Georgia Institute of Technology
Atlanta, GA 30332

Capstone Design

Robo Picasso

Formation Studios

Lance Crawford
Willam Duncan
Jaepil Goh
Eunkwang Lee
Nil Patel
Tirth Patel

ME 4182 - A

Advisor, Dr. Hassan Rashidi

Final Report

Date: 04/28/23

Spring 2023

Sponsors

Formation Studios

Tristan Al-Haddad: tristan@formations.works

Georgia Institute of Technology Research Program

Gerry Chen: gchen328@gatech.edu

Team Signatures:

Lance Crawford:	lcrawford40@gatech.edu
Willam Duncan:	wduncan@gatech.edu
Jaepil Goh:	jgoh33@gatech.edu
Eunkwang Lee:	elee426@gatech.edu
Nil Patel:	npatel443@gatech.edu
Tirth Patel:	tirthgp@gatech.edu

Contents

Executive Summary

The goal of Robo Graffiti is to design an end effector for an existing cable-based robot to allow the system to effectively mimic painting strokes and assist in painting building murals. In other words, the end effector will need to be able to pick up a brush and recreate an artist's paintings on a larger scale. It is important to note that the process the system uses to paint the art piece is considered just as important as the final completed piece to the end customers. To meet the end customers' desires, the system will have to be lightweight, effectively mimic human arm movements, and be able to swap between multiple paint brushes and colors.

The end effector design process starts with the house of quality tool, which determines the critical objective of minimizing assembly costs while maximizing degrees of freedom. A specification sheet is then made to approximate the optimal technical objectives, with a maximum cost of $3000 and a minimum of three degrees of freedom. The system's required high-level functions, such as obstacle avoidance and end effector position calibration, are investigated using a function tree tool. These tools are used together to create an evaluation matrix, which mathematically ranks the six designs created in ideation based on the technical requirements.

The SCARA based platform design ranked highest in the evaluation matrix. It utilizes a robotic arm with a ball joint end effector that mimics human wrist movements. The platform has brush holders and paint reservoirs for the robot to pick up and dip the brush into. The four degrees of freedom of the robot arm allow for human-like motion, and the ball joint actuated by multiple servo motors allows for redundancy in degrees of freedom. However, the downside is the cost and complexity of the design, including more components and actuators, leading to a heavier end effector and more complex motion planning.

The chosen system will be evaluated based on performance, user interface, and overall design. The locational accuracy must be within 1 cm, while the system should minimize human interaction to a maximum of two instances. Power usage should be under 1.5-kilowatt hours, and the system's mechanical durability will be verified with a shear test and finite element analysis to ensure it can withstand strong winds.

Market research and milestone progress points were used to prove the viability of the chosen design. Existing designs, like E-David Project and Scribit confirmed that the robotic arm and moving platform components, respectively, can work independently. A prototype using one brush and paint color will be created to validate the feasibility of extending the system to multiple colors.

The engineering analysis of the robotic arm considers the weight of components and determines torque requirements at each joint. It is found that two servo motors are needed at the base, and one is required for the upper arm. To prevent failure, the torque applied should be less than the servo motor's

stall torque. The maximum torque at joint A should be 2.2 ft-lb, and the total torque of the system should be less than 1.5 ft-lb. The analysis shows that the Robo-Picasso system using servos can function without failure. The engineering analysis provides important information for the safety and workability of the system.

It is important to note that while Finite Element Analysis can provide valuable insight into the structural stability of a system, the accuracy of the results is highly dependent on the assumptions made during the analysis. As mentioned, the simplifying assumptions made in this study may not accurately reflect real-world conditions and may result in a calculated factor of safety that is lower than the actual factor of safety. The analysis showed a maximum Von Missies stress of 1.61 MPa at the base joint, resulting in a factor of safety of approximately 16. The expected displacement under the chosen force was 0.642mm, which would not likely be noticed in the system's output. Additionally, the use of pure PLA in the analysis may not accurately reflect the material properties of the 3D printed arm.

To ensure feasibility of the design, a mockup test and a power consumption test are necessary. A simpler version of the arm design will be used to conduct the mockup test, which will determine if an active or passive damper is needed and measure power consumption. The system will also undergo a power consumption test using Lithium polymer batteries, comparing the total stored energy to the time the system can operate. The weight added by the batteries is expected to result in negligible extra power consumption. The test assumes the batteries can charge to their full capacity, and non-negligible energy may be spent in AC to DC conversion when the final system is powered from a typical house outlet.

After multiple tests, the final design is created that fixes all the issues that came from the prototyping stage. The base design includes side panels that are used to attach to the cable support system. The robotic arm utilizes 6 servo motors to introduce 3 degrees of freedom to mimic human arm movements. The base is manufactured with Baltic Birch aircraft plywood with its strong and light weight characteristics. The arm is made with PLA for fast prototyping while also being cost efficient, structurally strong, and light weight.

Moving forward, some future work can be done to improve the final design. A new design can be added onto the end of the arm to introduce a way to change paintbrushes automatically. The arm can be programmed to utilize multiple paint colors instead of just one color. The base can be remade to improve stability and reduce it from shaking on the cable support system.

Nomenclature and Glossary

Active Damper - Utilizes a sensor to actively account for unwanted motion by actuating a counterbalance.

ASME - The American Society of Mechanical Engineers; a professional association of engineers.

Degrees of freedom - The number of independent variables that may be used to define all possible positions and motion in space for a mechanical system. Practically, the number of independent directions of movement for a mechanical system.

Delrin - Polyoxymethylene. A thermoplastic with low friction and high stiffness.

Engineering Specifications - Specifications that are quantifiable characteristics of a product design that may be used to evaluate its efficacy as such.

End-effector - A device that is typically located at the end of a robotic arm or system; the segment of a device that interfaces with its environment.

Envelope - The range of motion for a robotic system often semicircular in shape. The envelope accounts for singularity conditions of the mechanical system and helps details possible system movements.

Evaluation Matrix - An engineering design tool used to rank and weigh different designs' ability to satisfy engineering specifications.

Function Tree - A tree chart that depicts more and more specific functions of a device as the chart descends. An engineering design tool.

House of Quality - An engineering design tool that serves as a conceptual product map. The tool allows for product and technical benchmarking through the enumeration and weight of customer requirements and the definition of their relationship with enumerated engineering specifications.

IEC - International Electrotechnical Commission: An "organization that prepares and publishes international standards for all electrical, electronic and related technologies.

ISO - International Organization of Standards; an independent, non-governmental, international organization that develops standards to ensure the quality, safety, and efficiency of products, services, and systems.

Kilowatt hours - A unit of energy commonly abbreviated as kWh. The meaning of which can be represented as one kilowatt of power for one hour. For example, a battery that is rated for 50 kWh can output 50 kilowatts of power for one hour or can output one kilowatt of power for 50 hours. One kWh is equivalent to 3.6 megajoules.

Morphological Chart - An engineering design tool used to visualize and explore necessary product functionality through many different design alternatives and approaches.

OSHA - Occupational Safety and Health Administration; to ensure safe and healthful working conditions for workers by setting and enforcing standards and by providing training, outreach, education and assistance.

Passive Damper - A method of reducing unwanted vibrations typically with a with a fluid. This system does not require electronics or any electronics to function.

SAE - Society for Automotive Engineers. SAE is a professional engineering association that is known for their industry standards of engineering components like bolt and nut threads.

Specifications Sheet - An engineering design tool used to enumerate and evaluate engineering specifications. This evaluation includes their quantification, categorization as a demand or want, and a description of any necessary validation process that can be used to measure the success/design of the product.

Stakeholders - Any person or group with interest and/or influence in a business, product, or market

SCARA -Selective assembly compliance robotic arm.

WRT - with respect to

FMEA – Failure Mode and Element Analysis

Introduction and Background

The main purpose of Robo Graffiti is to scale and reproduce artwork onto large walls like in Figure 1 that people could have difficulty working on. The system is intended to be used by various markets such as the entertainment industry, billboard companies, businesses, advertising agencies, mural artists, and even for personal use. The operating environment of the product could be not only a professional artist's workspace but also a personal office or on the side of a building. Robo-Picasso is expected to mimic artists' movements, reproducing designs and artwork with a high degree of freedom, accuracy, and motion using multiple colors and strokes. Furthermore, this product uses computer software for motion planning and for system control.

Prior to explaining the product, technical issues and challenges must be discussed. The product is intended to be used on huge walls or canvases having various textures. There could be unexpected vibration from obstacles or system error. To solve these issues, obstacle detection is required to prevent failure. Also, since there could be vibrations while operating, controlling the system with high accuracy could be challenging. To design a robot which overcomes these issues and creates a high precision design, a mobility system minimizing vibration and delicate painting technologies are required. The content that follows will further explain how Robo Picasso is demanded by customers, explain the numerous functions it requires, and how the preliminary concept was selected.

Figure 1: An example of a mural painting on a huge wall, which shows the potential operating environment for the product. [Rankin, Charles. "Seven Artists, Including Brady Scott & Darren Morzwitz, Are Painting Murals Live in Salina." *Salina Journal*, Salina Journal, 19 May 2022, https://www.salina.com/story/news/2022/05/19/salina-hosting-artwork-alley-mural-expo-22-beginning-friday/9794161002.]

Existing Products, Prior Art, and Applicable Patents

In today's market, there are multiple existing products and patents invented by numerous people that relate to our project of creating a robot that can create drawings on a larger scale. Each product and patent try to improve on past designs by implementing newer technologies to express new ways of art with the use of robotic actuations.

One example of a product that is currently in today's market is the Scribit designed by MIT Professor Carlo Ritti seen in Figure 2. He believed that the world was too consumed in spending time in front of digital screens so he designed a robot that could take real time data and digital content and reproduce it in an artistic form. Scribit is a write and erase robot that draws and scales up any drawing from the Internet. It uses up to four markers interchangeably by rotating the markers in and out of a socket that places the marker on a wall. It has two wheels where pieces of string are attached to it to allow the robot to hang with gravity and move around on vertical surfaces [1]. This robot is a simple yet complex machine that allows users to see their personal data and images in new ways. Along with this, this robot provides numerous benefits with safety and time. This device substantially reduces the amount of labor and time that would be needed to design such large-scale drawings while upholding a high level of safety by eliminating any potential human accidents. Scribit is like this project with how it can use multiple markers where their rotation method could provide a basis for a design that uses multiple paintbrushes and a cable system to allow the robot to work on vertical surfaces. However, the team’s project requires the use of paint brushes where the robot can translate artist strokes to a large-scale canvas.

Figure 2**:** Picture of the Scribit Product

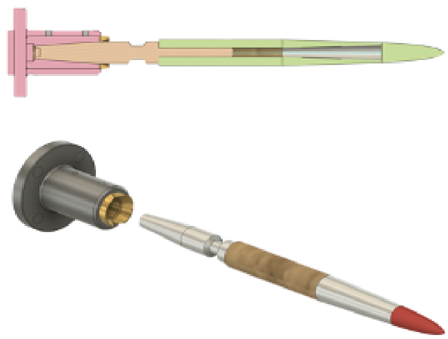


Figure 3**:** Diagram of the tool holder in the E-David Project

Another example of an existing product is an ongoing robotic research project called the E-David Project that was started by the University of Konstanz in 2009. The whole concept of the project is to design and build a robotic painting system to create paintings with robots that can wield multiple paintbrushes. When looking at the applications of the robot, their goal is to have easier development of painting programs, work with artists interested in robotic paintings, and to showcase exhibitions to the interested public. This project focuses on improving the visual feedback system, using a range of painting colors, and optimizing the stroke placement [2]. To improve on these issues, an adequate paintbrush holder is needed to accommodate a variety of brushes. Most of the brush is replaced by a part that the machine can hold with a tapered adapter to eliminate any play between the robot and brush handle interface as shown in Figure 3. With the use of magnets, the holder is held in place and allows for tool changes while minimizing the complexity of the design and increasing its' reliability. This research faces similar problems to our project of creating an end effector that can utilize multiple paint brushes and different colors but also ensure that the robot can be as precise as possible to improve the accuracy of human translated painting strokes. The project provides a much-needed basis when looking at ideas that can best improve our current system. The team's robot will be different from this research project since it will be mount with a cable system instead of a stationary base.

As of now, there are currently patents that utilize cable driven robots to maintain large scale paintings. For the first patent, the idea was to create a design that could automate specific facade maintenance operations to avoid dangerous working conditions shown in Figure 4. In most cases, workers have to be restrained by using ropes or cables to do tasks such as window cleaning or painting on the exterior of buildings that could lead to serious injuries or even death in the case of accidents. The cable system utilizes motors and winches that are installed on the ceiling and floor of the facade where this can control the cables to allow the platform to travel in different positions [3]. This invention helps avoid any

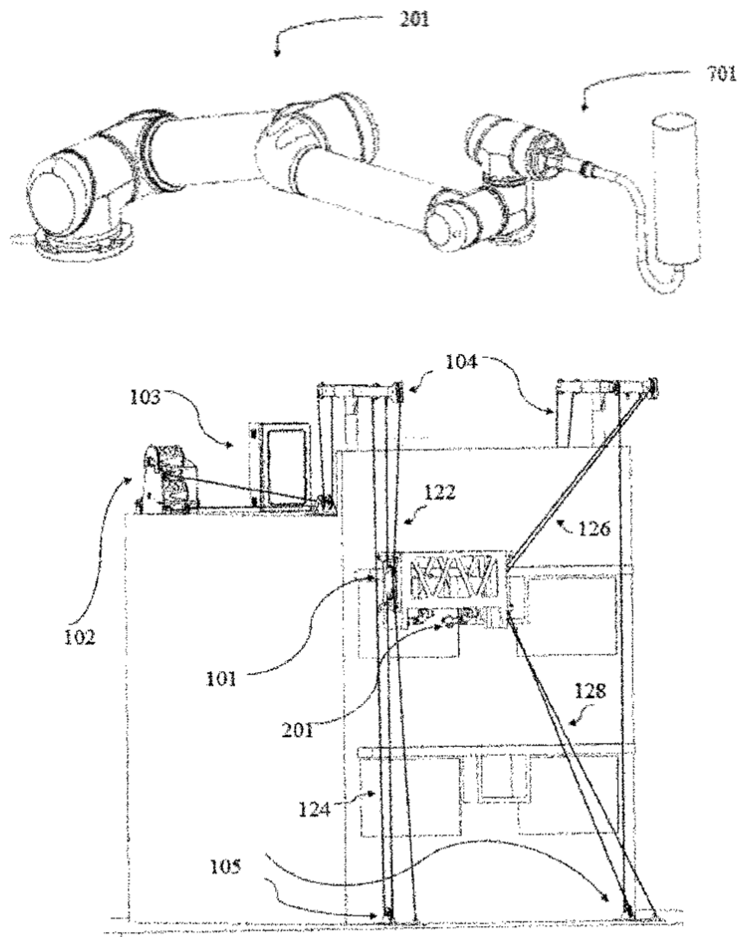


Figure 4: Schematic of the cable driven robotic system.

potential harm to workers by creating robot arms that can be mounted on a platform with the cable system to operate over large areas. When looking at the end effector, the robot arms use at least 6 degrees of freedom to mimic human arm movement for cleaning and painting. Along with this, a solution dispensing system for paint is attached to the arms to reduce human intervention. With multiple degrees of freedom, the robot arms can paint in the complex, hard to reach areas while being able to control the amount of paint applied on the surface. This robot is different from our design because it does not have a solution to how the painting tool will be switched or how multiple colors will be used.

