Leonardo Bot Vinci: Orthographic Projection Robot

A Technical Report submitted to the Department of Electrical and Computer Engineering

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Bachelor of Science, School of Engineering

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On my honor as a University Student, I have neither given nor received unauthorized aid on this assignment as defined by the Honor Guidelines for Thesis-Related Assignments

Signature ____ Date __________
Emily Flynn

Approved ____ Date __________
Harry C. Powell, Jr., Department of Electrical and Computer Engineering

Statement of work

Sammy Burr

The majority of my work focused on the mechanical aspects of the project. I designed and built the X-Y drawing table that moved the dry erase marker to produce images. To begin the task I first met with members of past teams to seek advice and permission to acquire previously used parts. I dissected the old projects and determined which parts would be viable for our design. Then I decided upon additional parts that would be necessary to complete the design and filled out an order form. After that I began physically constructing the design I held mentally which I later documented through CAD in Solidworks. My approach was largely based on trial and error. Problems I ran into included unexpected alterations to recycled parts and the incompatibility between those parts and newly ordered ones. When I needed an extra set of hands Maansi and Emily were present to assist with stabilization, advice and additional help.

In addition I built the green screened lighting box which acted as the environment when taking photographs of the objects. Some design decisions regarding this box were made as a team. After a group prototyping session we decided the design should contain three cameras and LEDs situated along the perimeter of each side a camera was present. Other decisions I resolved myself, such as the height of the cameras, the dimensions of the box, and the presence of a handle and hinges. With faculty aid, I constructed the box using a variety of mechanical machines found at Stacey Hall and the Mechanical and Aerospace Engineering buildings. These included a table saw, drill press with hole saw bits, and an electric screwdriver. Lastly, I determined the best way to produce the green screen effect would be to attach fabric to the sides with command strips and hot glue; Maansi and Emily contributed largely to the cutting and attachment of the fabric. The mechanical aspects of design that I produced allowed for consistent photographing to occur and facilitated the translation of computer images to physical drawings.

Emily Flynn

I worked on the LabView portion of the project. This was divided into two main parts: image processing and sensor/actuator interfacing. For the image processing, I looked into different ways to isolate edges of an object. Based on preliminary tests for our lighting box, we decided to use green screening to remove the background, so I developed LabView code to filter out a green background and smooth the edges of the object. I tested this code against images found on the internet and taken against a green background in the lab. I also developed code to sort the pixels representing the edge of the object into an ordered array, so the X-Y drawing robot would be able to draw continuous lines instead of individual pixels.

My code interfaced to the limit switches, motors, and solenoid through Maansi's PCB. With help from Professor Powell, I developed a Virtual Instrument (VI) to control each motor individually. I also created VIs to raise and lower the solenoid holding the marker and sense the limit switches, which provided an initial known starting point for the robot to draw from. Finally, with Sammy helping me debug, I integrated the image processing and sensor/actuator code to create a functional drawing system.

Maansi Mehta

I was responsible for designing the printed circuit board that powered the various parts of the X-Y drawing table and allowed the myRIO microcontroller to interface with these drawing table parts. The X-Y drawing table needed many electronic parts to function completely which included 2 bi-phase H-bridge stepper motors, 2 limit switches, and a solenoid. The circuit board also allowed the myRIO microcontroller to be connected to it so that myRIO pins could be interfaced with various circuit board parts that controlled the drawing table.

The myRIO pins provided the PWM signals needed to control the stepper motors and digital I/O pins to control the solenoid movement, as well as read the state of the limit switches. Specific pins of the myRIO were routed to through the PCB to read the limit switch states (closed or open) and to turn on and off a transistor that controlled the up and down movement of the solenoid. The PWM pins of the myRIO, as well as digital I/O pins were programmed to produce PWM signals that were routed to two motor driver integrated circuits that connected to the stepper motors. The entire board received DC power via an AC to DC adapter that could be plugged into an outlet. The 15 V DC power supply on the board was then routed through multiple voltage regulators that stepped down the DC voltage to 12 V, 5 V, and 3.3 V to supply power to the various integrated circuits and myRIO that were connected to the board. The board I designed bridged the gap between the image processing software coded in LabView and the mechanical drawing table, to make the whole machine an integrated, and well communicating contraption.

Lastly, besides working on the electrical portions of the project, I helped Sammy build the lighting box for the final demo by helping line the insides with precisely cut green felt and LED orientations for the inside edges. I helped put together the hinges and handle to make the box easy to handle, and also assisted with fine-tuning the green-screening of the image processing portion of the LabView code. Fine-tuning the image processing at the very end for the demo was a team effort when a majority of the image processing was working, but changing small details of green screening values was required with a lot of testing of objects, taking pictures, and varying the LED colors to get the best set of green-screen values that worked well with all the objects used.

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Abstract

The Leonardo Bot-Vinci is a robot that automates orthographic sketches of 3 dimensional objects. The overall functionality of the robot can be split into 3 parts: the camera, the image processing, and the drawing. The robot has a constant lighting environment box that contains LifeCams as well as LED strips to provide lighting for the cameras. The cameras are oriented to take an X, Y, and Z plane picture of an object that is placed inside the box. Then, these pictures are acquired and processed by LabView algorithms to arrive at clean edges that can be drawn. The image information is translated into a set of coordinates that are sent to the stepper motors on the XY drawing table in order to reproduce the edges of the object in the box. The drawing table consists of two NEMA-17 bi-phase stepper motors controlled by PWM output with an H-Bridge driver configuration, two limit switches, and a pull solenoid that controls the drawing instrument. The XY drawing table can use a white board marker to draw orthographic projections on a white board surface.

Background

Since the Christian Era artists and architects have been crafting drawings to communicate designs and ideas, however, the theory of projection views from imaginary planes was not fully developed until the late 1700s [1]. Leading up to the invention of orthogonal representation, renaissance men like Leonardo Da Vinci used perspective renderings to detail their designs. Modern engineers and builders had no standard way to convey their models and proposals until Gaspard Monge of the French military devised a system to communicate a three dimensional object around the world: orthographic projection.

The concept of an automated drawing robot is not new either. These devices are different from machines such as the printing press because of their relative freedom of movement: while the printing press can only reproduce images from stamps, a drawing robot is self powered and can move freely on the xy-plane, allowing the robot to mimic a human’s drawing process. Patents for drawing robots go back to 1961 [2]. Some robots have been commercialized and are sold by companies as large as Bloomingdale’s [3]. Today, with the widespread use of hobby boards like Arduinos, it is relatively simple for people to build their own devices. Likewise, edge finding in image processing is an old field and has patents as far back as 1990 [4].

Our project combines edge finding and drawing robots to construct orthogonal perspectives. While there are some robots that can reproduce an image on paper, many of them require digital images drawn on a computer or phone. Others may reproduce a live photo by drawing dark regions of the image [5]. Our project focuses on a more specific application of the drawing robot; since we plan to work on orthographic projections, our robot will draw the edges of physical objects instead of reproducing images based on dark regions. This focuses on edge finding in image processing, as opposed to determining relative color values.

We chose this project because we were interested in a more “fun” capstone project. While our project does have practical applications like orthographic projections, it is also interesting to watch. During the capstone fair, we found that younger visitors were interested in the project and had many questions, so the project is an interesting example of engineering for young people. We also had experience with machine vision in LabView and interfacing hardware with the myRIO. We felt that this project would be interesting and fun while tying together concepts we learned throughout the Fundamentals series, digital signal processing, and other electrical engineering classes.

Our project will heavily involve background from Professor Dugan's Mariobots class, which emphasizes the use of and tools available in LabView. Two of us took that class, and have experience integrating the myRIO with external devices. We also will use experience gained in Introduction to Embedded, especially with respect to the motor projects. That experience will help us integrate the motors with our microcontrollers. Finally, we expect to draw on knowledge from the Fundamentals series, especially PCB and analog design.

Constraints

Design Constraints

Many of the components used in this project were from previous capstones so there were a number of design constraints that had to be worked around. The existing aluminum beams used for the drawing table were not cut to be 8"x11", which was the original idea for the dimensions of the drawing table. Using the existing parts from previous projects cut down on our costs greatly, but required some design changes in terms of the dimensions of the X-Y drawing table. The drawing table that was built for the project was approximately 18"x33" which didn't change much of the functionality of the project - it just took up more space on the lab bench.

Using the existing stepper motors from previous capstone projects rather than buying new ones, again, cut down on costs for the project, however, there was a difference in gear size of the stepper motors which had to be accounted for in the LabView code. In the Y direction, a larger number of steps were needed to move the same amount of distance in comparison the X direction as the X direction stepper motor had a larger gear. This did not pose any significant design changes, but just had to be compensated for in the LabView code when calculating step numbers versus distance moved on the drawing table. There were no other significant design constraints for this project in terms of parts availability, parts ordered, or PCB manufacturing and fabrication.

Economic and Cost Constraints

A major constraint we had to consider was cost. The OpenBuilds ACRO systems that our project was similar to were very expensive, at around $300 for a small table [6]. To alleviate this, we used parts left over from previous Capstone projects, which had the added benefit of letting us start right away without waiting for parts to arrive. We also ran into cost constraints when looking at LEDs. We had hoped to get a flexible strip of LEDs or LED tape to line our lighting box, but again, these were simply too expensive considering our other costs. We ended up purchasing LEDs from the store instead of using Digikey parts. The wood to build the lighting box was also costly, at around $50 total. These costs, along with PCB and table parts, added up, so we were not able to purchase a new OpenBuilds system or LED tape.

