February 21, 2018

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

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

Dear Dr. Rawicz,

The attached document specifies the requirements for successfully implementing our design for an automated room-painting robot as described in our Project Proposal [1]. Our goal is to drastically reduce the manual labor involved in painting the interiors of apartments, condos, and other residences by partially automating the process - requiring only that the human operators mask the room appropriately and fully enclose the robot within it (i.e. close any entrances).

This requirements specification document aims to outline any requirements associated with our product throughout its different design stages, namely the Proof of Concept, Prototype, and Final Product. We will first detail PaintBot's functional and structural requirements from a high-level perspective before further detailing the requirements across 4 categories: Mechanical, Hardware, Electrical, and Software. Lastly, we will list the Engineering Standards and Sustainability/Safety concerns that PaintBot must address.

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 requirement 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: Requirements Specification for an Automated Painting Robot

Requirements Specification

Automated Painting Robot

Make life simpler, one stroke at a time

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Submitted to: Steve Whitmore (ENSC 405W)
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Issue Date: February 21, 2018

Abstract

This document specifies and defines the functional requirements of the automated room-painting robot, PaintBot. These requirements will first be described holistically in terms of PaintBot's desired functionality. Then, each one of PaintBot's components will be detailed further within the corresponding sections. In addition to discussing the behavioural functionality, this document highlights Engineering Standards and Sustainability/Safety factors that our product must meet.

PaintBot can be considered in terms of four main systems:

1. **Drive System**
   Allows PaintBot to move around the room that is being painted.
2. **Sensor System**
   For detecting the environment and characteristics of the paint surface.
3. **Paint Delivery System**
   Provides vertical mobility to the spray gun and maintains a consistent spray pattern.
4. **Structural System**
   Composed of the base and vertical tower supports.

The user interface 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. This is a revolutionary and innovative method for reducing the labour requirements of residential wall painting - costs are lowered while productivity is raised.

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compressor Supplies the pressure to push paint through a hose and out of the spray gun head. 8

CSA Canadian Standards Association. 15

GPIO General Purpose Input/Output pins between environment and sensors where signals are generated. 13

ISO International Organization for Standardization. 15

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

multi-threading Refers to a running process that contains multiple threads, or distinct roles, executing at the same time, and which are able to communicate with the main process. 13

operational lifetime Period of time over which product maintains acceptable quality of operation without repair or replacement of parts. 5

RGB 3 colour channels (Red, Green, and Blue) represented by 8 bit integers. 3

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. 7

Ultrasonic rangefinders 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. 3

1 Introduction

The past century was marked by the automation of many manual processes 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.

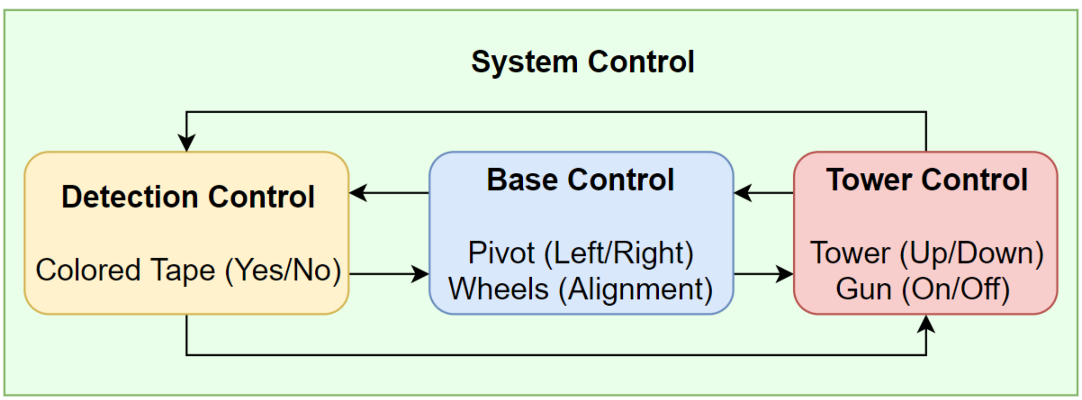


Figure 1.1: Basic Behavioural Overview

This document will outline and describe the requirement specifications for achieving this functionality. These specifications will be organized into three major categories:

1. **Functional Requirements** (Sections 3–7)
   PaintBot's core requirements are presented. Additionally, more detailed requirements for each of its components are provided.

2. **Engineering Standards** (Section 8)
   Lists and briefly discusses the engineering standards which PaintBot must comply with in order to be considered for industry use.

3. **Sustainability and Safety** (Section 9)
   Describes the importance of sustainable practices/materials and how these are being followed/utilized by PaintBot.

1.1 Scope

It is the intention of this document to specify the individual requirements of PaintBot as well as its compliance with Engineering Standards and efforts towards Sustainability/Safety. The functional requirements presented will be segmented into 4 parts: Mechanical, Hardware, Electrical, and Software. These requirements will allow the team at PaintBot Inc. to realize a fully automated room painting robot.

1.2 Intended Audience

This document will serve as PaintBot's functional and structural requirements guide for PaintBot Inc. members, potential clients/partners, Steve Whitmore, Dr. Andrew Rawicz, and teaching assistants. For ease of reference, the core requirements and standards for each design stage are clearly stated. Future revisions and inquiries will draw from the outlined preliminary framework.