For the second patent, a robot arm and an end effector are used for the painting of automobiles with spray gun and other applicators displayed in Figure 5. This invention created a painting system where a stand is mounted on a stationary base and rotates around the first axis. The first arm is then mounted to the stand around the second axis and the second arm is mounted to the first arm around the third axis. Finally, an end effector is connected between the second arm and the painting tool that would be used for the painting booth [4]. With the three different axes, the arm can move with three degrees of

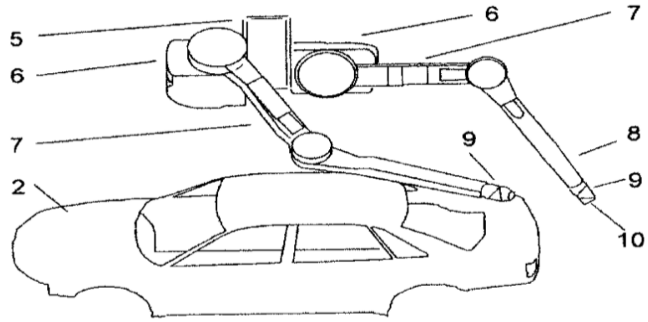


Figure 5: Schematic of the robotic arm design used in painting automobiles

freedom and allow the end effector to orient the painting tool in whatever way. While the robot arm may be similar in some ways to our intended design, the end effector will be much different since the patent is more applicable for spray painting uses whereas ours must be able to utilize paintbrushes. Along with this, the painting tool must be manually changed whereas our design must automatically change multiple brushes while using different colors of paint.

Codes and Standards

A robotic painting arm is a complex machine that requires adherence to a number of engineering standards to ensure safe, efficient and reliable operation. Safety standards are of utmost importance as the robotic arm will be handling hazardous materials such as paints and solvents.

Relevant safety standards include OSHA 1910 Subpart O, IEC 60204-1, and ISO 10218-1 which outline the requirements for machinery safety, electrical safety and robot safety respectively [5, 6, 7]. Mechanical engineering standards include standards for the design and manufacture of robotic arm components. Relevant mechanical engineering standards include ISO 9283, ISO 10218-2 and ISO 13849-1 which outline requirements for the repeatability, accuracy, and performance of robots [8, 9, 10, 11]. Robotics standards such as ISO 11228 and ISO 11352 outline requirements for the design and performance of robotic systems and cover topics such as accuracy, speed, repeatability, and reliability [12, 13]. Electrical control systems standards include standards for the design and operation of the electrical and control systems used in the robotic arm. Relevant standards include IEC 61131-3, IEC 60204-1 and IEC 61784-1 which outline requirements for programmable controllers and the design of electrical systems in machinery [14, 15, 16].

Another relevant standard is the SAE International J2954 standard for safety guidelines for mobile robotics. This standard provides guidelines for the design, manufacturing, and testing of mobile robots, including those used for painting applications. It covers topics such as the selection of sensors and actuators, the design of power and control systems, and the development of safety protocols, and can help ensure that the robotic painting arm is designed and manufactured to meet the necessary safety criteria [17].

As the end effector will be attached to a cable system to maneuver across the canvas, it is important to ensure the design is adequate for use in a public space. The ASME B30.2 standard for overhead and gantry cranes is also relevant to this project, as it provides guidelines for the design and construction of overhead cranes and gantries, including those used for painting applications. This standard covers topics such as the design of structural components, the selection of materials, and the development of safety protocols, and can help ensure that the robotic painting arm is designed and manufactured to meet the necessary safety and performance criteria [18].

It is important to note that different industries and applications may have additional standards specific to their requirements. For example, the food industry may have additional standards for the use of robots in different environments. The development and deployment of a robotic painting arm requires strict adherence to relevant engineering standards to ensure safe, efficient, and reliable operation. A thorough review of relevant standards should be performed at the beginning of the project to ensure compliance and minimize the risk of potential problems during operation.

Customer Requirements and Engineering Design Specifications

A large part of the preliminary design stage for a product is the definition of the scope. The scope of the product is based on the influence and interests of multiple different groups of people. These groups are referred to as stakeholders. The stakeholders for the Robo Picasso product are the Robo Graffiti sponsors, the student team, “Robo Picasso,” and Dr. Rashidi, the team advisor, as depicted in Figure 6. The sponsors’ motives are that they would like to design and prototype a robot for employment in the mural art industry. The sponsors’ main wishes for the design are that it has little human involvement in its operation and that it is able to mimic a human artist’s strokes on the canvas. Currently, the sponsors are at a stage in development in which large mechanical and design changes are necessary to improve the current product to the desired level of mimicry and artistry. The Robo Picasso team is composed of six mechanical engineering students with important skills in manufacturing, fabrication, design, and mechatronics. This set of skills means that the team will be able to effectively mesh with and understand the previous product design very well. The manufacturing, fabrication, and design skills address the necessary creation of a newly developed robot that must interface with the previous product. The mechatronics skill is extremely useful in allowing the team to design toward ease of use and development on the back end as the product must also interface with the previously utilized software design.

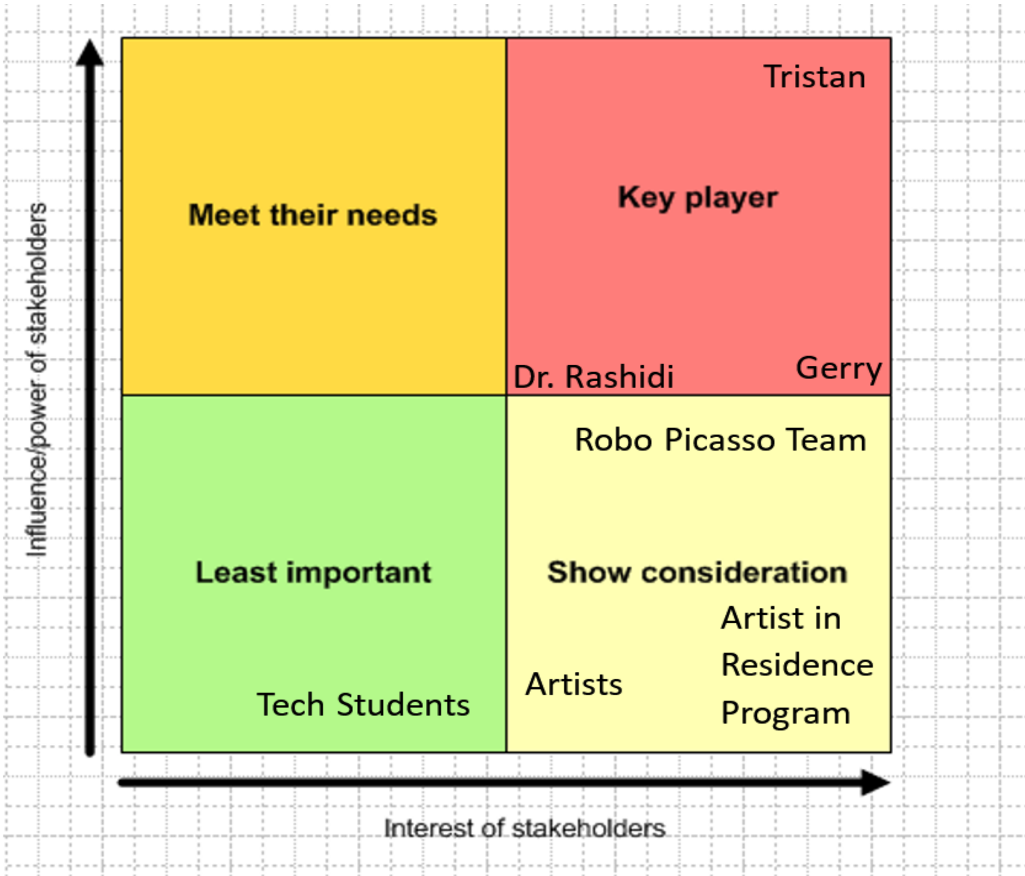


Figure 6: A “2x2” stakeholder chart showing the relative influence and interests of all stakeholders. Tristan and Gerry are the team sponsors.

Creating a product necessitates the definition of a design process. The Robo Picasso team has identified five initial components as such. These being the definition and use of customer requirements, engineering requirements, product functions, product specifications, and design ideation. The first step, definition of customer requirements, being the exploration and identification of the scope of the product development through the lens of the stakeholders. The team conducted market research and customer surveying and identified a list of 16 customer requirements enumerated in Table 1. This list also includes a weight for each requirement that was used to assess the importance for product design. The most important/impactful requirements being those that are conducive to product integration into the current system, safety, and to the mimicry of a human artist’s painting ability. The human factors within this design are mainly addressed by looking closely at safety, as the product, ideally, should require very little human interaction to function, so there are few design considerations to be made for human compatibility as such; however, two worth mentioning are size and weight, as the product must be able to be carried and setup under human power.

Table 1**:** A list of weighted customer requirements as seen in the House of Quality engineering design tool.

Weight	Customer Requirements (Explicit and Implicit)
3	Astheticly Pleasing
10	Integrate into current system
6	Stable
8	Needs to be Scalable
8	Accuracy
9	Must change colors
9	Must be compatable with different brushes
9	Mimic different kinds of strokes
10	Useable Indoors
7	Mimic Artists Movements
10	Avoid Obstacles
6	Minimize Human involvement
5	Affordability
5	Lightweight
10	Safe to Work with Humans
5	DC Powered

Based on the customer requirements listed previously, the team developed a set of functions that the product should be designed to perform. These functions are found in the Function Tree in Figure 7. The lowest branches of the tree are the most specific functions and are those that should be defined quantitatively, when possible. The functions concerning signal processing are present because of the necessary use of sensors that will provide feedback that is important for the previously made software to mesh properly with the product. Toward that end, the end-effector product must include the use of hardware capable of running and/or communicating with such software, which includes the integration of certain circuitry, like the use of DC power and the calibration of the sensors. Also included are functions that are much more mechanical in nature. The overall function of the Robo Picasso end-effector is to be able to mimic an artist's painting. Toward this end, the product must be capable of translating the brush in several different ways including tilt/rotation and application of the brush to the canvas. The movement of the brush is ultimately what decides the product's capability to maneuver the canvas and paint as a human artist would. So, it is important to quantitatively define performance metrics that can be used to address the extent of the robot's capability within the scope of the product market. This is done as a penultimate step to product ideation via the definition of engineering specifications that can be used to assess a design.

Robo Picasso is being designed as a nearly autonomous robotic system. Thus, one of the goals of the design is to minimize human interaction. Due to the lack of human interaction, many typical constraints will not need to be considered. In their place, however, the system has a few important constraints itself. This system is both a robotic end-effector as well as the robotic cable system used with previous designs. Some constraints the system imposes on the design include weight, size, software, and hardware constraints, like the integration with previously developed custom software and mounting hardware.

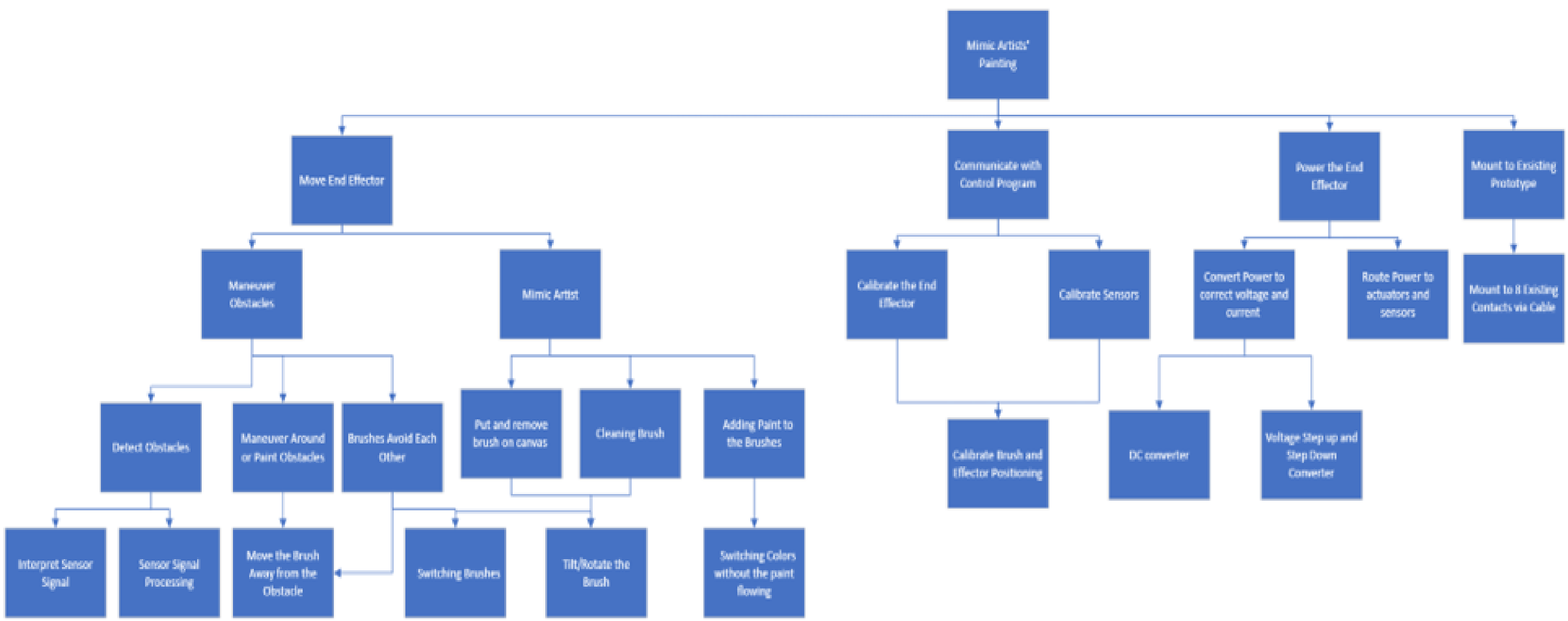


Figure 7: The Function Tree for the Robo Picasso end-effector. This function tree defines necessary product actions becoming more specific as the tree flows down.

