ENSC 405W Grading Rubric for Design Specification

Criteria	Details	Marks
Introduction/Background	Introduces basic purpose of the project.	**/05%**
Content	Document explains the design specifications with appropriate justification for the design approach chosen. Includes descriptions of the physics (or chemistry, biology, geology, meteorology, etc.) underlying the choices.	**/20%**
Technical Correctness	Ideas presented represent design specifications that are expected to be met. Specifications are presented using tables, graphs, and figures where possible (rather than over-reliance upon text). Equations and graphs are used to back up/illustrate the science/engineering underlying the design.	**/25%**
Process Details	Specification distinguishes between design details for present project version and later stages of project (i.e., proof-of-concept, prototype, and production versions). Numbering of design specs matches up with numbering for requirements specs (as necessary and possible).	**/15%**
Test Plan Appendix	Provides a test plan outlining the requirements for the final project version. Project success for ENSC 405W will be measured against this test plan.	**/10%**
User Interface Appendix	Summarizes requirements for the User Interface (based upon the lectures and the concepts outlined in the Donald Norman textbook).	**Graded Separately**
440 Plan Appendix	Analyses progress in 405W and outlines development plans for 440. Includes an updated timeline, budget, market analysis, and changes in scope. Analyses ongoing problems and proposes solutions.	**Graded Separately**
Conclusion/References	Summarizes functionality. Includes references for information sources.	**/05%**
Presentation/Organization	Document looks like a professional specification. Ideas follow logically.	**/05%**
Format/Correctness/Style	Includes letter of transmittal, title page, abstract, table of contents, list of figures and tables, glossary, and references. Pages are numbered, figures and tables are introduced, headings are numbered, etc. References and citations are properly formatted. Correct spelling, grammar, and punctuation. Style is clear, concise, and coherent. Uses passive voice judiciously.	**/15%**
Comments		

March 31, 2018

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

Re: ENSC 405W/440 Design Specification for an Automated Painting Robot

Dear Dr. Rawicz,

The attached document provides the design specifications for implementing an automated room-painting robot as described in both our Project Proposal [1] and Requirements Specification [2]. Our goal is to produce a robot capable of autonomously applying paint to a residential room, requiring only that the human operators mask the room appropriately and fully enclose PaintBot within it by closing any entrances. To achieve such functionality, it is required that we design a number of independent systems and synchronize them appropriately.

This design specification document aims to outline the designs we have developed for each of these systems and the controller system for coordinating them. We will first detail each of these systems individually. This will include the following systems: drive, base position/orientation, paint application, object detection, and power distribution. Lastly, we will detail the controller system that will coordinate all of these subsystems.

PaintBot Inc. consists of 5 hardworking and talented senior engineering students: Bradley Barber, Lior Bragilevsky, Hyun Gyu (Billy) Choi, Ben Korpan, and Peter Kvac. Coming from various engineering concentrations, our team has extensive hardware and software experience to aid us in realizing this proposition.

Thank you for taking the time to review our design specifications. If you have any inquiries regarding the document, please contact our Chief Communications Officer, Lior Bragilevsky, by phone (778-991-1051) or by email (lbragile@sfu.ca).

Sincerely,

Bradley Barber
Chief Executive Officer
PaintBot Inc.

Enclosed: Design Specification for an Automated Painting Robot

Design Specification

Automated Painting Robot

Make life simpler, one stroke at a time

Project Members: Bradley Barber
Lior Bragilevsky
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Submitted to: Steve Whitmore (ENSC 405W)
Dr. Andrew Rawicz (ENSC 440)
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Issue Date: March 31, 2018

Abstract

This document specifies and defines the design specifications of the automated room-painting robot, PaintBot. First, the design specifications for each of PaintBot's independent sub-systems are presented. Their individual design is described separately by outlining the functionality of the components within the system (along with their dimensions) and focusing on the core design specifications that they satisfy. Then, the document details the design specifications of the top level controller system, which coordinates all of these subsystems.

PaintBot's 5 independent sub-systems along with the controller system are:

1. **Drive System**
   Allows PaintBot to move around the room that is being painted.
2. **Base Position/Orientation Sensor System**
   Uses sensors to observe PaintBot's environment and determine when the room painting task is complete.
3. **Paint Application System**
   Provides vertical mobility to the spray gun and maintains a consistent spray pattern.
4. **Object Detection System**
   Provides detection of objects and masking tape in areas where paint needs to be applied.
5. **Power Distribution System**
   Outlines the power requirements necessary for PaintBot's successful operation.
6. **Top Level Controller System**
   Merges each of the above-mentioned subsystems to work together effectively.

PaintBot's user interface design consists of only two buttons, one *on* button and one *emergency stop* button, as all setup and operation is performed autonomously and PaintBot shuts down upon completion. Additional features, such as status display screen and speed control level switch, will be integrated in later design stages.

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Glossary

compressor Pushes paint through a hose and out of the spray gun head. 27

counterweight An added weight used to balance a vertical movement pulley system. If it is well matched to the load the drive system will only apply force to overcome friction, rather than the force of gravity on the entire load. 64

mask Masking in the industrial painting context is the process of applying tape, or some other form of covering, to edges and/or other features of the room to which paint is not to be applied - or to define painting boundaries. 1

PWM Pulse-Width Modulation is a modulation technique for encoding a signal amplitude into the pulse width, or pulse duration, of a carrier signal. 18

revenue The income that a business receives from regular operation, typically from the sale of goods and services - but may also be from collected interest, royalties, and other fees. This excludes income from investors or personal cash-flow into the business. 67

Servo Motors Rotary actuators designed for precise control of angular position (translatable to linear position), velocity, and acceleration. Typically consists of a multi-polar electromagnet motor and internal sensors for position feedback. 11

SPI Serial Peripheral Interface allows for communication between micro controllers and other peripherals. 18

Timing Belt A toothed mechanical drive belt designed for non-slipping. In our application, this refers to a flexible belt with teeth molded into it's inner surface. 71

Ultrasonic sensors A device that uses sound waves to calculate its distance from a given object. To achieve this with precision, it sends the sound waves at a specific frequency and measures the amount of time the sound waves take to bounce back. 64

1 Introduction

The past century was marked by the automation of many manual processes, spanning from assembly line manufacturing to home appliances. This trend of automation is continuing to breach new frontiers due to current advancements in robotics and machine learning technology. As a result, the team at PaintBot Inc. introduced its first product, PaintBot - an innovative and high-tech solution which provides an efficient, effortless, and cost effective means for rapidly painting residential interiors.

To date, this laborious process must still be completed manually using either a roller or spray gun. PaintBot aims to automate this labor while delivering quality and performance on par with current industry standards. To accomplish this, PaintBot will autonomously traverse the perimeter of a room while painting the wall in vertical strips. Any objects/features that are not to be painted, such as windows and outlets, will be marked with colored tape. This will allow PaintBot to detect their boundaries through the use of a real-time camera and machine learning algorithm. Following PaintBot's traversal of the room, contractors will only need to perform any remaining "detailing" work. A high-level behavioural diagram describing this functionality is provided in Figure 1.1.

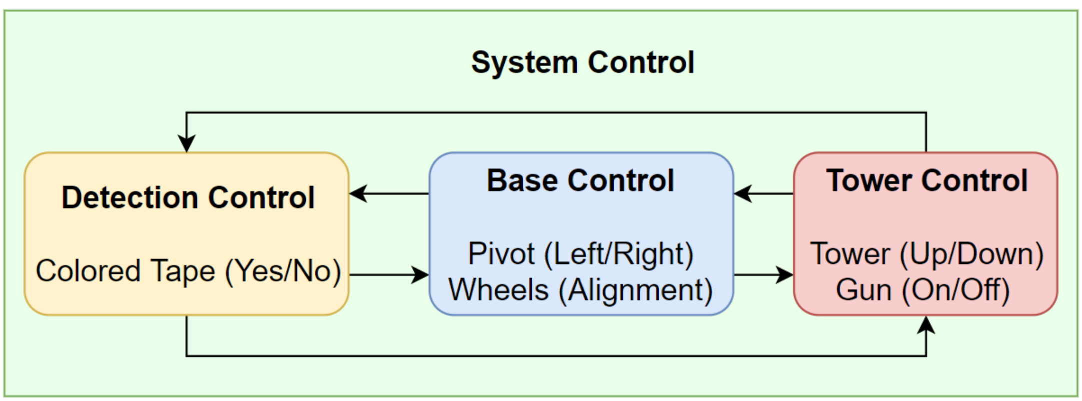


Figure 1.1: Basic Behavioural Overview

This document will specify PaintBot's design, describing in detail how it will achieve the above functionality. These specifications will be organized into the following 6 major systems:

1. **Drive System** (Section 2)
   The design of PaintBot's drive system will be detailed here, providing the specifications for achieving PaintBot's mobility and maneuverability.

2. **Base Position/Orientation Sensor System** (Section 3)
   This section will describe PaintBot's environmental sensing system. This system will allow PaintBot to navigate a room in a methodical manner while avoiding obstacles, maintaining a steady distance from the current wall being painted, and finally determining when a room has been fully traversed.

3. **Paint Application System** (Section 4)
   The design specification for PaintBot's paint application system will be provided here. This section will specify how the team will achieve the ability for PaintBot to apply clean, even layers of paint to residential sized walls.

4. **Object Detection/Avoidance System** (Section 5)
   This section will present the design specification for PaintBot's object detection/avoidance system, used to plan and monitor the paint application area. This will include object and painter's tape recognition as well as quality control monitoring.

5. **Power Distribution System** (Section 6)
   This section outlines PaintBot's power distribution mechanisms. Throughout the section power calculations will be provided and wiring conventions present in PaintBot's design will be presented.

6. **Top Level Controller System** (Section 7)
   This final section will present the design specifications for the controller system required to coordinate all of the subsystems described throughout this report.

1.1 Scope

This document discusses PaintBot's subsystems and how they interact to form the overall product. Throughout the document strong emphasis will be placed on PaintBot's prototype iteration, however other design stages (PoC and final product) will also be mentioned. Other important information, such as a functional test plan, user interface design, and ENSC 440 Planning are provided as appendices. The design specifications presented will allow PaintBot Inc. to realize an automated room painting robot.

1.2 Intended Audience

This document will serve as PaintBot's technical guideline for PaintBot Inc. members, potential clients/partners, Steve Whitmore, Dr. Andrew Rawicz, and teaching assistants. The team at PaintBot Inc. shall refer to the document in order to clear any ambiguities that may arise during the implementation phase of PaintBot's design stages. Near the completion of PaintBot's prototype development phase, it will be tested against the cases specified in the test plan (Appendix A).

1.3 Design Classification

To indicate a design specification, this document will adopt the following scheme [2]:

Des {Section}.{Subsection}.{Requirement Number}−{Design Stage}

The different design stages and their corresponding coding schemes are outlined in Table 1.1.

Table 1.1: Design Stage Coding Scheme

Coding Scheme	Design Stage
C	Proof of Concept (PoC)
P	Prototype
F	Final Product

For example, the first functional requirement in Section 3.1 corresponding to the prototype design stage, will be labeled as

Des 3.1.1−P

1.4 System Overview

An overview of PaintBot's prototype iteration is presented in Figure 1.2.

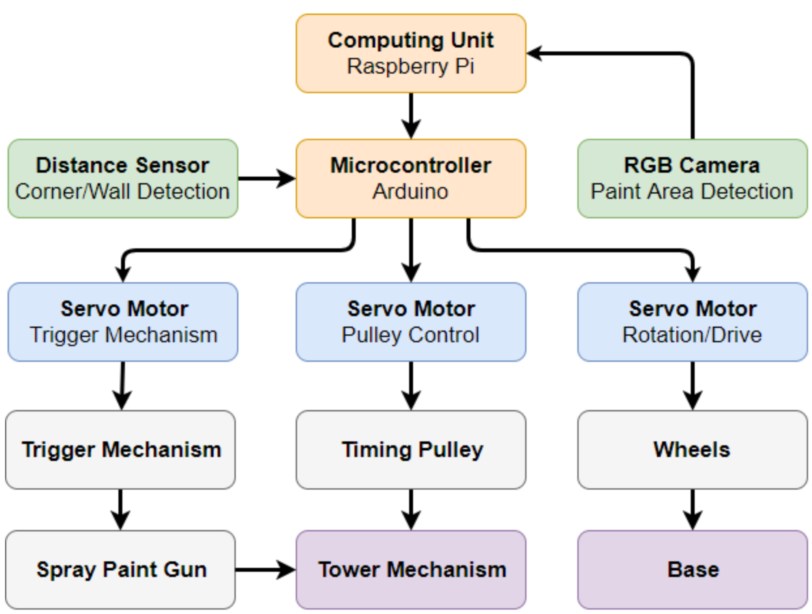


Figure 1.2: PaintBot's System Overview

All of the components shown in Figure 1.2 on the previous page, will work together to provide PaintBot with the performance characteristics outlined in Table 1.2.

Table 1.2: PaintBot's Overall Performance Requirements [2]

Des 1.4.1–C	Adjust itself to achieve correct distance from the target wall, if needed.
Des 1.4.2–C	Detect distance and orientation to target wall.
Des 1.4.3–P	Travel along the perimeter of the room, maintaining a constant distance.
Des 1.4.4–P	Apply paint efficiently, evenly, and accurately.
Des 1.4.5–P	Detect approaching corners of any angle.
Des 1.4.6–P	Turn precisely, ensuring correct distance from the target wall is maintained.
Des 1.4.7–P	Detect upcoming objects for general purpose obstacle avoidance.
Des 1.4.8–P	Apply paint to the walls in a controlled, even, and reliable pattern.
Des 1.4.9–P	Be capable of navigating a room of any size or shape - though height will have to be set to a standard value.
Des 1.4.10–P	Track location to determine when room painting is complete.
Des 1.4.11–F	Detect and respond appropriately to objects protruding or receding from walls/ceilings.
Des 1.4.12–F	Detect masking tape, used to signify areas not to be painted, before the paint head reaches them.
Des 1.4.13–F	Store the location of upcoming areas not to be painted and act on this information.

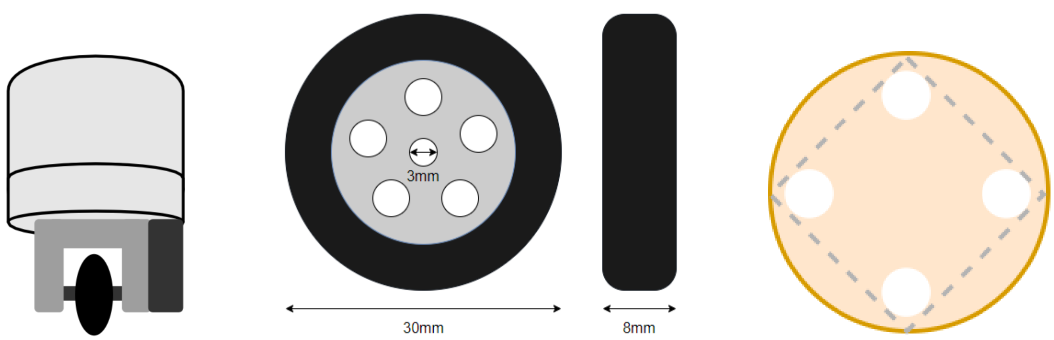
It is important to note that while Table 1.2 lists the design specifications for all three design stages, this document emphasizes PaintBot's PoC and prototype iterations.

2 Drive System

The drive system of PaintBot will feature 4 wheels that are able to rotate both along the axis perpendicular to the base of the robot, and the axis parallel to the floor. This will be achieved by utilizing two separate motors to actuate each wheel. The wheels will be mounted to the circular base at the corners of an inscribed square to facilitate accurate rotation about the geometric center of the base. The base itself will be circular so that rotations will not alter the footprint of the robot, minimizing the possibility of collisions with nearby walls while rotating. The material used for the base, and its construction, will be required to support the weight of the robot while remaining rigid. The following sections will describe the design of the drive system.

2.1 Wheel Configuration

As shown in Figure 2.1, the first motor will be attached to the top of the wheel housing and will be rotated when needing to turn the robot or close the gap to the walls. This will allow translation of the base along the plane of the floor in any direction without altering the orientation of the base, as well as allow precise rotation around the geometric center of the base. The second motor will be attached directly on to the wheel to accomplish the forward and reverse rotation of the wheels.



(a) Wheel Drive (b) Wheel Dimensions (c) Wheel Arrangement

Figure 2.1: Wheel Drive & Arrangement

Figure 2.1a shows the wheel and motor configuration; the top, cylindrical component houses the motor that will achieve wheel pivoting while the dark grey component attached to the right side of the wheel bracket shows the position of the drive motor.

Figure 2.1b provides the dimensions of the wheel to be used in the proof of concept model. Four such wheels will be used for the drive system - one for each corner of the base. These dimensions will be used to calculate torque requirements in the Motors subsection.

Figure 2.1c illustrates the base configuration, where the circular holes located at the corners of the inscribed square show the locations that the wheel and motor configuration of Figure 2.1a will be mounted. The wall facing, paint applying face of PaintBot would be positioned parallel to one of the sides of the inscribed square.

Design Alternatives

Before reaching the final configuration of having two separate motors per wheel, the team considered the following options:

1. **Two Wheel Actuation**
   Actuating only a subset of the wheels has the benefit of reducing the motor count. This would allow for reduced cost projections and a simpler control system. However, in achieving the feature to rotate on spot without any displacement, the inability to control the orientation of all of the wheels was assessed to be a risk by the team.

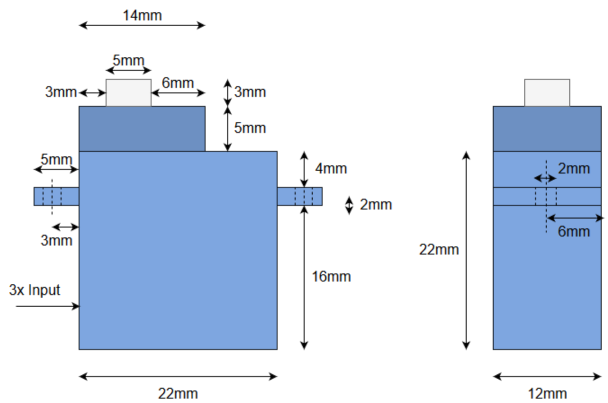
2. **Drive Motors Only**
   Not utilizing the orientation motors on the top of the wheel housing was also considered by the team, since it is possible to achieve in place rotation without them. However, the main concern with this model was the process of closing the distance from the robot to the wall. Without being able to rotate the wheels in the vertical axis, PaintBot would require a correction algorithm which resembles parallel parking, consisting of several forward and backward displacements. This could lead to a larger development time with little benefit and decreased mobility, which is why the team decided that utilizing the extra motors would be worth the cost investment.

2.2 Motors

Table 2.1: Motor Requirements [2]

Des 2.2.1−C	The motors for the robot's drive wheels and paint head pulley system will be capable of indefinite rotation.
Des 2.2.2−C	The motors which rotate the orientation of the drive wheels about their central-vertical axis will be capable of accurately adjusting to any desired angle.
Des 2.2.3−P	All motors will provide enough torque to perform their given task with adequate acceleration. For example, the drive motors will output enough torque to achieve appropriate accelerate for the prototype based on its mass (Table 2.4).
Des 2.2.4−P	Angular displacement of the rotor for all motors must be easily and accurately calculable or ensured based on inputs.

