Creating a User-Controllable Pickleball Serving Machine

(Technical Topic)

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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

Advisor

Adam Barnes, Senior Lecturer, Electrical and Computer Engineering

Pickleball Machine Final Project Report

Statement of Work

Christian Bliss:

I began the project in charge of the initial STM32 ramp up and setup. For this, I learned the basics of how to operate in STM32CubeIDE, STM32CubeMX, and the TouchGFX GUI platform. This began with simply blinking the LED on the STM32 and writing block diagrams to map out the code. I eventually wrote template functions to drive the outputs to the motor and LED drivers, which Sharon adapted later to suit our project's updated needs. Throughout the project, I worked with Sharon and Clara to test the STM's outputs to ensure that the microcontroller properly interacted with the other components of our machine.

In the last month or so of the project, I worked a decent bit more with Clara and Sharon in pulling everything together. The three of us each did portions of soldering and desoldering, assembling extra structural details as necessary, debugging hardware problems, and testing our machine's functionality. The last few weeks of doing this took up the largest portion of my time spent on the project, as there was a lot of debugging that needed to be done.

Clara Li:

This semester, I was in charge of our PCB design. I first selected the initial circuit components to be able to control the speed and direction that our motors are spinning in. I initially had decided to use the SN754410NE motor driver to control all our motors and linear actuators, but because this motor driver was only rated for up to 1A of output current, it didn't end up supplying enough current to power the launching motors. I purchased a new DRV8871 motor driver with a higher current rating of 3.6A, but there were persisting issues with powering the launching motors. I proposed the idea to instead try using TIP120 transistors as a means of controlling our motors, and this was ultimately a more successful option than sticking with the original motor drivers. After finalizing all circuit components, I routed the first version of our PCB. While the PCB was shipping, I did extensive testing of our circuit components on a breadboard with Sharon and Christian, and I found that many adjustments had to be made to the PCB. I didn't account for direct heat dissipation via the PCB by laying the transistor flat on the board, so I had to revise the board by making copper cutouts.

While working on the PCB design, I also worked with Sharon to build the frame for our launching mechanism using the metal beams that she had cut. There were also other smaller tasks revolving around mechanical assembly that I would help Sharon with, like cutting the acrylic for the casing and general reconfiguring and testing of our machine. Throughout the last quarter of the semester, I worked with Sharon to become familiar with the STM32CubeIDE and TouchGFX and used those to help set up base functions necessary for the states of our sliders to persist on the LCD. Sorting out the STM32 and the LCD allowed me to straighten out the PCB's pin mappings between the microcontroller, the LCD, and the available GPIO/TIM pins needed to send digital and analog signals into our circuit components.

Sharon Lu:

During the project, I was in charge of the mechanical construction of the pickleball machine prototype. I selected the parts for each of the subcomponents and designed how they would be constructed after considering feedback from the group. I sourced most of the mechanical parts from Amazon and Lowe's. I constructed the dispensing mechanism out of wood, a plastic bucket, and a flexible pipe. Then, I prototyped the launching mechanism with wooden beams as the launch frame. After thoroughly testing this, our group pivoted to using aluminum beams for added stability. I cut the aluminum beams at Lacey Hall to the precise lengths needed and helped Clara build the launch frame. To create the vertical adjustment mechanism for the pickleball machine, I sourced heavy duty fence hinges from Lowe's and a linear actuator from Amazon. To construct the horizontal mechanism, I purchased a double layered Lazy Susan from Lowe's and the same linear actuator for the vertical adjustment mechanism. I thoroughly tested these mechanisms to ensure that they met the desired specifications. For the casing, I measured out and cut the acrylic using the scroll saw in the NI lab, then drilled holes in the acrylic to mount to the beams. Once this was finished, I put all the subcomponents together.

After wrapping up the mechanical work, I pivoted to focus on the embedded development. I created a new user interface using TouchGFX and tested the functionality with the hardware button. After the front-end work was completed, I pivoted to developing the logic behind the launch parameter adjustments and drills. Working with Clara, I developed the framework to save user-selected launch parameters and have them persist on the front-end. Referencing the functions Christian had developed earlier in the semester, I adapted the code to satisfy the new GPIO output pins we had mapped on our PCB. I wrote the Quick Start and Drill functionality and thoroughly tested the outputs with the AD2 oscilloscope. Throughout the semester, I also helped to troubleshoot the electrical issues and test the PCB.

Table of Contents

Table of Figures

Abstract

Pickleball is a rapidly growing sport in the United States, gaining popularity within communities of all age demographics due to its ease of learning and social nature [1]. Studies have shown that adults experience numerous mental and physical health benefits when playing pickleball [2]. Because improving one's pickleball skills and endurance without a partner is challenging, the goal of our project is to design a functional prototype of a pickleball machine that launches balls to the player from across the net. The machine launches balls at a wide range of speeds and oscillates horizontally and vertically. The horizontal oscillation range is large enough to ensure full court coverage from the left corner to the right corner of the baseline, and the vertical oscillation provides up to four feet of ball clearance over the net. The machine also has an intuitive user interface, allowing the player to configure both speed, spin, and direction as well as select from pre-set drills.

Background

Pickleball has been the fastest growing sport in the United States for the past few years [1]. While the sport has similarities to tennis, pickleball players experience less physical stress when playing due to the smaller court and slower ball speed [2]. Pickleball has historically catered to older demographics, but this has begun to shift. A study conducted in August 2022 by the Association of Pickleball Professionals (APP) found the average age of avid pickleball players to be 34.8 [3]. Our team is capitalizing on pickleball's growing popularity among all demographics by building a pickleball machine that trains the user by shooting pickleballs from across the court at varying speeds and angles. This training companion serves to help the user improve their pickleball skills, hand-eye coordination, agility, and overall cardiovascular fitness.

Being able to practice rallies independently is difficult, and many pickleball training machines are expensive. Popular, highly rated pickleball machines such as the Erne and Pickleball Tutor Plus retail for $1799 and $1199, respectively. This steep price tag comes with many useful features, though. The machines can serve a variety of pickleball strokes including serves, groundstrokes, dinks, lobs, and drives. They also have different timing configurations and shot location customizations [4, 5]. A popular cheaper alternative is the Furlihong Launch Machine, which retails for around $200. Nevertheless, it falls short in critical aspects. The machine shoots balls at a maximum distance of 9 feet, which is a fraction of the 44-foot length of a pickleball court [6]. Additionally, the machine's vertical adjustment is manual, and it does not have a rechargeable battery [7]. Other do-it-yourself projects aim to provide cheaper alternatives, but these launchers lack automatic angle adjustments and ball reservoirs [8]. Those that have these features have a limited user interface [9].

The primary goal of this project is to enhance solo training by designing an affordable machine capable of launching pickleballs across the court at different speeds, spins, and angles. To increase the range of pickleball shots, our machine pivots horizontally using a linear actuator mounted to a rotating base below the metal launching frame. To adjust the vertical angle, a linear actuator pushes and pulls the launching frame about two hinges. Two motors spin concurrently to eject pickleballs, and the varying speed of the two motors allows for different types of shots such as topspin and backspin. Our machine also has an LCD screen interface so users can control the ball trajectory more precisely.

For our pickleball machine to deliver on its training features, our team ensured that the mechanical components of the project integrated seamlessly with the embedded and electrical components. Knowledge of kinematics from Physics I for Engineers was used to calculate the specifications for the motors and the angle they should be mounted. Background from Introduction to Embedded Computer Systems enabled us to interface with the hardware components and program our desired shot configurations. Finally, concepts from the Electrical and Computer Engineering Fundamentals series were used to design the PCB that powered our motors and linear actuators.

Societal Impact Constraints

Ensuring the public health and safety of all stakeholders in the development of the pickleball machine is not only a priority from an ethical standpoint but also crucial to mitigate potential legal liabilities. From a public health perspective, the machine's design incorporates features that minimize the risk of injuries or accidents during its operation. Being a device that is marketable to a large age range, the instructions are clear, and the user interface is simple. The circuitry has been enclosed with an acrylic case to protect the user from any hazardous electrical connections or moving parts. Additionally, because this machine is intended for outdoor use, the casing also ensures a slight degree of protection against water splashes and small amounts of dirt or debris. The machine will also have a warning stating that users should not stand in front of the machine during operation and should keep clear of any moving mechanical components.

Environmental sustainability is an important factor in today's market. The machine uses a rechargeable sealed lead-acid battery, which, according to the United States Environmental Protection Agency, must be disposed of properly through retailers with battery disposal services or local collection programs [10]. The supports and joints on the machine are aluminum, which are recyclable. The pickleball machine also has a few plastic components, such as the ball hopper, polyvinyl chloride (PVC) ball guide, launching wheels, and acrylic casing. PVC is a group 3 plastic, and acrylic is a Group 7 plastic. These plastics are recyclable, but the process is difficult, so some recycling plants do not recycle them [11, 12]. The rest of the materials used cannot be recycled.

Economic factors impact the manufacturers, distributors, and end users of the pickleball machine. The concerns of manufacturers and distributors revolve around production costs, quality control, and supply chain management. The production costs should be managed effectively without compromising the safety or quality of the machine. It is also crucial to ensure that the production costs can be covered by the retail price without compromising the machine's affordability. The end users of the machine include players who competitively or casually play pickleball and are interested in improving their skills. Their expectations include the machine's price and value, ease of use, performance, and durability. Coaches, trainers, and owners of pickleball facilities will also have similar expectations of the machine. This is because the machine's effectiveness directly impacts their training programs.

Physical Constraints

The budget for developing a functional pickleball machine was $500. This cost constraint was a challenge to work around due to the number of mechanical components that needed to be purchased for prototyping. A tradeoff that we had to make early on to alleviate some room in the budget was using existing components in the lab. For example, one of the cost constraints revolved around the launching motors. Because of the nature of the project, our machine needed to shoot pickleballs 44 feet, which is the length of a pickleball court [6]. We were able to find motors that satisfied our speed needs, but we were unable to find proper datasheets for these motors, so we had to work around certain issues regarding current and voltage draw differently than we would have if we knew the specifications.

Another constraint that arose was the limited selection of off-the-shelf parts that were suitable for our prototype. While certain components, such as the dispensing bucket, PVC elbow ball guide, and metal beams, were easily modified using power tools, others were not. Sourcing light wheels with the correct outer diameter and hub diameter for the launching mechanism was a major challenge. The wheel options from manufacturers were dense, rugged, and designed to carry heavy objects, which did not align with our project's needs.

When looking for motor drivers for our launching motors, we ran into a couple of issues with physical constraints. Our first motor drivers were not rated for a high enough current, so we ordered new ones that we expected to be able to produce enough current to spin the wheels. However, the driver was operating close to the higher end of the maximum current output, so it did not perform the way we needed it to. To remedy this, we pivoted to using transistors to drive the motors. These had much higher current output ratings than the motors required, so they performed as needed. Due to the high power draw of the heavy rubber launching wheels, however, the transistors would still heat up beyond their operating temperature. As a solution, we ordered much lighter launching wheels, made of plastic and foam, which mitigated the heat problem.

In terms of supplies, it was difficult to anticipate how the work schedule would be affected by part order delays. This persisted both when ordering parts through the class orders, as well as ordering them ourselves. As a result, there were times when we needed to test but did not have the necessary supplies, so we were left to wait. When we ordered the PCB, the supplier we used required a 5-board minimum, meaning that we had four extra boards that went unused. Additionally, due to the high current draw of our motors, ordering PCBs capable of dissipating high amounts of heat was crucial. Given the budget constraints and limited ground plane options, we had to settle with a 2 oz. copper ground plane.