External Standards

Since our project has motors, it is important to follow standards set for moving parts. The National Electrical Manufacturer's Association (NEMA) has standards for stepper motors such as the ones we are using. Our motors were rated NEMA 17, so they follow the NEMA requirements for position control motors [7]. The driver chips are also NEMA 17, so they too follow the requirements for motor control and feedback devices [7]. We also looked into the American Society of Mechanical Engineers and Society of Automotive Engineers standards. However, the standards from those organizations are aimed for large motors such as those in cars or cranes, and we did not find their requirements relevant to our project. However, we did ensure that we followed the Occupational Health and Safety Administration's requirements for moving parts [8]. One important aspect to consider was the accessibility of nip points, or points where something could get stuck between two moving objects. One such point is where the timing belt meets the gear, as seen below. Our gear is placed close to the aluminum rail such that it would be very difficult for something to get stuck in that small space. Both motors have similar setups, which makes those nip points difficult to access.

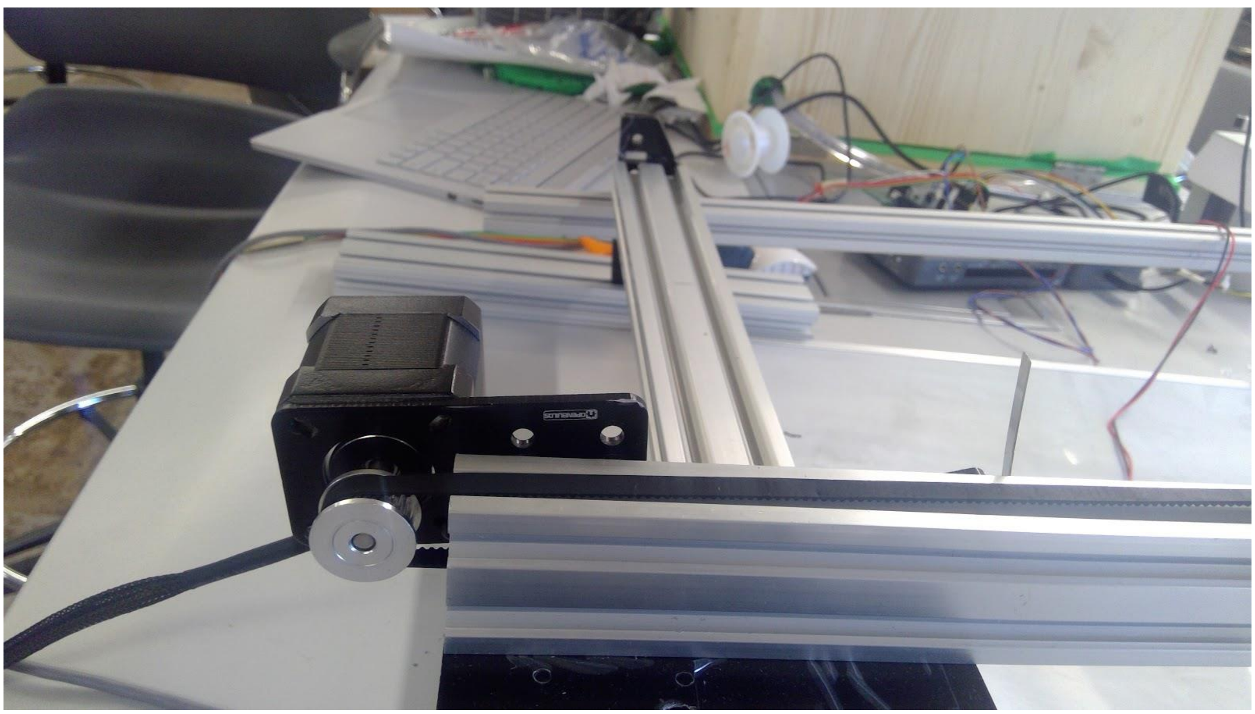

Figure 1: Motor, gear, and timing belt setup

Another aspect of OSHA regulations is about transverse, or lateral, motion. The timing belt moves laterally and if the two opposing sides of the belt were to get stuck on something, they could twist that, causing injury or damage. However, only half of the timing belt is easily accessible. The other half is threaded through the aluminum rail, making it nearly impossible to access. This complies with the OSHA requirement for safeguards.

Our PCB has to follow the Association Connecting Electronics Industries (IPC) qualifications for printed board, which is IPC-6012 [9]. Our board is class 1, which is for general purpose boards [10]. The IPC-6012 standards dictate aspects such as conductor width and spacing, finishes and coating requirements, and via size [9]. Our design rule checks ensured IPC-6012 standards so they would be manufactured. Some aspects of IPC-6012 we did not have control over, like thermal stress requirements, but we assume that the PCB manufacturer followed these standards.

Finally, we were concerned about the LEDs in the lighting box, and initially thought we would have to use NEMA standards. However, since we simply purchased a string of LEDs from a store and made no changes to it, it is NEMA rated.

Tools Employed

To program the myRIO, we used National Instruments LabView [11]. Specifically, we used the I/O pins to get input from the limit switches, and control the motor and solenoid. We also used LabView on a computer to perform image processing. The Vision Acquisition Software [12] was used to remove the background, isolate edges, and smooth the image for drawing. As we had some experience with LabView, programming the myRIO and image processing was not a major challenge. NI's Measurement and Automation Explorer [13] was used to interface with the cameras attached to the myRIO and take images.

KiCad [14] was used for schematic capture and layout of the PCB. KiCad was chosen as it has a very extensive symbol library with many standard footprint libraries for the layout. It is very easy to find symbols for parts on Digikey and attach any layout in the library. It is a lot more versatile than Multisim/Ultiboard and required much less custom part creation, as most parts on Digikey, along with most standard part footprints, already exist in the library.

Ethical, Social, and Economic Concerns

Environmental Impact

An initial concern we had for the device was wasting paper. Our plan for the project was to have the robot sketch orthographic projections on sheets of paper, which could then be taken for reference. This has the potential to use a lot of paper. If the robot is unable to draw correctly and accurately, or if the image processing fails to correctly isolate the edges of the object, the physical sketches may not be usable. However, in our final product, we decided to use a white board and marker instead of paper. While production of the white board and marker has a small environmental impact, it is more reusable than paper, so we were able to reduce paper waste from our original idea.

This device does have a significant energy impact. The LEDs, myRIO, motors, solenoid, and computer all needed to be powered independently. Image processing can be moved to the myRIO to remove the laptop and reduce energy consumption. Additionally, the device does not need to be on all day, which reduces overall energy consumption. The solenoid uses about 3W. The motors use a lot of power, at about 40W each. However, the motors we used in our project were extremely large, and reducing the table size would allow for smaller motors to be used, reducing energy consumption. The LEDs used were not picked to be low power, so again those could be replaced to lower energy consumption. Overall, while our current design for the project is relatively high-power for a non-appliance device, it could certainly be reduced by picking better parts.

Sustainability

As previously mentioned, the project's final design was not very energy efficient, but could be made more efficient by picking parts for energy efficiency. In general, production of motors, LEDs, solenoids, ink, and more can create chemical waste that harms the planet. If bought new, the aluminum rail used for the drawing table is most likely mined. Finally, the lighting box was made from pine wood. Again, picking a different material for the box could reduce its environmental impact.

Despite all those issues, this is a relatively specialized device that is not supposed to be marketed to all consumers. The target audience of mechanical drafters is relatively small, which limits the amount of devices that could be sold. Considering the small amount of devices needed, if manufacturers take proper precautions, this device could be manufactured with a low impact on overall global sustainability.

Health and Safety

A major priority for this device is safety, since it is meant to be used by people to actively make orthographic sketches of self picked objects. Consumers should be able to safely use this device to take pictures and watch a robot create the sketches without any sharp, high voltage/current, or otherwise dangerous parts being exposed. The wiring between the cameras and myRIO as well as the robot was neat and insulated. Aside from the solenoid, no parts on the device dissipated too much heat or energy as that makes the device dangerous to be around. The solenoid was programmed to be off when idle to reduce heat dissipation. There is always danger with moving parts like motors and the solenoid. However, precautions were taken to reduce the chance of an incident, by ensuring that the wires were as far from moving parts as possible and the timing belt was low-profile and hard to hit by accident.

Manufacturability

Most parts used in this project were readily available. There were no 3D printed parts, and the most specialized parts were for the table itself, such as the aluminum rails or plates. These are not particularly affordable when purchased from the manufacturer we used, OpenBuilds, as a kit costs around $300 [6]. However, if mass producing this device, it would be possible to create these components at a lower cost. The microcontroller used is also not readily available or affordable. The myRIO 1900 ranges from $567 for academic use to $1,136 for general use [15]. To make this device affordable, the microcontroller used would have to be changed to something cheaper, such as an MSP 430.

Ethical Issues

It is possible that this kind of device could put mechanical designers or sketch specialists out of a job. If a device can automate the process of making orthographic sketches as well as scaling up or down, it means it could make a sketch for a variety of sizes of objects, in a controlled and automated way which may be preferred compared to a human sketch designer or mechanical engineer. However, mechanical engineering is a very robust field, and making orthographic sketches of designs is a small cog in a big machine. Having a device do that automatically would reduce the time needed for specialists to spend on sketches. They could instead focus on other aspects of the industry, such as creating datasheets or CAD models, which is a better use of their time and skills. Thus, automated orthographic sketches would likely improve productivity rather than causing a loss of jobs.