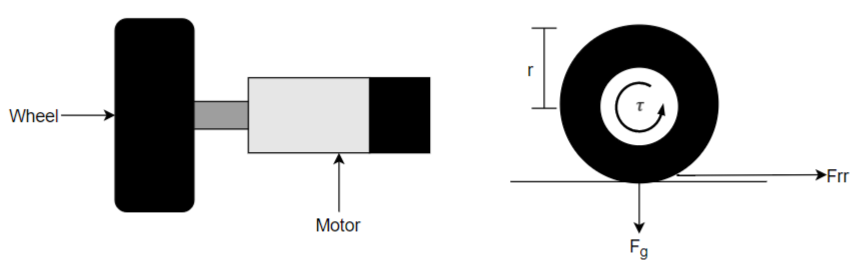
Power consumption and torque requirements are two key constraints which inform motor selection. PaintBot will be powered from a battery source, thus frequent recharging will be needed if the motors consume too much power. This consideration must be balanced with PaintBot's need for reliable, accurate, and smooth movement. However, the critical path during operation is the painting routine, not the movement around the room. Additionally, PaintBot will be working within relatively small residential rooms, thus the drive torque is not required to sustain high velocities or produce quick acceleration. This is precisely why the team at PaintBot Inc. decided to use the wheel pivot motor shown in Figure 2.2.



Specification	Value
Stall Torque	1.2 kg-cm @ 4.8 V
Operating Speed	0.12 s/60° @ 4.8 V (no load)
Mass	9 g
Power Requirements	3.0 to 7.2 V DC
Operating Temperature	−30 to 60 °C

Figure 2.2: Wheel Pivot Motor [3]

The calculations of the drive motor torque requirements for PaintBot's prototype and PoC iterations, using the parameters listed in Figure 2.3, are presented next. The mass estimates utilized will be later computed in Section 2.4.



Parameter	Value
Mass of Robot (m)	22.9 kg
Acceleration due to Gravity (g)	9.81 m/s^2
Maximum Velocity (V_{max})	0.2 m/s
Time Required to Reach V_{max} (t)	1 s
Rolling Resistance Coefficient (μ_{rr})	0.01
Radius of the wheels (r_{wheel})	0.020 m

Figure 2.3: Drive Motor & Wheel [4]

Prototype

Rolling Resistance

$$F_{rr} = m \cdot g \cdot \mu_{rr} = 22.9\ kg \cdot 9.81\ m/s^2 \cdot 0.01 = 2.25\ N \tag{2.1}$$

Acceleration Force

$$F_a = \frac{m \cdot V_{max}}{t} = \frac{23.2\ kg \cdot 0.2\ m/s}{1\ s} = 4.64\ N \tag{2.2}$$

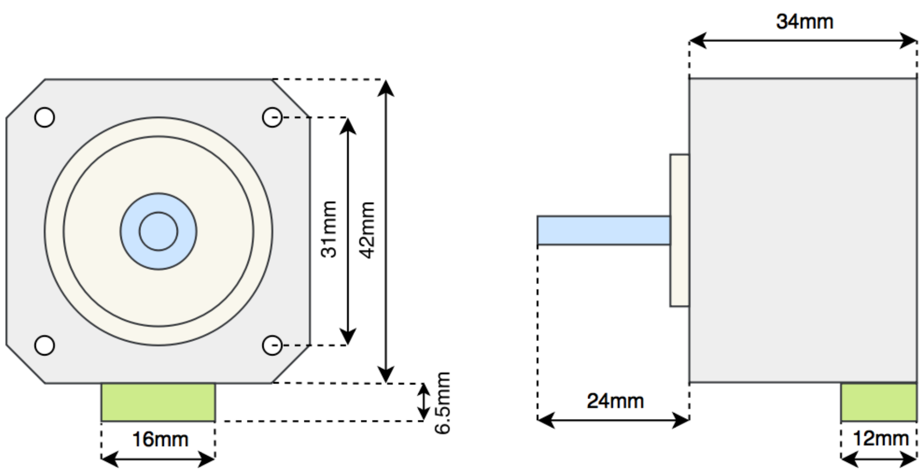
Total Force

$$F_{tot} = F_a + F_{rr} = 4.64\ N + 2.25\ N = 6.89\ N \tag{2.3}$$

Motor Torque

$$\tau_{dr} = F_{tot} \cdot r_{wheel} = 6.89\ N \cdot 0.020\ m = 0.138\ Nm \tag{2.4}$$

The stepper motor described by Figure 2.4 exceeds this torque requirement, while presenting a compact footprint and precise control characteristics.



Specification	Value
Step Angle	1.8°
Rated Voltage	5 V
Rated Current	0.4 A
Holding Torque	0.260 Nm @ 5 V
Mass	200 g
Operating Temperature	−20 to 50 °C

Figure 2.4: Stepper Motor [5]

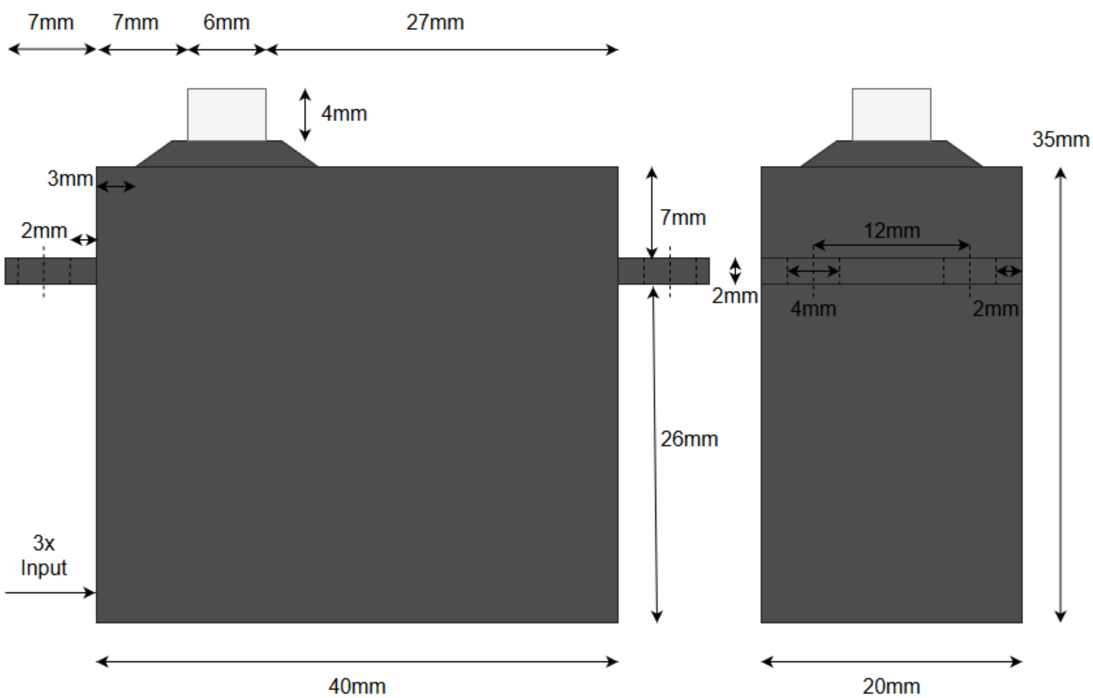
Proof of Concept (PoC)

Using the 0.658 *kg* projected mass of PaintBot's PoC iteration, the same calculations can be performed to obtain Table 2.2.

Table 2.2: Drive Motor Torque Requirements - PoC

Rolling Resistance	Acceleration Force	Total Force	Motor Torque
6.45×10^{-2} N	0.132 N	0.196 N	3.92×10^{-3} Nm

Small servo motors are preferable for PaintBot's PoC iteration due to their low cost and simplicity of control. Thus, the team has decided to use the Parallax servo motor (Figure 2.5) due to its bidirectional continuous rotation feature, light weight, and sufficient torque output.



Specification	Value
Control Signal	PWM
Torque Output	0.2683 Nm @ 6V
Mass	0.0425 kg
Power Requirements	4 to 6 V DC
Operating Temperature	-10 to 50 °C

Figure 2.5: Servo Drive Motor [6]

2.3 Base

Table 2.3: Base Requirements [2]

Des 2.3.1−C	The base shall be circular to ensure the outermost horizontal dimensions of the base are constant in all radial directions during rotation.
Des 2.3.2−C	The base shall be made out of wood.
Des 2.3.3−C	The base shall contain 4 wheels placed at the optimal configuration (Figure 2.1c).
Des 2.3.4−P	The base shall be made out of aluminum.
Des 2.3.5−P	The base shall be capable of providing sufficient support and rigidity for the prototype with mass of 22.9 kg (based on estimate below) under the expected horizontal and angular accelerations and the force exerted by the paint delivery system under all use cases.
Des 2.3.6−P	The base shall be 60.96 cm in diameter.
Des 2.3.7−P	The base shall not exceed 0.3175 cm in thickness.
Des 2.3.8−F	The base shall be capable of supporting weights up to 91.6 kg (assuming four times scaling) under the expected horizontal and angular accelerations and the force exerted by the paint delivery system.
Des 2.3.9−F	The base shall be 76.2 cm in diameter to account for the increased height while being sufficient width to fit through most residential doorframes.
Des 2.3.10−F	The base shall contain handles to provide users with a means to tilt/lay PaintBot on its side.

To ensure the horizontal dimensions of base remain constant during rotation, it is required that the perimeter of the base be radially symmetric about its central, vertical axis. A further requirement is that all components of the robot be within the footprint of the base. The base must also be capable of supporting the other components of the robot during all expected functional behaviours.

An estimate for the load which the base is required to support is presented in Table 2.4 for the prototype and Table 2.5 (on the following pages) for PaintBot's PoC iteration. It is important to note that these are a lower bound estimate for both. Some component weights for the prototype could not be accurately determined, as they have not been definitively decided upon. For the PoC iteration, the weight estimate is more accurate; some components are neglected from the estimate, such as the marker that will be used as a substitute for the paint sprayer, but these components are small and will represent a negligible addition to the overall weight.

2.4 Weight Bearing Calculation

Prototype

Table 2.4: Prototype Mass Estimate

Component	Mass (g/unit)	Mass for Prototype [1] (g)
Stepper Motors	280 [5]	1,400
Wheels	12.2 [7]	48.8
Aluminum (g/cm^2)	2.68 [8]	15,500
Servo Motors	41.7 [9]	166.8
60T Pulley	15 [10]	30
32T Gear	22.68 [11]	90.72
16T Gear	5.67 [12]	22.68
Tower Support Rails	635 [13]	2,540
Paint Delivery System	3,103 [14]	3,103
Total Mass		**22,902 g**

For a conservative calculation, we will use a simple loaded beam model to calculate the weight bearing capability of the base and assume that the wheels will be located at its extremities. For ease, and to ensure a conservative estimate, we will use 10×10^6 psi. First, we can use the equation for the moment of inertia of a rectangular cross-section to determine the moment of inertia of the largest possible cross-section of the base, that is a cross section that passes through the geometric center:

$$I = \frac{b \cdot h^3}{12} = \frac{60.96\ cm \cdot (0.3175\ cm)^3}{12} = 0.1626\ cm^4 \tag{2.5}$$

where b is the width of the cross-section (diameter of the base) and h is the thickness.

Assuming the worst case, a point load of PaintBot's full weight located at the geometric center of the base, the maximum stress between the load and the wheels can be found with the equation:

$$s_{max} = \frac{W \cdot l}{4 \cdot Z} \tag{2.6}$$

In this equation, W is the weight of the load (in this case 22.902 kg/50.49 lbs), l is the distance between supports (we will choose the worst case, the full diameter of the base) and Z is the section modulus. The section modulus of a rectangular cross-section is found using:

$$Z = \frac{2 \cdot I}{h} = \frac{2 \cdot 0.1626\ cm^4}{0.3175\ cm} = 1.0242\ cm^3 \tag{2.7}$$

Therefore, the maximum expected stress is:

$$s_{max} = \frac{22.902\ kg \cdot 60.96\ cm}{4 \cdot 1.0242\ cm^3} = 340.78\ \frac{N}{cm^2} = 3.4078\ \frac{N}{mm^2} \tag{2.8}$$

The yield strength, the maximum stress a material can be put under before moving from elastic deformation (will revert to original shape) to plastic deformation (is permanently affected), is typically ~95 $\frac{N}{mm^2}$. The maximum stress expected for the PaintBot prototype is over an order of magnitude below this, suggesting that the choice of 0.3175 cm sheet aluminum will be appropriate and provide a very acceptable buffer in our estimates for any increase in load that may occur.

We can also determine the maximum deflection expected from this load. To do so we need the modulus of elasticity, E. For aluminum, the modulus of elasticity varies from ~$10 - 10.2$ ($\times 10^6$ psi) [15]. To make the most conservative estimate, we will use the larger value, which corresponds to ~7.033 $\frac{MN}{cm^2}$. The maximum expected deflection can then be calculated as follows:

$$d_{max} = \frac{W \cdot l^3}{48 \cdot E \cdot I} = \frac{22.902\ kg \cdot (60.96)^3}{48 \cdot 7.033\ \frac{MN}{cm^2} \cdot 0.1626\ cm^4} = 0.0945\ cm \quad (2.9)$$

The maximum expected deflection, in the worst case scenario and with very conservative values, is less than 1 mm. This is well within an acceptable range, so we are very confident in choosing aluminum to construct the base for our PaintBot prototype.

Proof of Concept (PoC)

Table 2.5: PoC Mass Estimate

Component	Mass (g/unit)	Mass for PoC (g)
Drive Servo Motors	42.5	212.5
Pivot Servo Motors	9	36
Wheels	6	24
2.6 mm Wood Sheet (g/cm^2)	0.21	243.95
Tower Guide Rails	10	40
20T Gear	4.5	9
Timing Belt	42.5	42.5
Arduino Uno [16]	25	50
Total Mass		**657.95 g**

Following the same methodology as in the previous section:

$$I = \frac{b \cdot h^3}{12} = \frac{30.48\ cm \cdot (0.3175\ cm)^3}{12} = 0.0813\ cm^4 \quad (2.10)$$

$$Z = \frac{2 \cdot I}{h} = \frac{2 \cdot 0.0813\ cm^4}{0.3175\ cm} = 0.5121\ cm^3 \quad (2.11)$$

$$s_{max} = \frac{0.65795\ kg \cdot 30.48\ cm}{4 \cdot 0.5121\ cm^3} = 9.79\ \frac{N}{cm^2} = 0.0979\ \frac{N}{mm^2} \quad (2.12)$$

Since we do not have the specifications for the exact wood fiber board we are using for the PoC, we will have to refer to another source to determine our estimates. Table 2.6 gives a range of values for different sheet wood products.

Table 2.6: Wood Panel Static Bending Properties [17]

Panel Material	Modulus of Elasticity ($\times 10^6 \cdot lb \cdot in^{-2}$)	Modulus of Rupture ($lb \cdot in^{-2}$)
Medium Density Fiberboard	0.52	5,200
Hardboard	0.45 – 0.80	4,500 – 8,200
Particleboard	0.40 – 0.60	2,200 – 3,500
Oriented Strand-board	0.64 – 0.91	3,161 – 5,027
Plywood	1.01 – 1.24	4,890 – 6,180

To get the most conservative estimate, we can compare the max stress estimate to the product with the lowest modulus of rupture, particleboard, with a low-end value of $2200 \ \frac{lb}{in^2} = 15.16847 \ \frac{N}{mm^2}$. From this, we see that the worst case stress from our expected load is less than two orders of magnitude smaller than this modulus of rupture. We can be certain that the material we are using, a wood fiber board, will have a modulus of rupture at least as large as this and, therefore, will be an acceptable material for building our PoC.

To determine the maximum deflection, we need to know the modulus of elasticity of the wood fiber board we will be using. Again, we do not have the exact value available to us, so we have to refer to Table 2.6. Since the maximum deflection is inversely proportional to the modulus of elasticity, to get the most conservative estimate we will use the product with the smallest modulus value, particleboard again, with a low-end value of $0.40 \times 10^6 \ \frac{lb}{in^2} = 2,757.9 \ \frac{N}{mm^2}$. Thus,

$$d_{max} = \frac{W \cdot l^3}{48 \cdot E \cdot I} = \frac{0.65795 \ kg \cdot (30.48)^3}{48 \cdot 2,757.9 \ \frac{N}{cm^2} \cdot 0.0813 \ cm^4} = 1.73 \ cm \tag{2.13}$$

While this isn't a great result, 1.73 cm would almost result in the deflection being great enough to touch the ground, this estimate is guaranteed to be an overestimate as the model assumes the wheels are at the very edge of the base, an impossibility, and is based off of a more flexible material than we will be using. If we use a more reasonable surrogate material, medium density fiber board with a modulus of elasticity value of $0.52 \times 10^6 \ \frac{lb}{in^2} = 3,585.3 \ \frac{N}{mm^2}$, we get:

$$d'_{max} = \frac{W \cdot l^3}{48 \cdot E \cdot I} = \frac{0.65795 \ kg \cdot (30.48)^3}{48 \cdot 3,585.3 \ \frac{N}{cm^2} \cdot 0.0813 \ cm^4} = 1.33 \ cm \tag{2.14}$$

A more acceptable value while still being a likely overestimate.

Based on the above calculations, we have determined that the wood fiberboard that we have considered for constructing our PoC is an appropriate choice.

3 Base Orientation System

3.1 Ultrasonic Rangefinders

Table 3.1: Ultrasonic Rangefinders Requirements [2]

Des 3.1.1–C	Two ultrasonic rangefinders shall record the distance from the wall being painted.
Des 3.1.2–P	Ultrasonic rangefinders shall have a dead-zone of at most 5 cm and a range exceeding 100 cm.
Des 3.1.3–P	Ultrasonic rangefinders shall have a resolution of at least 1 cm.
Des 3.1.4–P	Two ultrasonic rangefinders shall record the distance to an approaching obstacle in the direction of motion.
Des 3.1.5–F	An ultrasonic rangefinder shall detect the closest obstacle for general avoidance, as illustrated in Figure 3.3.

Table 3.1 lists the design requirements at each stage of development. For PaintBot's PoC iteration, ultrasonic rangefinders will be employed to ensure reliable and accurate wall detection for distances within 500 ± 10 cm.

As depicted in Figure 3.1, four ultrasonic rangefinders will be required, labelled: Side1, Side2, Front1, and Front2. Additionally, the distances labelled "Side Wall Distance" and "Front Wall Distance" are the uniform distances that PaintBot is expected to maintain from the wall, namely 12 cm and 40 cm for the PoC and prototype iterations, respectively.

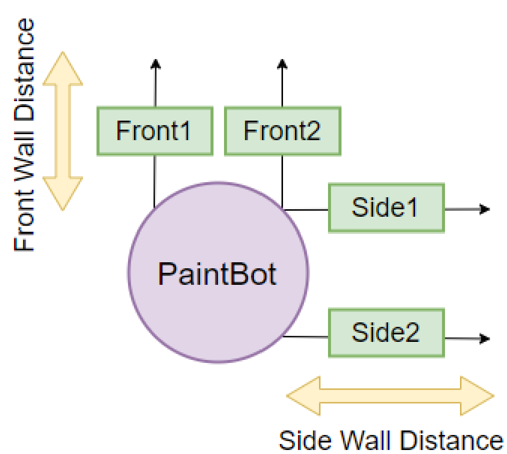
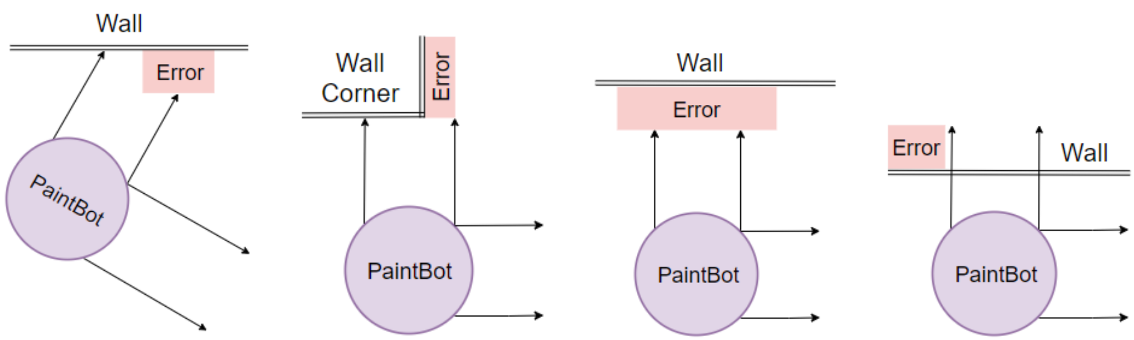


Figure 3.1: PaintBot's Sensors

Two ultrasonic rangefinders will be required to maintain the Side Wall Distance, i.e, 12 ± 0.5 cm for the PoC iteration. For distances greater than this tolerance, the "Base Position/Orientation" function will begin after the current cycle is complete. Similarly, if PaintBot is too close to a wall, it will rotate in the clock-wise (CW) direction.