Development Tools

KiCad was used to design the schematic and construct the PCB. Because this was a new tool, there was an initial ramp-up process to become familiar with it. However, because the KiCad schematic builder was like Multisim's, and its PCB designer was similar Ultiboard's, the learning process was straight forward. The design was then exported and verified through Free DFM to ensure that there were no design flaws. The embedded system was designed for the STM32 NUCLEO-G071RB microcontroller, so the programming was completed through the STM32CubeIDE. Because we did not have previous experience with this microcontroller, we had to learn how to configure pins and generate the PWM signals for driving the motors, which was made easier through the IDE's STM32CubeMX attachment. The code development was done in the STM32CubeIDE, and due to its similarities in layout to other IDEs, the IDE itself was easy to navigate. The software used to design the user interface and interactions within the LCD was TouchGFX Designer. This was also a new piece of software that we had to learn, and we did this by exploring the provided demo projects and watching tutorials. To test the functionality and outputs of the embedded code, the Digilent Analog Discovery 2 was used with the Waveforms software. During the physical testing stages of our machine, we used video analysis via the PASCO Capstone software to analyze the horizontal and vertical velocities of the launched ball.

External Standards

NEMA 3 guidelines were referenced to construct an enclosure to protect the enclosed circuitry from solid foreign objects and outside weather. While the pickleball machine is not advised to be used in wet conditions, there is a level of basic protection that the case offers if it starts to rain, and the machine must be moved to a safe location [13]. The enclosure also protects the user from moving mechanical parts. 16 CFR Part 1115 by the Consumer Product Safety Commission outlines requirements for manufacturers to indicate the potential safety hazards of their product [14]. The manual provided by Lob-ster Sports, a manufacturer of tennis and pickleball launchers, was referenced to determine which safety precautions were included in existing products [15]. Because there is an opening in the casing for balls to shoot out, written warnings advise against reaching into the machine's moving parts or standing in front of the machine since it can launch pickleballs at high speeds.

The pickleball machine is powered by a rechargeable 12V sealed lead-acid battery, which means that it is classified as a Class 1 circuit. Class 1 circuits are limited to 30V and 1000VA [16]. The IEEE Std 484-2002 outlines the safety standards of storing, mounting, and charging lead-acid batteries. It was crucial to ensure that the battery was safely stored and wired throughout the development of the pickleball machine [17]. All electrical components were used in accordance with their respective datasheets and manufacturer guidelines. This ensured that the components were able to handle the power requirements of the machine.

The PCB was designed to follow the standards set by IPC. Specifications for design considerations such as trace spacing and part spacing are implemented to prevent electrical interference and short circuits between adjacent traces. Trace spacing specifically refers to the distance between the conductive traces on the PCB. Our PCB falls under the category of a low voltage Class 1 PCB since we are running less than 50V through it and it's designed for a general consumer product. The IPC-2222 standard [18] for a Class 1 PCB recommends a minimum trace spacing of 0.25mm for low voltage applications, which is the same constraint we configured when designing our PCB. The IPC-2221 [19] standard further defines recommended constraints of component placement. For an operating range between 0V to 15V, the minimum clearance between external conductors was specified to be 0.13mm. This was reflected in the design of the PCB by implementing a design constraint of a 0.2mm clearance. Designing the PCB in accordance with IPC standards ensures the correct manufacturing of our board and eliminates electrical interference within our board.

Intellectual Property Issues

To assess the patentability of our pickleball training machine, it is essential to consider existing patents that encompass similar features. U.S. Patent 7,445,003 B2 filed on November 22, 2005, describes an "Oscillating Ball Throwing Machine" [20]. This patent is under Lob-ster Inc., which manufactures both tennis and pickleball launchers. Claim 1 is an independent claim that details a ball throwing machine with a moveable yoke assembly for throwing balls at different angles. This is coupled with a dual-motor assembly. The first motor moves the yoke to a nominal throwing angle, and the second motor vertically oscillates the yoke assembly. Claim 2 is dependent on Claim 1 and details at least two throwing wheels responsible for throwing the balls. Claim 10 is an independent claim that introduces a third motor for the yoke to move in the left and right directions. Our project shares some similarities with Claim 2, as it also has a dual-motor launch mechanism. However, our project distinguishes itself from Claim 1 and 10 in the way our vertical and horizontal launch angles are adjusted. Instead of using a motor coupled to the yoke to adjust vertical movement, our pickleball machine uses two linear actuators. One linear actuator tilts the launching frame about two hinges which adjusts the vertical angle. The other linear actuator pivots the turntable the launching frame is mounted on to adjust the horizontal angle.

U.S. Patent 9,937,400 B2 filed on December 31, 2015, describes an "Automatic Ball Pitching Machine" [21]. The patent owner is Thomas Hart. Claim 1 is an independent claim that outlines a ball throwing machine comprising of a base, support frame, at least one rotating wheel controlled by an electric motor, and a human-machine interface that allows the user to customize at least one launching parameter from the following: "drive wheel rotation speed, ball spin speed and direction, ball speed, and target location." Dependent Claims 2 through 7 hinge on Claim 1 and dive deeper into the user interface's visual aids, including visual aimpoints on a grid for baseball or softball. Our designed pickleball machine also has a base, rotating wheels controlled by electric motors, and an interface to customize the same launch parameters. However, the display options and customizations are different from the specifications in Claim 1, which means our project does not directly infringe on this patent.

Finally, U.S. Patent 5,125,653 titled "Computer Controller Ball Throwing Machine" was filed on October 25, 1990 [22]. Claim 1 is an independent claim that describes a tennis ball throwing machine with a microcomputer that can control the launch angle and speed. The microcomputer is able to calculate the placement of the ball using two target coordinates for calibration and trigonometric calculations. Claim 5 is an independent claim that describes the feed mechanism of the ball throwing machine consisting of a stirred ball container, a barrel feed tube with a piston, a gimbal to determine the movement of the ejecting wheels, and a strain gauge for measuring the physical characteristics of the ball. Our project distinguishes itself from Claim 1 and 5 because it does not employ sensors or a feedback mechanism to refine the ball trajectories. Additionally, our feed mechanism relies on the ball to grip onto the top wheel to launch, whereas the patented mechanism uses a piston mechanism to eject the ball.

Ultimately, the patentability of our pickleball training machine depends on how the independent claims are drafted to cover the unique aspects of our project. Under U.S. Code § 103, a patent examiner will be able to reject a claim if the invention is claimed as "obvious" [23]. This means that the examiner believes that combining multiple prior art references would lead to the detailed invention, and that a person skilled in the art would be able to reach this conclusion. However, there does not appear to be a patent that details the use of two linear actuators to adjust the vertical and horizontal launch angles. We would be able to combine this unique element of our project with the user interface and mechanical components in the launching mechanism to form an independent claim that is eligible for a patent.

Project Description

Performance Objectives and Specifications

To help the user hone their skills, the pickleball machine has been designed with flexibility in mind. The user can adjust the horizontal and vertical launch angles via sliders on two customization screens on the LCD interface. The vertical launch angle varies from roughly 15º to 50º. This covers a shot range from groundstrokes to lobs. Providing this vertical range is also sufficient in configuring a minimum of 4 feet ball clearance over the net. Additionally, the dual-motor launcher swivels 17º in each direction horizontally, providing a complete left to right range of 34º. This range has been expanded from the original specifications of 25.6º to increase court coverage of our launched balls. The horizontal range of motion has been maximized to ensure that the launching mechanism is able to swivel as far right and left before the launched ball interferes with the casing. Because the pickleball machine sits on the other side of the court from the user, this range of motion enables the machine to launch balls to each corner of the user's side of the court.

In addition to a wide range of ball trajectories, the ball can travel with different spins and speeds. This is executed by the dual-motor launcher, and the user can change speed and spin via sliders on two more customization screens. When the top motor spins faster than the bottom motor, the ball will rotate backwards when launched producing backspin. When the bottom motor spins faster than the top motor, the ball with have a forward spin creating topspin. The relative motor speeds were determined by analyzing the physics of a tennis ball with topspin and backspin [24]. The speed of the launched ball varies from around 15 to 35 mph. This has been measured using the PASCO Capstone software. The speed of the launched balls has been modified from the original specifications due to limitations with heat regulation for the launching motors. Due to the high current demand for the motors and budget constraints with the PCB, the duty cycle driving the launching motors shouldn't exceed 70% without overheating on a 2 oz copper ground plane. To account for the safety of the user, the original range of 15 to 50 mph was modified accordingly.

Another important feature to vary is the ball feed rate. The user will have time in between each ball launch to return the ball and prepare for the next. This is also a feature that is valuable for pickleball coaches if different players are taking turns returning shots. The motor on the dispensing mechanism will have an adjustable speed through the user interface to allow for balls to come from every 3 to 4 seconds. This has changed from every 5 to 10 seconds, as originally specified in the proposal, due to the specifications of the final motor selection. At a 100 percent duty cycle, the dispensing motor spins at 20 rpm, which dispenses a ball every 3 seconds. The motor is not powerful enough to dispense balls at below a 70 percent duty cycle, which is a dispensing rate of around 4 seconds.

An additional extra feature added to the pickleball training machine is the ability to run predesigned drills where the machine shoots a ball to a specific area of the court with a predetermined speed and spin. There are three drills at varying difficulties that allow the user to practice a wide variety of shots.

The pickleball machine is compatible with indoor and outdoor pickleballs. There is no difference in diameter between these pickleballs [25]. The ball hopper on the pickleball machine has a capacity of over 30 pickleballs. The capacity has increased since the proposal because a 5 gallon bucket was used for the hopper. For portability and convenience, the pickleball machine will be battery powered and can launch the full capacity of pickleballs in the machine before needing a battery replacement. The pickleball machine also features a custom-cut acrylic casing to protect the user from machinery and provide a degree of waterproofing. The machine also features lockable caster wheels for easy transport.

Functional Overview

Figure 1 shows an overview of the project architecture. The machine will be powered by a 12V rechargeable battery, and an STM32-Nucleo microcontroller will handle the control systems. The PCB is responsible for supplying power to different mechanical components, regulating the speed and direction of the motors and linear actuators, and ensuring that the board itself does not overheat. The microcontroller will run the internal logic for the system, controlling the dispensing frequency, launch speed, spin, and trajectory of the balls. It will also interface with the LCD screen where the user will select different settings or drills.

Figure 2 provides a detailed look at the computer aided design (CAD) model and prototype of the mechanical components of the training machine. A disk rotates at the base of the ball reservoir knocking pickleballs into the chute that feeds into the metal launching frame. Two motors spin concurrently to eject pickleballs, and the varying speeds of the two motors will allow for different types of shots such as topspin and backspin. The first linear actuator is mounted to the rotating base below the metal launching frame. As the actuator extends and retracts, the launching mechanism pivots horizontally. The second linear actuator is mounted to the metal launching frame. As it extends and retracts, it pushes and pulls the frame about the hinge which increases or decreases the vertical launch angle.

