UCF Senior Design Group I Project

Lazer Pong

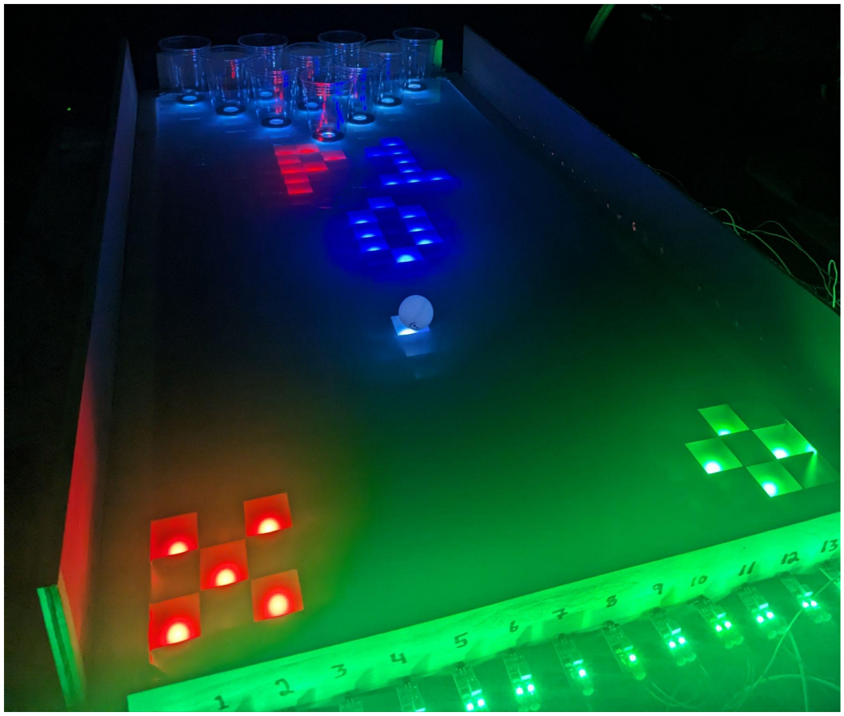

Figure 1: Lazer Pong final prototype. Image provided by the Lazer Pong project team.

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Final Project Documentation Draft

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1. Executive Summary

In an age where designed accessibility can give any traditional product the edge it needs to cut into a new market, consideration for a wide audience is at the heart of any successful invention. Simultaneously, the ease-of-use provided by a more accessible product can win over the current market from similar, competing devices as well. With this philosophy in mind, the purpose of this project was to combine the game "beer pong" with the accessibility features of an electronic arcade cabinet to create a new, broader reaching version of the game. The purpose of this new game was to give younger players a family-friendly entry point, while providing older players a new and exciting take on an old classic. In the end, our goal was to create a version of the game that more people feel more inclined to play.

Even for this sort of game, our idea was not wholly unique; several electronic beer pong tables can be found on the market. However, our approach to the machine is where our design stands out: By using optical sensors to pinpoint where the ball is while it is on the table surface, the device builds an intelligent understanding of the game state. This not only allows it to see when the player scores in a cup, but when the ball is anywhere else on the table surface as well. The upshot of this is the game is seamlessly managed by the machine; player interaction with the game is reactively communicated by the display to give the impression of a living machine. This approach to game automation maximizes the accessibility inherent in arcade cabinets to provide an exceptional user experience to most players.

In order to truly be accessible, the machine also needed to be secure and safe. A machine that is not reliable enough to work correctly each and every time it performs, too unsafe to be used by the unprepared, or too complex to be understood by the uneducated, is not really an accessible machine. This means that player safety had to be as strong of a consideration as feature realization, and the only realizable features were the ones that could be durably performed. In addition to being safe and secure, these features needed to be realized in a 6-month timeframe. While these constraints limited the scope of this design, they also focused the efforts of this project on a set of realistic goals and objectives that exclusively furthered the mission of this project: To create a beer pong based arcade cabinet, which is simpler, more accessible, and more widely enjoyable than its ancestor.

2. Project Description

Given the scale of an optical, electronic and mechanical design task as exceedingly complex as an electronic arcade machine, this project required that careful consideration be made to the methodologies employed in the execution of this project. That is, the project background must be clearly established, and the project limitation definitions must be present at each step of the project. To this end, this chapter will be devoted to the outlining of these project qualities before the more meaningful design processes can be elaborated. In order to define these qualities, the central project purpose must be clear: The purpose of this project is to fulfill the project mission, as outlined in the executive summary, by designing an electronic beer pong table that improves the accessibility and enjoyment of the game. In order to accomplish this design, this project will entail these major steps:

1. Establish and analyze project goals, objectives, specifications and constraints (Chapter 2)

2. Research, define and defend project motivation (Chapter 3.1)

3. Research and define proposed technologies (Chapter 3.2)

4. Compare, contrast and select component parts (Chapter 3.3)

5. Clearly define standards and constraints and their impact on the design (Chapter 4)

6. Clearly define project design using the parts selected in Chapter 3.3 to employ the technologies researched in Chapter 3.2 (Chapter 5)

7. Outline validation, building and testing plan to ensure proper proposed functionality of design (Chapter 6)

Before the design process can be elaborated, the project mission must first be dissected into a set of high-level, achievable goals and objectives. These goals and objectives will be necessary to keep the focus of each design stage on the central mission. Without them, the design would have drifted away from its original mission through feature creep, compromise, and loss of focus. Next, the scope of the project must be set in order to keep both the design process and outcome attainable. The requirements that must be met in order to fulfill the project goals and objectives and the constraints that will limit the possible project design solutions will be clearly outlined. Similarly, administrative constraints, such as budgetary and time constraints, will be outlined as well. Finally, the project goals and objectives will be combined with preliminary market research to establish a clear set of values for the consideration of features. These values were used, in combination with all constraints, to produce a set of defining requirement specifications for the project.

2.1. Motivation

With the mission of designing an entertainment machine that was as interesting to design as it is to use, this project is an electronic table that allows the users to play beer pong with the assistance of intelligent lighting. This lighting, created by a display panel across the table surface, shows the player when and where scores are made, tracks the game score, and dances to any music that is playing. To inform the surface display of events that happen on the table surface, a sensor array that can detect a ping pong ball was laid over the entire surface. This project had its roots in the optics half of our team, as elements of it have already been practiced by Matthew Brislenn, one of our CREOL members. Our wish was to capitalize on these optics specialties within our team to come up with novel optical solutions to employ both this table surface and this sensor array. Beer pong is already a very simple game that is enhanced by modifications made by the players, so further enhancement via the game tracking automation principles and atmospheric conditions created by this table elevated this simple party game to a new form of entertainment.

Figure 2: Beer Pong table built by Matthew Brislenn. Image provided by the Lazer Pong team.

Since the creation of the pinball arcade machine, electronic game cabinets have increased the accessibility, entertainment, and ease of use of games that could otherwise be played without electronic assistance. To this end, our main goal was to create a low-cost electronic beer pong cabinet that assists the players with keeping track of the game and generally makes the game more accessible, while also increasing the amount of enjoyment the average player finds in playing the game. Our market research showed that consumers view these as real problems to be solved, as electronic beer pong tables, among other electronic game cabinets, form a thriving embedded electronics industry.

The project motivation can be broken down into a set of basic goals, advanced goals, and stretch goals. The tables already on the market tend to focus on score tracking and ambient lighting through music visualization, so those constituted the basic goals for this project. In addition, our optical solution to score tracking allowed the table to track the ball wherever it is along its surface. This was our advanced goal: To track the ball position across the whole tabletop, and to use this information to enhance our score tracking and ambient lighting. To ensure the viability of these core goals, the build was limited to half of a standard beer pong table, which gave enough room to demonstrate these functionalities at scale. Unfortunately, due to delays in the electronics bring-up process, the final stretch goals were not attempted, though those would have been to extend the design to a full-length table, and to add audio effects to complement the lighting effects. In the end, these implemented features created a beer pong experience that was more accessible and easier to enjoy than standard beer pong.

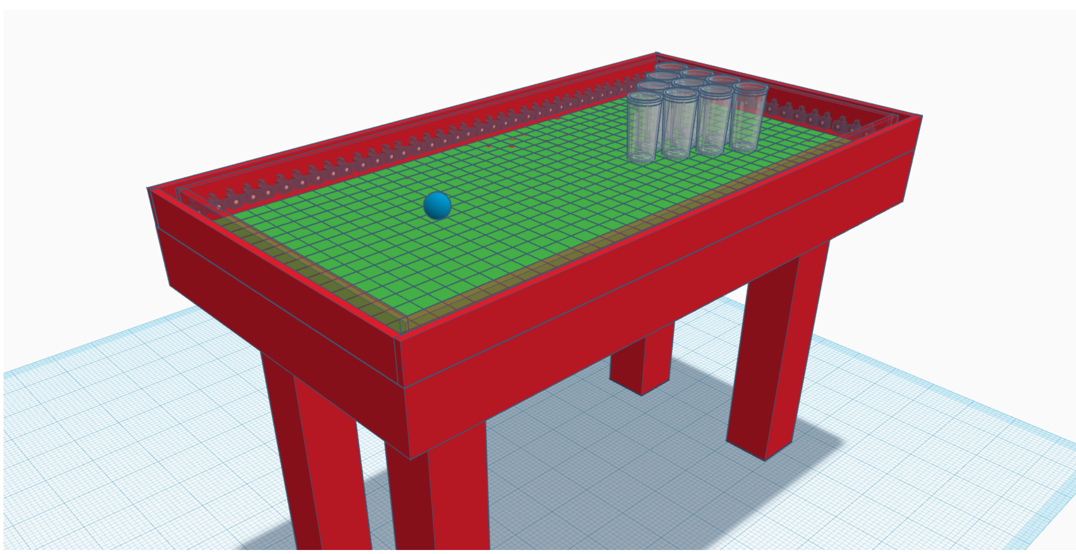


Figure 3: 3D Model of Half-Table Design With Full Laser Grid

To fulfill the goals of score tracking and ball tracking, the primary objective of this project was to detect the position of a ping-pong ball while it is on or near the surface of the table. In keeping with the optics focus of this project, this was achieved using an intersecting grid of laser transmitters and receivers. When the grid lasers are broken by the ball in both the X and Y directions, the table knows exactly where the ball is on the table surface. For simply detecting scores, it was originally discussed to make this grid over only the area with the clear scoring cups. Thus, when the ball enters a cup, it will break the laser grid and signal a score. However, we were able to extend this grid over the whole table surface, so that it can detect where the ball lands anywhere on the table. This allowed for complete ball tracking along the surface, as per our advanced goal.

The laser grid consists of one row and one column of laser transmitters, perpendicular to each other, producing collimated beams to shine onto one row and column of photodetectors opposite to the lasers. The lasers produce a low power, continuous wave beam that incites a constant electrical signal through the photodetector. When this signal is broken, and thus lost, the electronic systems of the design recognize the signal change and respond accordingly to the surface display. To produce a safe and reliable laser grid, the lasers were well-aligned and securely mounted to minimize risk of movement. For a standard ping pong ball, the diameter was measured to be 40mm. This laser grid must be tight enough to detect a break in the beam path in both the X and Y directions simultaneously. Thus, the lasers were spaced with less than 40mm between them. This is to ensure that when a ball hits the table or lands in a cup, it will always break at least one beam path from each direction. When these beam paths are broken by a ball, the electronic systems are able to see the signals and detect where the ball is on the board using the X and Y coordinates provided by the lasers. Using this position information, the board knows whether a ball has scored in a cup or simply rolled on the table, and relate this to the LED display.

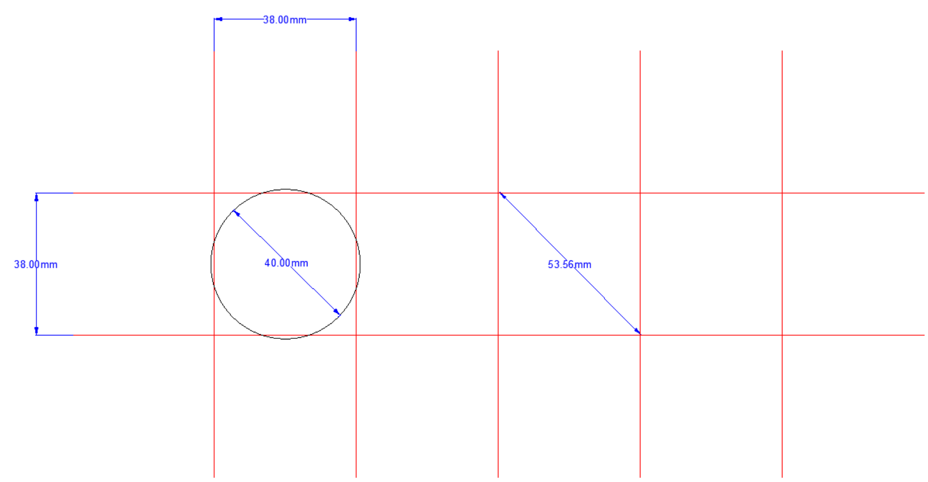


Figure 4: Example of Valid Laser Grid Dimensions. Image provided by the Lazer Pong team.

With the objectives of displaying game events recorded by the laser grid on the table surface as well as providing entertainment lighting in the form of graphical effects, a programmable display was placed within the surface of the table. This surface display serves to indicate to the player when a score is made and to illuminate cups that are in play, as well as to track and display the total score. Additionally, it was planned to place microphones around the table to inform music visualization effects, constituted by lighting patterns timed with the rhythm of any rhythmic sounds playing near the table. More advanced lighting effects could have been implemented, such as ripples when the ball bounces. This surface display was designed to be easily programmable by a simple microcontroller, and did not need to be of high resolution or deep color quality. This display was fabricated using individually addressable LEDs, arranged in a grid and diffused into a seamless pixel display. Because of this, it was simple to create graphics routines for the game.

The main goal of this project was to design and produce a visually stunning, low power and cost-effective game table that is widely accessible and enjoyable. This was achieved through the advantages created by our innovative optical solutions, which foster a memorable, worry-free gameplay experience. By demonstrating the viability of a half-scale design, this project will prove the implementation of these intelligent lighting and game automation features for scaling to a full size table. In the end, the hope is that this laser pong table will provide a novel solution to game automation and enhance the enjoyment of playing beer pong.

2.2. Goals and Objectives

Basic Goals:

- *To provide game automation by detecting and tracking scores, and relating these to the player.*
- *To enhance the game experience by producing ambient lighting effects, which respond to sound.*
- *To implement these features across a half-scale beer pong table.*

Advanced Goals:

- *To further enhance accessibility and game experience by tracking ball position anywhere on the table, and using this information to improve visual feedback provided by the ambient lighting.*

Stretch Goals:

- *To further enhance accessibility and game experience by adding audio feedback to scores and ball bounces.*
- *To extend the table to a full-scale beer pong table.*

Objectives:

- *Design an infrared laser sensor grid with less than 40mm spacing between lasers and no less than 20mm above the table surface, which can detect a ping pong ball passing through it anywhere in its coverage.*
- *Provide a response time less than 250ms for ball detection and corresponding visual feedback.*

- *Assemble an LED array to cover at least half of a beer pong table, which is fully addressable and can be driven by the MCU.*

- *Detect rhythmic ambient sound and translate this to a timing pattern for visual effects on the LED array.*

2.3. Requirements and Specifications

Table 1: Project Requirements and Specifications

Requirement	**Specification**	**Priority**
Laser Grid Dimensions	>20 mm above play area, <40 mm between adjacent lasers	High
Projected Laser Diameter	<20mm	High
Laser Classification	<Class 3B	High
Surface Display Dimensions	4’x2’ display, no less than 32x16 pixel display	High
Overall Response Time	<0.25 sec.	High
Microcontroller Pin Count and Capability	49 GPIO pins, 1 ADC pin	High
Microcontroller Performance	CPU speed at least 1 MHz RAM at least 16KB	Mid
Power Consumption	<150W	Mid
Power Delivery	Maximum 5 V at 30 A	High
AC to DC Conversion	100-240 VAC down to 5 VDC	High
Table Dimensions	Minimum 4’ x 2’ Overall (L x W x H): 4.5’ x 2.5’ x 27.5” - 36”	Mid
Weight	20 - 30 lbs.	Low

Table Dimensions

A regulation beer pong table is 8’x2’ [1], though the limited scope of this project reduced this size to a half-length table. The surface of the table shall be constituted by a playable area that is 4’x2’ in size. The extent of this playable table area shall be unimpeded such that the ball would bounce on any part of the surface with equal kinetic reaction. In addition to the playable area, space was needed around the perimeter of the table to allow for the laser sensors. For the prototype specifications, 6” of buffer space was provided to ensure plenty of room for these components and their necessary table structures. The height of the table is of less importance, and in fact legs were not built for the table. Instead, it was set on top of another table for demonstration purposes. [1, 2].

Laser Grid Dimensions

As stated in the motivation, the laser array must be close to the surface so that the position of the ball can be tracked as it relates to its position along the surface, but far enough away that the ball will pass through the laser grid at the ball’s center, its widest point. Given the standard ball dimensions of 40mm, this means that the grid shall be no less than 20mm above the surface to meet this requirement. The grid is as close to 20mm above the surface as possible to make the 2D position as accurate as possible.

Additionally, the laser grid must be tight enough to detect the ball passing through it at any point along the 2D plane. This means that the lasers shall be no more than 40mm apart. While tighter dimensions would potentially further improve the accuracy of ball position tracking, it would mean substantially increasing the number of necessary components. If sufficient feature quality can be achieved with the minimum viable number of laser sensors, this will be the goal and shall be the model for this specification.

Laser Classification

In designing a project that will be used for public use it is important to consider the classification of the lasers that will be used in the project. Anything below the laser class 3B will be acceptable for public use. For example, hand-held laser pointers used commonly by those giving presentations are class 3R. This is only one class lower than 3B, but still is a laser class that is actively used by the public. The 3B class of lasers starts at a power of 5mW up to 500mW and begins to have increasingly higher risks and safety precautions required for operating [3]. Such hazards associated with the increasing classes of lasers are eye damage from direct viewing or diffuse reflection of light, and potential hazards to the skin such as burns.

Surface Display Dimensions

The surface display shall cover the entire playable surface of the table, which shall be 4’x2’. The pixel density of this display must allow for no less than one pixel per indicable position on the laser grid, such that the maximum resolution for position identification is achieved. To this end, the surface resolution must facilitate the minimum specification for laser distance, 40mm per laser. The closest resolution that fits this spacing on a 4’x2’ surface is 32x16, or 1.5” square per pixel. The upshot of this is that, at minimum specifications, there would be one pixel per laser grid intersection, and that intersection would occur directly over the center of that pixel.

Microcontroller Pin Count and Capability

For a 4’x2’ surface with the minimum number of laser sensors, 48 sensors were needed. This assumes 1.5” between lasers, roughly 38mm, which sits neatly within that specification. Since no separate controller device was utilized to manage the wide datapath needed to transport 48 sensor signals to the microcontroller, those I/O devices needed to be wired directly to the microcontroller. In addition, a SPI connection was necessary to transmit sensor data from our electronic systems to the arduino device, which sends data to the display surface. The microcontroller chosen to be included in the final design shall facilitate no less than these 48 GPIO connections and 1 SPI connection, and should also provide extra room for potential design updates or changes later on.

Overall Response Time

For the purposes of this project, the overall response time is defined as the time it takes for the proper display elements to be shown once the correct laser signals have been interrupted. This time will be comprised of the transition period of the photoreceivers, the propagation delay between the photoreceivers and the microcontroller, the execution time of the microcontroller routine, the propagation delay between the microcontroller and the surface display, and the surface display’s own response time.

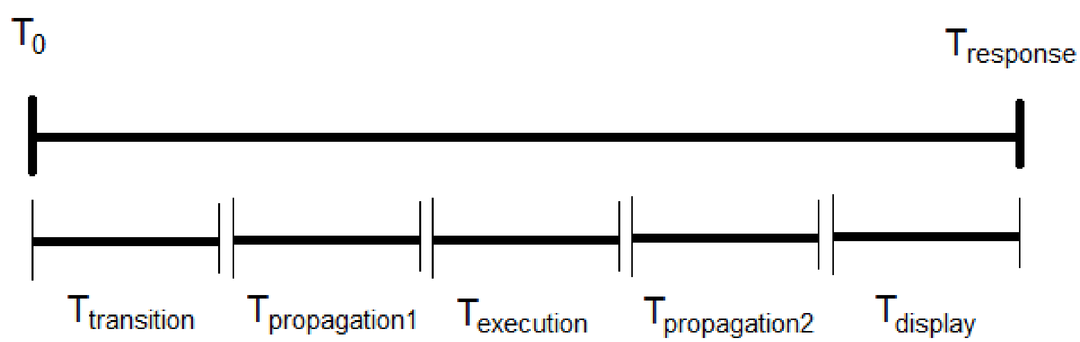


Figure 5: Response Time Chart. Individual response time components not to scale. Image provided by the Lazer Pong team.

A response time of less than 0.1 seconds was achieved. According to most empirical research into human awareness of response, this time produces the best visual feedback for the player. However, it was difficult to know more about the nature of each of these response time components before construction and testing of the whole system. Therefore, the minimum viable response time was used for this specification, with the goal of minimizing the response time as much as possible. This minimum viable response time was 0.25 seconds, long enough to produce visible delay but short enough to not interrupt the players' enjoyment of the game.

Power Consumption

The only component with a potentially high power draw in the design was the surface display. If a prefabricated dense display were chosen, one sufficient to cover at least this playable surface area could draw as much as 100-150W. No other components should draw nearly this much power, as the microcontroller and lasers devices will be low-power devices. To this end, the power draw for the entire system shall not exceed 150W. However, since this design was implemented with a simple array of 512 LEDs, the power draw of the whole system was well under 150W.

Power Delivery

Now that an upper threshold for power consumption is established, it now becomes a question of how to deliver this 150W. Microcontrollers typically operate anywhere between 3.3V to 5V, which is similar to the operating voltages of common laser detectors and simple displays that may be used on the table surface. With these voltages in mind, then at the absolute maximum, the 150 W of power must be delivered at 5V and 30A. Additionally, since the LED surface display operates at 5V, that voltage was needed at the maximum.

AC/DC Conversion

All of the components utilized for this design required DC power to operate. Using US standards, a power supply unit capable of converting standard AC power to 5V DC power shall be used to facilitate this transformation. This is the same level established for power delivery, since 5V was sufficient enough for all components to function.

Microcontroller Performance

Microcontroller performance specifications can require extensive experimental research to truly understand. The consequences of a specific software application on performance can be difficult to estimate at a high level, and incorrect assumptions can widely swing the range of acceptable specifications. To that end, the strategy for identifying microcontroller specifications was to aim for a median in performance capability as determined by the market, then to select a product that appears to far exceed the requirements of the design without going over budget. To this end, the microcontroller specifications were based on the Arduino DUE development system, an affordable and beginner friendly board for electronics and coding that doesn't sacrifice processing power or memory space. As a widely used and well-documented product, it was a good reference to use when considering which microcontroller will be implemented into our design. This also ensured compatibility between our electronics and the arduino DUE platform used to control the lights. This was especially important for the purpose of SPI when considering operating voltage.

Weight

The final design should be considered as a piece of furniture, or a household appliance, when considering reasonable weight values. Not only will this weight value affect how the user experiences complications when transporting or otherwise handling the device, it will affect the durability and rigidity required by the materials used to compose the structure of the device. Comparable tables with useful load capacity can weigh anywhere from 15-30lbs. Therefore, this range shall be the weight specification for this design.

Other Considerations

The positioning of the laser array shall be carefully measured so that they are able to accurately detect ball movement around the play area. This is necessary for many of the game functions we plan to incorporate. The dimensions of the balls that will be used are provided by the *World Series of Beer Pong*, so we are able to account for their size when designing the laser grid. Additional table space outside of the play area was also needed to host the laser grid, as well as any other peripherals.

Ideally, our final product should be low-power. However, due to the implementation of laser and display devices, we needed to draw power from a local outlet rather than from a battery-powered source. This means we needed an AC to DC converter that can transform the standard 120 VAC from an outlet to 5VDC for our devices to function. A voltage regulator was also needed for the MCU, lasers, and photoreceivers. Preferably, the table should consume no more than 50 W when operating. This value was determined with respect to other common, smaller household appliances.

2.4. Standards and Constraints

The importance of acknowledging and adhering to relevant standards and design constraints must be stressed for any kind of project. These principles play a critical role, especially for engineers, as they provide guidance towards achieving a quality solution. We ensured that the standards and constraints handpicked by us play a significant role in our project's design.