Figure 3.2 shows a sample of the different common orientations PaintBot might be in while painting a given room.



(a) Oblique Angle (b) Wall Corner (c) Normal Angle - Far (d) Normal Angle - Close

Figure 3.2: Sample Common Orientation Cases

For all the cases presented in Figure 3.2, PaintBot is not correctly aligned with the wall, as indicated by the red "Error" label. These labels show the adjustment distances needed for the sensors to produce correct readings.

In case 3.2a, the side ultrasonic sensors are at oblique angles to the wall, causing sensor Front2 to produce faulty readings. In this case PaintBot would turn counter clock-wise (CCW) and re-adjust its vertical positioning. By doing so, the two front sensors will line up with the wall and provide reliable readings. It is important to mention that a CW rotation would be needed if PaintBot was positioned such that the sensor Front1 was in error.

Likewise, even though the sensors are normal to the wall in case 3.2b, the sensor Front2 is unable to read the distance to the wall being painted. Here a CCW rotation will be made, causing PaintBot to orient itself into a similar position to case 3.2a. After this, PaintBot will move horizontally away from the corner and repeat the procedure outlined in case 3.2a.

Lastly, cases 3.2c and 3.2d indicate wall distance errors - being too far and too close to the wall, respectively. To recover from these situations, the drive motor speeds will be slightly varied to gradually correct the distance. In case 3.2c the rear-facing wheels would be driven slightly faster than the front-facing wheels. The opposite correction strategy is applied in case 3.2d. Once PaintBot reaches the required distance, the drive motor speeds will equalize and the front sensors will be able to provide reliable readings.

It is important to mention that the cases described in Figure 3.2 all refer to errors occurring for the front sensors, however similar errors can also occur for the side sensors. More specifically, for the side sensors only cases 3.2c & 3.2d are relevant. In these situations, the correction strategy will be to slowly move PaintBot forwards or backwards (in the horizontal direction) until an ideal distance from the wall is achieved. Following this, PaintBot's turning routine can execute.

In PaintBot's final iteration, general purpose object detection will also be performed with ultrasonic rangefinders. At a high-level, Figure 3.3 illustrates the ultrasonic rangefinders' operation for correcting the base position/orientation or object detection. Ultrasonic pulses of sound are launched from the rangefinders, and the time which elapses before the first echo returns is used to calculate the distance to the nearest object. PaintBot requires an accuracy of approximately 1 cm for reliable performance.

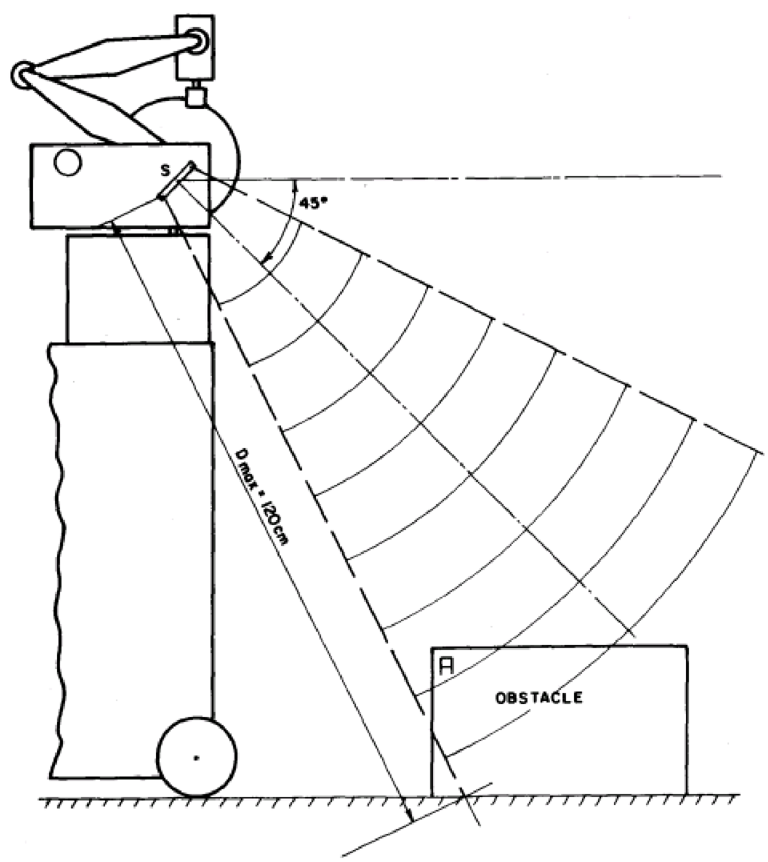
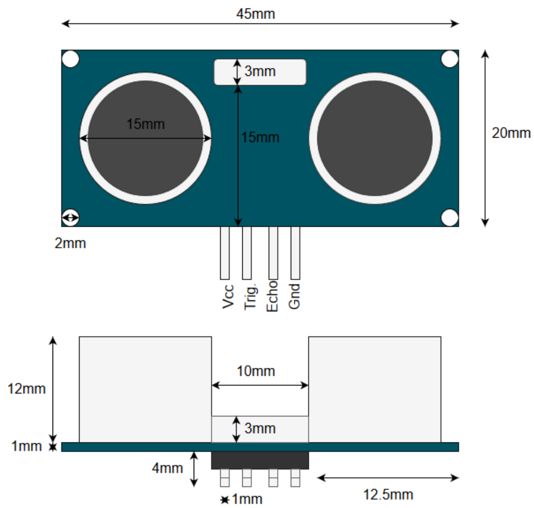


Figure 3.3: Ultrasonic Rangefinders for Obstacle Detection [18]

On the next page, Figure 3.4 shows the ultrasonic rangefinders that will be used in PaintBot's PoC, prototype, and final product iterations. With very accurate distance readings (5 – 10 mm), these sensors provide sufficient resolution for base position/orientation and wall detection purposes.



Specification	Value
Accuracy	5 – 10 mm
Dimensions	45 × 20 × 15 mm
Weight	45 g
Working Voltage	5 V DC
Working Current	15 mA
Ultrasonic Frequency	40 kHz
Max Range	4 m
Min Range	2 cm
Measuring Angle	15°
Trigger Input Signal	10 μs TTL Pulse

Figure 3.4: Ultrasonic Rangefinder [19]

Design Alternatives

1. **LIDAR-lite Rangefinder**

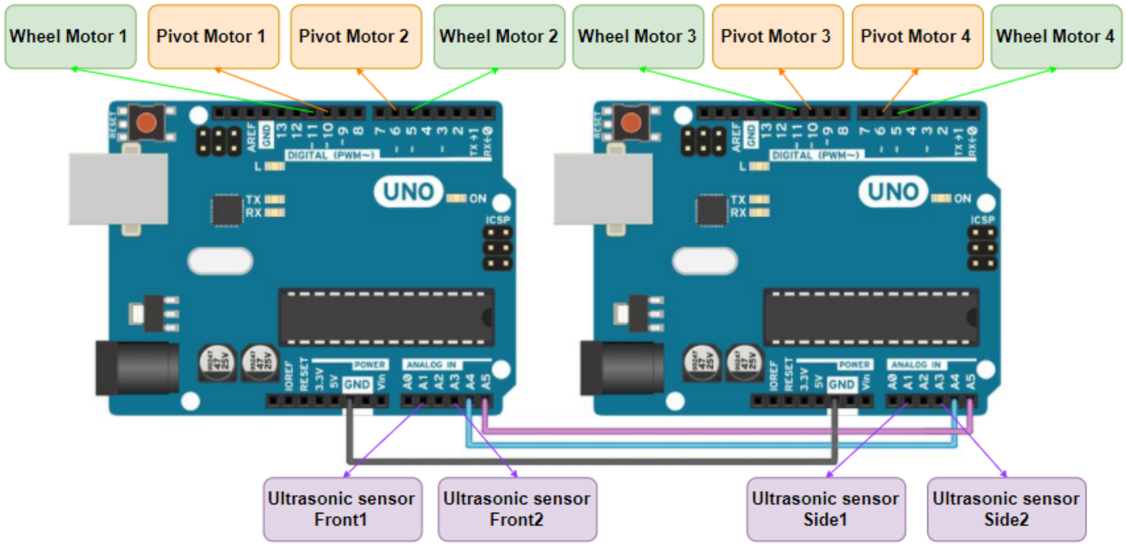
   A LIDAR-lite rangefinder could also be used for PaintBot's prototype iteration. However, due to poor reading accuracy at distances under 30 cm [20], this rangefinder would not be appropriate for the PoC. This was the main reason this option was not chosen for our application. Additionally, the price is also a factor, as a single LIDAR-lite module costs over $100 - compared to the per unit price for the ultrasonic rangefinder of only $15.

2. **Infrared Rangefinder**

   An infrared (IR) rangefinder was also considered, but the relatively narrow usable distance range of many of the models available, typically operating within only a small range such as 20 – 150 cm [21], kept this from being a viable option.

3.2 Arduino Uno Micro Controller

The Arduino Uno micro controller is equipped with GPIO functionality to generate and interpret control signals. These signals include drive/pivot motor control and ultrasonic rangefinder readings. As shown in Figure 3.5 (on the next page), two such micro controllers will be utilized to arbitrate these signals and execute control algorithms.



Specification	Value
Dimensions	68.6 × 53.4 × 15 mm
Clock Speed	16 MHz
Weight	25 g
Working Voltage	5V DC
Working Current GPIO pin	20 mA
Working Current for 3.3V pin	50 mA
Digital I/O Pins	14 Digital 6 PWM 4 SPI
Analog Input Pins	6
EEPROM	1 KB
Flash Memory	32 KB
SRAM	2 KB
Operating Temperature	−45 to 80 °C

Figure 3.5: Arduino Uno Microcontroller [16]

It is important to note that Figure 3.5 illustrates the mappings of control signals onto GPIO pins, such as the wheel drives, pivot motors, and ultrasonic sensors. Additionally, from the provided Arduino Uno specifications (Figure 3.5), it can be seen that only 6 PWM pins are present on a single device. However, 8 PWM pins are needed to implement PaintBot's motor control, requiring the use of an additional Arduino.

4 Paint Application System

PaintBot requires a mechanism that is able to steadily hold the spray paint gun and translate it vertically to result in an even strip of paint on the wall. In order to achieve this, the team at PaintBot Inc. has decided to build a tower mechanism that is supported by 4 vertical beams consisting of a platform carrying the paint gun. To move the paint gun, a pulley system will be utilized with the belt attached both on top and the bottom platforms that will be actuated by a motor. Additionally, to trigger the paint gun a linear actuator will also be mounted on to the platform in front of the paint gun and will listen to signals from an Arduino for control.

4.1 Overall Tower Structure

The tower is a central component of PaintBot's design: it vertically positions and triggers the paint gun. Figure 4.1 outlines the overall design of PaintBot's tower mechanism.

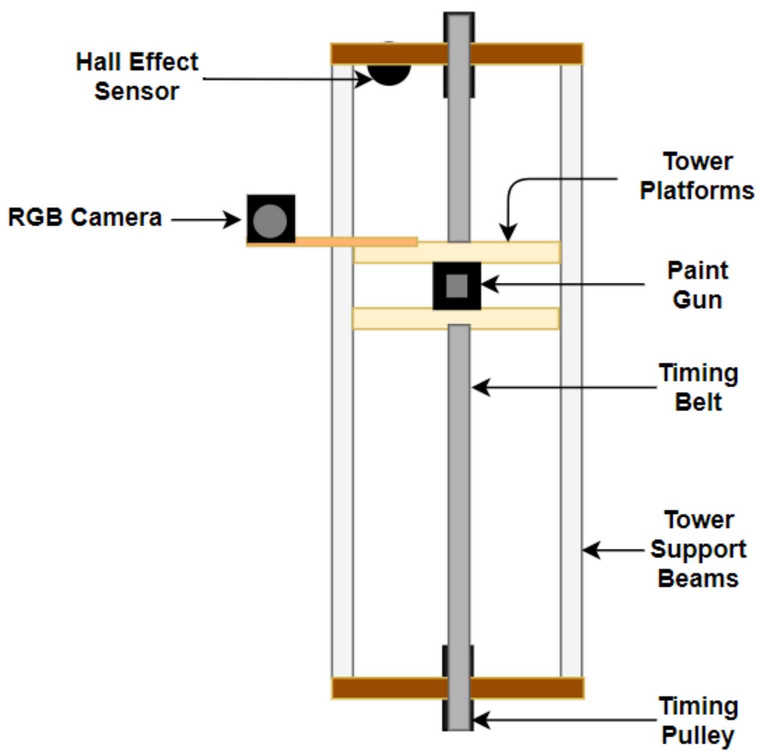


Figure 4.1: Overall Tower Design

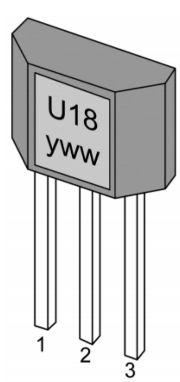
Design Alternatives

1. **Scissor Lift for Spray Paint Gun**
   One considered alternative to building a pulley driven tower was to provide the vertical movement of the paint gun with a scissor-lift. This would allow for easier maneuvering while transporting the robot, since the tower would not be at a significant height when collapsed. Additionally, it would provide better flexibility in handling ceiling heights. However, the price of a stable Scissor-lift alone was projected to be around $600, which would impact our projected cost drastically. Additionally, the mass of the lift would be significantly higher than the pulley system, requiring the team to purchase higher torque motors for the base.

2. **Three Support Beams**
   During PaintBot's early design stages, there were discussions of building a triangular shaped tower using only three support beams. An advantage of this model is that it reduces the tower's weight and associated costs as one less support beam is required. Additionally, this decreases the amount of material concentrated in the center of PaintBot's base. However, there are many difficulties that are introduced with this design, such as placing spray paint gun on the moving platform while providing clearance for the pulley system.

4.2 Paint Platform - Height Feedback

Figure 4.2 shows a Hall Effect transducer, which varies the output signal voltage in response to a magnetic field. It will be placed near the top of the tower (Figure 4.1) to signal to the System Control Process when the paint platform has reached its maximum height, providing feedback compensation for any error in height estimates from the pulley system, as well as signalling when Object Detection should cease.



Pin Number	Functionality
1	Supply Voltage
2	Open Drain Output
3	Ground

Figure 4.2: Hall Effect Sensor

4.3 Tower Support Beams

Table 4.1: Tower Support Rails Requirements [2]

Des 4.3.1−C	The support beams shall be 76.2 cm in length.
Des 4.3.2−C	The support beams will support a sliding mechanism to allow the paint head to move up and down.
Des 4.3.3−C	The rails and their mountings will maximize the range in which the paint head can move vertically up and down the tower to maximize the allowed vertical paint coverage.
Des 4.3.4−C	The rails will be rigid enough to adequately reduce unwanted movement during standard operation to ensure an acceptable standard of paint quality.
Des 4.3.5−P	The support beams shall be placed around PaintBot's center of mass in a square configuration.

The tower support beams will provide the structure of the tower, and will guide the spray paint head platform up and down the tower. This requires that the support beams be adequately rigid and machined to allow the use of linear sliders. These support beams must also have a consistent diameter without interruption throughout the entire operating length of the rod. Due to the above mentioned reasons, the tower support beams shown in Figure 4.3 will be used for PaintBot's prototype iteration. Their small radius will reduce PaintBot's weight and the fact that they are made from steel affords stability to the tower structure.

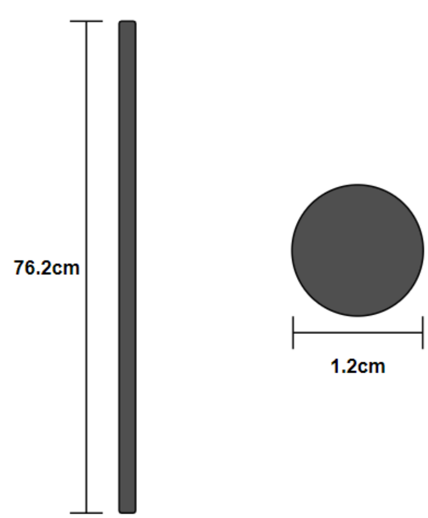


Figure 4.3: Tower Support Beam [22]

4.4 Paint Gun Platform

The two platforms that will be responsible for carrying the paint gun will be designed to be sturdy and add as little mass as possible. A material that suits both of these constraints is aluminum, since its density is relatively low at $2,700\ kg/m^3$ compared to steel which has a density of $8,030\ kg/m^3$ [23]. The two boards will share the same dimensions and the timing belt will be attached to both of the top and bottom platforms. The dimensions of the platforms for the prototype are illustrated below in Figure 4.4.

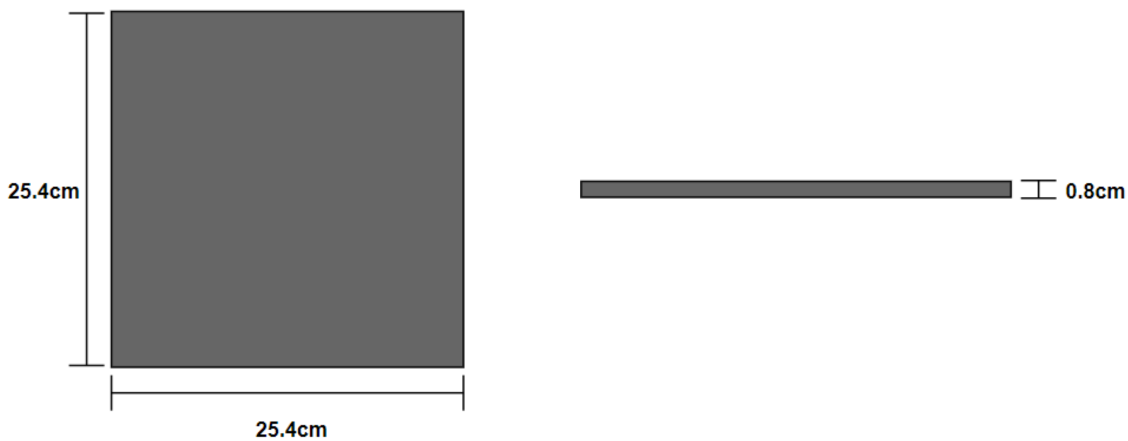


Figure 4.4: Tower Platforms Dimensions

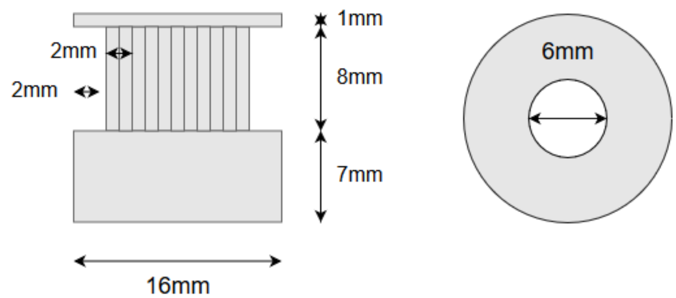
The width and the length of the tower were chosen such that there is sufficient room for all of the components to fit on the platform. This includes the spray paint gun, a bracket that will be fabricated to suit its dimensions, and the triggering mechanism in charge of actuating the spray paint gun. Additionally, the timing belt is mounted on a larger area to provide stability for the spray paint gun.