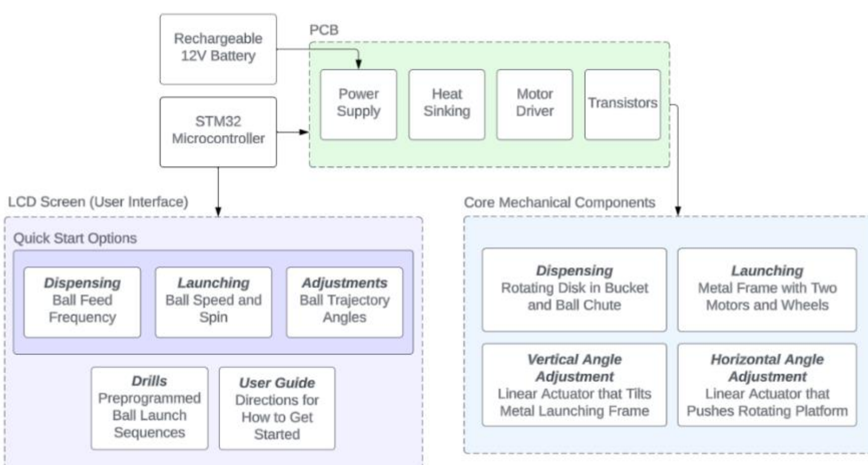

Figure 1. Pickleball Training Machine System Architecture

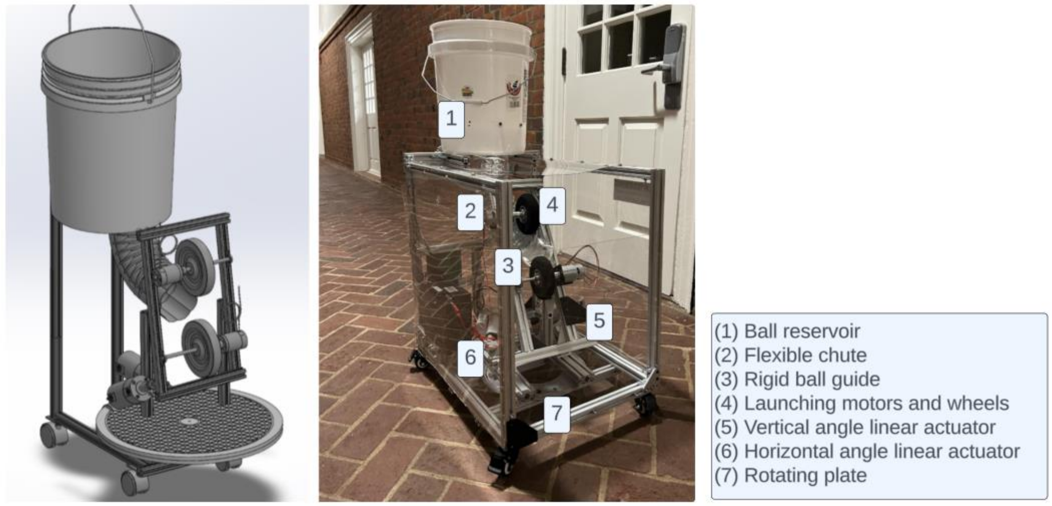

Figure 2. Pickleball Training Machine Mechanical Design

Figure 3 shows a block diagram of the user-interface screens and the button navigation. Figure 4 shows the logic behind the horizontal and vertical angle adjustments, where the light purple process blocks are where the GPIO pins are set. Figure 5 shows the processes executed on the Quick Start and Drills screens.

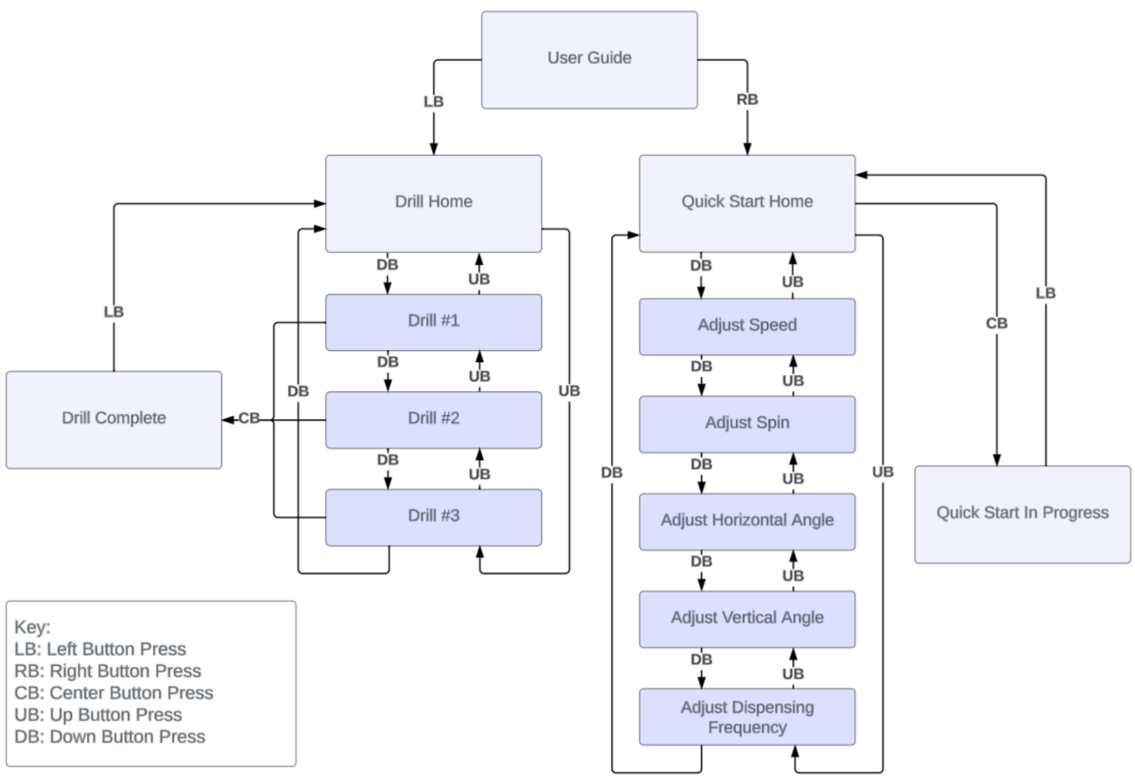

Figure 3. Block Diagram for User Interface Screens

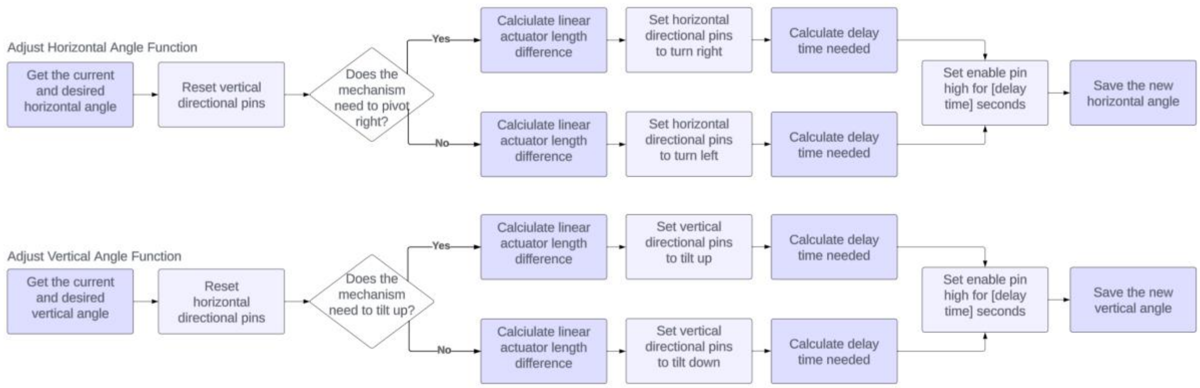

Figure 4. Block Diagram for Horizontal and Vertical Adjustments

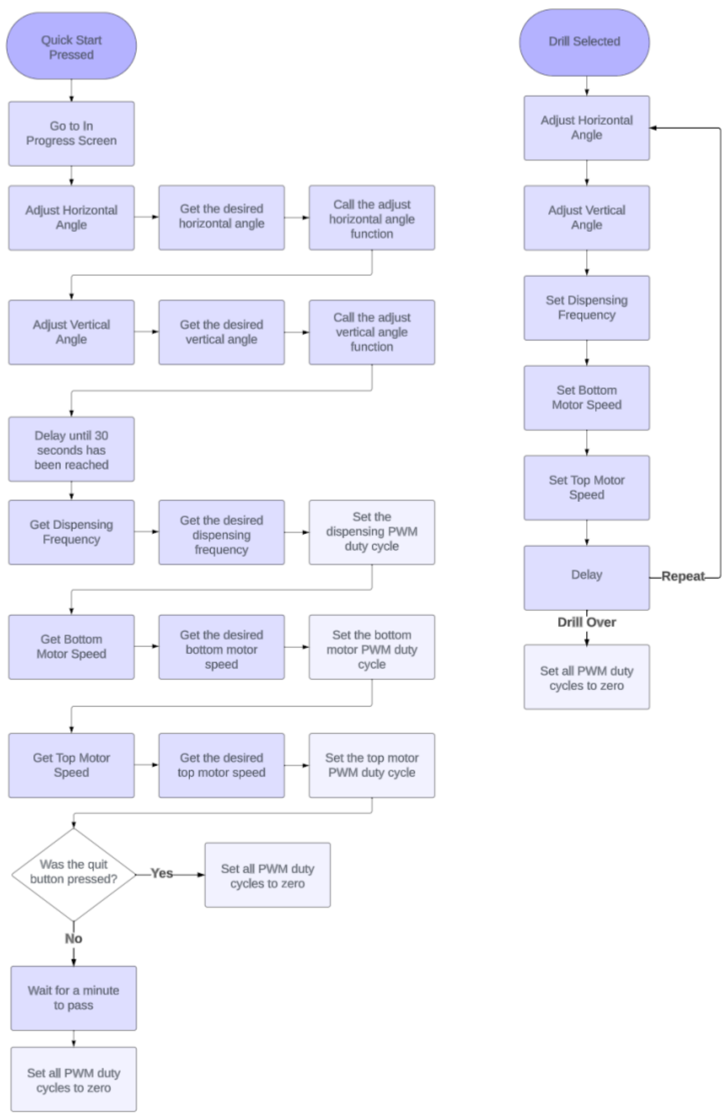

Figure 5. Block Diagram for Quick Start and Drills Process

Figures 6 and 7 show the circuit schematic and the designed PCB, respectively. The main purpose of our PCB is to route power to the respective motor drivers and transistors that we are using to power our linear actuators and motors. We use 10A rated transistors to control the speed of our launching motors, and because they draw a higher amount of current to spin up to speed, we included copper cut outs on the silkscreen for heat dissipation. When considering heat dissipation, we also designed the PCB with a ground plane.

We ultimately ran into issues with our SN754410NE motor driver overheating when trying to control the horizontal and vertical linear actuators. To address this issue, we decided to use a DRV8871 motor driver, which is rated for up to 3.6A of current. Because we caught this issue at the end of the semester, we didn’t have time to redesign and order a new PCB, so to integrate these new motor drivers into our current PCB, we redirected the digital signals and power traces from our PCB into separate breakout boards containing the new motor driver chips. The schematic of the manufacturer’s designed breakout board is shown in Figure 8 [26].

