Project Ponderosa – Bridging Engineering Education to Vocational Training

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Abstract

The application of robotics and automation in industry continues to be an increasing area of growth. Subsequently, this requires an increased demand for design engineering students as well as knowledgeable users trained for equipment maintenance. However, this can become problematic to adequately provide a realistic environment for both teaching design of robotics systems as well as the maintenance. In recent years, with the coordination between Cal Poly Pomona and Boys Republic, we have developed Project Ponderosa. Project Ponderosa provides Cal Poly Pomona engineering students the opportunity to design various robotics, mechatronics, and automation systems that are and will be operated and maintained by Boys Republic students for Christmas Wreath Production at their facility.

Prior to Project Ponderosa, the Boys Republic Christmas wreaths were predominately produced using various manual techniques including lacquer application and cutting operations. The robotics and automation systems have been designed to implement these and other tasks in the Christmas Wreath product at Boys Republic. This production is used as a seasonal annual fund raiser which ships approximately 40,000 units during the span of three weeks of production. Due to the period of operation and cost profiles, it is unrealistic to fund an outside engineering company to develop an automation solution. Using the partnership between the two schools provides Cal Poly Pomona engineering students the opportunity to learn and practice the engineering design process including capturing customer requirements for the task, preliminary design, simulation, detailed design, and test and integration while documenting the design throughout each phase. As the projects are completed, the students at Boys Republic gain the vocational experience for operation and maintaining the systems providing the experience for future opportunities upon completing their program at Boys Republic. To date, many engineering students have received engineering career opportunities as a direct result of their work on Ponderosa.

I. Introduction

Robotics and automation systems are now a standard method of manufacturing across many industries. The design of these systems requires careful consideration and thought for the integration of design topics including engineering disciplines of mechanical design, electrical design, software engineering, and controls engineering[1]. Within these disciplines, further discipline decomposition such as machine design, fluid dynamics, analog and digital electronics, computer vision, and real-time software are further required[2]. Designers of such systems must be able to understand the interdependencies of the designs while also working with one another from a systems perspective to ensure that the multidisciplinary nature of these systems interoperate with one another[3].

Knowing the demand for robotic automation design, it becomes imperative that engineering students can learn both the theory and have hands on design for such systems. Moreover, engineering students must also learn the ability to understand customer requirements and how to articulate them into full-fledged designs including testing and simulation. Finally, upon completion the design must be submitted with documentation to the customer who will be the operator and maintainer of the system.

Given the nature of cost and opportunity many engineering students in the senior year executing their capstone project are unable to fully realize the breadth of the "situation" particularly in the design and deployment of robotic and automation designs. Often it is impractical for engineering students to create a real-world equivalent problem to address full breadth that implementing a robotic system for automation requires. To address this challenge, a relationship between Boys Republic and Cal Poly Pomona was established which benefit both Cal Poly Pomona engineering students while providing a solution for Boys Republic in the assembly of Christmas wreaths.

Cal Poly Pomona's approach to its engineering curriculum, specifically the Department of Electromechanical Engineering Technology, focuses on teaching engineering students the relationship of the various mentioned disciplines while blending the necessary theory with application. In their efforts of their senior project, students are required to understand the requirements of a given design, decompose the design using the design processes with preliminary and detailed design stages and then perform both integration and testing of the design. Project Ponderosa is a project where Cal Poly Pomona engineering students worked with the staff from Boys Republic to design a robotic system that helps in the manufacturing of Christmas wreaths that Boys' Republic use as a source to generate revenue through the sales of the Christmas wreaths.

Boys Republic is a private, nonprofit, nonsectarian school and treatment community for troubled youth. Since its founding in 1907, it has guided more than 32,000 at-risk teenage boys and girls toward productive, fulfilling lives. On its central school and farm in Chino Hills, California, and in residential and day treatment centers in other communities, Boys Republic and its companion program, Girls Republic, help youth find within themselves the resources and skills to begin meaningful lives on their own. The rehabilitation process involves the development of academic, vocational, and social skills.

The goal of this community is to give troubled adolescents an opportunity to learn valuable life-skills to become productive and self-directed members of society. They do this by providing the young boys with hands-on real-life craftsman experience. Upon completion of the robotic system by Cal Poly Pomona engineering students, the boys from Boys Republic will learn how to operate and maintain the automation system while providing they boys additional vocational skills to help prevent recidivism, and instead help them continue to become productive members in society[4].

The staff and boys from of Boys Republic are responsible for the manufacturing and assembly of Christmas wreaths which are used to generate revenue for the facility. There are multiple operations that are required in making the wreath, however most of the process is done by hand.

This manual labor includes the cutting and application of pinecones and seed pods, adding small fruits such as apples, adding colorant to the Noble fir foliage and finally the final application of adding a clear lacquer sealant. Currently, the lacquer application to the wreaths is manually done by someone in a small painting booth. The production of the wreaths is only as fast as that one person can apply lacquer.