4.5 Pulley System

This section of the report will provide an in depth analysis of the pulley system, which is responsible for the movement of the paint gun platform contained in the tower. The design of the pulley system consists of 2 timing pulleys, a timing belt (compatible with the pulleys to be attached to the spray paint gun platforms), and a motor capable of delivering sufficient torque to move the platforms. This motor will be controlled independently from the drive system, and will never be in motion during PaintBot's movement phases.

Timing Pulley

The timing pulley that will be utilized for PaintBot's PoC iteration is shown in Figure 4.5.



Specification	Value
Teeth	20
Tooth Pitch	2 mm
Bore Diameter	5 mm
Flange	Double

Figure 4.5: Tower Pulley System Gear [24]

One of the core justifications for choosing the GT2 20T timing pulleys is that the diameter is only 16 mm, a relatively small value with respect to others. As will be shown in the motor torque requirement calculations for the pulley's actuation, the diameter of the pulley is proportional to the amount of required torque. If the pulleys are validated to provide a sufficiently stable vertical movement of the platform in the PoC iteration, the same components may be used in the prototype.

Timing Belt

The belt that will collaborate with the timing pulleys chosen is shown in Figure 4.6.

Specification	Value
Tooth Width	7 mm
Pitch	2 mm
Width	6 mm
Length	5 m
Material	Fiber reinforced rubber

Figure 4.6: Timing Belt [24]

The timing belt is provided as a package with the timing pulleys, guaranteeing that the parts will be compatible with each other. The 5 m length is sufficient for our tower design of both the PoC and prototype iterations.

Motor - Pulley Actuation

The pulley system will be operated by a single motor actuating the bottom pulley, as shown in Figure 4.7.

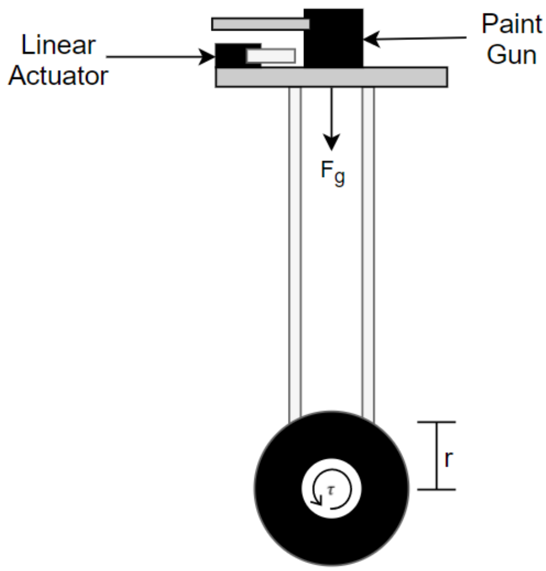


Figure 4.7: Pulley System Diagram

The minimal torque required to vertically actuate the platform at the desired speed is calculated below using the parameters listed in Table 4.2 on the next page. It is important to note that this will be an estimated value, neglecting the friction between the platform and the support shafts.

Table 4.2: Pulley System Inertia & Torque Parameters - Prototype

Parameter	Value
Inertia of Platform (J_L)	$3.13 \times 10^{-5}\ kg \cdot m^2$
Inertia of Pulleys (J_P)	$3.75 \times 10^{-8}\ kg \cdot m^2$
Inertia of Belt (J_{Be})	$0.25 \times 10^{-7}\ kg \cdot m^2$
Diameter of Pulley (D)	$0.005\ m$
Mass of the Pulley (m_P)	$0.006\ kg$
Mass of the Belt (m_{Be})	$0.04\ kg$
Mass of the Platform (m_L)	$5\ kg$
Acceleration due to gravity (g)	$9.81\ m \cdot s^{-2}$
Maximum Velocity (V_{max})	$1\ m/s$
Time required to reach V_{max} (t)	$1\ s$

Inertia Calculations

The inertia of the platform can be found as follows:

$$J_L = 0.25 \cdot m_L \cdot D^2 = 0.25 \cdot 5\ kg \cdot 0.005^2\ m = 3.13 \times 10^{-5}\ kg \cdot m^2 \tag{4.1}$$

Likewise, the inertia of the pulley mechanism is:

$$J_P = 0.25 \cdot m_P \cdot D^2 = 0.25 \cdot 0.006\ kg \cdot 0.005^2\ m = 3.75 \times 10^{-8}\ kg \cdot m^2 \tag{4.2}$$

Following similar calculations, the inertia of the belt is:

$$J_{Be} = 0.25 \cdot m_B \cdot D^2 = 0.25 \cdot 0.040\ kg \cdot 0.005^2\ m = 0.25 \times 10^{-7}\ kg \cdot m^2 \tag{4.3}$$

The total inertia is equal to summation of the above moments of inertia:

$$J_T = J_L + J_P + J_B = 3.16 \times 10^{-5}\ kg \cdot m^2 \tag{4.4}$$

Torque Calculations

Assuming perfect motor efficiency, the load(platform) torque is calculated by the formula:

$$\tau_L = \frac{m_L \cdot g \cdot D}{2} = \frac{5\ kg \cdot 9.81\ m \cdot s^{-2} \cdot 0.005\ m}{2} = 0.122\ N \cdot m \tag{4.5}$$

The acceleration torque required to move the platform reaching a rate of 1 m/s ($Vmax$) within 1 s (t) is calculated by the following formula:

$$\tau_a = \frac{J_T \cdot Vmax}{t} = \frac{3.16 \times 10^{-5}\ kg \cdot m^2 \cdot 1\ m/s}{1\ s} = 3.16 \times 10^{-5}\ N \cdot m \tag{4.6}$$

Finally, the total torque required, τ_t, for the pulley system is the summation of the acceleration torque, τ_a, and the load torque, τ_L.

$$\tau_t = \tau_a + \tau_L = 3.16 \times 10^{-5}\ N \cdot m + 0.122\ N \cdot m = 0.122\ N \cdot m \tag{4.7}$$

From the above calculations, we can observe that we are required to utilize a motor that is able to produce a torque of over 0.122 $N \cdot m$. To account for some marginal errors in the calculations and performance variance from motor to motor, the team will search for an actuator that has a maximum torque output of at least 0.2 $N \cdot m$ to be used in the prototype. For PaintBot's PoC iteration, the weight of the tower platforms will be relatively small due to the fact that the platforms will be wood in material and are holding only an object, such as a marker, in place of the spray paint gun. Additionally, the team at PaintBot Inc. will be utilizing a servo motor with the dimensions shown in Figure 4.8, on the next page.

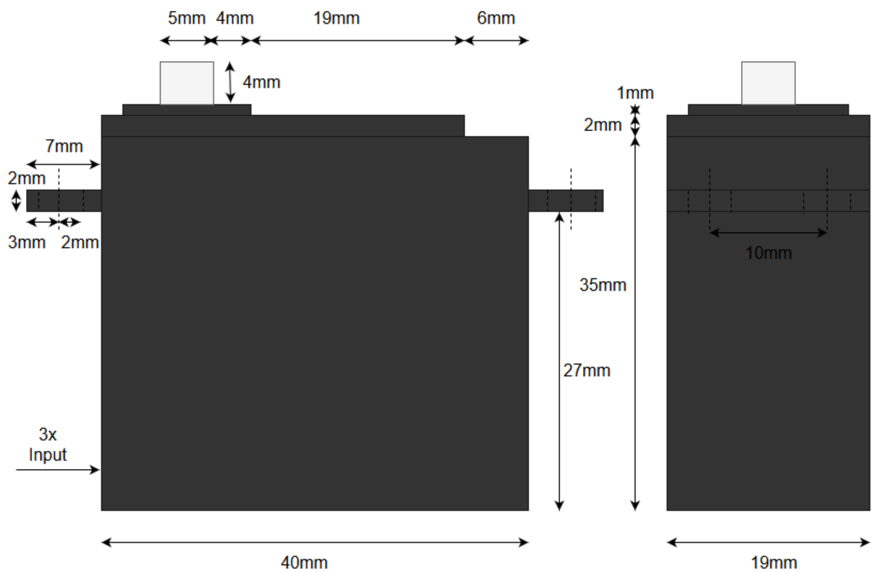


Figure 4.8: Tower Pulley Motor [6]

4.6 Trigger Mechanism

In order to automate the painting process, PaintBot requires an external control mechanism for triggering the paint gun. This feature will be an addition in the prototype iteration and thus the exact dimensions are unavailable at this point in time. However, the speculative visualization of the design is visible in Figure 4.9. A linear actuator will receive signals from a micro controller to determine when it should thrust forward and pull back. The paint gun will be stably mounted on the platform using a bracket fabricated by the PaintBot team in order to prevent the gun from exerting any undesirable movements during actuation.

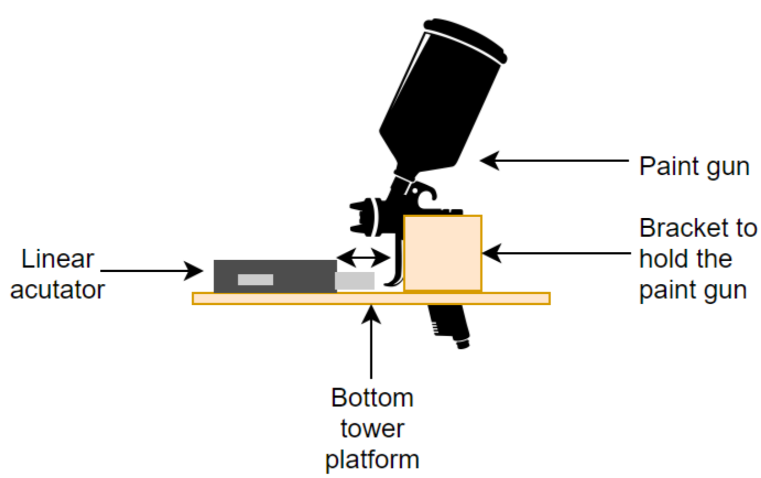


Figure 4.9: Trigger Mechanism Design [25]

4.7 Paint Delivery

Table 4.3: Paint Delivery Requirements [2]

Des 4.7.1−P	The spray gun will operate from a pressurized paint canister mounted on the base.
Des 4.7.2−P	The paint delivery mechanism shall be free of leakage.
Des 4.7.3−P	The paint delivery mechanism shall not effect the spray pattern of the gun.
Des 4.7.4−P	The paint reservoir shall be mounted on PaintBot in order to prevent unnecessary objects within the work space.
Des 4.7.5−F	The compressor shall turn off once PaintBot's paint reserves fall beneath the threshold level.

The consumption of paint in PaintBot's operation is an obstacle for the team to overcome in creating an automated robot. In order to minimize human interactions involved in refilling the paint, PaintBot's prototype will feature a large reservoir that is capable of feeding the paint to the gun through a tube mechanism. This reservoir shall be mounted on top of the base of the robot and travel along side PaintBot to reduce obstacles in the work space. The target for the prototype iteration is to be able to paint a 800 square feet area without needing to refill which requires approximately 2 gallons of paint. This is projected to be around 3.33 kg in mass that will be added to the base of the robot.

4.8 Paint Pattern

Table 4.4: Paint Pattern Requirements [2]

Des 4.8.1−P	The spray gun shall be able to cover at least a 22.86 cm (9 inch) wide strip (cross section), as shown in Figure 4.10.
Des 4.8.2−P	The spray gun shall be at most $8in \times 8in$ in size.
Des 4.8.3−P	The spray gun shall be kept at a constant distance from the wall to ensure a consistent spray pattern.
Des 4.8.4−P	The spray gun shall have a trigger mechanism which can be manipulated by mechanical means.
Des 4.8.5−P	The spray gun shall be responsive when triggered or released, having very little delay time between active and inactive states.
Des 4.8.6−F	The spray gun will require a compressor which can be autonomously turned on and off by the robot.

Efficiency in PaintBot's operation in regards to both time and energy is a very important aspect of its design. In the prototype design stage, the team at PaintBot Inc. will search for a combination of spray paint gun and compressor that is able to produce sufficient coating with a width of at least 22.86 *cm* on each vertical iteration. This number was chosen based on the analysis of other spray paint guns that are currently on the market, making it appropriate for our application. Having an optimal spray width conserves energy and time as the pulley system is required to perform less passes/iterations. Figure 4.10 provides a visual description of the spray pattern that the team will seek to achieve.

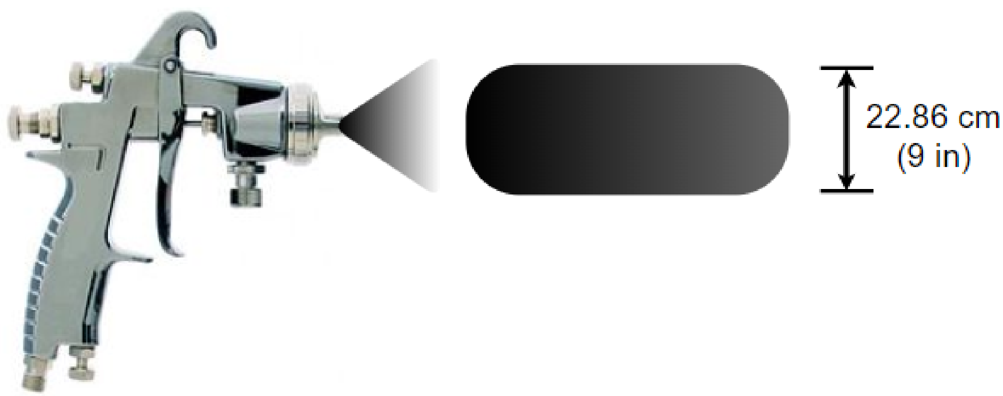


Figure 4.10: Spray Pattern

4.9 Tower Casing

Table 4.5: Cylindrical Case Requirements [2]

Des 4.9.1–P	The case shall be the same height (2.5 feet) as PaintBot.
Des 4.9.2–P	The case shall cover any component that is sensitive to air-born paint particles while not obstructing the spray pattern or movement of the paint head.
Des 4.9.3–P	The case shall be opaque to occlude the interior components.
Des 4.9.4–P	The case shall have easy to access openings for cleaning, adjustments, or maintenance purposes.
Des 4.9.5–F	The case shall be adequately ventilated to ensure that the operating temperature does not exceed the limit of the internal components and materials.

To hide PaintBot's interior while providing an elegant and professional appearance, an enclosing cylindrical case will be included in the prototype iteration. It is important to make sure that this enclosure does not interfere in any way with the users since minor adjustments, such as paint re-filling and compressor maintenance, are to be expected. This is precisely the reason why PaintBot will store these crucial components in easy to access locations. The material that will be used for the casing has not been definitively chosen, however the characteristics that we are prioritizing are light weight and durability. Aluminum, as in the construction of the base, may be a good choice. Figure 4.11 illustrates the appearance of the tower casing.

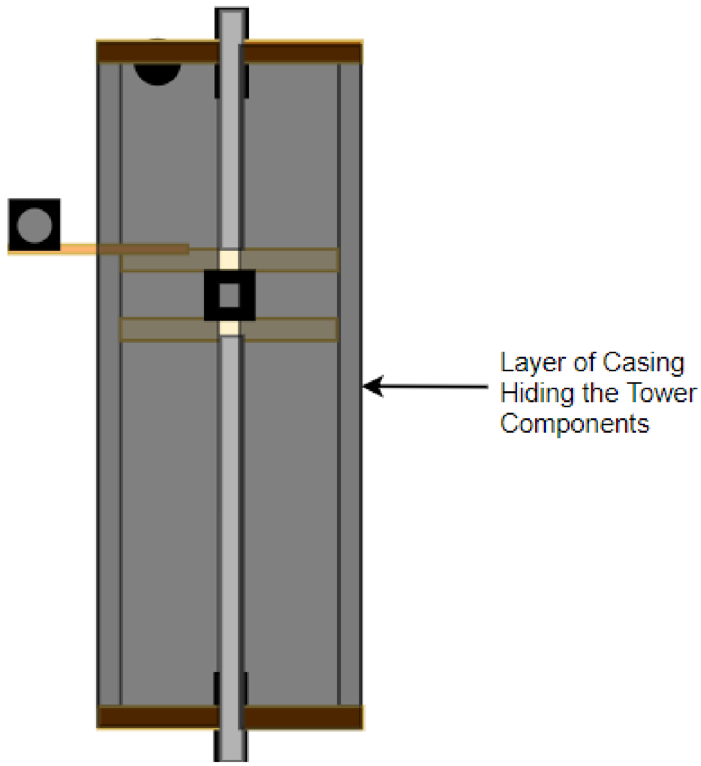


Figure 4.11: Tower Casing Appearance

To ensure that the mass estimates presented in Section 2.4 are not greatly exceeded as a result of the introduction of this casing, its mass will be estimated using the parameters provided in Table 4.6.

Table 4.6: Parameters for Casing Mass Estimate

Parameter	**Value**
Density of Aluminum (ρ_{al})	$2.70\ g/cm^3$
Diameter of Casing (d_c)	$35\ cm$
Height of Casing (h_c)	$60\ cm$
Thickness of Casing (t_c)	$0.1\ cm$

From Table 4.6, the mass of the casing, m_c, can be computed as:

$$m_c = \pi \cdot d_c \cdot h_c \cdot t_c \cdot \rho_{al} = \pi \cdot 35\ cm \cdot 60\ cm \cdot 0.1\ cm \cdot 2.70\ g/cm^3 = 1781\ g \tag{4.8}$$

which is an insignificant increase (7.78%) over the previous mass estimate (22.9 kg).

5 Object Detection System

5.1 Wall Camera

Table 5.1: Wall Camera Requirements [2]

Des 5.1.1–P	The camera will support a resolution of at least 8×10^6 pixels.
Des 5.1.2–P	The camera will support a framerate of at least 30 Hz.
Des 5.1.3–P	The camera will be mounted at the same height as the spray gun, offset by the strip width in the direction of motion.
Des 5.1.4–P	The camera will be compatible with the Raspberry Pi Model B+.
Des 5.1.5–P	The camera will be able to accurately identify tape used to mask objects from a distance 1+ meter.

As shown in Figure 5.1, a Raspberry Pi V2 digital camera will be used to allow robust, yet configurable detection of tape used for masking. This camera will constantly update PaintBot, informing it of boundaries for painting areas. The camera will be mounted on an arm attached to the tower (Figure 4.1), extending a full strip length ahead of the robot in the direction of travel.

