Carnegie Mellon University

Robotics Capstone Project

Requirement Specifications and Analysis

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1 Executive Summary

This report provides a requirements specification for our robotics capstone project. Through this document we aim to sufficiently specify the requirements for our project.

1.1 Project Overview

The goal of this project is to build a multi-agent system that collaboratively and efficiently recreates inputted images at variable scale. This system can be used for either reproducing works of art on a larger scale for aesthetic purposes or for marking elements of infrastructure. By using a team of robots that work together, as opposed to a single robotic system, we hope to gain greater efficiency as well as explore various coordination schemes.

1.2 Document Outline

Following this executive summary, we begin by outline the purpose of our project, including its goals (Sec. 2.1) and motivation (Sec. 2.3). We detail both our intended scope in this project (Sec. 2.4) and assumptions we make about our environment and operation (Sec. 2.5).

We then identify scenarios where our system could be deployed (Sec. 3). From these scenarios we can describe the various use cases of our system (Sec. 4).

This various scenarios informed the requirements of our system(Sec. 5). We begin by identifying our functional requirements (Sec. 5.1), which define the functionality of our system. Next we detail our non-functional requirements (Sec. 5.2), which provide us with testable performance benchmarks.

2 Project Description

We plan to build a multi-agent autonomous robotic drawing system. Our goals, motivation, definitions, scope and assumptions are provided below.

2.1 Product Goal

The goal of our project is to use robotics to bring people's ideas on paper into a reality. We aim to build a system that takes an image as input and reproduces that image on some surfaces, such as ground, poster, or pavement. This direct interaction with the physical world drives much of our design, as well as the need to use a dispensable writing tool, such as chalk or marker.

By using multiple robots, we hope to efficiently decompose a possibly large task into smaller, independent pieces which could be completed in parallel. In doing so we can also explore various coordination and scheduling strategies that naturally arise in a multi-robot scenario.

2.2 Definitions

System. The system includes all robots, user interface and any accessories, such as localization markers.
Robot. A single robot agent within the system.

2.3 Motivation

Traditionally robots have been pitched as excelling in the three D's: dull, dirty and dangerous. Our project primarily focuses on automating a dull task. The United States has nearly 47,000 miles of interstate highway and more than 5,000 airports with paved runways [1]. Each of these pieces of infrastructure in delineated and marked with drawn lines, which, when worn, must be repainted. These tasks are time consuming, expensive and, in many occasions, dirty, for example painting bicycle lanes would cost on average 133,170 dollars per mile [2].

By enabling robotic automation in painting these lines, we can improve the quality of our infrastructure while saving time and money in the long term. We can expand past transportation infrastructure to sporting arenas. Sports such as baseball, football or American football have fields with markings that must be regularly maintained to insure fair game play.

While this robot can serve a very functional purpose, it is not without its playful side. The robot can potentially be used as a children's toy for bringing the imagination of drawings to life.

While a fully operational system would ideally be able to cover all of the above motivational examples, we do not expect our system to. We discuss the expected scope of our project in Sec. 2.4.

2.4 Product Scope

While our system has a great deal of potential, we want to ensure that we can reasonably achieve testable goals. Therefore, in this section we will discuss robotic function and scenarios which are out of scope of this project.

We describe as system has being a multi-agent system. Based on our task, the number of robots in the system could scale up infinitely. Due to time, cost and planning constraints, we begin with a multi-agent system of two homogenous robots.

In our motivation and goal, we mention large scale applications such as airport runways and stadiums. However, for ease of testing we intend to primarily target this early version to smaller scale projects, such as drawing a design on a large, indoor poster.

Inherently, there is little that prevents our proposed project from scaling in this dimension aside from increasing the durability of our system. This level of durability, to functional well outdoors, is considering out of scope at this point.

In describing the functionality of our robot, we have purposefully not specified the exact type of writing implement. There are many possible tools including by not limited to chalk, marker, liquid chalk, etc. While we hope to explore several of these options, we do not anticipate being able to explore all options equally.