1.3 Requirement Classification

To indicate a specific functional requirement, this document will adopt the following scheme:

Req {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 6.1 corresponding to the prototype design stage, will be labeled as

Req 6.1.1−P

2 System Overview

PaintBot's system consists of two main electro-mechanical mechanisms: the tower and the base. The tower will consist of a pulley system that carries a paint gun vertically and the base will hold the 4 wheels that are able to rotate in two distinct axes. Ultrasonic rangefinders will be utilized to measure distance to nearby walls which the robot will attempt to maintain within a threshold, and the RGB camera will be used to detect areas that the user wishes not to be painted. Figure 2.1 provides a high level overview of PaintBot's hardware and software design. All of the subsystems shown in the figure will be present in the prototype.

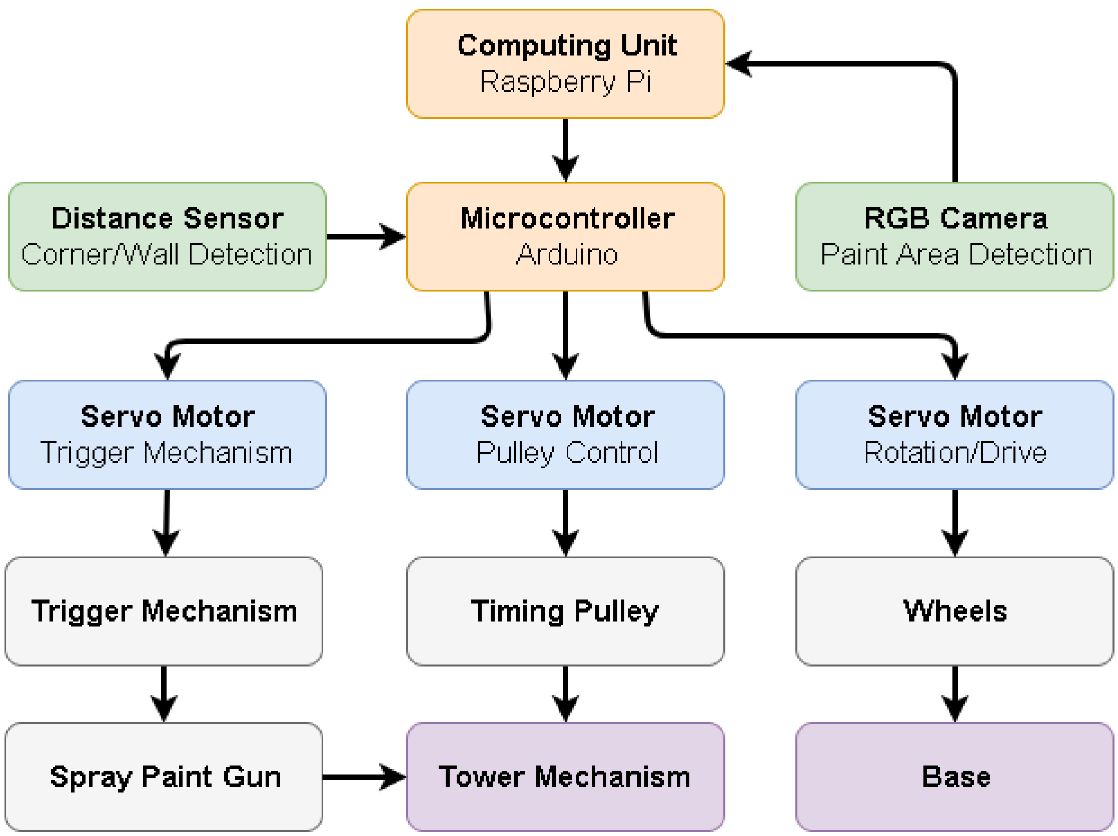


Figure 2.1: PaintBot's System Overview

3 High-Level Requirements

The high-level problem we are trying to solve with our project is the automated painting of residential rooms using an autonomous robot, reducing the need for human labour. To achieve this, the robot will be required to detect its environment, determine areas not to be painted, and orientate itself properly to apply paint evenly and predictably. The following are the high-level requirements which we will detail further in the subsequent chapters.

3.1 General

Table 3.1: General High-Level Requirements

Req 3.1.1−P	Apply paint to the walls in a controlled, even, and reliable pattern.
Req 3.1.2−P	Be capable of navigating a room of any size or shape - though height will have to be set to a standard value.
Req 3.1.3−F	Reliably recognize painter's tape and avoid applying paint to areas/objects marked by tape.

