Spring 2021

Adaptive Deposition of Difficult Materials

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ENTITLED

ADAPTIVE DEPOSITION OF DIFFICULT MATERIALS

BE ACCEPTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS
FOR THE DEGREE OF

BACHELOR OF SCIENCE
IN
ELECTRICAL ENGINEERING

6/5/21

Thesis Advisor(s) (use separate line for each advisor) date

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ADAPTIVE DEPOSITION OF DIFFICULT MATERIALS

By

Abel Daniel, Emily Holden, Gabriela
Sanches Carvalho Silva

SENIOR DESIGN PROJECT REPORT

SANTA CLARA UNIVERSITY

in Partial Fulfillment of the Requirements
for the degree of
Bachelor of Science in Electrical Engineering

Santa Clara, California

Spring 2021

Abstract

When using a robotic arm, the path that the arm follows is typically unique to the task it completes, but not to the object upon which the task is performed. Additionally, when extruding materials, those materials are typically easy to work with (i.e. smooth and uniform). In this paper, we discuss our three-pronged approach, focusing on the imaging of the cupcake, the robotic arm's movement about the cupcake, and the extrusion method, to achieve this goal of, simply-speaking, decorating a cupcake. While our results were not optimized or as broad as we'd initially hoped that they would be, we were able to decorate the cupcake in a reliable manner using all three components of the project. We ran into many issues along the way, but did find this to be a relatively successful project with many avenues for continuing research. Future research relating to this project should focus on three main avenues: an optimized image measurement system; increasing the vocabulary of designs for the robotic arm and optimizing them; and creating an automized system for the extruder with a frosting of a better consistency.

Acknowledgments

Our team would like to thank our Advisor, Dr. Wolfe, for his dedication and his guidance, without him we would have never made it to the end. We'd also like to thank Dr. Shoba Krishnan, Dr. Cary Yang, and all the other Professors and Advisors, without whom we would never be here. We'd also like to thank our families, for their support through the year, it meant the world and we got through it for you.

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Chapter 1: Introduction

1.1 An Open Market

While we live in an era of mass production, many of the tools used in these processes have a key flaw: They are not adaptive and often shy away from the use of difficult materials. For our project, we decided to therefore undertake trying to combat both issues with a proof of concept using difficult materials, cupcakes and frosting, to extrude adaptive designs that would conform to a cupcake's unique shape.

While there is currently a large market for robot-assisted tasks and machines that decorate mass-produced cupcakes, there is still a prevalent problem: When the objects being used for the tasks are inconsistent, the robotic mechanisms become unreliable and therefore are not commonly used. If the materials the robots extrude are difficult in addition to the objects to be extruded on lacking uniformity, there can be a lack of precision reminiscent of a game of pin the tail on the donkey. In order to execute the same action well on non-uniform objects, the machines must adapt to that specific object to make the desired outcome attainable. The current products on the market avoid these issues by relying upon the uniformity of mass-produced products to alleviate them.

Difficult to maneuver materials are often shied away from in mass production. They can be viscous, elastic, and sticky; frosting is a superb example. The extrusion of these materials can therefore be difficult to control. Additionally, the surface upon which the extruded materials will be placed can be imperfect. This means that it can be soft and have a unique shape; homemade cupcakes exemplify these characteristics. Because of the difficulties regarding maneuvering both of these materials, cupcake decorating, especially on a home baking level, is a distinctly human job. As difficulties arise with either the frosting or the specific cupcake that we're working on, we are able to instantly adapt so that we can create somewhat similar designs on a batch of cupcakes despite these obstacles; robots must take into consideration many pieces of data to do what humans innately do.

1.2 Current Markets

Our project therefore tackled two main markets: Construction robots working with difficult materials and automated decoration devices. While these markets can seem incompatible, they both face many of the same challenges.

Construction robots that work with difficult materials can often use difficult to extrude materials, but they often introduce unnecessary waste and still need human intervention to complete their intended tasks [1]. A prime example is Construction Robotics Semi-Automated Mason, or the SAM100 for short [2]. The SAM100 was introduced to the bricklaying market several years ago and has since been used on several construction projects like the UMHHC Brighton Health Center South in Brighton, Michigan, and the POFF Federal Building in Roanoke, Virginia, which laid 17,000+ utility bricks and 250,000+ modular bricks, respectively [3, 4]. However, this tool is not self-sufficient. As indicated in the name, it requires human intervention. The device extrudes its adhesive (mortar) upon the brick before placing it along the brick wall where the mason wipes away its excess, checks alignment, and works toward overall wall quality [5]. While this machine is successful in increasing productivity, reducing labor costs, and increasing safety for the mason workforce, it could be improved. If more adaptive methods were used, there could be a reduction in waste, higher wall integrity, and a decreased need for human intervention.

Decoration devices are also extremely non-adaptive. Truly automated decoration devices are focused on an industrial scale, meaning that they rely upon the uniformity of the objects upon which they extrude. A key example is Unifiler's (a Linxis Group subsidiary) Cake-O-Matic 1000i, the Self-Adjusting Cake Icer [6]. While self-adjusting is in its title, this characteristic is in regard to small differences between batches of extruder material. The sales documentation for the device proclaims its success for uniform portions of a cake's frosting, i.e., layers of filling and the base icing for the top and side of a circular cake. The Cake-O-Matic 1000i uses a stationary extrusion position in order to pump out flat and uniform extrusion paths on flat and uniform layers of cake. This is a common trend of automated decoration devices: They require flat surfaces to extrude upon, which completely neglects non-industrial settings. This is true of other types of decorators, as well, including the iView Picasso Smart Art Industrial Food-Grade Printer, a device that “prints" images using an edible ink cartridge but requires a flat surface to print upon [7].