Delving further into writing implements there are also many smaller, interesting sub-points that we do not believe we will be able to build, such as drawing with multiple colors simultaneously or accounting for a large variety of sized writing tools.

2.5 Assumptions

In designing and parameterizing the needs of our system we will make the following assumptions about or environment and operation:

A1: We assume that our drawing surface is free of any obstacles.

A2: We assume that our system functions indoors, thus removing the need to handle various weather conditions.

A3: We assume that the robots are working on flat, homogenous surface. This disqualifies uneven or muddy ground, which is considered out of scope (Sec. 2.4).

A4: We assume that the writing implement being used by each robot in the system can be loaded into the robot manually by a human. Thus we do not expect our robots to auto-load writing tools.

A5: We assume that the writing implement can by used by making contact between the tip of the implement and ground, such as a pencil. This assumption removes using writing tools like spray paint.

3 Scenarios

RH: Need to rework this as our scenarios are more like applications.

The robotic drawing system has many use cases, three of which are detailed below. These scenarios then informed the use cases, described in Sec. 4. These are the scenarios that motivate this project and are the scenarios that a fully developed multi-agent autonomous robotic drawing system is expected to achieve. However, for the scope of this class, the focus on the chalk drawing scenario, as detailed in Sec. 3.1, in an indoor environment.

3.1 Chalk Drawing

Chalk drawings are often used around campuses and different communities for aesthetic purpose, information sharing, and events announcements, as seen in Fig.1. However, these drawings are often limited by size and complexity of the drawing. Therefore, the robotic system will be designed to draw large-scale items on blacktop or asphalt surfaces with chalks.

Since chalk will be the main painting tool in this scenario and these robots may work outdoors, we need to design the system to prepare for situations like drawing on relative wet surfaces and protecting chalk from rain or excessive humidity. We also need to design the system to accommodate the fact that chalk becomes shorter as it is used.

Figure 1: Various Examples of outdoor chalk drawing for pure fun or more serious announcements.

Figure 2: Airports rely on gridlines (left), which are currently painted and repainted by human operators (right).

3.2 Infrastructure Lane Drawing

Drawing infrastructure lanes, such as those for parking lots, highways, streets, and airports, can often be dull and expensive [3, 4]. For example, in Fig.2, the massive amount of routing lines that airport runway systems rely on. However, these lines are usually painted via a human operator in a repetitive and time-consuming manner. This leaves an opportunity to improve this process through a robotic system.

Since the drawn lanes must be smooth and consistent, motor control becomes critical in this scenario. Completing this scenario requires working outdoors. Therefore, the robotic system needs to be more robust both in hardware and in software. The mechanical parts need to be weather resistant to a certain extent and the programming scripts need to account for unpredictable situations when working outdoor.

3.3 Sport Lines

Drawing lanes for sports fields, including soccer fields, football fields, basketball court, etc, could be another scenario for this robotic system. Similar to the infrastructure example, these lines are quite repetitive and must be redrawn often to ensure a quality field. Sports lines are especially motivating as labor can constitute around 95% of their maintenance costs [5] [6], which a robotic drawing system could help reduce.

When painting certain sports fields, like soccer fields or football fields, these robots need to travel

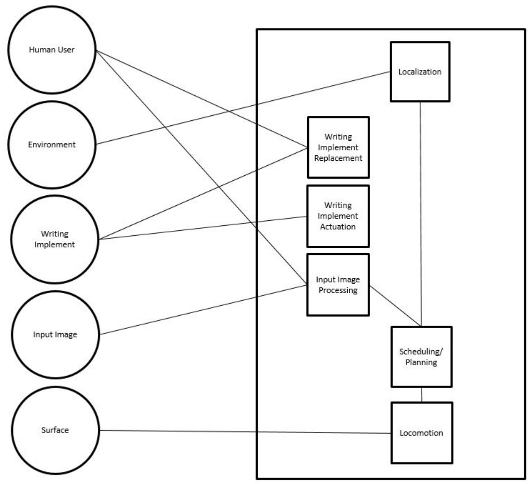

Figure 3: Diagram representing the relationship between use cases and actors in the system

on uneven surfaces, such as grass. Therefore, better suspension and drive system will be designed to complete these tasks. Similar to the infrastructure lane drawing scenario (Sec. 3.2), the robotic system needs to guarantee the quality of drawing lanes and being weather resistant.