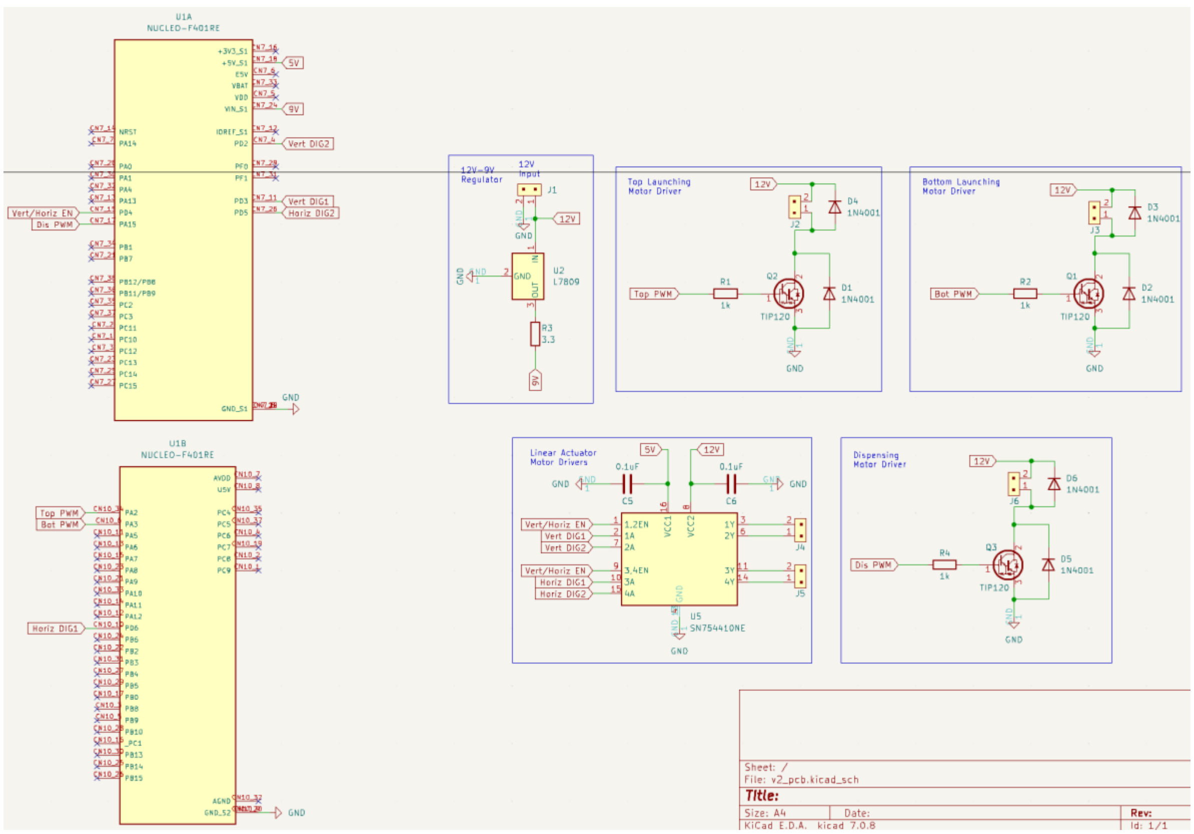

Figure 6. Circuit Schematic

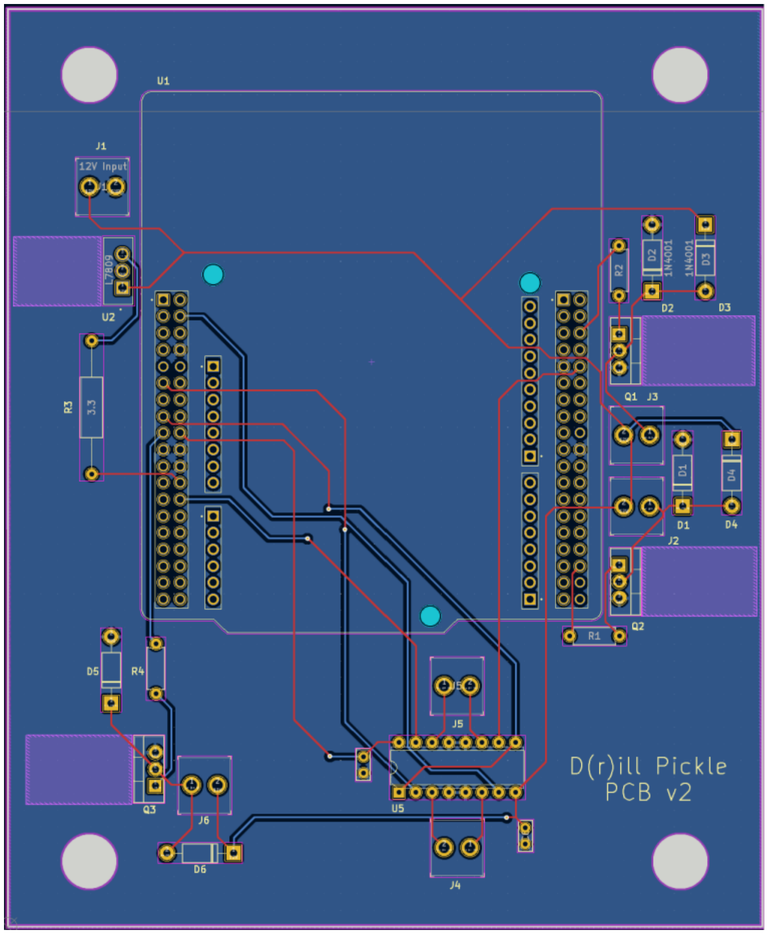

Figure 7. Designed PCB

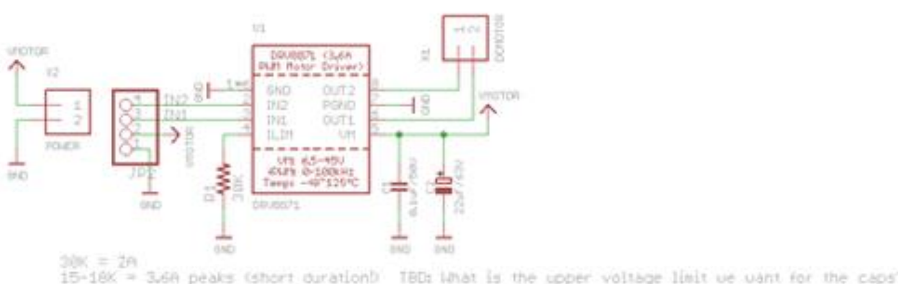

Figure 8. Schematic of DRV8871 Breakout Board

Technical Details

The design we ultimately decided to move forward with when dispensing the ball from the hopper into the ball launcher was using a rotating disc with two circular holes large enough and deep enough to securely hold a pickleball. The disc continually rotates in a clockwise direction for as long as the ball machine is in use. This ensures that all the balls in the hopper are consecutively fed at equal intervals into the flexible chute leading into the launching mechanism. Previous design considerations for this feature included incorporating a waterwheel which bridges the gap between a ball chute and the launching mechanism. We pivoted away from this design due to concerns regarding building this custom-sized component, as well as space concerns for another motor-driven component. We also wanted to have the dispensing mechanism incorporated within the ball hopper rather than as an external piece.

When designing the pickleball machine, we used two motors with a higher RPM for our rotating ball release mechanism. It was necessary for us to choose a strong motor to launch the ball up to an appropriate speed for it to travel over the net. The specific model of motor that we used is the RS775-6718 DC brushed motor. The operating voltage range of this motor is DC 12 to 24 V, and a minimum of 10000 RPM is produced under no load conditions when being powered by a 12V DC source [27]. We determined that the strength of this motor satisfies our requirements by drawing comparisons from a previous ball launching apparatus designed to train cricket players. This apparatus utilizes the Bola Professional Cricket Bowling Machine which has a launching mechanism dependent on two brushed DC motors [28]. These motors run at 4500 RPM, and the machine can launch a 163 g cricket ball up to 95 mph [29]. This demonstrates the adequacy of using a RS-775 DC motor for our launching mechanism, since the mass of a standard pickleball is typically around 24 grams, which is significantly less than that of a cricket ball, and we only need to launch it at a maximum speed of 50 mph. Further calculations with regards to power were verified to ensure that the power of our selected motor is enough to generate the maximum speed at which we want to launch the ball.

For ease of calculation, we are assuming that the ball has an initial kinetic energy (KE) of 0 J. However, because the ball will be travelling down a chute to be fed into the rotating ball release mechanism, it will carry a small amount of kinetic energy. This initial energy is negligible when considering the energy used in the overall launching mechanism since most of it will be generated by the two rotating wheels. The calculation of power requirements will consequently be slightly overestimated but will still be the conservative approximation. Continuing with the assumption that $KE_0 = 0$ J, the required energy will be generated by the rotational kinetic energy of the two stacked wheels. The initial amount of energy that is needed will be calculated using:

$$KE_0 = \frac{1}{2} I_{r1} \omega_1^2 + \frac{1}{2} I_{r2} \omega_2^2$$

Where the moment of inertia for a rotating wheel about a symmetrical axis is determined to be $I_r = \frac{1}{2} m_r r_r^2$ [30]. The wheels we intend to use for this project have a radius of 2.25 inches, which is equivalent to 0.05715 m, and have a mass of approximately 40 g [31]. The resulting moment of inertia for each wheel is $6.53 * 10^{-5} \frac{kg^2}{m}$. The angular velocity is calculated by considering the maximum linear velocity of 50 mph, which is equivalent to 22.352 m/s. Using $\omega = \frac{v}{r}$, the resulting angular velocity is calculated to be 391.1 rad/s. Knowing the moment of inertia and the angular velocity, we find that the required amount of kinetic energy is approximately 9.99 J. If it takes each ball at most a second to be launched, we need at least $P = \frac{E}{t} = \frac{9.99\,J}{1\,s} = 9.99\,W$ of power, and according to the datasheet of the RS775-6718 motor, when the motor is operating at maximum efficiency at 10000 RPM, it outputs 150 W of power [27], which exceeds the minimum amount needed to drive the launching mechanism.

We also need to consider the horizontal range of rotation of our machine in order to feed balls which cover the entirety of the court. For the lateral angle, we referenced the size of a standard pickleball court, which is 44 feet long and 20 feet wide [31]. Calculations for the angle of lateral rotation depend on the positioning of the ball machine in relation to the rest of the court. We assumed the ball machine would be placed directly behind the center of the baseline, as shown in Figure 3. There are two different lateral ranges to consider, denoted as θ_1 and θ_2. θ_1 represents the angle sweep between the left and right corners of the baseline on the opposing side of the court, and θ_2 represents the angle sweep between the left and right corners of the end of the no-volley zone on the opposing side of the court. We wanted to consider both ranges to accommodate for balls that can be launched at various distances along the court.

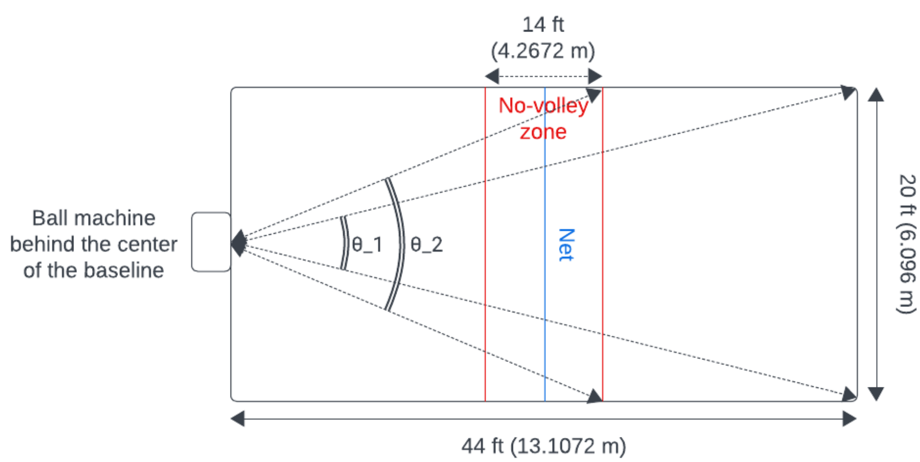

Figure 9. Aerial View of Court

The actual angles were calculated using simple trigonometry. The process to calculate both angles were the same, so we will only be detailing the calculations for θ_1. Because the ball machine is located behind the center of the baseline, we used $\tan^{-1}\left(\frac{10}{44}\right) = 12.82°$ to calculate $\frac{\theta_1}{2}$. This shows that the machine must be able to rotate $12.82°$ from a central position to either the left or right. This results in a total range of $25.6°$ to sweep the entirety of the baseline from across the court. Using the same process to calculate the range of θ_2 reveals that we need to accommodate for a rotation of $38.05°$ to cover the court between the left and right corners of the no-volley zone.