3.2 Overall Performance

Table 3.2: PaintBot's Overall Performance Requirements

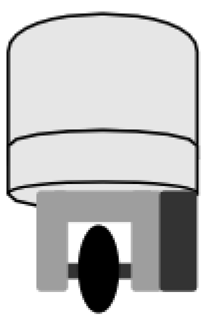
Req 3.2.1−C	Adjust itself to achieve correct distance from the target wall, if needed.
Req 3.2.2−C	Detect distance and orientation to target wall.
Req 3.2.3−P	Travel along the perimeter of the room, maintaining a constant distance.
Req 3.2.4−P	Apply paint efficiently, evenly, and accurately.
Req 3.2.5−P	Detect approaching corners of any angle.
Req 3.2.6−P	Turn precisely, ensuring correct distance from the target wall is maintained.
Req 3.2.7−P	Detect upcoming objects.
Req 3.2.8−F	Detect and respond appropriately to objects protruding or receding from walls/ceilings.
Req 3.2.9−F	Detect marker tape, used to signify areas not to be painted, before the paint head reaches them.
Req 3.2.10−F	Store the location of upcoming areas not to be painted and act on this information.
Req 3.2.11−F	Track location to determine when room painting is complete.

4 Mechanical Requirements

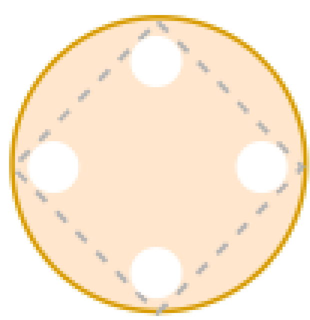
4.1 Drive System

Table 4.1: Drive System

Req 4.1.1–C	The wheels (Figure 4.1a) shall rotate at least ±180° about their central-vertical axis, allowing for turning about the geometric center of the base as well as horizontal movement in any direction.
Req 4.1.2–C	The wheels shall stop rotating once PaintBot reaches the next area to be painted.
Req 4.1.3–P	The wheels shall rotate freely with a clearance from the base of at least 1/8 inches.
Req 4.1.4–P	The drive motor will have to supply sufficient torque to overcome inertia of the robot and achieve adequate acceleration.
Req 4.1.5–F	The wheel shall have adequate tread to produce the necessary friction to operate on expected.
Req 4.1.6–F	The components used (wheels, motors, gears, etc.) will operate effectively over a reasonable operational lifetime.



(a) Wheel Drive



(b) Base-Wheel Arrangement

Figure 4.1: Wheel Drive & Base-Wheel Arrangment

PaintBot will use four wheels, as seen in Figure 4.1b, with independent drive motors for each, for locomotion. To allow PaintBot to navigate any floor plan, it is required to have at least three degrees of freedom: translation in both horizontal axis and rotation about the axis perpendicular to the plane of the floor.

While this is achievable with numerous arrangements, we have determined that the most viable is to have the system symmetric about both horizontal axes and be capable of rotation about the geometric center of the robot's base. This arrangement guarantees that, given all components of the robot remain within a radially symmetric base, collisions with nearby walls or objects during rotation will not occur.

Further, we have come to the requirement that the wheels or our robot be capable of fully rotating about their central axis perpendicular to the plane of the floor. This is to allow translation in any horizontal direction without altering the angular orientation of the robot's base. Specifically, because we are using sensors attached to the base and tower of the robot for the spatial sensing and orientation calculations, we have concluded that separating horizontal movement from rotational movement is required to reduces unnecessary complexities in the spatial calculations.

For PaintBot's prototype version, given the mass estimate in Table 4.3 on the next page, the expected torque of 0.2542 $N \cdot m$ from each stepper motor [2] and the 1.56 cm radius of the wheels [3], we can estimate a maximum linear, horizontal acceleration of 2.85 m/s^2. This is only an upper bound since the mass estimate is a lower bound. This is still a reasonable estimate, however, since the most significant contributors to the robot's mass have been considered.

4.2 Base

Table 4.2: Base Requirements

Req 4.2.1–C	The base shall be circular to ensure the outermost horizontal dimensions of the base are constant in all radial directions during rotation.
Req 4.2.2–C	The base shall be made out of wood.
Req 4.2.3–C	The base shall contain contain 4 wheels placed at the optimal configuration (Figure 4.1b).
Req 4.2.4–P	The base shall be made out of aluminum.
Req 4.2.5–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.
Req 4.2.6–P	The base shall be 60.96 cm in diameter.
Req 4.2.7–P	The base shall not exceed 0.3175 cm in thickness.
Req 4.2.8–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.
Req 4.2.9–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.
Req 4.2.10–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.

The further requirement for this is that all components of the robot be within the footprint of the base - this will be further discussed later in this section. The base must also be capable of supporting the other components of the robot during all expected functional behaviour.

For the prototype, an estimate for this load is presented in Table 4.3. It is important to note that this is a lower bound estimate as some component weights could not be determined.

Table 4.3: Prototype Mass Estimate

Component	Mass (g/unit)	Mass for Prototype [1] (g)
Stepper Motors	280 [2]	1,400
Wheels	12.2 [3]	48.8
Aluminum (g/cm^2)	2.68 [4]	15,500
Servo Motors	41.7 [5]	166.8
60T Pulley	15 [6]	30
32T Gear	22.68 [7]	90.72
16T Gear	5.67 [8]	22.68
Tower Support Rails	635 [9]	2,540
Paint Delivery System	3,103 [10]	3,103
Total Mass		**22,902 g**

4.3 Tower Support Rails

Table 4.4: Tower Support Rails Requirements

Req 4.3.1–C	The support beams shall be 76.2 cm in length.
Req 4.3.2–C	The support beams will support a sliding mechanism to allow the paint head to move up and down.
Req 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.
Req 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.
Req 4.3.5–P	The support beams shall be placed around PaintBot's center of mass in a square configuration.

