Carnegie Mellon University

Robotics Capstone Project

Requirement Specifications and Analysis

Friction Force Explorers:

Don Zheng

Neil Jassal

Yichu Jin

Rachel Holladay

supervised by

Dr. David Wettergreen

October 6, 2016

Contents

List of Figures **1**

1 Executive Summary **2**
- 1.1 Project Overview . . . 2
- 1.2 Document Outline . . . 2

2 Project Description **2**
- 2.1 Product Goal . . . 2
- 2.2 Motivation . . . 3
- 2.3 Product Scope . . . 3
- 2.4 Assumptions . . . 3

3 Scenarios **4**
- 3.1 Chalk Drawing . . . 4
- 3.2 Infrastructure Lane Drawing . . . 4
- 3.3 Sport Lines . . . 5

4 Use Cases **6**
- 4.1 Reload Writing Implement . . . 6
- 4.2 Process Input Image . . . 6
- 4.3 Localization . . . 7
- 4.4 Scheduling and Robot Planning/Coordination . . . 7
- 4.5 Move Robot . . . 8
- 4.6 Use Writing Implement . . . 8

5 Requirements **9**
- 5.1 Functional Requirements . . . 9
- 5.2 Non-Functional Requirements . . . 11

References **12**

List of Figures

1. Various Examples of outdoor chalk drawing for pure fun or more serious announcements. . . . 4
2. Airports rely on gridlines (left), which are currently painted and repainted by human operators (right). . . . 5
3. Model for reloading the writing implement (left) and model for processing the input image (right). . . . 7
4. Model for localization . . . 8
5. Model for scheduling and robot planning/coordination (left) and Model for moving a robot (right) . . . 9
6. Model for using the writing implement . . . 10

1 Executive Summary

This report provides a requirements specification for our robotics capstone project. Through this document we aim to sufficiently outline 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. 2.2). We detail both our intended scope in this project (Sec. 2.3) and assumptions we make about our environment and operation (Sec. 2.4).

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, scope and assumptions are provided below.

2.1 Product Goal

The goal of our project is to use robotic 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 surface, 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 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.

2.3 Product Scope

While our robotic system has a great deal of potential, we want to insure 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 immeasurably. Due to time, cost and planning constraints, we begin with a mutli-agent system of two 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 outside, 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, spray paint, 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.

2.4 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 the robots are working on flat, homogenous surface. This disqualifies uneven or muddy ground, which is considered out of scope (Sec. 2.3).

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

A2: 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-loaded.

A3: 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.

A4: We assume that between the robots and any controlling host we have near perfect, clear communication. Therefore we will not account for scenarios with excessive noise that would compromise robot communication.

3 Scenarios

Our drawing robotic system has many use cases, three of which are detailed below. These scenarios then informed our use cases, described in Sec. 4.

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, we plan to design our robotic system to draw large scale items on blacktop or asphalt surfaces with chalks.

Drawing designs will be loaded to the control hub which will then analyze the images and generate paths for each robot to follow. Each individual robot will receive commends from the control hub and proceed to complete its responsible section. If these robots encounter any errors or difficulties during the painting process, they need to notify the control hub to make further decisions. Since chalk is the main painting tool in this scenario and these robots may work outdoors, we need to design the robot to be ready for drawing on relative wet surfaces and be able to protect chalk from rain or excessive humidity. Chalk becomes shorter as it is used more; a mechanism that is insensible to chalk's length and can ensure chalk tip always be in contact with the ground is needed.

3.2 Infrastructure Lane Drawing

Drawing infrastructure lanes, such as those for parking lots, highways, streets, and airports, can often be dull and expensive. For example, in Fig.2, we can see the massive amount of routing lines that airport runway systems rely on. However, these lines are usually painted via a human operator. Therefore, we have the opportunity to improve this task through our robotic system.

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

Digital or physical engineering drawings of the intended lanes will be scanned and loaded into the control hub which then delegates tasks to different robots. Each robot will be in charge of drawing lanes within a bounded area defined by the control hub. When drawing lanes, each robot has to travel at a constant speed and deposit the ink evenly, because the drawn lanes need to be smooth and consistent.

Therefore, motor control becomes critical during this process. During the drawing process, if any robot runs out of ink or experiences any sort of accident, it needs to report its status to control hub. The control hub will command it to return home base to change painting tool, call other robot to cover its task or call for human control.

When drawing is done, all robots will return to home base automatically. Since completing this scenario requires working outdoors, these robots need 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 possible 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 our infrastructure example, these lines are quite repetitive and must be redrawn often to ensure a quality field.