The Della Robbia wreath program was introduced originally by Boys Republic founder Margaret B. Fowler to serve as a work experience vehicle for students of the non-profit school. The wreaths were patterned after a centuries-old ceramic design created by the Della Robbia family of Florence, Italy. In 1923, the first year of the Boys Republic Della Robbia campaign, only a few dozen wreaths were produced. They were sold on the streets of Pasadena. The program grew to meet increasing demand. Today, Boys Republic's students produce and ship more than 40,000 wreaths, each year, to destinations throughout the United States and around the world[5].

Figure 1. (Left) Boys' Republic Christmas Wreath. (Right) Final assembly and production of the wreaths. Notice along the back wall the hook line assembly line that travels throughout the various assembly areas.

The challenge the engineering team addressed for this aspect of the wreath production was the application of the clear lacquer sealant.   The project's primary goal was to replace the manual application of the lacquer which can expose the workers to various chemicals if they are not wearing the necessary protection and while also alleviating the long days that can cause the workers to become fatigued while slowing down production. These problems can lead to waste in time and money. The engineering students created an industrial robotic spray system that can detect the wreath and apply the appropriate amount of lacquer to the wreath.

The detailed project objective was to build a robot arm to paint the wreaths with a water-based lacquer. Specifically, the team worked with machine design and mechatronics, fluid dynamic principles, computer vision and multi-loop control systems. The system was required to apply the lacquer to two different size wreaths. One wreath measured 22 inches in diameter, while the system also had to apply the lacquer to a 28-inch diameter wreath. The assembly hook line yield-rate ran at 720 wreaths per hour for the smaller wreath, and 480 wreaths per hour for the larger wreath.

This paper addresses the tasks that the Cal Poly Pomona students have undertaken in partnership with Boys Republic towards helping in the manufacturing of the Christmas wreaths. In this effort, the Cal Poly Pomona engineering students' initial objective was to understand requirements for the application of lacquer to the wreath as it traveled along an assembly hook-line as the wreaths were assembled. This was done through several meetings with the Boys Republic staff and observing the actual manual application of the lacquer. After the Cal Poly Pomona students understood the requirements, they established a preliminary design and schedule and presented it to Boys Republic for review and approval. Upon a successful preliminary design review, the students then undertook the detailed design efforts and the test and integration phases of the engineering project. After completion of the project, the engineering students were able to understand how to develop engineering requirements for a real customer and ultimately implement the design for a robot system that can be used for a real-world project.

II. Project Elements

As discussed above, the intent of the project was to design and implement a robotic arm that applied a sealing lacquer coat to the wreaths. The overall project was decomposed into four fundamental tasks. These tasks included a mechanical sub-team responsible for designing the mechanism and structure of the arm, a fluids team responsible for controlling the application of the lacquer onto the wreath, a controls team that implements the controls algorithms for the motors, and a computer vision team that used computer vision techniques to track the wreaths as they move along the assembly line. Throughout the project, each sub team was required to work in unison with the other sub teams.

A. Mechanical Design

For this project, the mechanical team developed a gantry-based robot arm that performs translation motion via prismatic based joints along the X-Axis and Y-Axis, and rotary motion of the end effector. The mechanical team also created a support framework for the entire system. The team decided to use T-slotted aluminum extrusions due its strength and rigidity yet also being lightweight and easily adapted to various designs. Using the aluminum extrusion frames also allowed the system to be easily reinforced with brackets and braces at the installation location. The seamless integration of hardware further allowed the team to create a sustainable system that will endure the repetitive nature of wreath production. Figure 2 shows the design of the overall support framework. The framework is composed of 6105 aluminum alloy extrusion.

The gantry approach was selected instead of a more familiar 5 or 6 degree-of-freedom based design due to the simplicity of the kinematics. Developing the inverse kinematics for a high degree-of-freedom arm is often a daunting challenge especially at the undergraduate level. In contrast, the inverse kinematics of a gantry is easily solved due to the axis independence[6]. The specific implementation of the design includes three industrial stepper motors which are used to achieve the desired motions along the X-Axis, the Y-Axis and to rotate the end-effector spray mechanism assembly. Each motor uses its own electronic driver and feedback control system to correct for any inaccuracies while maintaining the necessary movements to apply the lacquer. The motion along the A-Axis horizontal I-Beam is achieved by a trolly that also provides support for the end effector. The trolley is further supported by linear bearings along the I-Beam to ensure smooth travel. The Y-Axis motion is achieved using two motors that are coupled to two pulleys on each end that act as counterweights. Finally, using the counter weights further reduces the loads placed upon the motors and linear slides.