The support rails for the robot will provide the support and structure for the tower, as well as guide-rails for the paint head to travel up and down the tower. This requires that the rails be adequately rigid as well as machined to allow the use of linear sliders. These rods must also be, or assemble into, a consistent diameter without interruption throughout the entire operating length of the rod.

4.4 Paint Delivery

Table 4.5: Paint Delivery Requirements

Req 4.4.1–P	PaintBot shall receive paint delivered from a large reservoir in order to reduce necessity of frequent refills.
Req 4.4.2–P	The paint delivery mechanism shall be free of leakage.
Req 4.4.3–P	The paint delivery mechanism shall not effect the spray pattern of the gun.
Req 4.4.4–P	The paint reservoir shall be mounted on PaintBot in order to prevent unnecessary objects within the work space.
Req 4.4.5–F	The compressor shall turn off once PaintBot's paint reserves fall beneath the threshold level.

One PaintBot Inc.'s goals is to minimize human interactions in the process of automated painting. In order to avoid the need of re-filling the paint gun frequently, PaintBot will utilize a mechanism where the paint is delivered from a reservoir that is mounted on the base of the robot.

4.5 Cylindrical Case

Table 4.6: Cylindrical Case Requirements

Req 4.5.1–P	The case shall be the same height (2.5 feet) as PaintBot.
Req 4.5.2–P	The case shall cover any and all components which are sensitive to air-born paint particulate while not obstructing the spray of the paint delivery system or movement of the paint head.
Req 4.5.3–P	The case shall be opaque to occlude the interior components.
Req 4.5.4–P	The case shall have easily accessed openings for cleaning and/or any required adjustments or maintenance.
Req 4.5.5–F	The case shall be adequately ventilated t ensure that operating temperature due not exceed the maximum safe operating temperature 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. 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.

5 Hardware Requirements

5.1 Ultrasonic Rangefinders

Table 5.1: Ultrasonic Rangefinders Requirements

Req 5.1.1–C	Two ultrasonic rangefinders shall record the distance from the wall being painted.
Req 5.1.2–P	Ultrasonic rangefinders shall have a dead-zone of at most 5 cm and a range exceeding 100 cm.
Req 5.1.3–P	Ultrasonic rangefinders shall have a resolution of at most 0.5 cm and an accuracy of at most 5%.
Req 5.1.4–P	Two ultrasonic rangefinders shall record the distance to an approaching obstacle in the direction of motion.
Req 5.1.5–F	An ultrasonic rangefinder shall detect the closest obstacle for general avoidance, as illustrated in Figure 5.1.

To ensure reliable and accurate obstacle detection for distances within 100 cm, ultrasonic rangefinders will be employed [11]. We will require two rangefinders facing in the direction of the spray gun, allowing the robot to maintain a steady distance from the wall and to obtain a correct orientation following a turn. As PaintBot will traverse rooms in a clockwise manner, it will require a second set of rangefinders facing in the direction of travel (90° to the direction of the spray gun) to detect approaching corners.

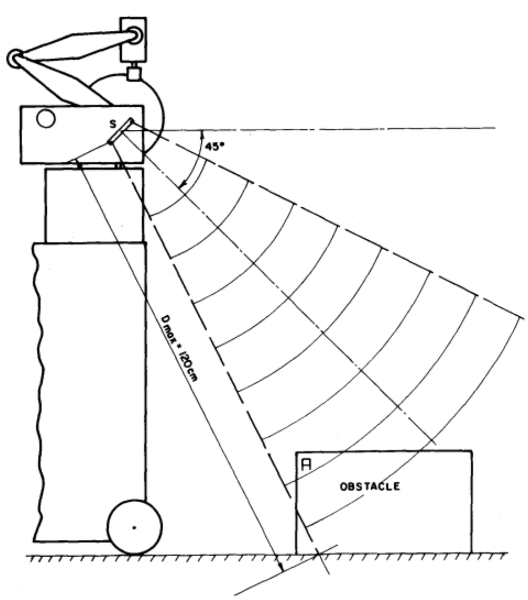


Figure 5.1: Ultrasonic Rangefinders for Obstacle Avoidance [12]

5.2 Buttons & Switches

Table 5.2: Button & Switches Requirements

Req 5.2.1–C	There shall only be 2 buttons, one (green) to turn PaintBot on and another (red) to stop in case of an emergency.
Req 5.2.2–P	The buttons shall be located at easy to access and highly visible areas.
Req 5.2.3–F	There shall be a multi-level switch located in between the 2 buttons to control PaintBot's painting speed.

For ease of operation, PaintBot will only contain 2 buttons, namely *on* and *emergency stop*. This arises from the fact that PaintBot is fully automated and only needs to be prompted to begin painting the room. The speed control switch will provide further separation between the 2 buttons, making the user more aware of which button they are pressing.