Using a live camera to draw orthographic sketches could result in privacy concerns, as people might be concerned about appearing in an image saved by the MyRio. Our final project followed our initial plan to have cameras mounted in a box, with all images taken of the inside of the box. Thus, there should be no concern with bystanders being inadvertently seen by the cameras, because they would have to actively put themselves in the lighting box to be seen.

Intellectual Property Issues

There are multiple patents related to our project going back many years. In 1971, Wilbur Manning filed a patent application for his automatic orthographic projection device [16]. His independent claim is for a device traces the orthographic projection of an object in two views, then uses the combination of the two views to develop an orthographic projection of a third, unseen side. This patent is related to our project on multiple levels. Our device also traces multiple orthographic projections of an object. However, our device does not use those projections to determine a third view; rather, we simply have a third camera providing the view. Manning's patent also claims a device that is able to determine the orthographic projection of an object from a fixed, known view. Our project does exactly that, by using image processing to isolate the edges of an object.

Another patent from 1965 by Little, Kliever and Wiemels is for a drafting-digitizing apparatus [17]. This is an extremely broad patent with multiple independent claims relating to our project. One claim is for a machine that is able to take digital input and automatically produce a visual representation of that data on a flat surface. Our project is extremely similar to this, since we use image processing to digitize the edges of the object, and then send those edges to a machine which is then able to reproduce those edges on a whiteboard. Another claim is for a machine that completely automates the drafting process. This is slightly different from our project in that ours focuses on orthographic projections instead of drafting. However, our project partially automates orthographic sketches in the same way that this patent application fully automates drafting. An area of this patent that our project does not overlap with is the reproduction of existing writing or drawing on a sheet of paper. This device aims to be capable of analyzing lettering or lines and then reproducing that on another surface. In contrast, our device only analyzes three-dimensional objects and does not aim to reproduce lines, but only edges. For example, if our image processing were to scan lettering, it would not be able to reproduce the letters themselves, only the edges of the letters, which would appear as "bubble text" instead of a set of lines. This is a key difference between our project and the device claimed Little's patent. Another major difference is that this patent claims an "electro-optical scanner" that moves over a sheet of paper to scan the lines drawn there. The scanner can also be used to determine the current position of the motors. Again, this is very different from our project, which does not have a camera monitoring the position of the pen and motors. However, this patent is so broad that vast swathes of our project fall into the independent claims asserted.

A 2001 patent by Okuyama claims an apparatus for multiple-exposure drawings and the method used to draw [18]. It is intended for masking processes, not drawing on a sheet of paper or similar surface. The relevance to our project is in the method of conceptualization used to draw images. This patent asserts the independent claim that the drawing method is a group of optical modulation elements stored in a matrix, which are then used to calculate address and exposure data. Our project is much simpler, because there is no need to store exposure data, only address data. However, there is some similarity because our project's drawing methods are similar to an individual layer of the optical modulation elements. In short, our project's drawing methods are a subset of Okuyama's claims.

A survey of existing US patents indicates that our project is not patentable. The concept of the X-Y drawing table itself is extremely similar to Little's patent for a drafting-digitizing device. Our method for drawing projections onto a surface is a small subset of what is claimed in Okuyama's patent, and is extremely simplistic compared to the majority of patented drawing methods. Finally, the purpose of our project is not a completely new idea either. Manning's device goes a step beyond our project by using two projections to determine a third, while we only trace projections immediately visible by our fixed cameras. Our edge detection uses built-in functions from LabView's Vision Assistant and does not involve any novel forms of image processing. Thus, since our project does not have a unique purpose and does not present any new drawing devices or techniques, we do not feel that it is patentable.

Detailed Technical Description of Project

The overall purpose of our project is to create a device to draw orthographic projections of three-dimensional objects. The object is first placed in a lighting box, which is designed to provide consistent, controlled lighting and a green background that can be screened out. Three cameras mounted in the box take pictures of the object from three different axes. The images are then processed to remove the background and isolate the edges of the object. Finally, these edges are sent to an automated XY drawing table that draws the object on a white board.

Major Components Used

Below, we list the most important components of our device. Commonly used parts such as resistors, capacitors, screws, and jumper wires are excluded.

- LifeCam cameras (x3) [19]
- MyRIO [15]

- MyRIO X-[HUB] [20]
- Pine wood: 18” x 20” x 0.75” (x2), 16.5” x 16.5” x 0.75” (x2), 16.5” x 20” x 0.75” (x2)
- OpenBuilds NEMA 17 stepper motor (x2) [21]
- OpenBuilds V-slot linear aluminum rail [22, 23]
- ACRO Acrylic Plate Set [24]
- GT2-2M Timing Belt (12 ft) [25] and GT2-2M Timing Pulley [26]
- M5 ball bearing smooth idler pulley (x2) [27]
- V-10G3-1C24-K limit switch (x2) [28]
- Solenoid [29]
- LED lights [30]
- Whiteboard with dry erase marker (x2) [31]
- Green cloth [32]
- DRV8848 Dual H-Bridge Motor Driver (x2) [33]
- Power N-Mosfet [34]
- 2x17 pin connector for myRIO [35]

System Overview

A diagram detailing our overall system can be found below.

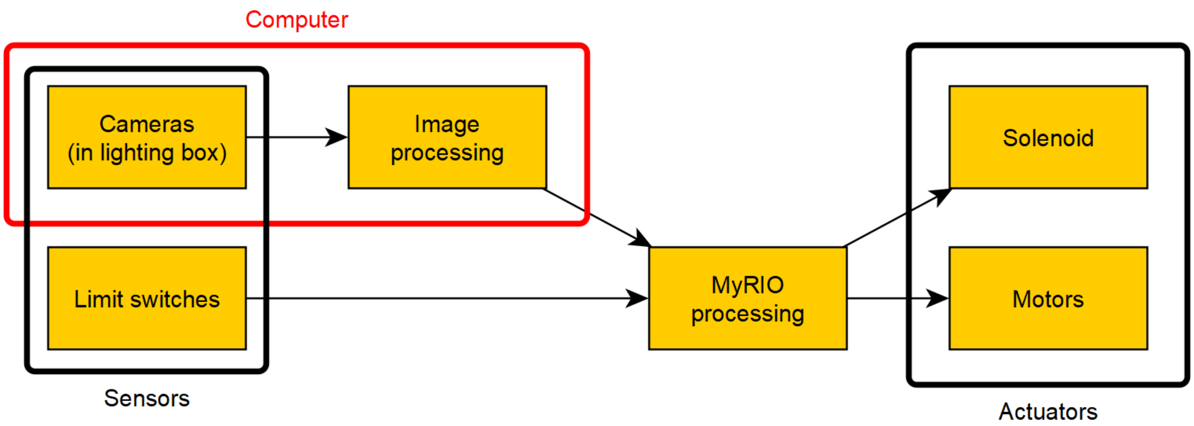

Figure 2: System overview

First, the cameras connected to the myRIO X-[HUB] are viewed using NI MAX. The image is then selected and processed on the computer. Next, the processed image, which results in a set of ordered coordinates, is sent to the myRIO, along with the status of the limit switches. Finally, based on input from the image processing and limit switches, the robot is able to take appropriate action using the solenoid and motors.

LabView Programming

There were two main portions to the LabView programming. The first was the image processing performed to extract object edges. This was performed on a computer. The second was the actual control of the robot. This was performed on the myRIO.

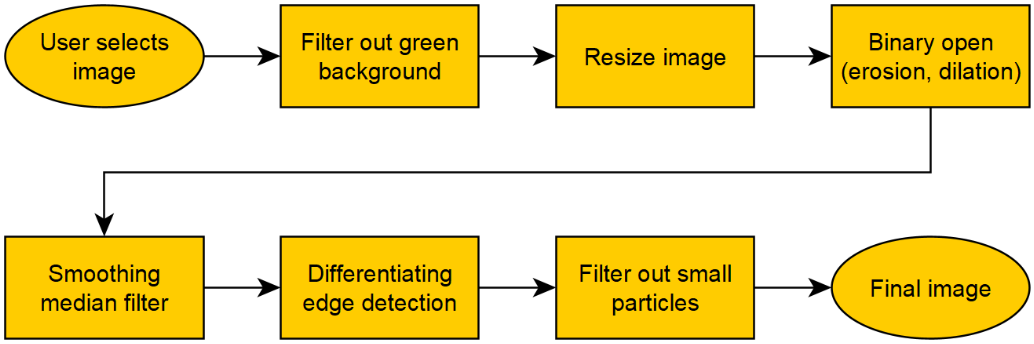

Figure 3: Processing performed on each image

The figure above shows the processing done on each image to acquire the object edges. After the user selects an image, the green background is filtered out using color thresholding. Next, the image is resized to 800x600 pixels. This limits the physical size of the drawing made by the robot. Next, a binary opening function is performed. This performs a binary erosion, which reduces the number of stray pixels in the image, followed by a binary dilation, which adds pixels to the existing edges. Overall, this function remove irregularities and smooths the edges of the object. A smoothing median filter is applied to further smooth the object. Finally, edge detection using differentiation gets the edges of all the objects seen in the image. Particles, or groups of pixels, that enclose a small area are removed, which removes noise in the image. This final image is then sorted into a set of coordinates and returned to the user. An example of our actual image processing is shown below, where Figure 4 is an actual image taken in our lighting box, and Figure 5 shows the result of the image processing.