Also similarly to the infrastructure lanes drawing, engineering drawings of the designed lanes will be loaded into the control hub which will assign tasks to each individual robot. These robots will then proceed to painting the lanes with the goals of making lanes smooth and straight. If an error occurs with any robot, such error message will be reported to the control hub. The control hub will then makes decision on calling the robot back or calling for human control. Robots will return to home base automatically when finished painting. When painting certain sports fields, like soccer fields or football fields, these robots need to travel on uneven surfaces, such as grass fields. Therefore, better suspension and drive system will be designed to complete these tasks.

4 Use Cases

In detailing the various scenarios that our robot 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.

4.1 Reload Writing Implement

Summary: The 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 tool, 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 robot agents in the system so they can re-plan drawing paths accordingly.
Model: Fig.4.1.

4.2 Process Input Image

Summary: The robot 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 agents.
Alternative: If this step fails the robotic system should report an image processing failure.
Description: The robot's task will be input using a human-produced image following specific guidelines. From the image, the robot can determine where to place markings in the real world, and how the work should be distributed amongst the workers.
Model: Fig.4.1.

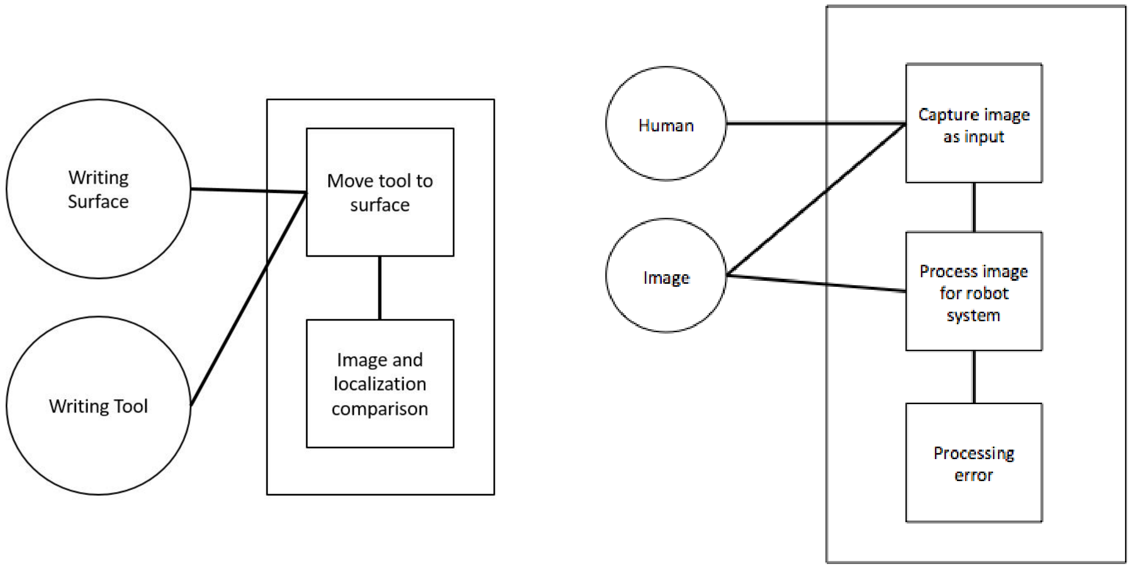

Figure 3: Model for reloading the writing implement (left) and model for processing the input image (right).

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.
Model: Fig.4.

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.

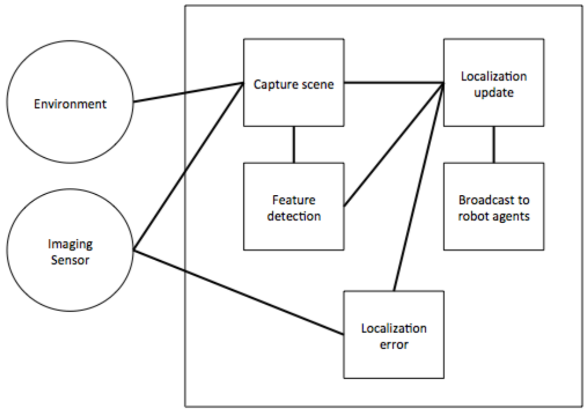

Figure 4: Model for localization

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.
Model Fig.5.

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.
Model: Fig.5.

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.