Using the customer requirements, the team developed a list of functions, and then engineering specifications that the product design should meet and address. This list can be found in Table 2. The functions that are the most important to discuss and develop are those necessary to allow the product to meet its overall goal of being capable of mimicking the artistry and strokes of a human. The main specifications that address this are the holding of the brush, the tilting and rotation of the brush, the calibration of sensors and other components, and the swapping of colors and brushes as robot paints. The movement and handling of the brush is addressed by the requirements necessitating at least 3 degrees of freedom for the brush, and a minimum of 6 paint colors and 3 brush types. These are the minimum specifications the robot should meet to be able to effectively mimic human artistry.

Table 2: The Engineering Specifications Sheet is essentially a table meant to quantify each engineering specification to understand the wants and demands of the product (D/W), and to understand the process through which each specification can/will be validated.

				Issued:	**1/29/2023**	
			For: Robo Graffiti	**Page:**	**1**	
			Specification			
No.	**Date**	**~D/W**	**Requirements**	**Responsible**	**Source**	**How Validated**
General						
1	1/29/2023	W	Assembly Cost Less than $3000	Nil	Sponsor	BOM
2	1/29/2023	D	Max Power Consumption 1500 W	Lance	Standard	Comsumption Time
3	1/29/2023	D	Wireless Connectivity	JP	Sponsor	Testing
4	1/29/2023	W	Less than two instances of human interaction	EK	Sponsor	Testing
5	2/6/2023	D	Integrate with 4 motor cable system	TP	Sponsor	
Physical Characteristics						
5	1/29/2023	W	Weight: 2kg		Sponsor	Analysis
6	1/29/2023	D	Volume (14"x14"x14")		Sponsor	Analysis
7	1/29/2023	W	Aestetic Design (survey satisfaction >90%)			Survey
8	1/29/2023	W	Material strengh(>8000 psi)		Standard	Testing
Electrical						
9	1/29/2023	D	Run on 5v or 12v dc power		Sponsor	Testing
Mechanical						
10	1/29/2023	D	Minimum of 3 degrees of freedom		Sponsor	Anylsis
11	1/29/2023	D	Must actuate 6-8 inches Z direction		Sponsor	Analysis
12	1/29/2023	W	Speed of machine (20cm/s)		Sponsor	Testing
Performance						
13	1/29/2023	W	Minimum of 6 Usable Colors		Sponsor	Analysis
14	1/29/2023	W	Minimum of 3 Changeable Brushes		Sponsor	Analysis
15	2/6/2023	W	Can handle minimum of 500 grams		Standard	Testing

The importance of each of these is ranked using a weighting system through the House of Quality. The weights in Table 3 are assigned and then used to evaluate different potential designs for the product, and these designs are ranked based on their cumulative relative importance. Assembly cost, power consumption, and material strength were all given a low relationship value of five. This means their associated impacts on the customer requirements are of less import than the others which were all given a relationship value of nine. These relationship values are used to calculate each specification's technical importance for the design by essentially quantifying the importance of each specification with each customer requirement. Doing so gives the technical importance ratings found at the bottom of Table 3. The highest rated importance is cost, followed by the number of brushes, number of human interactions, power consumption, and the degrees of freedom. As with any engineering project, a huge goal is to keep costs low for a product, which explains why cost is the most important for this design matrix. The number of brushes and degrees of freedom as well as the number of human interactions are all integral components to the design of the robot based on customer demands and needs of the system.

Table 3: A portion of the House of Quality table that depicts the specifications and their importance, and customer specifications. The specifications are listed vertically at the top, and their relationships and importance ratings are depicted with their target values listed toward the bottom of the table.

Weight	Customer Requirements (Explicit and Implicit) / Engineering Requirements	Assembly cost	Power Consumption	Material Strength	Degrees of Freedom	Stroke Types	Capacity of color options	Operating Time	Durability	Nubmer of Brush Options	Locational Accuracy	Weight	Number of steps involving people	Aesthetic	Size	Speed of mahcine	Degree of Mimicry
3	Astheticly Pleasing	○		○	▽	○	▽		▽	○		▽		●	○	▽	●
10	Integrate into current system	○	▽	●					▽			○	▽		●	○	▽
6	Stable	●	●		●	▽		○	○	●	●	●	▽		●	●	▽
8	Needs to be Scalable	●	●	●			▽	▽	○	●	▽	●	●		●	○	
8	Accuracy	●	●		●	○	○	●		●	●	○		●	○	▽	●
9	Must change colors	○	▽		○		●	○		○		▽	●	●	○	○	
9	Must be compatable with different brushes	○	▽		▽	●	●		▽	●	○		●	●	○	○	
9	Mimic different kinds of strokes	●	▽		●	●	▽	○	▽	○	●		▽	●	○	▽	●
10	Useable Indoors	○						▽		▽		▽	●		▽	▽	
7	Mimic Artists Movements	●	○		●	●	▽			●	○		▽	▽			●
10	Avoid Obstacles	●	○	○	○	○		○	○	▽	▽		●		▽	○	
6	Minimize Human involvement	●	●		○	○	○	●	○	○		○	●		▽	▽	▽
5	Affordability	●	●	●	●	○	▽	○	●	○	○	▽				▽	▽
5	Lightweight	○	●	●	○	▽	▽	▽	●	●		●			▽	○	▽
10	Safe to Work with Humans	●	▽	▽	▽			▽	▽	▽		▽	○			●	
5	DC Powered	○	●							▽				▽		●	▽
	Target	$3,000	1500W	8000psi	3	Brush	6	10hr	1000 square feet	3	5mm from target	2 kg	2 or less	Survey showing 90% satisfaction	14"x14"x14"	20 cm/s	Complete Mimicry
	Max Relationship	5	5	5	9	9	9	9	9	9	9	9	9	9	9	9	9
	Technical Importance Rating	498	313	189	287	232	169	220	181	346	196	204	322	202	265	299	172
	Relative Weight	12%	8%	5%	7%	6%	4%	5%	4%	8%	5%	5%	8%	5%	6%	7%	4%

Market Research

The application of robotics in the arts can demonstrate the potential of robotics to perform complex and delicate tasks, like those performed by humans in artistic fields. By using robotics in the arts, it becomes possible to create new forms of expression and explore new possibilities in art. Additionally, robotics can also help in preserving traditional art forms and techniques by automating them and making them accessible to a wider audience.

Market research plans typically involve a combination of different research methods to gather information about a particular market and its potential customers. Surveys can be conducted through various methods such as online, phone, or in-person to gather information about customer preferences, opinions, and needs with the focused group as the companies that want to advertise their products or the public organization that wants to advertise for the public interest etc. Expert consulting is needed in the process of doing market research so that it can provide valuable insights into the market and help identify potential growth opportunities. There were not many surveys on robots that make artistic acts, so a market survey was conducted on robots that perform medical surgery.

The market size for painting graffiti robots would be estimated based on the demand for automated graffiti systems in the arts and entertainment industries. The market size would provide an understanding of the potential revenue for the painting graffiti robot. According to the ‘Painting Robots Market’ from IMARC, the global painting robots market size reached $2.4 Billion in 2022 and is expected to grow at a compound annual growth rate of 9.4% during 2023-2028 to reach $4.1 Billion [20]. The target demographics for painting graffiti robots would be artists, creative professionals, and entertainment companies looking for innovative ways to create large-scale murals and public art installations. The target demographics could also include individuals looking for a more efficient and precise way to paint their own graffiti. Target prices are very diverse. It may vary depending on the level of work desired by the customer and the estimated time required for the work. Products using markers are currently being sold for around $500 in the market. However, because robots using brushes other than markers are much more difficult and complicated, surgical robots can be chosen in terms of mimicking human movements with similar competitive products where they are currently being sold for at least $30,000. So, the price between the surgical robot report and the current price of the robot using markers will be the target price. The go-to-market strategy for painting graffiti robots would involve targeting individuals, artists, creative professionals, and entertainment companies through direct sales, partnerships with distributors, and online marketing efforts. The number of potential procedures or uses per year for a painting graffiti robot would depend on the demand for the product and the number of robots sold. However, since it is not known how many robots are currently being sold, the growth rate of potential procedures or uses per year is expected to be around 10% like the combined annual growth rate. The number of potential procedures or uses per year would be an important factor in determining the potential market size and revenue for the product.

By understanding the current competitive products and procedures in the market, Robo Picasso's unique distinction and the robot's biggest purpose from this distinction were to figure out which parts to focus on. Particularly, incorporating ball joints into the design of the wrist area can indeed provide the graffiti robot with a high degree of freedom, allowing for a wider range of motion and greater versatility in painting. This type of design would allow the robot to move and adjust its wrist in many different directions, making it easier to paint intricate designs and patterns with greater accuracy and precision. In addition, the problems of robots currently on the market were able to identify disadvantages to avoid in designing robots. By incorporating the insights obtained from market research, designers can make informed decisions that increase the chances of success for the graffiti robot in the market.

Design Concept Ideation

Using the information researched, customer requirements, and engineering specifications, a function tree is made to design concepts for the product. Multiple solutions for each function are displayed below in the morphological chart in Figure 8. The product will essentially be a combination of the solutions to perform the necessary tasks for the customer.

The robotic arm can be programmed to interpret signals through various microcontroller boards such as Arduino or Raspberry Pi, or motor controllers. These boards receive signals from the software and convert them into actionable instructions for the motors to follow. The signals sent to the robotic arm can be processed using various programming languages such as MATLAB, C++, Python, or custom software. The programming language chosen will depend on the level of complexity and precision required for the painting task.

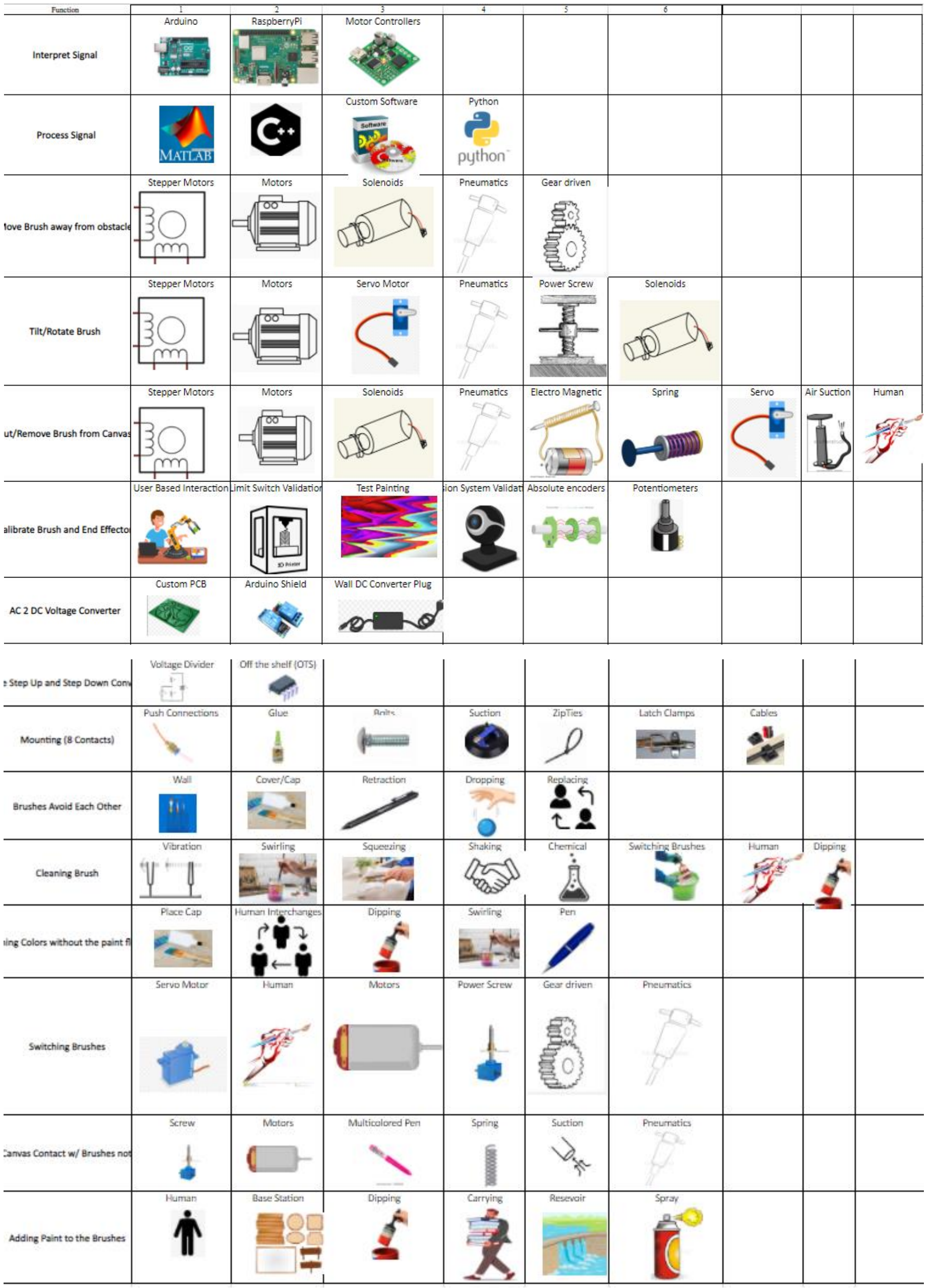


Figure 8**:** The morph chart

To avoid collisions while painting and moving, the brush can be mounted on a system of stepper motors, motors, solenoids, pneumatics, or gear-driven systems. These systems help the brush to navigate around obstacles and maintain its painting position. To mimic hand-like painting strokes, the brush can be tilted or rotated using stepper motors, motors, servo motors, pneumatics, power screws, or solenoids. These systems allow the brush to make fine adjustments in its angle and direction for precise painting. The brush can be placed or removed from the canvas using various methods such as stepper motors, motors, solenoids, pneumatics, electromagnets, springs, servos, air suction or a human. The method chosen will depend on the desired level of automation and the nature of the painting task.