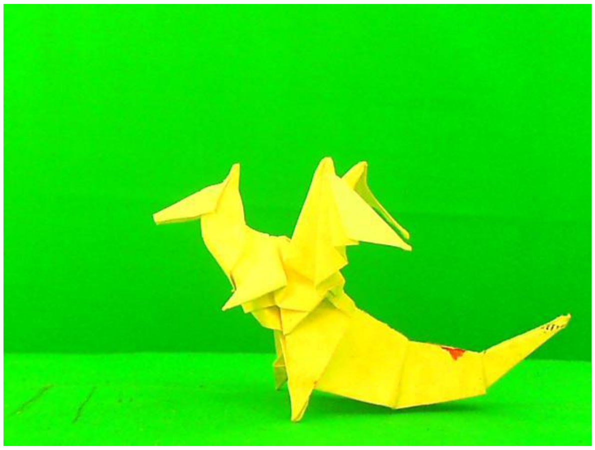

Figure 4: Example of image processing input

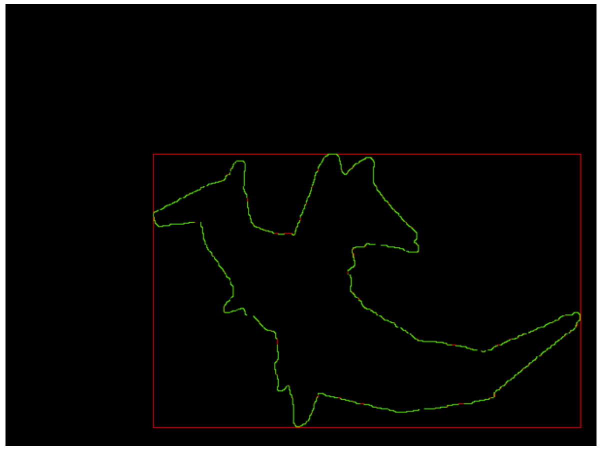

Figure 5: Example of image processing output

Many changes were made in the image processing design from our proposal to the final product. In the proposal, we planned to use brightness and contrast grading to remove the background. Based on initial test results, we changed to color thresholding. We also considered color segmentation to classify and remove the background, but test results were not promising. Our final product included brightness and contrast grading on the cameras but mainly relied on color thresholding. Picking color thresholding values presented a challenge, because it was difficult to filter out the entire background while retaining all aspects of the object. To deal with this, we limited the color of objects that could be placed in the box. For example, some objects tended to be too reflective and would appear as green in the box, so we weren't able to draw them. Despite carefully picking threshold values, our final product still had some problems with differentiating shadows from black objects. The overall box design minimized dark shadows, so we did not encounter this problem too often, and were still able to get a good result from the image processing.

We also considered using contour extraction instead of edge finding to determine the edges of the object. The advantage of contour extraction is that the contours are represented by mathematical equations, so the robot would have been able to draw a smooth line instead of moving from pixel to pixel. However, the contour extraction provided in LabView was difficult to use, and struggled to detect all contours in an image. Edge detection was much more successful in our tests. In a similar vein, we also considered fitting curves and lines to the edges, again to help the robot draw more smoothly. We encountered the same problem, where it was difficult to match lines and curves to each pixel on the edge. Our final product used edge detection on the image. This may have had a small impact on the smoothness of the line being drawn, but the resolution the drawing robot was able to achieve was small enough that any impact on the shape of the edge was minimal.

There were two other major tradeoffs made. First, the particle filtering that removed smaller particles may have affects small holes and details in the object. However, it was worth it as we were able to remove stray particles from the background of the image, which would have had a much larger impact on the image processing. Second, we resized the image to 800x600 pixels, which certainly sacrificed some image quality. Again, this was worth it as we were easily able to restrict the size of the image being drawn. It also improved the speed of our image processing code.

Aside from the image processing, we also used LabView to interact with sensors and actuators. There were three main components: the motors, the solenoid, and the limit switches. We did not interact with the lighting box cameras through LabView.

The motors were the most complicated to control. We implemented a VI that moved a motor by a single step instead of by a full cycle of four steps. This was difficult to design, but drastically improved the resolution of our drawing and was easier to implement in the overall code. The limit switches and solenoid were very simple to interact with, as the limit switches were a simple input and the solenoid was a single pin output. These three sensors and actuators were combined into a single VI.

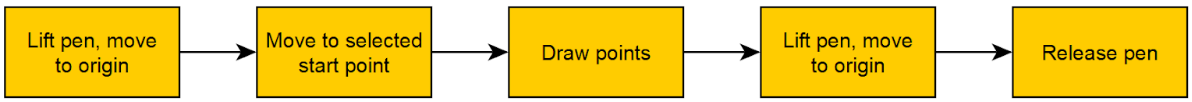

Figure 6: System block diagram for drawing an image

Once the image was processed, we used a very simple VI to draw the image. First, the solenoid was activated so the pen was lifted, and the robot moved to the origin, as defined by the limit switches. Next, the user selected a start point and the robot moved there. It would then draw the image relative to its selected start point, lifting and lowering the pen as necessary. Once finished, the pen was again lifted and the robot moved back to the origin. Finally, once at the origin, the pen was released. This was necessary because the solenoid would overheat relatively quickly. It did result in a lot of stray pen marks at the origin, but that did not impact the overall drawing quality.

PCB Schematic

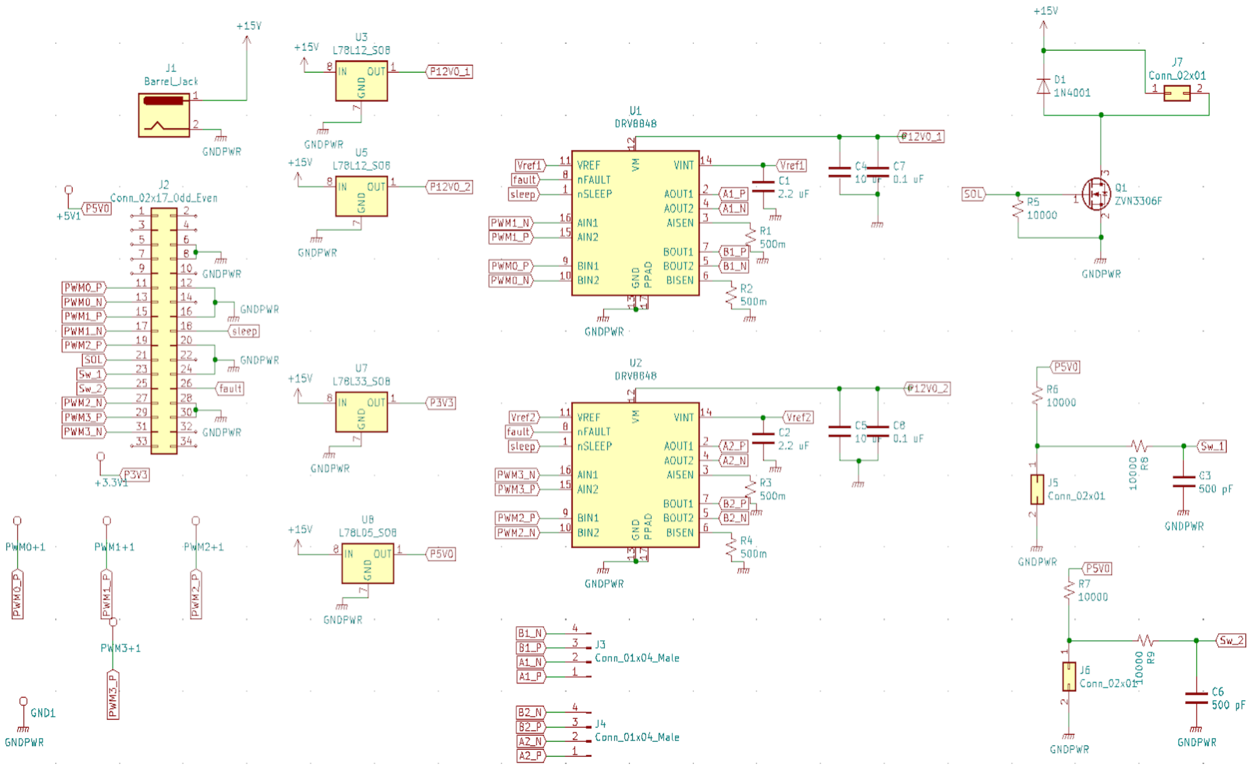

Figure 7: PCB Schematic

Figure 7 is the schematic of the board designed for this project. There are several interacting parts including an adapter that provides AC to DC power for the board, the myRIO connector, various voltage regulators, motor driver chips, connectors, and the circuitry for using the solenoid and limit switches.