Standards

Four disciplines were established to organize a selection of standards that were deemed noteworthy and crucial to the Lazer Pong Table's design: Safe Use of Lasers, Acceptable Electronic Design, Hazards & Protections of Energy & Power, and Accessibility. Within these disciplines are several standards that served as guidelines for the aspects of this project that must conform to certain practices. Some of these include: ANSI Z136.1 (American National Standard for Safe Use of Lasers), IPC-A-600 (Acceptability of Printed Boards), NFPA 70 (Florida Electrical Code), and much more. See Section 4.1 for more detail on all of the project relevant standards.

Physical Constraints

- Table: 8' x 2' x 27.5" (L x W x H)
- Balls: 40 mm (Diameter)
- Cups:
  - Top width: 3 ⅝"
  - Height: 4 ⅝"
  - Base width: 2 ¼"
  - To be weighted with a washer

The *World Series of Beer Pong (WSOBP)* is one of the largest and longest-running officiated beer pong tournament organizers. They have publicly provided official rulings for almost all aspects of how they host beer pong games, keeping in mind fairness to all players, efficiency, and minimal disputes. These rulings were a perfect guideline to follow for the sake of our own design choices, as well as to make our final product potentially tournament legal. As seen in the list of constraints above, WSOBP has specified physical dimensions of each major component necessary to play beer pong, including the table, balls, and cups. These dimensions will be closely followed as a baseline so that the design of our laser array, LED display, etc. all are able to function on the same table [1].

While our final design is short of the table dimensions required by the WSOBP, those dimensions will be at a scale that could easily be expanded up to the full length. As long as all of the technological implementations are proven to be both sound and scalable, a full length table would be fully achievable given enough time and budget to complete the design. In addition, it is likely that the simplicity of this design would allow for two half-tables to be placed opposite each other, in the formation of a full length table. This would have some differences from a standard full length table, most notably that there would be a short barrier and gap where the two tables meet. However, this could be overcome in the design if required.

Environmental Constraints

One of the most important considerations here is protecting all primary components of the design from spillage of cup liquids. Keeping this in mind, we will be following the IEC 60529 ingress protection (IP) rating system, which grades the resistance of an enclosure against the intrusion of dust or liquids [4]. These ratings are widely used throughout the industry and will help us create a design that is protected from errors caused by environmental factors. A rating of IP54 (dust-protected, protected against splashing water) is reasonably achievable for the purposes of this project.

Health and Safety Constraints

Lasers have the potential to cause considerable damage to the human eye, so it was important to consider safety measures when designing a product that relies heavily on the use of lasers. The ANSI Z136.1 provides guidance for the safe use of lasers and laser systems that operate at wavelengths between 180 nm and 1000 m by defining certain control measures [5]. These recommendation guidelines were considered when choosing the specific model of laser we used.

Accessibility

Our project primarily considered design choices to facilitate a barrier-free environment and allow for all people to be entertained and have an enjoyable experience. Considerations such as adjustable height, controllable LEDs, additional audio/visual peripherals, and so on were discussed and weighted just as equally as any other design choice. Useful resources when factoring in accessibility are those that can provide descriptions of specific measurements that are important to follow when considering use by all persons, or those that provide helpful tools to evaluate just how accessible the project actually is.

2.5. Block Diagram

The overall project structure was divided into three main sections: The Power Supply Network, the Data Controller, and the Table Optics. Most of the project goals and objectives were accomplished primarily by the optics components of the Table Optics. These are used to identify the ball position while it is on the table surface, and to display the project graphics as they relate to the ball position. Additionally, these components communicate through a data path managed by the Data Controller. This system processes the signal data from the laser grid to determine the ball location, then uses a game routine to determine whether this ball position counts as a score (the ball is in a position occupied by a scoring cup), and changes the surface display accordingly. Finally, all of these systems are provided operating power by a Power Supply Network, which ensures all components receive the correct power level and magnitude for their operation.

Each section was owned entirely by a subset of the project group. Highlighted in blue below, the Power Supply Network was owned by Kyle Fallejo, the only electrical engineering major within this project group. He worked closely with the rest of the group members to determine power requirements, and how best to deliver that power. Highlighted in green below, the Data Controller was owned by Michael Dodd and Sean McElvogue, the computer engineering majors of the group. They were responsible for designing the microcontroller environment, including I/O handling and software needs, in addition to the general PCB design. As the resident software expert, Michael handled the majority of the software design, while Sean handled the majority of the hardware design. However, both worked closely together to ensure harmony between the two. Highlighted in red below, the Optical Table was owned by Matthew Brislenn and Jeffrey Cain, who together constitute the optics majors of the group. They were responsible for researching the optical background of the major optical systems, and designing these systems to accomplish the project goals and objectives. More specifically, Matthew was responsible for the surface display research and design, while Jeffrey was responsible for the laser grid. A high-level block diagram representing this division of project components and labor can be found below.

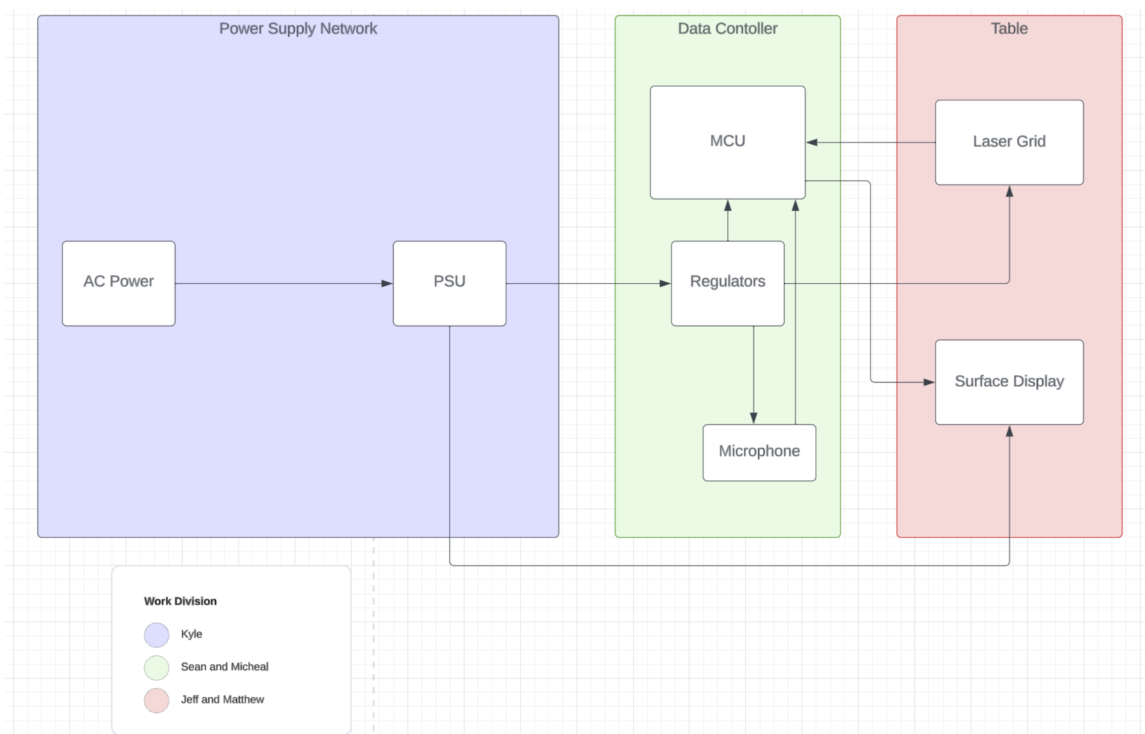


Figure 6: High Level Block Diagram with Division of Labor. Image provided by the Lazer Pong team.

2.6. Overall Schematic

The following figures give an overall schematic of how our final design ended up looking. First, you'll see an isometric and top view of a new 3D model depicting how we installed each of our components, with every block being color coded. Red represents the lasers, blue represents the receivers, yellow is the LED lights, green is the microelectronics, which includes our PCB as well as a supplemental Arduino, and finally white is our power supply unit. The following figure is a schematic drawing of how all of our components will connect together, using the same color code as the 3D models.

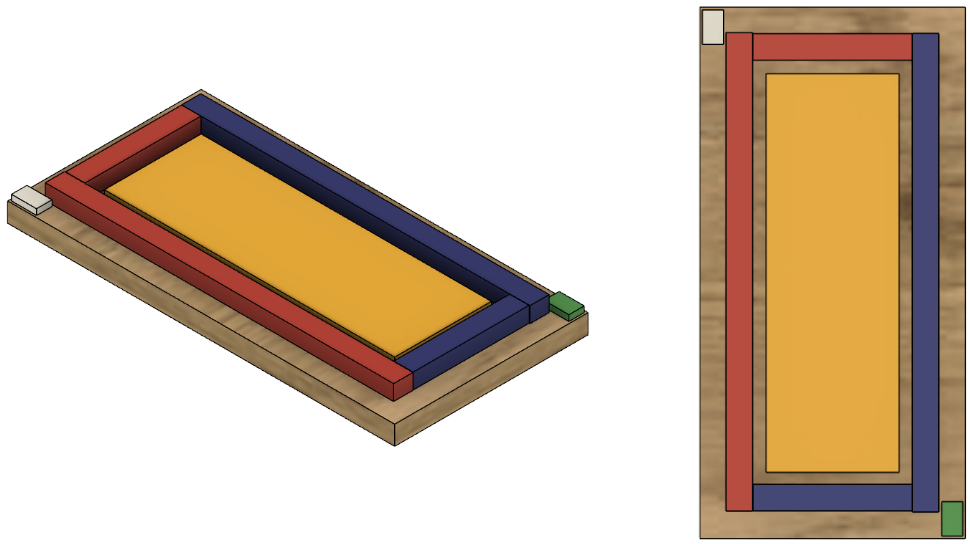


Figure 7: Isometric and top 3D view of our final setup. Image provided by the Lazer Pong team.

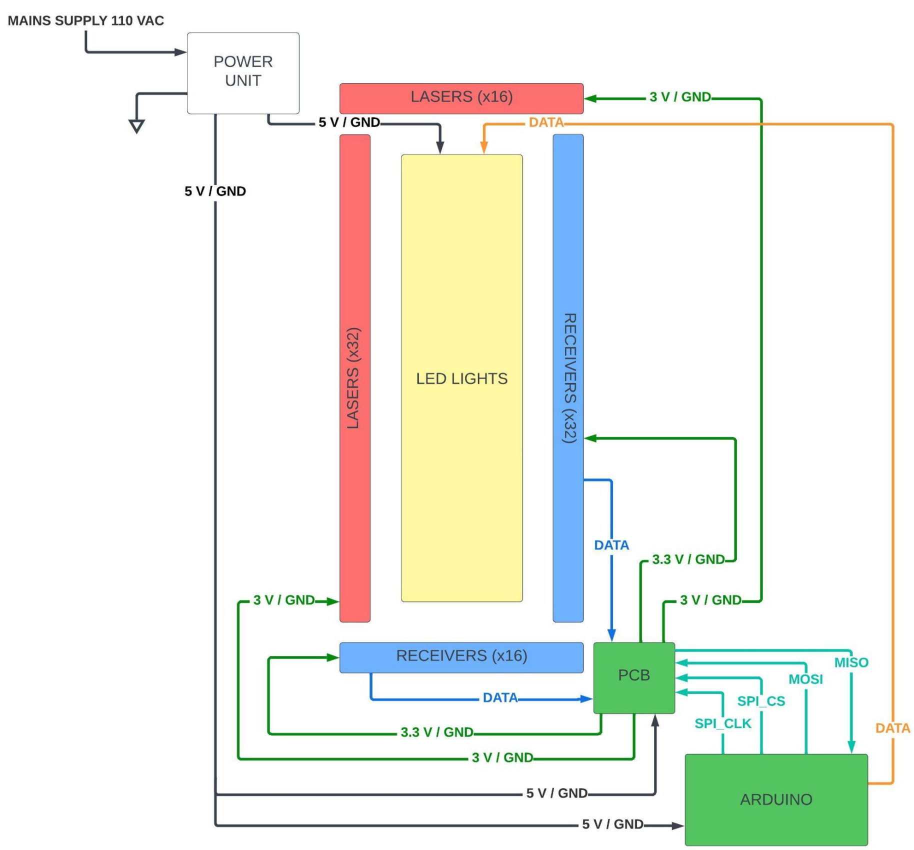


Figure 8: Overall schematic of our final design. Image provided by the Lazer Pong team.

2.7. Marketing and Engineering Requirements

To accomplish the project motivation, it was necessary to make this design accessible to as many consumers as possible. By determining the potential user needs and the priority of each need, it was possible for the design to meet the most severe user needs, not simply the most straightforward. For this project, we determined that the users will require the table to be easy to operate, reliable, low cost, and visually interesting. Some lower priority needs were ease of transportation and portability. Our group used these customer needs to guide us in the design and development of the Lazer Pong table.

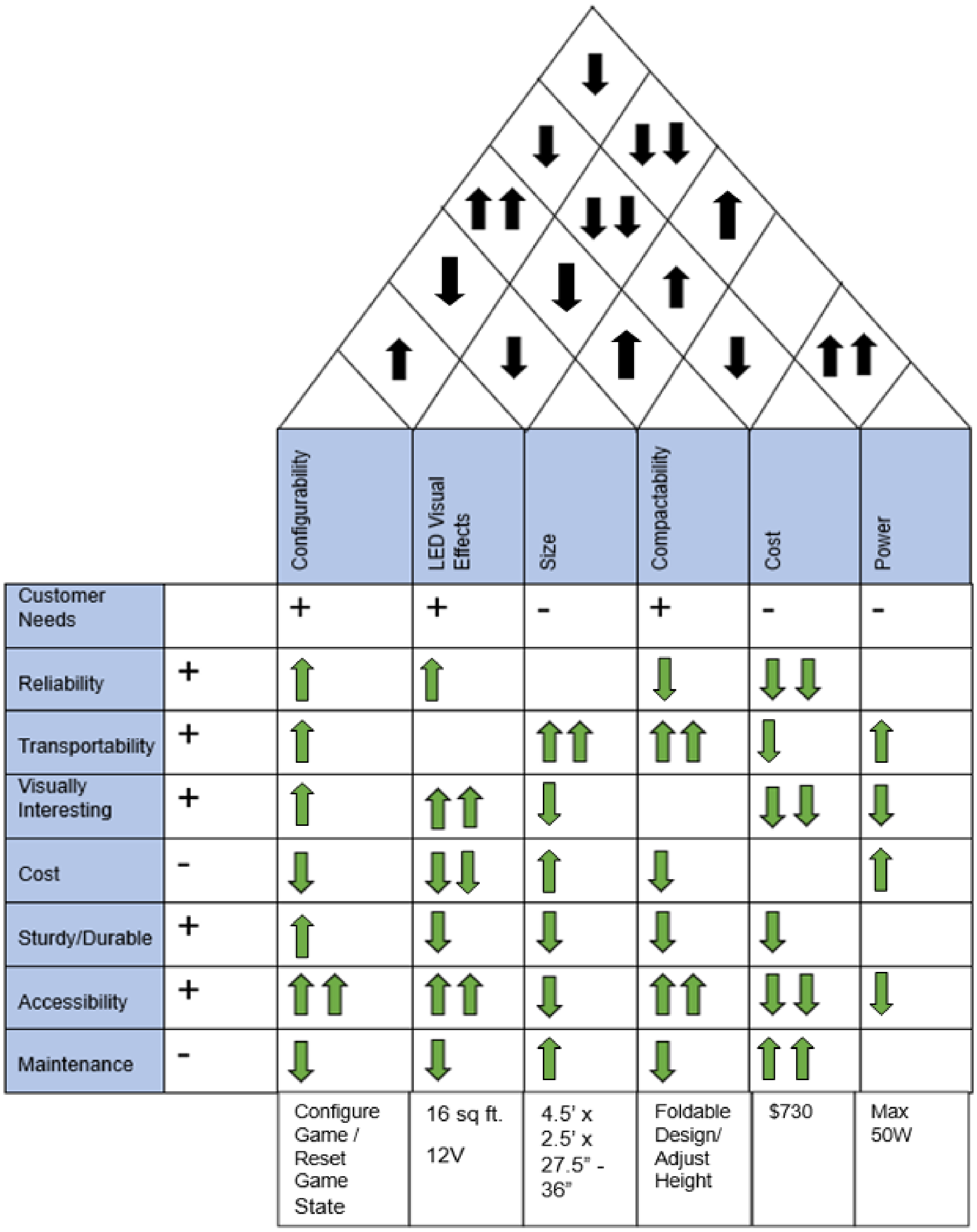


Figure 7: House of Quality Diagram. Image provided by the Lazer Pong team.

3. Project Research

With the project guidelines clearly established, the next step of the design process was to ensure the full scope of the project was well researched. This required in-depth analysis into the high-level, abstract components of the project in order to more completely understand the context of the project goals and objectives. This high-level research covers game research into the project game–beer pong–as well as market research into comparable products. Between these two avenues of background research, the project goals should be provided with enough clarity to allow for a full contextual understanding of the needs of the project pertaining to its technical components.

These technological components then had to be thoroughly researched, given the newfound project scope from the background market research. At that point, it was mostly clear what was needed from these technologies so that the research could be fully informed. The beginnings of this project came from a set of expectations about what certain optical and electronic technologies are capable of. Therefore, before the design of the components which employ those technologies could begin, those technologies needed to be explored to the extent that they applied to this project. The end result of this technical research was the background knowledge required to identify the components that were needed in this design, as well as what those components required and what was required of them.

The final goal of this research was to identify a list of parts to be assembled for the final design. For each component, the relevant background research findings will be discussed and used to assemble a selection of parts that fit the project requirements. These parts were weighed against each other using the hierarchy of project goals and values outlined in the project description, and one part for each component will be selected to use in the final build.

3.1. Game Design and Market Research

The motivation for this project began with a model, which must be thoroughly explored in order to ensure its accuracy. The application of this model, the game of beer pong, offers a set of challenges for its implementation that must be considered carefully, especially given the project constraint of designing a table that is only half of a traditional beer pong table. The rules of the game must be analyzed to identify any potential conflicts with any other project design constraints, and to ensure that any ways that the technologies of this design might improve the game experience are identified. The upshot of this background research will be an alternate set of game rules and conditions, which will allow Lazer Pong to become a new game in its own right.

This project was not the first to undertake this research for the purpose of designing an electronic beer pong table, however. A market already exists for products that perform similar functions to those outlined in the goals and objectives of this project [6, 7, 8]. The notion that arcade machines are a marketable way to introduce accessibility to a previously designed game can be observed in the way these existing market products have been selected by customers, capitalistically, to operate. That is, within this active market for entertainment electronics exists a set of common functionality that can be observed in order to learn more about the average consumer’s desires. While these market products are all quite similar and do offer some commonality, there are also critical ways they stand out from each other, which identified possible avenues of continued innovation for our design.

3.1.2. The Official Beer Pong Game

One main goal for our background research was to identify ways the game of beer pong can be revolutionized to enhance the overall player experience of the game. At its heart, beer pong is a simple game where players throw ping pong balls into red solo cups [1]. While the game is often trapped in a web of “official rules”, this research aims to find ways to break outside of these traditions to expand upon the game’s potential. We can first look at the conventional table that the game is played on: A cheap, foldable table measuring eight feet by two feet [1]. The official World Series of Beer Pong organization sets these regulations based on the dimensions historically used for the game, but there is no research or game theory behind these “rules”. In fact, the World Series of Beer Pong itself admits that the purpose of these rules is to “[Minimize] possible disputes between participants.” [1] While there is nothing inherently wrong with these rules, many of them will hinder our strategies to enhance the game.

At its core, the game is centered around the experience of shooting a small, lightweight ball into a difficult-to-hit target [1]. This physical, skill-based challenge is widely enjoyable because of its low skill floor and high skill ceiling. New players find few barriers to getting started in the game, and experienced players find endless joy in perfecting their skill and strategy. Even players that effectively “skill out” of the game by developing to the point of making every shot easily find new ways to increase the difficulty or change the experience [1]. In the end, all of this experience is independent of the rules listed below. The more arbitrary rules of the game exist solely to create a regimented competitive atmosphere, which is not the goal of our design [1]. Our goal is to isolate this experience of the game, facilitate it to the best of our abilities, and add extra features to maximize the player’s access to this enjoyable skill-based challenge.

Table 2: Beer Pong Rules that Collide With Project Goals. Rules derived from WSOBP official rules list [1].

Ruling	Details	Collision With Design	Game Design Change Proposed
Table Dimensions: 8’x2’	Sets the standards for table dimensions such that two sides of the table can be played back and forth.	Time and budgetary constraints will not allow this design to employ the proposed technologies across an entire full-length table.	Reduce table dimensions by half, and use only one set of ten cups.
Content of Cups: ⅓-½ full with water	Defines what to weigh the cup down with, and how much.	Water is unsafe for the electronic table, and will affect our ability to detect the ball in the cup.	A heavy washer, or other similar round, metal weight in the bottom of the cup will suffice to weigh it down.
Win Condition: Score 10 cups to win	Defines what the player must accomplish to win the game.	Only one set of cups will fit on the half-length table, so all players will have to play on the same set of cups.	Another scoring scheme will need to be developed. Several options are discussed below.
Bounce Shots: Swatting	When an opponent makes a bounce shot, the opponent can swat the ball away.	Our design encourages bounce shots, since they produce fun light effects.	This rule can simply be ignored. The game will still be balanced, and could become more accessible to beginner players.
Cup Reformation	When the number of cups is reduced to the next perfect triangular dimension (6, 3, 1), the cups are reformed to that triangle at the back of the play area.	While this can be implemented, if performed incorrectly by the player, the table will not function correctly. Since the table cannot verify where the cups are, it is best to leave this out.	Cups will be removed in place, or not at all, depending on the scoring system chosen. No cup reformation will be allowed.

3.1.2.1. Redesigning The Game: Win Condition

The biggest challenge in redesigning the game of beer pong for the Lazer Pong machine is in the game's objective. In traditional beer pong, the players are organized into two teams, and each player is assigned a side of the table [1]. The teams play back and forth, shooting into the cups on the opposite side of the table [1]. When a shot is made in a cup, it is removed and the score is counted. Once all ten cups have been removed, the team shooting into those cups wins the game. Our design will not be able to facilitate this traditional game format, as our table will only have room for one set of cups. The overall goal of the game can be changed without reducing the enjoyment of the game itself, so our design will have to include a modification to this scoring rule.

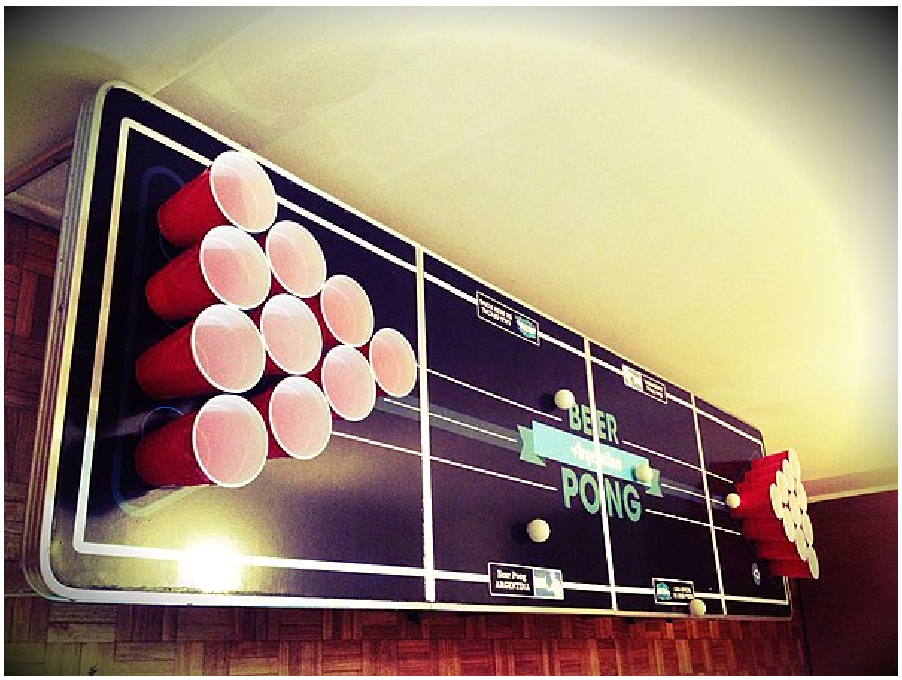


Figure 8: A Traditional Beer Pong Table Setup, Highlighting The Traditional Scoring Mechanic. Used under creative commons [9].