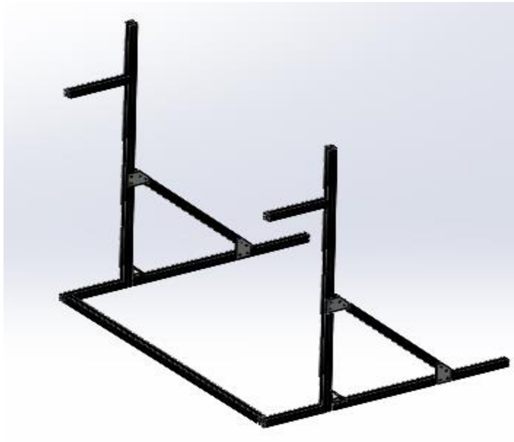

Figure 2. Frame structure for the robot assembly

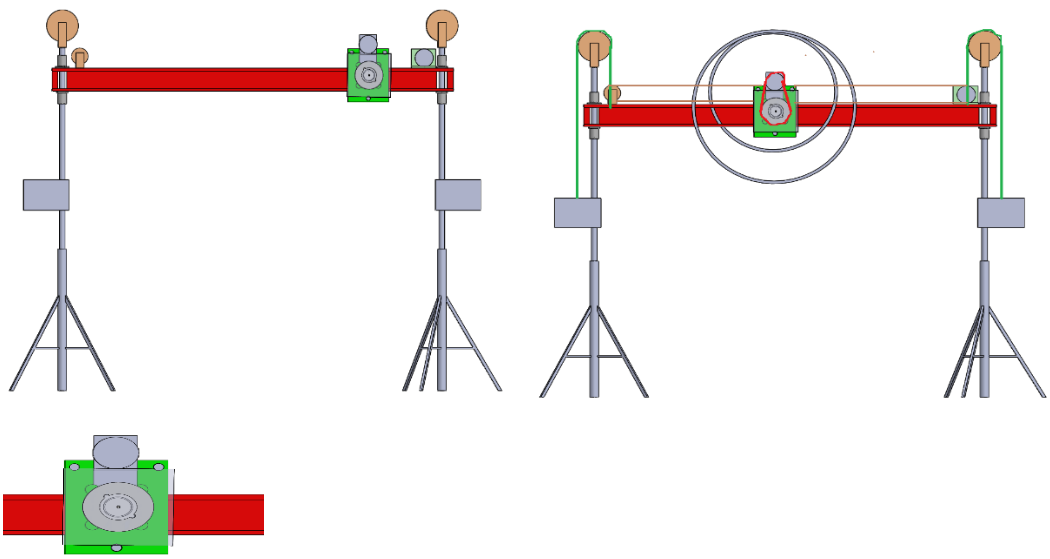

Figure 3 (Top Left) Concept drawing of the Gantry Arm Design. The trolley car moves along the X-Axis (red beam) left and right. (Top Right) Concept drawing of the Gantry Arm design showing the Y-Axis allowing it to adjust for the various size wreaths. (Bottom Left) Z Axis rotary end effector mounted to the trolley car.

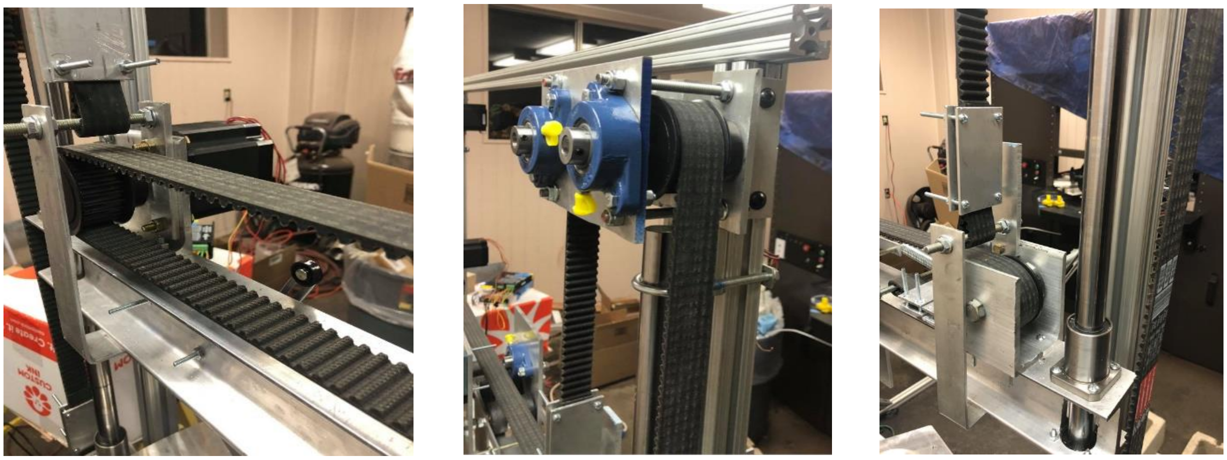

Figure 4. (Left) Close-up of the X axis assembly. (Center) Close-up of the Y-Axis pully mechanism. (Right) Close-up of the Y-Axis pully mechanism with the linear slides and bearings.