4 Use Cases

RH: Lots of changes to individual use cases and how we consider them in general.

In detailing the various scenarios that our system might encounter, described in Sec. 3, we developed a series of common uses cases that are necessary to the robot's functionality. These use cases are intended to describe the key functions of our robot and are further used to inform the requirements listed in Sec. 5.

New Image

4.1 Reload Writing Implement

Summary: A robot's main consumable, the writing implement, must be reloaded or replaced when empty or when a different implement (with different color or stroke) is desired.
Actors: Writing implement, human
Precondition: No writing tool in the system or the one that is currently loaded is no longer needed for the task.
Post-condition: System has desired writing tool loaded.
Alternative: If the robot is unable to load the implement then the system should report improper loading results to the user. Additionally, other robot agents should be told that the robot to be reloaded is broken, and therefore cannot draw. Hence, in order to complete the picture the other robots must re-plan accordingly.
Description: When the robot is working on a large or intricate drawing that requires a large amount of consumable writing material, the robot may not be able to carry enough material to

complete its allocation of the drawing. Additionally, some drawings may involve a variety of colors, strokes, or other properties that necessitate the use of different writing materials. Thus, the robot must be able to replace its writing implement with human assistance. The robot must be able to recognize reloading failures and alert the human operator of their occurrences. If the failure is not corrected, The robot must communicate its inability to perform to other robots in the system so they can re-plan drawing paths accordingly.

4.2 Process Input Image

Summary: The system must take in a human-provided image and interpret what the robot system is required to draw.
Actors: Image, Human
Precondition: No existing image being actively drawn by the robot system.
Post-condition: The image is processed and ready for work distribution between robots.
Alternative: If this step fails the robotic system should report an image processing failure.
Description: The system's task will be input using a human-produced image following specific guidelines. From the image, the system can determine where to place markings in the real world, and how the work should be distributed amongst the robot workers.

4.3 Localization

Summary: The robot must be able to determine where it is in the world.
Actors: Environment
Precondition: If the robot needs to localize, then there must be a large amount of uncertainty about current location and orientation of the robot.
Post-condition: Following localization we hope to have minimal uncertainty about the current location and orientation of the robot.
Alternative: If the robot cannot localize then this should be reported to human operator and the other robots should be alerted of the robot's inability to localize and orient itself. Additionally, any robot that cannot localize can potentially draw incorrectly or collide with another component of the system. Thus any robot that fails to localize should halt all movement.
Description: In order to create an accurate reproduction of the input image, the robot know how its location maps to a location on the input image. If it is unable to do so, it cannot continue drawing and must alert other robots to the fact so that they can re-plan and reschedule the workload.

4.4 Scheduling and Robot Planning/Coordination

Summary: The robot workers must determine an efficient allocation of the work.
Actors: Robots, Input image
Precondition: No plan or schedule currently exists.
Post-condition: Each robot has an allocation of work and a planned path.
Alternative: If we fail the plan, the human user is alerted and the operation is aborted.

Description: The work required must be determined from the input image, and analyzed to determine an efficient allocation of work, as well as a path schedule for each of the robots. Additionally, robots must communicate work completed and failure states to each other in case re-planning is required.

4.5 Move Robot

Summary: The robot moves across flat terrain.
Actors: Ground
Precondition: Robot is stationary.
Post-condition: Robot is moving as commanded.
Alternative: If the robot is unable to move, the the human user is alerted and work is redistributed between remaining robots.
Summary: The robot moves across the writing surface, using its writing implement when required.