Neither of these markets fully address the issues that we wanted to tackle: adaptivity and an efficient use of difficult materials.

Chapter 2: Statement of Problem and Objectives

2.1 Statement of Problem

When using a robotic arm, the path that the arm follows is typically unique to the task it completes, but not to the object upon which the task is performed. Additionally, when extruding materials, those materials are typically easy to work with (i.e. smooth and uniform).

2.2 Objectives

Throughout the course of this project, our objectives did alter slightly but remained generally consistent. Our objective in its purest form was to decorate a cupcake. To do so, however, we needed to find the measurements of a unique object, a cupcake, using imaging software, and then use those measurements to alter a pre-coded design, and finally create an extrusion method that would make the design in the physical world. This project is a proof of concept that difficult materials can be extruded reliably and precisely on non-uniform objects.

Chapter 3: Project Plan and Methodology

3.1 Project Plan

As Electrical Engineering majors, we worked on this project for four quarters. We looked to our advisors, our predecessors, and our professors in order to try to come up with the best plan of action for our project. However, because all four of the quarters that we were working on this project were in the midst of a pandemic, we did have to adapt our goals throughout its longevity.

3.1.1 Spring 2020

In Spring 2020, Dr. Andre Wolfe first introduced this project to the Electrical Engineering Department's juniors, and at the end of the quarter we, Abel Daniel, Emily Holden, and Gabriela Sanches, formed a team to work on the project under the supervision of Dr. Wolfe. The first few meetings of our team focused on discussing each members' technical backgrounds so that the limitations of this project could be defined. During Summer, we decided to focus on researching and understanding more about robotic arms so that we could purchase the hardware we would need by Fall.

3.1.2 Fall 2020

During Fall quarter, we first studied how to use a robotic arm with 4 degrees of freedom in order to effectively decorate the cupcakes, yet after extensive research and advice from Dr. Wolfe, we decided that we would need a robotic arm with at least 6 degrees of freedom. Dr. Wolfe was kind enough to allow us to buy the robotic arm himself so that we could go above the budget provided by the School of Engineering. Toward the end of the research portion of this project, we were deciding between the Niryo One Robotic Arm and WLkata 6-Axis Mini Robot Arm Mirobot Education Kit [7], [8]. *Table 1* below, compares the robots' attributes that we were considering for this purchase. Thus, based on these specifications and a budget of around two thousand dollars for the robot purchase, we chose the Niryo One Robotic Arm with a heavy benefit being its compatibility benefits.

Table 1. Robotic Arm Comparison

Point of Comparison	Niryo One 6-Axis Robotic Arm for Education	WLkata 6-Axis Mini Robot Arm Mirobot Education Kit
Price (pre-tax, pre-shipping)*	2k	1.3k
Weight (kg)	3.2	1.5
Interchangeable Grippers	Yes	Yes
Grippers Included w/ Purchase	1	3
Educational Amenities	Lessons online including technical support	Graphic Programming
Operating Board	Raspberry Pi	Arduino
Programming Language	Wide Variety including Python, ROS, Matlab, and Blockly	Python and Matlab only
3D Simulation Capability	Yes	Only thru external devices

**The pricing written is from Fall 2020.*

3.1.3 Winter 2021

In Winter 2021, we decided to divide the work into three parts because of the constraints caused by the pandemic. In those divisions, each member would lead one part of the project with a second member as an auxiliary. Abel was the lead of the Raspberry Pi group with Gabriela as the auxiliary member of the team. Emily was the lead of the extruder team with Abel's help. Finally, Gabriela was in charge of the OpenGL portion (which turned into a Python, ROS and mathematically focused team) with Emily's help. However, the members continuously worked together on the writing assignments, presentations, and other needed documentation.

3.1.4 Spring 2021

During spring quarter 2021, our team was the busiest because of the deadlines like the Senior Design Conference that came up throughout the quarter, as well as the in-person integration of the project. We were responsible for finishing our specific parts of the project together and connecting them so that they would work properly. Below is a more detailed description of the different tasks. The final products of the Spring quarter are detailed further as our results for the project.

3.2 Methodology

Due to the separation that we had to face because of Covid-19, we decided to split up the three main portions of our project. We had to continuously adjust to both constantly changing Covid-19 restrictions on top of the hardware and software issues that arise in all projects. However, like our project's title implies, we learned to adapt in order to complete our project.

3.2.1 Robotic Arm Methodology

At the start of the project, the OpenGL portion of the project had the intent to control the robotic arm's movement and design library. However, as the project progressed, we shifted away from this imaging software and transitioned to focusing on the robotic arm's movement and the math behind it.

