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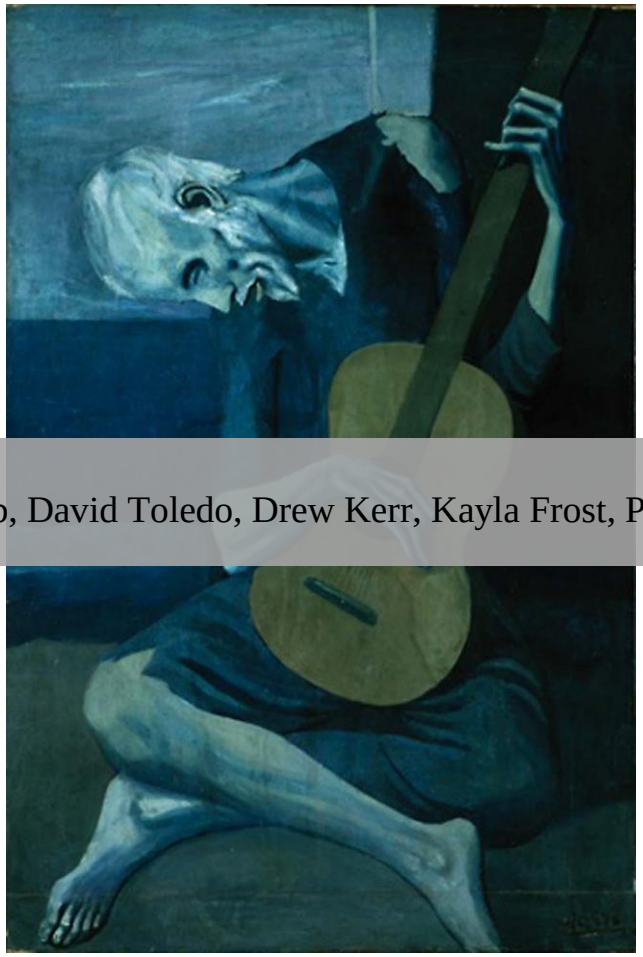

PICASSAU

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Cycle 2 Report | Team 2 | ELEC4000 | Dr. Roppel | Fall 2013 | Auburn University

Executive Summary – Peter Gartland

PICASSAU is a robot designed to produce a painting of a simplified digital image. PICASSAU mimics a human artist by painting on an upright canvas. The paintbrush hangs from two motors at the upper corners of the canvas. By controlling these motors and several servos attached to the paintbrush carriage, PICASSAU can run a calibration routine to determine the paintbrush's position on the canvas, dip the paintbrush into different paint reservoirs, and paint paths onto the canvas. The paths that PICASSAU follows are determined by a series of coordinates that come from vectorizing the simplified image. PICASSAU meets the Cycle 2 goal of successfully painting a three-color image from a webcam image.

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List of Acronyms

ADC	Analog to Digital Converter
FTDI	Future Technology Devices International
GPIO	General Purpose Input/Output
GUI	Graphical User Interface
IR	Infrared
LCD	Liquid Crystal Display
MDF	Medium-Density Fibreboard
OpenCV	Open Source Computer Vision
PVC	Polyvinyl Chloride
PWM	Pulse Width Modulation
RBBB	Really Bare Bones Board
RPi	Raspberry Pi
SVG	Scalable Vector Graphics
TTL	Transistor-Transistor Logic
UART	Universally Asynchronous Receiver Transmitter
USB	Universal Serial Bus
XML	Extensible Markup Language

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1. Introduction – Drew Kerr

Our goal is to build a low cost robot that is able to paint pictures on a canvas taken by a webcam. We desired the painting process to be quick and efficient such that people could enjoy a quick self-portrait on the way to a football game or on an E-day tour without missing the game or falling behind on the tour. We also wanted the device to be easily visible during the painting process.

PICASSAU was created to meet these criteria. PICASSAU accepts an image by taking it with a webcam. The computer will then convert the webcam image into a list of vectors and will send these vectors as a series of commands and coordinates to an Arduino. The Arduino moves the paintbrush by controlling two stepper motors at the top of the physical structure to match the coordinates and commands delivered by the computer. At the end of this process, PICASSAU will be able to generate a simplified painting from the original photograph.

The rest of this document describes the aforementioned process in more detail. It will detail the technical aspects of the project including the graphics type, carriage kinematics, brush control, software and computing, communication, image processing, and vectorization. In addition, the document discusses the standards and constraints involved in the project, the budget, the timeline and finally the performance of our robot. The document will then conclude with our technical accomplishments and discuss the lessons learned in the second development cycle of PICASSAU.

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2. Framing and Support – David Toledo

2.1 Framing Design

The framing for the canvas and its support was constructed out of PVC. The other option we considered was to construct the framing out of 2X4 lumber. Table 1 shows the Pugh chart constructed to determine the better option. Using the Pugh chart we decided to construct the frame out of PVC. This also gave us the ability to use manufactured parts to help ensure the frame's corners and joints were square and level. The greatest benefit from using PVC over lumber was the total weight of the structure because 2x4 lumber is more than twice the weight of PVC per unit length. As shown in Fig. 1, two options were considered for the geometry of the robot. The base of the frame was constructed to have a rectangular base, for stability while painting and moving, opposed to the general design of an easel, with four unconnected legs angled from the canvas to the floor.

Table 1: Pugh chart comparing the different framing material options.

		Framing Material options:	
Criteria:	Weight:	PVC	2X4 Lumber
Cost	2	++	0
Strength	3	+	++
Weight	4	+	-
Easy of use	2	++	+
+		15	8
0		0	2
-		0	4
Net Score		15	4

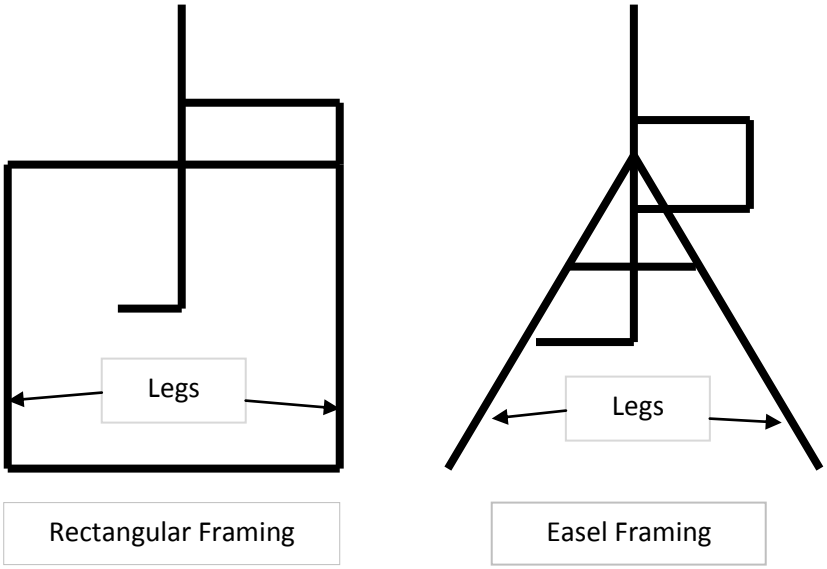

Figure 1: Frame design options.

We decided to mount the motors to the frame above the canvas, as to have the painting carriage suspended parallel to the canvas. We decided on this design as opposed to a horizontal design for two main reasons: one being the fact that a horizontal painter resembles a printer too much and the second being that we wanted the design to resemble a natural painter's posture. The motors are mounted approximately 1.5 feet above to canvas and approximately 1 foot away from the edges of the canvas horizontally.

2.2 Support Design

Built into the frame are two platforms: one was built to support the paint containers and water and the second was built to support the power source, motor drivers, Arduino, and the RaspberryPi. The canvas support was constructed using MDF instead of plywood for two simple reasons: weight and cost. We also used MDF as the platforms to support the paint cups and the electronics.

To protect the electronics from potential damage such as transportation jostling, water spills, small particles and dust, and non-team members, a housing was constructed (Figure 2). The housing is constructed out of MDF and framed with PVC for structural integrity.

Built into the housing are two fans for cooling the motor controllers inside. For simplicity reasons, holes were drilled in the MDF as vents instead of constructing the housing with the fans built into the walls. This design for the fans also protects the fans from being damaged during transportation and operation. As shown in Figure 2, much of the hardware is also built into the housing including the webcam, monitor, pushbuttons, and potentiometers.