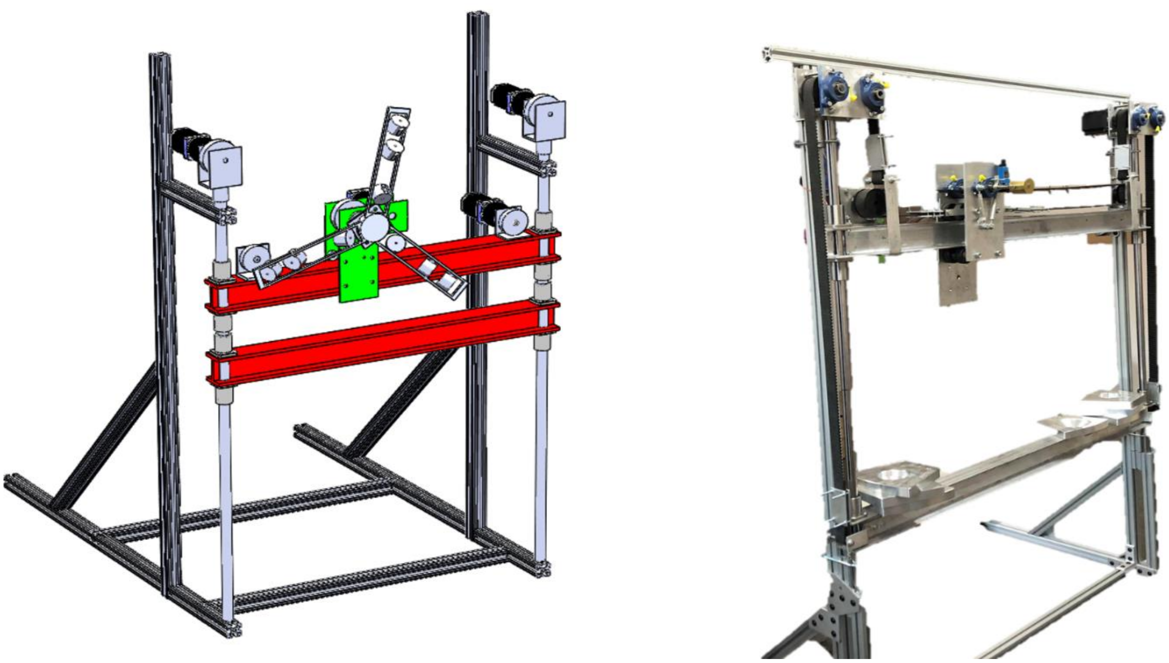

Figure 5. (Left) CAD assembly model of the mechanical design. (Right) Finished design of mechanical assembly

B. The Fluid System Design

The objective to this fluid systems team was to develop the delivery of the sealant lacquer that is applied to the wreath. This includes both accurately and efficiently spraying the lacquer onto the wreaths in a consistent manner while taking to account the movement along the X-Axis and as the arm is rotating.

The application of the lacquer is achieved by designing and implementing a rotating end effector with multiple HVLP (High Volume Low Pressure) nozzles. A High-Volume-Low-Pressure end effector is used to limit the amount of overspray and emissions of the paint during operation. The HVLP end effector operates between 40-70 psi. At pressures above 70 psi, atomization of the liquid creates significant amounts of overspray, however at pressures below 40 psi, there is not enough pressure to ensure correct atomization of the lacquer for consistent coverage[7]. The final nozzle design integrates multiple nozzles at various angles to ensure that the wreath receives adequate coverage.

Due to the variability in wreath sizes, the overall design of the end effector includes three extensions (arms) each with three nozzles for a total of nine nozzles for the end-effector. Since the wreaths are circular in shape, the end effector rotates 120^{o} for a complete application. This method was selected versus using a single three-nozzle assembly to allow for quicker application of the lacquer as the wreath moves along the assembly line. In addition, this approach also alleviates the amount of stress on the tubing for the lacquer that would occur if there was a 360^{o} rotation.


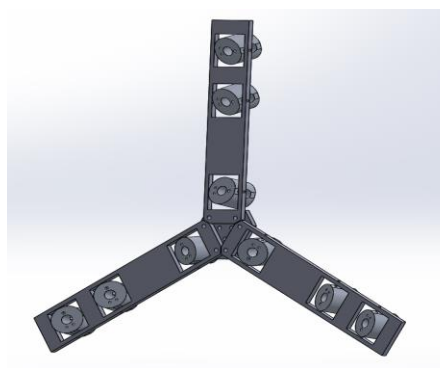

Figure 6. (Left) CAD model of the nozzle assembly front view. (Right) CAD model of the nozzle back view.