3.2.1.1 OpenGL Limitations

During the research phase, we read a lot about the benefits of OpenGL and initially believed that it would be the ideal program to use. As we found out, even with an immense number of online resources, OpenGL was a code that was difficult to both understand and to use**.** Nonetheless, a few models were still created. These were deemed unnecessary to the project's result. The figure below shows one of those OpenGL tests:

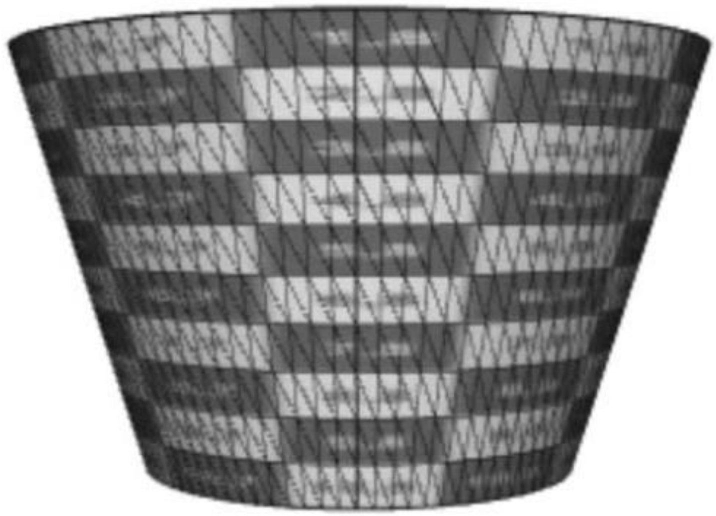

Figure 1- OpenGL Test.

Although we decided not to proceed with this method, we did learn about the coordinates that the robotic arm needed to account for. *Figure 1* helped us visualize the coordinates that we would need in order to control the robotic arm.

3.2.1.2 Robotic Operation System

Niryo One's developers provided documentation regarding all the programming languages that have been explored in relation to their robot, so we looked through that documentation to explore what programming languages we could use to program the arm's movement. On their website [7], they have examples using Blockly, MATLAB, and a Python integrated with Robotic Operating System (ROSPY). Because MATLAB is often used in our electrical engineering classes, we decided to explore this option first while still exploring the ROSPY language. However, after some initial tests with MATLAB and ROSPY, the latter proved to be more user friendly than MATLAB. Developers also seemed to prefer ROSPY, meaning that there was more documentation available to work with. The use of ROSPY also allowed us to work with the Niryo One Studio (the native application for the robotic arm) open at the same time, facilitating calibration and small tweaks.

3.2.1.3 Complementary Methods

In order to use ROSPY, we used a Mac desktop computer that we attached to the robotic arm. However, to do so we had to erase the computer's original operating system and download Linux to work with Ubuntu [9]. Additionally, we needed to purchase an external hard drive in order to accommodate the Linux system and the Niryo One Studio that we were using to decorate the cupcake. In the end, we used Python, and ROS in the Linux system in order to achieve the robotic arm's movement goals. Finally, in order to complete the tests, we used a hair band to attach a marker to the robotic arm to demonstrate and visualize the movement of the robotic arm. Due to the immense number of trials required, we improvised a white board on a desk using a plastic folder and painter's tape as demonstrated in *Figure 2*.

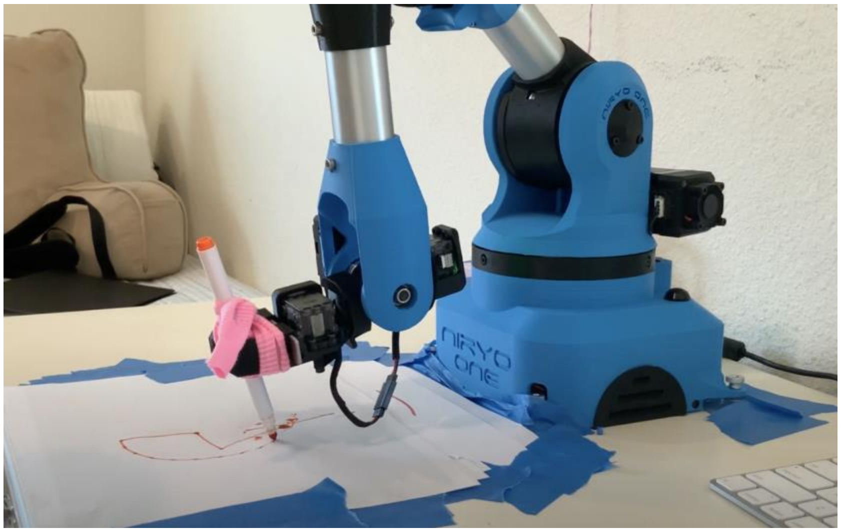

Figure 2 - Robotic Arm Testing

3.2.2 Raspberry Pi Methodology

There were multiple avenues of cupcake measurement that we investigated, all of which used a Raspberry Pi v3 and its camera extension. The objective of the Raspberry Pi was to measure the cupcake that would be decorated, and use its dimensions so that the robot could adapt its movement to each cupcake's unique size and shape.