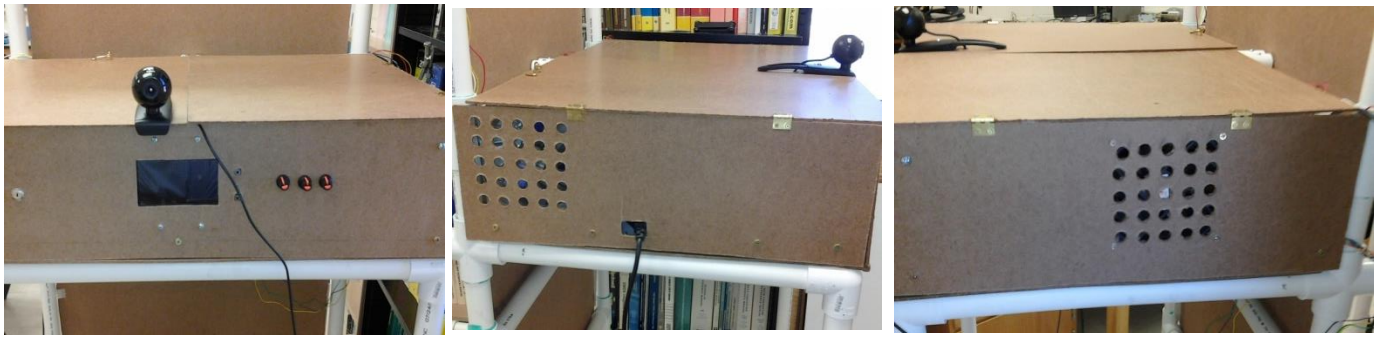

Figure 2: From left to right: front view, left side view, and right side view of the housing.

3. Motors – David Toledo

Our motor decision was based on four variables: cost, holding torque, weight, and ease of use. Table 2 is a Pugh chart showing the pros and cons for five motor options we considered. The HY100 1713 was a motor readily available to use and our first option. After we tested the HY100 motor we found that the holding torque and the moving torque for this motor were insufficient for the constraints of our project. As shown in Table 2, our best option was the 57BYGH420; this motor gave us a holding torque more than three times the holding torque of the HY100.

The 57B motor was also well within our projected motor budget of $100, costing only $24 each. Another plus to the 57B was the fact that the motor driver needed for these motors, a 4988 stepper driver, has a potentiometer built-in enabling us to maximize current flow, which in turn maximizes our holding torque. The best attribute to this motor, however, is the number of steps per revolution; the HY100 has only 100 steps while the 57B motor has 200. Doubling the number of steps helped to increase our painting resolution.

Table 2: Pugh chart comparing the different motor options.

		Motor options:				
Criteria:	Weight:	HY100 1713	SY57ST56-0606B	SY57STH56-1006A	SY57STH76-1006A	57BYGH420
Cost	4	++	0	0	-	+
Holding Torque	4	--	0	+	++	+
Weight	1	++	+	--	--	--
Easy of use	2	+	0	0	0	++
+		12	1	4	8	12
0		0	10	6	2	0
-		8	0	2	6	2
Net Score		4	1	2	2	10

4. Motor Controllers – Ben Straub

In order to drive the motors, it is necessary to have motor controllers. These motor controllers must be able to handle the necessary current required by the motors without overheating.

At the beginning of the project, we used a pair of dual channel – one channel per stepper motor coil — H-bridge motor controllers based around the L298 [1]. These motor controllers are not specific for stepper motors. Also, they do not contain any active current-limiting. Active current-limiting maintains a steady average current independent of the supply voltage by pulsing the current with a PWM signal. While these motor controllers were suitable for the original motors, using them with the new motors required added difficulty. This is because the new motors ran on a lower voltage at a higher current; specifically, they required up to 2A at 3V per coil. Firstly, the higher current pushed the capabilities of our motor drivers. Secondly, due to the lack of current limiting, a 3V power source capable of supplying 8A would be needed for full power operation. Additionally, in order to adjust to a lower current level, the supply voltage would need to be lowered. While 5V and 12V supplies are relatively common, 3V and lower supplies are much more difficult to find.

To address these issues with our motor controllers, we considered switching to a pair of active current-limiting stepper motor drivers based around the A4988 [2]. These in particular were considered because they were readily available to us. These motor controllers allowed us to use any supply voltage between 8V and 35V. Additionally, an on-board potentiometer allowed us to easily adjust the current limit, a feature that proved useful in finding the current levels that produced an acceptably low level of heat in the motors and motor controllers. Another advantage of the A4988 was that it was a dedicated stepper motor driver, and was therefore easier to use for driving our stepper motors than the previous motor controller was. For these reasons, we chose to use the A4988-based motor controllers.

5. Power Supply – Ben Straub

An essential but sometimes overlooked component of nearly any electronics-related project is the power supply. A poor power supply choice can cause many issues including random restarts, a lack of motor torque, or even permanent damage to other components.

The main consumers of power in PICASSAU are the motors. The stepper motors we selected can draw up to 2A per coil at 3V each. With two coils per motor, this comes out to 24W. To reduce heat in the motors as well as the motor controllers, we chose to run these at about 1.4A each, which was selected by testing various current levels and observing their levels of heat. 1.4A corresponds to a power level of about 3W per coil, or a total of 12W. It should be noted, though, that, because the motor coils are kept at the appropriate voltage and current using PWM, the power draw will not be a constant 12W, but will have peaks that go above 12W.

The next biggest consumers of power are the Raspberry Pi and its peripherals, including display, keyboard, and mouse. The RPi, keyboard, and mouse together, consume around 0.5A on 5V, or 2.5W [3]. The display, which has not yet been purchased, is anticipated to draw an additional 2W on 12V.

Factoring in the other components, such as the microcontroller, the servo motors, and sensors, along with efficiency losses in the motor controllers and wiring, we estimate a bare minimum power requirement of 25W.

We considered the following options for our power supply:

- Initial Enercon power supply – We used this at the beginning of our project because it was on hand. This is an AC adapter, commonly referred to as a “wall wart”, with an adjustable voltage,

and a maximum power output of 30W at 12V. However, in testing, it proved to be somewhat flaky at high power consumption, and would occasionally reset.

- Standard computer power supply – This is somewhat bulky but can be obtained cheaply and typically can supply plenty of power. Additionally, it has the convenience of having both 12V and 5V already, eliminating any need for regulating a 5V line from the 12V line.
- 12V AC adapter – This is similar to our initial power supply, except that it can supply 6A, or 72W. Additionally, instead of being an outlet-attached "wall wart", it is more similar in appearance to a laptop power cable.

These options were analyzed using the Pugh chart in Table 3.

Table 3: Pugh chart detailing the advantages and disadvantages of the various power supply options.

		Power Supply Options:		
Criteria:	Weight:	Initial AC Adapter	Computer Power Supply	New AC Adapter
Cost	4	++	+	+
Power capability	3	--	++	+
Need for 5V regulator	1	-	+	-
Size	1	++	--	+
+		10	11	8
0		0	0	0
-		7	2	1
Net Score:		3	9	7

We therefore selected the computer power supply option.

6. Graphics Type – Drew Kerr

For our project, we needed to convert a webcam image into vectors that the computer parses and converts into sets of coordinates and instructions. Essentially, this would be converting other image types such as jpeg or jpg into a vector graphics file.

The industry standard for a vector graphics file is Scalable Vector Graphics (SVG), which is an XML-based vector image format for two-dimensional graphics [4]. The main functionality of SVG files falls within its path feature. This file feature stores movements and coordinates for drawing lines, Bézier curves and elliptical curves, which are the backbone for constructing any image using this format. In addition, these paths store information about the colors of the lines or curves defined in the path. Furthermore, the paths contain information about the height and length of these curves and lines that we scale to fit our canvas. Using these attributes, we are able to convert these paths into instructions that the Arduino uses to control the paintbrush carriage that paints the picture.

The SVG file type offers many advantages over other image formats for our project. For example, users have the ability to search and index SVG files. This is particularly important because it allows us to parse SVG files into coordinates and instructions that the Arduino can interpret as painting instructions. In addition, SVG images are scalable and printable with high quality at any resolution. This feature permits us to be able to receive any image size and scale that image to fit onto our canvas without losing resolution. Along those same lines, we can scale any image to fit any canvas size. Furthermore, SVG is an open standard and thus has many resources available to maximize our understanding and usability of the format.

7. Paintbrush Carriage Kinematics – Ben Straub

7.1 General kinematics and motion control

In order to have a painting robot, one of the key challenges is being able to accurately move the paintbrush, along with the carriage on which it rests, to the desired locations on the canvas. The control of the movement of the carriage was made particularly challenging due to the physical structure of the robot. For reasons discussed in Section 2.1, the carriage is suspended from two motorized spools mounted at the top of the frame. To move the carriage, the spools are rotated to increase or decrease the length of the fishing line between the spool and the carriage. When moving upwards, the line is wrapped around the spools to pull the carriage up. When moving downward, the line is unspooled, and gravity pulls the carriage down.

The kinematics of such a system becomes complex because moving in a straight line is not a simple linear process. Consider, for example, a starting point A and a destination point B. Each of these points can be defined by two quantities: the distance from the left spool and the distance from the right spool. Let A and B have an equal distance from the left spool and different distances from the right spool. An initial attempt at a control scheme might be to keep the left spool still and simply move the right spool to get from point A to point B. While this would get the carriage to the correct location, it would travel in an arc with a constant radius from the left spool. In order to move in a straight line, a more complicated control scheme is required.

To help simplify the kinematics and the implementation of the controls, we normalize all distance and coordinates in terms of steps of the stepper motors. Thus moving a stepper motor one single step causes the distance between the carriage and the corresponding spool to change by 1 unit. As another simplification, instead of storing all coordinates as their distances from the two spools, we store them as

rectangular x and y coordinates. Lastly, as a final simplification, all of the coordinates are relative to the top left spindle such that (0,0) is at the top left spindle, moving to the right increases the x coordinate, and moving down increases the y coordinate.