4.6 Use Writing Implement

Summary: The robot creates a mark on the writing surface.
Actors: Writing surface, Writing implement
Precondition: The robot has a plan to draw an mark, but that mark has not currently be drawn yet.
Post-condition: The robot's planned mark is drawn on the writing surface.
Alternative: If the robot cannot write, the robot alerts user that the writing implement must be replaced (or inserted if one does not exist).
Summary: The robot creates markings on the surface with the given writing implement, and ensures that its movements do not disrupt drawing accuracy.

5 Requirements

We outline our system's requirements, both functional and nonfunctional. A priority number is provided for each requirement. The system requirements are prioritized on a Likert scale from 1 to 7, detailed below. To describe the scale, a 1 is considered a desirable but unnecessary requirement, a 4 is considered a necessary requirement but open to significant changes, and a 7 is considered an uncompromisable requirement for a minimum viable product.

	Lowest (1)	Low	Medium-Low	Neutral (4)	Medium-High	High	Highest (7)
Priority	☐	☐	☐	☐	☐	☐	☐

5.1 Functional Requirements

FR1: Omnidirectional Movement Priority 7

· Robots must be able to move instantaneously in any commanded direction on a 2D plane represented by the floor of motion. Omnidirectional movement is necessary to ensure agents can adequately and efficiently cover the drawing workspace, while simultaneously being able to draw lines of varying curvature.

NJ: Feedback underlines some words and has an X, not sure what to change **FR2: Autonomous** Priority 6

· Given an input image to draw, robot agents must be able to autonomously complete the drawing. This includes the following steps: processing the input, planning and commanding individual agents, and having robots move and draw without external input. We allow for human intervention only in the case of system failure.

FR3: Robots Localize Globally and Locally Priority 7

· All drawing robots can determine their locations and orientations on a global and local scale. Global scale is relative to the localization markers and the specified drawing surface. Local scale is relative to other robot agents. This requirement is necessary so the robot system can coordinate planning together to avoid collisions or an inefficient spread of work. Robot localization should be accurate to within one inch - that is, each robot agent should know its position to within 1 inch of its true location and within 10 degrees of its orientation.

FR4: Within Bounds Priority 3

· While in operation, all robot agents must stay within bounds of the workspace. This is important to minimize external collisions, including possibly unsafe interactions with the world, as well as to ensure localization maintains accuracy while drawing occurs.

FR5: Insert Writing Tools Priority 2

· A writing implement must be able to be inserted by a user into one robot under 1 minute. New writing implements will need to be inserted whenever existing ones become unusable, or upon first-time setup.

FR6: Remove Writing Tools Priority 2

· .A writing implement must be able to be removed from a single robot by a user under 1 minute. Writing tools will need to be removed when the existing implement becomes unusable.

FR7: Replace Writing Tools Priority 2

· A user must be able to remove and then insert a writing implement. Following in accordance with Functional Requirements FR5 and FR6, this process must be done in under 2 minutes. Tool replacement is necessary whenever an existing tool becomes unusable for system operation.

FR8: Reliable Communication Priority 7

· Robot agents and any system controllers must have the consistent ability to communicate between each other. This is necessary to ensure accurate and timely planning, and status updates between agents. Connection strength must be such that send information to each other within 1 second.

FR9: Drive Control System Priority 5

· Robot agents must have a controller to ensure motions made are accurate. Accurate motions is paramount to ensure an accurate drawing. The drive control system must be in compliance with motion accuracy parameters, as specified in functional requirement, FR**??**.

FR10: Turn on or off writing tool Priority 1

· All robot agents need to be able to enable or disable use of the writing implement. The robot must also have the ability to move regardless of the state of the writing implement. Not all drawings are contiguous lines, and as such the robots must be able to disable the writing tool to move to a new drawing location.

FR11: Input Drawing Plan Priority 6

· The main system controller must be able to receive an input that allows it to command the robot agents to draw an appropriate image. The system must be able to parse the input into a state usable for robot planning and control in order to draw the input.