3.2.2.1 Measuring Distance of an Object from Raspberry Pi Camera

The first tools we approached were OpenCV image processing tutorials. The first piece of code that looked interesting was a Python OpenCV one that could measure the distance from the camera lens to the object in focus [10]. This *pyimagesearch* tutorial intrigued us because it would measure more dynamically by picking certain points on the edge of a target and using those measurements to create a set of coordinates for or dimensions of the object. The source for the OpenCV code used the similar triangle rule, and required having an object in the frame of the image with a known width. By using the similar triangle identity, the object with the known width, *W*, was set a distance, *D*, away from the camera, and the Raspberry Pi then found the distance in pixels, *P*, using :

$$F = \frac{P * D}{W}$$

This equation found the focal length, *F*, and used the known width, *W*, of that object, and based on the number of pixels could find the distance from the camera by reordering the equation to become:

$$D = \frac{F * W}{P}$$

Figure 3 - Figure 3. Measurement Tool from pyimagesearch, measures distance from camera to object in focus. [10]

3.2.2.2 Measuring an Object using Reference Object with Known Dimensions

The second OpenCV code that we tried was a drastic improvement from the previous method of coordinate generation, also found using *pyimagesearch*. This code directly measures an object as long as it has a reference object in frame, with known dimensions **[11]**. Similar to the previous code, this uses the method of assigning contours to every shape in the photo, then uses the leftmost object as the control object (with known dimensions). It then counts all of the pixels that makeup that item in the image, and finds the ratio of pixels per centimeter or millimeter depending on the size of the control object. This code is significantly better than the first method. However, it did take a long time to find, which was a setback to our schedule. The only drawback of this program is that the image must be taken at a right angle to the subjects that are measured. While this seemed like a serious problem originally, the reliability of the code didn't falter when the Raspberry Pi was taking pictures at approximately 10°.

Figure 4 - Image with Reference Object Dimensions [11]

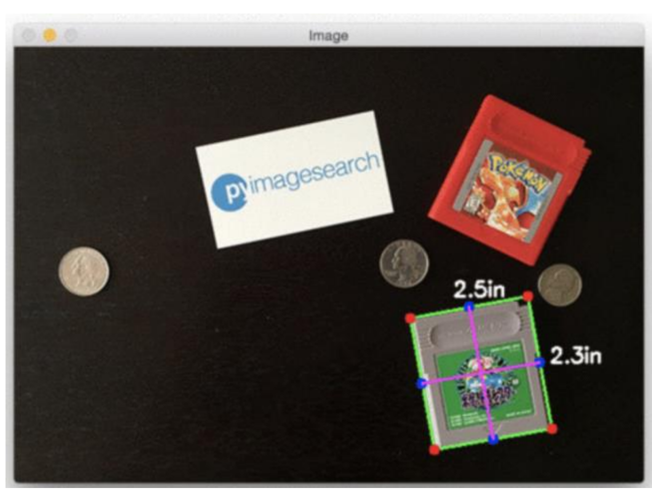

Figure 5 -. Processed Image with Measured Object and Measurements Displayed [11]

3.2.2.3 Attempted Additional functionality- Adaptive Placement of Cupcake

The function that is described in this section was a more complicated way of completing the same measurement as **Section 3.2.2.2**, while adding the ability to place the cupcake everywhere in a certain zone, rather than a fixed location.

There were 3 main functions involved in this idea; first, a perspective transformation, displayed in *Figure 6*, takes an angled picture and transforms it to the version that appears to be right angled, to apply to the function in **3.2.2.2** [12]. The other way to make the project more adaptive would be to remove the restriction of where the cupcake could be placed while being frosted. In *Figure A-5*, the reference object is still the leftmost object, and uses the same "pixels per metric" system to find the distance between the reference object and the selected object [13].

The calibration and setup of this function works in testing, however when we were moving to the space in Guadalupe Hall, we did not have the time to set up this more involved system. However, this would add more adaptive capabilities to the robot's functionality.

Figure 6 - Perspective Transform Results [12]

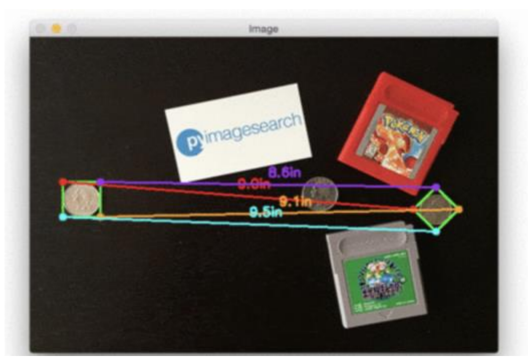

Figure 7 - Figure 7 - Measuring Distance Between Objects [13]

3.2.3 Extruder Methodology

Throughout the course of this project, we went through several iterations of extruders. We looked into different types of motors throughout this process, like a servo motor or a roller pump in order to control frosting extrusion. Our thoughts as we went through the project were to simultaneously research both motorizing methods and different extruder types to see what the best options available might be for the best combination of the two.

3.2.3.1 Extruder Motor Research

We began the project with the idea of creating our own extruder and motorization method. We started by looking at peristaltic pumps, but as we did more research, we found that these, while very useful for more liquid extruder materials, the wouldn't not be as useful for such a thick material as frosting [14]. We then shifted more toward looking into different devices that could extrude the frosting, specifically focusing on devices in the cake/cookie decorating market.

3.2.3.2 Icing Bag

We began with a typical icing bag set-up for our initial ideations [15]. However, we quickly realized that this would not be ideal as using them manually required multiple axes of movement that would have been overly complicated to achieve.

Figure 8 - The Original Piping Bag.