Our control scheme works by checking multiple possible moves and deciding which move is best. This is broken up into several steps. The first portion checks each motor and determines if moving it in the positive direction or negative direction moves the carriage closer to its destination. It also checks to see if moving both motors simultaneously gets it closer. Any moves that get the carriage closer to the destination is considered a valid move. If there are no valid moves, then the carriage has arrived as close to the destination as it can get and the movement is done.

If there are valid moves, then the system next checks how far from the line of travel – that is, the straight line from the starting point to the destination point – that each valid move will put the carriage. Whichever valid move gets the carriage closest to the line is the chosen move.

This process is iterated until there are no valid moves.

Several equations are required to make this system possible. This includes calculating the distance from a point to another point, calculating the position of the carriage based on the two distances from the spools, and calculating the distance from a point to a line defined by two points [5]. For a complete list of the equations used in this movement control system and where they come from, see the Appendix.

7.2 Calibration

In order for the control scheme to work properly, it is essential to know the initial position of the carriage. In order to accurately achieve a known initial position, we developed a calibration routine. This routine starts the carriage in the lower half of its range. It then slowly brings the carriage up until it gets detected by a distance sensor that is mounted to the frame and facing horizontally across the carriage's range. The y value of the carriage's coordinates is then known to be the y value of distance sensor's coordinates. The x value is known to be the distance seen by the distance added to the sensor's x value. Because distance sensors often have certain ranges at which the precision and accuracy are higher than others, this calibration can be further fine-tuned by moving the carriage horizontally to this range. Lastly, because the distance sensor viewing beam is not perfectly horizontal, the vertical calibration can vary based on how far away the carriage is when it first comes up to calibrate. To correct this, we lower the carriage and slowly bring back up while monitoring the sensor to recalibrate the y value. A simple diagram showing these movements can be seen in Fig. 3. The blue boxes represent the different positions of the carriage at different times. The red arrow represents the viewing beam of the distance sensor, which in this case is explicitly stated to be an IR distance sensor.

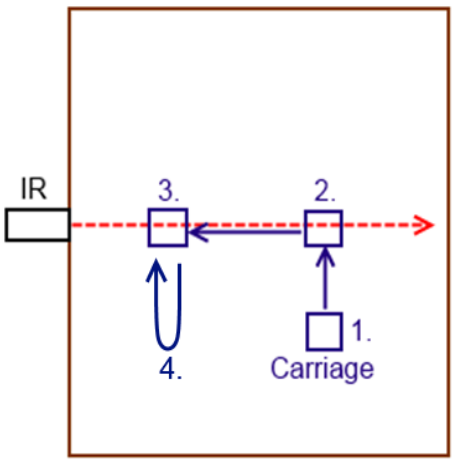

Figure 3: Diagram demonstrating the movement of the carriage during the calibration routine.

This calibration process relies on having a sensor to sense distance. We considered two options: an IR rangefinder and an ultrasonic rangefinder. Specifically, we looked at the Sharp GP2Y0A21YK IR rangefinder and the Parallax PING))) ultrasonic rangefinder, because of both of these sensors were immediately available and on-hand. Both sensors were fairly easy to use. The PING))) sensor was slightly easier, as libraries were readily available for it, and it required little math to determine the distance. The IR sensor was only slightly more difficult, requiring an equation with floating point exponents. However, we selected the Sharp IR sensor because, unlike the PING))), it has a very narrow beam of detection, which was a desirable trait for our calibration sensor.

7.3 Curves

In vector-based graphics, such as in SVG files (see Section 6), it is often necessary to be able to define curves. The common way of doing this is by means of a cubic Bezier curve [6]. These are defined by four points: a start point, an end point, and two control points. In order to draw these, we considered two options. First, we considered letting the Arduino's control system handle it, and, secondly, allowing the computer to handle it by breaking up the curve into straight-line segments.

The only additional calculation required on the Arduino to handle curves would be a calculation of distance from a point to the curve. However, this problem yielded a quintic equation, which can be very difficult to solve programmatically. On the other hand, Bezier curves are particularly easy to split into linear segments because they are parametric equations; simply evaluating it at evenly spaced intervals spanning the range of the parameter t yields evenly spaced points along the span of the curve. Thus, the second option would be much easier to implement than the first. The only tradeoff to the second option would be a loss of accuracy. We use an adaptive algorithm provided by the Potrace library to break up the curves into an ideal number of linear segments.

8. Brush Control – Peter Gartland

We mounted three servomotors to the paintbrush carriage in order to control the brush during its three primary functions of idling, painting, and dipping. One servo controls the brush strokes (referred to as "wiggling") as well as the brush's Painting, Idle, and Dipping positions illustrated in Figure 4(a). Another servo controls the arm that extends the entire carriage away from the canvas to prevent the brush from making a stray streak of paint as it moves from the Idle position to the Painting position or vice versa. The last servo is attached to the end of the brush and controls its rotation as shown in Figure 4(b).

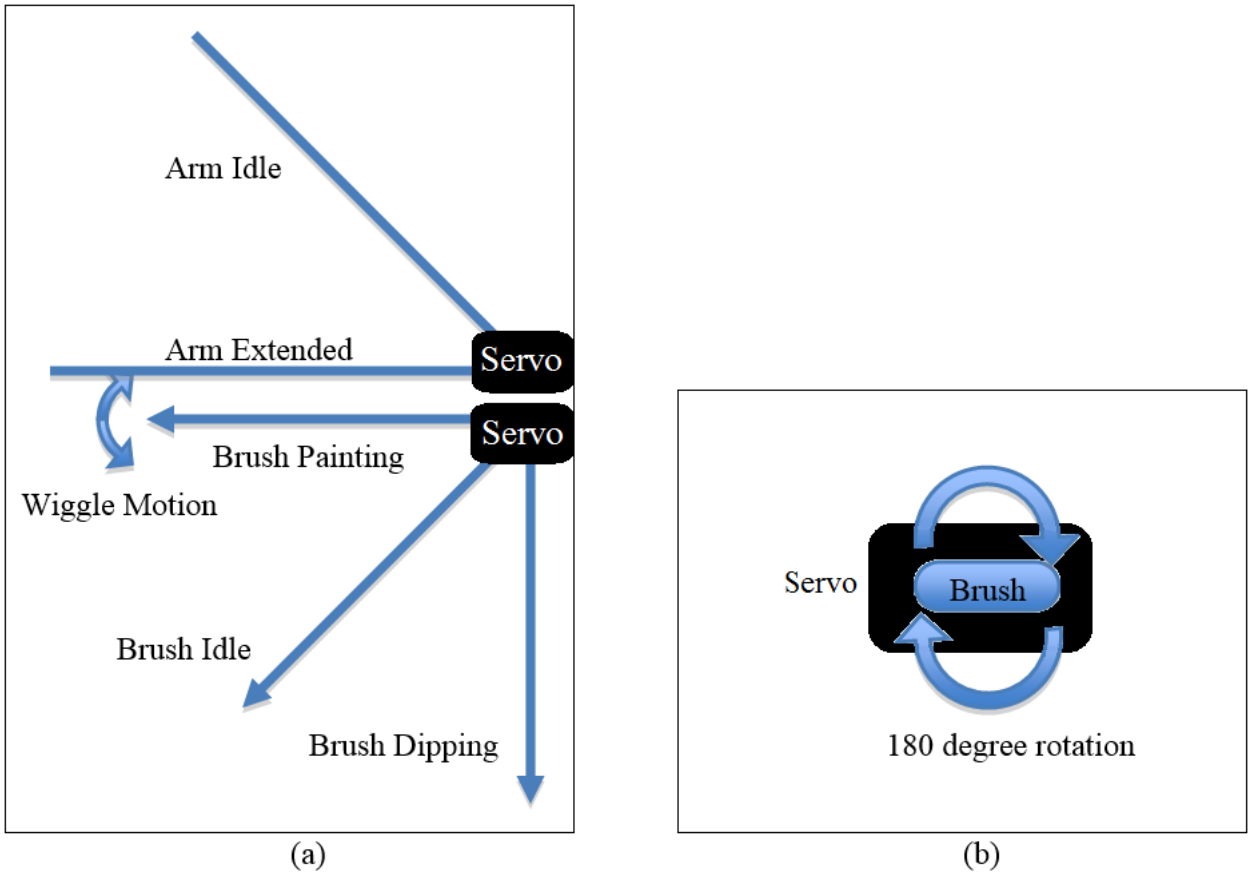

Figure 4: (a) Side view of brush carriage showing range of motion of the arm and paintbrush. (b) Head-on view of the brush showing its rotation that keeps the paintbrush wiggling in the direction of the path.

Referring to Figure 4(a), the brush and arm go to their Idle positions when the carriage moves around the canvas without painting. The brush moves to the Dipping position when it lowers itself into a paint reservoir or the water cup. When the paintbrush is about to start painting a new series of paths, it carries out the following actions: first, the arm moves down to the Extended position; next, the brush moves up to the Painting position; and last, the arm moves back up to Idle so that the brush comes into contact with the canvas ready to start wiggling. The wiggle servo moves the brush back and forth at a small angle to create the brush strokes as the motors move the carriage along the paths. Figure 4(b) shows how the brush rotates so that it wiggles in the direction of the path it follows. The brush rotation ensures that PICASSAU paints smooth lines.