To provide accuracy and precision in the painting process, the brush and end effector can be calibrated through various methods such as user-based interaction, limit switch validation, test painting, vision system validation, absolute encoders, or potentiometers. These methods ensure that the robotic arm is able to perform painting tasks with the desired level of accuracy and precision. An AC to DC voltage converter is needed to convert the electrical power supply to a form that can be used by the robotic arm. This can be achieved through custom PCBs, Arduino shields, or wall DC converter plugs. To ensure that the correct voltage is supplied to the motors and other components of the robotic arm, voltage step-up and step-down converters can be used. These can be achieved through voltage dividers or off-the-shelf (OTS) solutions.

The robotic arm can be mounted onto a cable system using various methods such as push connections, glue, bolts, suction, zip ties, latches, clamps, or cables. The method chosen will depend on the desired level of stability and the operating environment. To prevent the brushes from colliding when not in use, they can be covered with a wall cap or retracted, dropped, or replaced. These methods ensure that the brushes are stored in a safe and secure manner when not in use.

To clean the brush and remove paint, several solutions have been proposed such as using vibration, swirling, squeezing, shaking, a chemical solution, switching brushes, human intervention, dipping, and burning. Each of these solutions aims to effectively remove the paint from the brush without causing damage to the brush or affecting its performance. To switch colors without the paint flowing or dripping, several solutions have been proposed such as placing the cap, human intervention, dipping, swirling, and using a pen. These solutions aim to prevent the paint from flowing or dripping when the color is being changed. To switch brushes with different types, several solutions have been proposed such as using a servo motor, human intervention, motors, power screws, gear-driven systems, and pneumatics. These solutions aim to switch between different brush types effectively and efficiently as required. To avoid contact with the canvas when the brushes are not in use, several solutions have been proposed such as retraction, motors, a multi-colored pen, springs, suction, pneumatics, screws, and a cap/lid. These solutions aim to prevent the brushes from contacting the canvas when not in use. To add paint to the brushes, several solutions have been proposed such as human intervention, using a base station, dipping, carrying, using a reservoir, a feed system, and spray. These solutions aim to add paint effectively and efficiently to the brushes as required.

The Multi Color Brush design is made up primarily of a spring actuated brush system with a linear arm in Figure 9. This design can change automatically using the rotating drum in the arm. A base station is not needed because the paint is stored and automatically makes the brush wet. The brushes don't touch each other because the paint in each cartridge is usually separated by a divider or seal to prevent mixing of the colors. With the small form factor, the Multi Color Brush can use more than six colors at a time. One downside is that if the robot's movement is not fully controlled, it can be difficult to make various movements of the brush because the brush is fixed in the middle of the machine.

The SCARA Platform involves using a multi degree of freedom robotic arm on a platform in Figure 10. This design will be adaptable and modifiable since the robotic arm maneuver in multiple degrees of freedom, which can minimize human involvement. The arm would be able to access a base station on the platform which would house the paint, brushes, and cleaning system. With the use of a platform and a robotic arm, the design can have size and weight conflicts with other applications. For the robotic arm to complete these tasks, the system would involve relying on a complex vision system which increases failure.

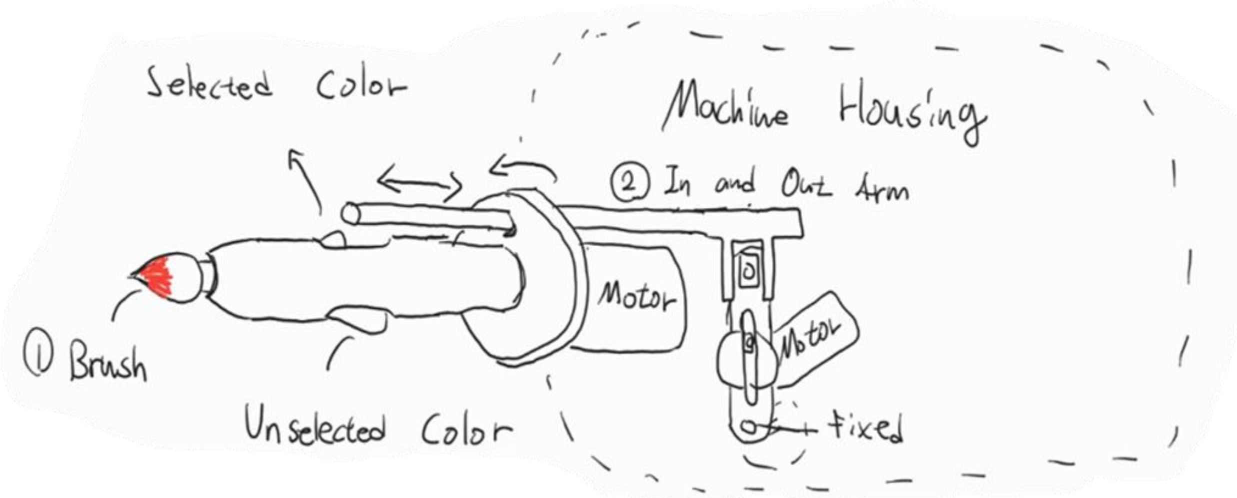


Figure 9**:** An initial concept sketch for one of the six ideation designs. This design in particular uses a system similar to a multicolor pen to swap paint colors

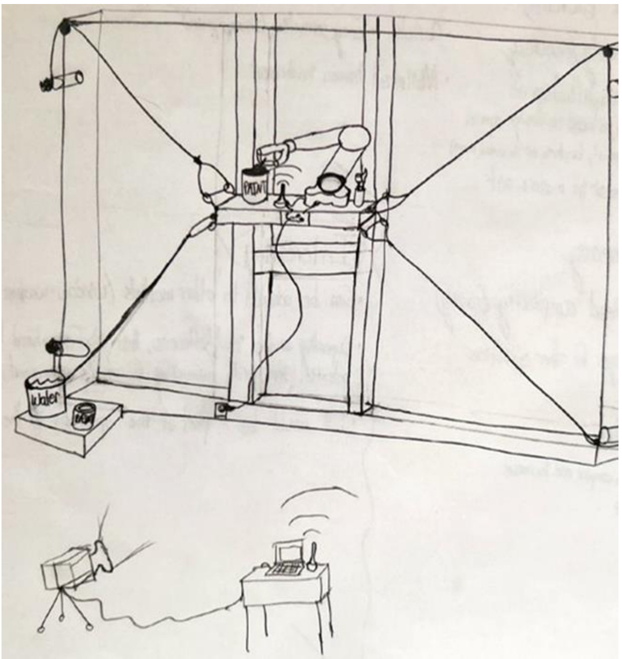


Figure 10**:** An initial concept sketch for the SCARA platform ideation design. This design uses a robotic arm to pick up a brush and paint like a person.

The 3D Wire Ball Joint Design utilizes a ball joint and wire design to rotate the bush with 3 degrees of freedom in Figure 11. The entire unit will move on a rack and pinion gear system to reach the window. Three individual brushless motors will control the joint with absolute encoders. Having a ball joining design allows for fluid motion to mimic hand-like painting. The small form factor also keeps the product within engineering specifications for weight and size. This design has difficulty in switching out the brushes if there isn't a base station.

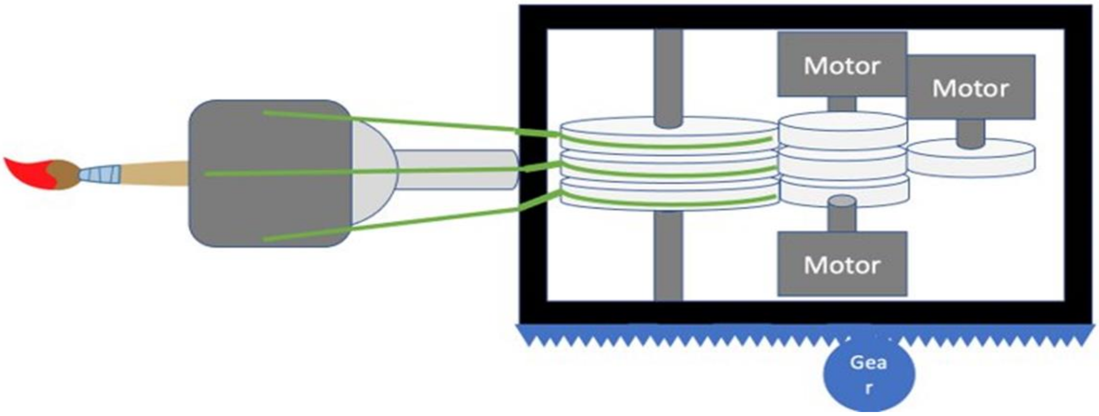


Figure 11**:** The is an initial concept sketch for the 3D wire ball joint design. This design utilizes a ball joint mechanism to actuate the brush with three degrees of freedom.

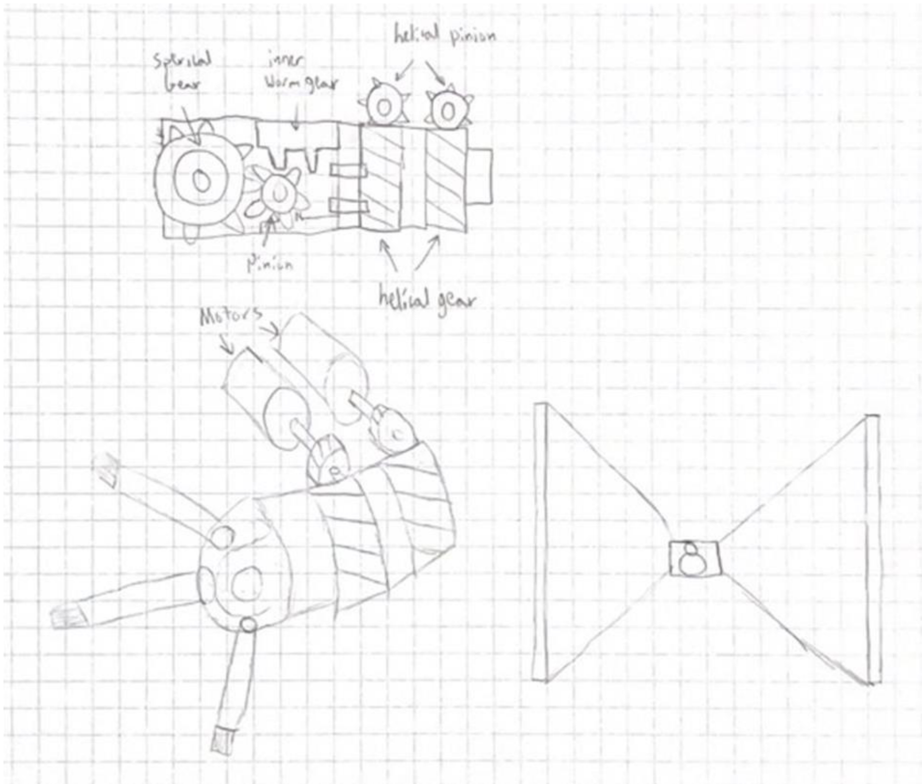


Figure 12**:** An initial concept sketch for the active ball joint mechanism ideation design. This design utilizes a rotating array of brushes to swap colors and brushes.

The Active Ball Joint Mechanism is designed to use multiple gears to allow the spherical ball joint to rotate in multiple directions in Figure 12. Each motor would be able to spin the joint on a specific axis to provide hand-like movements when painting. This design uses multiple gears which can be a source of failure if not manufactured properly. The paintbrush cannot move linearly, so there would be difficulty in removing the brush.

The Drum Serial LRR Design uses a rotating drum to allow the end effector to swap brushes to brushes with different colors in Figure 13. The brush moves using a multi-segment joint system actuated by stepper motors. The drum would be able to hold more than 6 brushes and colors, and the simple design without complicated joints allows for a smaller form factor. There is some difficulty changing and cleaning brushes with the joints having limited movement.

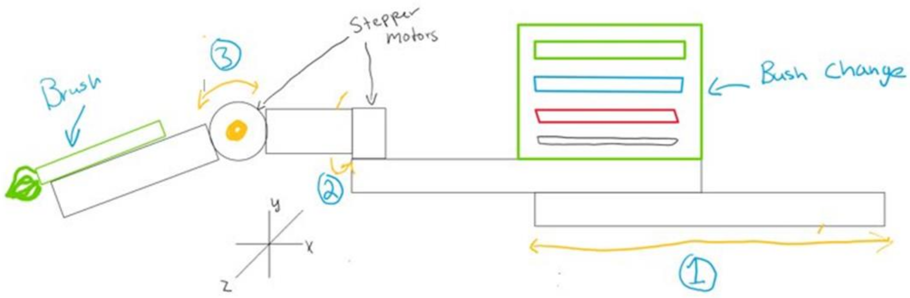


Figure 13**:** An initial concept sketch for the drum serial LRR ideation design. This design utilizes a rotating drum of brushes to swap brushes, and revolute joints to actuate the brush.