3.2.3.3 Wilton Dessert Decorator Plus Cake Decorating Tool and Cake Icing Tool

We then focused on a more syringe-type approach, working with the Wilton Dessert Decorator Plus Cake Decorating Tool and Cake Icing Tool [16]. This, however, brought its own set of issues. With this decorating tool, instead of having a steady syringe press of extrusion, the device used a single thumb press to unevenly extrude frosting for a short period before needing to reload and be pressed again. From our tests of the force required to make the pump extrude properly, we found that 1.5 kg, or 14.715 N, was the maximum force applied to get the frosting pump to extrude. We deemed this to be unreliable and, again, unnecessarily complicated to try to control. During this stage in our prototyping, we also began to look at motors like gripper motors, and lead screw constant pressure motors [17]. We deemed that both would have been too involved and difficult for the arm to maneuver, especially considering its limitations.

Figure 9 - The Wilton Dessert Decorator Plus Cake Decorating Tool and Cake Icing Tool.

Figure 10 - A gripper motor.

3.2.3.4 Wilton Icing Writer Pen

Finally, we turned to the Wilton Icing Writer Pen [18]. This extruder uses an air pump in order to push icing out of its barrel in a syringe-like fashion. This ended up being the best option due to its relatively easily controllable and reliable extrusion. This was the most ideal extruder that we found because it only needed one axis upon which to exert a force in contrast to multiple (**3.2.3.2**), and it had a consistent and steady extrusion capability as opposed to needing to reload after each small amount of extruded material.

Figure 11 - The Wilton Icing Writer Pen [18]

Chapter 4: Results and Discussion

4.1 Robotic Arm Movement

Although, as detailed in **Section 3.2.1**, we ended up using a different method to control the robotic arm than we'd initially anticipated, we achieved our desired movement by the Senior Design Conference. The Niryo One functioned fully with our Linux operating system where we could use ROSPY to code the arm's movement while also running the robot's native Niryo One Studio.

Furthermore, the robotic fully recognized the plane that surrounded it after calibration (where it would fully scan its surroundings). To have the best accuracy, we would manually calibrate the machine after the auto-calibration was complete. For the basic tasks of calibration and confirming gripper connection, we used Niryo One Studio. We then created a program using ROSPY (including measurements from the Niryo One Studio) to control the robot's movement. ROSPY was ideal for these more complex movements that included patterns, repetitions, and mathematical equations to determine the coordinates. In the final stages of the robotic coding before it started to work in conjunction with the other components, the Niryo One was capable of drawing lines, triangles, squares, and circles. For our final demonstration on our cupcake, we used a simple circular pattern so that we would not need to do the intense calculations to find the z-coordinates to create straight lines across a curved surface, opting instead to have a consistent z-coordinate for each circle on the cupcake and focusing instead on finding the x- and y-coordinates.

4.2 Cupcake Measurement

We decided to follow through with the measurement method detailed in **Section 3.2.2.2**. We decided that using a reference object with known dimensions to determine another object's dimensions was the easiest method to use for our project. This was key to have a successful demonstration because of how late in our timeline we were able to connect the three portions of the project. If we'd had more time in a physical location together, we could have followed the method in **Section 3.2.2.3**, however taking the time to recalibrate when we had such a limited amount of time together before the demonstration deadline seemed wasteful.

Although we started using the Raspberry Pi and this specific measurement method relatively early on in the process, the setup came close to being completely reversed. The room setup was flipped from how we had been trying it individually meaning that our code based on having a leftmost object with known dimensions would need to change drastically. However, after contemplating it, we brought a longer ethernet cable from home to the room where we were working so that we were able to use the original set-up that we had been using for testing.

The measured cupcakes were in the position where the robotic arm was calibrated, and after inputting the dimensions of the cupcake, the robot arm had the instructions described in **Section 4.1** to make the design adapted to the cupcake.

4.3 Extruder

The Wilton Icing Writer Pen from **Section 3.2.3.4** was not a perfect device. However, it was the best extruder that we worked with over the course of the project. We had purchased our robotic arm with one gripper end attachment, but because of how early in the process we purchased it, we did not know what size we truly needed. The gripper that we ordered only had a one inch opening while the extruder we decided on in the end had a diameter of one-and-a-half inches. This meant that our gripper could not attach to our extruder and have control over its extrusion mode as we had initially planned. We eventually came to a design that left the extruder in a persistent extrusion mode when the motor was turned on so that we could limit the gripper's activity to merely holding the device in order to accomplish at least basic extrusion. This was successful, however, it did not accomplish our goal of decreased human interaction. In order for the extruder to be turned on to complete the decoration program, we needed to press a button to start the air pump during a determined pause at the start of the robotic arm's movement. Additionally, with the interesting set-up using wooden blocks to connect the extruder to the robotic arm, some of the air pressure from the pump was lost. This meant that the icing had to be much runnier than initially anticipated. The pump even at its maximum air pressure was fairly minimal in its output, so with the extra escaping air, the pump was very weak. The icing had to have a much higher water content than we'd initially anticipated. This meant that our design became somewhat droopy due to the curvature of the surface. Before moving to actual cupcakes, we began with clay for the testing process.