5.3 Motors

Table 5.3: Motor Requirements

Req 5.3.1–C	The motors for the robot's drive wheels and paint head pulley system will be capable of indefinite rotation.
Req 5.3.2–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.
Req 5.3.3–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 4.3).
Req 5.3.4–P	Angular displacement of the rotor for all motors must be easily and accurately calculable or ensured based on inputs.

It is important to acquire powerful motors that are easily programmable. In addition to the performance of these motors, their accuracy is crucial as PaintBot will need to be precise when turning in order to apply paint to the room in an appropriate manner.

5.4 Wall Camera

Table 5.4: Wall Camera Requirements

Req 5.4.1–P	The camera will support a resolution of at least 1 megapixel.
Req 5.4.2–P	The camera will support a framerate of at least 30 Hz.
Req 5.4.3–P	The camera will be mounted at the same height as the spray gun, offset by the strip width in the direction of motion.

To allow robust, yet configurable detection of markings on the wall, a digital camera will be mounted next to the spray gun. As the robot paints a strip, the camera will be scanning the following strip, allowing the next spray pattern to be planned.

5.5 Paint System

Table 5.5: Paint System Requirements

Req 5.5.1–C	The spray gun shall be able to cover at least a 22.86 cm (9 inch) wide strip (cross section), as shown in Figure 5.2.
Req 5.5.2–C	The spray gun shall be at most $10in \times 10in$ in size.
Req 5.5.3–C	The spray gun shall be kept at a constant distance from the wall to ensure a consistent spray pattern.
Req 5.5.4–C	The spray gun shall have a trigger mechanism which can be manipulated by mechanical means.
Req 5.5.5–P	The spray gun shall be responsive when triggered or released, having very little delay time between active and inactive states.
Req 5.5.6–P	The spray gun will operate from a pressurized paint canister mounted on the base.
Req 5.5.7–F	The spray gun will require a compressor which can be autonomously turned on and off by the robot.
Req 5.5.8–F	The spray gun shall run off of a built-in compressor and a paint loading mechanism.

While the final product will require a built-in compressor and large paint reservoir for consistent, long-lasting performance, the weight and size constraints for the scaled prototype do not facilitate this. For this reason, the delivery system for the prototype will instead utilize a compressed canister delivery system.

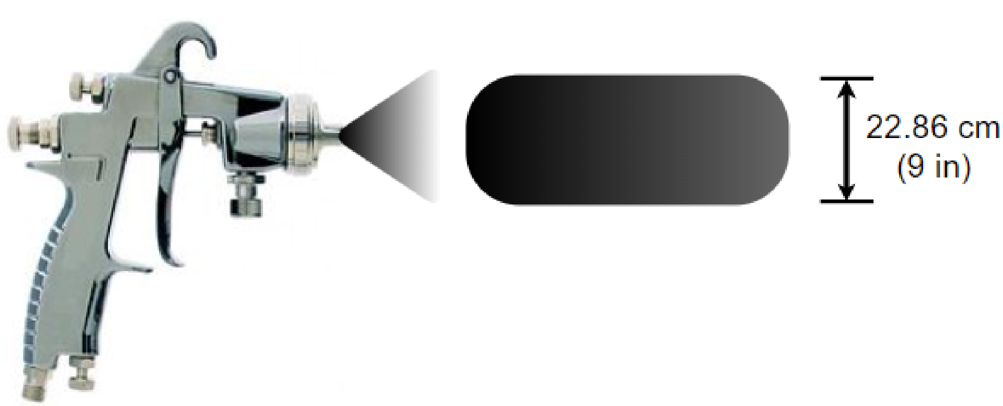


Figure 5.2: Spray Pattern

6 Electrical Requirements

6.1 Power Supply

Table 6.1: Power Supply Requirements

Req 6.1.1–**C**	The power source shall supply 25 Watts at 12V DC.
Req 6.1.2–**C**	The power source shall provide a 12V DC rail.
Req 6.1.3–**C**	The power source shall provide a 5V DC USB rail.
Req 6.1.4–**F**	The power source shall supply 50 Watts at 12V DC.
Req 6.1.5–**F**	The power source shall be rechargeable, having a capacity in excess of 100 watt-hours.

The prototype shall utilize a rechargeable DC power supply, able to supply ample power through a 12V rail. An additional 5V USB rail shall be available for low-power components such as the Raspberry Pi or Arduino. To guarantee several hours of operational time between charges, we will require a capacity of at least 100 watt-hours. As the utilized DC motors have a maximum power draw of 5 watts each, and at most 5 such motors will be active at once, we will need to ensure our power supply is capable of delivering at least 25 watts.

6.2 Wiring

Table 6.2: Wiring Requirements

Req 6.2.1–**C**	A 12V DC supply line and ground line shall connect all DC motors to the power supply.
Req 6.2.2–**P**	A 5V USB - Micro USB line shall connect low power components to the power supply.
Req 6.2.3–**P**	All wires shall be insulated.
Req 6.2.4–**P**	Wiring shall be organized and clamped down.

We require the connection of our DC motors to the 12V DC and ground rails of the power supply. Additionally, a USB connector shall bridge the Raspberry Pi and Arduino to the power supply. Wires will be layed out in an organized manner and clamped down tight to the chassis. This serves to improve the aesthetic appeal of the design and minimize the risk of wires catching during movement.