Figure 7. Finished nozzles

C. Computer Vision

The goal of the computer vision team was to (1) detect each wreath passing by the spray location on the assembly line, (2) alert the robot to when the wreath would arrive at the work area, (3) notify the robot when to initiate painting, and (4) verify that the lacquer was sufficiently applied. The objective for the computer vision was to track the wreath and determine the velocity of the wreath as it passes in front of the end effector. The computer vision team selected the use of the OpenCV computer vision library to implement most of the computer vision fuctions[8]. Initially, the design of the computer vision algorithm detected the wreath's shape features and color as it enters the field of view of the camera, however this approach was not always reliable due to the variations in the foliage and color.

To overcome the inconsistent detections, the team developed a set of algorithms that detected absence of a constant background. The concept begins with a background with a very distinguishable color that is the opposite of green wreath on the color wheel. This color is magenta. Next, the software was required to identify the different shades of green and set them to be true if it a pixel of color is green or set to false if a color is not green. Initially the team used RGB (Red-Green-Blue) values for green, however, they realized that other colors including white, gray, or yellow also include a component of a green value. Therefore, the team modified the design and decided to use the OpenCV computer vision library to apply a mask to the images to look at HSV (Hue-Saturation-Value) values, specifically the hue and saturation of green and the range of all the shades of green that would most likely be seen throughout the process of painting the wreaths on the assembly line[8]. The team created a simulation of the wreaths with the magenta background and validated this approach was enough to detect the wreaths as they moved through the field of view.

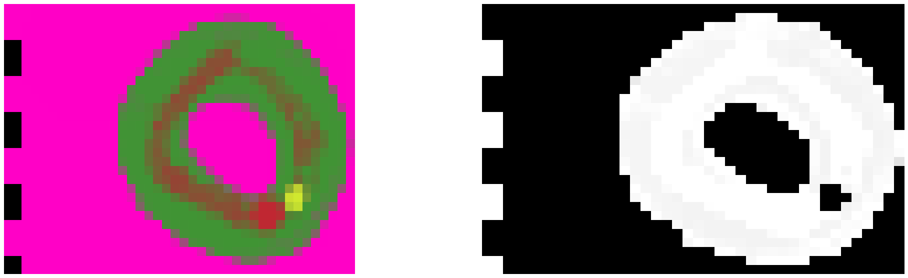

Figure 8. Simulation of the original image and the associated image mask

To detect when a wreath entered the camera's field of view, the team utilized the mask to find the edge of the wreath. The software then compared the image of the wreath passing in front of the magenta background. The mask would be applied, and the vision algorithm was able to discriminate the wreath from the background[8]. To detect when a wreath was in the frame of the camera, the software used the magenta background with the mask, and the image columns were processed. To perform wreath detection, the team implemented an edge detection algorithm and waited until a solid column of magenta pixel values, followed by a column of pixels that were not completely magenta pixel values were detected. As earlier stated, since the magenta and green are drastically different color values, the software would detect the succeeding column to be the edge of the wreath. It should also be noted that although the wreath has a hole in the middle, this method still successfully detected the wreathy since there were still non-magenta pixel values processed.

Next the team had to overcome when multiple wreaths were in the field of view of the camera. To check for a new wreath entering the field of view of the camera, the software would wait until a new edge would enter the frame. The first check for differentiating the wreaths was to see if the pixels of the wreath on the right edge would become a solid column of magenta once again, accounting for the wreath.

Once successful detection and image processing of a wreath was achieved, the software had to determine the position and velocity for each wreath. The change in position was found by the difference of position in every frame. The camera capture and image processing were performed at 20 frames per second allowing the difference in position to simply be the difference in position per frame rate. The image processing code processing rate was able to execute within the 20 frames per second to ensure successful wreath tracking.