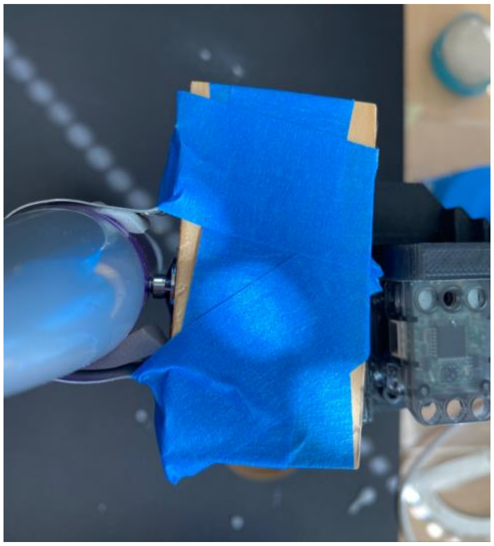

Figure 12 - An aerial view of the extruder.

Figure 13 - A side view of the extruder attached to the gripper

While the extruder was not perfect in its execution, it did accomplish its goal of extruding icing on a cupcake. We had initially wanted there to be a portion of the program that would control the extrusion mode and a thicker frosting extrusion material, but at its base, we decorated a cupcake using an image, the robotic arm, and an extruder.

Chapter 5: Final Design

5.1 Final Demonstration Product Setup

We completed our final demonstration in Guadalupe Hall, 326 [*Figure 5-1*]. We recreated the set-ups to those we had created while testing our individual portions and then set up the connections to integrate the pieces together [*Figures 5-2, 5-3*].

Figure 14.Final set up in the room including our work space and our desk set up with the robotic arm.

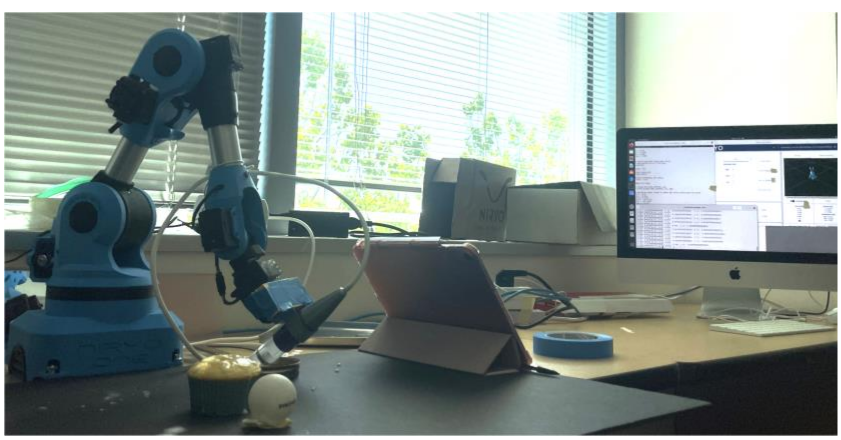

Figure 15 - Setup of the Robotic Arm Ready to Decorate Prior to Demo

Figure 16 - Clay Model Cupcake with Known reference object

The final design from the full setup in *Figure 5-2* shows an iPad prepared to record the decoration demonstrations using the target cupcake's measurements from the Raspberry Pi. In *Figure 13* from **Section 4.3** there is a close up image of the robot's gripper connected to the extruder, hovering over the target as demonstrated in *Figure 16,* with the ping pong ball pictured next to the clay model cupcake as the object of a predetermined size. The ping pong ball with a known radius of 40 mm allowed us to measure the cupcake. Additionally, prior to our tests with real cupcakes, we practiced the motion of the robotic arm and the extruder by placing a paper towel over the cupcake form of clay that could be easily wiped off between tests.

5.2 Analysis of Final Design

The performance of the final design is shown in *Figure 5-4* below, and we achieved our most basic goal: We used a robotic arm to decorate a cupcake with frosting. We are very happy with our starburst design, but issues did arise with the Niryo being very temperamental about its internet connection, and during the week before the demo, the Raspberry Pi lost its operating system, and we had to download a new operating system onto our Raspberry Pi once again.

Figure 17 - First successful Demonstration on a Cupcake

Despite those setbacks, we created a delicious cupcake, with a complex, pretty, and repeatable decoration. We are on the way to a full library of decorative frosting designs.

5.3 Bill of Materials

The materials required to complete this project:

- Niryo One – 6-Axis Robotic Arm for Education
- Raspberry Pi v3 with Camera
- Hicdaw Piping Set Icing Tips Cake Decorating Tools Cake Decorating Supplies with Icing Pastry Bag Icing Bag Tips Piping Bag Coupler Frosting Bags Tie (33PCS)
- Wilton Icing Writer Pen
- A 40mm ping pong ball
- Cupcake/Frosting Materials
- Modeling Clay
- Cupcake Liners
- Painter's Tape

Chapter 6: Professional Issues and Constraints

6.1 Ethical Analysis

The ethical justification of this project is that it was a very interesting concept, with a fun twist to make the research and a successful demonstration more sweet. Analyzing this project as Engineers, we also were sure to uphold strong ethics throughout the full year. This was particularly necessary during COVID-19 so that we could respect each other's safety, as well as respecting each other's time and work enough to properly share the load of work equally. Although we all were fairly local, we never broke the rules to see each other or shared a space working during the quarters when we felt unsafe. Additionally, when in these shared spaces, we followed the posted protocols from the school as well as our instructor, Dr. Cary Yang, during ELEN 194 & 195.

Considering the risk assessment for the project, we've concluded that our project is incredibly safe.