Further calculations were made to gauge the range of the vertical angle ϕ the ball machine needs for balls to be launched up to four feet over the net. A corresponding diagram is shown in Figure 4. According to pickleball court specifications, the net is required to have a height of 34 inches at the center and 36 inches at the side lines [31]. For the purposes of approximating the vertical range of our launch angle, all calculations were made with the assumption that the net has a height of 36 inches. This is a conservative approach, as it will not result in an underestimate of the angular range we need for four feet of net clearance.

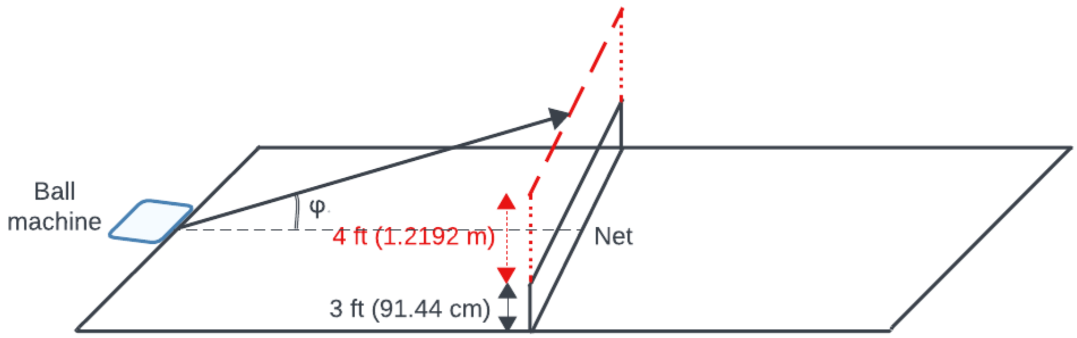

Figure 10. Side View of Court

These calculations were performed using the following kinematic equation:

$$v_y^2 = v_{y0}^2 + 2a_y(y - y_0)$$

We would like to calculate the angle the ball needs to be launched at for it to have an apex of four feet over the net while traveling at a launched speed of 50 mph or 22.35 m/s. Rearranging the above kinematic equation to calculate the velocity in the y-direction results in:

$$v_y = \sqrt{2gh} \text{ where } h = y - y_0$$

This is because there is no initial velocity in the y-direction, and the only contributing acceleration is the gravitational constant. The height that we want to use in this calculation is seven feet or 2.1344 meters when considering the net's height of three feet. This results in $v_y = 6.47m/s$. Because $v_y = v_0 sin\phi$, rearranging this equation in terms of ϕ results in:

$$\phi = \sin^{-1}\left(\frac{v_y}{v_0}\right)$$

The initial launch speed is $\mathrm{v}_0 = 22.35 \text{ m/s}$, which results in a launch angle of $\phi = 16.8°$ when plugged into the equation. This calculation was repeated to calculate the necessary angle for four feet of net clearance at the slowest the ball machine will launch the ball, 15 mph or 6.71 m/s. Additionally, vertical angle requirements were calculated at both maximum and minimum speeds for the ball to barely clear the net, which we determined to be at an apex of six inches above the net. Table 1 details all these results and shows that our machine needs to accommodate up to $74.8°$ of vertical angular adjustment to successfully feed balls up to four feet over the net.

Table 1. Vertical Angle Ranges

Launch Speed (m/s)	Height From Ground (m)	Vertical Angle, ϕ (°)
6.71	1.0678	43.1
	2.1344	74.8
22.35	1.0678	11.8
	2.1344	16.8

The last consideration to discuss is the PCB and our microcontroller. The PCB handles power conversion and management to the various motors. It also handles connections to external devices like the LCD display. The PCB has header sockets so the STM32 microcontroller can mount on top of it [32]. The power supply draws from an external power source, which is a rechargeable 12V battery, and it drives dependent electronic components, such as the microcontroller, motor drivers, and voltage regulators. We have chosen to use the BP20-12-B1 lead-acid battery as the power source [33]. It was important to design heat sinks in the PCB to preserve the performance of the system over long periods of time [34, 35]. This addition was especially crucial after observing the high temperatures our transistors reached after powering our launching motors for a few seconds. Our heat dissipation was done by using 2 oz copper throughout our board and designing a ground plane. Copper cutouts were also made on our PCB to allow the transistors to lay directly on the copper for better heat dissipation.

The LCD takes user input when the user toggles the button pad. The pad has four directional arrow keys and a select button. Depending on the configurations selected on the LCD, the microcontroller will output analog and digital signals to the PCB and direct power accordingly to the various components. To power the STM32 using our 12V battery, our solution was to step down the 12V to 9V, which falls within the supply constraints of the microcontroller. The specific voltage regulator that we chose to use for this was the L7809ACV regulator. There were no applied constraints to the current since the STM32 would only draw what was needed.

We also wanted to consider including a motor driver chip into the PCB to ensure that the amount of current being supplied to the motor is sufficient in powering it at maximum efficiency [36]. The amount of no-load current flowing through the RS775-6718 is 1.05 A, and this current will only increase as we add resistance to the motor in the form of a load. Therefore, the chip we choose must be able to maintain a constant current of at least that. We ultimately decided on the MJE2955T Power Transistor, which has an absolute maximum current output of 10A, well above what is needed. We initially encountered problems with this motor when we had an input PWM with around 50Hz frequency. After a lot of consideration, we determined that the low frequency was causing the transistors to heat up much faster than they should and burn up, so we increased this frequency to 10kHz, which solved the problem. For the dispensing motor, which only needs to run at 20 RPM, much less current was necessary. We decided to drive this motor with the MJE2955T as well to keep things simple.

In order to drive the linear actuators, we needed a part capable of changing polarity, as this is how the actuators determine whether to extend or retract. We chose the SN754410 Quadruple Half-H Driver, as we believed that the output current was high enough to drive, and their directional pins were useful to us because we could use them to switch the input polarity. Upon testing the linear actuators within our final setup, they began overheating which led us to believe that their current draw was higher than expected. As a result, we shifted to the DRV8871, a driver rated for 3.6A, which we believed would be high enough. This ended up being the case, and the two new motor drivers were able to provide enough current for their respective linear actuators to extend and retract.

Test Plan

The test plan outlined ensured that the pickleball machine functioned according to the specifications. The pickleball machine was expected to meet the following criteria: hold multiple pickleballs, feed one pickleball at a time to the launching mechanism, adjust the shot angle, direction, spin, and speed, and operate via a battery long enough to dispense all pickleballs held in the machine.

Embedded System Testing

Testing was done routinely during embedded system development. For each subcomponent, the basic functionality was verified by checking the GPIO output pins on the STM32 Nucleo development board with the AD2 oscilloscope. The following test cases were performed.

I. User Interface (UI) Navigation

Test Objective: Verify that the UI is comprehensible.

Procedure: Have a user unfamiliar with the control systems navigate the UI. Record any confusions or feedback.

Results: The user was easily able to navigate to all different screens with no prompting.

II. Launch Parameter Adjustments

Test Objective: Verify that the LCD screen reflects the adjustments to the ball feed speed, horizontal angle, vertical angle, shot spin, and shot speed. Verify that the selections persist on the screen when the adjustment screen is changed.

Procedure: Navigate to the Speed screen. Increase the value on the slider to the maximum value, then decrease the value on the slider to the minimum value. Then, move the slider to a value in the middle of the slider. Change to a different screen. Return to the speed screen to verify that the slider position has persisted. Repeat for all launch parameter screens.

Results: The screens can save slider data after toggling from the changed screen to another screen, then back to the changed screen.

III. Quick Start Outputs

Test Objective: Verify that desired launch parameters are reflected in the output pins once the center button is pressed on the Quick Start home. Verify that the Quick Start launch ends, either by the user pressing quit or the practice timing out.

Procedure: Adjust launch parameters. Navigate to the Quick Start screen, then press the center button. Read the output PWMs from the corresponding pins for the dispensing motor, top launching motor, and bottom launching motor with an oscilloscope. Verify the GPIO outputs for the motor driver pins with an oscilloscope. Press the quit button and check that all outputs and PWMs have reset to ground. Repeat the procedure, this time checking that all outputs and PWMs have reset to ground after a minute.

Results: The PWM and GPIO enable signals are exactly as they were planned to be, so they are ready to act as inputs to their respective mechanical components.

IV. Drills Outputs

Test Objective: Verify that desired drill is reflected in the output pins once the center button is pressed on the selected Drill page.

Procedure: Navigate to the desired drill screen, then press the center button. Read the output PWMs from the corresponding pins for the dispensing motor, top launching motor, and bottom launching motor with an oscilloscope. Verify the GPIO outputs for the motor driver pins with an oscilloscope.

Results: The outputs for the drill selected are as expected, set to enable each various component at different times as planned out.

The proposal did not originally outline a test case to verify the ease of use of the UI. Given that the machine is designed for people of all ages, this test was added to ensure that there was no unnecessary learning curve. The original UI plan was to have a series of dials to adjust the different launch parameters. However, after ordering the LCD screen and experimenting with the included hardware button and a series of sliders, the user controls were modified accordingly. A check for whether launch parameters persisted after the screens were changed was added to ensure that the user would be able to refer to previous changes.

The Quick Start and Drills Outputs test cases were not included in the original proposal. The inclusion of Drills was initially a reach goal, but we were able to incorporate this feature. The tests were added to ensure more thorough testing of outputs prior to system integration with the PCB. As a result of testing, both the duration of Quick Start routines and Drills were shortened to ensure that the transistors used did not overheat.

Mechanical System Testing

After the construction of each mechanical subcomponent, the durability and functionality of the subcomponent was thoroughly tested. The following test cases were performed.

I. Ball Feed Speed and Consistency

Test Objective: Verify that the machine can feed balls one at a time into the launching mechanism at the appropriate speed.

Procedure: Start the ball feed. Time the frequency of a ball falling into the chute. Check that this aligns with the feed rate set by the slider.

Results: The dispensing frequency accurately reflects what is expected, and only one ball is dispensed at a time.

II. Ball Compatibility

Test Objective: Verify that the standard ball can fit in the hopper dispensing mechanism, chute, and the launcher.

Procedure: Feed in one ball. Check that it can move through each stage unobstructed.

Results: The ball moves from the hopper to the chute unobstructed and is launched from there as expected.

III. Stability

Test Objective: Verify that the launch frame is able to withstand the motion of the high-speed wheels.

Procedure: Run the launching mechanism at varying speeds and angles. Visually check the state of the launch frame during operation and check the security of the screws after operation.