The dipping routine executes at every color change or after PICASSAU has painted a predefined distance. This distance is calculated from the lengths of the paths since the last dip. The dipping routine consists of the following steps: the brush moves to the dipping position; the carriage moves above one of the paint containers; the carriage lowers itself until the brush is in the paint; the brush wiggles in the paint; the carriage moves back up; PICASSAU dabs the brush against the dabbing sheet below the canvas; and finally the carriage moves back to its position before the routine began.

PICASSAU runs a rinsing routine at each color change to clean the brush in water so that the colors do not mix with each other. The rinsing routine is almost exactly the same as the dipping routine; the only difference is that the rinsing routine has a more rigorous dabbing subroutine that attempts to clean as much paint out of the brush as possible. For example, while rinsing, PICASSAU paints several strokes on the dabbing sheet after dipping in the water. The rinsing mechanism is not perfect, but it removes most of the previous color out of the brush.

9. Software and Computing – Kayla Frost

In the Proposal Phase, we determined that we needed software capable of doing the following:

- Perform image processing
- Interface with a USB webcam
- Present a GUI to interact with images
- Parse vector image files for paths
- Convert paths to a series of motions for the brush
- Calibrate the stepper motors
- Perform calculations to determine how to travel from point to point
- Control stepper motors to move the brush carriage
- Control servo motors to create paint strokes
- Dip the brush at the appropriate interval into the correct container

9.1 Platform

One option we investigated was running all of these functions on a microcontroller. We found that microcontrollers would not have the processing power necessary for the image processing we required. Also, implementing complex tasks such as a USB host interface or generating a GUI on a microcontroller would have been prohibitively difficult.

We considered exclusively using an inexpensive, small single board computer, such as the Raspberry Pi. Utilizing the GPIO of the Raspberry Pi, or RPi, to control motor functions would have been much more difficult compared to using a microcontroller. The RPi also does not have all of the ports necessary, such as an ADC [7].

We decided to combine these solutions and split the software tasks between the two platforms:

1. A small computer to handle computationally complex tasks and interface with users
2. A microcontroller to manage the embedded software responsibilities and interface with hardware

We used this configuration to take advantage of the benefits of each separate device without having to force a function onto a platform where it does not belong. This solution divided the software into two isolated sections, which made debugging easier. Having both of the necessary components available at the beginning of the Proposal Phase also made this method a logical choice.

9.2 Computer Software

The main decision to be made on the Computer Software side was selecting which language to use to implement all of the functions. We discussed three different options, which are described in Table 4, and decided to use Python.

Table 4: Pugh chart for determining which high-level programming language to use on the RPi.

		Programming Language Options:		
Criteria:	Weight:	C/C++	Java	Python
Team's amount of past experience	5	++	0	+
Image processing utilities (OpenCV)	4	+	-	+
Efficiency	1	+	0	-
Ease of use	4	0	-	++
Readability	3	0	0	++
+		15	0	23
0		7	9	0
-		0	8	1
Net Score		15	-8	22

This Python script combines and coordinates the four main functions of the RPi:

- User Interface
- Image Processing
- Vectorization
- Communication

Each of these functions is contained within its own class within the overarching script. A basic flow chart of the computer software processes performed by the script is shown in Figure 5.

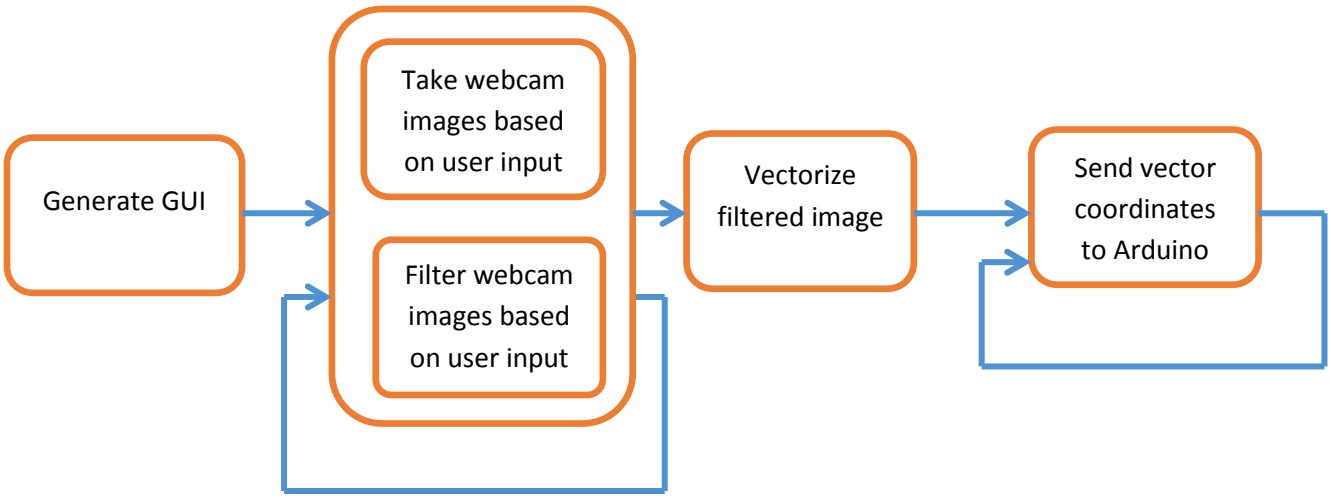

Figure 5: This diagram shows the tasks handled by the Python script running on the RPi.

9.3 Embedded Software

The main decision for embedded software was to decide what kind of microcontroller to use. We identified the Really Bare Bones Board (RBBB), an Arduino clone, as an option [8]. For simplicity, when we refer to the RBBB, we will call it the Arduino in this report. The other microcontrollers/boards we considered were: the DragonFly module used in ELEC 3040/3050, PIC microcontrollers, and an ARM-based microcontroller. When looking at these other microcontroller options, we found that they were very similar relative to our needs. Because of this, we evaluated them as a group against the Arduino, as shown in Table 5.

Table 5: Pugh chart for determining which microcontroller to use to control hardware.

		Microcontroller Options:	
Criteria:	Weight:	Arduino	All others
Team's amount of past experience	5	+	0
Cost	3	0	0
Efficiency	1	0	+
Ease of use	4	++	-
+		13	1
0		4	8
-		0	4
Net Score		13	-3

Note that the cost for the two boards is approximately the same. The Arduino is more expensive than the other microcontrollers, but the others would require buying a specific programmer. In contrast, the Arduino can be programmed using an FTDI cable that connects directly to a computer via USB. We selected to use the Arduino primarily because of its ease of use.

The first task for the Arduino is to read in user input. When a user pushes a button or changes a knob, it communicates this information to the RPi.

Once the painting process begins, the Arduino is responsible for calibrating the motors using the IR sensor mounted on the frame. Then, it accepts the instructions from the Python script and calculates how to move the various motors to accomplish the given task. Next, it interfaces with the motors to carry out the instructions. During the painting process, the Arduino controls the servos on the brush carriage that are used to move the arm, rotate the brush, and effectively dip and wash the brush. It also calculates, based on distance painted, when to re-dip the brush into the paint.

10. Communication – Kayla Frost

After deciding to split the software onto two different platforms, we needed a way to communicate between them. We looked at different options available to link the RPi and the Arduino. We decided using the Pugh chart in Table 6.

Table 6: Pugh chart for determining what kind of communication link to use between the RPi and Arduino.

		Microcontroller Options:		
Criteria:	Weight:	Bluetooth	GPIO on RPi	Serial
Team's amount of past experience	5	-	-	++
Cost	4	-	+	0
Efficiency	1	+	-	-
Ease of use	3	-	+	0
+		1	7	10
0		0	0	7
-		12	6	1
Net Score		-11	1	9

We selected to use the serial connection because it was much easier to implement than the other alternatives. The serial interface we selected uses the serial communication protocol defined by the RS-232 standard, but at TTL voltage levels instead of the original RS-232 levels [9]. This TTL RS-232 interface is easily used by the Arduino's built-in UART. An FTDI USB-to-serial cable is used to convert the computer's USB interface to the Arduino's TTL RS-232 interface.

10.1 Communication Protocol

We developed a communication protocol to send information between the RPi and the Arduino. GUI communications use the process depicted in Fig. 6. Painting command communications use the process depicted in Fig. 7.