6.2 Science, Technology, and Society

The joy of scientific discovery, and the benefit that exploration brings to our lives is invaluable, and even though the nature of this project was not as complex as we'd initially anticipated. As a proof-of-concept project, we investigated the ability use tools that don't work together normally to adapt imperfect shapes with difficult materials. With more time and practice, running the full setup for A few months or a year, the applications could potentially reach commercial levels, but it could also serve as an even better educational tool, like for example something that peaks interest in technology from diverse backgrounds that are sorely lacking in the STEM fields.

6.3 Sustainability and Environmental Impact

Environmental conscientiousness is a key component of one of our main goals. As described in **Chapter 1**, a key market is construction automation devices like the SAM100. The brick-laying device, which can lay hundreds of thousands of bricks for a single job, has many positive attributes, such as improved safety and production speed, however, it also is rather wasteful with each individual brick disposing of excess mortar, which adds up as a project progresses [1-2]. One of our goals was to decorate cupcakes in a way that would not waste icing to address this issue in our proof of concept. Additionally, our robot, the Niryo One, was 3-D printed therefore minimizing production waste, and is made out of fully recyclable aluminum.

We also did not waste any food products through our testing/prototyping process. In order to complete the pressure testing measurements detailed in **Section 3.2.3.3**, we used vegetable shortening because of its reusable nature. We could repeatedly use it only losing some of it to the device's cleaning process. For our measurement tests using the Raspberry Pi and the drawing tests with the robotic arm, clay molds and other household objects were used as cupcake models due to their repeatable nature so as to not introduce cupcake making supplies prematurely to the project. Additionally, all cupcakes that were not used for testing purposes were either consumed or composted, and the icing was water soluble and therefore created little impact on the environment.

Additionally, though we could not avoid electricity use due to the electrical nature of our project, we made sure to keep devices in a low power state unless their testing required it at that moment.

The project overall was fairly sustainable with some of its purpose stemming from attempts toward greater sustainability.

6.4 Health & Safety and Economic Impact

The project was held in an incredibly safe fashion, especially with regards to protecting ourselves and each other during the pandemic while working toward completing our work. We chose to work remotely over Zoom and met multiple times each week. This way, rather than taking the risk of working together in person during the height of the pandemic, we only met socially-distanced to pass on materials or physical components of the project between members. We only connected the components of the project once it was safer and the members of the group were either fully vaccinated or on their second dose. We also conducted the final construction of the project for our demonstration in a lab space in Guadalupe Hall that was cleared for us to use, providing we followed Santa Clara University's Covid-19 Testing Tier 1, 2, 3 for Essential Access working on campus.

Additionally, as we were not selling our prototype cupcakes and largely using them for personal consumption or composting, we did not choose to follow the rigor of FDA guidelines. As no profit was being made, we found no need to follow these heightened standards and were very safe in doing so.

6.5 Manufacturability, Usability, Civic Engagement

The manufacturability of this project is currently something that could be greatly improved. The complications once connecting the components of the project was a large impediment to the project. The technical difficulties that we had to navigate during our demonstration confirmed that the project could have benefited from more time to work on the connections of the components. However, due to the pandemic, we had difficulties finding a safe and easy to access shareable space until far later in the year than we had initially anticipated. Also, since the robotic arm is advertised as an educational tool, the potential for it to be used in a similar capacity is high, and it is going to be accessible for future students to interact with the project, also lessening the cost of materials for future students. If it were to remain as a part of the displays at Santa Clara's School of Engineering or a basis for future projects, it could end up potentially as a kitchen or bakery product. However, if future studies were to focus on this path, there would need to be a larger focus on obtaining proper Food and Beverage Permits requiring Class-A Permit at the minimum, or Class-B to sell through stores, while having annual kitchen inspections to receive these [19]. Additionally, as this project is a proof of concept that is not at the commercial stage yet, it could theoretically become a more commercialized construction tool someday.

Chapter 7: Conclusions & Future Work

7.1 Summary and Conclusions

The objective of this project is to use our Niryo One to adapt a design to an imperfect terrain and decorate that terrain using a difficult material without crashes, spills, or need for human intervention and reducing waste. This project was a success since we were able to complete a design on a cupcake with icing while only having three instances of required human interaction: turning on the motor; manually finding the starting coordinates for the robotic arm's movement; and manually inputting the measurements that we received from the Raspberry Pi into the movement program.

If we were to continue this project, we would add more functions to limit this need for human intervention. However, overall, the robotic arm did extrude a decoration that was fairly reliable. The robotic arm could repeat its motions easily and extruded the design we coded for it, with only some extra drops due to the icing's watery consistency. We completed our achievable objective for this project.

7.2 Future Work

This project's applications could be broadened in the future if we or another team were to continue our research. There are all of the potential additions to the Raspberry Pi image recognition and processing capabilities like the method explored in **Section 3.2.2.3** and the measurements accomplished would ideally not need human interaction in order to be added to the program. Additionally, the design library could be vastly increased to include more shapes and take into account the speed of the robotic arm's movement and the pauses in its paths of motion. The robotic arm could also be worked with further in order for its origin calibration to be more reliable and so that it would not require human intervention to find the origin. Furthermore, the extrusion system could be automated and a thicker consistency would be ideal in order to have the decorated cupcakes be more akin to those found in pastry shops.

Moreover, as this project is a proof of concept, if this example of decorating cupcakes were to be improved, future research could branch out to either monetizing the project for commercial use in this form or could cross over into the construction market.