7 Software Requirements

7.1 General

Table 7.1: General Software Requirements

Req 7.1.1–C	PaintBot's driving process shall detect the distance from walls in both front and side sensors.
Req 7.1.2–C	PaintBot shall actuate the vertical tower to raise and lower the paint head at appropriate intervals.
Req 7.1.3–P	PaintBot will need Linux OS and Python support for SimpleCV/object detection algorithms.
Req 7.1.4–P	PaintBot shall have at least 500MB of memory.
Req 7.1.5–P	PaintBot will need reliable RGB camera, GPIO pin, and integrator readings, plus several hardware requirements.
Req 7.1.6–P	PaintBot will need the capacity to handle abstract data types using data structures, especially arrays and classes.
Req 7.1.7–P	Hardware, software, or GPIO exceptions and interrupts will not result in unpredictable/unsafe system behavior.
Req 7.1.8–P	PaintBot's painting process shall move the spray-tower vertically up and down, and actuate the gun.
Req 7.1.9–P	PaintBot's object detection process shall detect RGB color values to disable spraying mechanism.
Req 7.1.10–F	Any failures should be communicated to users.
Req 7.1.11–F	PaintBot's control signals process will manage all the inter-process signals in real-time.

Some processes are expected to operate in parallel, such as object detection, painting process, driving process, and control signals process. The prototype control signals and object information will be read a cycle ahead of the spray gun, and processed into a signal array in memory to determine the next stage of the control signals.

To meet these requirements we will utilize a system that supports multi-threading to run these processes in parallel, and has sufficient GPIO accessibility and memory storage, such as Raspberry-Pi Model B+. To prevent painting specific locations in the room, a machine learning object detection architecture will be implemented. SimpleCV is an open source library that supports this functionality, where RGB processing and detection may be done from the Pi-Camera.

Additionally, collision avoidance and distance detection are algorithms specific to the driving and painting processes. Linux, multi-threading and Python support will be required to use SimpleCV and collision avoidance algorithms on the Raspberry-Pi Model B+.

The system is expected to handle exceptions and interrupts from either software or hardware components without major system breakdown or unpredictable behavior. Coherence between GPIO, software, and hardware is expected, but not guaranteed, and should be accounted for. Additionally, device and software failures should be made apparent to users.

7.2 Machine Learning

Table 7.2: Machine Learning Requirements

Req 7.2.1–P	The images obtained from the wall camera (Section 5.4) will be resized to 128×128 pixels.
Req 7.2.2–F	A built in machine learning pre-trained architecture will detect the edges present in the images.
Req 7.2.3–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) [13] - 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 7.1.

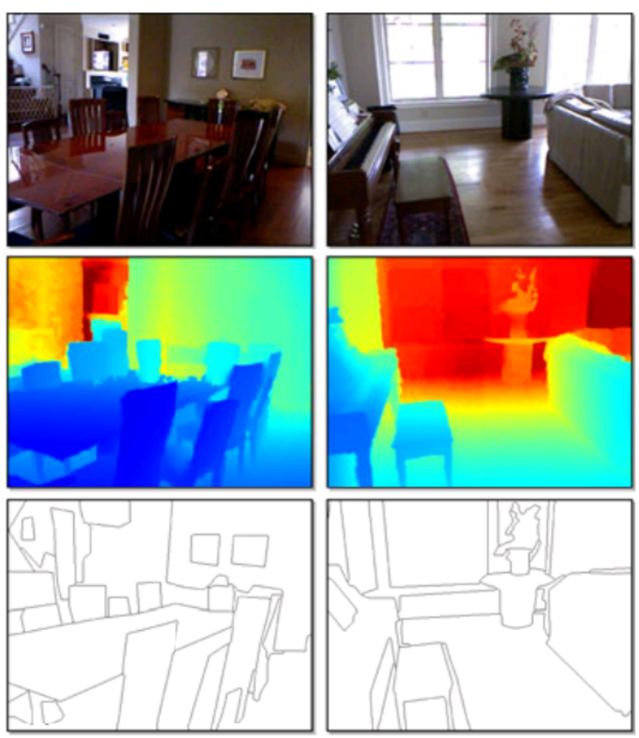


Figure 7.1: Machine Learning Edge Detection [14]

8 Engineering Standards

Following proper standards for both the design and integration process in development is a crucial aspect in producing a long lasting and maintainable product. The standards published by acclaimed organizations such as CSA and ISO will act as a guideline to the team at PaintBot Inc. The construction and operation of PaintBot shall comply with the following engineering standards.

8.1 Electrical & Mechanical

Table 8.1: Electrical & Mechanical Standard Requirements

Req 8.1.1–C	The ultrasonic rangefinders shall comply with the safety standards listed in CAN/CSA-C22.2 NO. 61010-1-12 [15].
Req 8.1.2–F	During operation PaintBot's components shall not surpass temperature values cited in NFPA (Fire) 70 standards [16].
Req 8.1.3–F	The design process of PaintBot shall conform to the safety requirements of industrial robotic equipment stated in CAN/CSA-Z434-14 [17].
Req 8.1.4–F	The rechargeable power sources utilized in the operation of PaintBot shall conform to the general standards stated by ANSI C 18.2M [18].