First, the myRIO connector shown is a standard 34 pin header connector, and has many labelled tunnels used throughout the schematic. These are the specific pins used for routing PWM signals to the motor driver chips (U1 and U2). The pins used for PWM signals are pins 11, 13, 15, 17, 19, 27, 29, and 31. They are labeled "_P" and "_N" to identify which pairs of PWM signals are inverses of each other which is the configuration needed to run the stepper motors off of the motor driver chips. There is a "SOL" pin on the myRIO, which is digital I/O pin 21 which is connected to a transistor (Q1) on the schematic which, when activated, pulls down the voltage of the solenoid to ground, activating it. This pin was used to switch on and off the transistor to control the up and down movement of the solenoid. Pins 23 and 25 labeled "Sw_1" and "Sw_2" are digital I/O pins which are able to detect the voltage of the limit switches. When the switches are closed, the myRIO pin reads 0 (GND), and when open, the myRIO pin reads 5 V which is a logic high. Using this logic, we were able to detect when the moving carts had hit the limit switches and programmed the LabView code to stop the stepper motors from moving the carts any further, essentially providing a "home location" for the X and Y directions.

Next, the voltage regulators used on the board are 12 V, 5 V, and 3.3 V regulators which take the 15 V DC input power from the adapter jack on the board (J1). The 12 V output is used to provide the power supply for the two motor driver chips (U1 and U2), the 5 V output is used to provide the VCC for the limit switch circuits, and the 3.3 V output is not used on the board, however, was included in case it was decided to power the myRIO on-board rather than with the external power chord.

The motor driver chips are bi-phase H-bridge stepper motor drivers with the correct voltage and current output ranges that allow the motor drivers to interface properly with the specifications given for the two NEMA-17 stepper motors used in the project. The motor driver chips were connected to various pull down resistors and bypass capacitors as per the recommendations of the data sheet provided for the IC.

All other parts on the board (J3, J4, J5, J6, J7) are various standard header pin connectors chosen so that the physical electronic parts like the solenoid, switches, and motors, could be plugged directly into these connectors and easily receive signals from the myRIO and power from the board.

PCB Layout

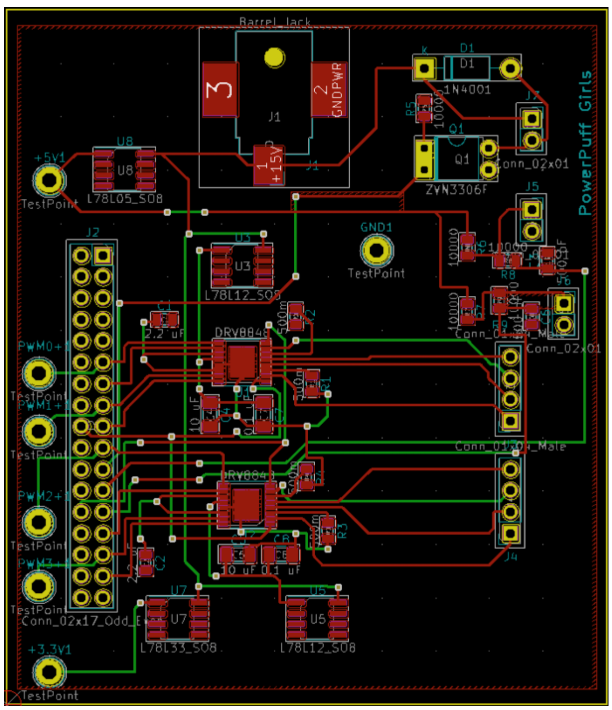

Figure 8: PCB Layout

Figure 8 shows the layout for the schematic that was described. The layout was done using standard 10 mil traces to accomodate for the slender surface mount pads of the motor driver chips as well as for routing between the pins of the myRIO connector. Thicker traces would not have fit between the myRIO pinholes or onto the 10 mil wide surface mount solder pads of the IC’s used. Some floor planning was done to ensure that each IC had all its associated resistors and bypass capacitors close to the IC it was associated with to reduce power loss and noise on the board. As can be seen, most of the traces are done on the copper top as surface mount parts lay only on the copper top layer. The copper bottom traces in green were used to avoid crossing traces, and vias were used to appropriately switch between layers to route to surface mount parts as well as through hole parts.

In the layout, the bypass capacitors were all chosen to be 1206 sized surface mount parts rather than the standard 0805 parts used for the rest of the board. Bypass capacitors are typically larger in size on PCB's, so the same practice was used when designing the layout of the board.

The only major design modification done was between the first and second iterations of the PCB. The very first PCB did not include the circuitry to power the solenoid or limit switches. The parts and design of those had not been properly detailed in the beginning, so the first board had the myRIO connector interfacing with the motor driver chips only. This board allowed us to test and run the stepper motors and we had gotten the X-Y drawing table moving in both the X and Y directions. The second and final iteration of the board simply included the limit switch and solenoid circuits so those could be tested and used in conjunction with the rest of the drawing table. The only error on the board was that the power MOSFET used for the solenoid had not been routed properly, and the drain, gate, and source pins were switched around. This was a relatively simple fix, as jumper wires were soldered to the board and were used to jump to the correct drain, gate, and source pins of the power MOSFET. This fixed the solenoid circuit, and everything else on the board was working as is.

Lighting Box

The purpose of the lighting box was to provide a controlled environment to photograph objects. The box was made of pine wood and was 20" x 18" x 18". There were three circular holes cut on three of the sides for the LifeCam cameras, and the interior of the box opposite those sides was lined with green cloth to be screened out of the image. The box had an attached handle and hinges for ease of use. Inside the box, we placed a platform to rest objects on, which was also wrapped in green cloth. Finally, the inside of the box, especially the faces which contained cameras, was lined with a single strip of LEDs to provide illumination.

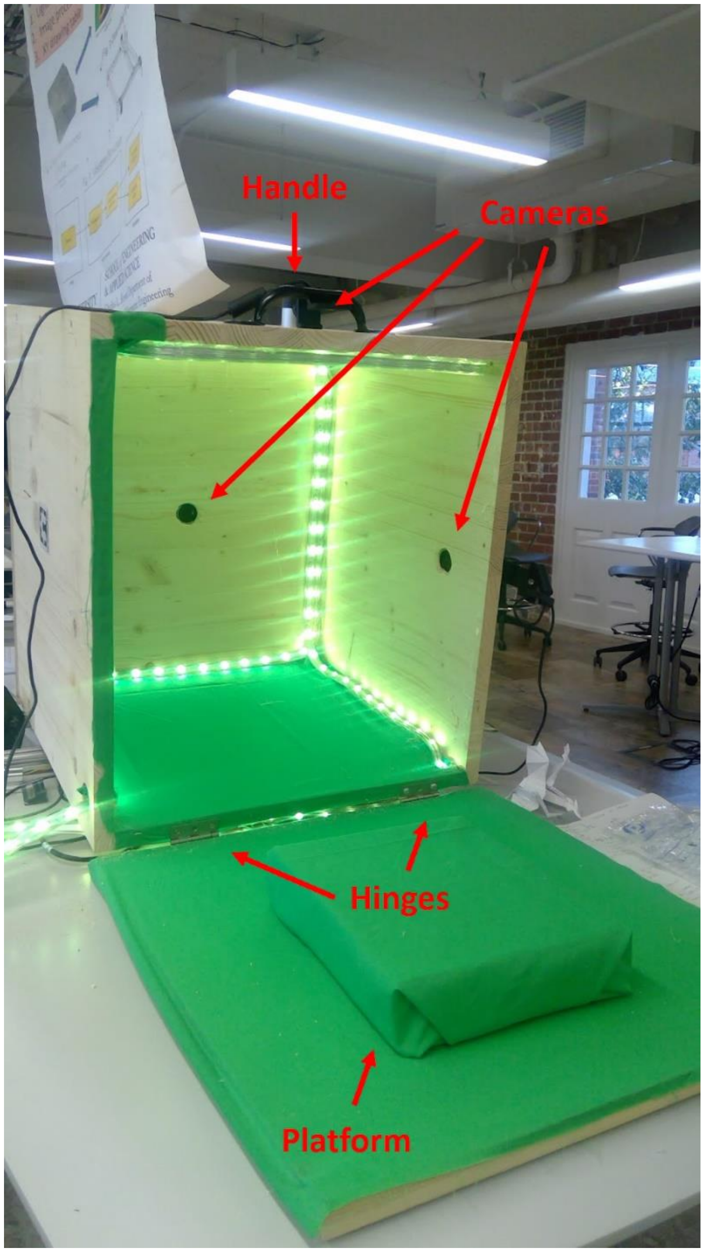

Figure 9: Opened lighting box

We originally intended to have three strips of LEDs that could be turned on separately, but decided to use a single strip for simplicity, lower cost, and due to lack of time. We also tested different colors of LEDs with the interior of the box. While we initially thought we would use white LEDs, we found that the yellow LEDs were better for emphasizing the green background while not tinting the object in the box.

XY Drawing Table

The core of the drawing table is an aluminum rectangle frame that supports three total gantry carts (Figure 10). The sides are bolted together to increase stability. A crossbar is located parallel to the minor axis which is shorter in length than the major axis. This crossbar rests on two bottom gantry carts that ride parallel to the major axis. When bottom cart moves across the major axis it brings along with it the entire crossbar and the other bottom cart. A third top cart, smaller than the first, moves along the crossbar parallel to the minor axis and perpendicular to the major. Because the bottom and top carts can move in different directions along different axes it grants a full range of motion to the top cart.