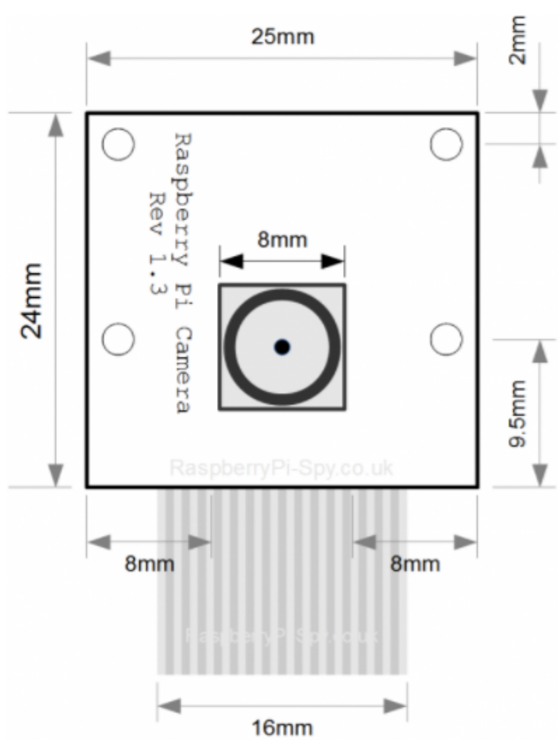
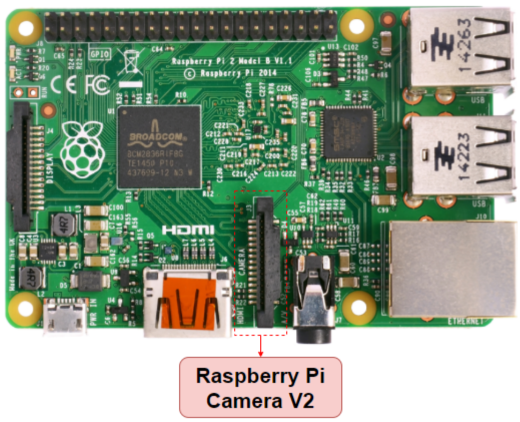


Figure 5.1: Raspberry Pi Camera V2 [26]

The wall camera will be attached to the Raspberry Pi Model B+'s camera serial interface connector, shown in Figure 5.2, with a 16 mm wire strip.



Specification	Value
Dimensions	$24.89 \times 22.86 \times 8.89$ mm
Weight	3 g
Resolution (pixels)	1440×1080 Video 3280×2464 Static Images
Sensor Size	3.674×2.760 mm
Angle of View	$62.2 \times 48.8°$
Power Requirements	3.3V DC
Operating Temperature	-40 to 85 °C

Figure 5.2: Raspberry Pi Model B+ & Camera Dimensions [27]

As detailed in Figure 5.3, when PaintBot paints a column, the offset camera will be scanning the following column for Strip1, and its closing strip, Strip2.

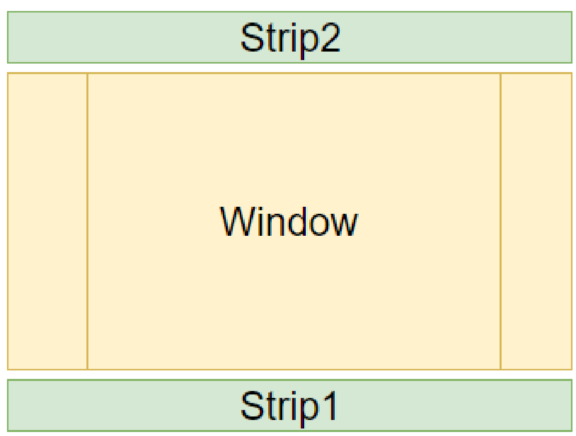


Figure 5.3: Window Masking

For object detection purposes, the camera will be located between 40 $cm - 1\ m$ from the wall. To identify tape strips used for masking, a camera whose resolution is 8×10^6 pixels (with $3,280 \times 2,464$ pixel static image resolution) will be implemented. Once PaintBot's leading camera comes upon these tape strips it will send control signals back to calculate the distance between them as:

$$d_{strips} = \text{Strip2} - \text{Strip1} \tag{5.1}$$

With this distance stored internally, PaintBot will be able to start/stop painting as needed - avoiding areas not to be painted.

Resolution Calculations

Based on the specifications given in Figure 5.2 on the previous page, we can determine the resolution at the wall of the camera - that is, the physical dimensions on the wall covered by each pixel. This will allows us to estimate the minimum size for any objects that are required for the camera to detect and discern from the wall.

From the dimensions of the sensor:

$$3.674 \times 2.760\ mm = w_{sensor} \times h_{sensor} \tag{5.2}$$

And the angle of view:

$$62.2^\circ \times 48.8^\circ = a_w \times a_h \tag{5.3}$$

We can calculate the dimensions of the view size at the wall as:

$$w_{wall} = w_{sensor} + 2 \cdot distance_{sensor-wall} \cdot tan(a_w) \tag{5.4a}$$

$$h_{wall} = h_{sensor} + 2 \cdot distance_{sensor-wall} \cdot tan(a_h) \tag{5.4b}$$

PaintBot's prototype iteration will maintain a uniform distance (40 cm) from the sensor to the wall that is approximately equal to the distance from the paint gun head to the wall. Thus, this distance can be used to give:

$$w_{wall} = 3.674\ mm + 2 \cdot 400\ mm \cdot tan(62.2^\circ) = 1,521.01\ mm = 152.10\ cm \tag{5.5a}$$

$$h_{wall} = 2.760\ mm + 2 \cdot 400\ mm \cdot tan(48.8^\circ) = 916.59\ mm = 91.66\ cm \tag{5.5b}$$

Now that we have the dimensions of the camera's view at the wall, we can determine the size of individual pixels based on the camera resolution for both video ($1,440 \times 1,080$ pixels), of aspect ratio $4:3$, and still images ($3,280 \times 2,464$ pixels).

Video

$$min\_pixel\_width_{video} = \frac{w_{wall}}{resolution_{width}} = \frac{1,521.01\ mm}{1,440} = 1.0563\ mm \tag{5.6a}$$

$$min\_pixel\_height_{video} = \frac{h_{wall}}{resolution_{height}} = \frac{916.59\ mm}{1,080} = 0.8487\ mm \tag{5.6b}$$

Still Image

$$min\_pixel\_width_{image} = \frac{w_{wall}}{resolution_{width}} = \frac{1,521.01\ mm}{3,280} = 0.4637\ mm \tag{5.7a}$$

$$min\_pixel\_height_{image} = \frac{h_{wall}}{resolution_{height}} = \frac{916.59\ mm}{2,464} = 0.3720\ mm \tag{5.7b}$$

It is important to note that for the video calculations, the results are a slight underestimate as the video mode crops the area of the sensors used. This produces smaller sensor dimensions and therefore leads to a reduced angle of view. The team at PaintBot Inc. did not consider cropping, as much more complicated calculations are needed and only minor deviations from the pixel dimensions calculated above will be obtained. These deviations are insignificant as the dimensions of the tape required to mask objects are orders of magnitude larger than the ones calculated currently.

5.2 Machine Learning

Table 5.2: Machine Learning Requirements [2]

Des 5.2.1−P	The images obtained from the wall camera (Section 5.1) will be re-sized to 128 × 128 pixels.
Des 5.2.2−F	A built-in machine learning pre-trained architecture will detect the edges present in the images.
Des 5.2.3−F	The architecture should be accurate enough to effectively detect objects of similar dimensions to standard wall tape.

The team at PaintBot aims to implement an on-board machine learning algorithm capable of detecting objects in an accurate and efficient manner. In recent years, machine learning architectures began to outperform humans while setting the bar high at the ImageNet Large Scale Visual Recognition Challenge (ILSVRC) [28] - the golden standard of computer vision data-sets. Incorporating a pre-trained architecture will give PaintBot an edge over its competitors and appeal to the market.

A sample of edge detection results that can be achieved using machine learning architectures is shown in Figure 5.4.

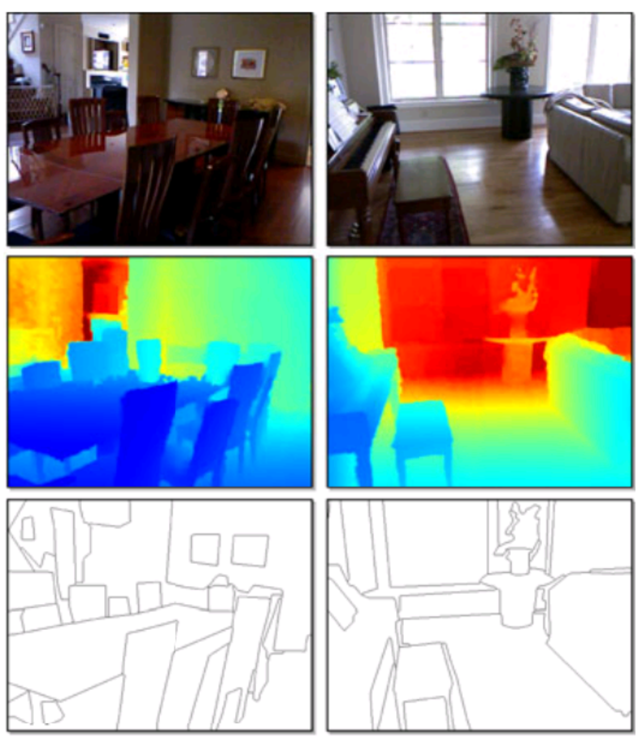


Figure 5.4: Machine Learning Edge Detection [29]

6 Power Distribution System

6.1 Power Supply

Table 6.1: Power Supply Requirements [2]

Des 6.1.1–P	The power source shall provide a 12 V DC rail.
Des 6.1.2–P	The power source shall provide a 5 V DC USB rail.
Des 6.1.3–P	The power source shall supply 50 W at 12 V DC.
Des 6.1.4–P	The power source shall be rechargeable, having a capacity in excess of 100 watt-hours (Wh).

In this section the power requirements of PaintBot's prototype iteration will be evaluated, driving the selection of a rechargeable DC power supply. Table 6.2 lists the parameters which allow an accurate estimation of the power consumed by the stepper motors utilized in the drive and pulley systems.

Table 6.2: Stepper Motor Power Parameters [5]

Parameters	**Value**
Phase Winding Resistance (R_{phase})	30 Ω
Maximum Rated Current (I_{max})	0.4 A

The maximum possible power draw from the 12 V DC rail due to the 9 stepper motors is given by:

$$P_{drive,max} = 9 \cdot R_{phase} \cdot I_{max}^2 = 9 \cdot 30\ \Omega \cdot (0.4\ A)^2 = 43.2\ W \tag{6.1}$$

However, this represents an unrealistic maximum; at most, 4 of the 9 motors will be simultaneously active. Additionally, stepper motors experience a reduction in power draw while in motion due to the back-EMF induced in the active phase. As a result, a conservative estimate for typical power draw is given as the maximum for 4 of our 9 motors.

$$P_{drive,typ} = 4 \cdot R_{phase} \cdot I_{max}^2 = 4 \cdot 30\ \Omega \cdot (0.4\ A)^2 = 19.2\ W \tag{6.2}$$

The power draw on the 5V DC USB rail due to the utilized control units, namely a Raspberry Pi and 2 Arduino Uno boards, must also be considered. Estimates of maximum current draw for these units are listed in Table 6.3, on the following page.

Table 6.3: Controller Power Parameters [30, 31]

Specification	Value
Raspberry Pi Max Current (I_{Rpi})	1.2 A
Arduino Uni Max Current (I_{Ard})	0.2 A

The estimated maximum power for the control units can then be computed as:

$$P_{ctrl} = (5\ V)(I_{Rpi} + 2 \cdot I_{Ard}) = (5\ V)(1.2\ A + 2 \cdot 0.2\ A) = 8\ W \tag{6.3}$$

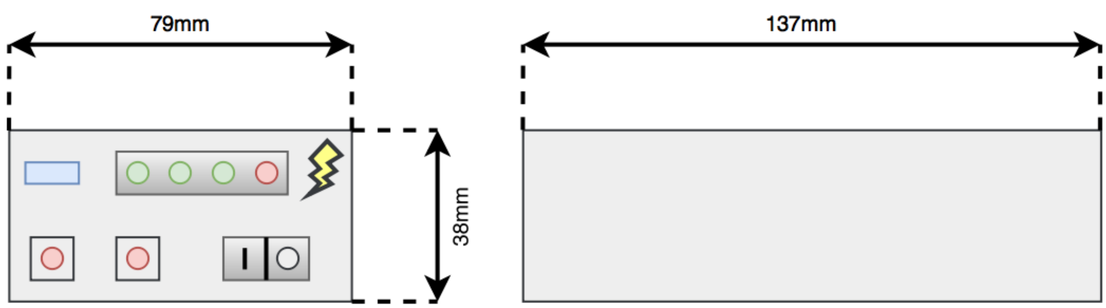
Thus, a conservative estimate for typical power draw is:

$$P_{total,typ} = P_{drive,typ} + P_{ctrl} = 19.2\ W + 8\ W = 27.2\ W \tag{6.4}$$

and an upper bound for worst case power draw is:

$$P_{total,max} = P_{drive,max} + P_{ctrl} = 43.2\ W + 8\ W = 51.2\ W \tag{6.5}$$

The above-mentioned estimates dictated the selection of a power supply unit with the specifications and appearance given in Figure 6.1. This power supply provides both a 12 V DC and 5 V DC USB rails as required. Additionally, it is able to supply sufficient power through these rails to exceed above conservative estimates. Finally, its capacity of 100 Wh will allows for operational times of nearly 4 hours, based on the estimate $P_{total,typ}$.



Specification	Value
12 V Maximum Current	6 A
5 V Maximum Current	2 A
Maximum Power Output	72 W
Energy Capacity	100 Wh
Mass	682 g

Figure 6.1: Power Supply [32]

6.2 Wiring

Table 6.4: Wiring Requirements [2]

Des 6.2.1−P	A 12 V DC supply line and ground line shall connect all DC motors to the power supply.
Des 6.2.2−P	A 5 V DC USB - Micro USB line shall connect low power components to the power supply.
Des 6.2.3−P	All wires shall be well insulated, with appropriate material.
Des 6.2.4−P	Wiring shall be organized and clamped down.

We require the connection of our DC stepper motors to the 12 V DC and ground rails of the power supply. Additionally, a 5 V DC USB connector shall bridge the Raspberry Pi and Arduino to the power supply. Wires will be colour-coded, placed in an organized manner and clamped down tight to the chassis, as illustrated in Figure 6.2.

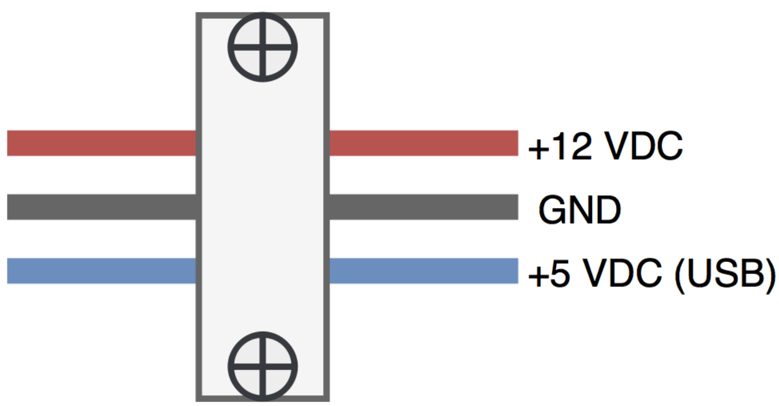


Figure 6.2: Wiring Appearance

Safety

The team at PaintBot Inc. believes that following proper electrical wire conventions will provide an extra layer of security to PaintBot's users. In addition, the above-mentioned wiring scheme serves to improve the design's overall aesthetic appeal, increase user understanding and minimize the risk of wires catching/slipping during PaintBot's operation or movement. Although the voltages being distributed are low, all wires will be thoroughly insulated to further mitigate any conceivable fire or electrocution hazards.

7 Top Level Controller System

PaintBot requires for multiple processes to be synchronized, more specifically: the base position/orientation, paint application, and object detection.

These control processes will operate in real-time for PaintBot's PoC iteration. However, the object detection process will be designed such that they are one cycle ahead of the spray paint gun for PaintBot's prototype and the final product iterations.

The inputs gathered from these processes will be stored in a control signal array inside the computing unit's memory (Raspberry Pi B+). These input signal dictate the next stages of system control for the paint application system (Section 4).

Figure 7.1 illustrates the top-level behavior that PaintBot will be designed to follow.

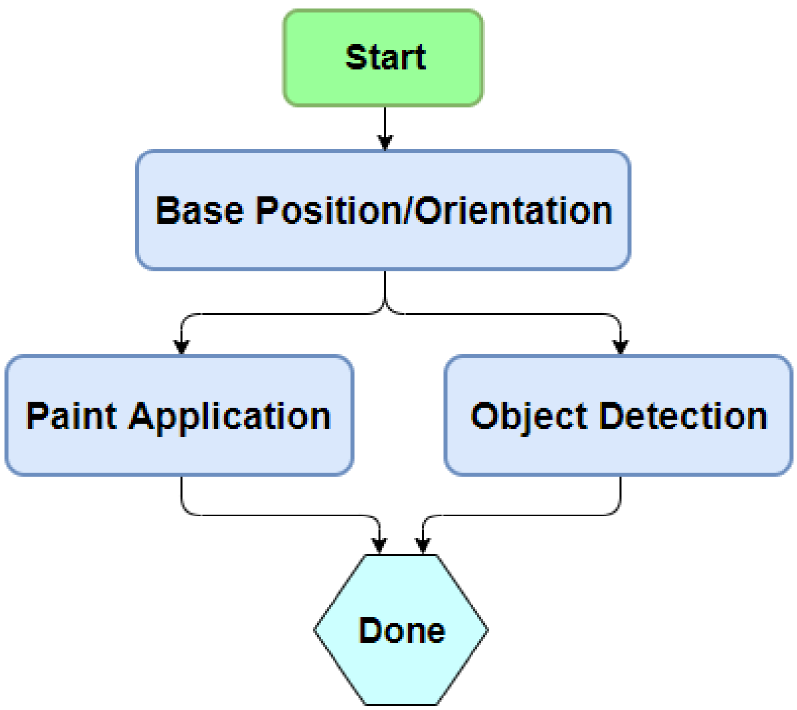


Figure 7.1: PaintBot's Top Level Controller Algorithm

The room painting process begins at the block labelled "Start". It is essential that the base is properly oriented in the room, at a specific distance from the wall, before any paint is sprayed. Thus, the base position/orientation algorithm (Figure 3.2) gets initiated first, allowing PaintBot's sensors to provide reliable readings. This algorithm requires the time averaged readings from PaintBot's front and side base sensors (Figure 3.1).

7.1 Base Position/Orientation

As seen in Figure 7.2, the front sensors are given precedence over the side sensors as PaintBot first seeks to avoid forward collisions. All of the 4 orientation cases mentioned in Figure 3.2 are now tested, one by one. Note that only 2 of these cases are shown in Figure 7.2, as indicated by the first 2 decision nodes.

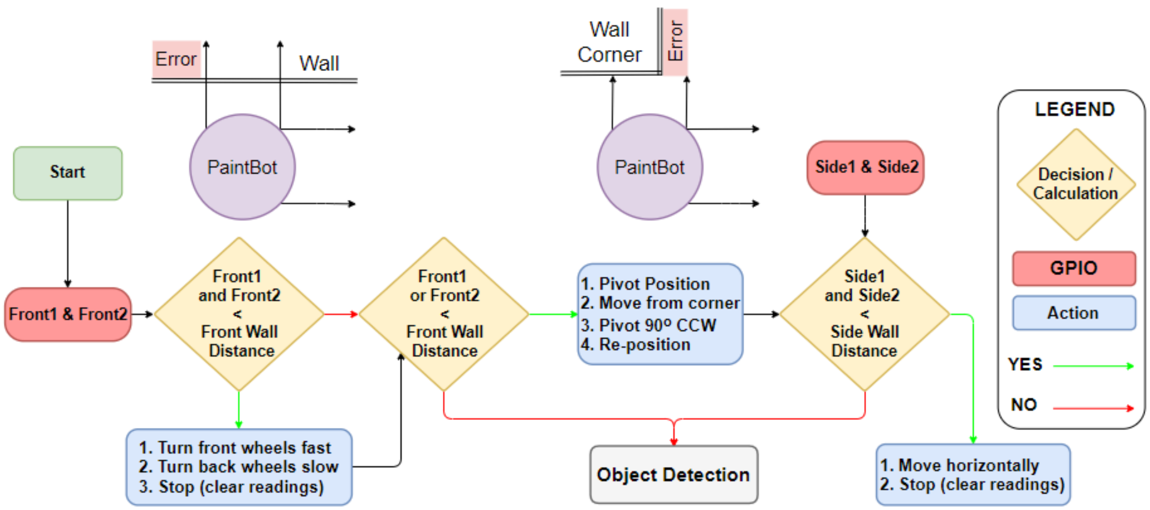


Figure 7.2: Base Position/Orientation

For example, decision node one discusses the case where the readings from the front sensors are both less than the front wall distance. This is identical to case 3.2c and thus PaintBot performs the corresponding procedure. Once a correction is completed or if no correction is needed for a given case, PaintBot checks the next case (second decision node) until all the cases were checked/corrected.