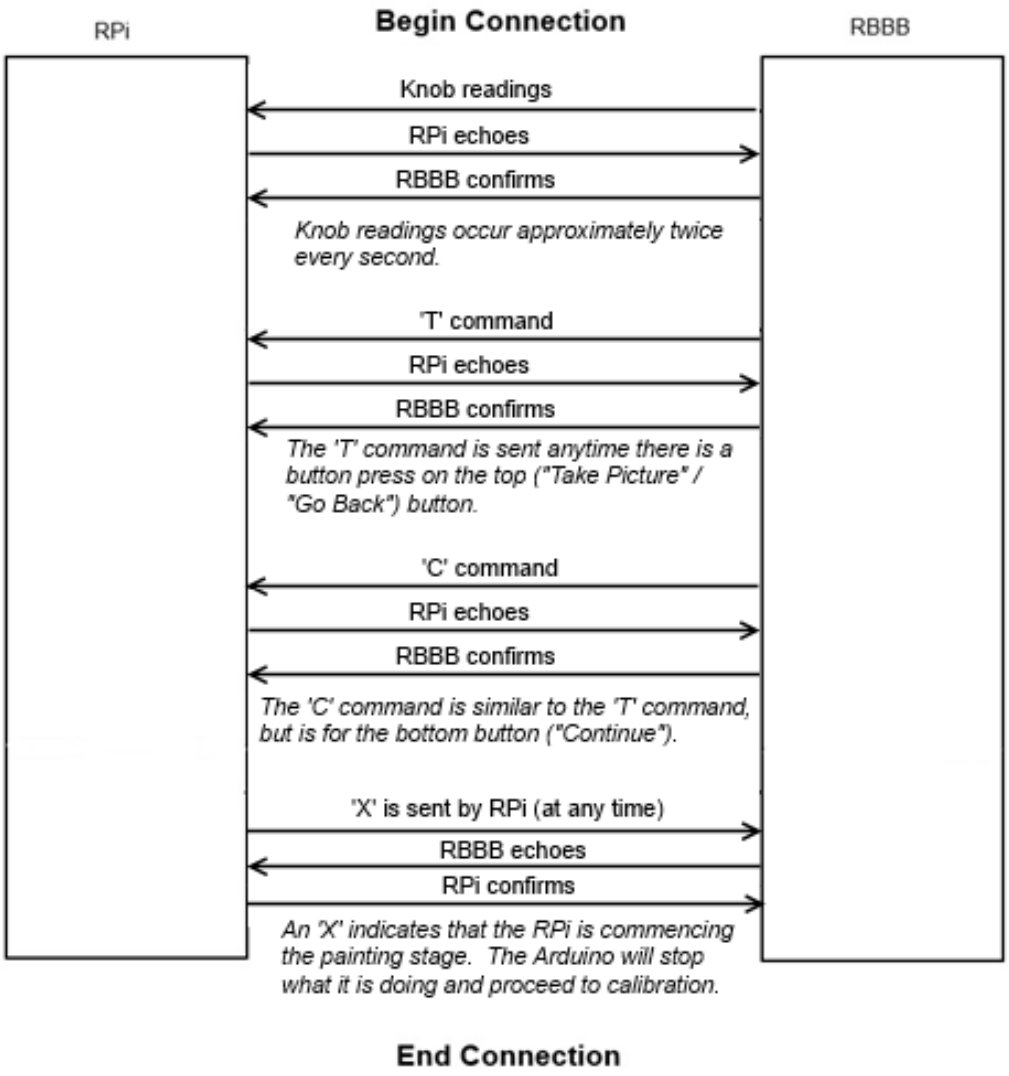

Figure 6: This figure outlines the process for communicating user input information between the RPi and the Arduino. This information is used for the GUI.

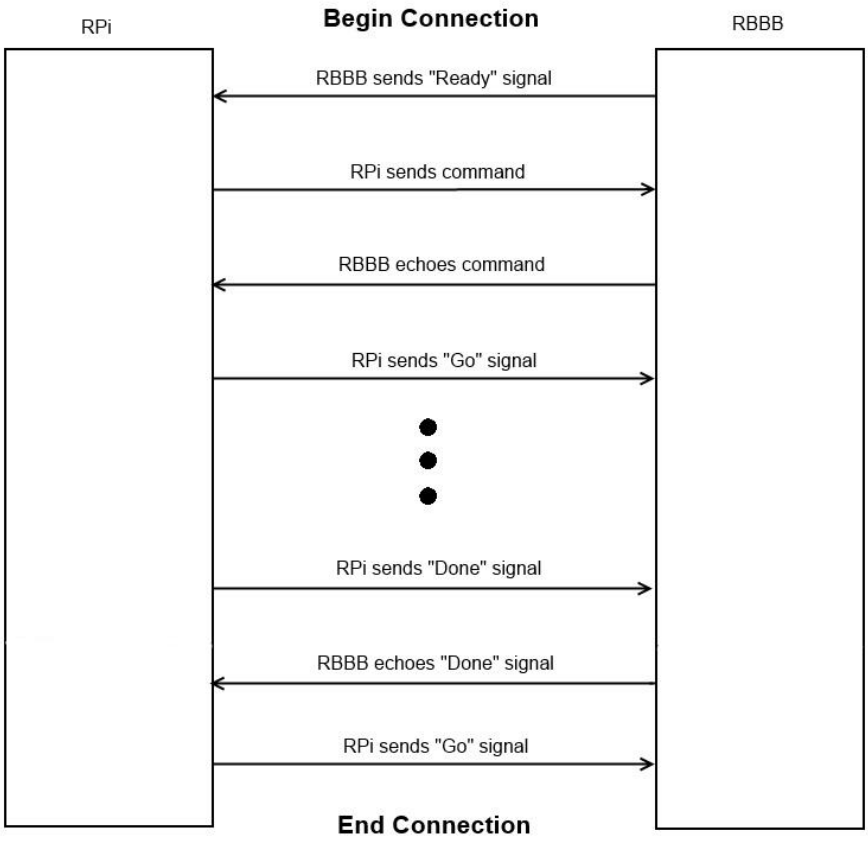

Figure 7: This figure outlines the communication process for sending a command from the RPi to the Arduino.

10.2 Error Checking

For our communication link, we decided to use a serial connection, which can be unreliable. To overcome this, we implemented some error checking into our communication protocol in order to avoid data loss. Referring to Fig. 7, the RPi will not issue the “Go” command until the Arduino echoes back the exact statement the RPi sent. If the RPi does not receive this, it will reissue the command to try again. This means that if any part of the packet was corrupted to or from the Arduino, no action will occur. A very similar process is also used for the communication protocol described in Fig. 6. One disadvantage to this method is that it is less efficient and requires several more instruction cycles on both sides of the connection. It also took significant time to develop and debug this protocol. However, the reliable output that resulted is worth the sacrifice of efficiency and time.

11. Image Processing – Drew Kerr

In order to give our paintings artistic flare, we decided to send the webcam image through a filter that modifies the image to only have four colors. The team's Auburn background influenced the color selection to be blue, light blue, orange, and the white canvas background.

The filter that we use is based on the OpenCV library that contains many built-in filtering functions. The filtering process begins by converting the colored image shown in Fig. 8 to the grayscale image shown in Fig. 9.

Figure 8: The original image.

Figure 9: The grayscale image.

After we convert the image to grayscale, we smooth the image with a median filter that replaces each pixel with the median of its neighboring pixels [1]. We filter the image in this manner to reduce pixel noise and the sharpen edges where there is a significant color contrast. One can see the smoothed image below in Fig. 10.

Figure 10: The smoothed image.

Next, we reduce the number of colors in our grayscale image to four. Each pixel in the grayscale, smoothed image has a value of 0 to 255 associated with it, depending on how light or dark the pixel is. For example, the circled point on the left side of Fig. 10 corresponds to a grayscale value of 25, while circle closer to the center of the image corresponds to a grayscale value of 240. Using each pixel's grayscale value and the user-defined color thresholds shown in Fig. 11, we assign every pixel one of four values: 0, 85, 170, and 255. One can adjust these thresholds to match the light settings of the original image or to create more contrast within the image. These values correspond to different shades of gray and convert the image into a new image composed of the four shades of gray. One can see the new image below in Fig. 12.

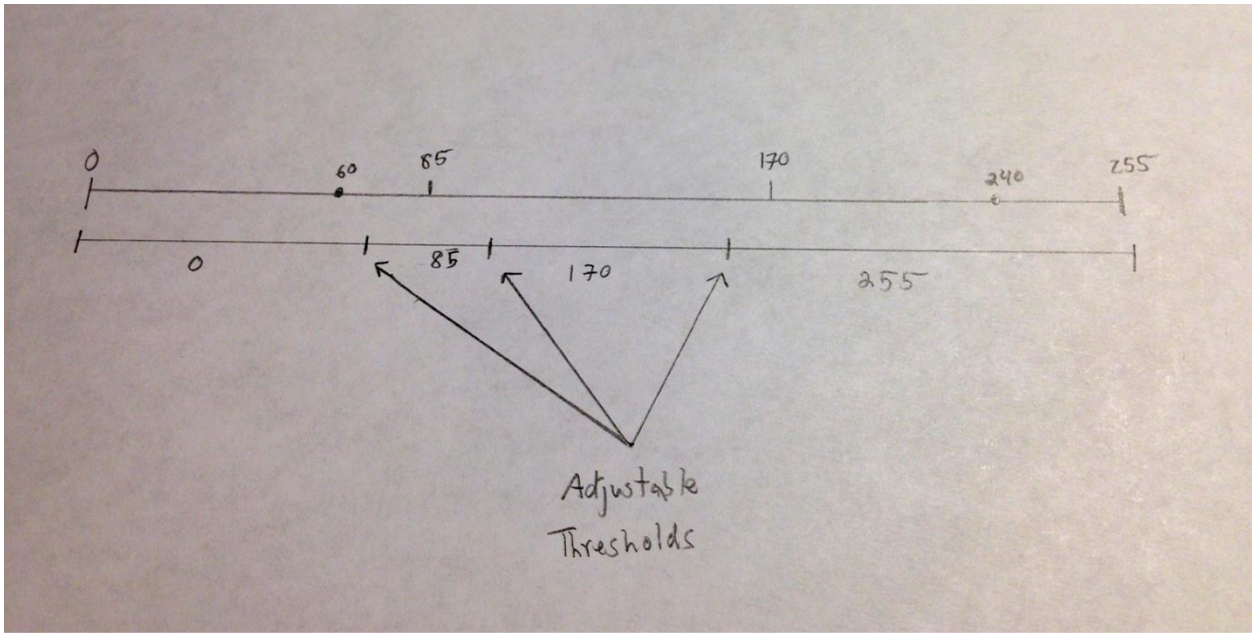

Figure 11: Threshold system for assigning colors.