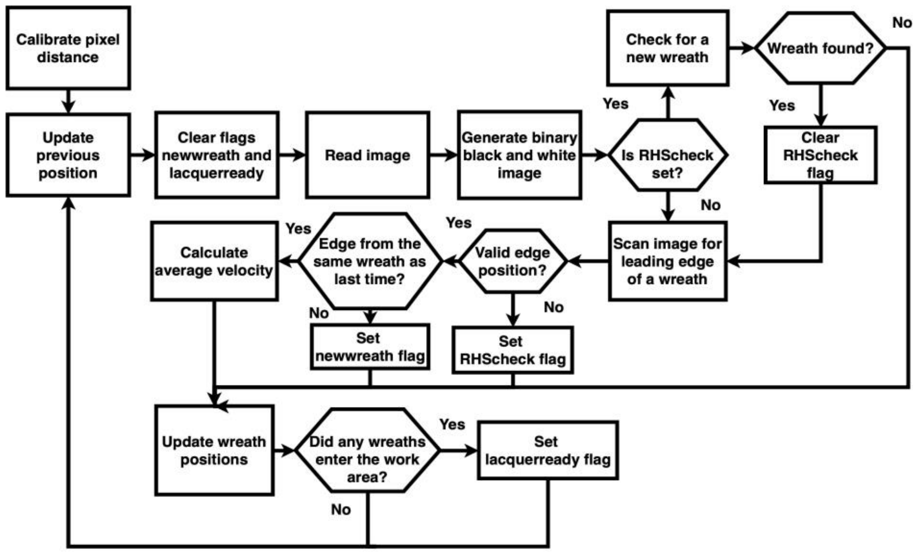

Figure 9. Computer Vision Processing flow diagram

D. Controls System Design

To perform controls processing of the robot system, the controls team selected the Jetson TX2 embedded processing board from Nvidia as the controller for the system. The computer vision software was also implemented with this hardware as well. The Jetson TX2 was configured with a JetPack version 3.3 using the Linux 16.04 called Linux-4-Tegra (L4T). The key software packages were the Nvidia Nsight Eclipse Edition IDE on OpenCV for the image-processing libraries[9].

The controller software interfaced with the computer vision software regarding the wreath position and velocity and the control software and calculated the output velocities for each stepper motor. Additional inputs to the control software include limit switches which perform an initialization on power-up to a known "home" location. Once the wreath enters the home position, the X-Axis motor with the end effector will accelerates until it matches the wreath velocity. As the X-Axis motor matches wreath speed it maintains the matched velocity as the nozzles and air valve will actuate the end effector and spray the wreath. The end effector will turn one-hundred and twenty degrees while spraying to ensure proper lacquer coverage. Once the wreath is sprayed, the end effector will decelerate and return to the home position. When both the wreath and end effector are in the home position the system repeats the processes.

To achieve adequate lacquer application, the robot requires a robust motor control system to ensure that the end effector maintains synchronous, parallel movement with the wreaths on the hook line conveyor system. The mechanical team determined that the 2-axis gantry design would be the simplest and most effective way to meet the positioning requirements of the project. The team chose to use 8718M-06P bipolar parallel stepper motors manufactured by Lin Engineering to control end effector positioning[10]. Two motors control the Y-Axis positioning of the cross beam, one motor controls the X-Axis positioning of the end effector, and one motor provides the rotational movement for the nozzles and hoses on the end effector. The vertical motors move the end effector to the appropriate height, such that the end effector position corresponds the size of the wreath being sprayed.

The motors are rated at a draw maximum current of 4.2 Amps at full load (39 lbs.) while delivering a continuous operating torque of 70 in.-oz at 720 rpm. The actual load on the X-Axis motor is measured at 27lbs. These characteristics are imperative in the system to ensure the stepper motor does miss and step thereby ensuring the system accurately tracks the velocity of the assembly line[10]. If missing steps occur, this will result in incomplete lacquer application and the system will need to be reset. The control system was designed to maintain the accurate lacquer application ensuring that travel in the X-Axis direction was the same velocity of the hook assembly line.

The software architectural used to implement the controls is based on an object-oriented approach using C++ with classes thereby enabling in code reduction. This design philosophy focuses on software architecture optimization with the primary executive role of the program being to simply call functions and/ or class members that do most of the code execution for the algorithms. This approach also allows the file structure of the program to be separated and the background of the program to be partitioned from the user to prevent incidental changes. Moreover, instead of one large file containing all the functions required for the program, the functions are distributed amongst multiple files containing related code. This approach provides for ease of maintenance and updates for future efforts.

Finally, the integration with the computer vision team required the ability to pass variables such as the velocity of the line to the controls program. The computer vision team's software is executed in different processes managed by the operating systems. To accomplish the inter-process communication, the controls team implemented a system of shared memory queues using the "shm library" to create and process shared memory locations[11]. Ten different timer values reside in the shared memory space used to convey the velocity and other shard data such as the wreath size in order to support the control algorithms. The shared data types utilize floats for ease of programming and accuracy and are accessed with an array of pointers protected by semaphore structures.