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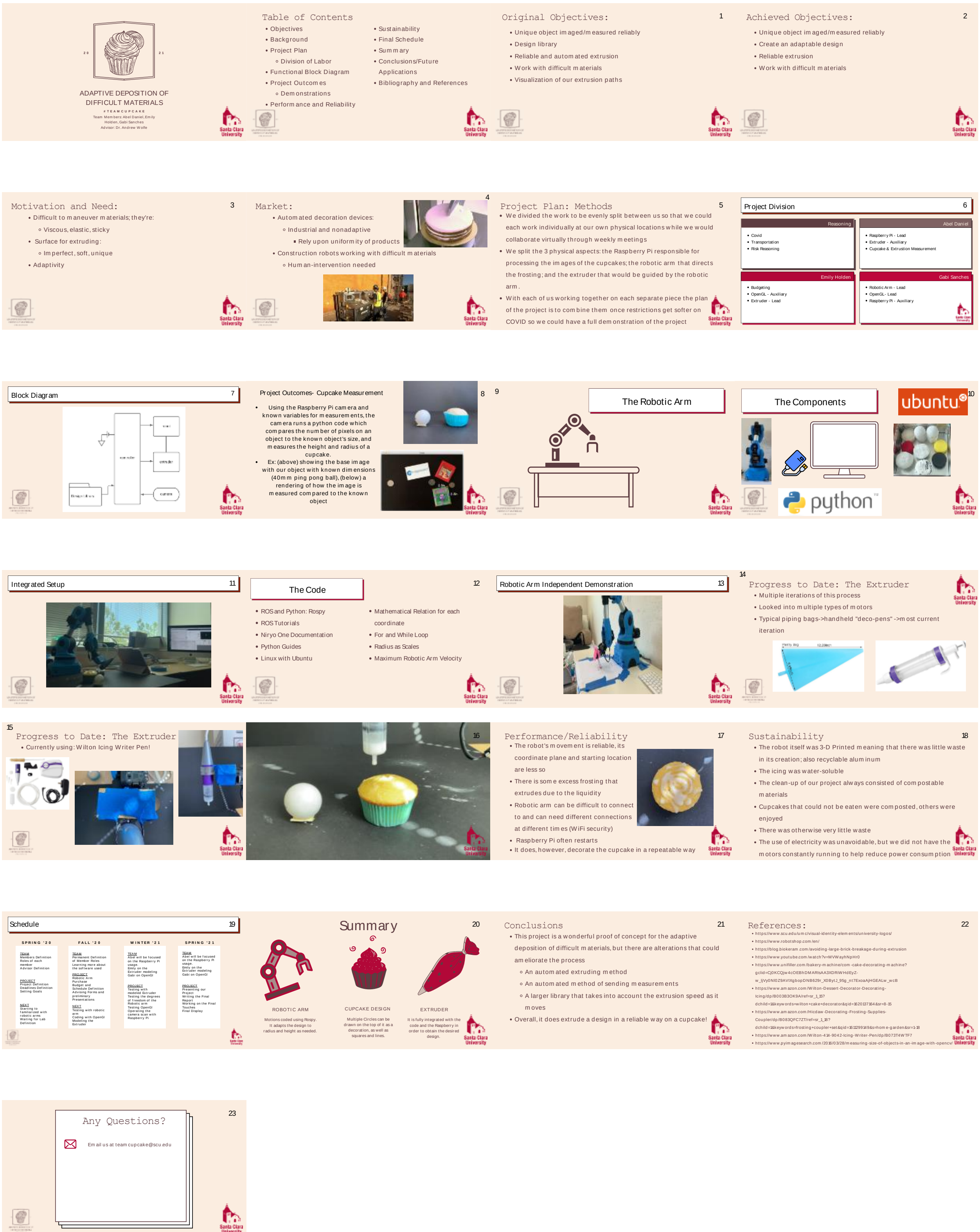
Appendix A: Senior Design Slideshow



Appendix B: Santa Clara University's Covid-19 Testing Tier 1, 2, 3 For Essential on Campus Access

Testing Tier	**Testing Frequency**	**Target Groups**	**Examples**
1	**WEEKLY**	➔ Essential faculty/staff/student employees accessing campus routinely (weekly basis) ➔ F2F instructional Faculty (teaching on campus weekly) ➔ Students ➔ Full-time campus contractors	➔ Students in residence halls ➔ Students taking F2F classes - grad and undergrad ➔ F2F instructional faculty ➔ Nearby off-campus students ➔ Research faculty and students ➔ Facilities/IT ➔ Medical staff ➔ Contractors - Able, Bon Appetit ➔ Essential faculty/staff/student employees ➔ Residence hall staff and families/CFs/RDs
2	**BI-WEEKLY**	➔ Essential faculty/staff/student employees accessing campus frequently (less than weekly but more than monthly basis) ➔ F2F instructional faculty (teaching on campus < weekly)	➔ Essential faculty/staff/student employees ➔ F2F instructional faculty
3	**MONTHLY**	➔ Essential faculty/staff - accessing campus infrequently (monthly basis) ➔ Contractors intermittently on campus	➔ Essential faculty/staff ➔ Intermittent contractors

Appendix C: Budget

Budget

Appendix D: Niryo One Mechanical Specifications

1.2 Dimensions

Degrees of Freedom	6
Weight	3,3 kg
Reach	440 mm