One proposed scoring scheme is to change as little as possible from the traditional scheme. Our design could easily support two or more teams scoring on the same set of cups, with each score counting towards the team that made that shot. Each cup would still be removed when it was scored in, and the game would be over when all ten cups were removed. Then, the winner would be the team that scored the most points. In the event of multiple teams scoring the same highest number of points, the tie could be left as is or a tie breaker could be assigned. This scheme has many advantages, because it keeps much of the gameplay structure that beer pong players are familiar with, while introducing a new difficulty mechanic. The first few shots will be the easiest to score since there will be more cups close together, thus more "scorable area" to aim for. As cups are removed from the play area, the difficulty will increase due to two factors: Cup proximity and scorable area. With fewer cups in play, there will be less scorable area to aim for. Likewise, since players will not be allowed to reform the cups as they are removed, the cups will be further apart, which will reduce the cup proximity, and thus the contiguous scoring area. In this way, this scoring scheme should introduce enough intrigue to justify the drastic change from the traditional ways.

Another proposed scoring scheme is to move away from the traditional scheme completely, and focus on the fun of shooting the ball into the cups. In this scheme, cups would not be removed by the player when scored. Instead, each score would be tracked on a scoreboard, and the first player to reach an arbitrary max score would be the winner. By leaving all ten cups on the table for the duration of the game, the player will no longer find the difficulty of the game increasing as the game progresses. Instead, other methods could be implemented to introduce fun challenges to the player. For example, each round, one cup could be marked as the “bonus cup”, which would reward the player with bonus points for scoring in that cup. Likewise, one cup could be marked as a “penalty cup”, which would either reward the player with no points, deduct some amount of points, or impose some other penalty. The benefit to leaving all of the cups on the table is twofold: The machine does not have to rely on the player correctly removing cups, and having more cups on the table increases the accessibility of the game to more inexperienced audiences.

Both of these scoring schemes would produce an interesting and fun beer pong experience, and ideally both would be employed alongside each other. Once the table was activated, the player would be able to select which game mode they would like to play, and how many players/teams will be playing. However, for the scope of this project, there was only time to employ one scheme. To keep the project scope as simple as possible, the scoring mode in which the cups are left on the table was used. This was the simplest design to code, and thus made it a perfect starting point.

3.1.2.2. Redesigning The Game: Cup Weights

In its original spirit, the game of beer pong was played with beer in the cups [10]. This was done for two reasons: The cups needed weight so they could not be knocked over by the ball, and the game was originally a drinking game [10]. When you made a shot, the other player had to drink the cup. This would reward the winner with a victory, and the loser with a hangover. It was eventually recognized that the game encouraged irresponsible drinking habits, not to mention unsanitary conditions for the ball and the drink. Because of this, the standard moved from filling the cups with beer to filling them with water [1]. They still had to be filled with something to provide ballast, and water would not dirty the ball, so it seemed the clear choice. However, since the design of Lazer Pong will make putting any liquid on the table surface risky, the cup ballast had to be redesigned once again.

As a reminder, the constraints for the cups up to this point are these: The cups must be clear and unobstructed up to ~20mm to allow the laser grid to see through them at that height, the ball must be able to fall to the bottom of the cup so that it breaks the laser grid, and the cups must be able to be removed from the table. This means that the cups could not be fixed to the table, and so required physical ballast placed inside them. This ballast could not add much thickness to the center of the bottom of the cup, and could not rise more than 20mm up the side of the cups. The ideal ballast would be a small, flat disk with high density placed at the bottom of the disk. If this disk had a hole in the center to allow the ball to rest all the way on the bottom of the cup, it would be more than ideal. Luckily, such a disk is already in mass production around the globe: A washer. A ⅞" fender washer is roughly the size of the bottom of the clear cup, provides ample ballast to keep the cup from tipping, and does not hinder the detection of the ball at all. In fact, it actually provides a benefit: The washer causes the ball to always rest in the center of the cup, providing a precise location that is easily aligned directly with the laser grid to maximize visibility. Because of how well this technique complements the other technologies implemented on the table surface, this was the strategy employed to provide cup ballast.

Figure 9: Clear scoring cup with washer weight. Image provided by the Lazer pong project team.

3.1.2.3. Final Thoughts On Beer Pong and Game Redesign

At its heart, beer pong is a fun and enjoyable game. Despite the heavy drinking element, people tend to find the game an accessible, light-hearted and fun-filled experience. Our mission with this project is not to overhaul the game itself, nor to expand heavily on it. The goal is simply to manage the game for the player more directly, and to influence the player to focus on the visceral experience of the game by adding visual feedback to their gameplay. The changes to the game, as discussed in this document, are solely to allow the technologies implemented to track the ball to operate correctly. There is no fault with a full length table, nor with water-filled cups, nor with the traditional scoring system and win condition. However, necessity is the mother of invention, and all of these features of beer pong will have to evolve in order to facilitate the technological specifications of this design. The proposed game design changes are summarized in the table below.

Table 3: Rule Changes From Official Beer Pong Rules.

Previous Rule	**New Rule**
Play Area Dimensions: 8'x2'	Play Area Dimensions: 4'x2'
Content of Cups: ⅓-½ full with water	Content of Cups: 1-2 2" flat washers
Each team has a set of ten cups. When a shot is made in a cup, the cup is removed. Once all ten cups are removed, that team wins.	All players/teams take turns shooting at a set of ten cups. When a player/team scores, they get a point. Once a team scores 5 points, they win the game.
Players may swat the opponents ball away if it bounces off of the table before going into a cup.	Touching the ball while it is in the air is disallowed.
When the number of cups remaining is reduced to 6, 3, or 1, the cups are reformed into a triangle centered at the back of the play area.	Cups are not removed when a cup is scored.

3.1.2. Market Research Overview

From its very inception, our idea has been heavily influenced by the work of others: Our problem-solution, design strategy, and feature selection were all based on a combination of existing market products and previous senior design projects. Through these products and projects, our design has been shaped from a general mission statement down to a focused design philosophy. The process by which this research shaped our project will be outlined here. While the design approaches across the market vary, there are some features that remain consistent:

- **Game Automation**: Every design attempts to, in some way, track the game for the player. Some designs simply allow the player to tally the score themselves using the table, while others automatically detect scores and update a digital scoreboard.

- **Entertainment Lighting**: The one thing every single design has in common is LED lighting. Whether it is simple mood lighting, helpful score tracking, or even complex dynamic music visualization, every similar device employs LED lighting to provide additional entertainment value while facilitating any and all accessibility features.

- **Waterproof Construction**: Since the game is often played in a social atmosphere, most designs are advertised as waterproof or spill-resistant. Given the large number of electronic components that make up these tables, this is also an important safety concern.

By analyzing how and why these features were implemented by similar market products and previous design projects, the feature implementation of this design were focused by this past experience and research. Additionally, since multiple distinct design iterations found these features to be valuable, they were more likely to be helpful in designing a desirable and accessible consumer experience.

3.1.3. Chexal Technologies' RaveTable

The closest market equivalent to this design proposal is the RaveTable, an interactive LED beer pong table designed by Chexal Technologies [6]. This table operates as a traditional beer pong table with the addition of a ring of LED lights around each of the scoring cups, as well as an LED sub-display in the center of the table [6]. The device detects when scores are made using proximity sensors underneath the cups, and similarly detects when cups have been removed. Using these sensors, the RaveTable manages the game by detecting when a score is made, prompting the user to remove the cup, acknowledging when the cup has been removed, and updating the scoreboard on the central display [6]. When considering feature coverage, the RaveTable is the market product that is closest to fulfilling the objectives of this project.

While this product informed much of our early design, there were several drawbacks to consider. First, the table had LEDs placed in uneven, strategic patterns around the table, leaving much of the table unilluminated. This sufficed for the purposes of the RaveTable, but our design would need full table coverage to support the equally full-table laser grid. In the same vein, the RaveTable was designed as a full length table, where our design constraints limited us to designing for a half length table. Finally, since our IR lasers need to pierce the cups in order to see the ball within them, the design is not able to detect when cups are on the table. These trade-offs in design will help our project stand out from these without losing much in the way of final design functionality.

3.1.4. IBBB: A Past Senior Design Project

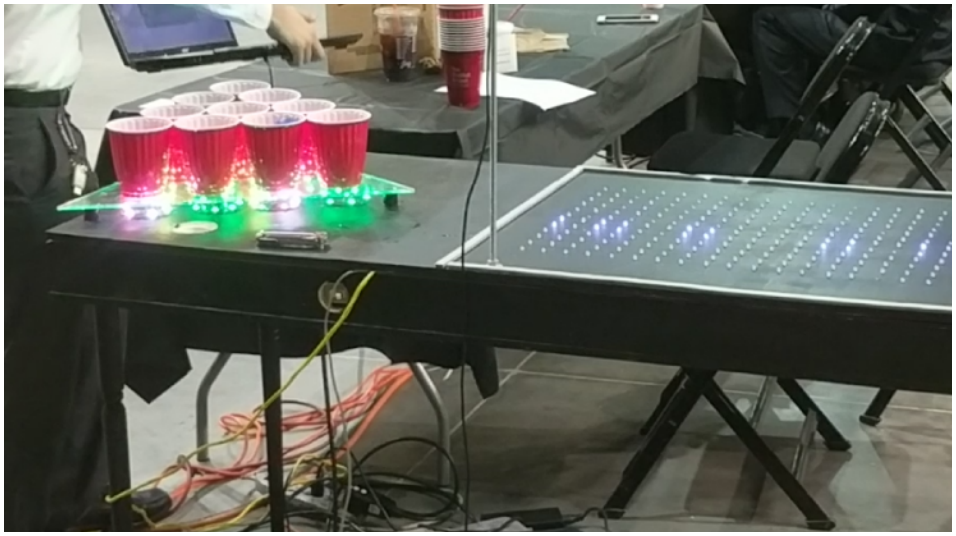


Figure 10: IBBB Demo Prototype. Image of prototype from IBBB Senior Design page [x].

As our first exposure to this quality of Senior Design project, the IBBB was the inspiration for the selection of this project topic. The design is straightforward: A 12x32 central LED display shows ambient lighting effects and the game score, while 10 rings of 6 LED lights underlight the 10 scoring cups and signal when a cup is or is not in play [7]. High-sensitivity pressure sensors under each cup detect when the ball has been scored in that cup, signaling the cup's LED ring to prompt the player to remove it. In the figure above, this can be seen as white rings of lights beneath a few of the cups [7]. Additionally, like the RaveTable, proximity sensors underneath the cup detect when the cup has been removed, and signal the cup's LED ring to deactivate. All in all, this table functions almost identically to the RaveTable. Both tables employ separate LED patterns spaced across the table to display game state information and ambient lighting, and both tables use sensors underneath the cups to detect scores, and to identify when the cups are present.

It was after initially analyzing this project that our group came up with the idea of using a novel optics technique to solve the score detection problem. Pressure sensors worked here, but it seemed clumsy to need both pressure sensors (to detect the ball in the cup) and optical sensors (to detect the cup on the table). To keep the optics spirit of the in-table optics sensors used by IBBB and RaveTable, as well as to satisfy our project requirements for having members in the optics program, we created a design that, using one sensor array, solves all ball detection needs.

3.1.5. Bay Tek Games' Beer Pong Master

One of the only beer pong arcade cabinets that can actually be found in arcades in the United States, the Beer Pong Master is an example of how breaking away from the norms associated with a game can create an all new game experience. Beer Pong Master is an arcade cabinet with one set of ten cups. The player is given a large number of balls, and asked to make a ball in each of the ten cups in as little time as possible [8]. The faster the player can win the game, the more points–or tickets–the player will receive.

While the player still shoots a ball into one of 10 cups to score, many of the other features of the game have been altered to fully utilize the advantages created by the electronic cabinet implementation of the game. First, unlike traditional beer pong, there is no penalty for bouncing the ball into a cup [8]. That is, in traditional beer pong the opposing players get to swat your ball away when you make a bounce shot, but not here. Additionally, the cups aren't removed when scores are made. This means that the player will have to work harder to aim for the last few cups remaining (tracked by LEDs in the cups, which go dark when a cup has already been scored). Finally, since the arcade machine has tracks to deliver the ping pong balls back to the player quickly, the player is encouraged to throw many balls in quick succession [8]. All of these feature design decisions work together to change the form of the game, without losing the spirit. In the end, the player is using their hand-eye coordination to perform the difficult task of shooting a small ball into a small cup at a measurable distance. The rest of the trappings of the game are there for the player's enjoyment, and nothing more.

3.1.6. Miscellaneous Market Products

In addition to the electronic beer pong tables described previously, some smaller devices were found that were designed to enhance the experience of beer pong. Many of these devices were designed to do what Lazer Pong, IBBB, and RaveTable are designed to do, but with a much smaller impact and footprint. These include small surfaces that sit at each end of a regular beer pong table, with the cups on top of the surface. The surface will then perform game management features similar to those above: Lighting rings of lights around the cups when they are in play, signifying to the player when scores are made, and providing mood lighting to the game [11]. Another example of a unique tabletop beer pong accessory is the "Pongbot" created by Pongbot LLC [11]. This small robotic device adds an element of unpredictability to the game by spinning the cups around randomly to make the game more spontaneous. The Pongbot is a motorized platform that features five different slots for cups to be placed into the device [11]. It also has sensors on the bottom to ensure that it stays on the table during gameplay. These devices are a testament to how little can be added to the game to add a large amount of enjoyment.

3.1.7. Cross Comparison

All around, the mission, goals and objectives of this project find their origin in the extensive market research performed herein. Without the inspiration from the

IBBB and its talented team of engineers, our group would not have found a design concept that so resonated with our shared interests. By leading the way with their innovative design choices, they laid the groundwork that we were able to build upon with our own innovative improvements. It was our hope that, through the design steps taken throughout this project, we could prove that we were able to make marked improvements on these original concepts provided by past senior design experience.

Beyond just the IBBB, multiple devices made their way into the vast well of past experience we have chosen to draw from, which have informed the design decisions made thus far. RaveTable, as the only true market product that closely resembles our design, built the foundation of our goals and core features. Because of the success of the RaveTable, it was clear that this design needed to accomplish two main feats: Detect and track the players scores for them, and provide awe inspiring lighting effects. Even beyond the RaveTable though, the decision to focus on these features was unanimous among all similar market products. The Beer Pong Master accomplished the same goals, though with less focus on the lighting. Even the smaller tabletop devices that litter the market focus on these features. Prescribing to the idea that the market represents the consumer's vote on what features are important, the message from the consumer is clear: "Track the game for me, and give me a lightshow."

These various related products and projects greatly informed our feature choice and design, but there were ways in which our design branched away. First and foremost, a majority of the devices on the market represent a full 8' beer pong table with two sets of scoring cups. Even by the standards of the Beer Pong Master, which also only uses one set of ten cups, our prototype will be short. However, our goal is to maximize the fun in using this smaller table by providing a unique experience. The full table LED surface is quite unique in this market, with the next closest being RaveTable and IBBB's partial LED surface in the center of the table and surrounding the cups [6]. While there are some beer pong tables with a full LED surface on the market, as a rule, they do not include any game management features. In addition, the ability to see reactive feedback to the ball bouncing on the table surface will add an arcade experience to rival even established arcade cabinets, like the Beer Pong Master. Music visualization, while not wholly unique to Lazer Pong, is a rare feature for these types of devices, which would produce dazzling lighting effects when combined with our full table LED surface, if it were implemented.

The specific feature comparisons between these comparable devices and the proposed specifications for Lazer Pong are listed in the table below. From a features and specifications sheet standpoint, Lazer Pong profiles out to be a comparable, yet smaller scale device that promises all of the features of the leading competitive products, in addition to a slew of novel features. Likewise, there is little the market regularly offers that is not covered by this design, most notable of which are smartphone control capability and onboard audio. While these are stretch goals this project would strongly consider, they were not included in the final design, and so are omitted here.

Table 4: Feature Comparison for Related Products and Projects. Specifications derived from each device's respective storefront page [6, 7, 8].

Feature	RaveTable	IBBB	Beer Pong Master	Lazer Pong
Surface LEDs	840	444	Dense Display	512
Surface Sensors	40	20	10	48
Scoring Cups	20	10	10	10
Table Length	8'	8'	6'	4'
Table Width	2'	2'	2.5'	2.5'
Scoreboard	✔	✔	✔	✔
Score Tracking	✔	✔	✔	✔
Ball Detection (outside of scores)	✘	✘	✘	✔
Ambient Lighting	✔	✔	✘	✔
Audio	✘	✘	✔	✘
Music Visualization	✔	✘	✘	✘
Smart Phone Control	✔	?	✘	✘
Water Resistant	✔	✘	✔	✔

3.2. Technical Background Research

In its totality, this project covers four main areas of technological specialty: Display, lasers, microcontroller systems, and power management. Across these four subsystems, various techniques and strategies were employed to facilitate the overall objectives of the final design. This section will cover these subsystems, the research done on their operation and requirements, and the novel implementations that we discovered for use in our final design. Through thorough research into these topics, the project and design specifications used to outline the initial design drafts will be realized.

In order to accurately and enjoyably visualize the activity along the table surface, the LED panel needed to be designed to be as responsive as possible, first and foremost. In addition, the LED panel needed to have a high enough resolution to display text to the viewers, so that the game score and menu prompts can be displayed. The objective for the LED-lit table surface was to cover the whole of the surface that is covered by the laser grid, so that it can respond to ball impact anywhere along the grid. To this end, several display technologies were cross compared: An LED array built from individually addressable LEDs, an LCD display, and a dense LED display. The goal for this research was to discover which display technology would provide the best control access, the best surface coverage, and the best resolution, all while being drivable by a simple, low-power microcontroller.

The purpose of the laser grid is straightforward, but due to the safety and security concerns involved when using any laser emitting device, this design needed strong consideration for the devices and methods used to employ this component. Laser safety is an incredible risk to user health, so great effort will be needed to ensure the safest laser technologies are used. Similarly, the laser grid requires extreme security to ensure, along with the health and safety of the user, reliable connection is made between the transmitting and receiving units. Beyond these concerns, the greatest challenge in designing this component was in handling its output. The dense laser count of this laser grid produces a large number of outputs, all of which need to be handled individually.

Between these two subsystems, a robust data path was necessary to allow the LED panel to respond quickly to events recorded by the laser grid. The success of the entire design relies on how quickly events can be displayed to the LED panel once discovered, so a sufficiently reactive control path and routine is critical to the realization of our goals and objectives. Several models were researched and compared, which include a direct-mapping of all I/O devices to the MCU, and independent management of I/O devices by another black box device, which will communicate data efficiently with the MCU via some channel, such as SPI.

3.2.1. Laser Grid

There have been many ideas thought up to detect objects and have been implemented in many different ways throughout technological advancements. Ideas like sensing a difference in weight have been implemented specifically for a concept similar to one of the goals of this project, which was for sensing a ping pong ball inside of a scoring cup using the weight difference of the ball. The idea of the laser grid is to instead use a laser diode module and a photodiode as a photodetector in order to create a sensor using light. Having the laser grid span over the entire table will not only allow for accurate detection of the ping pong ball inside of the cup, but also anywhere it may come into contact with the table. Different versions of this type of sensing have been used in many different applications, so this section will dive into some of those options and discover which one best suits the goal of the laser grid.

The laser grid, in principle, will be a version of a photoelectric sensor [12]. This form of detection has been rapidly advancing and evolving since the conception of semiconductor technology. The photoelectric sensor type that will be used in our design will be for object detection. A through beam form of object detection will be employed in the design of the laser grid. Other options for photoelectric sensors for object detection include retroreflective detection and diffused detection [12]. Some of the major concerns when deciding which method to use include those such as: Detection range, false trips, cost, and type of object to be detected.

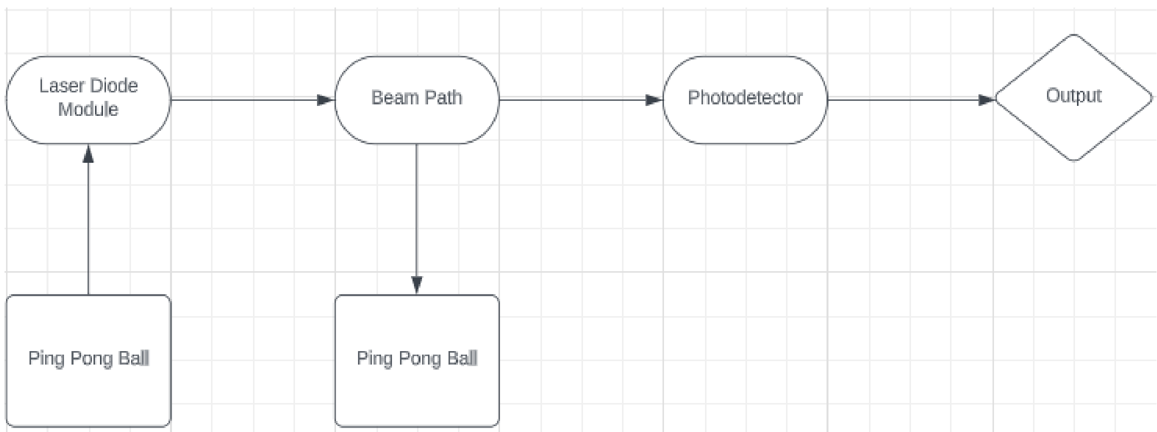


Figure 11: Flowchart of Operation Process for Photoelectric Sensors. Image provided by Lazer Pong project team.

Retroreflective sensor

For a retroreflective sensor the emitter and receiver are located in the same module [13]. A reflecting mirror is placed opposite to the module to take the beam emitted and reflect it back onto the module's receiver [13]. This strategy has a lower cost since it only contains one module instead of two. The detection range of the retroreflective sensor is in the middle of the two methods as it requires the beam to travel from the module to a destination and back [13]. This means that it would have twice the optical path as that of a through-beam sensor. For the Laser Pong Table, the longest distance is 4 feet, 8 if one of the stretch goals were to be accomplished, so doubling the distance traveled is suboptimal for the project. Also, in the design of our project a retroreflective sensor would effectively create two beam paths to be blocked by the ball. This would create issues such as false trips if a ball were to be thrown at an angle that would cause it to break multiple different coordinates of the grid on its descent, or even just break the same coordinate of beam paths multiple times due to the reflected beam path.

Diffuse sensor

Diffuse sensors also come with the emitter and receiver in a single module. However, instead of a reflecting mirror in the retroreflective method, the object that is to be detected is what reflects light back onto the detector [13]. This costs even more, even with the removal of the reflector, and adds additional difficulties. Given that the beam will not be directly aligned to hit the detector, the sensitivity of the detector must be very high to record smaller changes in light intensity [13]. For the residential purpose of the Laser Pong Table, detectors with that range of sensitivity are not practical as they would employ a much higher cost. Along with that downside, another is that diffuse sensors have a shorter range given that the reflected light intensity is already lower, the object must be closer to the sensor to provide the required feedback [x]. When played, the Laser Pong Table will not have the ball hit in the same spot every single time, so that would suggest that a large range of intensities would be received depending on where the ball lands.

Through-beam sensor

In contrast to the other two sensor methods, through-beam sensors have separate modules for the emitter and receiver. Through-beam sensors are a very simple design in that the beam from the emitter goes directly to the receiver with no reflection whatsoever [13]. With the two modules being separate it reduces the occurrence of false trips that would occur from reflection. Given that the two are separate it becomes slightly more expensive than the retroreflective sensor, but in our case still more cost effective than the diffuse sensor. There is also an increase in difficulty with wiring in this method due to the separation of the emitter and receiver. When the object is in between the emitter and receiver, the signal will simply be cut off.

The method that we have opted to incorporate in our project for the laser grid is the through-beam sensor. This sensor has a separate module for the receiver and emitter, which means a higher cost than retroreflective and more wiring. Through-beam is much simpler in terms of how the detection works, which pairs perfectly with the desired goal of this part of the design. There is only one beam path which travels directly from the emitter to the receiver in a straight line [13]. This allows for a much longer distance of detection to be achieved. The position of the emitter and detector can be tightly secured after proper alignment is achieved, since the light will always be traveling to the same destination. The risk for false trips in this configuration is minimal as the range of detected intensity will be very strict and the ball will only have one beam path per emitter receiver pair to block. These reasons along with the details of the other given methods are why we have elected to use through-beam sensors for the laser grid.