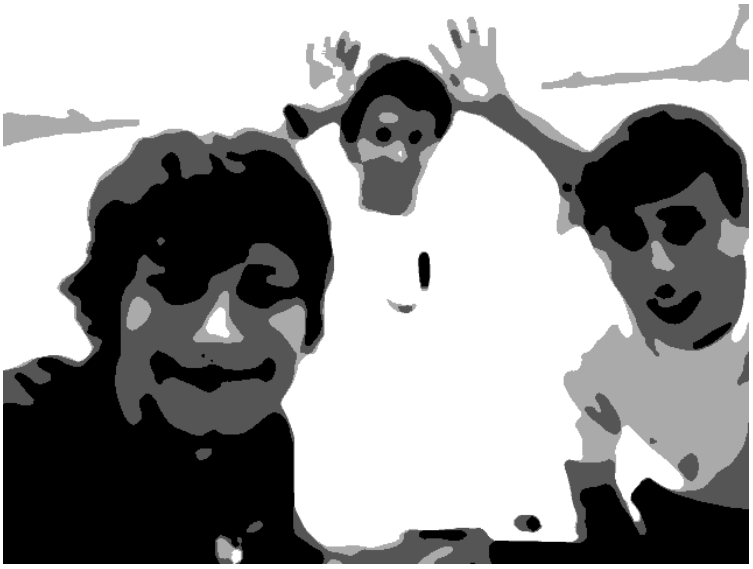

Figure 12: The thresholded image.

After we assign the pixels to one of the four values mentioned above, we delegate each of the four values to a color: blue, light blue, orange and the canvas background. One can see this final image in Fig. 13 below.

Figure 13: The final image that the robot will paint.

12. Vectorization – Ben Straub

The image processor works with raster, pixel-based images while the microcontroller requires vector based coordinates. This requires the ability to convert our processed images into lists of coordinates that describe to the microcontroller exactly where to move to trace and fill in everything in the image.

We begin our vectorization process by breaking the posterized image into three separate binary images, corresponding to the three paint colors. Each of these binary images shows everything that needs to be painted for its corresponding color.

Our vectorization is based mainly around the Potrace tool, specifically the Python library version of it, called pyPotrace. Potrace is a tool that will trace the outlines in a single-color binary image and return the SVG-style paths it contains, consisting of straight line segments and Bezier curves. The pyPotrace library provides a "tessellate" function that can then adaptively break the combination of line segments and curves into a list of straight line approximation coordinates.

Using pyPotrace only gets the outlines of the blobs in each color. It does not fill them in. Originally, we intended to fill in the blobs by scanning with either vertical or horizontal lines, painting where the lines were inside the blobs, much like a printer. However, this technique is unnatural and unrealistic for a painting. It produces distinct linear brush strokes which would be very distracting in an image.

Our solution to this was to use an erosion filter using openCV. An erosion filter sets a pixel to the minimum value in a defined neighborhood around it. This has the effect of shrinking blobs inward. Tracing this newly eroded image allows robot to paint one step inward on all the blobs. This process can be repeated until the erosion leaves nothing left to paint. Using this method causes the robot to fill in shapes in a way that follows the natural curves of each shape. This erosion-tracing process is performed on each color's binary image individually. The overall process of vectorization is shown in Fig. 14.

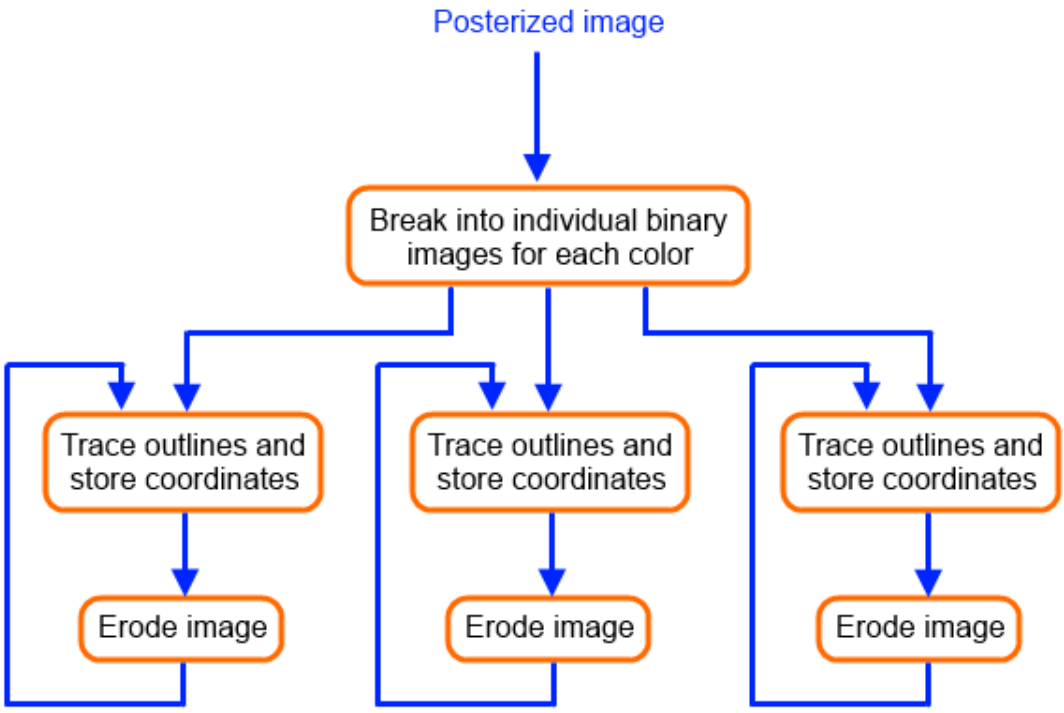

Figure 14: Data flow chart for our base vectorization algorithm.

In addition to this basic algorithm, a few optimizations are made to improve the quality of the end result and the time it takes to paint it. The first improvement is to perform a smaller erosion on the initial binary image. This serves two purposes. For the middle color layers (orange and light blue), there are sometimes small slivers of the color in sharp contrast areas that may only be a few pixels wide. This small erosion removes any tiny blobs that appear at these sharp transitional areas, preventing PICASSAU from painting somewhere that a particular color does not really belong. The second purpose is to reduce the overlap of color layers. If using non-eroded images, the edge of one color is also the edge of its neighboring color, causing an overlap in the painting.

The other optimization we made is to erode away from the edges of the canvas. A normal erosion filter does not erode blobs away from the edge of the image. Painting a blob on the edge of the canvas causes

the robot to repeatedly paint the same straight edge where the blob hits the side every iteration inward. For larger blobs, this can mean tracing the edge of the canvas dozens of times, wasting time and paint. We solved this issue by padding the image with a border of zeros, and then offsetting the traced coordinates to counteract the padding. The border of zeros allows the erosion filter to erode away from the edges.

13. Constraints – Peter Gartland

In the second development cycle, we identified several constraints PICASSAU must meet or work around:

- Cost
    - The total cost of PICASSAU should not exceed our budget of $300. This was the primary consideration for much of PICASSAU's performance. The cost affected our choices of motors, processor, power supply, and building materials.
- Performance:
    - PICASSAU runs off of a power supply plugged into a wall outlet, which limits its area of operation to the length of extension cords.
    - The time it takes PICASSAU to paint a picture became a concern this cycle. The first full-scale painting took two hours and twenty minutes to paint, but there are some easy fixes we made to reduce the time to less than two hours.
- Marketability:
    - Because much of PICASSAU's value is in the novelty of watching a robot paint a painting, its consumption may be limited to those intending to display it in a public setting as an attraction; however, after our recent unveiling of the first full-scale painting, we received a lot of interest from people wanting their own picture painted by PICASSAU.
- Reliability:
    - PICASSAU's exposed moving parts have made it a relatively fragile product and may require expert maintenance to keep operational. A simple interface and clear documentation will help keep PICASSAU painting for E-Days to come.

14. Budget – David Toledo

As shown in Table 7, our projected budget of $265 met our team budget $300. At the end of cycle 2 our actual budget of $292 is $8 short of our team budget, but $27 over our projected budget. A couple of main points to bring up are that the selection of motors purchased for PICASSAU was 43% cheaper than projected, saving $43 which compensates for the underestimated costs of the framing hardware. Also, due to the amount of testing we performed, our anticipated painting supplies budget exceeded our budget by more than double our initial estimate.