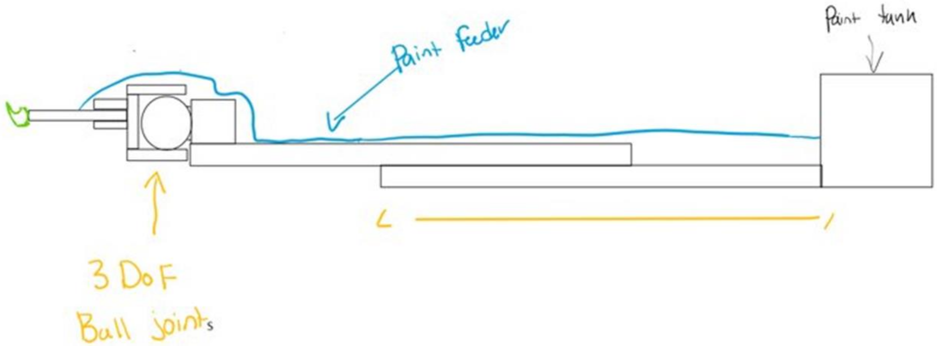


Figure 14**:** An initial concept sketch for the parallel wrist translation ideation design. This design utilizes a tube feeding system that connects to the back of the brush to add paint to the brush.

The Parallel Wrist Translation utilizes the same 3D ball joint as design 3 and a linear track in Figure 14. The system houses a tank that delivers paint to the brush through a tube. This design can easily mimic hand-like painting motions with the ball joint. Since there is a tube to provide paint to the brush, the system would need to purge the previously used paint from the tube before using another color of paint.

Concept Selection and Justification

After creating multiple initial ideas, they needed to be ranked to determine the optimal solution. For this objective, the engineering requirements detailed in the House of Quality (Table-4) utilized as ranking criteria in a decision matrix shown below.

Each design was ranked through a group discussion of evaluating the designs capability and difficulty in meeting the criteria set out in the specification sheet. The active ball joint design received the lowest overall score in the ranking matrix. Due to the design having multiple paintbrushes that rotated around the end effector, there were extreme concerns about the design's ability to detect obstacles before they could deal irreversible damage to the system. This along with concerns about durability of the design lead to it achieving a low score. The multi-color brush and drum serial LLR design had similar flaws in mechanical complexity. The need to have a rotating system to change brushes lead to concerns about the durability of the system. The paint brush changing system for both designs also caused concerns with paint color contamination between the brushes and led to a lower score in the designs.

The parallel wrist translation design achieved the third highest score with its ability to achieve six degrees of freedom while remaining compact. Its biggest drawback was that it required special brushes with the ability for paint to be fed through the handle. This system would include a purging process to change the paint color but concerns about the affectability of this process lead to the design achieving a low score for paint contamination. The painting system also caused concerns with the ability of the system to change paint brushes. This is because this design also required the brushes to be connected to the paint feeding system and would cause concerns with tubing getting tangled or complexity with attaching and removing the brush from the feeding system.

Table 4: This details the evaluation matrix utilized to rank the initial concept designs for the end effector.

WT- Weighted Total		Design											
		Multi-color brush		SCARA Platform		3D wire ball joint		Active Ball joint		Drum Serial LRR		Parallel Wrist Translation	
Criteria:	Importance:	Rating	WT	Rating	WT	Rating	WT	Rating	WT	Rating	WT	Rating	WT
Swtiching color	**10**	4	40	3	30	3	30	3	30	3	30	3	30
Detecting obstacle	**8**	2	16	4	32	3	24	2	16	3	24	3	24
Move end effector in high DOF	**10**	2	20	4	40	4	40	4	40	3	30	4	40
Adding paint to the brushes	**8**	4	32	3	24	3	24	3	24	3	24	2	16
Put and remove brush on machine	**9**	3	27	3	27	3	27	3	27	4	36	1	9
Brushes avoid each other	**9**	3	27	3	27	4	36	3	27	3	27	3	27
Increase platform Stability	**5**	1	5	3	15	3	15	1	5	1	5	3	15
Durability	**6**	2	12	4	24	3	18	2	12	2	12	3	18
Paint Erasing	**5**	1	5	4	20	4	20	2	10	3	15	4	20
Cost	**8**	3	24	2	16	3	24	4	32	3	24	2	16
Minimizing Human involvement	**6**	2	12	4	24	3	18	3	18	3	18	3	18
Total	84	220		279		276		241		245		233	
Relative Total(Div 336)	336	0.655		0.830		0.821		0.717		0.729		0.693	
Rank		5		1		2		6		4		3	

The 3D wire ball joint design achieved the second highest score due to its ability to compactly achieve six degrees of freedom without needing to use a paint feeding system. The design utilizes a ball joint actuated by motors through cables. This allows for the center of mass of the end effector to be near its base and increases the stability of the design compared to the other concepts. The parallel manipulator ball joint also allows for the system to emulate human wrist movements more accurately. This is because the ball joint utilized in this design has degrees of freedom like a human wrist. The main downside of this design is the complexity involved with putting paint on a paint brush and cleaning it. While the ball joint allows for the design to more accurately mimic human wrist movements, the overall design lacks a method to automatically put paint on the brush and change brushes. This requires human involvement to stop the system and change the brush.

The highest ranking and chosen design was the SCARA platform design in Figure 15, as it has an unique solution to tackle the problems from the previous designs. By utilizing a robotic arm on the platform, the system can accurately mimic the motions of a human arm. While the arm-based design is likely heavier than the other designs, it makes up for it with adaptability. This design allows for the system to fully mimic a human arm from picking up a brush, dipping it in paint in Figure 16, to making large continuous paint strokes on a building.

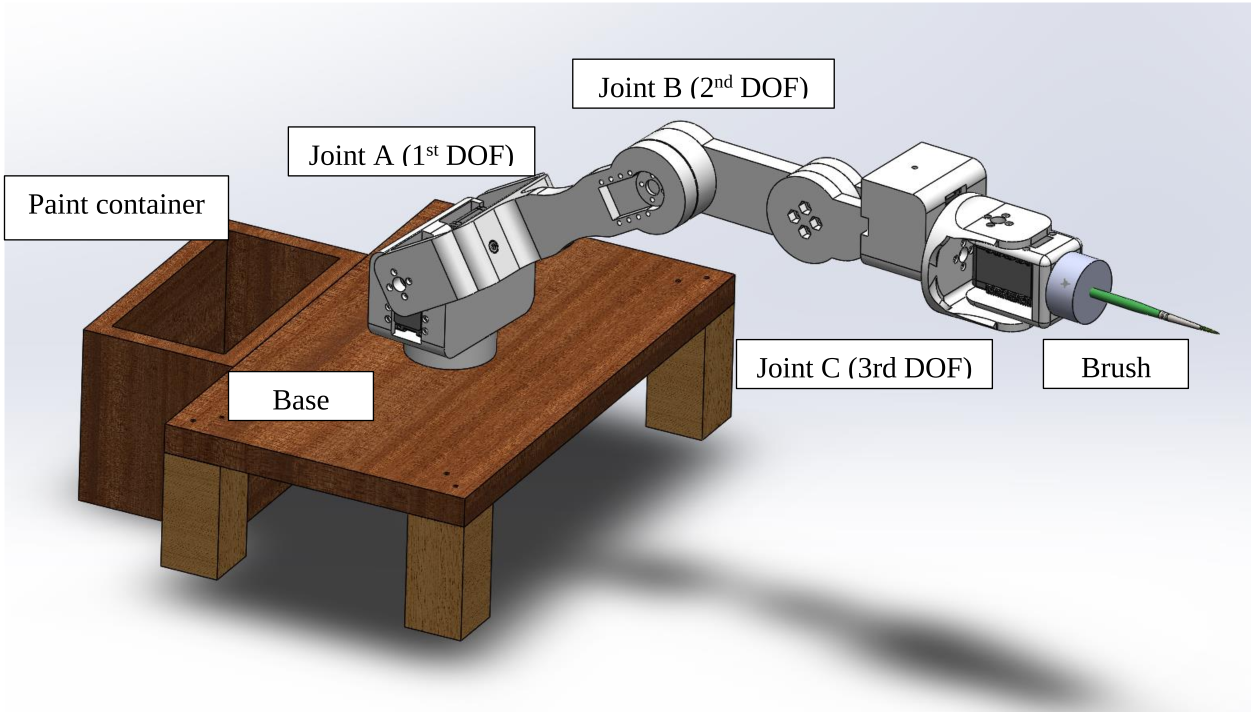


Figure 15: The CAD model for the selected SCARA platform-based solution painting in a painting position for various types of surfaces.

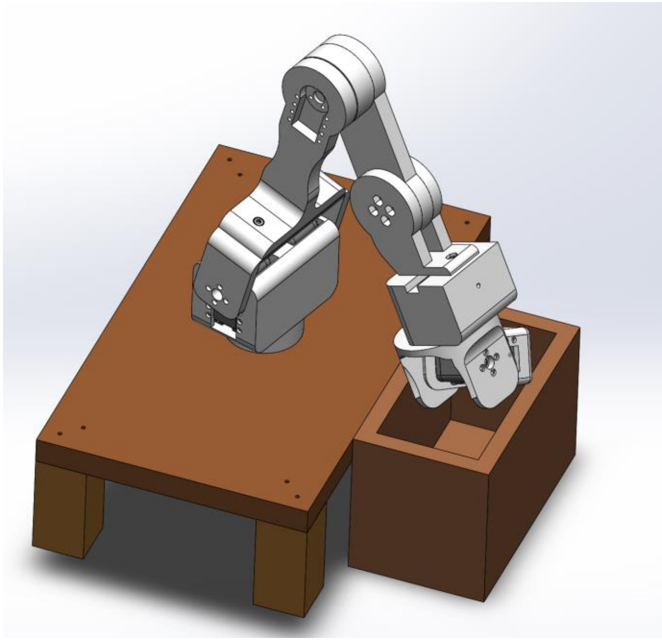


Figure 16: The desired CAD model moving the brush attachment end effector to the paint storage areas.

By utilizing a robotic arm, the system can easily switch between the desired three brushes and six different colors. The design integrates a platform to move along the obstacles in the environment to increase its stability. The arm utilizes a gimble end effector similar to the second highest ranking design to allow for the system to further emulate human wrist and arm movements while painting. At the end of the wrist gimble is an electromagnet that allows for the holding and switching of brushes. With the wrist gimble allowing the design to have two extra degrees of freedom, the system will be able to account for slight position errors from the moving platform and increase the accuracy of its output.

There are still several downsides to this design. The main downside of this design is its complexity and software hurdles. While allowing for the system to be adaptable and easier to scale, this design requires more complex motion planning. Having redundant degrees of freedom allows for the system to be accurate, but it also requires having a software algorithm to determine the optimal path of motion and the optimal joint configurations for the system while in that path of motion. With this design, there is also the risk that the system will encounter a singularity condition. In other words, the joints could be positioned in a unique way such that the system would be unable to move in the desired direction. The multiple degrees of freedom decrease the probability of this scenario, but it is still something that needs to be kept in mind.

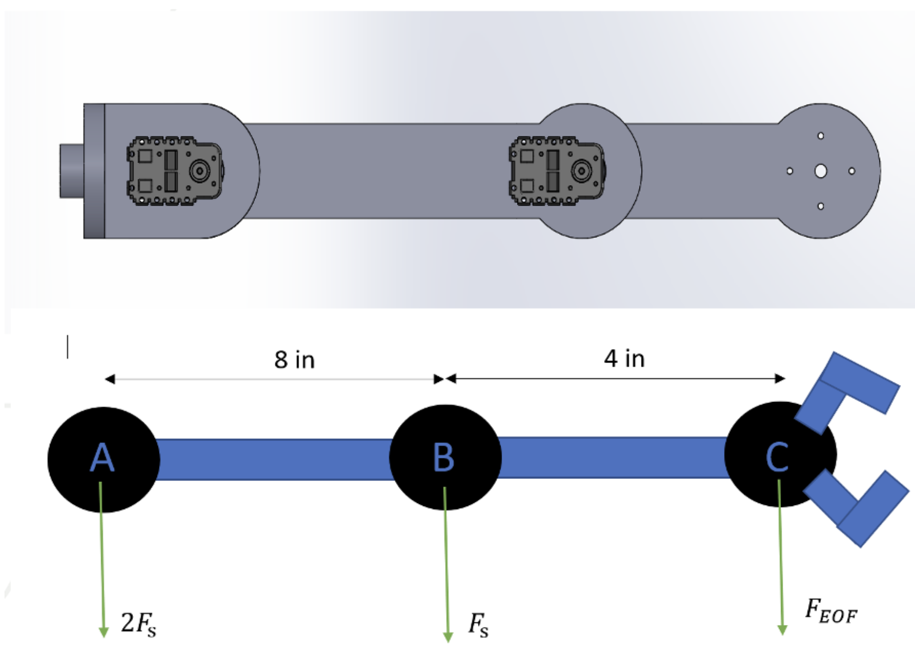
With any product that will have to traverse large heights, there are risks involved. For our system, some of the key identified risks include the mounting bolts for the arm shear, all eight of the cables attached to the system, and the system losing power while suspended. Depending on the height of failure, every one of these events could possibly have critical to marginal consequences. To combat the probability of these failures, several precautions will need to be taken. To decrease the likelihood that the bolts would shear off, the system will have a minimum of eight points of contact with the base station. If the bolts do fail however, the cable system, known as a dress pack, will be designed to hold the end effector for a short time while the system is lowered. The cable system for the design utilizes a Delrin plastic-based cable where this cable is highly resistant to stretching and has an approximate tensile strength of 10,000 psi. With a large tensile strength and multiple cables attached to the system, the probability of failure is extremely unlikely, and if one cable breaks, the cables will still be able to safely lower down the system without harming any civilians. In case of a power outage, there is a possibility that the cable system will fail and allow the system to free fall. A possible solution to prevent this would be to include a battery pack with the cable system. The battery pack will be able to feed enough power to the motors to safely lower down the system and alert the user.