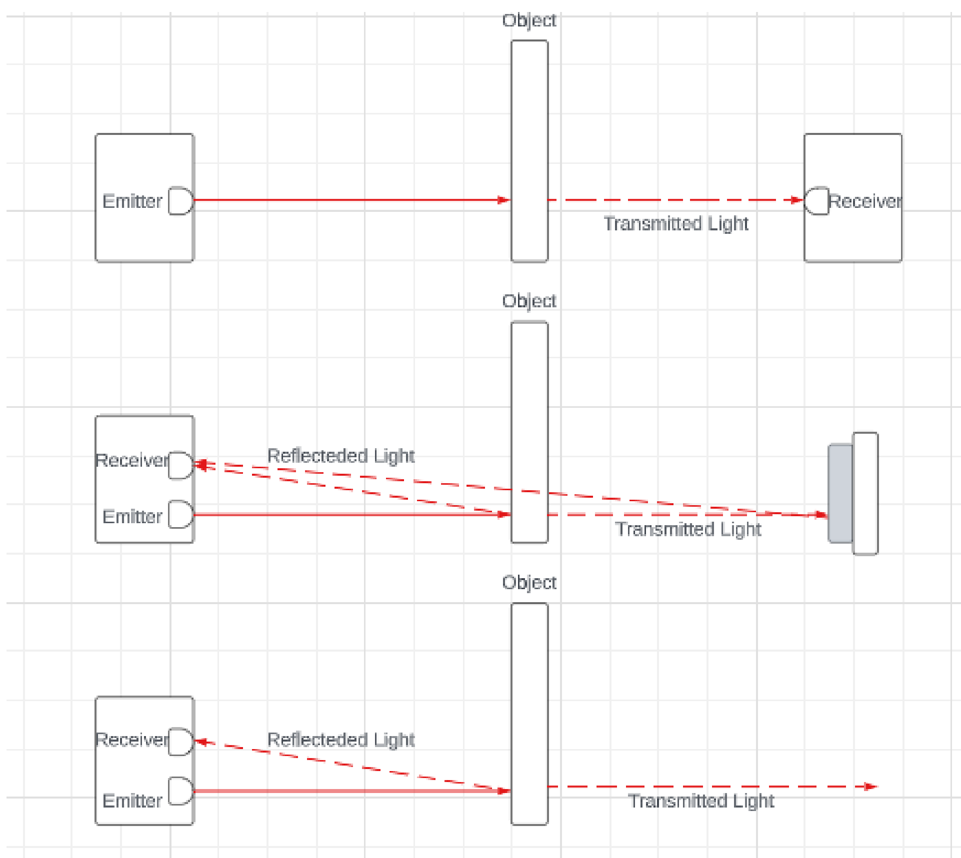


Figure 12: Different Methods of Photoelectric Detection. From top to bottom: Though-beam, Retroreflective, Diffuse.

As it can be seen in the figure above, the through-beam is the most simplistic method of the three. This method accomplishes the goals of our project with ease and much more so than the other two methods. Along with fitting the bill for the technical aspects of the project it also will provide less risk since there is less dependence on reflected light. The fact that the game is meant to be played as a recreational activity and there are lasers involved, health is also a major concern in picking a method. With the two methods that reflect light there is worry that the reflected beam may come too far up from the original beam's position, which is nearer to the table surface. With the through-beam method there is much less concern with reflected light as it will be aimed directly to the receiver, also located close to the table surface.

As discussed in the project description, a total of 48 through-beam laser and receiver pairs will be required to provide full coverage for the table surface. The absolute furthest the lasers could stand from each other would be 1.5”, just under the 40mm diameter of a ping pong ball. With table dimensions of 4’x2’, exactly half of a standard beer pong table, 16 lasers 1.5” apart would cover the short side and 32 lasers at the same spacing would cover the long side. While increasing the laser density would likely increase the accuracy with which the ball position could be determined, managing this high number of signals could prove problematic. Thus, the minimum number of lasers will be designed to fulfill the project goals and objectives, and a stretch goal for greater sensor density will be considered if managing these signals proves more trivial than anticipated.

The three methods of through-beam, retroreflective, and diffuse sensors mentioned above are all viable photoelectric sensors. However, for the purpose of achieving the goal of ball tracking across the entire table, the through-beam sensor is the most viable option. Through beam sensors provide the most direct beam path, which is the best solution for the object to be detected in this case. It also is the most cost-effective method, and since this is to be a product that would want to be on sale for the public, this allows for easier marketability.

3.2.2. Surface Display

The greatest technological marvel of this design to the user will certainly be the edge-to-edge surface display across the play area. This display will dynamically light up to indicate the ball activity across the table surface, to relay crucial game information to the user such as menu prompts and game instructions, and to dance with any ambient music. Given the importance of this display to the overall experience of the user, we are looking to create the optimal design for the surface display, which will work hand and hand with the laser grid to achieve these dynamic lighting features. The primary objective is to seamlessly integrate this display with the IR laser grid while ensuring a visually pleasing and captivating experience for the user.

To ensure the display meets the minimum resolution requirements, its resolution must be no less than 32x16 pixels. By achieving this pixel density, guaranteeing that each cross section of the laser grid will be faithfully represented, facilitating precise and accurate visualization of data and graphics. The importance of a thoughtful pixel layout to optimize clarity and avoid any unwanted visual artifacts ensures our consumers have a smooth and enjoyable experience. In addition, the display must also meet the response time requirements of the design. While this might not be an issue for any modern dense display, simpler programmable displays may produce substantial response time. The selected display technology must also conform to the power standards set aside for this project. Some more advanced displays may draw too much power, and may hurt the energy efficiency of the design. Finally, the display should be drivable from a simple control system, with no more than an average microcontroller or simple microcomputer.

Beyond the straightforward requirements and constraints, other important factors to consider are the visual performance, response time beyond what is required, and energy efficiency. Each display technology has its tradeoffs between these factors, and so must be carefully cross compared to identify the ideal technology. In the end, this ideal technology will be the one that produces the best surface response for the lowest resource expenditure.

Display Technologies

There are several display options that could be utilized when designing the table top, so all options which meet our specifications should be considered. The simplest solution would be a fabricated panel consisting of an array of Light-Emitting Diodes arranged in a grid. This solution would be designed and built for this project using individually addressable LEDs and would be driven by simple graphics library routines on the central microcontroller or microcomputer. Addressable LED panels such as these are often employed to enable versatile applications such as simple dynamic lighting displays and signage, which utilize precise control over the individually addressable LEDs to display routine graphics patterns using simple control schemes [14].

Liquid Crystal Displays are another popular display used in smartphones, televisions, tablets, and computer monitors. LCDs are made up of several layers, including a backlight, glass substrate, polarizing filters, color filters, and liquid crystal cells. The liquid crystal cells are placed tightly between the layers of glass. Once an electric field is applied to the liquid crystals they will align themselves in different orientations allowing for different amounts of light to pass through. The first polarizer aligns the light and the second polarizer either blocks or allows the light based on the orientation of the liquid crystals. Red, green, and blue color filters are placed on each pixel to create different color images. LCDs can have a pretty high resolution and sharper image depending on the pixel density. These displays also have a response time which is the time it takes for pixels to change states, slow response times result in a motion blur [15]. LCDs have evolved over the years but are not the optimal for this design because of the complexity of the construction.

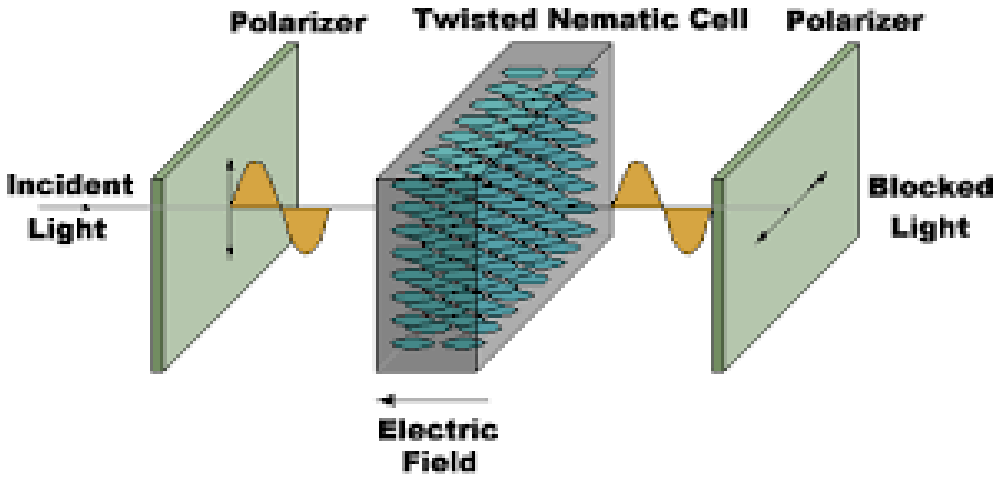


Figure 13: LCD Display Technology Diagram. Image from MIT CSAIL lecture on LCD technology [16].

As the dominant display technology for the modern television, LED dense displays provide a high resolution and full color range at the cost of higher power draw and predesigned form factors. Each of these display technologies have their own advantages and disadvantages that need to be considered to create the ideal design. LED displays are known for having a very low power consumption compared to other display types. As with all LED displays, each pixel is addressable and can be turned on and off, which is one reason these displays consume less power than competing technologies [17].

The backlight for these displays can either be edge-lit or direct-lit. Edge-lit backlighting is where LEDs are positioned along the edge of the panel and the light is guided to the display screen with diffusers or light guides. These edge-lit LED displays tend to have a more uniform brightness and also tend to be thinner. Direct-lit displays, on the other hand, have an array of LEDs spaced out around the entire display. Direct-lit displays tend to have good contrast because there is more individual control over each area on the display. Dense LED displays generally have excellent color accuracy and cover a large color gamut [18]. They are also very thin and lightweight while still being one of the brightest display types on the market. The lifetime of LED displays is much longer than its competitors. This display type could be the most ideal for our project, as it is thin and bright while also being reliable.

Comparison of Display Technologies

Table 5: Comparison of Display Technologies [19, 20, 21].

Display	LED Array	LCD Dense Display	LED Dense Display
Picture Quality	Limited by fabrication techniques	Sharp images	High Contrast
Color Depth	24 bit	8 bit- 24 bit	24 bit
Energy Efficiency	High	Moderate	High
Dimensions	Built to specification	16:9 typically, dimensions in regular increments	16:9 typically, dimensions in regular increments
Viewing Angle	<160 degrees	<120 degrees	<160 agrees
Refresh Rate	1920hz-3840hz	100hz-240hz	1920hz-3840hz
Resolution	16x32 - 36x72	<1920 x 1080	<3840 x 2160
Average Lifespan	100,000 hours	30,000 hours	50,000 hours
Screen Size limitation	Built to any size	Limited to standard or wide-screen ratio	Limited to standard or wide-screen ratio
Environmental Impact	Low Power, Low Material Use, Very Eco Friendly	Higher Power, Eco friendly	Low Power, Eco friendly

After analyzing the differences between LED and LCD technology, it is clear that, for the accessibility, safety, and longevity of a device with this design, LED technology is superior. LCD technology has the unfortunate issue of burn-in, which can cause longevity issues with the device. LCD panels also tend to have larger and more unwieldy frames, given the large number of controlling components necessary to oscillate and drive the LCDs. For simplicity of design, versatility of implementation, and long-lasting capability, LEDs will be the perfect technology to use for the light-up display on the table surface.

With the display technology chosen, the next decision becomes which form of implementation to use. LEDs are small, simple and addressable, but these come in many forms and packages. The primary packages that will be considered here are linearly linked and addressable LEDs in the form of LED light strands, and dense LED displays in the form of pre-packaged screens.

LED dense displays have a wide range of applications, most commonly used in televisions and smart devices like phones, tablets, laptops, etc [22]. They are constructed by having modules that are connected together to create a unified screen. Each of these modules can be resized or reconfigured so the screen can easily be made into many different sizes. LED dense displays usually have a high resolution because each of the modules can have many LEDs which will create a sharper image. LED dense displays also often cost more to produce because they have more of a complex assembly process, more modules, and higher component requirements.

16x16 pixel Array 1080p LED dense display

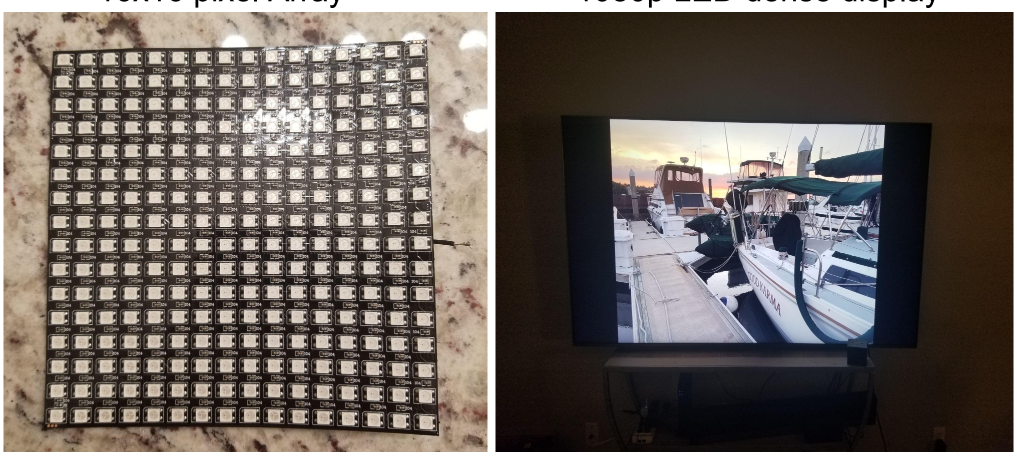


Figure 14: LED Array vs Dense Display. Images provided by Lazer Pong project team.

An LED array is a much simpler designed LED dense display. Arrays are configured of single LEDs without any specific grid structure and can be arranged in any particular pattern. They are usually not as flexible for major modifications as screens are. These do not require as much of a complex input as LED dense display do and can function on a simple controller, whereas a screen will require a complex input, such as HDMI or Display Port. LED arrays are mostly used for signage and other versatile designs that could require any specific shape or design. These arrays do not have as good resolution as the LED dense display because of their simple design, though LED arrays are much cheaper to produce, which is optimal for this project. As long as the necessary images can be created with this simpler display, an LED array fabricated for the surface display of the Laser Pong table seems to be the most ideal solution.

Table 6: Cross Comparison Between LED Implementations [19, 20, 21].

Device	Array	Dense Display
Construction	Individual LEDs arranged in a grid	Matrix of LEDs mounted on display panel
Resolution	Lower, Limited pixel density, Pixel spacing visible, Suitable for simpler graphics	High, Greater pixel density, Pixel spacing almost invisible, Suitable for detailed visuals
Pixel Density	Up to 9 LEDs per 4 square inches	Up to 7200 LEDs per square inch
Cost	$10-$100	$100-$1000
Usage	Signage , decorative applications, artistic installations	Large scale displays, video walls
Viewing Angle	Limited, Lesser visibility at extreme angles	Wide, Consistent picture quality from any angle
Maintenance	Easier to Maintain, LED replacement if needed	Requires professional installation, regular calibration

Light Diffuser LED Array

A light diffuser is an indispensable component when working with LED arrays, as it serves a multitude of essential purposes that greatly enhance overall lighting performance and user experience. LED arrays consist of numerous individual light sources densely packed together, and without a diffuser, these LEDs can create harsh and uneven light distribution. The diffuser's primary function is to spread and scatter the light emitted by the LED array and ensure a more uniform and even distribution of light across the entire surface [23]. By doing so, it minimizes the appearance of bright spots and shadows, resulting in a softer and more pleasant illumination.

Additionally, a light diffuser plays a crucial role in reducing glare, which can be particularly bothersome in direct line of sight when dealing with the intense and concentrated light produced by LED arrays. By dispersing the light, the diffuser lowers its intensity and softens the overall appearance, making it easier on the eyes and preventing eye strain. The diffuser also helps eliminate hotspots that may occur when individual LEDs emit varying levels of brightness. By blending the light from multiple LEDs, the diffuser creates a smoother and more visually appealing lighting effect. This, in turn, enhances the overall aesthetics of applications, hiding the individual LED points and providing a clean and seamless appearance.

In RGB LED arrays, where individual LEDs emit different colors, the diffuser is especially valuable as it helps blend the colors together, creating smooth color transitions and gradients. This is crucial for applications like color-changing lighting displays, where a seamless transition between colors is desired. A diffuser can soften sharp shadows that may be cast by the individual LEDs, making it essential in applications such as photography or video lighting, where harsh shadows can be unflattering. It also helps create a more subdued and diffuse glow that enhances the overall ambiance of the space, making it perfect for mood lighting or architectural lighting.

Individually Addressing LED

When examining the LED array technology, it is important to understand how these LEDs are addressable and how they function. Most addressable LED arrays use WS2812B programmable LED lights. In recent years, the WS2812B programmable LED lights, also known as NeoPixels, have captured the lighting world's attention with their compact size, vivid colors, and incredible flexibility. These tiny modules house separate red, green, and blue LEDs, accompanied by a microscale control chip that grants them "smart" capabilities [24]. As a result, each LED can be controlled individually and linked together to form a continuous chain of lights. Setting up a WS2812B LED strip for use with a microcontroller board is a straightforward process, requiring just three connections: a data line, power source, and ground [24]. Thanks to numerous libraries available, microcontrollers can easily manage the LED's illumination [25].

Within each WS2812B LED unit, individual red, green, and blue LEDs can emit light at 256 different brightness levels, represented by eight bits for each color channel (24 bits in total). The microcontroller transmits an eight-bit sequence for green, followed by eight for red, and another eight for blue to the first LED in the chain [26]. Additionally, the microcontroller transmits an address offset. When an LED receives this display data, it checks to see if the address value is zero. If it is not, it decrements the address by one and passes all of the display data to the next LED [26]. This continues until the address value is reduced to zero, at which point the RGB values are applied to the component LEDs inside the device. This process is applied for each LED in the chain that needs to be lit, resulting in a harmonious and synchronized chain of illuminated lights.

To communicate binary signals to the LEDs, the microcontroller employs pulse width modulation (PWM) to produce a rectangular signal to communicate each of the binary values in sequence. A one is indicated by a high signal lasting .8

microseconds, followed by a low signal of .45 microseconds [26]. On the other hand, a zero is conveyed through a high signal of .4 microseconds, followed by a low signal of .85 microseconds [26]. By accurately controlling these timing sequences, the microcontroller effectively conveys the desired colors and brightness levels to each LED. The data stream commences with the most significant bit, ensuring that each signal includes leading zeros to maintain a consistent length for each color element (GRB) [25, 26]. Additionally, a reset low signal lasting 300 microseconds or more is sent by the microcontroller to initiate a new data transmission cycle, allowing the LED chain to synchronize and process the data sequence anew [25, 26].

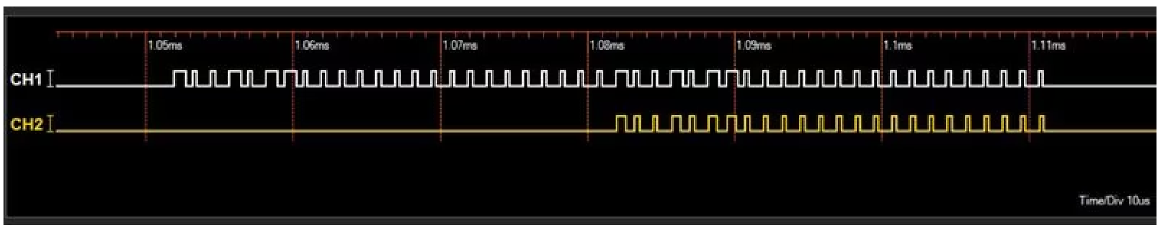


Figure 15: PWM signal to drive WS2812B LEDs. Image from Arrow.com [26]

Although programming WS2812B LEDs with precise timing can pose challenges, readily available libraries abstract this complexity, making LED programming accessible even to developers without extensive experience in assembly programming. These libraries provide functions like delay(), delayMicroseconds(), millis(), and micros(), enabling users to experiment with LED programming and explore its possibilities [25]. While it may not be necessary to delve deeply into the intricacies of controlling WS2812B LEDs to employ them for simpler electronics designs, understanding these fundamental principles will assist us in problem resolution when it comes to the build stages of this design.

The conclusion of the display research provided for this design is that the Ideal technology for the surface display of the Lazer Pong table is a custom-built array of individually addressable LEDs. This LED array will transform an otherwise normal pong table top into a visually captivating centerpiece for this project. The ability to customize the lighting effects using information from the game state will bring a dynamic element to the game, and the LED array's versatility and programmability will enable these visual effects to be efficiently designed. These are very energy efficient, generate minimal heat, and have a much longer lifespan compared to other display types. However, the reduced pixel density of this display technology in comparison to the dense display technologies will reduce the variety and magnitude of visual effects the table surface could produce. This solution would be the classic embedded electronics solution: Simple, efficient and easy to control, yet compromising. Compromise can inspire designers and creators to craft awe-inspiring lighting effects, though. By experimenting with various color combinations and brightness levels, one can create captivating visual displays that will infuse any space with an almost magical ambiance [26].

In the course of Senior Design 2, it was discovered that the drivers for these WS2812B leds are only compatible with Arduino development platforms, and thus would be incompatible with our design without writing our own drivers, or even bitbanging the bespoke pattern. We decided instead to include a driver-compatible Arduino platform in our design, which receives the sensor information from our electronics, which still operate as intended.

3.2.3. Controllers and the Datapath

The data flow of this design is fairly straightforward, but caused some complications when it comes to the control scheme. When a break occurs on the laser grid, it sends an array of active-high signals to the control scheme from any receivers that lose signal from their transmitters. The controller uses these signals to determine which intersections of lasers are broken, and where those breaks correspond to locations on the table. These will then be translated to a sequence of graphics library routines, which will subsequently be pushed to the addressable LED panel using a prewritten graphics driver [25]. The data flow diagram below describes the general structure of this system.

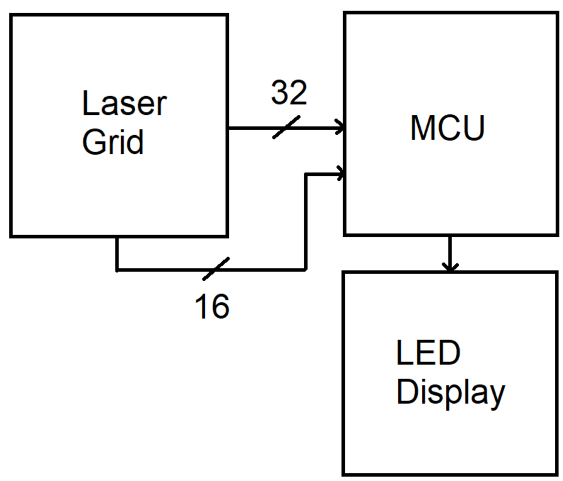


Figure 16: Block Diagram for Data Flow To and From The MCU. Image provided by the Lazer Pong project team.

The original design was as simple as this, but it was discovered that the LED light drivers are incompatible with our custom PCB environment. To resolve this, an intermediate device was added between the MCU and the LED display. This Arduino is fully compatible with the LED display, and receives the sensor information from our electronics.

Given the simplicity of driving the LED display, the control needs for this project lie mainly in managing the input from the laser grid. 48 signals in total are sent to the control scheme by the laser grid: 32 signals given by the X-coordinate sensors, and 16 given by the Y-coordinate sensors. Additionally, since there is no way to guarantee that only one sensor will be tripped in each direction, using encoders will not be a valid solution to efficiently deliver the input from this laser grid to the MCU. A controller needs to view all 48 of these signals simultaneously to determine the coordinates of any and all breaks in the sensor grid. Then, this coordinate information is sent to the Arduino device and combined with the game state to decide what graphics to push to the LED display, if any. Therefore, if a break is detected within a scoring cup, a score will be recorded, while a break anywhere else on the table surface results in a simple LED light trick.