Once all the front sensor cases are checked/corrected, PaintBot begins checking the side sensor cases (third decision node). If both sensor readings indicate that the side wall is too close, PaintBot moves horizontally (away) from the side wall until the sensor readings become reliable again.

When PaintBot finishes positioning/orienting itself in the room, the paint application and object detection algorithms begin in parallel. Now PaintBot is able to autonomously paint the room and and understand which objects should be avoided. As mentioned in this document and in PaintBot Inc.'s requirement specification document [2], these objects will be masked by the users prior to the room painting process, aiding PaintBot recognize them more accurately.

7.2 Paint Application & Object Detection

While painting the room, PaintBot will continuously monitor the room's contents using the object detection algorithm. This algorithm performs a look-ahead sweep with the camera (Figure 5.1), searching for masked areas which indicate position/objects that are not to be painted. A visual description of the paint application and object detection algorithms is shown in Figure 7.3.

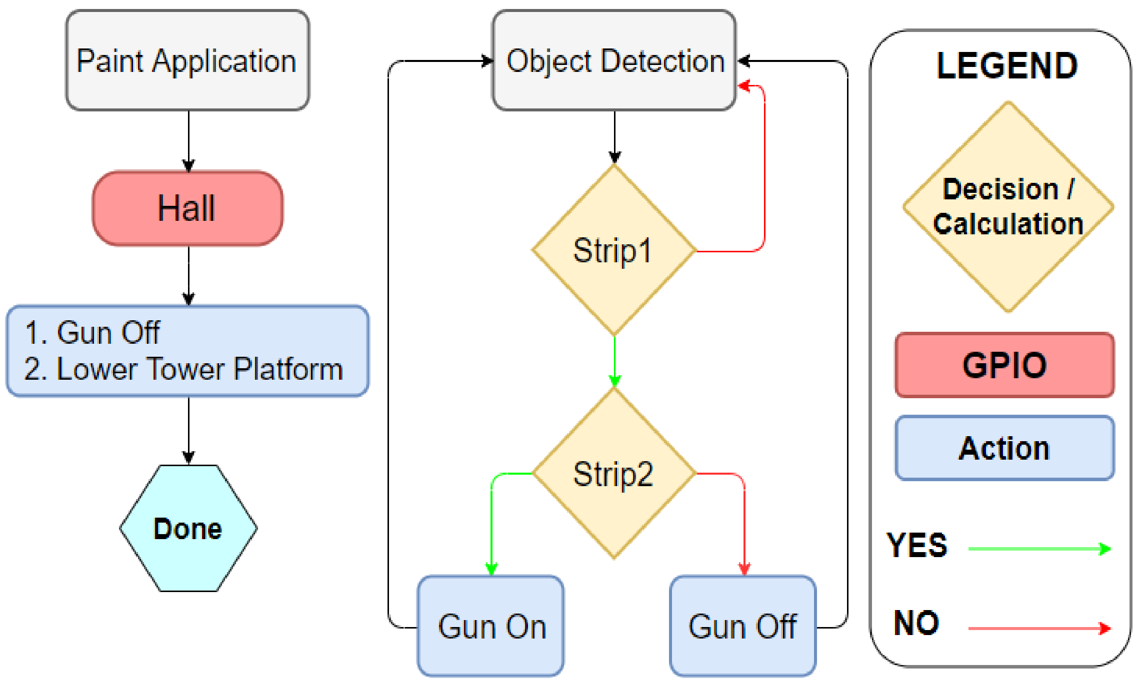


Figure 7.3: Paint Application & Object Detection

As indicated in Section 5.1, the first tape strip (Figure 5.3) encountered is marked as "Strip1", and will indicate the start of the detected area's boundary. The spray paint gun which is located on the tower head will continue spray painting the wall as it moves upwards, and the camera will look for "Strip2".

The relative positions of the two strips will be saved in memory. Note that when a room is masked properly, there may be many more tape strips whose locations and boundaries need to be stored using the same process outlined above. The tower will continue moving up until reaching its maximum extendable height, where the hall effect sensor (Figure 4.2) is triggered. This GPIO signal is labelled "Hall" in Figure 7.3 and it instructs PaintBot to do the following operations:

1. The spray paint gun needs to disabled;
2. The tower platform needs to be lowered.

At this point, a single iteration of PaintBot's painting process is complete and the following occurs:

1. The spray paint gun is disabled;
2. The tower platform is lowered;
3. The base is translated to the position of the next vertical strip;
4. The next coating pass (iteration) begins.

During the application of the paint coat to this subsequent vertical strip, the paint gun's activation will depend on the boundaries stored from the previous iteration. This process continues until PaintBot has spray painted the entire room. Once PaintBot reaches the end of the room, it turns off the spray paint gun and backs away from the wall. For PaintBot's prototype and final product iteration, this is the moment where it will notify the users that the painting process is complete through the status display screen.

8 Conclusion

This document encompasses detailed design plans for PaintBot as a whole, as well as for each of its subsystems. Chosen components and implementation decisions are justified through the calculations and analysis of corresponding materials. Additionally, the document discusses design alternatives that were considered for several crucial systems, such as the paint application and drive mechanism.

Below is a summary of each subsystem described throughout the document:

1. **Drive System**
    - Establishes the dimensions of PaintBot's base and details its components.
    - Specifies how PaintBot will travel throughout the room.
2. **Base Position/Orientation System**
    - Describes the locations of the ultrasonic rangefinders on PaintBot's base.
    - Outlines how PaintBot will maintain a steady distance from a wall.
3. **Paint Application System**
    - Describes how the spray paint gun will be translated vertically.
    - Computes the amount of torque needed to actuate the pulley mechanism.
4. **Object Detection System**
    - Specifies PaintBot's algorithm for detecting areas that are not to be painted.
    - Describes the potential of integrating machine learning into the detection process.
5. **Power Distribution System**
    - Includes the calculation of the power required to operate PaintBot.
    - Outlines the components that will distribute power within PaintBot.
6. **Top Level Controller System**
    - Mentions the algorithms/logic that PaintBot will use to operate successfully.

This design specification document will serve as a technical guideline for PaintBot Inc. as the team enters the prototyping stage of the project. It is important to note that this shall be a living document - as PaintBot evolves, any deviations from the stated design specifications will be logged accordingly.

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A Test Plan

PaintBot's main purpose is to automate the process of painting a room, thus certain performance criteria must be met to ensure that a system failure will not lead to potential injury/property damage. To maximize the efficiency and validity of the performance test cases, PaintBot Inc. members will verify the functionality of PaintBot's individual components. Table A.1 illustrates the proposed test plan scheme.

Table A.1: PaintBot's Proposed Test Plan Scheme

Mechanical		
1. Drive System - Rotation		
Turn on the DC motors and vary the horizontal shift using the servo-motors.		
Expected Outcome		
Wheel rotate at $10 - 20$ revolutions per minute (RPM) and can shift up to $\pm 180°$ in the horizontal direction to provide steering abilities.		
Actual Outcome/Comments		
Initials:	**Date:**	**Pass|Fail**
2. Drive System - Torque		
Let the wheels rotate (using the DC motors) and increase the load on the base to 25 kg.		
Expected Outcome		
With a full load put on the base, the DC motors produce a drive torque of at least 0.138 Nm (Equation 2.4).		
Actual Outcome/Comments		
Initials:	**Date:**	**Pass|Fail**
3. Tower Support Rails		
Once in position on the base, apply light pressure to the tower structure from each one of the fours sides.		
Expected Outcome		
The tower structure remains steady and internal components are not compromised in any way.		
Actual Outcome/Comments		
Initials:	**Date:**	**Pass|Fail**

4. Paint Delivery		
With the paint reservoir and compressor system prepared, turn on the compressor and engage the trigger mechanism.		
Expected Outcome		
No leakage occurs and the compressor turns off once the paint reservoir only contains 5% of the original volume.		
Actual Outcome/Comments		
Initials:	**Date:**	**Pass|Fail**

5. Cylindrical Case (Enclosure)		
Mount the enclosure onto the base and check all openings to ensure ease of access to the main components/features.		
Expected Outcome		
Main features, such as the paint reservoir and compressor, can be adjusted/fixed within $5 - 30$ seconds.		
Actual Outcome/Comments		
Initials:	**Date:**	**Pass|Fail**

Hardware

1. Ultrasonic Rangefinders		
Once the ultrasonic rangefinders are in place, position PaintBot within 1 meter away from a wall and let the rangefinders measure the distance.		
Expected Outcome		
Sensor measurements are within $\pm 5\%$ of actual distance when at most 1 meter away from the wall being measured.		
Actual Outcome/Comments		
Initials:	**Date:**	**Pass|Fail**

2. Buttons & Switches		
Press the green ("on") button, let PaintBot work for 2 minutes and press the red ("emergency stop") button.		
Expected Outcome		
Once turned on PaintBot starts painting the room strip by strip. When the user presses the red button, all operations halt within $1 - 3$ seconds.		
Actual Outcome/Comments		
Initials:	**Date:**	**Pass|Fail**

3. Pulley System Motors		
Once tower and pulley systems are constructed, turn on the pulley's DC motor after assigning a specific vertical direction (up or down) and measure the movement speed.		
Expected Outcome		
The spray gun head moves with the pulley in the vertical direction at a constant rate of 1 ft/s.		
Actual Outcome/Comments		
Initials:	**Date:**	**Pass|Fail**

4. Wall Camera		
Turn one the mounted camera and capture images while PaintBot "paints" 2 consecutive strips on the wall. This can be simulated without using any paint.		
Expected Outcome		
The camera captures images of the wall at a frame-rate of 30 Hz with a resolution of 1.56×10^6 pixels.		
Actual Outcome/Comments		
Initials:	**Date:**	**Pass|Fail**

5. Paint System		
Maintaining a constant distance from the wall, engage the trigger mechanism for 30 seconds. Allowing a 15 second cool down period and repeat 4 times in a row (total of 3 minutes).		
Expected Outcome		
A delay time of less than 250 ms when trigger mechanism changes states. When trigger is engaged, the paint pattern is at least a 9 in wide strip.		
Actual Outcome/Comments		
Initials:	**Date:**	**Pass|Fail**

Electrical		
1. Power Supply		
Turn on the power supply/generator and measure the voltage at the output (supplied to PaintBot) for both main (DC) and USB rails.		
Expected Outcome		
For main rails the voltage is 12±0.5 V. For USB rails the voltage is 5±0.25 V.		
Actual Outcome/Comments		
Initials:	**Date:**	**Pass|Fail**

2. Wiring		
Check that all wires are appropriately insulated and organized/clamped down in a safe manner.		
Expected Outcome		
Wires are insulated such that the amount of exposed bare wire is minimal. Wires are organized as follows: • A 12V DC supply and ground line connects all DC motors to the power supply (expect 3 wires in total, as pictured in Figure 6.2). • A 5V USB (Micro USB) line connects all low power components, such as the Arduino and Raspberry-Pi microprocessors, to the power supply.		
Actual Outcome/Comments		
Initials:	**Date:**	**Pass|Fail**

Software		
1. General - Pulley Stops		
While PaintBot paints the room, use a wooden ruler to interrupt the pulley mechanism by preventing the spray gun head from moving for 5 seconds.		
Expected Outcome		
PaintBot continues to paint the same spot without moving around the room and informs the user through the main display about the issue. PaintBot stops painting if the issue is not resolved within 3 seconds.		
Actual Outcome/Comments		
Initials:	**Date:**	**Pass|Fail**

2. General - Occluded Sensor Readings		
Position PaintBot more than 1.5 meters away from the wall to be painted and turn it on.		
Expected Outcome		
PaintBot moves forward to obtain clear distance readings from the wall to be painted. The trigger mechanism remains disengaged until clear readings are obtained and PaintBot positions itself properly.		
Actual Outcome/Comments		
Initials:	**Date:**	**Pass|Fail**

3. Machine Learning		
Place PaintBot near windows/outlets (mask these objects with wall tape as needed) and turn it on to start painting the room.		
Expected Outcome		
Objects detected in the 128×128 down-sampled images captured by the wall camera are avoided (using a machine learning architecture).		
Actual Outcome/Comments		
Initials:	**Date:**	**Pass|Fail**

Additionally, once each of the individual components meet ("Pass") the criteria outlined in Table A.1, the final product will be constructed and key functional performance requirements will be confirmed. For PaintBot's final product iteration to successfully complete this secondary testing stage it must possess/demonstrate the following:

1. Once positioned in place and turned on (green button is pushed), begin painting the room strip by strip. Each strip gets an "up" and "down" coating pass.
2. Analyze the room one strip in advance of the current strip using a camera to detect any objects "masked" with wall tape.
3. Once an object is encountered disengage the trigger mechanism to stop painting (obstacle avoidance).
4. When reaching the last strip (indicated by user) stop painting, back up from the wall, and shut down.
5. If placed far from the wall to be painted, re-adjust position and begin painting once proper placement is achieved.
6. In the unlikely event that the pulley system gets stuck, display a message to the user and stop painting if the issue is not resolved within 3 seconds.
7. If - at any moment - the user presses the emergency stop button (red), stop all processes immediately (instant shut down).

ENSC 405W Grading Rubric for User Interface Design

(5-10 Page Appendix in Design Specifications)

Criteria	Details	Marks
Introduction/Background	Appendix introduces the purpose and scope of the User Interface Design.	**/05%**
User Analysis	Outlines the required user knowledge and restrictions with respect to the users' prior experience with similar systems or devices and with their physical abilities to use the proposed system or device.	**/10%**
Technical Analysis	Analysis in the appendix takes into account the "Seven Elements of UI Interaction" (discoverability, feedback, conceptual models, affordances, signifiers, mappings, constraints) outlined in the ENSC 405W lectures and Don Norman's text (*The Design of Everyday Things*). Analysis encompasses both hardware interfaces and software interfaces.	**/20%**
Engineering Standards	Appendix outlines specific engineering standards that apply to the proposed user interfaces for the device or system.	**/10%**
Analytical Usability Testing	Appendix details the analytical usability testing undertaken by the designers.	**/10%**
Empirical Usability Testing	Appendix details completed empirical usability testing with users and/or outlines the methods of testing required for future implementations. Addresses safe and reliable use of the device or system by eliminating or minimizing potential error (slips and mistakes) and enabling error recovery.	**/20%**
Graphical Presentation	Appendix illustrates concepts and proposed designs using graphics.	**/10%**
Correctness/Style	Correct spelling, grammar, and punctuation. Style is clear concise, and coherent. Uses passive voice judiciously.	**/05%**
Conclusion/References	Appendix conclusion succinctly summarizes the current state of the user interfaces and notes what work remains to be undertaken for the prototype. References are provided with respect to standards and other sources of information.	**/10%**
CEAB Outcomes: Below Standards, Marginal, Meets, Exceeds	1.3 Engineering Science Knowledge: 4.1 Requirement and Constraint Identification: 5.4 Documents and Graphic Generation: 8.2 Responsibilities of an Engineer:	

B User Interface Design

B.1 Introduction

PaintBot Inc. strives to create a robot, namely PaintBot, that automates the laborious process of interior room painting. This automation gives rise to a User Interface (UI) which is simplistic in nature and requires only quick inputs from users.

"Truly elegant design incorporates top-notch functionality
into a simple, uncluttered form." -David Lewis

PaintBot's prototype iteration will contain the following main UI elements:

1. **On Button**
   Once PaintBot is positioned in place, the user will press this button (green) to turn it on and the room painting process will commence.
2. **Emergency Stop Button**
   In case of an emergency, this button (red) allows the user to turn PaintBot off immediately. Once pushed all operations cease instantly to prevent any human/property damage.
3. **Status Display Screen**
   During operation this screen immediately provides/updates PaintBot's status to the user. For example, if the pulley mechanism is not able to move, a warning indicating this issue is flashed to the user.

B.1.1 Purpose

This document aims to aid potential users in understanding PaintBot's main features and how to utilize them through its simple UI design. To achieve this, diagrams illustrating key UI design related concepts and component placements will be presented. These diagrams will be followed by brief descriptions explaining the reasoning behind each UI design choice.

B.1.2 Scope

As PaintBot is in its early design stages, this document will focus on the its Proof of Concept (PoC) and Prototype iterations. As a result, the following key topics will be discussed:

1. **User Analysis** (Section B.2)
   Looks into the required user knowledge for safe operation procedures. Additionally, clearly states any restrictions which the user needs to be aware of.

2. **Technical Analysis** (Section B.3)
   Presents the 7 crucial elements of any UI design/interaction, namely discoverability, feedback, conceptual models, affordances, signifiers, mappings, and constraints.

3. **Engineering Standards** (Section B.4)
   Lists specific engineering/safety standards that PaintBot's UI must adhere to in order to be a marketable product.

4. **Usability Testing** (Section B.5)
   Details both the analytical (designer perspective) and empirical (client perspective) usability testing/scenarios that PaintBot Inc. members need to consider.

B.2 User Analysis

Due to the associated cost and expected frequent use case, PaintBot's primary intended consumers are companies that get contracted for medium to large scale painting projects with some prior knowledge of the room painting process. When it comes to UI design, PaintBot's main goal is to avoid interfering with the common industry practices that are already well established. For example, the functionality of detecting areas that should not be painted only requires that users mask the corresponding area (as shown in Figure B.1), which is a common standard in the current manual painting process [33].

Figure B.1: Masking Procedure [33]

As mentioned above, PaintBot aims to automate as much of the painting process as possible. This drastically simplifies the UI components, making them both simple to understand and use for any potential end users - even those who possess minimal prior experience with robotic equipment.

To follow suit with the popular convention, the buttons for PaintBot's activation and emergency operation termination will be colored green and red, respectively, as shown in Figure B.2. This will allow users to easily distinguish between different functionality, preventing accidents from occurring. Furthermore, in PaintBot's final product iteration, a speed control switch (shown in Figure B.2) will be implemented to further separate the buttons, while providing extra functionality.

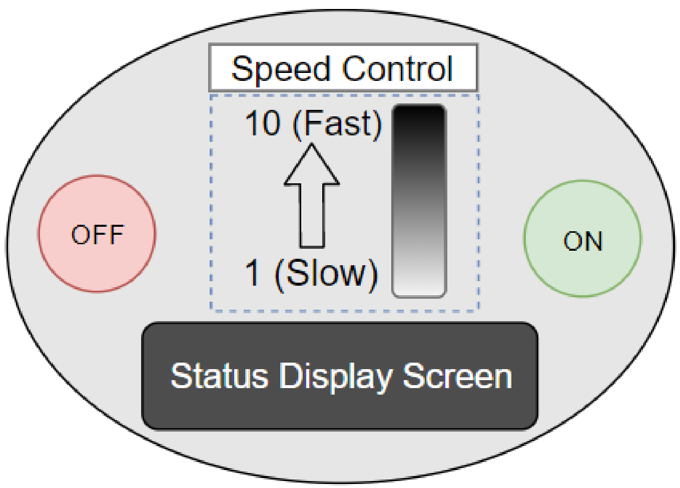


Figure B.2: User Interface Buttons & Switch

For long term operation, the user should also be aware of proper methods for refilling paint reservoirs and recharging batteries. Due to this, an instruction manual outlining key tasks for successful operation will be well documented and shipped along with the product. For PaintBot's final product iteration, when the paint or battery charge levels fall below their corresponding thresholds, all users will be notified through PaintBot's status display screen (shown in Figure B.2).