Table 7: Budget, including estimated and actual costs.

Item	Purpose	Estimated Cost	Actual Cost
Stepper Motors	to replace the underpowered motors used in the prototype	$100	$57
Frame Hardware	to support the hardware	$20	$62
Mounting Hardware	to mount the spindles onto the motors	$15	$20
Painting Supplies	brushes, paint, and canvas/ poster-board	$15	$34
Motor Controllers	to drive the stepper motors	$20	$20
Raspberry Pi	to run the software	$35	$40
Display	to interface with the raspberry pi	$15	$20
Webcam	to take pictures to paint	$15	$4
Microcontroller	to interface with the hardware	$10	$20
Miscellaneous Electronics Hardware	wires, sensors, servos, etc.	$20	$35
TOTAL		**$265**	**$292**

15. Timeline – Kayla Frost

We created a Gantt chart at the beginning of Cycle 1 to schedule project objectives and group them by subsystem. The chart was used to guide our process each week. According to the chart, we successfully completed most of the tasks planned on the Gantt chart.

All tasks in the following subsystems were completed:

- Mechanical Hardware
- Electrical Hardware
- Image Processing

We did not budget enough time to finish some optimization we had originally planned. Specifically, we did not fully optimize the drawing paths, which was part of the computer software subsystem.

Additionally, we did not optimize calculations in embedded software. This was not due to lack of time, but rather this was not identified as an issue. The microcontroller was able to successfully handle all necessary calculations without delay. We decided to focus our efforts on other tasks instead.

Remaining tasks for the project are mainly finishing testing as well as completing all necessary documentation. In the remaining two weeks of the project, we plan to paint several more paintings in order to fully test the system. We will also complete all documentation, including the website, Google documents, presentation boards, and the Github repository.

Please refer to the full Gantt chart in Figure 15 for complete timeline information.

15.1 Gantt Chart

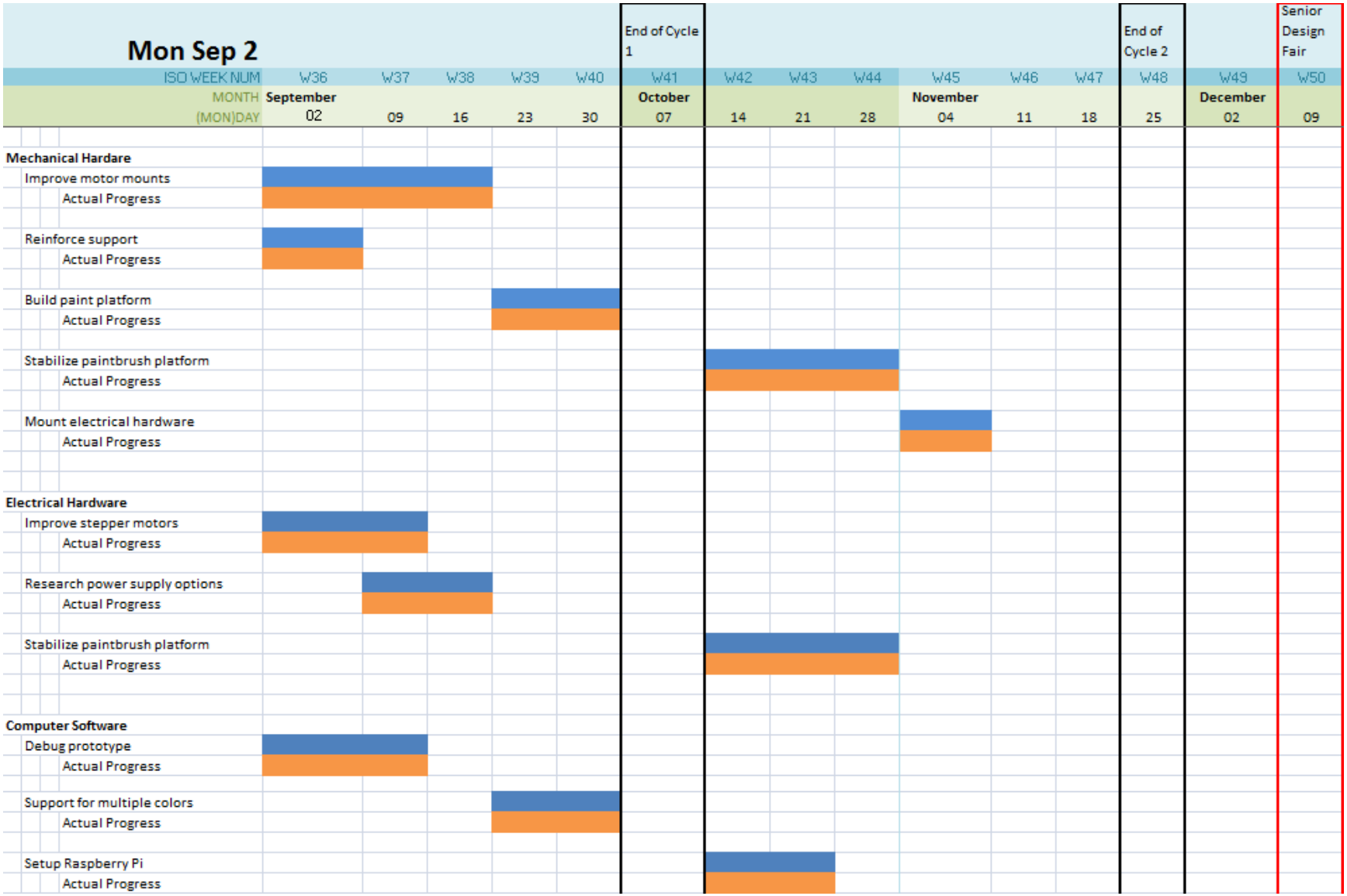

Figure 15: This Gantt chart outlines the timeline for the project.

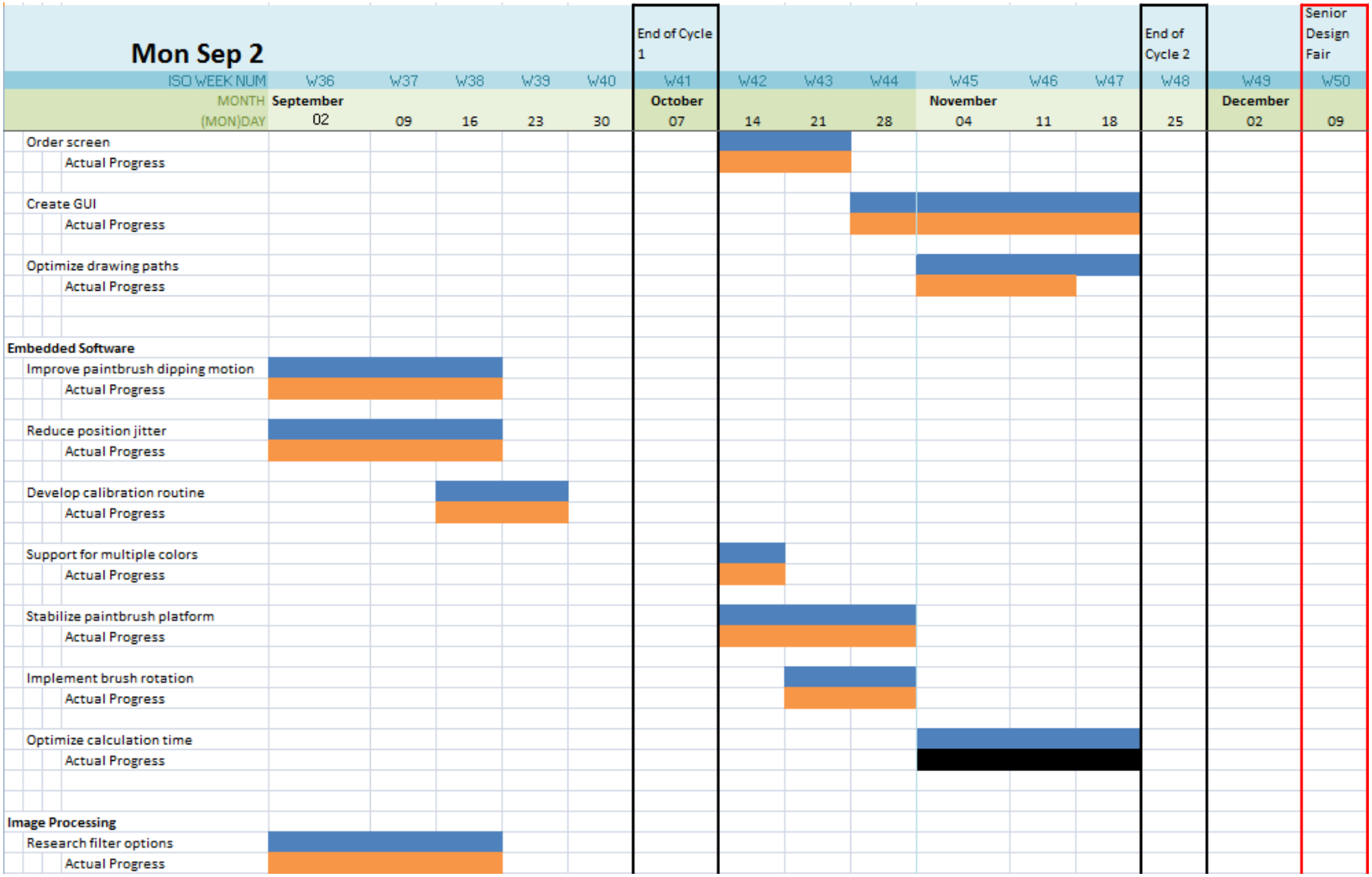

Figure 15 continued.