Datapath 1: Laser Receivers to MCU

While technologies exist to simplify this high-width data flow, they come at the cost of loss of resolution. Encoders could have been used to reduce the 32b X-signal down to 5b and the 16b Y-signal down to 4b, but the system would behave unpredictably when multiple breaks were created along one plane, such as if someone set their hands on the table or decided to throw multiple balls at once [27]. Similarly, multiplexers could be used to put many signals on one input line and poll them at regular intervals by feeding the select lines with a counting signal [28]. This solution would be more viable than using encoders, but would come at the cost of complex timing algorithms and could potentially introduce unnecessary latency. The only other viable strategy to simplify the data before it made its way to the MCU would be to use another controller to parse the signal locally, then transmit coordinates of any breaks identified to the MCU using a low-pin communication line, such as UART or SPI. However, this could introduce additional latency, and would add another layer of vulnerability to the design. If the transmission failed or a bit was flipped erroneously, the MCU could receive erroneous coordinates, which could destabilize the current game state. Additionally, this intermediate controller would also need to accept 48 GPIO inputs, completely ignoring the original issue of avoiding that many connections. In the end, connecting all sensors to GPIO pins and polling these pins produced the best results.

There are some major advantages to having all 48 laser receivers connected directly to the MCU. Mainly, this allows the MCU to use simple algorithms to determine where the intersections of the receiver interrupts are located. By setting the GPIO pins connected to the receivers to pull down the input signal, then polling those pins at regular intervals for a high input signal, the MCU is able to identify intersections using an array of bits defined by the relative indices of the receivers (32x16 bit array). Using the pins as a mask, the MCU can record the intersections of those masks in the array of bits, which it then communicates as break locations to the game routine on the Arduino. This is the simplest algorithm that could possibly be implemented to solve this problem. On a 16-bit microprocessor, this was done with a single array of 32 integers representing the X-coordinate receivers, with each bit of each integer representing the

Y-coordinate receivers. Masking the integers using the Y-coordinate receiver flag values is an O(N) operation, with N being the number of Y-coordinate receiver flags. This algorithm is represented in the figure below.

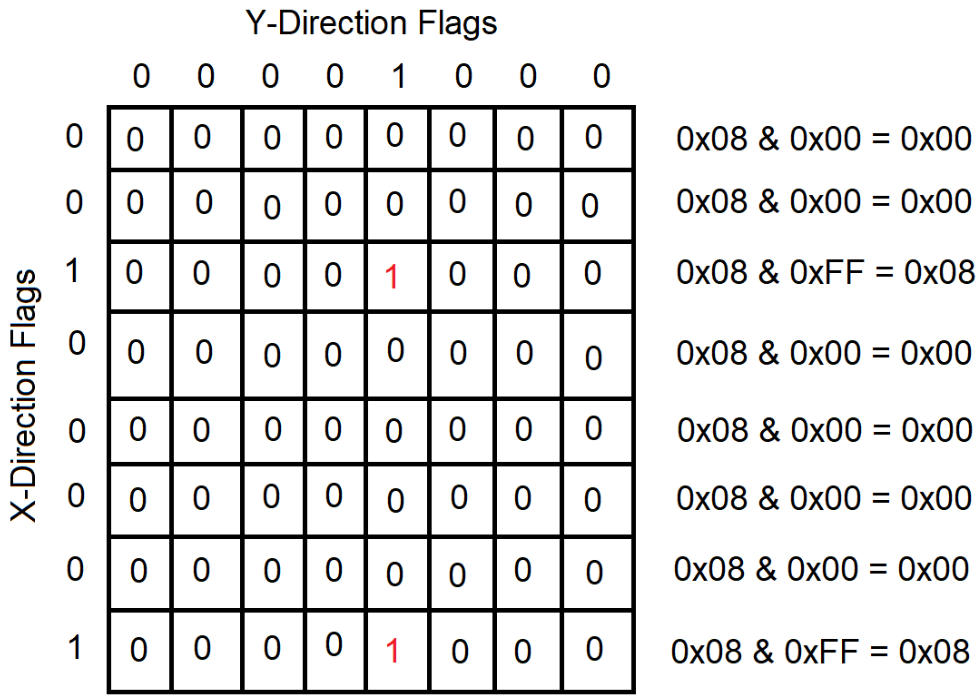


Figure 17: Bit Masking Using GPIO Port Flags, Simplified To 8bit x 8bit

On the other hand, there are trade-offs to consider with this strategy of direct mapping. First, having a need for 48 total GPIO ports limits the pool of possible components to select for the MCU microcontroller. There was a chance that this increased the cost of the part, made it challenging to find a quality part in stock, or forced us to use a part that compromises on other areas of the microcontroller. Second, utilizing 48 GPIO pins requires running 48 traces for these devices, along with all of the other combinational circuits required for the PCB. This was not impossible, but was very challenging, and required two things: The connection points for the wires to the receivers themselves had to be dispersed around the board, and the board itself needed to have proper spacing consideration for these traces. This all could have incurred more cost and potentially greater time to produce the PCB, as well as greater odds that an unknown issue occurs with the PCB.

While there certainly were challenges with this method, the benefit it produced in streamlining the control scheme far outweighed the challenges it created. Connecting and lining up 48 PCB traces is far from ideal, but the convoluted components or controllers necessary to simplify the datapath are much less desirable, as is coming up with a more abstract, potentially object-oriented algorithmic solution. As long as the PCB can be drafted, which it could, this scheme would be the superior method of data flow organization.

Datapath 2: MCU to LED Array

For the LED display itself, each pixel across the entire display is individually addressable from one control pin [26]. The LEDs are connected in a chain, such that a control signal can be created at one end of the chain that will propagate down the whole device [26]. Using a prewritten LED driver for embedded C called FastLED.h, the control program is able to access the brightness and RGB quality of each LED [25]. By utilizing algorithms with the knowledge of the dimensions of the panel and the snaking path of the LED strip, the system is able to draw whatever patterns are needed.

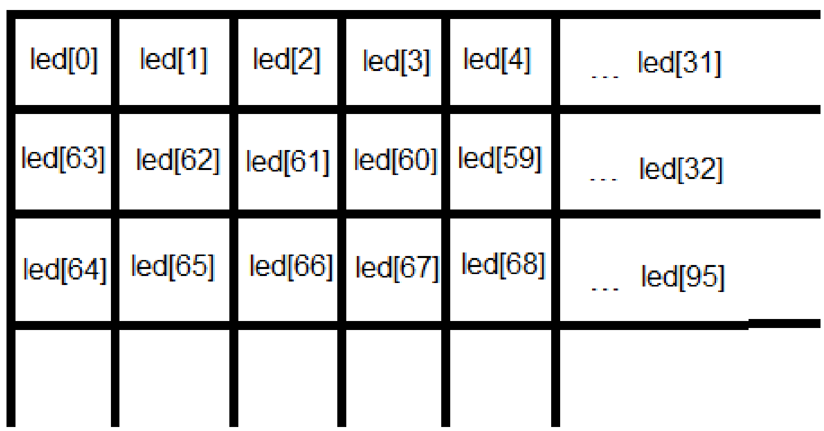


Figure 18: LED Addressing Scheme Using Snaking LED Strand

There is only one way the control program can interact with the LED array: Any individual LED can be set a red, green, and blue value from 0 to 255, with 0 as off and 255 as maximum brightness [24]. This value is then communicated to the LEDs using a proprietary single line communication protocol, similar to UArt, except using PWM for high/low values [26]. In essence, four values are fed to the first LED: a red value, a green value, a blue value, and an address [24]. The first LED then checks to see if the address is zero. If the address is not zero, it decrements the address and passes the values on to the next LED [26]. This continues until an LED sees an address value of zero, or the data falls off the end of the array [26]. Using this principle, the control program needed to establish a set of graphics library commands to draw the simple patterns necessary to represent the game events recorded by the laser grid. Control of the LED array was left entirely up to the software, with the data control simply keeping a single GPIO pin set to output for the LED device.

3.2.4. Power Delivery

The most critical step in ensuring the ideal performance of each electrical component in the design of the Lazer Pong Table was establishing a power supply of sufficient quality. Each electronic device needs to receive power at a certain voltage level to operate properly, so it is important to note these requirements, which are typically given in the respective device's datasheet or cutsheet. Along the same vein, those electronic devices also draw a certain range of current from the voltage source. Knowing both of these quantities allows for an engineer to carefully craft an appropriate power supply system that can give each and every necessary device the power that they need. However, before that system can be designed for this project, each factor of the power supply network must be carefully understood. This will ensure that damage to the other components will be avoided, their function will be unimpeded, and power efficiency will be maintained.

A well-designed and managed power supply system ensures that every electronic component of a whole network of devices operates correctly, efficiently, and safely. To achieve such a system for power delivery, it will be important to understand the types of power, different techniques used for supplying those types of power, and how to correctly manage the levels of the system's distributed power. Once all of these aspects that go into a power supply are completely acknowledged by the engineers and designers, then their final product will no doubt perform and function at its best and with precision and accuracy. The Lazer Pong Table will be no different, as through the following discussions on power as a crucial resource, we will demonstrate how we can improve our knowledge on power and as a result produce a sufficient system ourselves.

Mains Supply vs. Battery

To fully understand how power distribution systems are developed for products, it will be good to start with understanding the types of power supplies that exist. There are two primary types of sources of electrical energy: AC from the mains supply and DC from cells or batteries [29]. It is imperative to know the differences and benefits of both, as they each can lead to unique power system designs.

Mains electricity, or otherwise known as utility power or wall power, is the general-purpose power supply that is delivered to buildings through the national electric grid [30]. This electrical energy is distributed as alternating current (AC), flowing through transmission lines, typically at very high voltage to reduce the resistance of the lines themselves when distributed across large distances [30]. Then once the energy reaches its destination, it can be easily transformed down to the needed voltage level of the powered device from a wall outlet. In North America, the most common voltage and frequency of mains power is nominally 120 V and 60 Hz [30]. While this may seem like a very high level of voltage when compared to the Lazer Pong Table's device requirements, remember that this AC voltage is easily converted to the needed voltage levels through the use of dedicated converter circuits or components.

Alternatively, batteries are another common method of supplying power to a device. Batteries are able to store power within a certain shaped cell through the use of different chemicals, often alkaline or lithium, and deliver power through direct current (DC) [31]. This means a battery can provide a constant level of voltage and current to a device, albeit typically at lower levels compared to mains power. The common battery shapes of AA, AAA, C, and D are only able to output a nominal 1.5 V, and a car battery is able to output up to 12.6 V on its own [31]. Even though many of the components of the Lazer Pong Table require low levels of voltage to function, using batteries to power each of them will not be very efficient. This is mainly due to how battery capacitance works. This is a rating that all batteries have that measure approximately how long the battery can provide power based on how much current the load draws in.

Table 7: Ratings of voltage and capacity for common battery types [32].

Battery Type	Voltage Level (V)	Capacity (mAh)
AA	1.5	2400
AAA	1.5	1000
C	1.5	6000
D	1.5	13000
9-Volt	9	500
Car Battery	12.6	48000

The Lazer Pong Table is estimated to support a maximum current draw of 30 A for a voltage level of 5 V. Assume at least four D type batteries were used to provide a power supply. They will need to be wired in series to increase the voltage level additively to 6 V. Since they would be in series, each battery will be drained simultaneously at the same level of current. Consequently, this also means that, despite having multiple batteries, overall battery capacity is not increased. So if each individual battery has a capacity rated at 13000 mAh, then the entire series of batteries will have that same capacity. The following equation determines the time it takes to discharge a battery [32]:

$$Discharge\ Time\ =\ Battery\ Capacity\ /\ Load\ Current$$

With the D type battery rating of 13000 mAh, then at the absolute maximum current of 30 A, then these four batteries will only last about 26 minutes. The Lazer Pong Table will need the ability to function for long periods of time to facilitate long play sessions, so this battery lifetime is unacceptable for the design, especially if it ends up causing interruptions for the players. Most batteries are also non-rechargeable, so they must be replaced every so often. Having to replace the batteries every half-hour is incredibly tedious, inconvenient, and accrues additional costs for maintenance. All of these factors will significantly hamper the Lazer Pong Table's longevity as an enjoyable product.

With the options in front of us, it is clear that choosing the method of supplying power for the Lazer Pong Table using mains power will be much more efficient than using multiple batteries. Mains supply will provide a consistent and reliable flow of power, which will contribute greatly to the sustainability of the Lazer Pong Table and its continuous operation over long durations. Knowing that AC power will be preferred in the overall power design, it then becomes important to know the intricacies in converting that form of voltage to DC voltage, and how to manage that transformed voltage to remain just as consistent as the mains supply is to stay at the appropriate levels

AC to DC Converters

When drawing electrical energy from a typical wall outlet in the United States, recall that the voltage level is nominally at 120 VAC [30]. No digital electronics are designed to handle AC voltage, so it will be important to change the voltage type to DC. However, assuming a complete switch to 120 DC, this is still a very large amplitude for many electrical components to handle, let alone the components that will be integrated on the Lazer Pong Table. Both of these challenges are why a converter is necessary to serve as a bridge between the mains supply drawn from a local outlet and the end devices.

AC to DC Converters are primarily used to decrease the AC voltage input down to an appropriate level of output, and to regulate that alternating signal into a DC signal [34]. For the Lazer Pong Table, it will be necessary to achieve a level of around 5 V of DC voltage, which is the maximum value required by the electronic components that are planned to be implemented. But how is conversion accomplished?

At a high level, converters will first take in some level of AC power and then decrease the amplitude of that AC signal down to the desired amplitude of the DC voltage [34]. Of note, the power is still AC at this point. For example, a level of 120 VAC will be transformed to a level of about 5 VAC, not 5 VDC. This is accomplished through the use of a transformer. Once the amplitude of the AC voltage is turned down, it will then be rectified into DC voltage using a full-wave bridge rectifier [34]. A full-bridge rectifier is composed of four diodes connected in a special diode bridge arrangement [35]. Alternatively, a bridge rectifier integrated circuit (IC) can also be used if the power ratings are supported by the microdevice. This setup will essentially invert the negative peak of the alternating current to make it flow in one direction [35]. A capacitor is then used to reduce the transience in the voltage level, acting as a low-pass filter and smoothing out the signal as it is charged and discharged [35]. Finally, a voltage regulator is used to stabilize the voltage further at the desired level, which for the Lazer Pong Table will be at about 5 VDC. This can be done through either the use of a zener diode or a voltage regulator IC [34, 35].

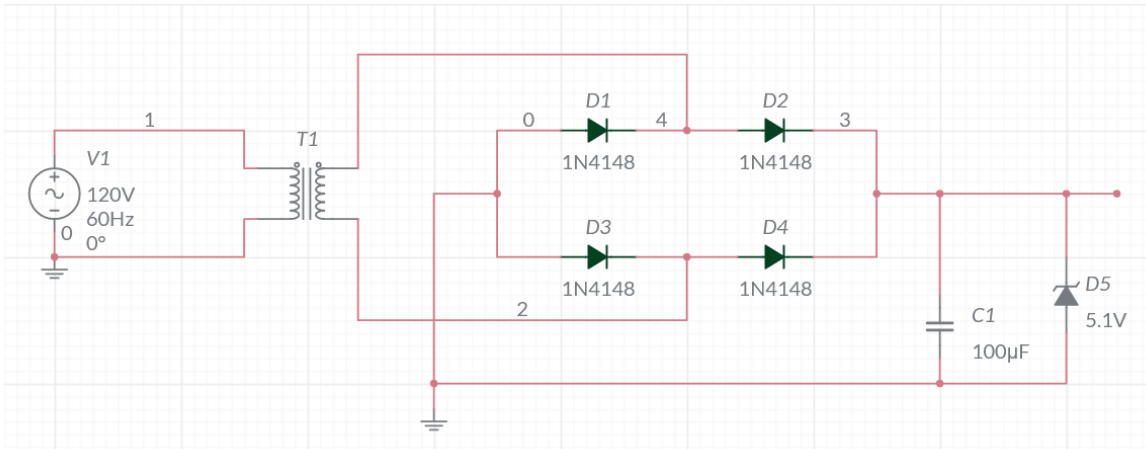


Figure 19: Possible AC to DC Converter circuit. Image provided by Lazer Pong project team.

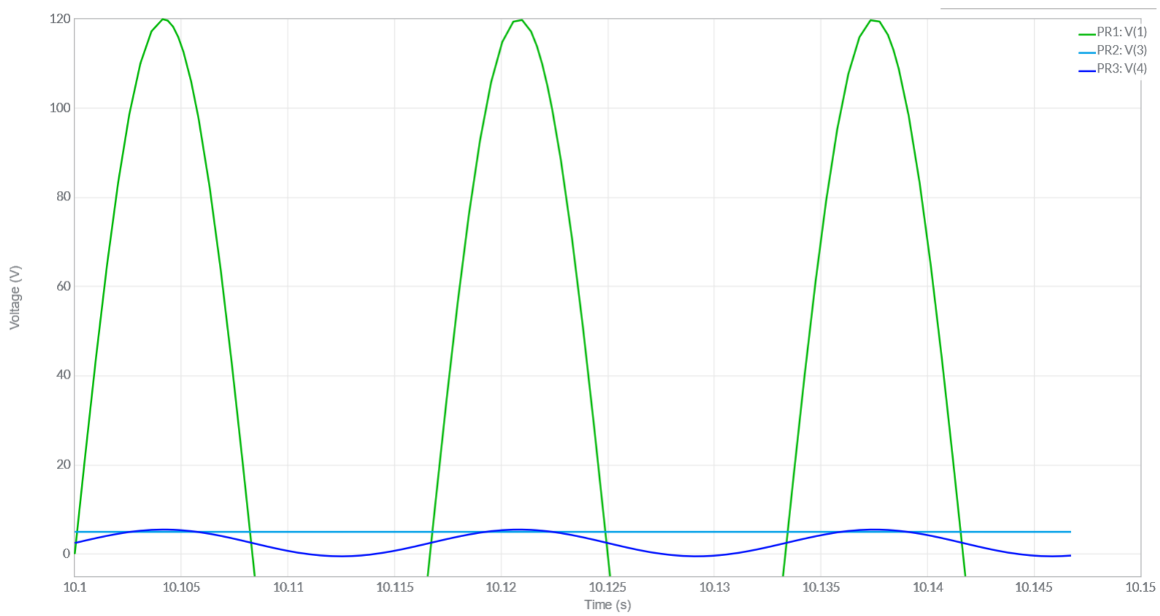


Figure 20: Signal analysis of the converter shown in Figure 19. The green line represents the initial AC voltage signal, the blue line represents the AC voltage signal after the transformer, and the cyan line represents the DC voltage signal after the diode bridge, regulated by the capacitor and zener diode. Image provided by Lazer Pong project team.

Voltage Regulators

Once the primary power supply is able to provide 5 V of DC power to the rest of the Lazer Pong Table, the next thing to consider is that not every component will operate at that voltage level. While the LED display may require an input of at least 5 V, the MCU, controllers, and laser transmitters/receivers may all require an input voltage of much less, typically 3.3 V [36]. Rather than needing several AC to DC converters to convert the wall power down to each of these DC voltage levels, instead wiring additional DC to DC converters or voltage regulators in parallel to the original output can be used to take the primary 5 V and convert to the lower voltage requirements. These DC to DC converters will take in some input voltage and generate a different output voltage. Depending on the magnitude of the required voltage drop, the type of regulator used with the converter can either be linear or switch-mode [37]. Since the voltage drop between the input and desired output is relatively small, a linear regulator can be safely used. These use a resistive element to simulate the voltage drop, reducing the input voltage down to the desired level [38]. Through the use of multiple of these additional regulator circuits, every major component of the Lazer Pong Table can receive its necessary input voltage of 3.3 V or 5 V and possibly any other value in between.

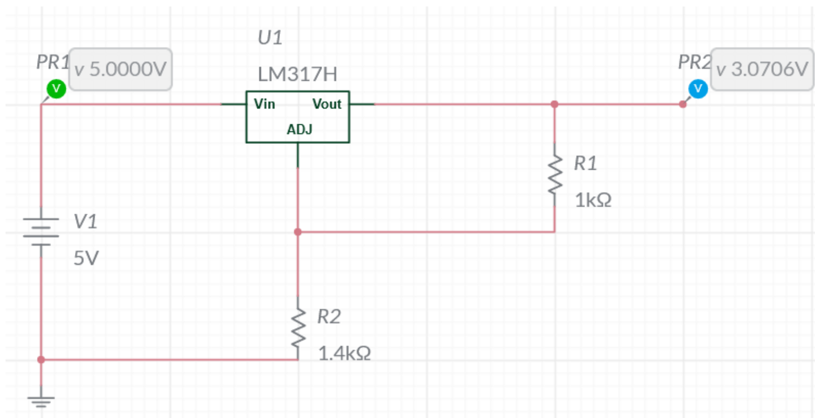


Figure 21: Typical DC to DC regulator circuit. Shown is a circuit that steps down a 5 V input to 3 V. Note the use of the linear voltage regulator IC, the Texas Instruments LM317. Image provided by Lazer Pong project team.

The main objective of any voltage regulator is to guarantee a steady, constant level of voltage for some load given variations in load currents. Along the same vein, an important parameter of voltage regulators is to control the amount of power dissipated between the regulator's input source and the load. This dissipated power, or wasted power, is directly proportional to the voltage drop that occurs across the regulator [38]. The larger the difference is between the input voltage and the output voltage, the more potential power is wasted as it is resisted and dissipated by the regulator component [38]. In order to minimize this waste of power, it will be important to confirm that the difference in voltages on either end of the regulator is not significantly large. A way to numerically assess this is by calculating the circuit's efficiency.

$$\eta = \frac{Power\ In}{Power\ Out} * 100\%$$

Where η is the total efficiency as a percent, "Power In" represents the amount of power being drawn into the regulator circuit, and "Power Out" represents the amount of power flowing out into the load. A value as close to 100% as possible is desirable, as that tells the designer that the regulator is very efficient at taking the inputted power and transferring that over to the load, while still maintaining a constant voltage level.

Redundant Power Supplies

One additional concept that may be important to discuss is that of repetitive or redundant power supplies. This practice is mainly used as a safeguard to ensure that the device can still work even in the event of some hardware failure or any unexpected power outages. While the implementation of such a practice has the potential to give the Lazer Pong Table a significant layer of extra reliability in terms of its functionality, there are some trade-offs to keep in mind before deciding if a redundant supply is worth including.

The redundant power supply is a special configuration of a power distribution system, wherein some electronic device operates utilizing two or more power supplies simultaneously [39]. These supplies can be the same type or can differ in type. For instance, a large computer server may include multiple connections to separate outlets [39]. Crucially, each of these individual power supplies that are hooked into the same end device must all have the capability to run the device on its own. When operating together, they may usually only contribute a portion of the total required power, but if one supply were to fail for some reason, then the other supply or supplies will be able to take over quickly and with little to no need for external assistance from a person.

However, redundant power supplies have some disadvantages as well. Namely, they are much more costly, with needing to implement basically double the power components. Furthermore, the more power supplies that are implemented into a redundant system, even if it is just one additional device, will still take up more space on the device itself, leading to additional physical weight and leaving less room for other necessary components.

Keeping in mind the scale of the Lazer Pong Table's components that require power, there are few that require a significantly large level of power to be delivered. In fact, many of them may only consume a few watts. Due to the relatively low amount of components that need to be powered on the Lazer Pong Table, a single power supply will be preferred over a configuration that involves using multiple.

3.3. Component Research and Part Selections

With all of the technological components of this project understood to the extent that was necessary to employ them across this design, the task at hand becomes to review the parts selected to represent each component. This is the most critical step before the design draft itself, as selecting the wrong component could have caused major difficulties when it came to building the prototype. For example, if lasers were chosen that required a much higher voltage level or current draw than the power supply was able to provide, either or both systems may have had to be overhauled. The goal of this section is to avoid any and all catastrophe at the design and build steps, while ensuring that all requirements and specifications, as well as project goals and objectives are met. While the design is inherently fit to support our goals of score tracking, ball tracking and impressive ambient lighting, the part selection process should keep these goals in mind when weighing the merit of similar parts. Essentially, if two nearly identical parts are being compared and one provides better feature coverage at little to no additional cost or feature penalty, that part was chosen.

The component selection process begins with the more goal and feature focused components, the laser grid and LED panel, then moves down towards the more foundational components, like the microcontroller and power devices. This strategy was employed because, in an integrated system such as this, components in disparate parts of the system often introduce constraints on components for other parts of the system. The first components selected were the ones that offered the most freedom, and that freedom was utilized to advance the project's goals and objectives. By leaving that freedom to the laser and LED components, the overall design was more focused on maximizing the effect of the ball detection and ambient lighting features. If the cost for selecting the ideal parts for these components was more complexity in the datapath, that could be compensated for when selecting the microcontroller part later on. Likewise, if the cost for selecting those ideal parts was higher power draw or another power concern, that can also be accounted for when selecting the PSU and other power management parts later on.