Results: The motion of the wheels does not affect the rest of the frame, and the little vibration that comes from them does not affect the stability of the launch frame or any part of the machine.

As a result of the Ball Feed and Ball Compatibility tests, different components materials were tested to see which one best fit the specifications. For instance, the dispensing motor started out as a 100 rpm DC brushed motor. This motor dispensed balls too quickly and was unable to operate reliably at a lower duty cycle. As a result, a 20 rpm motor was purchased. To prevent two balls from falling through the chute at once, we also installed two stopping rods above the opening. When constructing the chute, a gutter elbow was used initially. However, this was too stiff to move smoothly with the launching mechanism. As a result, an HVAC flexible heating duct was used instead. The original proposal test plan did not outline a test for launch A wooden launching frame was used in the initial prototyping. However, this did not provide the stability or flexibility of using aluminum beams, so the base materials of the machine were changed.

Electrical System Testing

The electrical components related to each mechanical subcomponent were tested thoroughly. The control circuits were breadboarded, but there were some limitations when testing the launching motors due to the high heat at which the transistors operated. The heat would cause the plastic on the breadboard to melt. Once the PCB was ordered, the components were soldered on, and the control system for each mechanical subcomponent was tested. These tests were not included in the original test plan because the specific PCB parts had not been selected.

I. PCB Power Connections

Test Objective: Verify that the power is routed to all components and the voltage readings going through each circuit component is as expected.

Procedure: Before connecting the PCB to any external motors or the microcontroller, connect the PCB to the 12V battery. Verify the voltage out of the voltage regulator is 9V. Verify that one terminal of the each launching motor and one terminal of the dispensing motor is 12V. Verify that VCC2 on the motor driver is 12V.

Results: The regulator successfully outputs 9V and inputs 9V into the STM32. The 12V battery is properly routed to one pin of each motor and linear actuator input.

II. Dual Motor Launchers PWM

Test Objective: Verify that sending different PWM signals through the base of the transistor alters the speed of the top and bottom launching motors.

Procedure: Power the PCB with the battery. Use W1 and W2 on the AD2 to send a PWM signal at a duty cycle of 60% to the top and bottom motors, respectively. After the speed stabilizes, decrease the duty cycle of W2 to 40% and observe the bottom motor slow down. Wait 2 seconds and repeat for W1 to observe the top motor slow down. Wait 2 seconds and set both W1 and W2 to a duty cycle of 0%. The motors should stop spinning.

Results: The motors properly respond to the varying duty cycles of the transistor's PWM input, with 60% being the fastest, 40% being slower than that, and 0% being off.

III. Dispensing Motor PWM

Test Objective: Verify that sending different PWM signals through the base of the transistor alters the speed of the dispensing motor.

Procedure: Power the PCB with the battery. Use W1 on the AD2 to send a PWM signal at a duty cycle of 100% to the dispensing motor. Wait 2 seconds and decrease the duty cycle to 80%. Wait 2 seconds and decrease the duty cycle to 0%. The motor should stop.

Result: The dispensing motor operates the fastest at 100% duty cycle, slower at 80% duty cycle, does not move at 0%.

IV. Horizontal and Vertical Activation

Test Objective: Verify that vertical and horizontal linear actuators only receive power when either IN1 or IN2 receive a digital high signal on the DRV8871 motor driver on each breakout board.

Procedure: Power the PCB with the battery. Direct the 12V from pin 8 of the previous SN754410NE motor driver into VM (pin 5) of both DRV8871 motor drivers. Ground the DRV8871 motor drivers to the battery ground. Using an AD2, set W1 and W2 to be a 3.3V DC signal. Feed W1 into IN2 of the motor driver for the vertical linear actuator (pin 2). Feed W2 into IN2 of the motor driver for the horizontal linear actuator (pin 2). Ground pin 3 on both motor drivers. Observe that both linear actuators are activated. Now set W1 and W2 to be a 0V DC signal. Neither of the linear actuators should be moving.

Results: The linear actuators behave as expected when fed a high signal into one of the inputs and a low signal into the other.

As a result of the initial testing of our electrical system, we realized that 9V was not supplying enough power to our dispensing motors for it to start churning out balls, even when the duty cycle was set to be 100%. Because we expect to also vary the dispensing frequency, we need to have some range to the PWM signals we can supply. To address this issue, we decided to reroute our power system and directly power our dispensing motor with 12V.

When powering our launching motors, we originally were using motor drivers. However, we had to pivot away from that due to the motor driver not being able to supply enough current to run our launching motors as fast as we needed them to run at. We also encountered many issues when trying to swap our original motor driver out for one that had a higher current rating. Ultimately, we decided to control the speed of our launching motors with NPN bipolar junction transistors. The transistors we are using in our board are rated up to 5A of current, which is more than enough for what our launching motors would be drawing.

The last significant change that we had to make was reorganizing the GPIO and TIM pins that we needed to use for our digital and analog signals. Because we encountered delays in the embedded system design, we didn't realize that some pins we were using for our circuit components conflicted with the pins that were needed for the LCD. There were also extensive issues with the available pins with regards to the peripheral they belonged to. Certain GPIO and TIM pins couldn't share the same peripheral without it disrupting the functionality of the entire LCD UI, so our pin selection became very limited. To remap the connections with what few functioning pins we had, we had to move the dispensing motor from a motor driver to a TIP120 transistor. This was a feasible solution because we realized we didn't need to vary the direction the motor turns in and just the speed. Making this switch then freed up two compatible GPIO pins that could be used for our linear actuators. Due to a previously unforeseen issue regarding overcurrent in the SN754410 motor driver, we had to pivot in favor of using two DRV7710 drivers. The new test plan for the two components is reflected above, and the switch was effective in providing enough current to the linear actuators.

Full System Testing

The following test cases will be performed for the entire system.

I. Machine Startup and Power

Test Objective: Verify that the machine can be turned on and the LCD screen turns on. Verify that the machine can be turned off.

Procedure: Turn the machine on. Verify that the machine and LCD display are on, and the LCD shows the user guide screen. Upon startup, the horizontal and vertical linear actuators should also be retracting to their maximum amounts.

Results: When the on switch is pressed, the STM32 turns on, as shown by the LED on the debugger and the LCD screen starting up to the user guide screen. Both the horizontal and vertical linear actuators retract all the way during this startup cycle.

II. Mechanical Adjustments

Test Objective: Verify that the horizontal and vertical mechanical adjustments have been made. Verify that the adjustments are made in a reasonable time.

Procedure: Once the shot parameter sliders have been adjusted, observe that the dual motors change speed accordingly. For horizontal adjustments, the base of the machine should swivel via the linear actuator extending or retracting. For vertical adjustments, the linear actuator should extend or retract causing the dual motor mechanism to tilt. Record the time the machine takes to adjust the horizontal mechanism from the left extreme to the right extreme (i.e. the leftmost horizontal configuration to the rightmost horizontal configuration). Ensure that this is no longer than 12 seconds. Perform the same test for vertical adjustments. Ensure that this is no longer than 12 seconds.

Results: The motors change speed in accordance with what we expect them to when the user changes the shot parameter sliders. When changing the vertical and horizontal angle on the sliders, the changes are reflected before the launch motors begin spinning. Each actuator takes 12 seconds to move from fully retracted to fully extended, and vice versa.

III. Dual Motor Launchers: Speed

Test Objective: Verify that the dual-motor launchers can launch balls at varying speeds.

Procedure: Set the speed dial to low. Observe how the ball launches and read its relative speed using PASCO Capstone software. Repeat the process for each increment on the slider.

Results: The launching motors are in fact capable of sending the ball at different speeds when the slider is adjusted.

IV. Dual Motor Launchers: Spin

Test Objective: Verify that the dual-motor launchers can launch with backspin and topspin.

Procedure: Set the spin slider to topspin. Observe how the ball launches. Indications of a ball traveling with successful topspin include the ball traveling with a clearer downward force and bouncing higher off the ground. Set the spin slider to backspin. Observe how the ball launches. For backspin, due to the greater upward force on the ball, it will appear to "float through the air as it flies." Compared to a normal shot and a topspin shot, the ball will also bounce much lower [6].

Results: There is a noticeable difference between two shots with identical launch parameters, where spin is the only difference. Backspin causes the ball to "float" a bit more, while topspin causes it to hit the ground more aggressively.

V. Power Supply

Test Objective: Verify that the machine can launch 10 balls without needing to charge the battery.

Procedure: Fully charge the 12V battery. Run the machine and launch 10 balls. Check that there is still power.

Results: The battery has the same voltage before and after launching 10 balls subsequently.

VI. Drill Functionality

Test Objective: Verify that each drill operates as expected.

Procedure: Select a drill. Verify that each shot parameter is reflected. Repeat for each drill.

Results: The drill runs the way it was designed, and shots travel with the expected trajectories to the expected places on the court.

When integrating all our individual components into our final system, we discovered some issues regarding current draw in the linear actuators that we had not previously encountered. The SN754410NE motor driver we initially used to control the direction of the horizontal and vertical linear actuators ended up having too low of a current supply. That specific motor driver is rated for up to 1.6A of current, whereas each of our linear actuators were rated to draw 3A with no load. Despite previously successfully powering the linear actuators with the SN754410NE motor driver, after integrating it into the system of our overall machine, the amount of current that they needed to draw exceeded the maximum rating of the motor driver. This caused our component to heat beyond its operating range. To address this issue, we ordered new DRV7881 motor drivers which were rated for 3.6A of current. Because this issue was revealed too late into the semester and we didn't have time to redesign and manufacture a new PCB, we purchased our motor drivers on breakout boards. With these breakout boards, we were able to easily direct the power and signals out of our PCB into the corresponding inputs on each respective board. Making this adjustment allowed us to correctly control and power the linear actuators via the STM32 microcontroller.

Timeline

Throughout the semester, we encountered many unanticipated setbacks which required modifications to our initial Gantt chart. We were not able to finalize our PCB design until we were able to determine what components could modify the speed of the launching motors, since routing power to our motors was the main purpose of our PCB. The process of finding a suitable component to vary the speed of the launching motors ended up taking more time than expected. We initially allocated 25 days to complete the launching mechanism, but due to issues revolving around our motor drivers not being able to supply enough current to power the motors up to an appropriate speed, we had to pivot to other options. We purchased and tested new motor drivers as well as new transistors to vary the speed of the launching motors. The shipping of the components along with the time spent testing them extended our launching mechanism timeline by approximately a month. Consequently, our PCB design was also unable to be finalized until the last quarter of the semester.

During the testing period of the motor drivers, we also damaged our STM32 microcontroller due to errors in pin connections when trying to use the 5V output as a VCC input to the motor driver. This delayed the work on our embedded system since we no longer had a working microcontroller to interface with the LCD or generate any of the digital or analog signals necessary to control our motor drivers. Due to this setback, we began to use the Digilent Analog Discovery 2 and the Waveforms software to generate our PWM signals for motor driver input, as well as to toggle the digital signals to enable our motors. Because we were able to simultaneously test our motor drivers while we waited for our microcontroller to be shipped, we were able to uncover issues with our motor driver sooner rather than later. When the STM32 microcontroller was delivered, we began to design and implement our embedded system. This process was extremely time consuming and we encountered many more issues than we had initially anticipated. Because we were unfamiliar with the microcontroller and how its pins interface with each other, we ran into a lot of inconsistent behavior across how pins operate on different peripherals. Troubleshooting all of this and figuring out what pins were available to use for our circuit components versus what pins were taken by the LCD took around a week and required an ultimate redesign of the PCB as well.