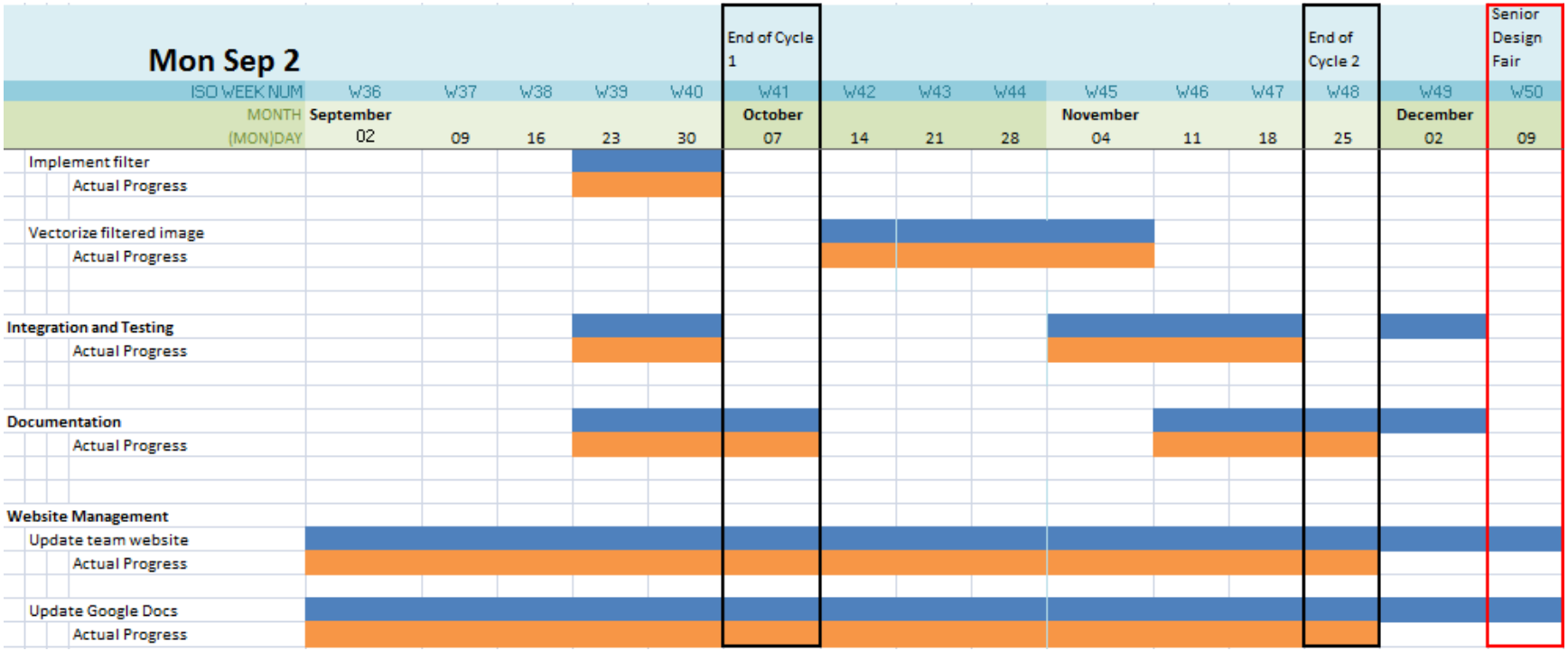

Figure 15 continued.

16. Performance – Peter Gartland

PICASSAU's performance at the end of Cycle 2 meets all of our design goals. These goals include retrieving an image from a webcam aboard PICASSAU, simplifying the image, reducing the image to four colors, vectorizing the image, extracting lists of coordinates from the vectorized image, painting along paths defined by the coordinates, and dipping and changing colors when necessary. We also implemented a GUI using a small LCD screen that presents a preview of the image before PICASSAU paints it. There are two pushbuttons that allow the user to interface with the GUI, and there are three knobs that determine how much of each color shows up in the picture.

In terms of the physical structure, we have improved on many of the temporary mounts by replacing all of the tape and most of the hot glue with more secure fastenings, such as screws. We mounted an electronics housing on the back of PICASSAU, which tidied up the external look by hiding much of the wiring, and we braided wires where possible.

The computer software turned out not to require the use of actual SVG files. We used the image processing library pypotrace to break the webcam image into a series of coordinates that resemble a portion of an SVG file. Each color gets its own set of coordinates, and these are sent serially from the RasberryPi to the Arduino. The Arduino controls the motors to make the brush carriage follow the coordinates around the canvas, and it controls the servos on the brush carriage to carry out the painting.

The plotting and painting performance of PICASSAU exceeded our expectations as far as how the final product looked. However, the first full-scale painting of an image from the webcam took two hours and twenty minutes to paint, but we made several easy changes to the plotting algorithm that reduced the time to paint to under two hours. A big obstacle during Cycle 2 was the different colors of paint mixing

with each other. We managed to overcome this by reducing the amount of water we mixed into the paint, switching to a fine-bristle brush, and painting the light blue portion followed by orange and finally dark blue.

17. Conclusions – Kayla Frost

We now have a robotic system that can interact with a user and reliably generate a 3-color painting from a webcam image. It performs all of the basic functionality we planned.

17.1 Learned Skills Outside of Curriculum

Through this project so far, we have learned valuable skills that are relevant to the field of Electrical Engineering but that are not covered in our curriculum. Some examples of these include:

- *Mechanical Design*
    - Creating a stable frame, mounting motors, designing an electrical enclosure, and using counter weights were all challenging problems to solve.
- *Motors and Motor Control*
    - We had used DC motors in the past, but this project exposed us to stepper motors. We learned that stepper motors are more useful in applications that require accuracy, like PICASSAU.
- *Communication Protocol*
    - We learned how to connect two separate devices to reliably communicate information in two directions.
- *Scripting Languages*
    - Programming without any hardware interaction taught us how to utilize the compiler tools to debug problems.
- *Image Processing*
    - We learned how to use several different filtering methods and image processing libraries.

17.2 Tasks Completed in Cycle 2

We completed all of our primary goals for Cycle 2. The major software tasks were to implement multiple color support, generate the vectors internally, and add a GUI to improve user experience. We developed several independent scripts and then consolidated them into a single piece of software. This required major integration and extensive testing. We were also able to design and build an electronics enclosure. This enhanced the aesthetics of the project and improved user safety by storing live electronics out of view. We made some small unplanned improvements such as adding a servo for brush rotation and changing the type of paintbrush used. At the end of the cycle, we ran several full-scale tests to ensure the system was fully integrated. An example of one of these tests is shown below in Figure 16.

Figure 16: On the left is the filtered webcam image of three team members. The right shows PICASSAU's painting of this image.

We have achieved our objective. PICASSAU is a sophisticated and reliable final solution that can accept a picture and output a complex painting of the subject. In order to accomplish this, we have applied several aspects the engineering design process in order to fulfil the requirements stated by the Accreditation Board for Engineering and Technology (ABET) .

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Appendix

These equations are used to determine how to move the carriage in an approximately straight line.

1) Calculating the distance d between two points P_1 and P_2.

This equation is simple, but very useful in our calculations. It is

$$d = \sqrt{(x_2 - x_1)^2 + (y_2 - y_1)^2}$$

2) Calculating the coordinates of a point P=(x,y) that is a distance d_1 from a point $P_1=(x_1,y_1)$ and d_2 from point $P_2=(x_2,y_2)$.

The general equations for this are

$$d_1 = \sqrt{(x_1 - x)^2 + (y_1 - y)^2}$$

$$d_2 = \sqrt{(x_2 - x)^2 + (y_2 - y)^2}\,.$$

However, these equations can be difficult to solve. It greatly simplifies the problem to let our point P_1, which is the location of the left spindle, to be defined as the origin, (0,0). Because the point P_2 is the right spindle, its location is simply (L,0), where L is the distance between the spindles. This reduces the above equations to

$$d_1 = \sqrt{x^2 + y^2}$$

$$d_2 = \sqrt{(L - x)^2 + y^2}\,.$$

These can then be easily solved for x and y:

$$x = \frac{d_1^2 - d_2^2 + L^2}{2 * L}$$

$$y = \sqrt{d_1^2 - x^2}$$

3) Calculating the distance d from a point $P_0=(x_0,y_0)$ to a line defined by points $P_1=(x_1,y_1)$ and $P_2=(x_2,y_2)$.

This equation is key for picking the optimal movement choice in our control scheme. As shown in [5], the equation is

$$d = \frac{|(x_2 - x_1)(y_1 - y_0) - (x_1 - x_0)(y_2 - y_1)|}{\sqrt{(x_2 - x_1)^2 + (y_2 - y_1)^2}}$$