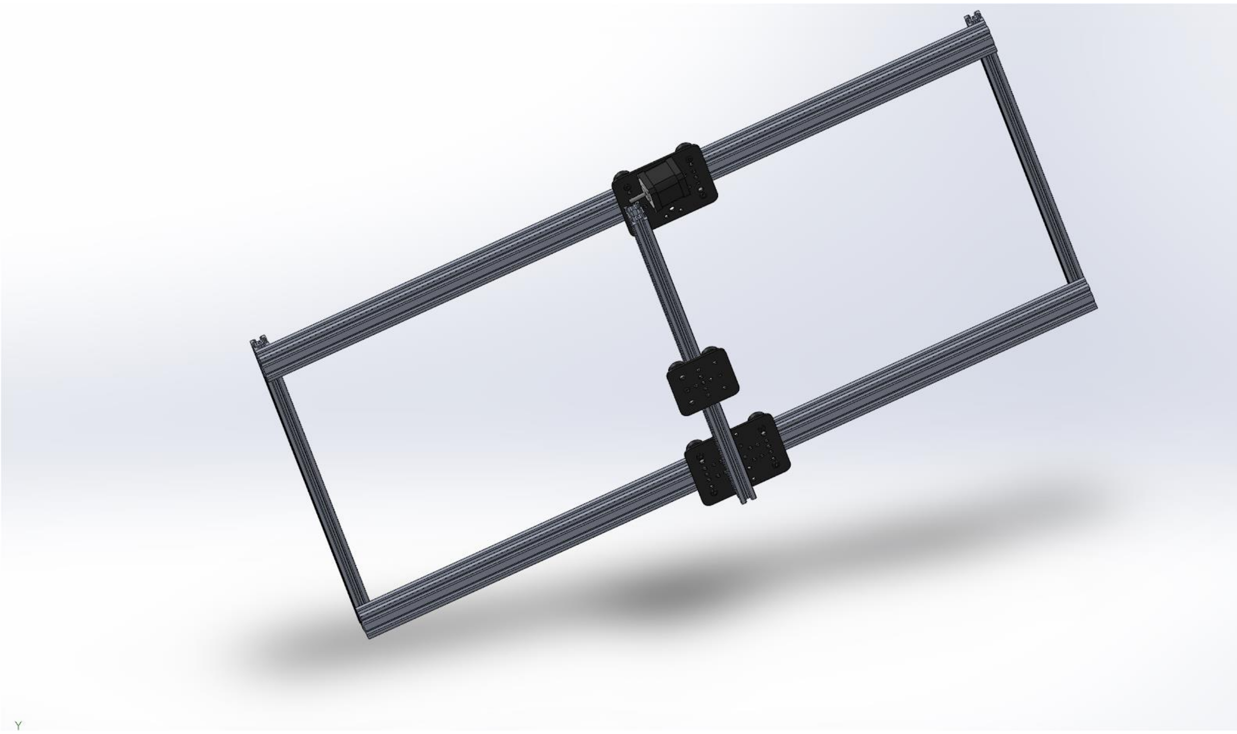

Figure 10: CAD rendering of frame, carts, and crossbar

Two of the gantry carts are each attached to a circular timing belt that move the carts along the rails within the larger pulley system. This pulley system includes a tooth gear on one side of the axis and a smooth idler pulley (Figure 11) on the opposite side. The carts move along the rails due to the turning movements of the gears which are powered by the stepper motors.

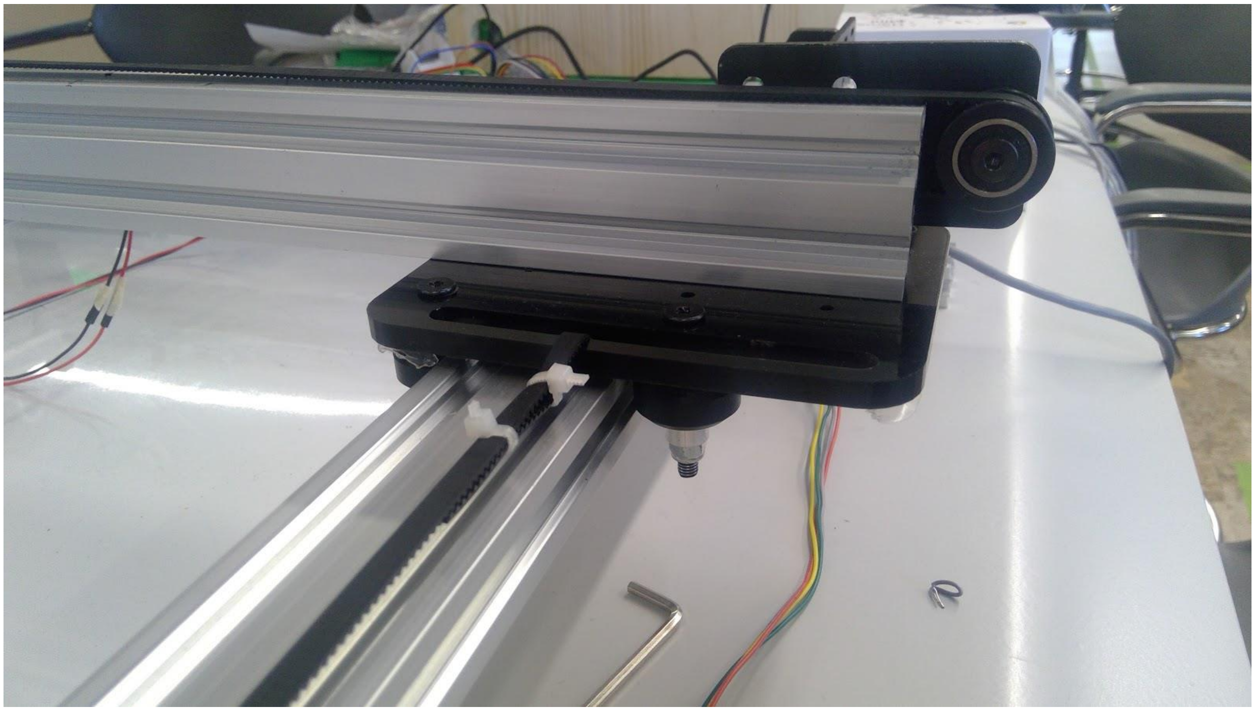

Figure 11: Major axis gantry cart and minor axis smooth idler

Next, limit switches were attached to the ends of both axis, as seen in Figure 12. These were used to determine when the cart had reached the end of the rail, establish the origin and allow the pen to be oriented.

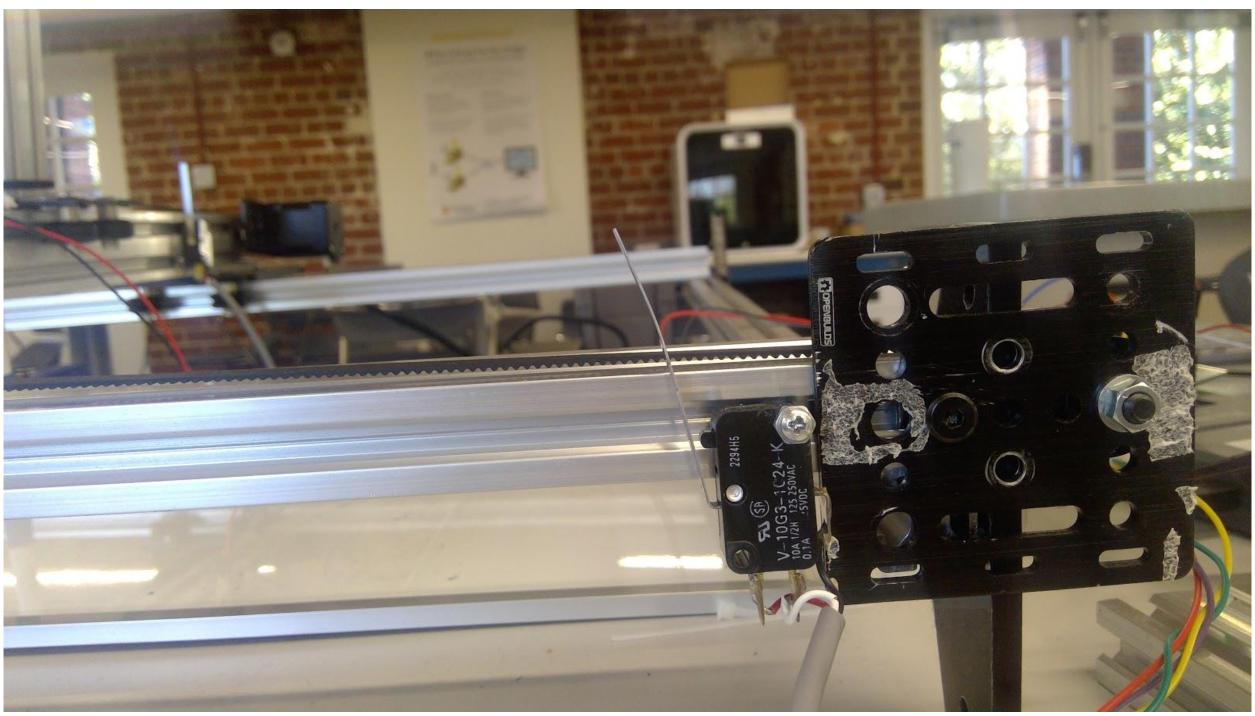

Figure 12: Limit switch

Lastly, a solenoid was bolted to an aluminum rail attached to the top gantry cart that traversed the minor axis (Figure 13). A pull up solenoid was used that lifted the pen whenever the device was not supposed to be drawing. It was powered by the printed circuit board.