These various unforeseen factors caused the most delay in the development of the embedded system as well as in the finalization of the PCB. We had to make the most adjustments in our Gantt Chart surrounding these two parts of our project. The initial chart is shown in Figure 11, and our modified chart is shown in Figure 12.

Instead of having a designated period of doing integration testing between the various motors in our circuit, we ended up testing as we were designing our PCB by breadboarding our less powerful motors with the various motor drivers and transistors that we're using. This allowed us to check the connections and performance of our circuit components before needing to integrate it into our machine. Although this didn't help us cut down on the final amount of time we spent on system testing with our PCB hooked up to our machine and all of the wires screwed into the board, it may have saved us the trouble of spending more time than we initially allocated on our Gantt Chart. Appendix B, C, and D document more detailed screenshots of the various phases of our final Gantt Chart. They are respectively project conception and initiation, MVP iterations, and final product testing and deliverables.

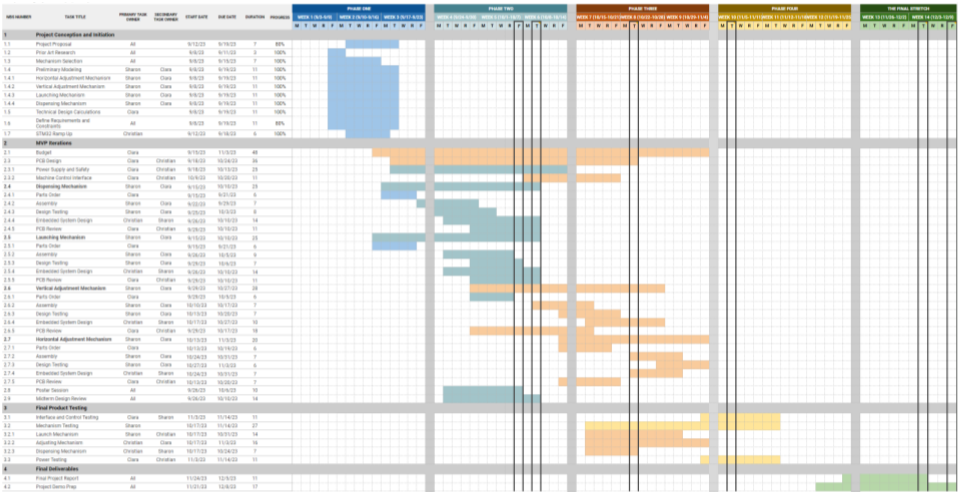

Figure 11. Initial Gantt Chart

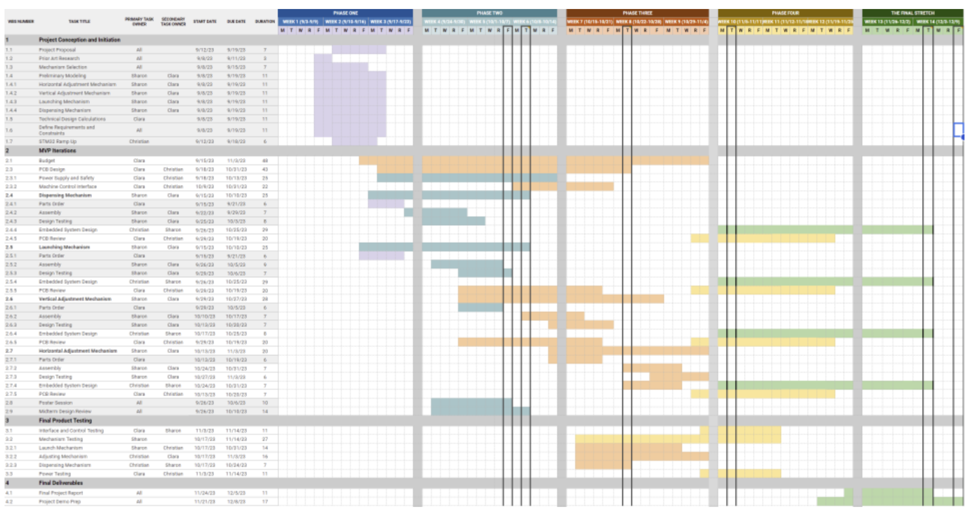

Figure 12. Final Gantt Chart

Costs

The cost breakdown of this project is detailed in Appendix A. The total cost of the mechanical components, which includes the ball dispensing mechanism, vertical and horizontal angle adjustment mechanisms, launching mechanism, and casing, is $373.87. The total cost of the electrical and embedded components, which includes the PCB, microcontroller, and rechargeable battery, is $75.59. When possible, the component cost for bulk pricing of 10,000 units was used. This led to a minor reduction. However, the listed total cost of $449.46 per unit is an overestimate due to the number of mechanical components purchased in-store, at Lowe's and Home Depot, and via online retailers, such as Amazon, that do not have bulk pricing options. If the pickleball machine were to be manufactured in large quantities, sourcing components that have bulk pricing options would be prioritized. There are also certain components that can be custom-manufactured and better suit the needs of the machine. For instance, the dispensing mechanism has a standard 5 gallon bucket, 4" flex duct, plywood disk, and 3" PVC pipe cut to fit our specifications.

Using automated equipment to assemble the pickleball machines would allow for quality control and a greater production scale. As mentioned above, if certain plastic components that were modified from on-the-shelf parts are customized, these specifications could be used to create molds for injection molding [37]. The initial setup for these molds would be costly, but the per-unit cost would decrease with larger production volumes. For precision cutting and drilling of metal components, computer numerical control (CNC) machines could be used [38]. This would significantly reduce the time needed to construct each machine when compared to manual assembly. Again, while the initial equipment costs would be significant, this would be a cost-effective strategy in the long run. Ultimately, the manufacturing costs for the machine must be factored into the pricing. While we would anticipate a slight decrease in component costs due to fewer off-the-shelf parts purchased per unit, this would be offset by the production costs and ultimately lead to an overall increase in price.

Final Results

In our project proposal, we defined six criteria, each with ten points assigned to them, leaving a possible total of 60 points. We defined 50-60 points as an A, 40-50 points as a B, and 30-40 points as a C. The six criteria are as follows: ability to launch a ball over the net; ability to pivot horizontally; ability to pivot vertically; ability to power the machine for a duration of time; ability to vary speed at which balls are launched; and ability to adjust speed and angle on the user interface. Each will be individually assessed for a score of 0, 5, or 10 points per category.

I. Ability to launch a ball over the net

The machine can launch all 15 of the balls in the hopper over the net. As we declared in the project proposal, this earns a 10/10 for this criterion.

II. Ability to pivot horizontally

The machine has a horizontal rotational range capable of covering the entire horizontal area of the court from either the baseline or the no-volley zone. This has a corresponding grade of 10/10 on this criterion.

III. Ability to pivot vertically

The vertical linear actuator has the capability to angle balls such that they can launch up to 4 feet over the net. As we previously stated in the proposal, this corresponds to a 10/10 for the vertical angling criterion.

IV. Ability to power the machine for a duration of time

The battery can provide power to this machine for well over 3 minutes at a time. The machine, however, operates at high temperatures when it runs continuously for this long, so it is advised that the user limits the time of use to a full hopper of balls. Since the hopper holds 15 balls, and dispenses a ball every 4 seconds, only one minute of operation will be needed at a time. Because the machine is capable of dispensing the whole hopper without stopping, as well as the fact that it can run for 3 minutes for testing purposes, we believe that this section earns a 10/10.

V. Ability to vary speed at which balls are launched

When we alter the duty cycle of the PWM signals fed into each of the driving transistors, we are able to alter the speed at which the motors spin. This means that we are able to vary the speed of launch. The lowest speed in this range is about 15mph, and the highest speed in this range is roughly 35 mph. This top speed was measured at a 70% duty cycle, so although the launch speed could be increased, we decided against this due to heat dissipation concerns. The wide range of speeds earns a 5/10 on this category.

VI. Ability to adjust speed and angle on user interface

The user can configure speed, spin, dispensing frequency, horizontal angle, and vertical angle using the LCD interface. This is done through sliders, and once the sliders are set and the user begins play, each of these training specifications are adjusted accordingly. This means that we have earned a 10/10 for this criterion.

Totaling the points from the rubric, this project has earned a 55/60, which corresponds to an A. In addition to the criteria we identified, we also built the functionality around preprogrammed drills that change the horizontal and vertical angles as the balls launch. This was initially a reach goal, but we were able to accomplish this.

Future Work

One of the main suggestions we would have to improve the project in the future is to get motors rated for higher current. Ideally, they would be able to take about 5A at least so that they can handle the wheels' inertia and launch the ball the full court length despite the wheels' weight. This would likely help with the overheating issue as well. With a larger budget, we would have gotten motors rated for a higher load, but these were very expensive, so they were outside of our project's scope.

Another thing that we could have done with a higher budget would be to get a PCB with better heat regulation, probably in the form of a heavier copper plane. Utilizing active heat sinks instead of passive heat sinks would also allow us to dissipate the heat more efficiently across our transistors. If this had the desired effect, we would then be able to run the launching motors at a higher speed, creating more possibilities for the machine to emanate different shot styles.

In terms of the product's external structure and casing, with more time and resources we could have made the casing more efficient. With the materials we had, it made sense to build a rectangular frame and use rectangular acrylic panels to case the machine. The screws we used to secure the acrylic to the sides were such that it was easier to affix the acrylic to the frame with the head of the screw on the inside. This resulted in there being screw ends sticking out of the sides of the machine, presenting a potential hazard. If we had room in our budget, we would have added caps to the ends of these so that if the user bumped into one by accident, it would not scrape them. There is a similar issue with the corners of the frame being a bit jagged, so we would also buy smooth corner caps if we had more funds. Additionally, we could have made the casing more customized to the launcher's shape, meaning that fewer materials would be necessary.

On the user-interfacing side, another opportunity would be to create a mobile application to control the machine. This would allow the user to change the launch specifications, start sessions, and end sessions without having to walk back to the machine. This would make the UI more convenient, which would make the product more marketable.

One procedural recommendation for students looking to complete this project or one like it is to learn which pins on the microcontroller can operate together in different modes. For instance, one of our issues was that we initially configured the outputs such that GPIOs and PWMs were using the same peripherals. In practice, this did not work. Discovering this issue took a large amount of debugging and troubleshooting, and it caused a significant delay in our workflow since we had to not only redesign the PCB but also regenerate a large amount of our embedded code. Starting work on the embedded system early is crucial to avoid significant setbacks down the line, especially near the end of the project's timeline. Additionally, we would recommend ordering parts that have absolute maximum ratings well above what is required. Initially, we thought we would need around 1.1A of current for our motors, so we ordered motor drivers that could supply slightly more than this. We had similar issues with the transistors, which we could have avoided if we ordered transistors rated for outputs much higher than what we needed.