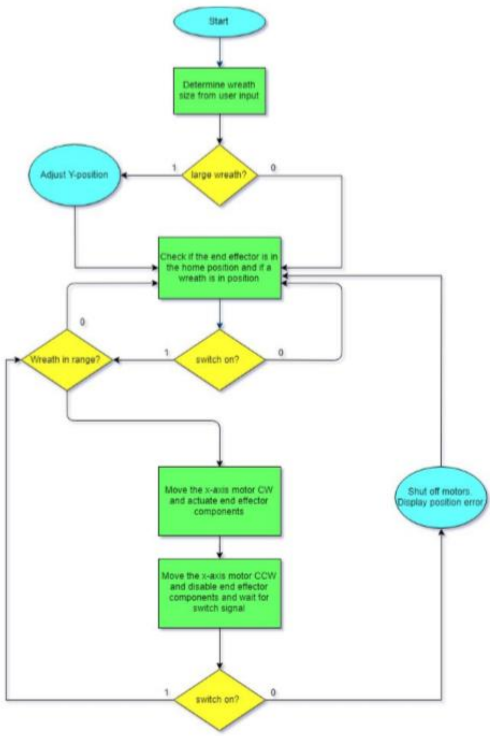

Figure 10. Controls Algorithm Processing Loop

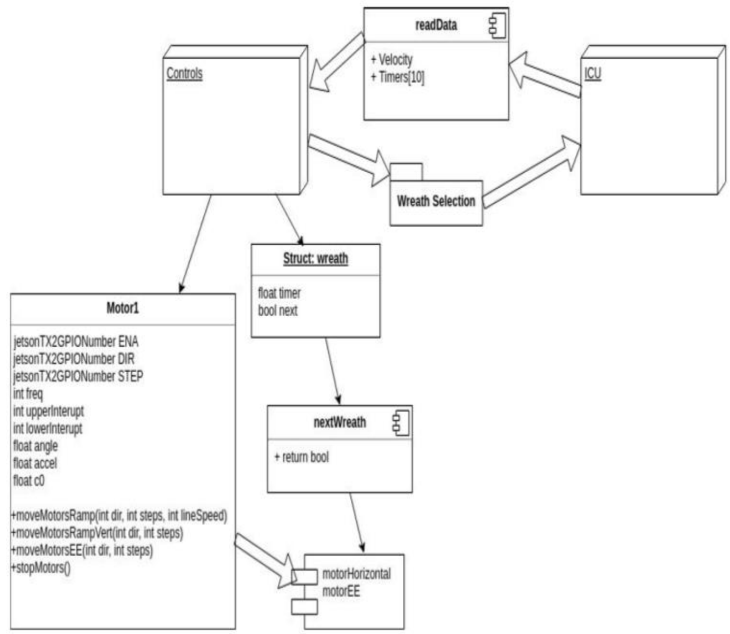

Figure 11. Controls Processing Class Diagram

E. **Simulation and Modeling**

Throughout the project several methods of modeling and were employed. The mechanical CAD designs were designed using Solid Works to ensure proper design of the assemblies. This also provided the teams the ability to track and document the procurement of the parts. A fundamental requirement for the team was that the design was to be sustainable for maintenance as much as possible by the boys and staff at Boys Republic upon completion. This requirement implies that while there were specific parts that were necessary to be machined, if possible, the design had to use off-the-shelf hardware and ideally a second source for the parts. However, if a part required custom machining, full documentation for the design via CAD was provided to allow Boys Republic the ability to have the part manufactured by an outside company or within the resources at Boys Republic.

Many of the algorithms were implemented initially in simulation. To do this, the CAD model was imported into Coppelia's V-REP robotic simulation tool[12]. Using this tool, various designs were analyzed for both the controls and kinematic modeling. Because the CAD models accurately represented the physical design, and the simulation tool accurately represented the kinematics, the designs were able to be evaluated on a technical merit of implementation without requiring the initial build. This provided the team the ability to design and build the robotic arm in the course of only one semester.

III. Program Management and Multidisciplinary Environment

As indicated earlier, the overall team was composed of four sub-teams. Overall the entire team was managed by the project manager. The project manager was responsible for ensuring the project, that the sub tasks were kept on schedule while providing a direct interface to both the customer and supervising faculty advisor. The program manager delegated the responsibility of parts procurement to the procurement lead. The procurement lead was responsible to work directly with Boys Republic staff and the individual teams to order parts or purchase work orders that were machined. In addition, a detailed bill of materials (BOM) was maintained by the procurement lead per the drawings in CAD to fully document the design and parts selection. Furthermore, the students that performed the roles of program management and procurement were also equally responsible for their own tasks within the technical element of the designs within their specific sub-teams.

