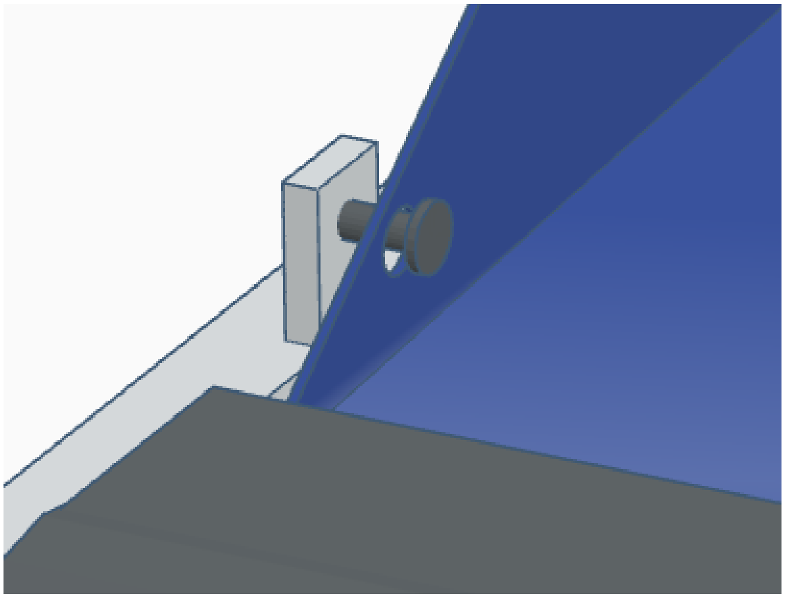

Figure C.6.5: Closeup of Mounting Peg for the Collection bag

The need to access internal components of the robot may be required. **Figure C.6.6** displays the rear compartment access to the electrical components.

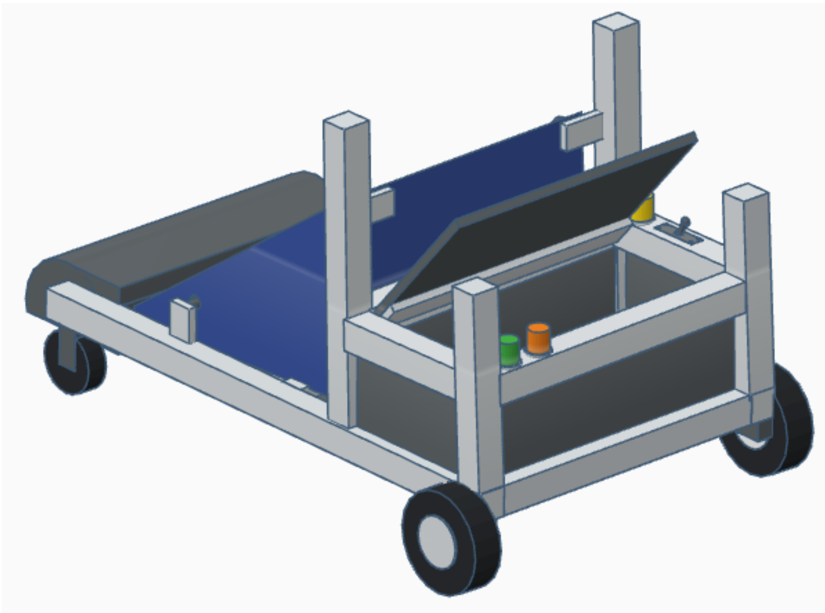

Figure C.6.6: Rear Compartment Access for Electrical Components

Figure C.6.7 below shows the Android application with its simple and intuitive method of pairing with the robot, connection status, along with the manual driving screen of the robot.