Additionally, as PaintBot is designed to paint rooms, it will naturally be moved around in small spaces with low overhead clearance. To ensure that it can be easily pass any overhead clearance, the final product iteration will contain handles which allow users to easily lower PaintBot to the ground (horizontally). Due to the fact that PaintBot will weigh approximately 25 kg, this task will require 1 – 2 users. PaintBot Inc. recommends that 2 users perform this task, each holding the side handles.

B.3 Technical Analysis

This section of the report will describe how PaintBot's UI complies with Don Norman's "Seven elements of UI Interaction" [34], namely discoverability, feedback, conceptual models, affordances, signifiers, mappings, and constraints.

B.3.1 Discoverability

Discoverability, sometimes referred to as learnability, specifies the ease with which a user is able to locate UI elements when they see a product for the first time [35]. PaintBot Inc. plans to provide high discoverability by minimizing the number of UI elements required for successful operation, thus simplifying the design.

PaintBot's control system will only consist of two buttons to specify the on/off state and the rest of the room painting requirements will be fulfilled internally using actuators. As shown in Figure B.2 on the previous page, the two buttons will be placed such that the user can easily see them to prevent accidentally triggering the wrong button.

B.3.2 Feedback

Feedback is a crucial consideration for any product that contains user interactions. In PaintBot's prototype iteration, a Light Emitting Diode (LED) will be utilized to indicate its active and inactive operation states, as shown in Figure B.3.

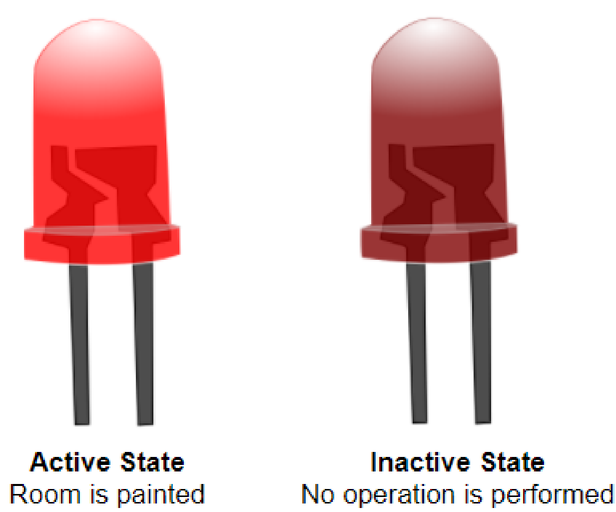


Figure B.3: LED Indicating Active & Inactive Operation States

For PaintBot's final product iteration, a status display screen (shown in Figures B.2 & B.4) will provide feedback regarding PaintBot's on/off state, as well as any other warnings that occur during the room painting operation. For example, the status display screen will alarm the users that the paint reservoir and battery charge levels are below the thresholds.

B.3.3 Conceptual Models

To have complete understanding and see the benefits of a product, users must intuitively understand how to use it. Conceptual models highlight/explain any hidden features to provide users with the understanding of key product operations. Figure B.4 shows PaintBot's overall conceptual model.

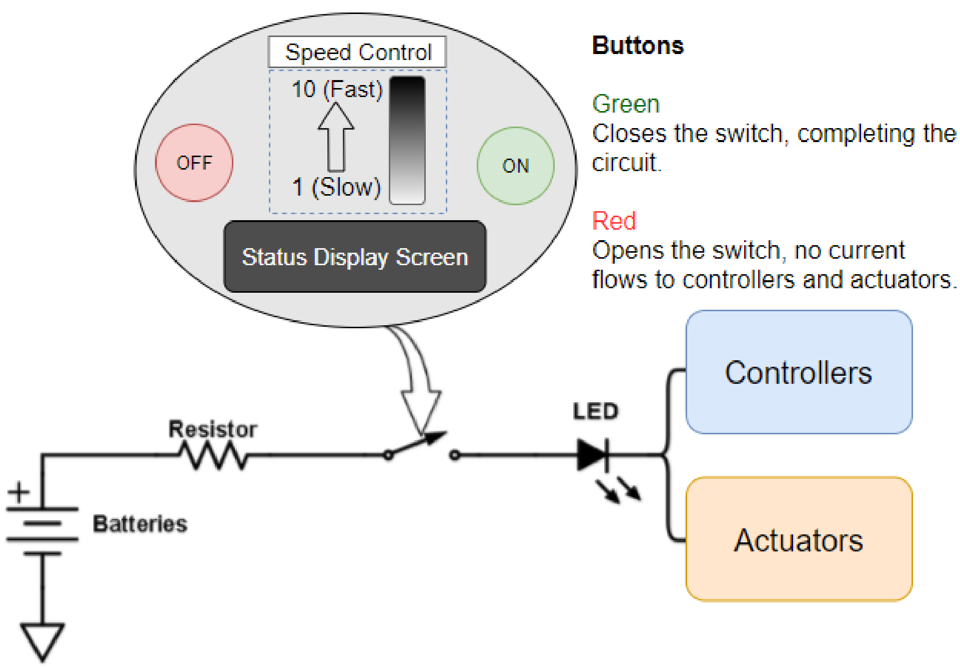


Figure B.4: UI Design - Conceptual Model

B.3.4 Affordances

A product's affordances specify its physical characteristics and how users can interact with it. PaintBot's UI design affords users the following key attributes:

1. **Limited Interaction**
   PaintBot fully automates the room painting process, affording users (room painting contractors) the ability to rest in between adjacent rooms after setup is complete.

2. **Quality**
   PaintBot uses a high quality spray paint gun along with precise algorithms, providing accurate coats of paint to each room. This minimizes the post processing operations that users need to perform.

3. **Precision**
   PaintBot's final product iteration will feature machine learning capabilities for object detection, further simplifying the setup process for users as the need for masking will be eliminated.

B.3.5 Signifiers

Signifiers are necessary when the perception from the affordances is not enough to notify the users on how to interact with the product's main elements. In addition to the LED (Figure B.3) and status display screen (Figure B.4), PaintBot will contain labels for various routine operations. For example, an arrow labelled "Paint Refill" will be visible to provide guidance to the users, as shown in Figure B.5.

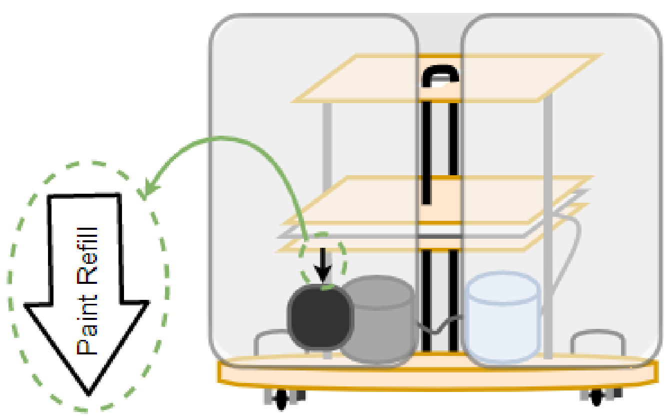


Figure B.5: Sample PaintBot Signifier

B.3.6 Mappings

Mapping takes into account UI element placement and intuitively indicates how these elements control various functionality of the product. As mentioned previously, PaintBot's activation and deactivation buttons along with the speed control switch (outlined in Figure B.2) follow conventional element mapping schemes, making them universally intuitive/understandable. Additionally, to prevent any confusion all wire connections are hidden inside PaintBot's enclosure.

B.3.7 Constraints

Constraints are the characteristics of UI elements that prevent users from performing unintended actions, forcing them to use the product appropriately. PaintBot's design forces the user to place the paint reservoir and compressor in areas that match their respective sizes.

Additionally, for PaintBot's final product iteration the activation/deactivation buttons will be protected by clear plastic casing. The users will need to prompt open these cases prior to pressing the buttons, forcing them to pay attention to their actions. This also prevents objects for accidentally triggering the buttons.

Furthermore, the universal battery recharging port will be covered with a rubber retractable case (Figure B.6) that must be lifted to plug in the power supply cord, adding a layer of security.

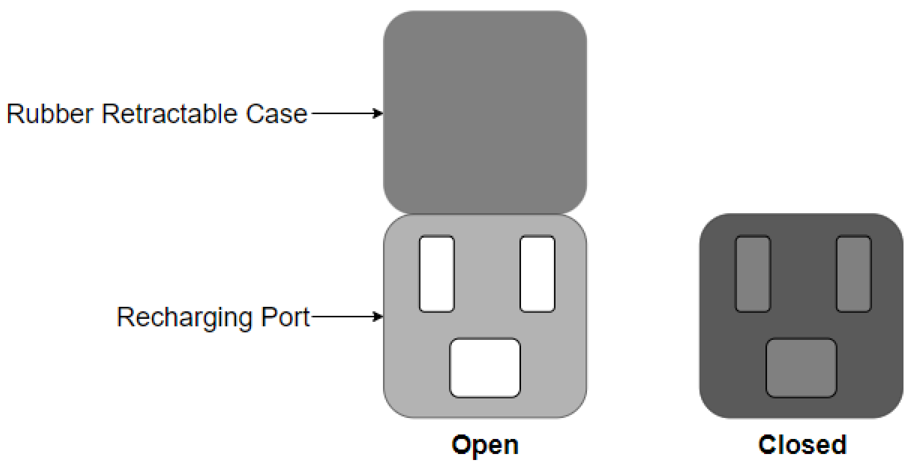


Figure B.6: Recharging Port - Rubber Retractable Case

B.4 Engineering Standards

To appeal to the market and offer optimal end user experience for all of the main interactions, such as activation and deactivation, PaintBot's UI design will be built by and tested against the following engineering standards:

1. **IEEE 1621-2004**
   IEEE Standard for User Interface Elements in Power Control of Electronic Devices Employed in Office/Consumer Environments [36].

2. **IEEE 1012-2012**
   IEEE Standard for System and Software Verification and Validation [37].

3. **ISO 9241-161-2016**
   Ergonomics of human-system interaction – Part 161: Guidance on visual user-interface elements [38].

B.4.1 Safety Considerations

Safety is the most significant aspect of any product's UI design. The team at PaintBot Inc. has considered various potential hazards that may impact the user, such as electrical shock while handling the batteries. To maximize user safety, PaintBot design stages shall meet the following standards:

1. **ANSI C 18.2M**
   Part 1-2013 American National Standard for Portable Rechargeable Cells and Batteries - General and Specifications [39].

2. **C22.2 NO. 0.23-15**
   General requirements for battery-powered appliances [40].

3. **NFPA (Fire) 70**
   Temperature thresholds for the electrical components [41].

B.4.2 Internal Rules

On top of these standards published by well established organizations, PaintBot's UI design will also adhere to the following rules:

1. The activation and deactivation buttons shall only become accessible after opening their clear plastic cover in order to minimize accidental triggering.

2. PaintBot's circuitry components shall be hidden internally from the environment to prevent contact with unwanted debris, such as paint particles.

3. PaintBot shall feature an alarm system to notify nearby users of any critical malfunctions and seize operation.

B.5 Usability Testing

Companies perform usability testing to gain further insight on potential difficulties users face when interacting with their product. This allows them to address any overlooked features before releasing their product into the market. The team at PaintBot Inc. will perform the usability testing phase in 2 different ways, namely analytically and empirically.

B.5.1 Analytical

In the analytical testing stage, the team at PaintBot Inc. will partake in a series of tests to discover any overlooked hazards or inconveniences present in PaintBot's UI. After all of the new issues have been documented, the team will then discuss possible suitable solutions to each problem and determine if the time and funding spent to address the issue will be worth the cost. The solutions that are selected will be implemented prior to PaintBot's market release. The following list summarizes the tests that PaintBot Inc. members will perform.

Activation & Deactivation States

1. The on/off buttons are under a transparent case that can be opened to access them.
2. The on/off buttons provide "physical" feedback when pressed down and let go.
3. The on/off buttons are located at highly visible area.
4. The on/off buttons are labeled with their corresponding functionality.
5. Once the green button is pressed, the LED is turned on representing PaintBot's active operation state.
6. Once the green button is pressed, PaintBot begins the room painting process within 10 seconds.
7. While PaintBot is active, pressing the red button will deactivate the painting process and turn off the LED within 3 seconds.

Paint Refill

1. The Paint refill station is easily accessible and no physical obstruction is present in the process of refilling.
2. The Paint refill station is properly labeled for increased visibility.

Battery Recharge

1. The recharging port is covered by a rubber retractable case that can be lifted.
2. The recharging port is not obstructed in any way to allow power cord access.
3. The recharging port is properly labeled for increased visibility.

Status Display Screen

1. The status display shows PaintBot's operation state and general information about the room painting process.
2. The status display alerts users when the battery charge level falls below the threshold.
3. The status display alerts users when the paint reservoir level falls below the threshold.
4. The status display alerts users when the circuitry operating temperature is above the threshold, stopping the room painting process if no action is taken within 3 seconds.

B.5.2 Empirical

In the empirical testing stage, PaintBot Inc. members will reach out to contracting companies/individual contractors that handle interior room painting projects. The users will then be asked perform a series of simple operations regarding PaintBot's functionality. The users will be supervised at all times, hence they must confirm their comfort with and understanding of the task at hand prior to being allowed to proceed. Lastly, PaintBot Inc. members will document any feedback the users provide about their experiences/interactions with PaintBot. The following list summarizes the functional exercises that the user will be asked to perform during the empirical usability testing stage.

Task 1
Activate PaintBot, wait 10 seconds, and deactivate it.

Questions

1. Was the activation & deactivation process intuitive?
2. Were you able to recognize that the LED turned on and off along with PaintBot?
3. When you pressed the activation button, did you receive sufficient feedback to know that PaintBot was on?

Task 2
Attempt to refill the paint reservoir.

Questions

1. Was the location of the paint reservoir easily identifiable and convenient to access?
2. Did the refilling process feel time consuming?

Task 3
Attempt to recharge the batteries.

Questions

1. Was the location of recharging port easily identifiable and convenient to access?
2. Did the recharging port appear sufficiently insulated and safe to use?

Task 4
Place PaintBot in a miniature apartment room model (provided by PaintBot Inc.) and then activate it.

Questions

1. Was the quality of the paint coat up to industry standards?
2. In comparison to an average painter, how fast/slow did PaintBot complete the task?
3. Do you have concerns that PaintBot is ill-suited to some apartment layouts?

After collecting a sufficient amount of feedback from the above experiments, PaintBot Inc. members will judge which features can be added or modified to satisfy the user's needs. Once all adjustments are made, PaintBot will be introduced to the market.

B.6 Summary

When a user first sees a product, the UI design can significantly influence their next course of action. Providing simple and intuitive UI elements in an elegant design which minimizes unintended use, will invite users to engage with the product.

For PaintBot's proof of concept iteration, its UI design will consist of the activation and deactivation buttons shown in Figure B.2. These buttons were assigned colors following universal conventions to prevent any confusion between different user groups. Furthermore, the buttons will be separated by sufficient distance to ensure users do not accidentally press the wrong one.

PaintBot's prototype iteration will incorporate the status display screen (Figure B.2) to provide users with valuable information regarding potential malfunctions/warnings. Additionally, an LED (Figure B.3) will be added to the UI design to indicated the active and inactive states of operation. This LED will be strategically positioned to allow the users to easily see it at all time.

PaintBot's final product iteration will feature a speed control switch (Figure B.2) to allow users to vary the rate at which the room is painted. In addition, the buttons will be covered with plastic cases to force users to pay attention when pressing the main buttons. Moreover, the rechargeable port will be covered with a retractable rubber case (Figure B.6) to add a layer of security.

Continuous improvements to the UI design will be integrated based on the market's overall response and as PaintBot generates feedback from its users. Ultimately, the team at PaintBot Inc. aims to keep PaintBot's UI design simplistic in nature, yet very effective and universally intuitive.

ENSC 405W Grading Rubric for ENSC 440 Planning Appendix

(5-10 Page Appendix in Design Specifications)

Criteria	Details	Marks
Introduction/Background	Introduces basic purpose of the project. Includes clear project background.	**/05%**
Scope/Risks/Benefits	Clearly outlines 440 project scope. Details both potential risks involved in project and potential benefits flowing from it.	**/10%**
Market/Competition/ Research Rationale	Describes the market for the proposed commercial project and details the current competition. For a research project, the need for the proposed system or device is outlined and current solutions are detailed.	**/10%**
Personnel Management	Details which team members will be assigned to the various tasks in ENSC 440. Also specifically details external resources who will be consulted.	**/15%**
Time Management	Details major processes and milestones of the project. Includes both Gantt and Milestone charts and/or PERT charts as necessary for ENSC 440 (MS Project). Includes contingency planning.	**/15%**
Budgetary Management	Includes a realistic estimate of project costs for ENSC 440. Includes potential funding sources. Allows for contingencies.	**/15%**
Conclusion/References	Summarizes project and motivates readers. Includes references for information from other sources.	**/10%**
Rhetorical Issues	Document is persuasive and demonstrates that the project will be on time and within budget. Clearly considers audience expertise and interests.	**/10%**
Format/Correctness/Style	Pages are numbered, figures and tables are introduced, headings are numbered, etc. References and citations are properly formatted. Correct spelling, grammar, and punctuation. Style is clear, concise, and coherent.	**/10%**
Comments:		

C ENSC 440 Planning

C.1 Introduction

Reliance on manual labor for the completion of repetitive tasks has been decreasing with advancements in robotics and machine learning technology. The benefits of automation include long term cost reduction for companies and improved living standards for society. The team at PaintBot Inc. aims to contribute to the field of automation by introducing a robot, PaintBot, that is capable of efficiently painting the interiors of apartments and condos.

At the push of a button, PaintBot will autonomously navigate the perimeter of a room and spray the walls with a professional quality coat while avoiding surfaces that should not be painted. This revolutionary innovation will provide contractors with the option of a time, cost, and labor efficient method of painting spaces using a spray gun - leaving only "detailing" work. With a continuous strive for improvement, we believe that it is only a matter time before PaintBot can be transformed to automate the painting of full scale commercial building exteriors.

This appendix will focus on planning related to PaintBot's prototype iteration, which the PaintBot Inc. team will be constructing during ENSC 440 in the upcoming semester. Section C.2 provides any necessary background information and briefly covers the scope of PaintBot's prototype iteration. Section C.3 outlines PaintBot's foreseen risks & benefits. Section C.4 analyzes the automation product market, discusses the need for PaintBot, and details any of PaintBot's competitors. Lastly, Section C.5 summarizes the project management structure that the team at PaintBot Inc. will follow.

C.2 Project Overview

C.2.1 Background

Initially, the team at PaintBot Inc. planned for PaintBot to be a large scale robot designed to perform exterior painting of commercial buildings. However, the costs associated with such a structure were projected to surpass our budget. Due to this, PaintBot Inc. has chosen to focus on creating a robot capable of painting the interiors of apartment buildings and condos.

Additionally, in keeping with industry trends, the team at PaintBot Inc. has decided to utilize a spray paint gun instead of a traditional paint roller. This guarantees higher quality paint coats for each pass and does not require pressure to be applied to walls.

Although our prototype aims to automate the laborious task of painting a wall, its core principles can also be adopted to automate other time consuming tasks. This property makes PaintBot appealing to many profitable sectors in the market, as outlined later on in this report.

C.2.2 Scope

The scope of ENSC 440 encompasses the design, assembly, and verification of PaintBot's prototype iteration. The prototype will be able to autonomously maneuver around any room and spray paint it in a fast, yet accurate manner due to its ability to:

1. Detect approaching corners at a range of angles.
2. Turn precisely, ensuring correct distance from the target wall is maintained.
3. Correct its position and orientation with information gathered from distance sensors.
4. Avoid painting areas that have masking tape around them.