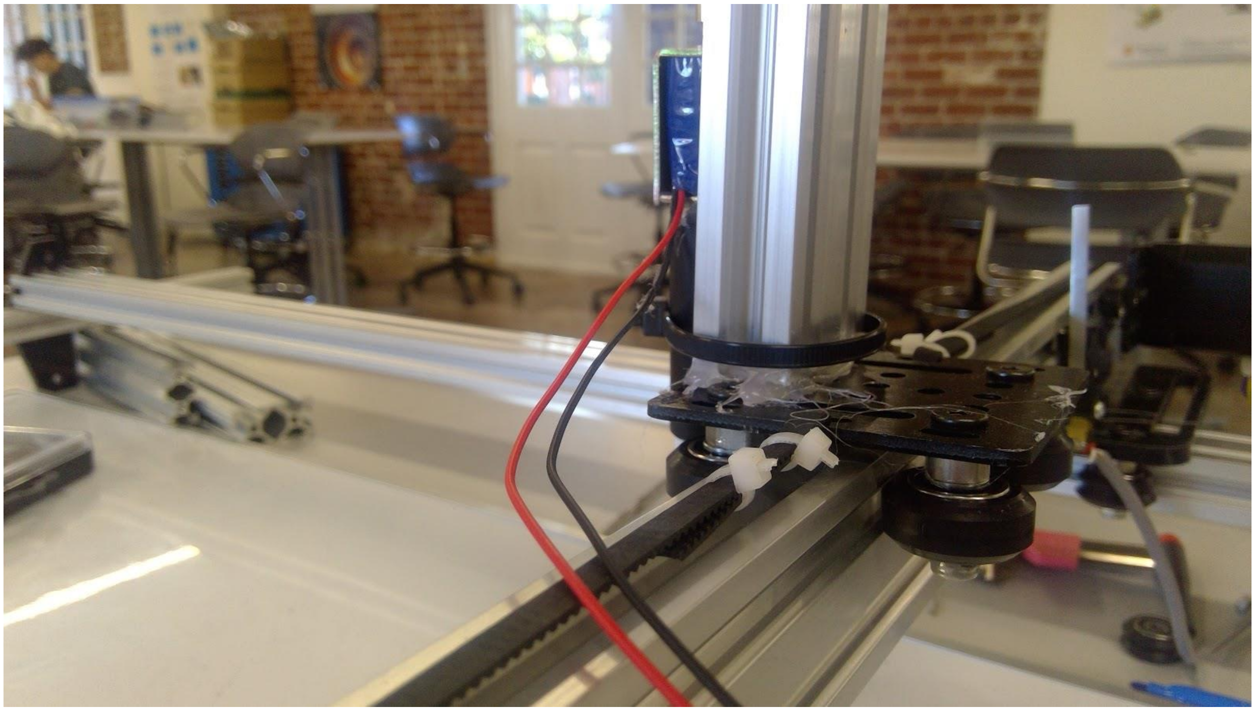

Figure 13: Solenoid set up on minor axis

One major design decision was determining the dimensions of the X-Y table. The size of the frame pieces had already been determined since they were recycled parts. However the point at which they were connected determined the drawing space of the device. Originally these rails were attached in a way that made the drawing space as large as possible so that the images produced would be big and visible. However, this made it difficult for the crossbar to remain straight and the bottom gantry cart on the side of the motor moved at a different pace than the bottom cart on the opposite side. This was later resolved by moving the attachment point inward and reducing the drawing space of the device by about 3cm.

Project Time Line

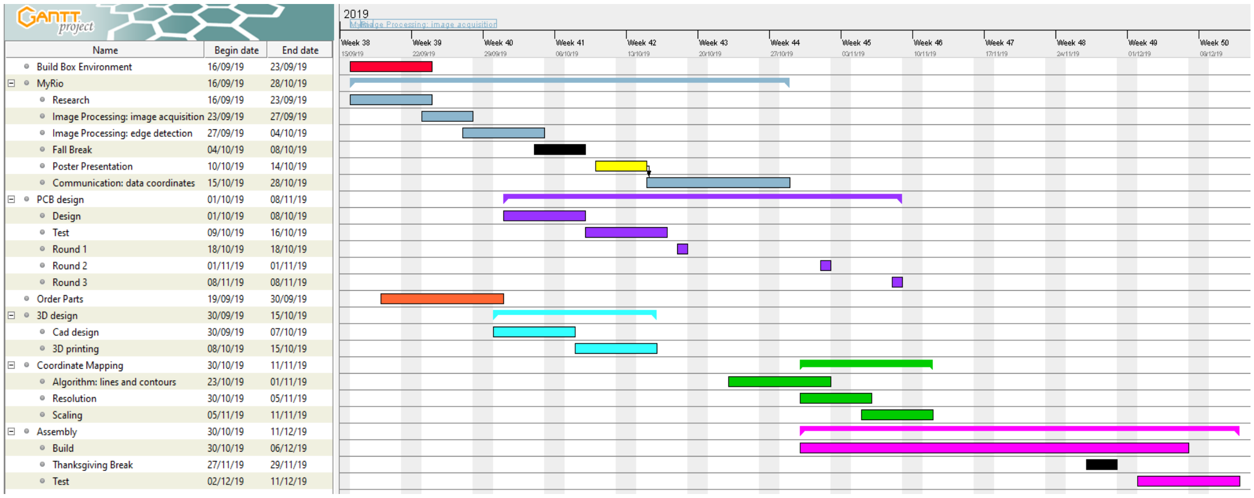

Figure 14: Proposed Gantt chart

Some tasks had to be completed before other tasks could begin. For example, the wooden lighting box had to be built before the green background could be attached and the green background had to be attached before checking testing the color filter code. The PCB had to be designed before the parts could be ordered and all the parts had to arrive before the PCB could be soldered together. Only once the PCB was soldered together could it fully be tested.

While there was a great deal of tasks that had to be completed serially, some tasks could be completed in parallel. For example, although we could not test the successfulness of the color filtering VI on our actual backdrop until the entire environment was finished, Emily was able to write the code and test it on green screen images from google. In addition while we were waiting for the PCB to arrive we were able to test some parts on a circuit board to make sure they were working for example the motors and limit switches.

The team was very successful in our approach of divide and conquer and doing so we were able to work successfully in parallel. During the first two months everyone was focused on their primary tasks. Sammy was working on the lighting box and X-Y table, Emily was creating LabView code for edge detection and image processing while Maansi was designing the board and soldering it together. All the while every week we were meeting to discuss progress and ensure each individual was staying on task. In November we began putting our separate systems together, beginning by connecting the LabView code to the myRIO and the myRIO to the PCB. once that was working we connected the PCB to the X-Y table. Finally we added in the cameras and lighting box. In December we made some last-minute adjustments to the color thresholds. This is also when we made the decision to switch from a marker and paper to dry erase boards. The day before demo day all the team had left was to make some adjustments to the height and stability of the pen.

There were a few changes to the timeline created in the proposal and they are outlined in the figure below. The first was a delay of finishing touches to lighting box. This was largely due to the fact that the team could not decide on the type of LEDs to purchase. Ultimately, we decided to buy a multicolor LED strip from Walmart and set it to yellow. The next addition was a period of LabView debugging, but this was not unexpected and should have been foreseen in the original chart. Next we added a period for additional PCB testing this was left out in the proposed Gantt chart because the team was not positive when we would receive the board from testing. Once the board came in we were able to update the chart. Then next change we made was to add in another parts order, since we decided to implement a solenoid to hold the pen later in project it was not order with the first round of parts. Lastly time was reserved to make the final adjustments to the color thresholds, magnification, starting points and pen height.