FR12: Robots Know Progress Priority 2

· All robot agents are required to understand how much of the drawing each one has completed, and which sections are left to be drawn. This is necessary to ensure an equal spread of workload across all robot agents. The ability to communicate progress can be guaranteed by consistent inter-robot communication, as defined by FR8.

FR13: Kill Switch Priority 3

· Human bystanders must be able to end all system operation instantaneously with a kill switch or power button. This is necessary to ensure that the system can be shut down in case of an unsafe error or problem.

FR14: User Interface to robot Priority 1

· An intuitive and useful user experience is necessary for efficient usage of the system. Having a simple to operate system also reduces the likelihood of user error during the input or operation stage. For industrial or commercial applications, accessibility becomes important as well. A quality user interface can be tested by running a user study or survey with potential users.

FR15: Battery Power Priority 4

· Individual robot agents must be able to run continuously for a minimum of 30 minutes before needing battery charging or replacement. This will provide enough time to complete a minimum of a single drawing.

5.2 Non-Functional Requirements

NFR1: Documentation Priority 3

· Documentation of the design process, software, and hardware implementation is important for debugging, recreation, and general understanding of this project.

NFR2: Error Handling Priority 6

- The system must be able to handle errors appropriately. This includes problems that arise from localization, locomotion, planning, or using the writing tool. The system must be able to determine, based on conditions of the failure, whether to halt all operation or to continue without using broken subsystems. Errors can occur inside of any of the use cases listed in Sec. 4.

NFR3: Weight Restriction Priority 4

- Individual robot agent weight must be under 50 pounds. This is one step in ensuring portability of the individual agents.

NFR4: Size Restriction Priority 5

- Individual robot agent size must be able to fit within a standard doorway. This is defined as 80 in. x 36 in. [**?**].

NFR5: Efficiency Priority 2

- Robot system must be efficient and complete drawing tasks quickly. Timeliness can be measured by the amount of time taken to complete drawings. Robot planning must also exist in such a manner that evenly splits the workload among all robot agents working in the system. Therefore, a speedup of a maximum of 2x the rate is expected when using two robots as opposed to one. The system should perform as fast or faster than a human attempting the same drawing task.

NFR6: Quality Priority 4

- The drawing that results from the robotic system must closely match the input image. Quality can be qualitatively measured by visual comparison, or using software via a number of image difference metrics.

NFR7: Mobile App Priority 1

- User interface and experience will be done using a mobile application. This application will allow users to remotely input images for drawing, enable, disable, and pause the robot system's operation. The app will also be able to track and display current progress.

NFR8: Reliability Priority 6

- Robot system must be robust, and be resilient to breaking down or failing to operate properly. Reliability can be measured by percent uptime relative to total time spent in use.

NFR9: Coordination Priority 4

- The key to a multi-robot agent system is to reduce the individual workload, meaning having coordinated and efficient work is vital. Robots must be able to work together to minimize overlap in the drawings, and to avoid duplicating work. A two-robot system that coordinates must perform faster than a single robot performing the same task.

NFR10: Budget Priority 7

- Design and implementation of this robotic system is limited by budget, which must be strictly adhered to. The budget is limited $2500.

NFR11: Safe Priority 4

- Robots must maintain safety with respect to each other and the external world at all times. This requires that all robot agents avoid collisions. Robot agents must also have an enforced maximum speed limit to avoid damage to themselves or human bystanders in case of collision.

NFR12: Positional Accuracy Priority 7

- Robots must be able to move with a positional accuracy of a 1 inch radius for every 3 feet of motion. Tight positional accuracy is vital to ensuring the robots can accurately complete the drawing.

NFR13: Rotational Accuracy Priority 7

- Robots must be able to turn with a rotational accuracy of within 10 degrees per 90 degrees turned. Similar to Sec. 13, rotational accuracy is necessary for the robots to accurately complete the drawing.

NFR14: Tool Switching Duration Priority 2

- Individual robots must be able to enable or disable the writing tool within 10 seconds.

References

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