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Appendix A

Source	Component	Quantity	Unit Cost	Total Component Cost (per Machine)
Dispensing Mechanism				
Lowe's	5 Gallon Bucket	1.00	$7.98	$7.98
Lowe's	4" Flex Duct	0.05	$15.98	$0.80
Lowe's	3" PVC Pipe	1.00	$11.48	$11.48
Amazon	6mm Rigid Flange Motor Coupling	1.00	$5.99	$5.99
Digikey	20 RPM 12V DC Motor	1.00	$11.90	$11.90
Lowe's	Plywood	0.25	$7.53	$1.88
Amazon	Motor Mounting Bracket	1.00	$8.99	$8.99
				$49.02
Adjusting Mechanisms				
Lowe's	Heavy Strap Hinge	2.00	$5.98	$11.96
Amazon	4" Linear Actuator	2.00	$30.95	$61.90
Lowe's	Lazy Susan	1.00	$15.98	$15.98
				$89.84
Launching Mechanism				
Lowe's	8mm Rod	0.25	$6.98	$1.75
Digikey	5mm to 8mm Shaft Couplers	2.00	$4.95	$9.90
Du-Bro	Super Lite XL 4.5" Wheels, 2 Pack	1.00	$17.07	$17.07
Amazon	10000 RPM 12V DC Motor	2.00	$17.99	$35.98
Amazon	4-pack 8mm Inner Bore Ball Mount	0.50	$9.49	$4.75
Amazon	2-pack Motor Mounting Brackets	1.00	$11.95	$11.95
Amazon	4-pack 8mm Flange Motor Coupling	0.50	$9.99	$5.00
				$86.39
Casing				
Amazon	4-pack Caster Locking Wheels	1.00	$11.99	$11.99
Amazon	5-pack 24" by 36" Acrylic	1.00	$37.04	$37.04
				$49.03
Other Structural Components				
Lowe's	#8 Machine Screws and Nuts	2.00	$5.98	$11.96
Lowe's	#4 Machine Screws and Nuts	2.00	$1.38	$2.76
Lowe's	20-pack Corner Braces	2.00	$12.48	$24.96
Amazon	10-pack 1000mm Aluminum Extrusion Linear Rails	1.00	$59.91	$59.91
				$99.59
PCB and Embedded Components				
Digikey	L7809 Voltage Regulator	1.00	$0.21	$0.21
Digikey	LCD Display	1.00	$35.35	$35.35
Digikey	DRV8871 Motor Driver	2.00	$0.98	$1.96

Digikey	MJE3055TG Transistor	3.00	$0.33	$0.99
Digikey	STM32 Nucleo	1.00	$11.10	$11.10
Digikey	2oz Copper PCB	1.00	$0.78	$0.78
Digikey	500' Hook-Up Wire	0.01	$0.14	$0.00
Digikey	Motor Driver IC Sockets	2.00	$0.45	$0.90
Digikey	Header Pins	1.00	$3.80	$3.80
Digikey	Resistors	3.00	$0.01	$0.02
Digikey	0.1uF Capacitors	4.00	$0.00	$0.02
Digikey	2 Position Wire to Board Terminal	6.00	$0.44	$0.43
Digikey	1N4001 Diodes	2.00	$0.02	$0.05
Home Depot	12V 7Ah Sealed Lead Acid Rechargeable Battery	1.00	$19.99	$19.99
				$75.59
		Total Cost per Manufactured Unit		$449.46

Appendix B

PHASE ONE: WEEK 1 (9/3-9/9), WEEK 2 (9/10-9/16), WEEK 3 (9/17-9/23)

PHASE TWO: WEEK 4 (9/24-9/30), WEEK 5 (10/1-10/7), WEEK 6 (10/8-10/14)

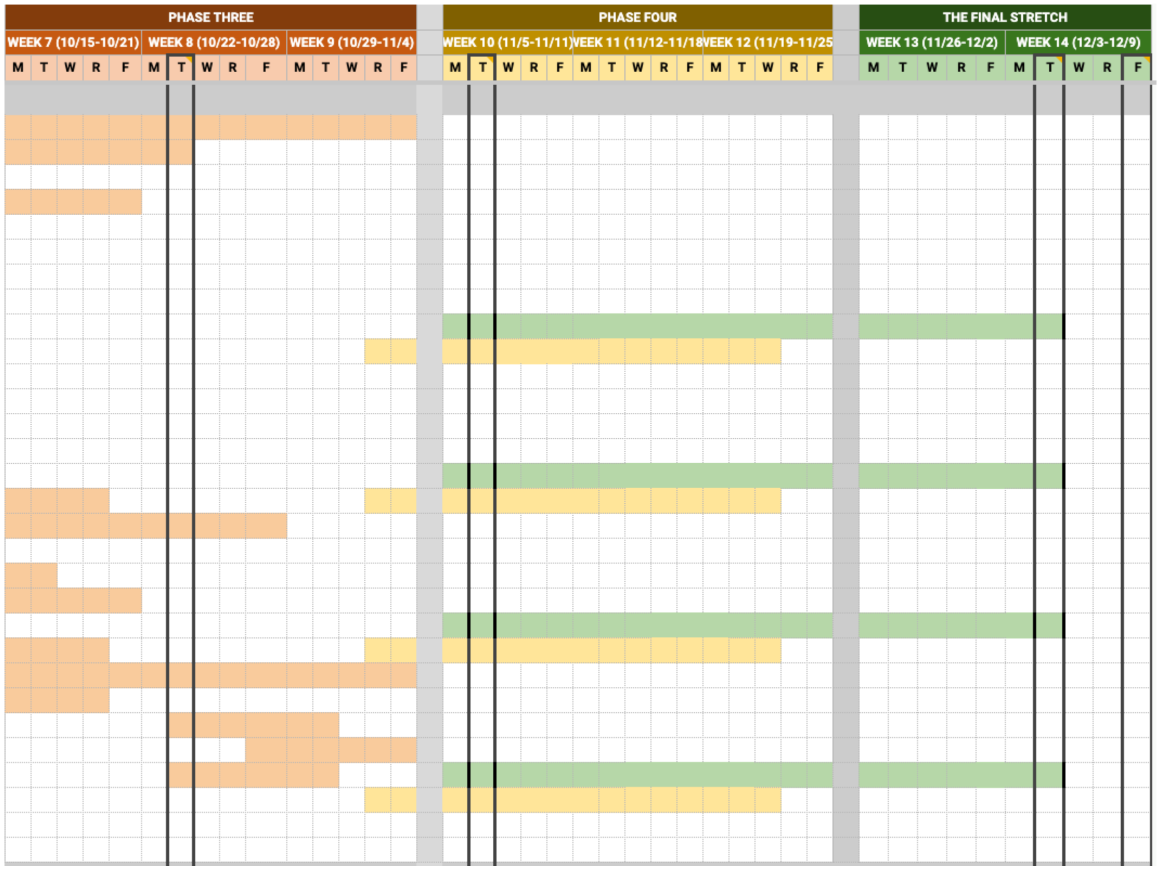
WBS NUMBER	TASK TITLE	PRIMARY TASK OWNER	SECONDARY TASK OWNER	START DATE	DUE DATE	DURATION
1	**Project Conception and Initiation**					
1.1	Project Proposal	All		9/12/23	9/19/23	7
1.2	Prior Art Research	All		9/8/23	9/11/23	3
1.3	Mechanism Selection	All		9/8/23	9/15/23	7
1.4	Preliminary Modeling	Sharon	Clara	9/8/23	9/19/23	11
1.4.1	Horizontal Adjustment Mechanism	Sharon	Clara	9/8/23	9/19/23	11
1.4.2	Vertical Adjustment Mechanism	Sharon	Clara	9/8/23	9/19/23	11
1.4.3	Launching Mechanism	Sharon	Clara	9/8/23	9/19/23	11
1.4.4	Dispensing Mechanism	Sharon	Clara	9/8/23	9/19/23	11
1.5	Technical Design Calculations	Clara		9/8/23	9/19/23	11
1.6	Define Requirements and Constraints	All		9/8/23	9/19/23	11
1.7	STM32 Ramp Up	Christian		9/12/23	9/18/23	6

Appendix C

PHASE ONE: WEEK 1 (9/3-9/9), WEEK 2 (9/10-9/16), WEEK 3 (9/17-9/23)

PHASE TWO: WEEK 4 (9/24-9/30), WEEK 5 (10/1-10/7), WEEK 6 (10/8-10/14)

WBS NUMBER	TASK TITLE	PRIMARY TASK OWNER	SECONDARY TASK OWNER	START DATE	DUE DATE	DURATION
2	**MVP Iterations**					
2.1	Budget	Clara		9/15/23	11/3/23	48
2.3	PCB Design	Clara	Christian	9/18/23	10/31/23	43
2.3.1	Power Supply and Safety	Clara	Christian	9/18/23	10/13/23	25
2.3.2	Machine Control Interface	Clara	Christian	10/9/23	10/31/23	22
2.4	**Dispensing Mechanism**	Sharon	Clara	9/15/23	10/10/23	25
2.4.1	Parts Order	Clara		9/15/23	9/21/23	6
2.4.2	Assembly	Sharon	Clara	9/22/23	9/29/23	7
2.4.3	Design Testing	Sharon	Clara	9/25/23	10/3/23	8
2.4.4	Embedded System Design	Christian	Sharon	9/26/23	10/25/23	29
2.4.5	PCB Review	Clara	Christian	9/29/23	10/19/23	20
2.5	**Launching Mechanism**	Sharon	Clara	9/15/23	10/10/23	25
2.5.1	Parts Order	Clara		9/15/23	9/21/23	6
2.5.2	Assembly	Sharon	Clara	9/26/23	10/5/23	9
2.5.3	Design Testing	Sharon	Clara	9/29/23	10/6/23	7
2.5.4	Embedded System Design	Christian	Sharon	9/26/23	10/25/23	29
2.5.5	PCB Review	Clara	Christian	9/29/23	10/19/23	20
2.6	**Vertical Adjustment Mechanism**	Sharon	Clara	9/29/23	10/27/23	28
2.6.1	Parts Order	Clara		9/29/23	10/5/23	6
2.6.2	Assembly	Sharon	Clara	10/10/23	10/17/23	7
2.6.3	Design Testing	Sharon	Clara	10/13/23	10/20/23	7
2.6.4	Embedded System Design	Christian	Sharon	10/17/23	10/25/23	8
2.6.5	PCB Review	Clara	Christian	9/29/23	10/19/23	20
2.7	**Horizontal Adjustment Mechanism**	Sharon	Clara	10/13/23	11/3/23	20
2.7.1	Parts Order	Clara		10/13/23	10/19/23	6
2.7.2	Assembly	Sharon	Clara	10/24/23	10/31/23	7
2.7.3	Design Testing	Sharon	Clara	10/27/23	11/3/23	6
2.7.4	Embedded System Design	Christian	Sharon	10/24/23	10/31/23	7
2.7.5	PCB Review	Clara	Christian	10/13/23	10/20/23	7
2.8	Poster Session	All		9/26/23	10/6/23	10
2.9	Midterm Design Review	All		9/26/23	10/10/23	14



Appendix D

WBS NUMBER	TASK TITLE	PRIMARY TASK OWNER	SECONDARY TASK OWNER	START DATE	DUE DATE	DURATION
3	**Final Product Testing**					
3.1	Interface and Control Testing	Clara	Sharon	11/3/23	11/14/23	11
3.2	Mechanism Testing	Sharon		10/17/23	11/14/23	27
3.2.1	Launch Mechanism	Sharon	Christian	10/17/23	10/31/23	14
3.2.2	Adjusting Mechanism	Christian	Clara	10/17/23	11/3/23	16
3.2.3	Dispensing Mechanism	Christian	Sharon	10/17/23	10/24/23	7
3.3	Power Testing	Clara	Christian	11/3/23	11/14/23	11
4	**Final Deliverables**					
4.1	Final Project Report	All		11/24/23	12/5/23	11
4.2	Project Demo Prep	All		11/21/23	12/8/23	17