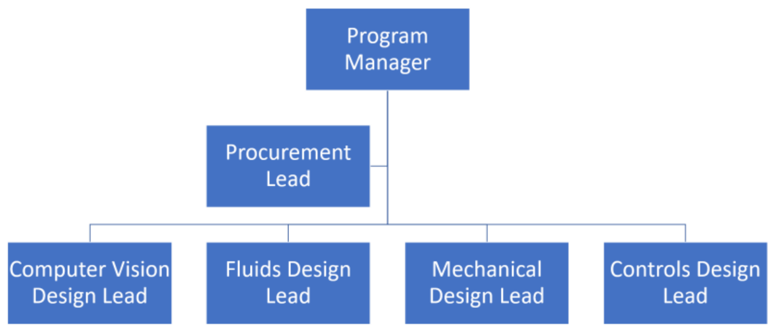

Figure 12. Team Structure Organization Chart

Throughout the work of the project, sub-teams would meet two to three times a week for one to two hours each meeting. During this time each sub-team would discuss the progress for the week and assign the duties to individuals. In addition to the program management and procurement roles, each sub-team had a sub-team lead. Each week team members of each team would write a 5-15 report. The idea of this is that it would take 15 minutes for each team member to write up their status, what they individually accomplished, what they were currently working on, and what was next on their work to do. The status report should take no more than five minutes to read. Team leads would collect the member's 5-15s and summarize the team's efforts and construct a team 5-15. The team's 5-15 was then provided to the project manager who would then provide them to the faculty advisor prior to the overall team's weekly meeting with the faculty advisor for the project.

The structure of the teams was established to allow various students the opportunity to understand both technical design as well as learn leadership roles within an engineering project. This enabled students to understand how to work together in both small and large teams and how to understand each other team's requirements. Two of the teams, fluids and machine design were predominantly mechanical engineering focused, while the other two teams, computer vision and controls were predominately electrical and software engineering focused. This multidisciplinary structure of integrated product teams provided the students the opportunity to learn how to interact with one another as they will eventually in industry.

The composition of the four teams consisted of three team members. Of the overall team structure there were three female engineering students and nine male engineering students.

Moreover, both the project manager and procurement responsibilities were performed by female engineering students.

IV. Assessment of Learning Outcomes

This project has been found to be very effective in providing opportunities for the students to understand the engineering environment they will likely have working in the real-world. The project has provided the engineering students the ability to design a multi-disciplinary robotic system with a real customer with a real need with real requirements. The project has also taught them how to manage and balance the technical design with a schedule and allocated costs through the provided funding from Boys Republic.

Throughout the life of the project, as the students interacted with the staff and resources with Boys Republic as well as one another, they were able to develop and understand the critical nature of both oral and written communication skills. This was sometimes evident during the overall weekly team meetings when clarifications between teams were done. In addition, the teams were required to present their work to the customer. Throughout the work, the design was documented electronically and delivered to the customer, Boys Republic, which allow them customer the ability to ensure they would be able to maintain the design in the future.

V. Conclusion

In conclusion, the Project Ponderosa, through a relationship between Boys Republic and Cal Poly Pomona Engineering Department of Electromechanical Engineering Technology has provided Cal Poly Pomona engineering students the opportunity to realize a robotic automation design using real-world processes and methods that will prepare the students for their future in the engineering industry. The results of the engineering efforts further provide the boys at Boys Republic the opportunity to further develop vocational skills and become contributing members to society. The engineering students have gained valuable technical skills in engineering disciplines of mechanical, electrical, and software engineering design. Beyond the technical skills, the Cal Poly Pomona students have also been able to develop better oral and written communication and leadership skills while working within a multidisciplinary environment. Finally, the project has given the students the opportunity to learn how to develop new skills not necessarily taught in the classroom. These skills are essential for engineers to develop as life-long learners as technology continues to evolve.

Acknowledgements

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References

1. Grau, A., Indri, M., LoBello, L., Sauter, T., "Industrial Robotics in Factory Automation: from the Early Stage to the Internet of Things*," 43rd IEEE Industrial Electronics Conference IECON*, Japan 2017.
2. Verner, I. and Gamer, S., "Reorganizing the Industrial Robotics Laboratory for Spatial Training of Novice Engineering Students," *Proceedings International Conference on Interactive Collaborative Learning,* Florence Italy, 2015.

3. Chang, G. and Stone, W., "An Effective Learning Approach for Industrial Robot Programming", *120th ASEE Annual Conference & Exposition*, Atlanta GA, June 2013.
4. Boys' Republic, https://boysrepublic.org/who-we-are/.
5. Boys Republic, https://boysrepublic.org/della-robbia-wreaths/.
6. Filiposka, M., Elmaraghy,W. and Djuric, A. "Kinematic Analysis of a 6DOF Gantry Machine," *Conference Paper in SAE Technical Papers*, Detroit MI, April 2015.
7. "How A Spray Gun Works." *Design and Function of Spray Gun* www.secondchancegarage.com/public/635.cfm.
8. OpenCV Computer Vision Library, http://opencv.org/.
9. Nvidia Jetson Developer, https://developer.nvidia.com/embedded/jetson-tx2-developer-kit.
10. Lin Engineering, https://www.linengineering.com/products/stepper-motors/8718-series/#fndtn-standard_motor.
11. Pthread_create - Linux man page. https://linux.die.net/man/3/pthread_create.
12. V-REP Simulation Tool, http://www.coppeliarobotics.com/.