Industrial Design

In today's market, there are multiple cable robots within the art industry, but they do not use acrylic paint in any sort of way. There are also robotic arms that utilize human-like motion to create paintings on canvases but are on stationary platforms. As mentioned before, the Scribit product uses cables attached to a vertical wall to produce large scale drawings with the use of erasable markers. The E-David project is a robotic arm that can produce portraits with multiple paints and brushes with several degrees of freedom. Team Robo Picasso’s design is somewhat a combination of these two products where a robotic arm is placed on a moving platform that is connected to a cable supported system. This project will be used to create paintings on glass windows compared to solid walls or canvases. The design must be as light as possible to make sure that the cable system can hold the end effector while still being strong enough to hold a paintbrush for long periods of time. Along with this, the design of the E-David project was referenced when designing the Robo Picasso end effector where two joints on the arm provide the same degrees of freedom with the arm moving in and out of a plane as well as up and down while ensuring a high factor of safety to avoid harm around its environment. For aesthetic features, the end effector will apply the Georgia Tech colors and logos to reach its target audience. Additionally, this project is completely open to students providing their own designs that could be painted onto the library windows for the students to have some sort of engagement with the school.

Detailed Technical Analyses, Experimentation, and Design Performance Prediction

After the selection of the design, the robotic arm must undergo engineering analysis to prove the workability and safety of the arm. An initial free body diagram of a robotic arm was used to analyze the expected toque requirements at each joint. In this system, there are 3 main loading points labeled A, B, and C in Figure 18 where each servo motor has an expected weight of 0.1 lbs. By treating the robotic arm as a simple beam, the moment can be taken around joint A to reveal that two servo motors would be needed at the base to allow for a factor of safety of 2. The moment could then also be taken around joint B to show that only one servo motor was required to rotate the upper robotic arm. To move the arm properly, torques applied on the joint should be lower than the servo motor's stall torque. To be specific, the maximum torque that can be tolerated at Joint A at the base is 2.2 ft-lb. Consequently, the total torque of the robotic arm system, including the weights from the other servos, PLA arm, brackets, servo holder, magnet, and brushes, should be less than 1.5ft-lb to prevent failure and stalling from excessive torque. In case of the Robo-Picasso, joint A will only have a torque of 1.2ft-lb acting on the entire system for the arm movement. Although the weight of the brush is not reflected in the current calculation, a stable result is obtained considering the weight of a general brush. This analysis shows that the system of the Robo-Picasso using servos can work well without failure.



- $\sum T_{max} = \frac{8}{12} ft * F_s + 1 ft * F_{eof}$

Figure 18: Free body diagrams with forces and torques to verify reliability of system.

To gain a better understanding of the structural stability of the system, a finite element analysis of the arm assembly was conducted in Figure 19. This analysis tested the strength of the arm in what was assumed to be the worst-case scenario as the arm is in its fully outstretched position maximizing the reaction moment, along with a resultant force with a value higher than the stall torque of the motors. This means that the motors would stall and allow the arm to move before this force could be applied. In this analysis study, some simplifying assumptions were required. Likely, the most important assumption is that the fastening mounts of the arm assembly to the base joint are fixed. For this assumption to be valid, the motors within the base joint must not reach their combined stall torque of 3 Nm or 2.2 Ft-lbs. The next major simplifying assumption is that the coupling between the two arm joints is bonded to the base joint connection. This assumption is only valid if the servo motor at this point has reached the stall torque. This assumption is blatantly incorrect as the applied torque in study is intentionally over the stall torque, but this assumption means that the torque applied on the joints is this study will be larger than the stresses expected in real use and that the calculated factor of safety is under the actual factor of safety. The final key assumption is that Solid Works considers the robotic arm to be made of pure PLA, but the arm will be made by three-dimensional printing. 3D printing creates a part by building stacking layers of the part on top of each other, and the connections between these layers are weak points for the system. This means that the system will likely fail at a point that is below the calculated value from the Finite Element Analysis.

Max Shear Force	1.61 MPa
PLA Yield Strength	60 MPa

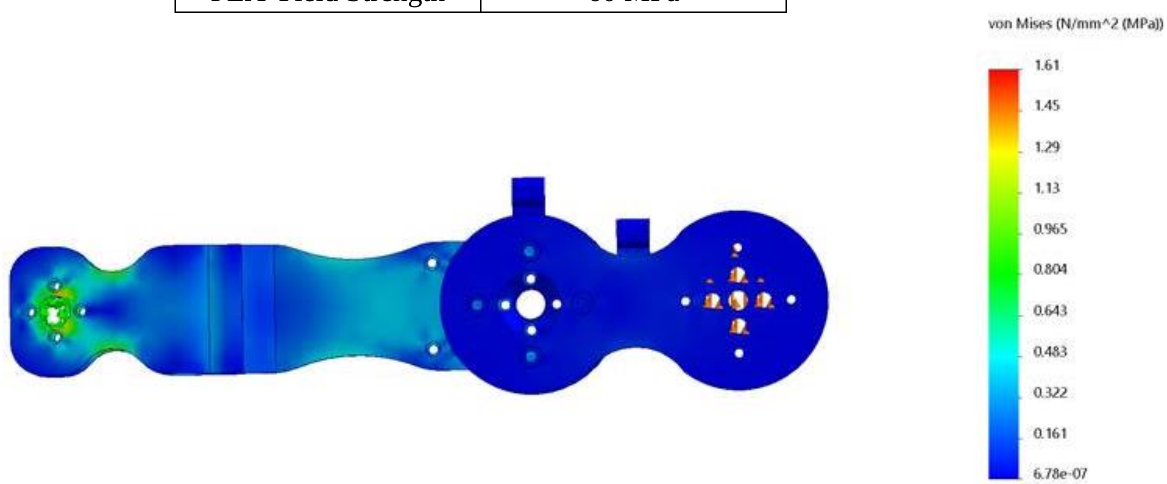


Figure 19: A finite element analysis of the arm in the stretched-out position. The analysis reveals that the arm can handle the expected load with an expected maximum stress at 3.1245 MPa.

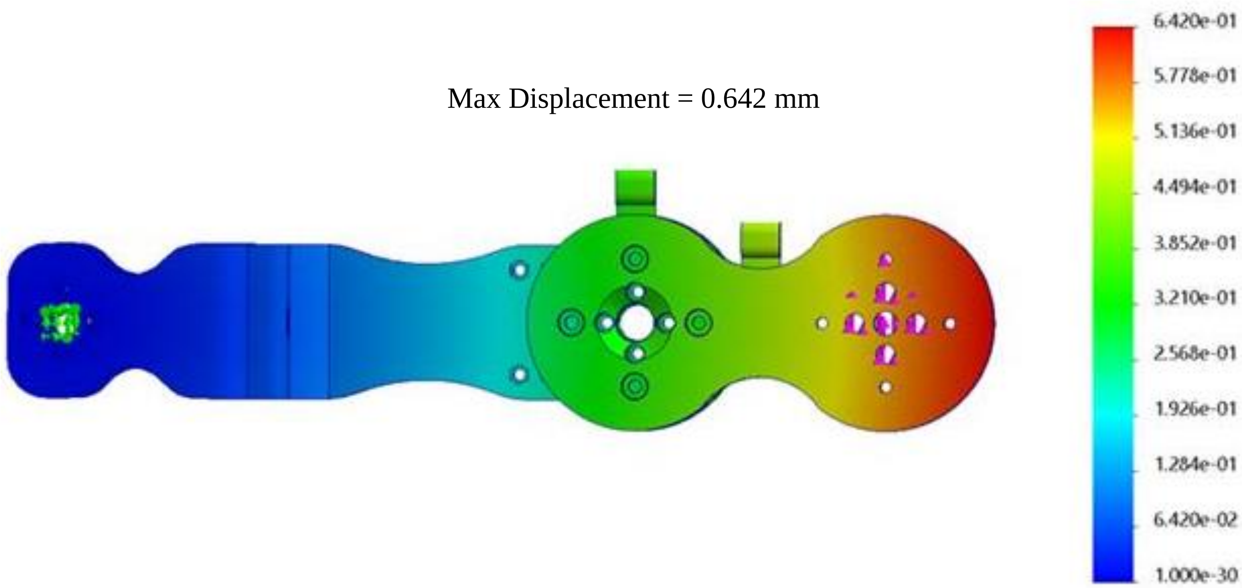


Figure 20: The displacement analysis of the robotic arm reveals that the largest displacement is expected to be at the end of the arm shown in red.

To create the finite element analysis of the stress on the arm, a force of 1.5lbs was applied to the end of the joint in an outstretched position. This force resulted in a maximum von missies stress to be 3.145*10^6 at the base joint. This is to be expected as the longest moment arm on the system will be at the base joint which means it will have the largest moment. Considering that the robotic arm for the system is made completely out of PLA, the joints on the arm have a yield strength of 60*10^6 and results in a factor of safety of approximately 16. Expected displacement analysis of the system under this stress was also created in Figure 20. The expected displacement under the chosen force was determined to be 0.642 mm. This expected displacement is less than the average diameter of paint brush and would not likely even be noticed in the system's output.

Figure 21 presents the results of the Inverse Kinematic solution for predicting the movement of the arm. By defining the range of maximum and minimum movement, the optimal position of the arm can be determined to ensure it reaches the wall for painting. This approach provides an efficient and effective solution for controlling the motion of the arm, enabling precise and accurate painting. The findings of this study highlight the potential benefits of using Inverse Kinematic solutions in industrial applications, where precise control of robotic arms is essential for achieving desired outcomes.

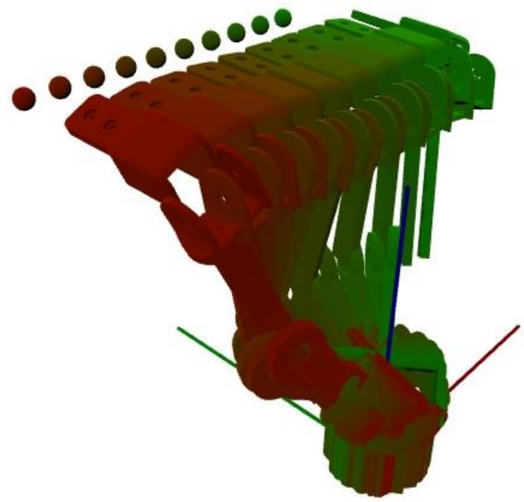


Figure 21: Example of an Inverse Kinematic (IK) solution for a horizontal line trajectory

Several experiments were conducted to verify the proper design and functioning of the robot, particularly in relation to being attached to a cable system, dipping into paint, and painting on glass. The stability of the base was tested by attaching the robot to it and applying force to see how quickly it returned to a stable state. The expected time was within 10 seconds where it returned to a stable state within 6 seconds, indicating that the high mass base made of plywood helped ensure stability. The robot was also used to draw various shapes to test its ability to draw as desired. It successfully created circles, squares, and even the letters "GT". Through this experiment, it was discovered that dipping the brush into the paint for each painting stroke was necessary to achieve a uniform thickness of the paint. The torque calculation, stress concentration analysis, and inverse kinematic solution were used to define the movement of the robot arm, with the primary objectives being to dip the brush into the paint and then reach the wall to start painting. Precisely calculating the trajectory of the robot arm ensured that it could successfully dip the brush into the paint without any mishaps and reach the wall with the right amount of pressure to create quality drawings. The cable system could track the orientation of the robot and replicate the input drawing on the wall. These findings demonstrate the effectiveness of using advanced methods to control the movement of robot arms, which has significant implications for industrial applications where precision is vital to achieving optimal outcomes.

Figure 22 shows applications of the robot being attached to the cable system, dipping into paint, and painting on glass. Overall, the results of the experiments and calculations provide evidence of the proper design and functioning of the robot and demonstrate the potential for using advanced methods to control robot arms in industrial applications.

Figure 22: The pictures of the application of the robot shows it attached to cable system, dipping into paint, and painting on glass in order.

The team at Robo Picasso anticipates that, based on all these designs, the robot will be able to replicate any type of shape based on the input drawing, as demonstrated in Figure 23. With this capability, the robot can mimic the artist's movement with a high resolution and scale it up for larger works in the future. This development could potentially revolutionize the art industry by providing a new method of creating high-quality artwork with precision and efficiency. Further experimentation and testing will be necessary to fully realize the potential of this technology, but the initial results are promising and pave the way for exciting advancements in the field of robotics and art.

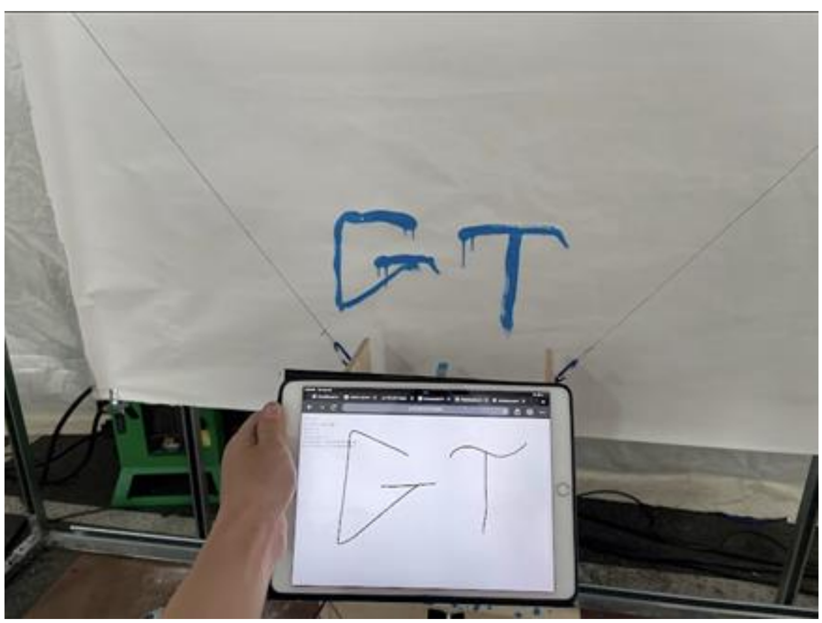


Figure 23: A picture depicting the robot mimicking a human's drawing on paper.

Final Design, Mockup and Prototype

From the initial concept to the end of the prototyping stage, numerous changes were made that lead to the final design shown in Figure 24. In this design, the robotic arm sits on a wooden base that is used to connect to the cable support system. Within the gap of the base is a servo motor that connects to the robotic arm and allows it to rotate 300 degrees around the base. At the bottom of the arm, there are two servo motors that apply enough torque to withstand the weight over the length of the entire arm, allowing the arm to move with one degree of freedom. This joint connects to another servo motor in the middle section of the arm to allow for an additional degree of freedom. From here, the wrist gimbal is created and add on two more servo motors to provide two more redundant degrees of freedom. As mentioned before, this design is modeled after the human arm. The base acts as the human body to allow for weight and stability, and the cable system would be the rest of the body to allow the end effector to move in x and y directions. This design allows the end effector to reach the canvas and mimic human painting strokes with wrist like movements.