Even still, there are no unbounded selection criteria for any parts, even the first parts selected. It was always possible that the perfect LEDs drew more current than was safe to employ, and would be unviable, regardless of the power management options. In this way, even though the strategy was to work from top to bottom assigning part selections, these selections were reviewed from bottom to top, to ensure no parts were wholly incompatible or would create impossible design scenarios. In the end, the part selection process needed to be iterative to ensure that the maximum synergy between each subsystem and its components was achieved.

Table 8: Summary of Required Components for Part Selection.

Component	Part Selection Subchapter
Laser Transmitter	Chapter 3.3.1.1
Photoreceiver	Chapter 3.3.1.2
Prefabricated LED Array	Chapter 3.3.2
MCU	Chapter 3.3.3.1
MCU PCB Voltage Regulator	Chapter 3.3.3.2

Microphone	Chapter 3.3.3.2
Power Supply Unit	Chapter 3.3.4
Secondary Power Supply Devices	Chapter 3.3.4
Non-PCB Voltage Regulators	Chapter 3.3.4

3.3.1. Laser Transmitters and Receivers

In the conception of the laser grid, there are two main hardware components that will be the bread and butter of the design. These items are the laser transmitter and the optical receiver. Included in both of these items are desirable and undesirable features that will ultimately lead to our project's choice in part selection for the laser grid. For the laser transmitter, some specifications to be considered include the center wavelength of emission, the output optical power, and the operating voltage and current. Additionally, it should be considered whether the laser diode is easily collimated. If a laser was not collimated, then multiple issues could arise, such as the receiver not collecting enough light intensity to produce a signal, or potentially causing divergence of the beam, which could overlap onto other sensors not intended for that specific emitter. However, the most important concerns with uncollimated beams are the potential for severe health consequences. Since the beam would diverge rapidly, it would have an increased chance of the light entering a player's eye.

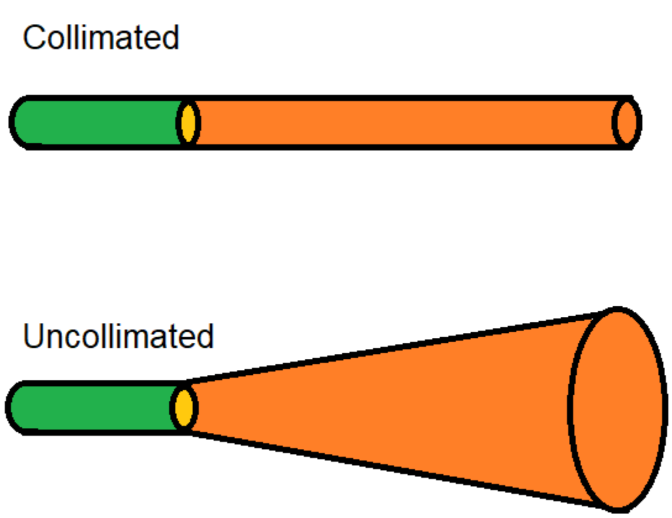


Figure 22: Simple diagram showing the difference between collimated and uncollimated light. Image provided by Lazer Pong project team.

Along with the laser transmitter, the corresponding receiver also has specifications that must be considered when designing the laser grid components. These features include responsivity to wavelength, response time, operating current and voltage, and the size of the detector area. The device must be responsive to the spectrum provided within the tolerances of the laser transmitter device while also being unresponsive to the spectrum outside this range, especially the visible spectrum produced by the LEDs directly in front of these receivers. It must also produce a signal that can be interpreted by the MCU, which will require a certain response time, voltage level output and clarity of signal edges.

In addition to the technical specifications for both of these parts, there are also other limitations that must be considered for the project when selecting parts. Because the laser grid will consist of 48 laser transmitters and photodetectors the cost per item is a large factor in which part will be used, so as to not bankrupt each member of the group. Another limiting factor is whether or not the part is actually in supply or not. Due to the fact that this project is on a strict timeline the availability of product could be detrimental to whether or not it is used in our design as we cannot wait months on end for a single item. Along with all of the aforementioned requirements, the laser transmitter and photodetector must work in conjunction. This means even if there are two great options for each individual part, if the wavelength of the laser does not match well within the responsivity of the photodetector, then they cannot be used together in the design of the laser grid.

Table 9: Table outlining requirements for laser grid hardware.

Requirement	Specification
Center Wavelength	750-3000 nm
Optical Power Output	< 5 mW
Operating Voltage for Laser Diode and Photodetector	≤ 5 V
Beam Diameter	< 15 mm
Responsivity of Photodetector	> 0.4 A/W
Response Time of Photodetector	< 1 ms
Detection area of Photodetector	2x2mm - 15x15mm

Center Wavelength

For the emissions of the laser diode the center wavelengths need to be in the IR range, and well enough into it that the emission range doesn't bleed into the visible light range excessively. Too much emission of the light being in the visible light range will diminish the amount of signal that the photodetector will be receiving. This is because the photodetector will ideally have a filter of some sort for visible light.

Optical Power Output

The optical power output is determined by the laser diode and should be low to conserve laser safety standards. For a commercial use the laser safety standards set were for the laser to be of class 3R or lower. This means that the optical power output needs to be less than 5mW [3]. Otherwise, the laser would not be safe for the use of the project, and would not be viable to sell as a product to the general public.

Operating Voltage

In the design of the whole table, most parts will utilize 3, 3.3 or 5 volts. This will allow for simplicity in the design of the power scheme. If a different voltage were to be utilized here it would only make the design unnecessarily more complicated than it needs to be.

Beam Diameter

The beam should be collimated and should not be much larger in size than the photodetector. This will ensure that the majority of the signal emitted from the laser diode module is received by the photodetector. Should the beam diameter be too much larger than the photodetector than the signal received by the photodetector could be too weak to properly function in the laser grid.

Photodetector Responsivity

The responsivity of the photodetector is how well it converts a detected wavelength of light into an electrical current [40] and a higher conversion rate is preferred. Similarly to if the beam diameter is too large, if the responsivity of the photodetector for the emitted wavelength is too low then the signal received would be very weak. Again, this would overall cause issues with the functionality of the laser grid at detecting the ball.

$$R = \frac{I_{ph}}{P_{op}}$$

Figure 23: Equation for responsivity of a photodetector, where R is the responsivity, I_{ph} is the output photocurrent, and P_{op} is the input optical power. Image provided by the Lazer Pong project team

Using the equation above and the specification from the table above the only value to find here is the output photocurrent produced by the photodetector. From the values of 5mW input optical power to the photodetector and a minimum responsivity of 0.4A/W, a photocurrent of 2mA would be produced.

Photodetector Response Time

Response time will add to the overall reaction time of the project and therefore a lower value is desired. The response time of the photodetector is only the first piece of the puzzle when it comes to the project as a whole. Therefore, setting a good baseline for the start of the response time is crucial to meeting the overall goal of having the project's response time being lower than 250ms. Generally, photodetectors have very fast response times due to their nature of dealing with optical signals, but the lower it is the more leeway the rest of the build will have with their response times.

Photodetector Detection Area

The photodetector area should match closely to the size of the beam diameter to ensure a strong collection of signals. Having the photodetector's detection area be too small would in turn cause the need for a tighter beam diameter. This would cause an increase in the irradiance of the beam, and would add potential risk to the users. However, on the other side of the size, if the detection area is too large then the design would suffer from increased bulkiness. Also the devices will be spaced relatively close together, so having them be too big might cause issues with that spacing and potentially even signal sharing between transmitters.

3.3.1.1. Laser Transmitter

Lasers in general have a wide array of application uses, but for the design of the laser grid, their function will be rather simple. The lasers will act as a means of sending a collimated beam of information to a receiver, which cannot diverge too wide as to avoid cross talk with other close proximity receivers. Since the function of the laser is trivial, it does not need to incorporate features that would allow advanced techniques such as q-switching or gain switching. The laser merely needs to provide a constant wave such that the signal obtained on the receiving end has very little fluctuation. This simplicity will work well for the overall price of the project when considering how other, more complex applications of lasers can be exceedingly costly. Along with needing a constant wave output, it is desirable to have a low optical power output. A low output optical power will ensure that cooling of the laser diodes is not a huge consideration, along with minimizing the risk of potential health hazards. Because the laser diodes will produce highly collimated beams of light, it is beneficial for the output power to be as low as possible without degrading the integrity of the laser grid design.

There is a wide range of wavelengths to be chosen from when working with lasers. When initially considering which wavelength to choose for the laser diode, visible light was almost immediately disconsidered. This was for a multitude of reasons that collectively added up to the conclusion that visible light lasers are practically unusable for the project. The first major reason was that, directly beneath and in front of the photodetectors, there will be an LED array that could change between all colors of the visible spectrum. This would cause issues when using a photodetector paired with a visible light laser because if the wavelength chosen were to appear on the LED array, it could potentially cause issues with the laser grid's detection system. Another huge issue is very simple: it would look ugly. Even if there were no technical issues with choosing a visible light laser, the fact that it would be very possible to see a grid of light shining over the playing surface would severely damage the overall aesthetic appeal of the project, and It would impair the player's view of the showcase that is the LED array beneath the laser grid.

With visible light out of the question for the laser diode, the solutions for the laser grid turns to light waves invisible to the human eye. This solves both issues of appearance and signal interference easily, since the lasers will be invisible and the LED array will not display light of wavelengths past the human perception. From the perspective of light outside of the visible spectrum, there are two directions to consider: Shorter wavelengths in the form of ultraviolet light, and longer wavelengths in the form of infrared. Ultraviolet light is not commonly used for photoelectric sensors, though, as shorter wavelengths have a tendency to scatter when interacting with transparent solids and liquids as well as gasses. They scatter much more than longer wavelengths, as described by Rayleigh scattering. Rayleigh scattering is the scattering of electromagnetic radiation due to particles of a smaller size than the wavelength of the electromagnetic radiation. The amount of scattering that occurs with an object when light interacts with it is inversely proportional to the fourth power of the light's wavelength [41]. With this information in mind, it is clear to see that there would be a drastic difference in scattering between ultraviolet and infrared light. Because the laser light for the laser grid will be traveling through clear plastic cups and ultraviolet wavelengths, having shorter wavelengths, would scatter much more than infrared, it was decided to use infrared laser light over ultraviolet.

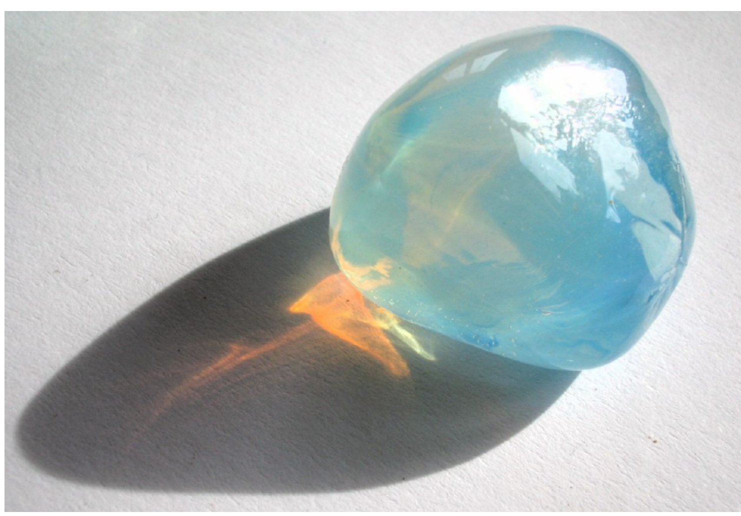


Figure 24: Example of Rayleigh scattering where it can be seen the shorter wavelengths (bluish) are scattered in the glass and the longer wavelengths (reddish) are transmitted [41]. Image used under creative commons.

Infrared light is one of the most prevalent forms of light used in industry when it comes to photoelectric sensors. With infrared light there is a range of wavelengths that span from 700nm all the way 1mm. For the design of the laser grid, it is more practical to use wavelengths ranging from 0.7-3µm. Splitting this up even further gives two separate ranges to be compared. These two subdivisions will be 0.7-1.4µm and 1.4-3µm. One of the main reasons for splitting this range up is due to the fact that there are major laser safety concerns to be considered between the two. Infrared light within the 0.7-1.4µm range is invisible to the human eye, but the range is dangerously close to visible light. The human eye has retinal receptors that do not respond to this range of light, but due to its close proximity to the wavelength of visible light it is still focused onto the retina. This can easily cause retinal burns if proper laser safety precautions are not followed. There is less risk of this occurring since the desired optical power is low, but not something to be dismissed when choosing a laser to use. In the latter range of 1.4-3µm the infrared light is completely absorbed by water before reaching the retina. This is not to say that this range is completely safe because other parts of the eye are still at risk. Having this in mind and other specifications previously mentioned the following options were discovered.

Table 10: Comparison of IR laser diodes. Table data pulled from each component's respective storefront page [42, 43, 44].

Laser	Q-BAIHE IR Laser Diode Module	THORLABS L785P5 Laser Diode	MITSUBISHI ML925B45F Laser Diode
Center Wavelength	780 nm	785 nm	1550 nm
Cost	$3.18 per ea.	$12.68-10.14 per ea.	$56.48-53.66 per ea.
Optical Power	3 mW	5 mW	5 mW
Input Voltage	3 V	2 V	1.5 V
Input Current	100 mA	40 mA	50 mA
Collimating Lens	Included	Not Included	Not Included

Comparing these three laser diodes, there are pros and cons to each one. Starting with the Q-BAIHE IR Laser Diode Module, this option is clearly the cheapest of the three. Along with this it also has the lowest optical power output, but also has the lowest power conversion efficiency [42]. The MITSUBISHI ML925B45F Laser Diode has the greatest power conversion efficiency, however its cost per unit is nearly 20 times greater than the cheapest option [444]. All three of the laser diode modules chosen have continuous wave output, which is the most optimal for the laser grid design [42, 43, 44]. Despite being the cheapest option, the Q-BAIHE IR Laser Diode Module has a small adjustable collimating lens that comes pre-manufactured with the device [42, 43, 44]. This is a huge upside to this choice over the others. The main negative of this laser is the fact that it is available only on Amazon and comes with a very limited data sheet. This gives the impression that little testing with this laser diode was done and therefore may not operate as stated by the information that is given on the store webpage. The THORLABS L785P5 Laser diode is a middle ground option that provides improvements over the Q-BAIHE IR Laser Diode Module without costing a large amount [43]. However, it also does not come with a collimating lens and because of this extra cost would be added to the overall system to collimate each individual diode. In terms of wavelength the MITSUBISHI ML925B45F Laser Diode is within the range of infrared light that is more desirable for safety reasons, but the cost per each and lack of collimation far outweighs that desirability [44]. The other two laser diodes have nearly the same center wavelength and are both within the range closer to the visible spectrum [42, 43]. The Q-BAIHE IR Laser Diode Module was selected due to its low optical power, low price, and its possession of a collimating lens. These benefits make it a better suit for the laser grid and the overall project.

3.3.1.2. Photodetector

With the laser diode specifications, it is then crucial to pick a photodetector that has specifications that will cooperate in order to form a functioning system. The main factors in determining whether or not the two will work together is the center wavelength of the laser diode and the responsivity range of the photodetector. Assuring that these two match is critical, but luckily not a hard task. On top of the responsivity range of the photodetector, ensuring a fast response time is exceedingly important. If the response time is too slow then the quality of the project in its entirety will be diminished. A slow response time will lead to delays in the LEDs that are intended to react to triggering the laser grid. This will make the game feel clunky and overall not fun to play. Another important specification that is to be considered in the selection of a photodetector is the area of sensor. If this area is too small then the light from the laser diode would have to be focused onto it, which would create a beam with a higher irradiance and in turn a more dangerous environment. The area also doesn’t need to be excessively large to cover an area bigger than the collimated beam.

One of the biggest factors to consider when choosing a photodetector to use is ensuring that the electrical signal it generates is capable of effectively communicating with the MCU. Without this the laser grid is essentially useless. Should the signal generated not be enough to be processed by the MCU then the MCU would just assume that every single coordinate on the table is currently being tripped. This can be very easily solved by adding a signal amplifier. Because the basis behind the photodetector will be converting the optical signal received into a photocurrent and the MCU requires a specific voltage level to be reached, a current to voltage amplifier will be required. This is known as a transimpedance amplifier. One might think that it would just be more simple to just use a resistor of some value to get to the required voltage, but there are advantages to using a transimpedance amplifier. Just using a large impedance resistor in series to achieve high current to voltage gain causes issues when a load resistor is connected across the current to voltage resistor by effectively lowering the gain by having two resistors in parallel. The transimpedance amplifier on the other hand does not have this issue and is therefore more desirable [45].

Table 11: Comparison of potential Photodetectors. Table data pulled from each component's respective storefront page [46-49].

Photodetector	CHANZON 940nm IR Receiver	THORLABS FDS100 - Si Photodiode	LUCKLIGHT LL-503PDD2E Photodiode	DKARDU IR Infrared Flame Sensor Module
Cost	$0.0799 per ea.	$16.08 per ea.	$0.20 - 0.099 per ea.	$1.30 per ea.
Response time	Not listed	10 ns	45 ns	Not listed
Responsivity ranges	Only 940 nm listed	350 - 1100 nm	700 - 1200 nm	Infrared - No range listed
Sensor Area	3 x 3 mm	3.6 x 3.6 mm	5 x 5 mm	5 x 5 mm
Max Reverse Voltage	Not listed	25 V	35 V	Not listed
Dark Current	Not listed	1-20 nA	2-10 nA	Not listed
Filter for visible light	Yes	No	Yes	Yes
Built in Amplifier	No	No	No	Yes

Taking the specifications needed for the photodetector, the three options presented above were the best choices for accomplishing the task of building the laser grid. Similar to a previously mentioned laser diode, the CHANZON 940nm IR Receiver was a very inexpensive option found on Amazon [46]. Unfortunately, the similarities continue in that there is no solid data sheet for this part and therefore it is a risk to know whether it will work properly. Similarly, the DKARDU

IR Infrared Flame Sensor Module has very little data posted on its Amazon webpage. However, it is the only option that comes with a pre-fabricated amplifier that will help greatly in ensuring the signal is communicated properly with the MCU [49]. The other two options both have fully fleshed out specification sheets that both meet the required needs for the laser grid [47, 48]. The LUCKLIGHT LL-503PDD2E Photodiode and the DKARDU photodiode both have larger sensor areas which is more desirable and is not too big. The LUCKLIGHT LL-503PDD2E Photodiode's response time is approximately 4x slower than the THORLABS FDS100 Si Photodiode, but is still well under the limit [48]. The THORLABS photodiode is the only option that does not include a black epoxy covering to block unwanted wavelengths of light [47]. Despite not being the cheapest of the four options, the DKARDU photodiode is still a relatively low-cost solution that checks all of the boxes needed for the photodetector.

3.3.2. LED Surface Panel

As decided in the technical research, the surface panel consisted of an LED array assembled into a grid, and diffused into a 32x16 pixel display to cover the 4'x2' play area. At its core, this display needed 512 LEDs to be isolated from each other in some sort of grid, and covered with a light diffusing surface to create the effect of a seamless pixel display. The WS2812B LEDs were employed for the LED technology, but there are many ways to use these devices for this purpose. The grid around each LED was used to isolate each pixel clearly from the next, and so should be dark, rigid, and roughly 1.5" square to cover the play area in a 32x16 grid. On top of this LED grid rested the light diffuser, a component that makes the light produced from the LED strips look less harsh and spreads the light evenly, ensuring that each pixel had consistent brightness and color across its entire face.

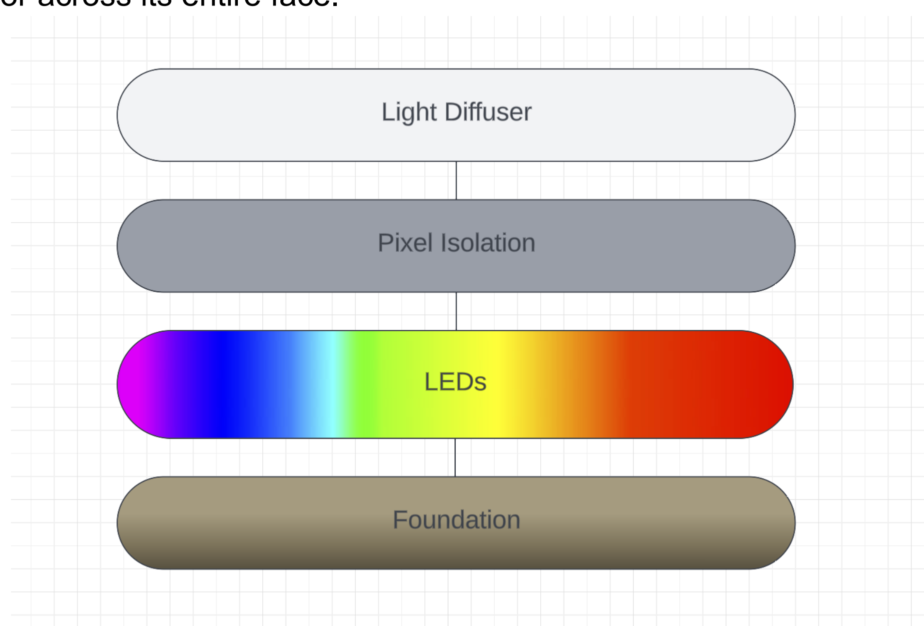


Figure 25: Abstract layering of display. Image provided by the Lazer Pong project team.

These WS2812B LEDs are individually addressable and linearly linked. While these LEDs could be purchased individually and a grid could be completely fabricated for this design, prefabricated PCB or wired components exist in the form of LED strips and LED panels. These prefabricated LED devices drastically reduced the build time and complexity of this component when compared to individually soldering each LED in six places. There are three varieties of prefabricated LED components on the market: ⅔” spacing, 1 ⅓” inch spacing, and 4” spacing. Since the 16x32 display will cover the entirety of the 4’x2’ play area, a spacing of 1 ½” was needed. This means that the only devices that did not require modification were ones of at least this spacing. Additionally, the freedom the strips provided in their implementation were needed, meaning that the LED panels were not considered for this part. These panels had to be found in exactly the dimensions required for this design since they are prefabricated in a rigid PCB makeup. The strips, on the other hand, offered greater manipulability and will be much easier to incorporate into the design.

Prefabricated LED Component

When searching for prefabricated LED components, it is important to recognize the key characteristics that will produce the best design. The primary factors to consider are: Implementation of the WS2812B addressable LED, distance between LEDs, waterproof rating, number of LEDs per component, and cost effectiveness. While products that do not include this specific addressable LED may still be acceptable, it was considered a detriment to the value of the part. As previously stated, the LEDs were placed 1 ½” apart in order to fulfill the design requirements. Strips with slightly narrower distances could have been used, but they would have required modification. After searching the market for available components across a variety of vendors, the following three prefabricated LED strips were worth the greatest consideration. From their characteristics, reviews, and customer feedback, we made an informed decision that lead us to the most suitable option for the LED array.

Table 12: Addressable LED Light String Comparison

LED Strip	BTF-LIGHTING WS2812B Flexible Strip	Tenmiro Led Lights	BTF-LIGHTING WS2812B Fairy String
WS2812B Addressable LED	✔	✘	✔
Distance between LED	1.33”	2.22”	3.93”
Number of LED per strip	150	540	50

Waterproof rating	IP30	N/A	IP65
Length	16.4 feet	100 feet	16.4 feet
Cost	$32.99	$19.99	$9.99

After conducting this comparison it was clear that the most suitable LED strip for this project was the BTF-Lighting Fairy String lights. These lights were the cheapest of the three with being only $9.99 for 16.4 feet of lights and they also satisfied each category we looked for. Being individually addressable and having a waterproof grade of IP65 were optimal for our design. Having a waterproof rating ensured their durability if any liquid were to get down into the table and touch the lights from the occasional spill. Each light source is roughly 4 inches apart which is much more than the required 1.5 inches between pixels. Considering all of these factors, it is evident that the BTF- Lighting Fairy String Lights was the ideal choice for this project.

Since we went with the BTF-Lighting Fairy string lights, these lights made our design much simpler. We needed 512 LEDs and each strip has 50 light sources on it so we needed at least 11 strips. We had originally thought that we would have to cut and splice each LED strips for each row of the array but since there were 4 inches in between each light source we wrapped the LEDs in a snaking pattern. We also needed to bunch up the extra wire in between each pixel since the space needed in between each pixel was 1.5 inches. The extra wire was bunched up on the underside of the table.