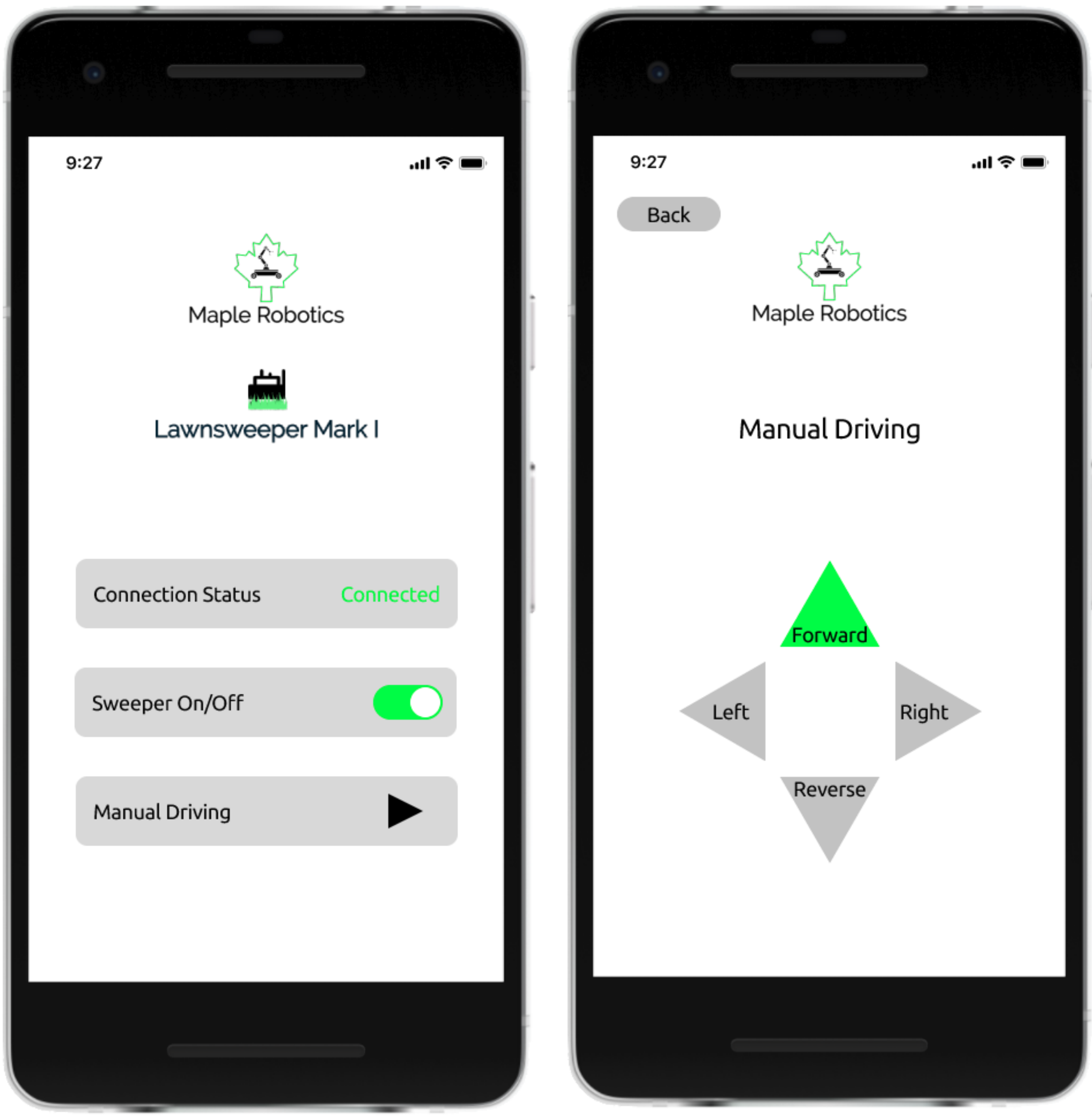

Figure C.6.7: Android Application Home Screen and Manual Driving Screen

C.7 Engineering Standards

To achieve and satisfy the safety, quality, and intuitiveness of the user interface for the Lawnsweeper Mark I, it is necessary to follow various engineering standards defined by CSA, IEC, ISO, IEC, RoHS and IEEE. The user interactions with the system are conducted through software and hardware. Moreover, software and hardware user interfaces should also meet the standards which protect users privacy and prevent bodily harm. Thus, the relevant standards should be considered during development.