Throughout the prototyping and experimenting process, multiple prototypes were fabricated to test potential issues and create plans to address them. In the first prototype, the base design is very different from the initial design where wooden planks were added to the sides like the final design, but at a smaller height to allow for better connection to the cable system. In this base design, the width of the base was not wide enough as the elbow joint of the arm sometimes interfered with the side panels, reducing the end effector's range of motion. The next iteration increased the width of the base and height of the side panels to provide more space and increase weight to increase its stability on the cable system.

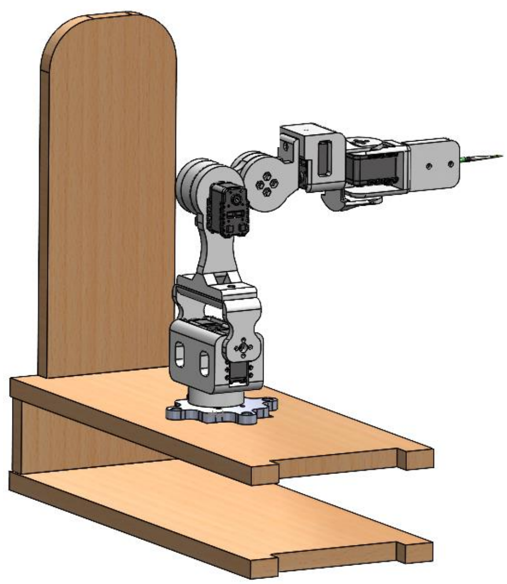


Figure 24: Final design of the robotic end effector

In the first prototype, the arm link lengths were somewhat long to keep a 15-inch reach from the start point to the canvas. Testing showed that the servo motors would stall at times due to the long length of the arm parts caused by large torques. The next iteration addressed this issue by decreasing the length of the arm while still maintaining the desired minimum reach.

Comparing the final design with the original requirements, many of the objectives provided by the sponsors were met. The design provides at least 3 degrees of freedom to mimic human movements. It includes a method to attach to the existing cable system. Multiple brushes can be attached to the robotic arm but they need to be changed manually. On the programming side, the end effector is able to collect paint and create simple drawings on a canvas. The team was ambitious in other aspects such as automatically changing multiple brushes and using multiple colors of paint as they were not able to be met during the time frame.

Manufacturing

The mockup of the final design was made almost entirely in-house. The only purchased components consisted of fasteners, thrust bearings, and servo motors. The base subassembly and the robotic arm subassembly were not purchased but were custom built. The base was manufactured using Baltic Birch aircraft plywood and cutting it to the size and shape needed with a water jet. The robotic arm was additively manufactured with 3D printing for its rapidity of the manufacturing process that allowed for multiple iterations to be quickly developed and printed. This was critical to the design of Robo Picasso as the novelty of the system required rapid testing and development of multiple designs. As for mass production, entirely new processes would need to be considered. For the base subassembly, it would be far more cost effective to use a CNC laser cutter for manufacturing due to less material waste, improved tolerances, and less tooling cost as compared to a water jet. The robotic arm subassembly could be 3D printed as the prototype was; however, another option that would be more cost-effective for mass production is injection molding. The material waste of either process is comparable, but injection molding is a quicker process that would decrease the machines necessary for the same volume of product, and it may be automated to reduce human capital costs.

The design and material selection of the Robo Picasso product were heavily influenced by the possible manufacturing processes. Many of the components in the robotic arm subassembly could have been integrated into one piece or could have used fewer fasteners with less complex geometries, but, due to the nature of 3D printing, this would greatly increase the cost and the waste involved with 3D printing. As for why 3D printing was chosen as the manufacturing process, that was due to the need for rapid prototyping and the accessibility of this additive manufacturing process. As such, the material chosen for the manufacturing of the arm was PLA for the same reasons. It is plentiful, cost effective, and strong for its weight, and it was readily available. Baltic Birch aircraft plywood was chosen for its ease of manufacturing, strength, and water resistance. Similar materials, like hardwoods, are harder to machine and more expensive.

Robo Picasso is a complex robotic system, but its' mechanical nature is contrarily simple. The base subassembly is made of birch plywood. One of the main concerns to produce the base is the inherit tendency of wood to warping, and this led to the selection of a Baltic Birch aircraft plywood as its construction process inherently flattens the boards. Due to the simplistic nature of the base design, there was a strong desire to make it manufacturable using typical power tools, and this led to the base being designed to withstand tolerances of 2mm in its construction. The main exception to the large tolerances are the bolt connection points to the other sub-assemblies as they will typically require a positional tolerance of 1mm. Moving to the robotic arm subassembly, every part was designed to be printed on a industry standard FDM printer. This leads to the main tolerance issue to be caused by thermal expansion of the base material and warping due to the printing process. Most components were chosen to have a tolerance of 0.15 mm. This is because larger variances in the tolerance suggests that there is thermal warping due to the printing process. This could lead to an increase of backlash in the arm and noticeable issues in the arm's performance. Like most three-dimensional printing filaments, PLA is prone to ultraviolet radiation damage. Moreover, an indoor, climate-controlled storage environment is suggested to prevent warping of the base, and to protect the sensitive electronics, like the servo motors and motor controller. Packaging should take these potential issues into consideration as well and an enclosed, plastic package for each individual part is likely the best method of delivery to prevent harm to the product.

The prototype for Robo Picasso cost $490 to create. That includes many components that ultimately were replaced during testing; however, in consideration of mass production, the true cost of production is difficult to determine. There are many considerations to be made when calculating the true cost, like the cost of labor, cost of material, material waste, energy cost, shipping costs, etc. The data shows that, in general, the cost of manufacturing is generally cheaper than the cost of prototyping, so the same behavior is expected for Robo Picasso. Through discussions with experts in the market of robotics and artistry, the product's sale price was estimated to be approximately $3,000 where this makes Robo Picasso a highly profitable product.

Societal, environmental and sustainability considerations

The social impact assessment (SIA) provides a step-by-step process to assist in the planning and implementation of the current product into the market, which aims to provide a better understanding of how a design may impact the surrounding world. Therefore, the Social Impact Assessment methodology was used to evaluate the potential social impacts of a painting robot designed to mimic artist hand movements using brushes and water-based paint. The assessment consisted of three steps which are defining the goal and scope, performing an inventory analysis, and interpreting the results.

Table 6 overlooks the defining of the goal and scope of the project. The functional unit is one painting robot, and the lifecycle stages considered are production, processing, assembly of components, and managing the drawing process. The associated activities involve designing a new end effector to allow for the use of brushes and designing a robot arm over 3 degrees of freedom.

Table 6**:** Goal and Scope Section Summary

Objective of Assessment	**Design Function**	**Functional Unit**	**Lifecycle Stages Considered**	**Associated Activities**
Assess social impacts of painting robot	Wants the robot to mimic artist hand movements by using brushes and water-based paint	1 painting robot	Production	Design a new end effector to allow for it to use brushes
				Design a robot arm over 3 DOF
			Processing	Assembly of components
				Managing the drawing process

Table 7**:** Inventory Analysis Section Summary

Product Lifecycle Stage	**Stakeholder Group**	**Social Impact Category**	**Impact Indicators**
Production	Workers	Occupational Health and Safety	Number of work-related accidents
	Local Community	Access to employment opportunities	Unemployment rate in the local community
Processing	Workers	Working Conditions	Hours of work per day or week

Based on robots sold and scope of the analysis, the stakeholder groups in the design context of the painting robot are likely to include workers involved in the production and processing stages, the local community where the robot will be used, and the end-users who will interact with the robot's artwork. These stakeholder groups may be impacted differently by the various stages of the product lifecycle and the associated activities. The social impact categories identified were occupational health and safety, access to employment opportunities, and working conditions. Impact indicators were identified for each category, such as the number of work-related accidents and the unemployment rate in the local community as shown in Table 7. However, this may depend on the specific environmental impacts and regulations in the region where the robot will be used.

The painting robot design is predicted to have both positive and negative impacts on human well-being. Positive impacts include increased efficiency and accuracy in the drawing process, while negative impacts could include adverse effects on the health and safety of workers and potential displacement of local community employment opportunities. To minimize negative impacts, measures such as providing adequate training and protective equipment to workers and actively seeking to employ and train local community members could be implemented. The selection of lifecycle stages was based on the most significant stages in the painting robot's lifecycle where potential social impacts could occur. Stakeholder groups were identified based on their potential interaction with the painting robot during its lifecycle stages. Social impact categories and indicators were selected based on their relevance to the stakeholder groups and the painting robot's lifecycle stages. Overall, this social impact assessment provides insight into the potential social impacts of the painting robot design, highlighting the need for proactive measures to mitigate negative impacts and enhance positive impacts.

Risk Assessment, Safety and Liability

To make the ensure the quality of the product, the potential failure modes need to be identified along with an evaluation of their risks. In this term, FMEA method is an essential process that can lead to a safe and reliable machine. The FMEA is shown in Table 5 where it outlines the various expected potential failures from the Robo-Picasso product. Severities of the failure effects are evaluated from each potential failure mode along with the ability to detect the failures and probability of occurrences. Using these values, a Risk Priority Numbers (RPN) was calculated where the RPN would be ranked from highest to lowest value. For the main power supply/battery section, a power surge that can short a circuit and the battery dying are considered high risk failure modes. From the table, a power surge was scored with 64 points from the RPN. The power surge short circuit can make the arm drop the paint brush, can fail to actuate, and could cause irreversible circuit damage. This problem can be triggered from a faulty battery or water spillage and paint leak. To prevent this failure, an inspection of the wiring before using the robot is needed. Also, the controller must be isolated from paint spills to avoid any spillage on the system. The battery dying is ranked as the second most dangerous potential failure with 48 points from RPN and has similar effects from failure as the power surge, where this problem usually is due to a loss of power. To mitigate the risk, regular monitoring of the signal is required to prevent any potential failures. For the servo motor, stall is identified as another risk-potential failure mode with 48 points from RPN tying with battery dying. Stall in the servo motor damages the arm so that the arm cannot actuate properly. This failure is caused by inadequate power supply and unexpected obstacles. To solve this problem, regularly checking the current draw for the servos is recommended to ensure that it is receiving enough power. Furthermore, loosening the connection in the electromagnet has high score as 30 points. Failure in the connection means that the magnet cannot hold the paint brush stably and the paint brush would drop during drawing. To prevent this failure, a brush clamp must be checked several times to ensure that connection is tight and to fix if it is loose.

Table 5: The FMEA table details the different methods in which components can fail and outlines different safety measures and recommendations to prevent the parts from failing.

Item / Function	Potential Failure Mode(s)	Potential Effect(s) of Failure	Sev	Potential Cause(s)/ Mechanism(s) of Failure	Prob	Current Design Controls	Det	RPN	Recommended Action(s)
Main Power Supply/ Battery	Power Surge Short Circuit	Arm drops brush Failure to actuate Irreversable Circuit damage	8	Faulty Battery Water or paint leak	4	Controller and wireing isolated from fluids	2	**64**	Inspect wireing before use and isolate controler from paint spills
Main Power Supply/ Battery	Battery Dies	Arm drops brush Failure to actuate Paint Spill	6	Faulty Battery Did not charge Battery Water or paint leak	4		2	**48**	Look into a low power light
Microcontroller	Failure to connect to system	Failure to actuate arm drops the paint brush	5	Enviroment Conditions Power Loss Programming issues	4		1	**20**	Have multiple backups
Microcontroller	Controller Failure	Failure to actuate arm drops the paint brush Damage to Enviroment Spill Paint	7	Paint Leak Power Surge	3		1	**21**	Have an event based programming architecture to let users know of the error
Servo Motor	Servo Failure	Arm can not actuate properly Controller Failure	5	Inadequate power supply Unexpected obstancles Fatigue	2		2	**20**	Test mulitple Servos and keep back ups
Servo Motor	Stalls	Arm can not actuate properly Controller Failure	4	Dead Battery Control Issues Inadequate power supply Unexpected obstancles	6	Controller is designed to avoid obstacles, and power control boards for servo motor	2	**48**	Look into current draw for servos and determine if capacitors are needed
Electro Magnet	Fails to or looses connection	Drops Paint Brush	6	High Surface Friction Inadequate Power Supply Unexpected Obstacle	5		1	**30**	Looking into a brush clamp to ensure connection
Base Cable Connections	Wire Snaps Base Bracket Breaks	Robot can loose stability Robot could fall Paint Spill	9	High Use and Fatigue Outside interference Inproper Care	2		1	**18**	If determine needed, we can add supports to cable connections on bracket
Base Robot Joint	Bolt Failure Joint Failure	Robot Can Fall off Base Station Paint Spill Damage to enviroment System can fall from a large height	10	High Use and Fatigue Outside interference Inproper Care Unexpected Obstacles	3	Joint Designed with a factor of safety of 5	1	**30**	
Arm Linkages	Bolt Failure Joint Failure	Part of Robot Can Fall From Large Height Paint Spill Damage to enviroment Hazardous Projectile	10	High Use and Fatigue Controller Error Unexpected Obstacle Outside interference	3	Bolts and joints are designed with a factor of safety of 5	1	**30**	
Base Bracket	Bolt Failure Structural Failure	Paint Spill Arm Disalignment Arm Failure Arm Falls off base	10	High Use Fatigue Unexpected interference Improper Use	2		1	**20**	Include extra supports around base connections

Patent Claims and Commercialization

The scope of the invention needs to be identified and meet the legal requirements for a patent claim. The product to claim is a multi-axis robotic arm suspended on a cable support system. The system comprises of a wooden base, a robotic arm, and multiple servo motors. The claim can be supported if the product is within the following boundaries:

1. The base and the cable support system together provide weight and stability to the robotic arm.
2. The robotic arm is designed to mimic human arm movements with at least three degrees of freedom.
3. The robotic arm contains a plurality of brushes configured to be manually attached to the end effector to perform painting operations.
4. The robotic arm is operable to collect paint and create drawings on a canvas.
5. An operable control system exists to control the movement of the robotic arm and the end effector.
6. The robotic arm is capable of movement in the x and y directions.