The second component considered and carefully researched was the light diffuser for the LED array. While this was a fairly simple component, the choice of a light diffuser played a crucial role in enhancing the look of the LED array but did not impact the design of the LED as much as other components. When first researching, we were going to use a diffusing cloth and a hard plexiglass or plastic to be the surface top to the table. Since doing deeper market research we considered having a clear frosted acrylic, this way the light diffuser possesses a dual functionality by acting as the hard top for the table top as well as a light diffuser. There are three viable options for this design that were identified. Looking at their characteristics, reviews, and customer feedback, many options exist on the market that are suitable for the needs of this design. Some of those characteristics considered include the thickness and size of the panels, as well as their cost effectiveness.

The most suitable light diffuser for this project is the Distinct and Unique Frosted Acrylic. The most crucial factor with this specific component is the size of this panel. The full 4’x2’ panel made the design much simpler because there was no need for combining smaller panels to make the entire 4’x2’ display. Having one panel is also beneficial because there are no cracks on the surface from multiple panels that could possibly obstruct the bounces of ping pong balls. The advantage that Distinct and Unique frosted acrylic has over the diffuser cloth and plexiglass is the cost. The Distinct and Unique frosted acrylic comes in at $66.99. From this comparison the optimal choice for this design was the Distinct and Unique.

Figure 26: Light diffuser panel softening a complex LED dense display image. Image provided by Lazer Pong project team.

There is one last major component when looking at the LED Array table surface, which is the grids for each pixel. When searching the market for grids that matched our requirements but could not find an exact fit for our needs. Our plan was to create these grids ourselves by 3D printing each one of these grid pieces and connecting them together. The design has a standard size for each 3D printed grid piece. Each grid was 6 inches by 6 inches providing a square shape and 1 inch thick and contained 16 individual pixels. These pixels are the building blocks that form the LED array. Given this size and quantity there was a total of 32 printed grids to cover the entire surface of the table

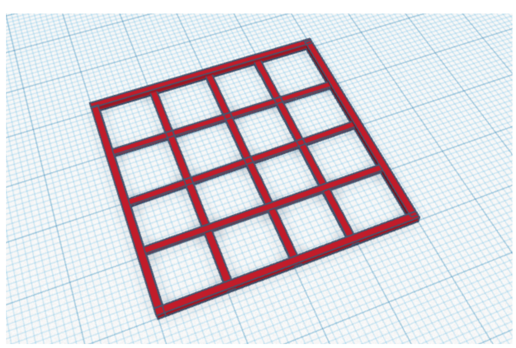


Figure 27: Draft of 3D printed grids for pixels. Image provided by the Lazer Pong project team.

To summarize, the LED table surface for this project was designed using an LED array panel fabricated by us. This panel began with 11 strips of BTF-LIGHTING Fairy String Lights connected together as one long strand. This strand was laid along a 4’x2’ play area, with LEDs fixed at 1.5” apart in a snaking pattern. The overall dimensions of the array will be 32x16, with the snaking bends placed at the shorter sides of the surface. Then, 32 of the 3D printed grid panels were secured over the LEDs. Finally, the acrylic fog pane will be adhered to the top of these grid panels. The final product was a striking 32x16 pixel LED surface panel, fully prepared to display any and all required visual effects.

3.3.3. MCU and Supporting Electronics

At this stage in the design process, the requirements of the microelectronic components in the PCB should be defined well enough to inform the selection of the components therein. It is now known that 48 GPIO signals will need to be received from the laser sensors, and one SPI signal will be used as well for the communication with the Arduino. Additionally, it is known that 5v power will be delivered by the power supply system, which must be taken into account with this part selection as well.

Since the details of the central microcontroller, the MCU, dictate the requirements of many of the other components on the PCB, that part must be decided before the decisions as to which supporting electronics parts could be used can be fully informed. At the very least, the MCU selection will determine what VDD level is required to be distributed around the board, which informs the requirements from the almost certainly necessary onboard voltage regulator. While this value is typically 3.3v for most microcontrollers that will be considered for this design, there are exceptions to that rule [50]. Other considerations will mostly lie within the needs of the specific microcontroller part. Some parts require extensive support systems to operate correctly, while others are more or less “plug and play”. In the end, the nature of the entire PCB design will depend on this first part selection.

3.3.3.1. MCU

For a project of this scale, few component decisions have the broad impact and overall design effect as the MCU, the microcontroller responsible for the highest level of control function. Between pin count, pin layout, processing speed, memory capacity, flash capacity, and architecture, no other single component has as much variety, either. This means that careful consideration of all of these microcontroller features, as well as what products are on the market and their availability, was critical to the success of the overall design. While the pin count is straightforward since the number of necessary GPIO pins has already been determined, the pin layout could be just as important, as routing traces for 48 GPIO components already poses a challenge without an inconvenient pin layout getting in the way. Processor speed and memory capacity simply need to be high enough to effectively eliminate noticeable response time, but it can be challenging to know exactly how much would be necessary before implementation in the prototype. Facing these challenges to determine the best microcontroller component implementation will be the goal of this section.

In addition to microcontroller specifications, there are other, more worldly factors to consider in part selection for this component. Nothing is free, and microcontrollers are no exception: Part cost needs to be evaluated when selecting this component. In a perfect world, the fastest microcontroller with the most convenient pinout would have been the part chosen for this MCU. However, fast 32-bit microcontrollers with more than 50 GPIO pins can be expensive [51]. While a part that has more speed and power than is necessary will still be the preferable choice, there will only be so much to be gained by exceeding the necessary specifications. Beyond cost, part availability also weighs into part selection. Many microcontrollers are in high demand or limited supply due to various electronics and silicon shortages, and the perfect part at the perfect price is useless if it cannot be purchased and shipped in time to build the prototype [52]. By using part cost and availability to effectively filter the pool of parts for selection, even before considering feature specifications, selecting the right part is made that much simpler.

Each of these main features will be discussed below, along with consideration for the limits provided by part cost and availability. Once each feature has been weighed, several parts that meet the design specifications will be selected for cross comparison, and the one that meets the values outlined for each feature will be chosen for the final design.

Table 13: Requirements for The MCU Microcontroller Component.

Requirement	Details	Specification
GPIO Pin Count	A high number of GPIO pins will be needed to directly hook all laser receivers to the MCU. Additionally, the pin configuration should make running the traces for these ports as simple as possible.	49 GPIO + 1 ADC pins
Processing Speed	Sufficient to easily manage the highest capacity of throughput possible, without noticeable response	At least 16KHz (see section 3.3.3.2 for elaboration)

	time. Industry standard is 2x necessary processing speed, to allow room for updates.	
Memory Capacity	Enough capacity to avoid running out of memory. Industry standard is 2x maximum memory required, to allow room for updates.	Minimum 2kB
Flash Storage Capacity	Enough capacity to store the entire software package. Industry standard is 2x maximum flash storage required, to allow room for updates.	Minimum 32kB
Microarchitecture	The processing/ALU microarchitecture is less important than the structure of the registers and GPIO ports.	Minimum 8 pins per port, minimum 16bit architecture
Package	The package should be easy to fix onto the PCB	Low-profile Quad Flat Package (LQFP)
Cost	This project is not being designed for mass production, but part budget should still factor into the part decision.	No more than $20/ea
Availability	This project is not being designed for mass production, so high stock count is not necessary.	At least 3, for redundancy

GPIO Capability

As previously discussed, the major specification for the MCU microcontroller is a sufficient GPIO pin count to support the 48 receiver signals from the laser grid. Several other I/O devices will need to be supported as well, including a full-duplex SPI line for communication with the LED-controlling Arduino. Aside from those pins, a single ADC pin will be necessary to include a microphone for music visualization. Again, while this feature was never implemented, the capabilities for it were designed into the electronics. No other microcontroller devices will be needed, as all of the I/O devices will be connected directly to the MCU. While finding a microcontroller that supports this high pin count was not challenging, it did limit the number of low-power and ultra low-power options available. This resulted in the design requiring a more expensive microcontroller with much higher capabilities than are necessary.

The upside of this specification is that, in the grand scheme of modern microcontrollers, 48+ GPIO pins is not that extreme. Some manufacturers, such as STMicroelectronics, produce as many microcontrollers with this pin count as ones with fewer [53]. Fortunately, this represents the extent of this project's I/O needs. In the original drafting of our design, the proposed controller software would listen for interrupts set to trigger when the output from any laser receiver transitioned from low to high. In order to properly interface with those laser receivers in this way, those I/O pins would all have needed to be set for interrupts. This means that, in addition to supporting that many GPIO devices, the microcontroller must also support that many simultaneous interrupts. Many devices with high pin counts do not have high interrupt support, so that requirement would have drastically reduced the number of options for this component. Fortunately, it was discovered that a polling technique simplified the software requirements for the design, and the need for many interrupts was removed.

Beyond the pin specifications and the limits it provides, this feature offers little else in the way of influencing part selection. This will be the primary specification to consider when selecting a microcontroller to operate as the MCU for this design: It must support 48 GPIO pins, one SPI connection, and one ADC pin. This is a minimum specification which must be met, and there is no advantage to going over the required pin count. Therefore, once multiple devices have been identified that meet this specification, the other features listed below will be used to weigh the individual merit of each device.

Processing Power

While the processing needs of this design are not as restrictive as the other specifications, they are paramount for its intended functionality. When the laser receivers trip, they send a signal to the MCU almost instantaneously, with some small amount of propagation delay. However, once the signal reaches the microcontroller, the device takes up to the polling delay to identify the flags. Then, it will take more time to determine where the intersection of the triggered sensors lies. Then, it will take even more time to calculate where and how to illuminate the LED display, and push that pattern to the display itself. All of these steps add latency between the ball hitting the table and the LEDs lighting up, and all of them depend somewhat on the speed of the MCU. The roughly estimated clock cycles required to complete each step of this process are listed below:

Table 14: Rough Estimates of Program Timing. Cycle estimates informed by ARM reference document [54].

Step	Description	Time
Poll the pins, identifying raised flags	The flags will only be polled infrequently, no more often than once every 50ms.	Up to 50ms, regardless of clock speed
Identify Intersection(s)	Once a flag is raised, the system checks each pin on the crosswise port(s) against any raised flags along the lengthwise ports. It notes all of these intersections, and hands control to the service routine for the LED panel.	~10 cycles X 32 flag checks = ~320 cycles
Display Graphics	After the interrupt, control will be handed over to a graphics display routine, which has some overhead. This routine will perform a series of function calls to set the LED lights on the display.	100-1000 cycles, depending on the number of light effects required.

Since these values are rough estimates, a generous fermi estimate would be around 2000 cycles per event at peak throughput. To reach our goal of less than .25 seconds of response time, this would require a microprocessor with at least 8KHz, far below the lowest Microprocessor speeds we could possibly use. This means that our microprocessor selection should be made mostly independent of its processing speed.

Storage Capacity

The software driving the overall control scheme is relatively simple, using functional practices to detect the input values and transmit that data over SPI. There is no need for complex interfaces, object oriented data structures, or any other memory intensive coding conventions. Since there's no need for long-term memory, there should be no consideration for non-volatile memory either. In the end, the memory needs of the microcontroller will be trivial. 2 kilobytes of memory is often seen as the entry level for modern low-power microcontrollers, and should be ample for the needs of this design [55]. However, it is likely that any part that meets the rest of the requirements will also far exceed this one.

Similarly, the flash memory required to implement this software are just as trivial. The code will consist mainly of several graphics library commands, with some launch-time setup and a few routines for driving the game state components, like scoring. The flash capacity is also fairly simple to expand, so if a collision does occur with the capacity of flash memory on the selected microcontroller, there is an avenue for resolving this [56]. However, this eventuality should be avoided. Flash memory on these systems varies widely, in part due to the fact that it is a well known and employed strategy to expand flash memory onto the board. However, few systems are seen under 32 kilobytes, so without more detailed analysis into the potential software application, this will have to suffice for a flash storage space requirement [55].

Microarchitecture

Any general microarchitecture structure should be sufficient for the needs of this design. ARM is the most prevalent architecture for the variety of microcontroller that this design is most likely to implement, but many others exist, including ATtiny, and Von-Neumann, in the case of Texas Instruments [57]. However, aside from the general microarchitecture of the processing structure, there are other more specific requirements. To facilitate the sensor detection algorithm, a 16-bit addressing structure is ideal. 32-bit is fine, but creates a need for some extra lines of code to compensate. Anything less than 16-bit, however, is insufficient. Additionally, the microarchitecture will need to support at least 8-pin ports, each with a flag register that can be raised when the GPIO input signal transitions from high to low. 16-pin ports would be far superior, but it can be challenging to find 16-pin ports in the variety of microprocessors that will be considered for this design.

Part Comparison

With all feature specifications and benefits laid out, the selection process for the MCU microcontroller becomes simple: This design needs a device that can support more than 48 GPIO pins, and has at least the bare minimum of processing capability and memory/flash capacity. Unfortunately, it seems the market has moved away from 16-bit architectures, and has split between 8-bit and 32-bit. This means that the microcontroller will have to be a 32-bit architecture. This will not cause major issues, but it will cause additional considerations for the software.

A wide range of viable microcontroller families fit the specifications of this design, which made it somewhat difficult to narrow down the selection. Most provide nearly the same specifications at the same cost, across the board. To help select from this wide pool, a decision was made to look at the most promising family of microcontrollers from each of the top three manufacturers for this quality of microcontroller: Atmel, STMicroelectronics, and Texas Instruments.

While Arduino is the most widely used name in microelectronics and microprocessing, they do not actually manufacture their microcontrollers [58]. Instead, they design and produce modular microcontroller systems using hand-picked chips [58]. The most popular Arduino 32-bit platform is the Arduino Due, which runs on the ATSAM3X8E microcontroller from Atmel [x]. This chip is designed on the ARM Cortex-M3 core architecture, with a very high GPIO pin count and middling speed and memory levels [59]. This chip comes highly rated by Arduino, giving it an edge in the competition against any similar parts. Unfortunately, the cost of the chip is somewhat high given its modest processing speed and onboard RAM.

STMicroelectronics is well known for producing industry leading performance microcontrollers, which drive powerful machine learning focused applications [60]. While this pedigree is far above the needs of this design, it does speak well for the quality standards of STMicroelectronics, and their catalog does include a family of devices that are within the range of consideration. The STM32F2 series of microcontrollers stack up well against that which was previously discussed, offering the same ARM Cortex-M3 core architecture, much higher processing speed and memory capacity, and a similarly high pin count [61]. Most importantly, it does all of this at a slightly lower price [62]. If the same brand recognition can be offered to STMicroelectronics that Atmel can claim through Arduino, this family of microcontrollers handily wins out.

Finally, Texas Instruments is well known for producing a large number of low-power and ultra low-power microcontroller families, which reliably perform small controller needs [63]. While the microcontroller needs of this design are hardly large, it may be difficult to justify going with a lower throughput device without more thorough study into the needs of the proposed software. Although big O analysis of the software's algorithms shows that any processor speed on the scale of megahertz should suffice, it is difficult to know exactly how much flash memory will be required to store the software, or how much RAM will be required to operate without running out of memory. Even one of Texas Instrument's more powerful microcontroller families, the TMS320F2800 series, falls short of the flash storage and RAM capacity of the next lowest device on this list [64]. It is hard to discount this device family because, while they may cause major issues for the design, they are also the cheapest device by far. Despite the low price tag, we will be avoiding this product to ensure no issues are encountered at the prototyping step of the design.

All in all, the STMicroelectronics STM32F2 series showed the most promise. STMicroelectronics is a well recognized brand with a history of top-notch quality, and the proposed microcontroller from their catalog exceeds every other part on the list while sitting near the middle in the way of cost. For all of these reasons, it will be the microcontroller chosen for the MCU of this design. The features of each microcontroller are compared in the table below, with the final part selection highlighted.

Table 15: Part Selection Summary for the MCU. Table data pulled from each component's respective storefront page [62, 64, 65].

Feature	ATSAM3X8E	STM32F205VC	TMS320F280033
Manufacturer	Atmel	STMicroelectronics	Texas Instruments
Data Width	32-bit	32-bit	32-bit
Architecture	ARM Cortex-M3	ARM Cortex-M3	C2000
Processing Speed	84MHz	120MHz	120MHz
Flash Memory Capacity	512KB	Up to 1MB	384KB
Memory Capacity	100KB SRAM	Up to 128KB SRAM	69KB SRAM
Package	LQFP-144	LQFP-100	LQFP-100
GPIO Pin Count	103	Up to 140	Up to 100
Cost	$13.15/ea	$12.62/ea	$3.78/ea

3.3.3.2. Supporting Microelectronics

Now that the necessary microcontroller component has been selected, the next task is to identify all of the proper supporting components that must be selected and implemented to correctly operate this device. Even the simplest of microelectronic components usually require several combinational circuits, or even other microelectronic components, to support their correct function within a given system. Therefore, it follows that a component as vastly complex as a microcontroller would potentially require many support systems composed of varyingly complex combinational circuits and other ICs.

As with all digital electrical components, the microcontroller requires a DC voltage level be applied to drive the logical levels of the computational subsystems within the device. According to the datasheet for the STM32 series of microcontrollers, a voltage level of 3.3 volts will be assumed for this VDD [36]. However, since other systems within the project design will require a higher voltage level and most economical power supply units tend to drive power at higher than 3.3 volts, a voltage regulator will be required to create this lower VDD. This regulator should be sufficient to support the maximum potential current draw of the microelectronic system it powers, as well as to establish a clean and consistent power signal.

Additionally, since one of the project stretch goals is to provide reactive lighting on the table surface that responds to ambient music, a microphone would be required to measure this ambient sound level and translate that analog sound data to the microcontroller. This microphone should only be compatible within the range of human hearing, and should be sensitive enough to provide sufficient signal clarity for the surface lighting. Most importantly, this microphone should be cheap and simple, given the low impact of the quality of this device on the overall quality of the design.

Voltage Regulator

There are two main technologies used for voltage regulation: Linear low-dropout (LDO) regulation, and switching regulation. LDO regulation works by utilizing an op-amp to compare the output voltage to the input voltage via a feedback loop, and incrementally adjusts the output to the correct level [66]. These devices are usually rated at fixed voltage levels for output and fixed ranges for input, but some devices offer adjustable ranges using a load applied to the output [66]. Each of these devices also has a dropout voltage, which is the minimum differential between the output voltage and input voltage. When this differential falls below the dropout voltage, the components within the regulator will not be biased correctly, and will not function [66].

Switching regulation, on the other hand, works by using switching circuitry employed by MOSFETs supplied with PWM signals to create an adjustable output [67]. This output has the advantage of adjustability and high-current capacity, but comes at the cost of expensive and complex circuitry and a high-noise output signal [67]. Since this design has simple needs from the voltage regulation component, not to mention that the ADC action of the microcontroller requires noise-free power, the LDO technology was used to regulate the 5v source power to 3.3v VDD for the microcontroller.

Three LDO devices that are capable of regulating 5v DC power to 3.3v DC power were identified, each representing a market sector dominated by one of three feature specializations: Low cost, high current output, and adjustability. The first device, the Texas Instruments TLV702 series of LDO devices offers the bare minimum of specifications at a low cost. With a typical output current of 300mA, the device will support more current draw than the MCU is capable of [68]. Additionally, if the laser receiver units require power through the PCB, this max current should support these devices as well. Texas Instruments offers another similar device, the LM3940, which offers a higher current output of 1A at the cost of a significantly higher price tag [69]. The final device, STMicroelectronics' LD1117, offers a combination of both features: Exceedingly high current support and low cost [70]. However, it is an adjustable regulator, which means that support will be required from other PCB components to create the correct output level [70]. With these considerations, it was decided to use the cheapest and simplest part: The Texas Instruments TLV70233 LDO regulator. This would have handily cover the power requirements of the MCU, while allowing the PCB design to be as simple and straightforward as possible. However, when ordering assembly for this PCB in Senior Design 2, it was discovered that our supplier could only supply the LD1117 regulator. Since this device worked just fine for our needs and was available by the supplier, it was chosen instead. It was also discovered that this regulator comes in fixed voltage output models as well, so one was used for each 3.0v and 3.3v without the need for voltage adjustment circuitry to support it. The feature comparisons for these devices can be found in the table below.

Table 16: PCB Voltage Regulator Part Comparison. Table data pulled from each component's respective storefront page [69, 71, 72].

Feature	TLV70233	LM3940	LD1117
Manufacturer	Texas Instruments	Texas Instruments	STMicroelectronics
Maximum Input Voltage	6 volts	5.5 volts	15 volts
Output Current	300mA	1A	1.2A
Output Type	Fixed	Fixed	Fixed
Dropout Voltage	220mV	310mV	1.1V
Cost	$0.63/ea	$2.17/ea	$0.62/ea

Microphone

The function of the microphone for this design is completely straightforward: Create an analog signal in the range of GND to VDD for the microcontroller to represent the ambient sound. The goal with this signal is to use this to identify music playing, and create an entertainment lighting effect on the table surface accordingly. To that end, the microphone should be cheap, small, and simple. The electret condenser microphone was identified as the style of microphone that best fits these requirements. These microphones are incredibly cheap, and with the right audio signal preparation, can actually produce some high quality audio recording. While this high quality of audio signal will not be employed in this application, the simplicity and versatility of this part will ensure our basic needs are met.

The electret microphone operates by using a statically charged diaphragm called an electret, which will oscillate with magnitude and frequency relative to the sound wave passing through it [73]. This electret is placed at the gate of a FET, which will allow the resulting output signal to be modulated by the device [73]. These devices are designed with a wide range of sensitivities and frequency ranges to be useful in a number of different applications. Three different electret microphones with different specialties are shown below.

Table 17: Electret Microphone Part Comparison. Table data pulled from each component's respective storefront page [74-76].

Feature	CMA-4544PF-W	POM-2738P-R	MO064404-1
Manufacturer	CUI Devices	PUI Audio	DB Unlimited
Sensitivity	- 44 dBA	- 54 dBA	- 44 dBA
Frequency	20 kHz	N/A	16 kHz
Directional Properties	Omnidirectional	Noise Canceling	Omnidirectional
FET Included?	Yes	No	Yes
Cost	$0.77/ea	$1.87/ea	$0.69/ea

The CUI microphone represents the widest frequency range with the lowest sensitivity, which would make it ideal for the use case of this project. The datasheet indicates a frequency range of 20-20,000 Hz, which falls neatly within the range of human hearing [77]. This means this device will be able to pick up any sound that the user can hear. Additionally, it comes included with the necessary FET, meaning minimal modification will be needed when implementing this microphone [77]. The PUI device was more specialized and had more versatile implementations, but the high price tag combined with the lack of prepackaged FET made this device undesirable for this design [75]. Perhaps if the package came with a FET and the frequency range of that configuration fell within our specifications, the higher price tag could be justified by the much higher sensitivity. This sensitivity would be beneficial because it would give the software better resolution to identify music from other noise. Finally, the DB device is almost identical to the CUI one, except that it has a lower maximum frequency and is cheaper [76]. While there will likely be little need for the top of the frequency range, it is hard to justify losing that frequency range for a mere 8 cents cost difference. All of these factors point to the CUI Devices electret condenser microphone as the preferred part for this component of the design. While this device was never actually implemented from a software perspective, lab testing did show proper operation of the device.

Resistors, Capacitors, and other Miscellaneous Components

While there is no need for a detailed part selection process for these basic electronics components, the general methodology used to select these parts should be made transparent. To simplify the assembly of the PCB, we requested assembly services from our PCB fabricator. All small components were sought in the 0402 and 0603 form factors, which allowed for plenty of room on the PCB for the many traces required by our sensors [78]. As the standard for PCB electronics, film resistors were used for the few resistor needs of the design. These are cheap to produce, and can be made in almost any form factor [79]. Ceramic capacitors were used for all capacitor needs, as those were required for the microcontroller's decoupling needs as per its datasheet [36, 80]. Since all of these parts were purchased in bulk quantity, it was efficient to use the same resistor or capacitor part for each component that requires the same value.

As described earlier, it was discovered that an Arduino development board would be required to interface with the LED lights. The decision for this board became very simple when looking at the requirements we had for it. Since SPI communication was used to communicate sensor data between our electronics and the Arduino, the Arduino needed to operate at the same voltage as our electronics to avoid causing damage to the sensitive GPIO pins driving the SPI communication. The ST microcontroller selected operates at 3.3v, and there are only two widely accessible Arduino platforms that operate at this voltage: The DUE and the ESP32. The DUE was chosen over the ESP32 because of significant issues in the programming of the ESP32 development boards for which we had access.