In order to achieve such functionality, PaintBot will have the following characteristics:

1. Round footprint for efficient maneuvering around corners.
2. Four independent wheels capable of rotating in two distinct axes.
3. An on-board spray paint gun with a fast and reliable trigger mechanism.
4. A tower containing the spray gun, allowing for smooth and accurate vertical movement through the utilization of a counterweighted pulley mechanism.
5. Ultrasonic sensors for maintaining distance from the target wall section and detecting the corners of a room.
6. RGB camera and machine learning algorithms to detect any region that should not be painted.

For PaintBot's prototype iteration, the tower will be ~2 feet tall, allowing the team to focus on demonstrating key features by simplifying the problems of stability and mobility. Additionally, this small scale allows for drastic reduction in material costs due to the smaller list of required resources.

C.3 Product Justification

C.3.1 Risks

Overheating of Components

With numerous points of actuation and long operating times, dissipated heat in combination with a high temperature environment may cause PaintBot's components to exceed their maximum operating temperatures. The team at PaintBot shall carry out extensive stress tests in order to ensure that this will not happen under normal operating conditions. Failures will be detected, resulting in an immediate halting of operations.

Generality of Collision Avoidance

We expect PaintBot to be deployed primarily inside newly constructed apartment buildings which generally contain very few obstacles. However, there are many complex cases which PaintBot is required to handle, such as small outsets and curved wall segments. Additionally, other obstacles such as workers could be present in PaintBot's vicinity. These situations will not be addressed by the prototype, and will instead be a target for the final product version.

Mechanical Issues

PaintBot will contain 9 independent motors and 1 linear actuator, introducing significant control complexity and many potential points of failure. To combat this, PaintBot should be maintained and verified regularly by the team.

Effect of Paint Fumes

The fumes from the spray gun may result in an accumulation of paint on the PaintBot's hardware. The majority of this would fall on the outer cylindrical casing. However, accumulation over the camera used for marking detection could be problematic.

Reliability of Computer Vision

We require the machine learning methods for detecting marked regions to be extremely reliable; missing a marking could result in, for instance, the painting of a window. These methods will be validated extensively prior to deployment, preventing damage to windows and other wall-mounted property.

C.3.2 Benefits

Health and Safety

One consequence of the automation of manual labour over the past century has been the gradual elimination of high-risk jobs. PaintBot will contribute to this trend as painters will no longer inhale paint fumes while using spray guns in confined spaces for long durations. This is due to the fact that users can exit the room after initial setup and get notified when the task is completed or a problem arises.

Limited Competition
The automation of manual labor is both a long-standing and rapidly progressing field. However, established commercial solutions for automated painting do not exist outside of assembly lines. We aim to bring automation to the realm of interior painting - a new and unexplored market. This gives PaintBot the advantage of novelty, and the lack of well-known competitors against which a direct comparison may be drawn.

Cost Reduction
The product will represent a moderate up-front cost, which will then provide significant savings over its operational lifetime. While some supervision will be required as mentioned above, it represents far less labor than fully manual painting.

Reliability and Quality of Service
A level of inconsistency is inherent in human labor, such as workers calling in sick or not reaching the project site promptly. PaintBot aims to provide a consistent, high-quality paint application that eliminates these concerns. Additionally, it will reduce the probability that absent workers incur delays in a project.

Research and Innovation
Since PaintBot's design space is relatively unexplored, found solutions may be of research value. In particular, the sensor setup and control algorithms developed could provide some value to the field of indoor robot navigation.

C.4 Market Analysis

US Market

While the most-recent industry numbers from the interior painting industry are costly to obtain, we can analyze some freely available statistics from 2013. As reported by the Bureau of Labor Statistics and the Institute of Business in Society, compiled by CorkCRM, we present the 2013 statistics for the US market in Table C.1 on the following page.

These statistics are quite limited, giving only a high-level view of the US painting industry. Furthermore, observations such as the approximate employment in the industry reporting a value below the number of operating businesses (approximate employment/number of

Table C.1: US Market Statistics [42]

Category	Statistic
Painting businesses	260,350
Approximate employment	192,890
Average hourly wage	$18.89
Average annual wage	$39,290

State	Number of Painters
California	27,220
Texas	18,000
Florida	14,750
New York	12,090
Washington	7,240

painting businesses = 192,890/260,350 = 0.74 average employees/business) in the industry casts doubt on their accuracy, or at least how comprehensively they capture the market. However, as a preliminary market analysis, the statics do suggest that there is a large painting industry in the US. This is a positive sign for our proposed product since it suggests that, if we can offer a product of value to these companies, there is a large market to be targeted.

The relatively low reported average hourly wage of $18.89 is not as promising. Since our product proposes to save these businesses money by replacing human labour with a more cost-efficient alternative capable of achieving results of at least equal quality, our product's unit cost would need to be scaled to ensure financial viability. This could limit the technologies we can utilize to produce our solution, potentially to the point of nullifying any benefits we could offer. However, more analysis is needed to determine the range of wages this represents, as well as the accuracy of these statics. At the moment, very few solid insights can be extracted from these numbers. They merely provide an outline of the industry and suggest areas for further research.

Canadian Market

The Canadian painting market statistics are much easier to obtain. The government of Canada provides the 2015 statistics for the industry, which we have reproduced in Table C.2.

Table C.2: Canadian Market Statistics [43, 44]

Category	Statistic
Painting businesses	17,824
Businesses with 0 – 99 employees	90.9%
Range of annual revenues	$30,000 – $5,000,000
Average annual revenue	$218,700

As reported by the Government of Canada, the number of operating painting businesses in Canada is predictably lower than the numbers reported in the US. A large fraction (90.9%)

of these businesses are rather small, having under 100 employees [44]. However, while these businesses are relatively small, the same percentage of businesses reported being financially profitable. This shows a very healthy painting industry in Canada, where only a small fraction (9.1%) of companies are failing to turn a profit [44].

C.4.1 Competition

Walt

Walt, shown in Figure C.1, will be PaintBot's main rival in the market. Using the same core principles and mechanisms as described above, its creators, Endless Robotics, claim that "While assisting humans in painting, Walt can enable a three-member team to accomplish 10 times the work they would have otherwise done in a day" [45]. One key difference between Walt and PaintBot, is that Walt is not fully automated and thus needs crew members to assist it with navigation through a built in mobile application. Nevertheless, it is important to mention that Endless Robotics was able to raise over $\$100,000$ in funding from investors [45], highlighting the fact that there is interest in the concept which we plan to improve upon.

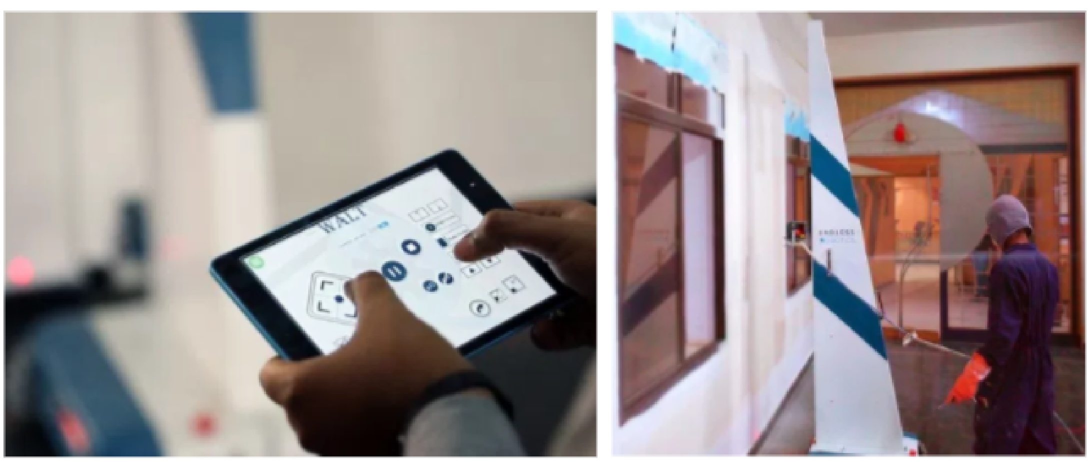


Figure C.1: Walt - Endless Robotics [45]

PictoBot

PictoBot, shown in Figure C.2 on the next page, is an automated painting robot that was developed by Nanyang Technological University in Singapore which targets large industrial spaces such as factories. The robot itself has dimensions of $2\times2\times3.5$ meters with an arm that can reach up to 10 meters. This makes it suitable for open environments, but impractical for use in residential buildings, which is why this robot has yet to become accessible to a wider audience. However, just like Walt, an operator uses a remote control to bring PictoBot to the correct position. Once at the required position, 3 mechanically controlled supports disassemble into a “tripod” configuration to lock PictoBot in place and the painting begins. Moving to a new location requires that these supports first retract to expose the wheels, drastically reducing PictoBot’s moving speed and overall painting efficiency.

Figure C.2: PictoBot - Nanyang Technological University’s Robotic Research Centre [46]

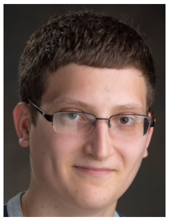
C.5 Project Management

C.5.1 Personnel

The main priorities of each individual team member with regards to PaintBot’s prototype iteration is provided below.

Bradley Barber
bradleyb@sfu.ca
Chief Executive Officer

1. Maintain even delegation of the workload across all team members.
2. Sourcing funding and monitoring finances.
3. Hardware assembly of PaintBot’s base.
4. Assembly of drive system and design of Arduino controller.
5. Validation of the prototype/product approval.



Lior Bragilevsky
lbragile@sfu.ca
Chief Communications Officer

1. Main communication link between PaintBot Inc. and investors/potential clients.
2. Hardware assembly of PaintBot's base.
3. Assembly of drive system and design of Arduino controller.
4. Implementation of machine learning algorithms to detect areas that are not to be painted.
5. Validation of the prototype's base functionality.

Hyun Gyu (Billy) Choi
hgchoi@sfu.ca
Chief Product Officer

1. Ensure that the team does not deviate significantly from the schedule.
2. Research of suitable components to be utilized for the trigger mechanism of the gun.
3. Arduino controller implementation for the trigger mechanism.
4. Assembly of the tower subsystem.
5. Validation of the prototype's tower pulley mechanism.

Ben Korpan
bkorpan@sfu.ca
Chief Technology Officer

1. Research and implementation of an appropriate power source.
2. Assembly of the tower subsystem.
3. Power & electrical wiring maintainance.
4. Arduino controller implementation for the tower subsystem.
5. Validation of the prototype's tower pulley mechanism.

Peter Kvac
pkvac@sfu.ca
Chief Operating Officer

1. Research and implementation regarding communication between multiple Arduino boards.
2. Research suitable paint gun to be utilized for the prototype.
3. Fabrication of the bracket holding the paint gun.
4. Validation of the prototype's tower support beam structure.

External Resources

During PaintBot's prototyping phase, the team may contact the following individuals for feedback and guidance:

- **Andrew Rawicz**
  The team will contact Dr. Rawicz when it is necessary to receive opinions about our design choices from a third person perspective. We will respectfully consider the suggestions provided and refer to them as deemed appropriate for integration.
- **Steve Whitmore**
  The team will contact Steve Whitmore when clarification of criteria is required for the documentation portion of the project. We will also seek guidance from Steve Whitmore if there are conflicts with individual team members that cannot be resolved internally.

C.5.2 Budget

Cost Analysis

The breakdown of each component for PaintBot's prototype is summarized in Table C.3.

Table C.3: PaintBot's Prototype Component Cost Breakdown

Function	Component	Quantity	Price ($/Unit)	Subtotal ($)
Painting Mechanism	MXL 60 Tooth Timing Pulley	2	3.04	6.08
	MakeBlock 3m Open End Timing Belt	1	16.99	23.07
	Linear Actuator (Trigger)	1	59.99	83.06
	HSR-1425CR Continuous Rotation Servo	1	20.37	103.43
	Linear Rail Shaft Rod	4	19.01	179.47
Driving Mechanism	Lynxmotion Base Rotate Kit (HS-422 Servo)	4	38.40	333.07
	HSR-1425CR Continuous Rotation Servo	4	20.37	414.55
	RW2 - Large Rubber Wheel	4	4.99	434.51
	Actobotics Gearmotor Pinion Gear (6mm) 16T	4	10.24	475.47
	Actobotics Gearmotor Pinion Gear (6mm) 32T	4	10.24	516.43
Extras	Arduino	2	25.99	568.41
	Paint Spray Gun	1	69.99	638.40
	Tower/Spray Gun Platform	2	17.04	672.48
	Cylindrical Wheel-Case	4	9.03	708.60
	Base Board	1	48.23	756.83
	Raspberry Pi Computing Unit	1	59.95	816.78
		Tax (12%)	98.01	914.79
		Contingency (10%)	81.68	996.47
			Total	996.47

Budgetary Contingencies

The team at PaintBot Inc. has decided that adding a 10% budgetary buffer (Table C.3) is sufficient for the project. This may come into use for purchasing spare parts to combat last minute hardware malfunctions. Additionally, it could come into use if online purchasing is not an option due to delivery times. This is due to the fact that buying from a local store may be more expensive (retail overhead) or from having to purchase a more expensive version of the part due to unavailability.

Funding Sources

PaintBot Inc.'s team believes that PaintBot will succeed in the market due to its ability to automate laborious tasks. However, as the projected cost is substantial, to successfully introduce PaintBot into the market an investment is required. In order to receive adequate funding for the PaintBot's prototype iteration, the team will reach out to the following sources in ENSC 440:

1. Wighton Engineering Development Fund, administered by Andrew Rawicz, is typically awarded to projects benefiting society. As mentioned previously, our product aims to automate laborious tasks and increase the productivity of workers, which is of great benefit to the society. We will apply for this fund during this semester.
2. The Engineering Science Student Endowment Fund is provided by SFU's Engineering Science Student Society (ESSS). Our prototype falls under Category B (Entrepreneurial), and we can apply in the upcoming (Summer 2018) semester.

Lastly, if all funding opportunities become unavailable, each member of our team has agreed to contribute at most $200 to the material costs. This will provide us with $1,000 which should be sufficient to successfully construct our prototype.

C.5.3 Time

Gantt Chart & Milestones

On the following page, Figure C.3 shows the Gantt chart which encapsulates PaintBot Inc's scheduling for the duration of ENSC 440 including milestones (green diamonds) for key tasks throughout the term.

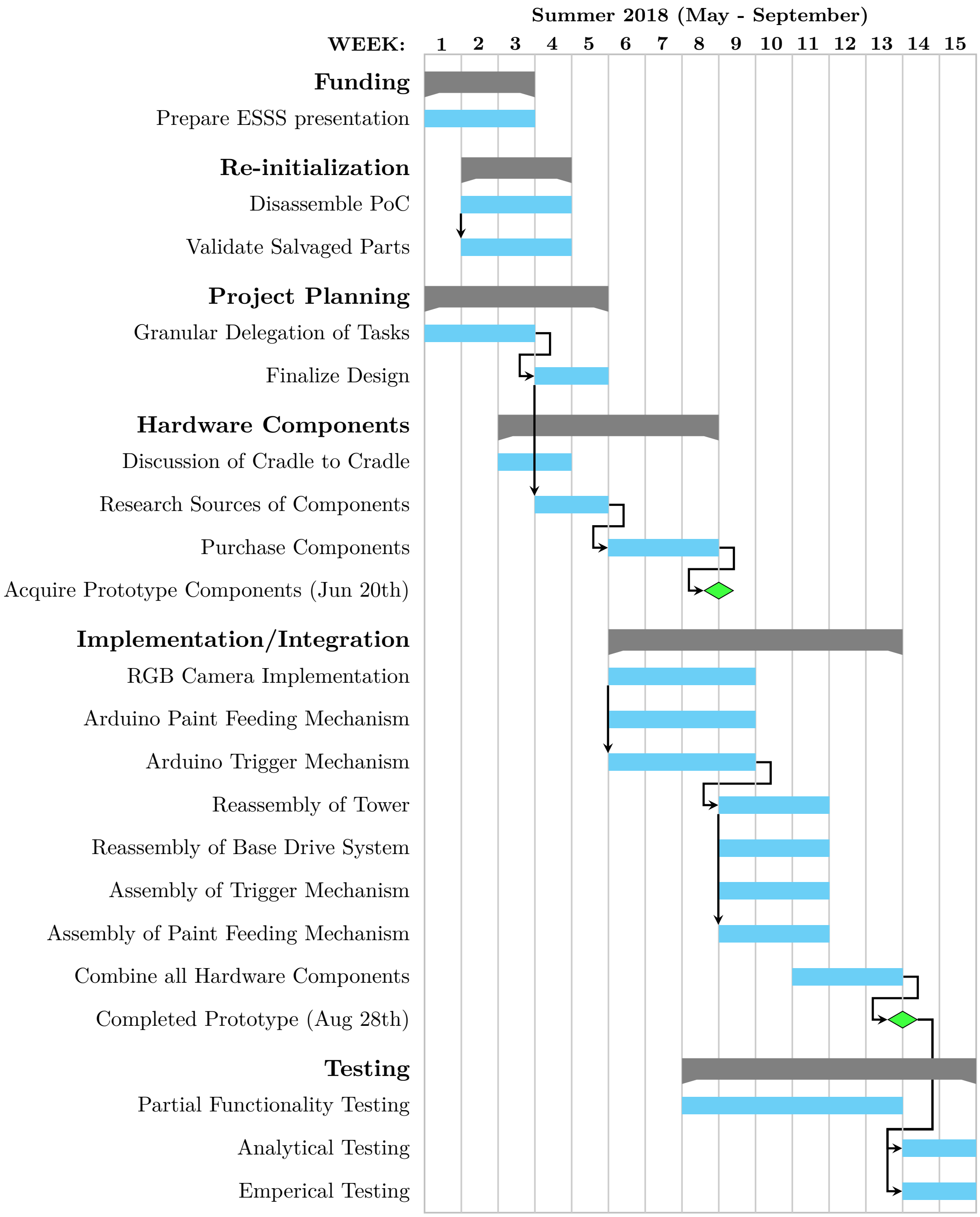


Figure C.3: ENSC 440 Project Schedule With Milestones

Contingency Planning

In scheduling PaintBot's prototype iteration the team has included general buffer time, allowing for unexpected events. The following list encapsulated some of these events which may incur delays, and the team's plans towards managing them.

- **Delivery date delays**
  In the case of a delivery date delay for an online order, we will search local shops which sell similar components and purchase them directly. Though inconvenient and time consuming, we will be able to acquire the components and unblock the tasks that are dependent on their arrival.

- **Hardware Malfunction**
  To combat last minute hardware malfunctions, such as a dead Arduino board or burnt out motor, the team will purchase some spare components for performing replacements. This will slightly increase the cost of creating our prototype but acts as an insurance factor for its success.

C.6 Conclusion

The advantages of automating simple tasks include increased productivity, reduction of human error, and elevated living standards [47]. Due to this fact, numerous simple repetitive tasks that were once completed with human labor, such as cleaning or painting of cars, have been greatly replaced by robotic technology. This type of paradigm shift will become more prevalent as technology grows and PaintBot Inc. aims to dive into the evolution in regards to the industry of interior painting.

PaintBot will feature four wheels that are able to rotate in 2 distinct axis, providing the ability to turn upon detection of a nearby object or wall. A pulley system will connect to the platform which holds the paint gun, allowing it to travel vertically for full coverage of the wall. A trigger mechanism utilizing a linear actuator will activate/deactivate the gun depending on the control signal received.

The members of PaintBot Inc. are excited to propose and build an ambitious but practical product for our Capstone project. With limited competition in the current market, we believe our project represents not only a real innovation in how painting companies and contractors can operate, but has the potential to achieve market viability as a product.