In summary, the present invention provides a robotic arm that can create human-like paintings on a canvas. The system can perform various artistic tasks and provides automatic adjustment of the pressure and angle of the brush based on the painting surface. The system also includes the necessary controls for feedback and a set of interchangeable tools for artistic tasks.

Team Member Contributions

Starting in the initial design phase, Jaepil Goh contributed mainly to the three-level evaluation matrix, morphological chart and contributed an ideation design. He also conducted in-depth market research for standards and comparable products. Lance Crawford contributed through the ideation process, creating the highest ranked design through the Evaluation Matrix. Additionally, he contributed to many of the other engineering design tools such as the House of Quality, Specifications Sheet, Morphological Chart, and Function Tree. Lance also wrote the customer requirements section of this report. William Duncan is the main point between the team and the sponsors. He has organized our weekly recurring meeting with the sponsors. He has also contributed throughout the ideation process from the house of quality to the morphological chart. During the ideation process he contributed two of the six total designs to the process, and he also made the Solid Works model for the highest-ranking design from the evaluation matrix. Nil Patel has contributed to the research of existing products and patents where he also wrote about in the report along the conclusion and helped with the presentation. He also created the

Gantt Chart to finalize dates for the design and prototype, created an ideation, and is the finance lead of the group. Tirth Patel contributed by researching the codes and standards for the product. He also helped format and proofread the report and the PowerPoint for the presentation. His ball joint is a part of the final design. In the report, Eunkwang Lee contributed for making various appendixes such as House of Quality, function tree, morphological chart, and Evaluation matrix. Also, he wrote engineering analysis part which are force verification, FEA and FMEA.

Moving into the prototyping phase, Nil and Tirth Patel have been instrumental by creating a more in-depth Gantt chart, and ensuring the team meets their weekly goals. Nil and Tirth also work with Jaepil Goh on the gimble end effector for Robo Graffiti. Together, the three have been researching efficient ways to connect and disconnect the brushes from the robot. The Cad models for the gimble end effector were made by Nil and have been iterated on by various team members. Tirth and Jaepil Goh have also worked with William Duncan to create the finalized bill of materials.

The main prototyping and iterated on arm assembly has been done by William Duncan. He has fabricated and iterated ten out of the ten parts for the arm and gimble assembly. He has conducted the engineering analysis for the arm assembly including the hand calculations and the finite element analysis. William has also worked with Lance Crawford and Eunkwang Lee to help create the functional failure modes and effects analysis. Together they identified failure modes and brainstormed solutions to problems outlined in the FMEA. Jaepil Goh and Eunkwang Lee work together on the design and iteration of the base and base couplings. They redesiged the connection points for the new actuators and are about to start prototyping the base. Finally the base system was redesigned and fabricated by Jaepil Goh and Will Duncan.

Conclusions, Future Work/Project Deliverables

Over the past few months, Team Robo Picasso has gone through several stages to create the final design for the end effector. The team conducted research on the three proposed subsystems and its components before finalizing a design to begin prototyping. Furthermore, one of the main updates from prototype was to improve the base which gives stable system for platform of cable system after consulting with multiple stake holders and analyzing each version of the model. At each point of the prototype phase, the engineering analysis was used to provide crucial details and verification for the part fabrication.

The main challenge with the design will be mimicking the artist brush strokes with the robotic arm. This involves the integration of all three subsystems with the preexisting cable system using the necessary software programs. The final design uses a multi-servo wrist unit to replicate a wrist like motion with multiple degrees of freedom to solve the paint stroke problem and to dip the brushes in paint and water. For the brushes, they are attached on Gimbal to move precisely as user's command. To refill color to brush, the arm is programmed to rotate for dipping the brush into paint container. This allows the robot to complete various large murals while using various colors and strokes. When fabricating the arm subassembly, there was a significant amount of backlash occur at the end of each joint. The team was able to assess the problem and concluded that the mounting hardware had exceeded the tolerance for the servo to be secured properly. Furthermore, the present prototype dips brush into a paint container at the beginning of every stroke as it takes a lot of time to complete work where this issue could be improved by updating program setting.

ROBO PICASSO

GT ARTS Initiative
Project Lead

SIMPLE GANTT CHART by Vertex42.com
https://www.vertex42.com/ExcelTemplates/simple-gantt-chart.html

Project Start: Mon, 3/13/2023

Display Week: 1

TASK	ASSIGNED TO	PROGRESS	START	END
Wrist Joint				
Intial Prints		50%	3/12/23	3/19/23
Version 1 Wrist		50%	3/12/23	3/19/23
Purchase/Source Components		0%	3/19/23	3/24/23
Subsystem Testing		0%	3/27/23	4/1/23
Arm				
Version 1 Arm Complete		80%	3/1/23	3/12/23
Subsystem Testing		0%	3/27/23	4/1/23
Purchase/Source Electronics		10%	3/9/23	3/23/23
Mechanical Components (Bearings etc.)		0%	3/16/30	3/30/30
Base				
Purchase Materials		0%	3/27/23	3/31/23
Version 1 Complete		0%	3/27/23	4/3/23
Testing Version (if needed)		0%	4/3/23	4/8/23
Intergration		0%	4/8/23	4/12/23
Overall				
Soft Test 1			3/8/23	4/13/23
Design of prototype			3/27/23	4/3/23
Mechancial Testing			4/3/23	4/8/23
Design update			4/3/23	4/12/23
Final Tests			4/17/23	4/21/23

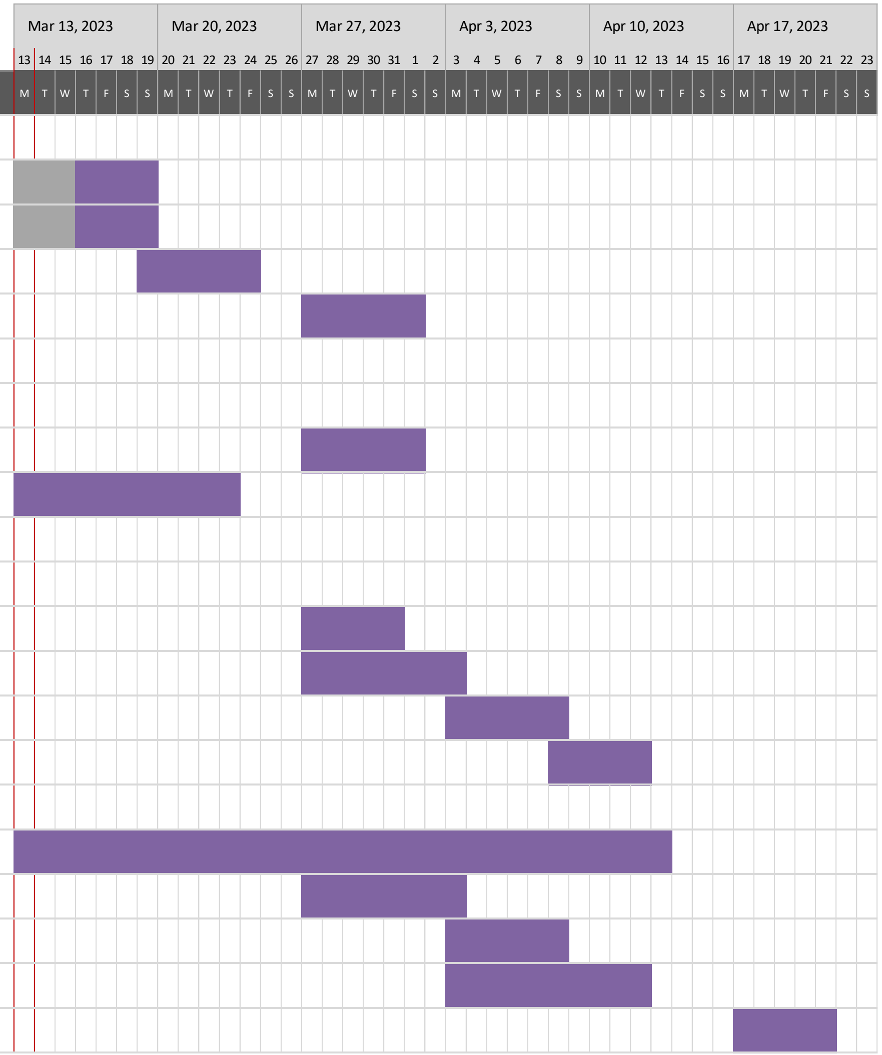


Figure 22: Gantt Chart overlooking all necessary dates for the team.

Table 8: The bill of materials of products and parts bought for the prototype

Material	**Quantity**	**Cost Per**	**Total**	**Purchase By Date**	**Source Link**
Brush (10)	1	$21.99	$21.99	4/6/2023	AROIC Acrylic Painting Brush Set, 10 Packs / 120 Pcs, Nylon Brush Head, Suitable for Oil and Watercolor, Perfect Suit of Art Painting, Best Gift for Painting Enthusiasts.
Paint Container (10)	1	$8.99	$8.99	4/3/2023	DecorRack 40 Plastic Mini Containers with Lids, 0.5oz, Craft Storage Containers for Beads, Glitter, Slime, Paint or Seed Storage, Small Clear Empty Cups with Lids (40 Pack)
Paint (12)	1	$57.00	$57.00	4/6/2023	Jack Richeson 101592 Tempera Powder Paint, Set of 12
Servo Motor	6	$50.00	$300.00	2/17/2023	https://www.robotis.us/dynamixel-ax-12a/
Thrust Bearing	5	$9.49	$47.45	3/17/2023	Rannb 51105 Thrust Ball Bearing Axial Ball Thrust Ball Bearings 25mm x 42mm x 11mm - Pack of 3: Amazon.com: Industrial & Scientific
Micro Controller with Shield	1	$24.90	$24.90	3/17/2023	OpenRB-150 - ROBOTIS
Cable 1100mm Long	1	$5.80	$5.80	3/17/2023	Robot Cable-3P 1100mm (LN-101) - ROBOTIS
Cable 200mm	1	$17.28	$17.28	3/18/2023	Robot Cable-3P 200mm 10pcs - ROBOTIS
Steel Phillips Flat Head Screws	50	$0.11	$5.50	3/19/2023	https://www.mcmaster.com/90031A249/
Total			$488.91		
Total Budget			$3,000.00		
Remaining Budget			$2,511.09		

References/Citations

1) “How it works,” *Scribit Shop*. [Online]. Available: https://scribit.design/pages/howitworks. [Accessed: 08-Feb-2023].
2) J. M. Gülzow, P. Paetzold, and O. Deussen, “Recent developments regarding painting robots for research in automatic painting, artificial creativity, and machine learning,” *MDPI*, 14-May-2020. [Online]. Available: https://www.mdpi.com/2076-3417/10/10/3396#. [Accessed: 08-Feb-2023].
3) “US20210180351A1 - system and method for building façade cleaning and painting with a dual cable-driven robot,” *Google Patents*. [Online]. Available: https://patents.google.com/patent/US20210180351A1/en?q=cable%2Bdriven%2Bpainting%2Brobots&oq=cable%2Bdriven%2Bpainting%2Brobots. [Accessed: 08-Feb-2023].
4) “US8726832B2 - painting system having a wall-mounted robot,” *Google Patents*. [Online]. Available: https://patents.google.com/patent/US8726832B2/en?q=painting%2Bend%2Beffector&oq=painting%2Bend%2Beffector. [Accessed: 08-Feb-2023].
5) ASME, "Overhead and Gantry Cranes (Top Running Bridge, Single or Multiple Girder, Top Running Trolley Hoist)," ASME B30.2, American Society of Mechanical Engineers, New York, NY, USA, 2019.
6) [IEEE] SAE International, "SAE J2954: Safety Guidelines for Mobile Robotics," SAE International, Warrendale, PA, USA, 2019.
7) IEC, "IEC 60204-1: Safety of machinery - Electrical equipment of machines," International Electrotechnical Commission, 2005.
8) ISO, "ISO 10218-1: Robots and robotic devices - Safety requirements for industrial robots," International Organization for Standardization, 2011.
9) ISO, "ISO 9283: Robots and robotic devices - Performance criteria for industrial robots," International Organization for Standardization, 1997.

10) ISO, "ISO 10218-2: Robots and robotic devices - Part 2: Safety requirements for industrial robots," International Organization for Standardization, 2011.
11) ISO, "ISO 13849-1: Safety of machinery - Safety-related parts of control systems," International Organization for Standardization, 2015.
12) ISO, "ISO 8373: Industrial robots - Vocabulary," International Organization for Standardization, 1990.
13) ISO, "ISO 11228: Robots and robotic devices - Presentation of data for path-related parameters of robots," International Organization for Standardization, 2009.
14) ISO, "ISO 11352: Robots and robotic devices - Presentation of data for additional kinematic parameters of robots," International Organization for Standardization, 2009.
15) ISO, "ISO 4413: Hydraulic fluid power - General rules and safety requirements for systems and their components," International Organization for Standardization, 2010.
16) ISO, "ISO 6020: Fluid power systems and components - Vocabulary and symbols," International Organization for Standardization, 2007.
17) IEC, "IEC 61131-3: Programmable controllers - Part 3: Programming languages," International Electrotechnical Commission, 1993.
18) IEC, "IEC 60204-1: Safety of machinery - Electrical equipment of machines," International Electrotechnical Commission, 2005.
19) IEC, "IEC 61784-1: Industrial communication networks - Profiles for Factory Automation and Process Control Networks," International Electrotechnical Commission, 2008.
20) IMARC, Painting Robots Market: Global Industry Trends, Share, Size, Growth, Opportunity and Forecast 2023-2028 Available: https://www.imarcgroup.com/painting-robots-market#:~:text=Market%20Overview%3A,US%24%202.4%20Billion%20in%202022
21) UNEP, “The Methodological Sheets for Subcategories in Social Life Cycle Assessment (S-LCA)”,Available:https://cpbusw2.wpmucdn.com/sites.gatech.edu/dist/2/334/files/2020/01/2011_Methodological_Sheets.pdf