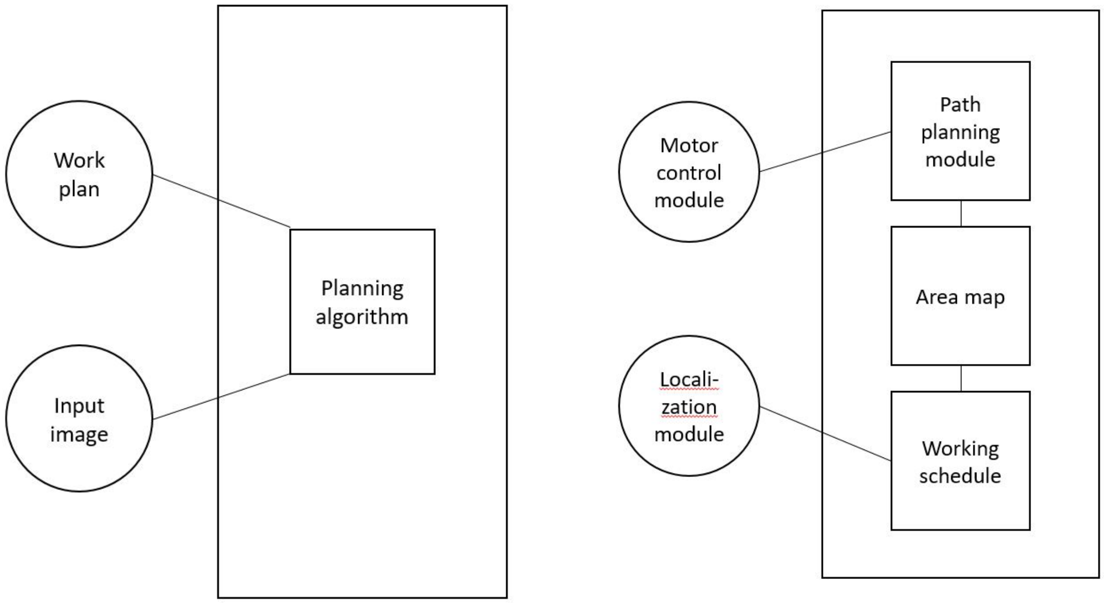

Figure 5: Model for scheduling and robot planning/coordination (left) and Model for moving a robot (right)

Model: Fig.6.

5 Requirements

We outline our systems requirements, both functional and nonfunctional. For each requirement we provide a number, for each of reference, a short description and a longer explanation. We prioritize our system requirements on a Likert scale from 1 to 7, detailed below.

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

5.1 Functional Requirements

FR1: Move in Specified Directions Priority 7

Robot must be able to autonomously move in a commanded direction on a flat plane. Omnidirectional movement is necessary to ensure robot agents can adequately and efficiently cover the drawing workspace.

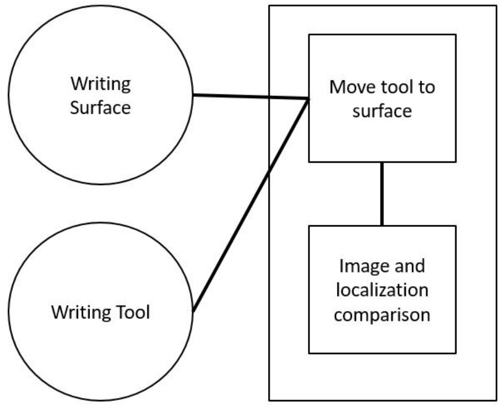

Figure 6: Model for using the writing implement

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.

FR4: Safe Priority 4

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

FR5: 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.

FR6: Change Writing Tools Priority 2

- Inserting, removing, and replacing writing implements must be convenient and fast.

FR7: 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.

FR8: 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 safely and accurately 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.

FR9: Input drawing Plan Priority 6

· The main controller system 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.

FR10: 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.

FR11: Kill Switch Priority 3

· Human bystanders must be able to end all robot 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.

FR12: User Interface to robot Priority 1

· An intuitive an 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.

FR13: Be In Budget Priority 7

· Design and implementation of this robotic system is limited by budget, which must be strictly adhered to.

FR14: Documentation Priority 3

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

5.2 Non-Functional Requirements

NFR1: Portable Priority 4

· Individual robot agents must be easy to move between locations. Portability can be measured by physical dimensions and weight.

NFR2: 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, we expect to observe a noticeable speedup when using two robots as opposed to one.

NFR3: 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.

NFR4: 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.

NFR5: 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.

NFR6: Battery Life Priority 2

· Individual robot agents must have a battery life capable of completing a minimum of a single drawing. Battery life can be measured by duration for which robot agents are in use before needing battery recharging or replacement.

NFR7: 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.

References

[1] Building America's Future. http://bafuture.org/key-topics/transportation. *Accessed 6 Oct. 2016.*

[2] Bushell, Max; Poole, Bryan; Rodriguez, Daniel; Zegeer, Charles. (July, 2013). *Costs for Pedestrian and Bicyclist Infrastructure Improvements: A Resource for Researchers, Engineers, Planners and the General Public..*