Table C.7.1: Engineering Standards for Visual Interface

Standards	**Description of standard**
CSA/ISO/IEC 29138-1:2018	Information technology — User interface accessibility — Part 1: User accessibility needs [14]
ISO 9241-161:2016	Ergonomics of human-system interaction — Part 161: Guidance on visual user-interface elements [15]
IEEE 1621-2004	User Interface Elements in Power Control of Electronic Devices Employed in Office/Consumer Environments [16]
IEC TR 61997:2001	Guidelines for the user interface in multimedia equipment for general purpose use [17]

Maple Robotics will construct the user interface of the Lawnsweeper Mark I based on CSA/ISO/IEC 29138-1:2018 which provides guidance for developers and designers to create user interfaces that are accepted by various societal groups. For instance, this standard will address any issues regarding elderly individuals experiencing difficulty in understanding the functionality of specific buttons in the mobile application. The Maple Robotics team will also follow the ISO 9241-161:2016 standard to design visual user interface elements. The user interface should be developed with visual clarity in mind, aiming to construct a clear, user-friendly and consistent user interface, which should be similar to other interactive systems in the market. Our team will use the IEEE 1621-2004 standard as a baseline to design user interfaces with the robotic system which provides users with system status. Since the smartphone device will use communication systems to connect with the Lawnsweeper Mark I via Bluetooth, the IEC TR 61997:2001 standard will be used by Maple Robotics to build a simple and clear user interface in media equipment.

Table C.7.2: Safety Standards

Standards	Description of standard
ISO/IEC 27033-6:2016	Information technology — Security techniques — Network security — Part 6: Securing wireless IP network access [18]
ISO 13854:2017	Safety of machinery — Minimum gaps to avoid crushing of parts of the human body [19]
EU RoHS 2	Directive 2011/65/EU on the restriction of the use of certain hazardous substances in electrical and electronic equipment [20]

Since the Lawnsweeper Mark I needs to be connected to users' private devices, our company has the responsibility and obligation to protect users' privacy and their wireless network security. With regard to the users' virtual property protection, we will follow the ISO/IEC 27033-6:2016. The user inevitably needs to touch or interact with the physical robot when removing the collection bag or moving the physical system. Thus, the Maple Robotics company must follow the ISO 13854:2017 standard to design minimum gaps of mechanical structure to avoid crushing or pinching of parts of the human body. To avoid the possibility of consumers coming in contact with toxic substances while using the product, Maple Robotics should follow EU RoHS 2, which restrains the use of certain hazardous substances.

C.8 Analytical Usability Testing

Analytical testing will be performed in the absence of user input by Maple Robotics in their capacity as product designers. This includes a review and evaluation of the UI and appearance design of the Lawnsweeper Mark I and the accompanying Android application. The usability of a given UI element will be reviewed and evaluated according to the following criteria, and feedback will be provided to appropriate team members in order to prepare for subsequent empirical usability testing and final release. Emphasis is placed on numerical data collection and analysis in order to distinguish it from empirical usability testing. The testing should take care to minimize recording sentimental opinions of the design to avoid designer bias.

C.8.1 Designer Testing

The following 11 steps are to be conducted by members of the Maple Robotics team.

1. Connect battery, Arduino board, and motor modules to the robot frame.
2. Connect motors to motor modules.
3. Turn on the power switch and verify that the yellow LED turns on.
4. Open the mobile application and connect with the robot via Bluetooth. Verify that the green LED turns on.
5. Through the mobile application, turn on the sweeper and verify that the collection system is moving and the orange LED is on.
6. Turn the sweeper off and verify the orange LED is now off.
7. Through the mobile application, select ‘Manual Driving’ and press ‘Forward’. Verify that the robot moves forward while the button is pressed.
8. Repeat step 7 for ‘Reverse’, ‘Left’ and ‘Right’, verifying that the robot moves in the appropriate direction.
9. Through the mobile application, turn the sweeper on and move the robot ‘Forward’ through a pile of fallen leaves.
10. To verify correct operation of the collection system, ensure that leaves have been swept into the collection bag.
11. Weigh the collected leaves in the bag and uncollected leaves on the path to verify the collection system efficiency.