8.2 Environmental

Table 8.2: Environmental Standard Requirements

Req 8.2.1–F	The painting process of PaintBot shall conform to the environmental standards set by Green Seal listed in GS-11 [19].
Req 8.2.2–F	PaintBot's operation shall obey the BC Building Code regarding safety when performing alterations to apartments and condos [20].
Req 8.2.3–F	The development process of PaintBot shall conform to CAN/CSA-ISO/TR14062-03 regarding consideration of environmental aspects during design and implementation. [21].

8.3 Miscellaneous

Table 8.3: Miscellaneous Standard Requirements

Req 8.3.1–F	The quality of coat produced by PaintBot shall comply with the definition of "Properly Painted Surface" defined by PDCA [22].

9 Sustainability & Safety

9.1 Sustainability

Table 9.1: Sustainability Requirements

Req 9.1.1–C	PaintBot shall use recyclable alternatives for materials when affordable and obtainable options are present.
Req 9.1.2–C	PaintBot shall rely on rechargeable power sources when possible in place of consumables.
Req 9.1.3–P	The disassembling process of PaintBot shall not cause damage to individual components.
Req 9.1.4–P	The path of operation for PaintBot shall be optimized to perform its task with minimal power consumption.

Cradle to Cradle (C2C) refers to a process of development where all of the components consumed in manufacturing of a product are able to be disassembled in a state in which they are able to be brought back into the development cycle. In order to accomplish this, it is crucial that engineers have the insight in not only creating an appealing product, but to have a design approach where the afterlife of the product is also kept in mind. The C2C model is to broken down into two distinct categories as shown in figure 9.1.

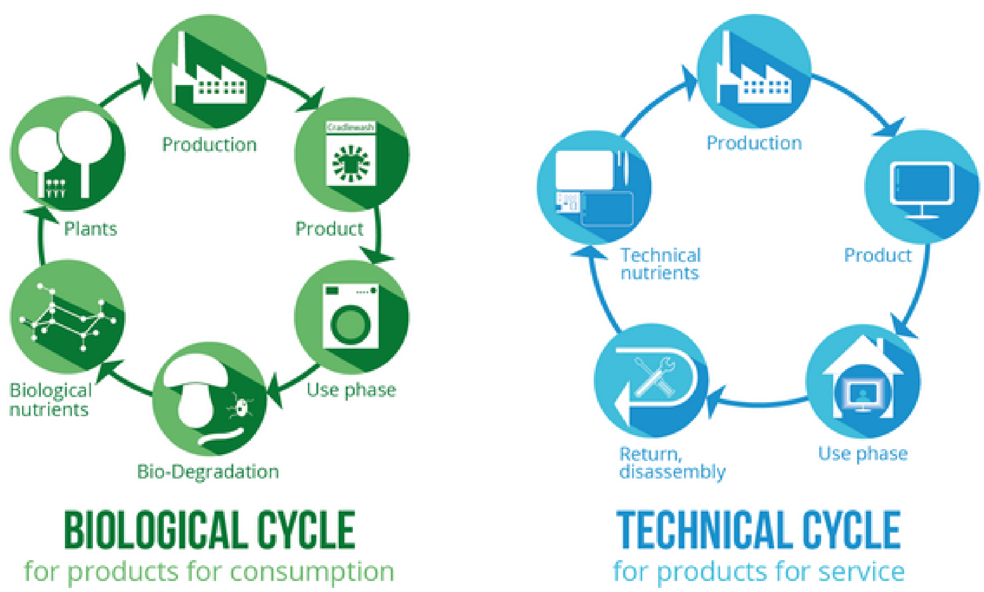


Figure 9.1: Cradle to Cradle Development Cycle (Biological/Technical) [23]

In the production of both the prototype and the market version of PaintBot, we plan on complying to the C2C development approach mentioned above as much as possible whilst being able to achieve the goals set for our product. Benefits of preserving the environment and adding additional value to our product are definitely worth pursuing for the team. It is worth noting that scaling the product up to the market version will also scale the benefits that were created by making choices towards sustainability. The following subsections outline some of the design choices we have made towards creating a sustainable and environmentally friendly product.

9.1.1 Components

The platforms that carry the paint gun and the robot's base make up a high percentage in volume of total required material. For the construction of these platforms we have chosen to use aluminum due to the following properties [24]:

1. **Infinitely recyclable**
   Aluminum is able to be recycled numerous times without loss of quality, Aluminum can be re-shaped at low cost.
2. **High corrosion resistance**
   Aluminum naturally generates protective oxide coating that combat corrosion which expands the material's life span.
3. **Lightweight, strong, and long lasting**
   The long lasting nature of aluminum reiterates the ability to recycle the materials used in our product towards the technical cycle of C2C.

PaintBot Inc. will also design our product so that no individual components are harmed during the disassembling process. In doing so, all of the electronic components used in the production of PaintBot such as wires and sensors shall be reusable in future projects after deconstruction or recycled at proper facilities [25].