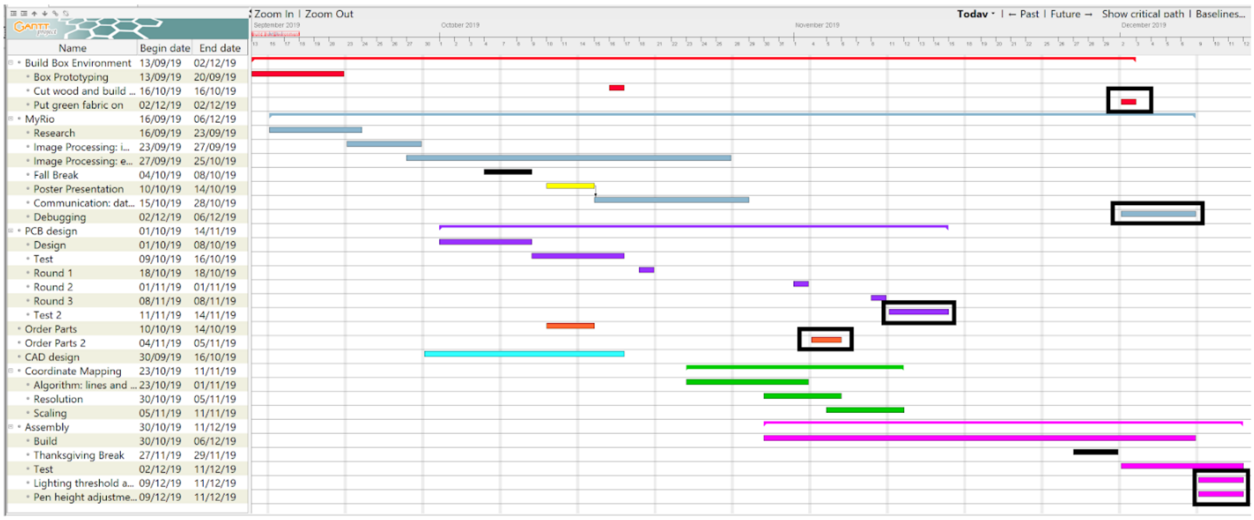

Figure 15: Final Gantt chart

Test Plan

Our test plan was defined in parts. The first thing that was tested was the effectiveness of the image processing. Before having the lighting box together, we tested the image processing by finding images online and putting it through the processing VI to make sure nice edges could be extracted from them. Next, once the first iteration of the board arrived, we tested the motors by just trying to get the gear on them to turn with a forward and backward step VI. Once it was tested that the motors could move individually, we attached the timing belt and pulley system to it to get the carts moving on the X-Y drawing table. Once the carts could move in both directions with the movement of both motors, we tested to see if the cart could move to a set of coordinates like a square. Next, we tested to see if the cart could move to a more complex set of coordinates like the outline of an actual image. Once the second and final iteration of the board arrived, the limit switches and solenoid were tested, and then the whole drawing table was tested again by seeing if the limit switches could be set as the "home" coordinate for the cart, and by testing if the solenoid could follow the steps of being pulled up, moving to the beginning of a set of coordinates, put down through the drawing of the coordinates, then pulled up again. That was the last piece of ensuring the whole table worked. Finally, we attached a pen to the solenoid, built the lighting box, and started refining the image processing and the pen pressure on the board to make sure that precise outlines could be drawn.

Final Results

We were able to meet all of the success criteria defined in our proposal. Using image processing, the device was able to employ machine vision to detect the edges of an object. It was then able to map those edges to a set of coordinates in an order that could be drawn by the robot. Using the limit switches as an origin point, the robot was able to move to a set of coordinates. Finally, the robot was able to draw the edges of the object at a set of coordinates.

There were some aspects described in our proposal that changed in the final product. In our initial proposal, and based on testing by the midterm design review, we expected that there would be three separate sections of LEDs in the box, and they would be turned on separately from each other to improve our image processing. In our final product, there was only one continuous string of LEDs, but we were still able to process the image effectively. Our proposal also provided for more complex programming with the box, including a turntable that would rotate the object 90 degrees and reduce the number of cameras needed. In the interest of simplicity, we did not use a turntable, as that would require an extra motor and more PCB work. Despite those changes, our final product met our defined success criteria.

Costs

Our estimated cost for a single unit is about $2,045. Much of this is due to the cost of the myRIO, cameras, and other technologies. We estimate that if mass-manufactured at 10,000 units, the cost per unit will decrease to around $1,833. This is still a very large cost, and does not include any of the labor needed to assemble the device. Replacing human labor might reduce costs, but it would still be a very expensive product at well over $1,500. If we truly wanted to manufacture this device in large quantities, it would be necessary to replace the cameras and microcontroller with other, cheaper options. A full analysis of our costs can be found in the Appendix.

Future Work

As an extension of our project, it would be nice to automate the image selection process. We encountered difficulties with taking and saving images from the camera, which prevented us from fully automating the process. The project could also be scaled down, for purposes like etching. Many parts of the project, such as the parts selection, image processing, and motor control could be streamlined and made more user-friendly.

A major issue we encountered was with designing the solenoid that raised and lowered the pen. We originally planned to use paper as the writing surface, but quickly found that the drag of the pen was difficult to manage, and switched to a white board. We still had problems with pen drag, which resulted in some of our images not being fully drawn, or drawn off to the side. We determined that this was mostly a mechanical issue, but solving this problem programmatically could be an interesting extension of our project.

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Appendix

A. Detailed cost list

Part	Quantity	Cost Each	Total Cost	Status	Unit cost/10k	Cost for 10,000
MyRio 1900	1	$1,136.00	$1,136.00	Borrowed	$1,022.40	$10,224,000.00
LifeCam camera (x3)	3	$100.00	$300.00	Borrowed	$90.00	$2,700,000.00
MyRio X-[HUB]	1	$289.29	$289.29	Borrowed	$260.36	$2,603,610.00
Pine wood	1	$50.00	$50.00	-	$35.00	$350,000.00
OpenBuilds Nema 17 stepper motor (x2)	2	$18.00	$36.00	Reused	$16.20	$324,000.00
20mm x 20mm x 61cm rail	1	$6.40	$6.40	Reused	$5.76	$57,600.00
20mm x 20mm x 69cm rail	1	$6.40	$6.40	Reused	$5.76	$57,600.00
20mm x 40mm x 101cm rail (x2)	2	$11.19	$22.38	Reused	$10.07	$201,420.00
20mm x 40mm x 66cm rail	1	$5.59	$5.59	Reused	$5.03	$50,310.00
20mm x 40mm x 10cm rail	1	$3.19	$3.19	Reused	$2.87	$28,710.00
Self tapping W9-14 x 30mm screws (x4)	4	$0.25	$1.01	-	$0.10	$4,000.00
M5 x 10mm bolt (x11)	11	$0.15	$1.49	Ten purchased, one reused	$0.05	$5,500.00
M5 x 16mm bolt (x4)	4	$0.20	$0.78	-	$0.10	$4,000.00
M5 x 25mm bolt (x10)	10	$0.16	$1.62	-	$0.05	$5,000.00
M5 x 40mm bolt (x4)	4	$0.31	$1.22	-	$0.10	$4,000.00
M3 x 18mm bolt (x5)	5	$0.21	$1.03	-	$0.10	$5,000.00
M2 x 10mm bolt (x8)	8	$0.29	$2.32	-	$0.10	$8,000.00
W8 x 40mm screw (x24)	24	$0.07	$1.69	-	$0.01	$2,400.00
M5 nut (x14)	14	-	-	Reused		$0.00
M5 6mm spacer (x16)	16	-	-	Reused		$0.00
M5 washer (x18)	18	-	-	Reused		$0.00
M5 Double Tee Nut (x9)	9	$0.31	$2.76	-	$0.10	$9,000.00
M5 Tee Nut (x5)	5	$0.60	$2.99	-	$0.20	$10,000.00
ACRO Acrylic Plate Set	1	$26.99	$26.99	-	$27.00	$270,000.00
GT2-2M Timing Belt (12 ft)	13	$2.49	$32.37	-	$2.49	$323,700.00
20 Tooth Timing Pulley	1	-	-	Reused		$0.00
30 Tooth Timing Pulley	1	$6.99	$6.99	-	$7.00	$70,000.00

4” cable ties (x9)	9	-	-	Reused		$0.00
M5 ball bearing smooth idler pulley (x2)	2	$5.99	$5.99	One purchased, one reused	$6.00	$120,000.00
V-10G3-1C24-K limit switch (x2)	2	$2.43	$4.86	Reused	$1.26	$25,187.00
Solenoid	1	$7.50		-	$7.50	$75,000.00
Hinges (+ 4 screws)	1	$4.37	$4.37	-	$4.37	$43,700.00
Handle (+ 2 screws)	1	-	-	Reused		$0.00
LED lights	1	$29.94	$29.94	-	$29.94	$299,400.00
Whiteboard and Dry erase marker (x2)	2	$9.76	$19.52	-	$9.76	$195,200.00
Connection/jumper wires	1	$1.95	$1.95	-	$1.95	$19,500.00
AC-DC 240V to 15 V adapter	1	$11.62	$11.62	-	$8.35	$83,524.00
DC Barrel Jack	1	$1.39	$1.39	-	$1.08	$10,811.00
12V, 5V, 3.3V voltage regulators	4	$0.46	$1.84	-	$0.31	$12,400.00
DRV8848 Dual H-Bridge Motor Driver (x2)	2	$1.53	$3.06	-	$0.65	$12,953.00
Power N-Mosfet	1	$0.92	$0.92	-	$0.36	$3,625.70
2 pin connector (x3)	3	$0.33	$0.99	-	$0.13	$3,900.00
4 pin connector (x2)	2	$1.42	$2.84	-	$0.65	$13,047.40
2x17 pin connector for myRIO	1	$5.23	$5.23	-	$3.03	$30,305.00
Standard multipurpose test points (x7)	7	$0.35	$2.45	-	$0.14	$10,038.00
500 mOhm (x4)	4	$0.29	$1.16	-	$0.06	$2,288.00
10 kOhm (x5)	5	$0.10	$0.50	-	$0.01	$317.50
2.2 uF (x2)	2	$0.19	$0.38	-	$0.04	$792.60
500 pF (x2)	2	$0.46	$0.92	-	$0.12	$2,403.60
10 uF (x2)	2	$0.59	$1.18	-	$0.17	$3,482.00
0.1 uF (x2)	2	$0.26	$0.52	-	$0.06	$1,100.80
1N4001 diode	1	$0.10	$0.10	-	$0.02	$188.90
Green fabric	1	$4.46	$4.46		$4.46	$44,600.00
Final unit cost:			$2,044.69			$1,833.16