C.9 Empirical Usability Testing

C.9.1 Heuristic Evaluation

Heuristic evaluation will be done in the form of a User Feedback Form. This evaluation is a report to identify usability problems in the user interface design that may have been overlooked during development. The development team can then review and implement solutions based on the received feedback. Requirements can be categorized in the two following stages:

For the proof of concept:

- Lawnsweeper Mark I's sweeper system works as intended
- Lawnsweeper Mark I's robot moves in forward and reverse directions
- Lawnsweeper Mark I carries the load of the system's component
- Switch turns on power to the system
- Collection bag will be located on the frame to collect leaves
- Robot pairs with the application effectively

For the prototype:

- Application looks and feel pleasing and doesn't overwhelm the user
- Application is able to control the direction robot is moving
- Lawnsweeper Mark I's power can be turned on at a flick of a switch
- Robot status lights provide clear understanding of current status
- Collection bag is easy to remove and intuitive
- Mean of charging the robot's battery will be simple and easy to locate
- User documentation will be concise and clear

C.9.2 Internal Testing

During development, our team at Maple Robotics will thoroughly test in parallel and provide feedback to the respective development team for troubleshooting and product refinement. Ranging from the physical build and appearance of the robot, to the user experience of the application and its intuitiveness. Testing methodology will include but not be limited to team members being given a 'fresh' device to be asked to set up the robot from pairing to starting the collection event.

C.9.3 End User Testing

To adequately test the Lawnsweeper Mark I, Maple Robotics will request the assistance of friends, family, and fellow students who have no prior experience using the product. Following their use and experimentation with the product, user's will be requested to complete a User Feedback Form. The feedback form aims to provide our team with information regarding ease of mobile application setup, intuitiveness of physical and mobile application designs, product satisfaction, and overall impressions of the Lawnsweeper Mark I which can then be applied to future iterations of the product.

Additionally, to ensure that end users are operating the Proof of Concept robot safely, end user testing and experimentation will be done under the supervision of members of the Maple Robotics team in a controlled environment. To certify the credibility of end user tests being conducted in an unbiased manner, members of the Maple Robotics team are to refrain from interrupting tests unless the safety of an end user is in question.

User Feedback Form

Test Environment:										
Rating Scale: 1-10 (1 = Bad and 10 = Excellent)										
Question	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
First Impression of Lawnsweeper Mk I	○	○	○	○	○	○	○	○	○	○
Ease of Setup	○	○	○	○	○	○	○	○	○	○
How helpful were the LEDs on the robot to provide status information?	○	○	○	○	○	○	○	○	○	○
How easy was the collection bag to remove?	○	○	○	○	○	○	○	○	○	○
How intuitive was powering-on the robot?	○	○	○	○	○	○	○	○	○	○
How well does this product address your lawn care needs?	○	○	○	○	○	○	○	○	○	○
How intuitive was the Android application?	○	○	○	○	○	○	○	○	○	○
How satisfied are you with your lawn after using the product?	○	○	○	○	○	○	○	○	○	○
How likely are you to recommend this product to other people?	○	○	○	○	○	○	○	○	○	○
Please rate your leaf collection experience using the Lawnsweeper Mark I	○	○	○	○	○	○	○	○	○	○
Additional Comments:										

C.10 Conclusion

User interface design is an integral part of a product's success. It dictates whether users with minimal technical knowledge become potential customers based on the product's ease of use and user satisfaction. This user interface and appearance design appendix was written to provide and illustrate the necessary UI components to provide users familiarity with the operation of our product. To achieve this goal, our team, Maple Robotics, analyzed Norman's seven fundamental design principles to provide users with an easy to use and intuitive product. Throughout the design and development process, the team will work with both internal members and external users to note issues and collect feedback to address areas of confusion and refine the product and documentation for a more enjoyable user experience. For our prototype and additional product revisions, we will strive to continually refine and polish our product to provide customers with a product that's both effective and intuitive to use.

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