9.1.2 Energy Consumption

With regards to energy consumption, PaintBot Inc will insure that the path of operation for the robot will be optimized to be able to perform a professional paint job with the smallest overlap in its process. This will be accomplished by analyzing the spray pattern from the gun and calculating the maximum distance from the robot to the wall that the quality of coat is not lost. With increased distance from the wall, the servos used for the pulley system will consume less power as it will reduce the number of iterations of vertical movement. We will also use rechargeable power sources when possible in order to reduce waste from our product.

9.2 Safety

Table 9.2: Safety Requirements

Req 9.2.1–C	PaintBot's power/emergency shutdown buttons will be located at places where they are unlikely to be triggered accidentally.
Req 9.2.2–C	PaintBot will not utilize any toxic materials in construction.
Req 9.2.3–P	All circuitry components and wiring shall be well organized and hidden from the user in order to prevent contact with any liquids, mainly paint.
Req 9.2.4–P	PaintBot's circuitry will be designed against overheating thresholds.
Req 9.2.5–P	All edges on PaintBot's platforms shall be rounded.
Req 9.2.6–F	PaintBot will feature stabilizers on the side of the robot to prevent falling during operation.
Req 9.2.7–F	PaintBot shall contain additional wheels that come in contact with the ground when it is tilted in order to aid the user in transporting the robot.

The operating process of PaintBot will be designed to have minimal intervention from humans thus it is unlikely to raise any major safety concerns directed to the users. Our prototype will be constructed with relatively light materials and only be reaching a height of approximately 3 feet which allows easier mobility. However, the final marketable product will target a height of 9 feet which may require external means of stabilization while in operation. Additionally, PaintBot's simple 2 button design requires careful placement considerations in order to avoid accidentally triggering the emergency shutdown state.

10 Conclusion

This document is introduced as an architectural and functional reference for PaintBot's conception - the prerequisites for an autonomous residential painting system. It is intended to categorize and elaborate on the functional requirements necessary to realize the product described in our Project Proposal [1].

A brief summary of these requirements is provided below:

1. **Mechanical Requirements**
   - The drive system will provide sufficient torque for the mass of PaintBot and be capable of free movement while maintaining angular orientation.
   - The support rails will provide the structural support to the vertical paint-head mechanism as well as guide rails on which to travel.
2. **Hardware Requirements**
   - Sensors will be utilized for environmental detection.
   - Accessible buttons will be used to turn PaintBot on and for an emergency stop.
   - Stepper/servo motors shall be used for drive, rotation, and tower displacement.
3. **Electrical Requirements**
   - A rechargeable power supply will provide DC current through 12V and 5V rails.
   - The wiring required for power distribution shall be compact and organized.
4. **Software Requirements**
   - Core software architectural requirements are assessed in terms of PaintBot's physical and behavioural requirements.
   - A machine learning pre-trained architecture will detect objects in the room.
5. **Engineering Standards**
   - The mechanical, electrical, and environmental standards published by acclaimed organizations that the team will follow as a guideline throughout the project.
6. **Safety & Sustainability**
   - The design choices the team has made towards producing a sustainable product.
   - The safety concerns regarding PaintBot and the planned solutions.

Moving through these phases of development, this document will provide a reliable reference for ensuring the satisfaction of functional requirements at each step, as well as a criteria against which to judge our success.

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A PoC Functionalities

Our intention for PaintBot's PoC iteration is to express its main concepts/ideas and to be able to demonstrate the core functionality of an automated room painting robot. While there may be potential for some errors to exist in the system, our goal is to create a version of the product which aids in the visualization of the following crucial tasks:

1. Wheels capable of adjusting ±180° in the horizontal direction and rotating with enough torque to set PaintBot in motion.
2. Tower mechanism capable of moving the paint gun vertically utilizing a pulley system.
3. Obtaining distance from objects utilizing ultrasonic rangefinders in order to maintain consistent distance from walls.
4. Ability to operate relying on a rechargeable power source.

In addition, PaintBot's PoC iteration shall meet all of the functional requirements outlined in this report. For ease of reference, Table A.1 lists all of these requirement specifications.

Table A.1: PaintBot's PoC Functionality Requirements

High-Level Requirements	Overall Performance	**Req 3.2.1**, **3.2.2**
Mechanical Requirements	Drive System	**Req 4.1.1**, **4.1.2**
	Base	**Req 4.2.1**, **4.2.2**, **4.2.3**
	Tower Support Rails	**Req 4.3.1**, **4.3.2**, **4.3.3**, **4.3.4**
Hardware Requirements	Ultrasonic Rangefinders	**Req 5.1.1**
	Buttons & Switches	**Req 5.2.1**
	Motors	**Req 5.3.1**, **5.3.2**
	Paint System	**Req 5.5.1**, **5.5.3**, **5.5.3**, **5.5.4**
Electrical Requirements	Power	**Req 6.1.1**, **6.1.2**, **6.1.3**
	Wiring	**Req 6.2.1**
Software Requirements	General	**Req 7.1.1**, **7.1.2**
Engineering Standards	Electrical & Mechanical	**Req 8.1.1**
Sustainability & Safety	Sustainability	**Req 9.1.1**, **9.1.2**
	Safety	**Req 9.2.1**, **9.2.2**