3.3.4. Power Supply and Management

When considering a power supply for the Lazer Pong Table, it was important to note three general requirements of each major component. The first was the required input voltage, which specifies the specific voltage level that the component demands in order to function properly. This needed to be specified to avoid hardware damage that could occur from too much input voltage, or even from not enough. Secondly, the maximum allowable input current. This specification describes the amount of current, or flow of energy, that the component can safely tolerate. Again, this was important for ensuring the proper function of the component. Thirdly, power consumption, which describes how much power that component draws from the overall power supply in order to function. Once these were determined, then a sufficient type of power supply unit (PSU) could be chosen.

As discussed previously in Section 3.2.4, an efficient method of supplying power will be to use the mains supply from a local wall outlet, rather than utilizing several batteries. With this in mind, the first step in actually drawing from the mains supply will be to utilize an AC to DC Converter to transform the 120 VAC input voltage to a more reasonable and useful level of voltage for the Lazer Pong Table's components. Before parts can be selected, however, an important choice in how this power supply will be constructed was whether or not to design a custom converter, or to simply acquire one from the market. Both options had advantages and disadvantages, namely in the cost of the parts, their compatibility with the rest of the system, and the amount of labor required for their implementation in the design.

The decision was heavily influenced by the chosen products for the other major components. The power requirements of the lasers, LEDs, and MCU influenced the requirements of the individual components that go into constructing a custom AC to DC converter, as well as affected which market PSU's would be available. To determine the power consumption of a device, if it was not provided, then only two other pieces of information were needed to manually calculate this value: operating voltage and current draw. The product of these two parameters will yield an estimated value of that device's power consumption.

The chosen laser modules have an operating voltage of 3 V and maximum working current of 100 mA. Considering that 48 of these modules will be implemented onto the Lazer Pong Table, then the total power consumption of the laser modules is 14.400 W. The laser receivers operate at 3.3 V, and have a small current draw of up to 15 mA. With such a small value, the laser receivers will not heavily influence the power requirements relative to the other major components, but it is still important to consider its power requirement, which is about 2.376 W. The chosen LEDs each can operate at 5 V with a maximum current draw of 30 mA at full brightness. Knowing that the Lazer Pong Table will implement at least 512 of these individual LED units then the total power consumption of the LED panel will be at least 76.800 W. The main microcontroller will require any voltage level between 1.8 V to 3.6 V. To reduce the number of voltage levels required in the whole design, let the microcontroller's input voltage be 3.3 V. The absolute maximum current draw of the chosen microcontroller is 120 mA, so the maximum power consumption will be 396 mW, or 0.396 W. All of these values were provided either on the product's storepage or datasheet [24, 36, 42].

Table 18: Design Component Power Requirements

Component	Operating Voltage	Maximum Current Draw	Power Requirement
MCU and supporting Electronics	3.3 V	120 mA	0.396 W
Addressable LEDs	5 V	30 mA x 512 = 15.36 A	76.800 W
IR Laser Transmitters	3 V	100 mA x 48 = 4.8 A	14.400 W

IR Laser Receivers	3.3 V	15 mA x 48 = 0.72 A	2.376 W

Regardless of the option taken for the AC to DC converter, the requirement to keep in mind is that it can provide a max voltage of 5 V, a supply of at least 93.972 W, and thus a current of at least 18.794 A. Let's explore what parts would need to be acquired for both processes, then a decision can be made as to which option should be preferred.

3.3.4.1. Option 1: Custom AC to DC Converter

The traditional AC to DC linear converter utilizes a set of crucial internal components, including a power transformer, a diode bridge, a voltage regulator, and several capacitors and resistors for limiting current and smoothing the voltage levels [30, 34]. The following figure summarizes each major component that goes into constructing such a converter. For more information on how AC to DC converters function, see Section 3.2.4.2.

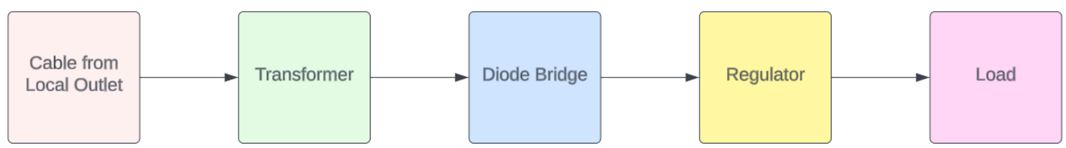


Figure 28: Flow diagram of the internal system of an AC to DC Converter.

The following sections will discuss some criteria to keep in mind when selecting the individual parts that would go into an AC to DC converter. It will be important to understand the purpose of each individual component, seeing how they all have their own specifications and capabilities outside of a greater system. It will also be equally important to understand how these parts will work together to serve the overall function of converting an AC voltage to a DC voltage.

Transformers

Starting with the transformer, this component is responsible for taking some input voltage level and transforming it from one value to another. Certain transformers are capable of raising the voltage level, and others are capable of lowering the voltage level [30]. For the sake of designing a traditional AC to DC converter, the transformer must be able to take the mains supply of 120 VAC and turn that down to a much lower level for the types of electrical components that the Lazer Pong Table uses, which will, at most, be around 5 V. It is important to note that the transformer itself is not capable of turning AC power into DC power, but instead is responsible for just one step during the entire conversion process. The following comparison table will show some of the researched transformer components:

Table 19: Part Comparison for a Transformer. Values taken from respective store pages [81-83].

Transformer	Hammond Manufacturing 167X5	Signal Transformer 241-8-12	Hammond Manufacturing 187E12
Input Voltage (Voltage Primary)	115 VAC	115 VAC	115 VAC
Output Voltage (Voltage Secondary)	5 VAC	12.6 VAC	12.6 VAC
Max Output Current	30 A	8 A	4 A
Max Output Power	150 W	100 W	50.4 W
Unit Price	$78.33	$28.73	$22.39

It is important to take into account the transformer's capability of taking in the voltage from a local wall outlet and transforming that down to a lower level first. Each of the listed transformers are indeed capable of handling an input voltage level around 110-120 VAC, which is the nominal level of voltage distributed through the mains supply in North America. Then, the chosen transformer needs to output a secondary voltage of at least 5 V, which is much more reasonable for the Lazer Pong Table's electrical components to handle. The Hammond Manufacturing 167X5 is capable of directly transforming to this value, while the Signal Transformer 241-8-12 and Hammond Manufacturing 187E12 are both capable of outputting around 12 V. What sets each of these transformer components apart, however, is their maximum output current, and consequently, their maximum output power. As discussed previously, to ensure every major component is able to receive their required power, the chosen transformer will need to be able to provide at least 18 A and 90 W. The 187E12 does not meet either of these requirements. The 167X5 and 241-8-12 are both able to provide over 100 W of power, however the latter can only output 8 A. Thus, between these options, the Hammond Manufacturing 167X5 will be preferred.

Diode Bridges

The next component to consider in an AC to DC converter is the diode bridge rectifier, which is responsible for taking the lowered AC voltage and converting it into a DC-like voltage, with miniscule but still present pulsating ripples. There are several types of diode bridge rectifiers, but the most relevant one here is the full wave diode bridge rectifier. This component utilizes four diodes arranged in a specific way that allows for the positive half of the AC signal to pass normally, but inverting the negative half of the AC signal to create a pulsating DC signal. A capacitor is then included as a low-pass filter, providing a smoothing effect on the output voltage signal, making it much closer to an actual DC signal [35].

While the diode bridge can be constructed manually by following the previously shown circuit diagram, there do exist integrated circuit components that act as diode bridges, reducing the number of circuit components to a single IC. When deciding on which one to implement, it is important to consider the peak reverse voltage, as well as the average rectified current. The peak reverse voltage defines the highest voltage value that the diode bridge can handle during the negative half of the input AC signal. Since the transformer will have already turned down the AC voltage from 120 V to 5 V, the minimum peak reverse voltage will need to be at least 5 V. Then, the average rectified current defines how much current the diode bridge outputs on average. Another specification to consider is the diode type, which can be either single phase, using four diodes, or triple phase, using six diodes [84]. Triple phase bridge rectifiers are typically preferred for systems with very high power requirements [84], so single phase is more appropriate for the Lazer Pong Table, which plans to have overall low power requirements.

Table 20: Part Comparison for a Diode Bridge IC. Values taken from respective store pages [85-87].

Diode Bridge Rectifier	**SMC Diode Solutions KMB22S**	**Micro Commercial GBU3010-BP**	**SanRex Corporation DF30NA160S**
Peak Reverse Voltage (Input)	20 V	1 kV	1.6 kV
Average Rectified Current (Output)	2 A	30 A	30 A
Diode Type	Single Phase	Single Phase	Three Phase
Unit Cost	$0.46	$1.29	$14.51

Taking a look at the Table 20 that summarizes some researched diode bridge rectifiers, it will be important to remember that the power requirements of the Lazer Pong Table call for at least 5 V at 18 A. All listed components are able to handle the required voltage, but only the Micro Commercial GBU3010-BP and SanRex Corporation DF30NA160S can support the current requirement. Their difference lies in their diode type. The DF30NAS160S is three phase, so while it can handle a much higher power level, the Lazer Pong Table does not call for that. So, the GBU3010-BP will be preferred, since it provides enough current and its peak reverse voltage is well within the necessary range as a single phase diode type.

Voltage Regulators

The last part of an AC to DC converter is the voltage regulator. This component is responsible for taking the pulsating DC signal from the bridge rectifier and providing a constant level of voltage to reduce fluctuations and stabilize the DC signal. A voltage regulator is also capable of taking some DC voltage and raising or lowering it even more to some other desired level, but only on a much smaller scale when compared to the transformer's ability to raise or lower AC voltage [38]. For instance, many of the Lazer Pong Table's microcontrollers only require around 3.3-5 V. Instead of using multiple AC to DC converters to supply each of these other components, it will be much more efficient to have this single level of DC voltage provided from the converter, which will then be able to be regulated to any other required level. The following table lists some options researched for a voltage regulator component:

Table 21: Part Comparison for a Voltage Regulator. Values taken from respective store pages [88-90].

Voltage Regulator	**Texas Instruments LM317T**	**Texas Instruments LM7805**	**STMicroelectronics LDL1117**
Range of Input Voltages	3 V - 40 V	~ 0 V - 10 V	2.5 V - 18 V
Range of Output Voltages	1.25 V - 37 V	5 V (Fixed)	3 V, 3.3 V, other fixed outputs
Max Output Current	1.5 A	1.5 A	1.2 A
Max Output Power	55.5 W	7.5 W	3.60 W, 3.96 W
Unit Cost	$0.80	$1.31	$2.02

When considering a component to use, the most important specifications to consider are the range of input and output voltages of the regulator, as well as the maximum output current. The range of input voltages should include the 5 V that would be provided from the AC to DC converter, and the range of output voltages should cover the additional potential voltage levels for some of the other major components. The ideal voltage regulators will be the ones that are flexible and cover a wide range of values for both the input and the output. The maximum output current is also important to consider when taking into account the total power consumption of the Lazer Pong Table. The STMicroelectronics LDL1117 is a very flexible unit, providing different models of fixed output voltages. Along with its reasonable output current, this makes it a suitable component to implement whenever voltage needs to be regulated, acting as a fits-all solution.

3.3.4.2. Option 2: Power Supply Unit

Designing a custom AC to DC converter has many benefits, including having full control over the specifications of its functions and enabling easier integration into the overall system. However, designing an efficient and safe converter requires an extensive amount of technical knowledge, and is not feasible for everyone. Each individual component as well costs a significant amount for a quality part, so that would take a large chunk out of the budget. So it will also be beneficial to consider preconstructed AC to DC converters that are available in the market. Using one of these will not only have the potential to be much safer to use, but they will also serve as a way to make the design process more efficient.

Table 22: Part Comparison for a Preconstructed AC to DC Converter, or Power Supply Unit (PSU). Values taken from respective store pages [91-93].

Power Supply Units (PSU's)	BTF-LIGHTNING Switching Power Supply Device	IMAYCC Adjustable Power Supply	Wefomey Adjustable Power Adapter
Input Voltage	110 - 240 VAC	110 - 240 VAC	100 - 240 VAC
Output Voltage	5 VDC	Adjustable; 0 - 24 VDC	Adjustable; 4 - 24 VDC
Max Output Current	30 A	Adjustable; 0 - 20 A	5 A
Max Output Power	150 W	1 - 480 W	20 - 120 W
Number of Outputs	Two	Two	One
Cost	$22.99	$55.99	$24.29

Looking at the table summarizing some researched AC to DC converters, it will be important to note many of the same specifications discussed previously. The converter will need to be capable of inputting the common voltage levels of the mains supply, outputting a useful level of DC voltage to use for each major component, and providing a large enough power supply for the overall system. The BTF-LIGHTNING Switching Power Supply has a high output power rating of 150 W, but is fixed to output a DC voltage of about 5 V, meaning some additional voltage regulators will need to be implemented to provide other common voltage levels, such as 3 V. The Wefomey Adjustable Power Adapter seems very flexible in its adjustable output voltage level, possibly removing the need for additional voltage regulators, but is only rated to output a maximum current of 5 A, which consequently results in a slightly smaller power supply at similar voltage levels. The IMAYCC Adjustable Power Supply is similar to the Wefomey device in that it allows for an adjustable output voltage, but it provides even more flexibility in its capability to adjust output current as well, making it a valuable component for designs that require different levels of voltage, current, and consequently power. However, despite having two output terminals to connect to two different devices, both terminals are restricted to outputting the same levels. This restriction applies to the BTF-LIGHTNING PSU as well. So even though these units are able to be connected to several other parts, those parts would need to require the same level of voltage and current, otherwise separate regulators would need to be implemented.

Considering the required voltage levels and power consumptions of all major components, it can be determined that the PSU will need to be able to provide multiple levels of voltage with a max of 5 V and a current of at least 18 A to supply at least 90 W. With these requirements, the BTF-LIGHTNING Switching Power Supply Device is well suited for the Lazer Pong Table, as it balances the necessary requirements with its relatively low material cost. While the IMAYCC PSU is both adjustable and has the possibility of providing more power, both of these features are unnecessary and the unit is significantly more costly. As stated before, the BTF-LIGHTNING PSU has two output terminals. These will both need to output the same voltage level, but this can be fixed through the implementation of two separate voltage regulators, one of which will regulate the output to 5 V, and the other will regulate an output of 3 V. The voltage regulator component to implement here will be the same product chosen earlier in this section: the STMicroelectronics LDL1117.

With the options fully explored, it is clear to see that it will be more efficient to choose to acquire a power supply unit to implement into the Lazer Pong Table's power system. Not only will this option be safer, as the designers won't need to work with AC power as closely than the other option of using a transformer component, but this will also allow the focus of the design effort to shift towards constructing a well-managed and efficient distribution system for the rest of the Lazer Pong Table.

3.3.4.3. Supplemental Components: Redundant & Uninterrupted Power Supplies

The Lazer Pong Table will most likely operate for long periods of time, where game sessions will ideally be uninterruptible so as to not dampen the overall play experience. Thus, it would be beneficial to consider a method of backup power in the event of hardware failure or a power outage that would allow the Lazer Pong Table to continue to operate. Two common methods of approaching this scenario are redundant power supplies, and uninterrupted power supplies.

As previously discussed briefly, a redundant power supply (RPS) is a system of multiple power supplies that serve the same device. During normal operation, each power supply would provide a portion of the overall needed power. Then, if one becomes suddenly unavailable, the other supply, or supplies, will be able to compensate for that loss and continue to provide the required power. For instance, having a custom AC to DC converter alongside a preconstructed one would serve as a redundant power supply. Each would be able to serve the entire system while remaining completely separate and independent of each other, which would allow for the operation of the device if an issue arises in one of the supplies [39].

Conversely, an uninterrupted power supply (UPS) is a device that typically serves as a battery backup in commercial environments, often connected as a middleman between the mains supply and the actual system. During normal operation, the UPS can supply mains power to the device, acting as another method for stabilizing voltage levels, not dissimilar to a voltage regulator. In the event of a power outage, where the mains supply becomes unavailable somehow, then the UPS will be able to supply DC power from its internal battery to the device instead to continue supplying the necessary power, maintaining function and protecting other electrical components from damage [39].

Table 23: Part Comparison for a UPS. Values taken from respective store pages [94-96].

UPS	Shanqiu Mini UPS	Xdorra UPS Battery Backup	Talentcell UPS Battery Pack
Max Input Voltage	12 VDC	12 VDC	12.6 VDC
Max Output Voltage	5 V / 9 V / 12 V (fixed)	5 V / 9 V / 12 V (fixed)	9 VDC - 12.6 VDC
Max Output Power	30 W	38.48 W	37.8 W
Battery Capacity	10000 mAh	10400 mAh	3000 mAh
Cost	$49.99	$51.00	$27.99

However, it is important to keep in mind other considerations, such as available physical space for the hardware, additional costs, and additional time to integrate into the entire system. These factors should always be weighted heavily when determining if a redundant or uninterrupted power supply is strictly necessary, as while they are very useful to have in a system, they are ultimately optional features that can only improve on a device's overall function. Once again, the decision to acquire such a device, like the Shanqiu Mini UPS, will mainly serve as a backup insurance plan to guarantee that we can implement a stable, consistent, and reliable power distribution system.

3.4. Bill of Materials (BOM)

In this chapter, the constituent components of each section of the design were identified, their requirements were clearly outlined, and the best available part options were compared and contrasted. These parts represent the best function of the project as defined by what modular components can be found on the market, as well as what features are available to this design given the time and budgetary constraints herein. Up until this point, the functionality of this project was defined by what the employed technologies are capable of in a vacuum. However, from this point forward, the scope of this design will now be defined by the features and implementations of these components using these selected parts. The end result of this process is a complete list of all the parts necessary to fulfill all of the major components of the design, which is summarized in the table below.

Table 24: BOM.

Part Name	Part Number	Part Purpose	Quantity	Cost Per
Q-BAIHE IR Laser Diode Module	780MD-3-0610	Laser Transmitter	48	$3.18/ea
DKARDU IR Infrared Flame Sensor Module	JK-US-487	Laser Receiver	48	$1.30/ea
BTF-LIGHTING WS2812B Fairy String	WS2812BLEDW-T12cm	Prefabricated LED Strip	11	$9.99/ea
STM32F2 Series Microcontroller	STM32F205VC	MCU	1	$12.62/ea
TLV70233 Series LDO Voltage Regulator	TLV70233DBVT	PCB Voltage Regulation	1	$0.63/ea
CUI Devices Electret Condenser Microphone	CMA-4544PF-W	Ambient Sound Measurement	1	$0.77/ea
BTF-LIGHTNING Switching Power Supply	BTF-30-5	PSU	1	$22.99/ea
STMicroelectronics Linear Voltage Regulator	LM317T	Power Voltage Regulation	1	$0.80/ea

4. Standards and Design Constraints

In the working environment of any profession, adherence to relevant standards and acknowledging design constraints cannot be overstated. It is not a simple formality that is forced upon the employee for no reason. Rather, for anyone, including engineers, standards and constraints serve as a critical foundation for the execution of project success. Both help guide the worker towards their end goal, acting as guiding principles that provide a framework for functionality, consistency, and reliability. By establishing such clear parameters and always being mindful of the industry's best practices, engineers become well-equipped to deliver a quality solution to whatever problem they face.

Elaborating further, standards act as a lighthouse, enlightening engineers towards their industry's most recognized and trusted practices. By following these beacons, the engineers ensure that their work coincides with well-established benchmarks that determine the success of their project. Standards not only guarantee compliance with accepted industry norms, but they also let the engineer demonstrate their commitment to quality above all. Whether these be guidelines encompassing safety protocols, specific measurements a system must have, or considerations for the betterment of end users, standards will always be important to be acknowledged. Their ultimate purpose is to give the engineer the tools that allow them to deliver a solution that not only meets expectations, but maybe even to surpass them, continuing to push for progress in their field.

Similarly, being aware of design constraints is just as paramount as being familiar with the industry's standards. Where standards may act as a lighthouse, the design constraints act as the engineer's vehicle. How will they get to their destination? What are the options that exist? How can they even begin to choose a path to go down? Constraints serve as realistic limitations to how one might go about solving a problem. While this may seem like a terrible thing, being so restricted to certain paths, but once design constraints are determined and embraced, then it becomes clear that they play an important role in a project's success. They allow the designers to gain insight on the boundaries of their solutions, which directs their creative focus towards more practical and feasible options. This allows them to optimize their designs to better accommodate the relevant standards with available resources.

In all, adhering to both standards and established design constraints is a crucial aspect in developing a project. Standards give engineers comprehensive tools needed to understand a problem, equipping them with invaluable knowledge of the industry. At the same time, being cognizant of constraints help engineers to navigate the seemingly endless ways of developing a solution. Understanding these concepts will lead to innovative, efficient, and user-friendly solutions, further leading the way towards progress and success.

4.1. Standards

It is important for any designer to consider regulations and standards set by their respective discipline. For all professions, including engineers, there have been numerous guidelines, codes, and detailed requirements developed over time to ensure proper and safe functionality of their products. Organizations such as the International Electrotechnical Commission (IEC) dedicate resources for the standardization of all things concerning the electrical and electronic fields. The IEC has published hundreds of international standards and technical specifications. The Lazer Pong Table incorporates many of these technologies, all of which have standards that should be complied with. Laser safety, power regulations, acceptable PCB and microcontroller design, and accessibility need all be considered carefully for the true success of this project.

Table 25: Summary of Industry Standards relevant to the Lazer Pong Table. Standards originally found through ANSI [97].

Standard Code	Est. By	Name of Standard	Discipline
ANSI Z136.1	LIA	American National Standard for Safe Use of Lasers	Safe Use of Lasers
ANSI Z136.7	LIA	Testing and Labeling of Laser Protective Equipment	Safe Use of Lasers
IEC 60825	IEC	Safety of Laser Products	Safe Use of Lasers
IPC-STD-001	IPC	Requirements for Soldered Electrical & Electronic Assemblies	Acceptable Electronic Design
IPC-AJ-820A	IPC	Assembly & Joining Handbook	Acceptable Electronic Design
IPC-2222	IPC	Sectional Design Standard for Rigid Printed Boards	Acceptable Electronic Design
IPC-A-600	IPC	Acceptability of Printed Boards	Acceptable Electronic Design
IPC-6012	IPC	Qualification & Performance Specification for Printed Boards	Acceptable Electronic Design
IEC 60950	IEC	Information Technology Equipment Safety	Hazards & Protections
NFPA 70	NFPA	Florida Electrical Code	Hazards & Protections

28 CFR 35.151 & ADAAG	DoJ	ADA Standards for Accessible Design	Accessibility
ICC A117.1	ICC	Accessible and Usable Buildings and Facilities	Accessibility

4.1.1. Safe Use of Lasers

Laser Safety: ANSI Z136.1

Laser safety standards are very necessary for ensuring the use of lasers safely across the industry. Standards provide regulations and rules to minimize potential hazards when working with laser radiation while also promoting the health of the people working with or exposed to lasers. These standards have significance in safeguarding lives and maintaining a safe workplace.

Safety standards employ a classification system that puts lasers into different classes based on their potential danger and hazards. The classes range from Class 1, which have little to no hazards, to Class 4, being the highest level of hazard. Class 1 lasers do not pose any potential hazards but Class 1M pose a low risk if viewed through different optical instruments. Class 2 are very low powered usually not exceeding 1 milliwatt, similar to Class 1M, Class 2M are safe for direct viewing until viewed through optical instruments. Class 3R lasers are a moderate risk laser that could cause eye damage if directly viewed, Class 3B are medium/high powered lasers that could lead to serious eye or skin damage. Class 4 lasers are very high powered that could cause serious damage to the eyes or skin and also pose a fire hazard. It is important to use this standard to be able to identify the appropriate precautions for each laser class, secure and safe work environment and operation of lasers.

Table 26: Laser Class and proper safety precautions. Table data provided by LIA [5].

Laser Class	Safety Considerations
Class 1	No specific precautions required under normal operating conditions.
Class 1M	Safe for direct viewing, but potential risks if viewed through optical instruments such as magnifying lenses or binoculars. Precautions necessary for extended exposure.
Class 2	Low-power lasers that pose minimal risk. Safe for direct viewing, but intentional prolonged exposure should be avoided.
Class 2M	Safe for direct viewing, but potential risks if viewed through

	optical instruments. Precautions necessary for extended exposure.
Class 3R	Moderate-risk lasers that may cause eye injuries if viewed directly, especially through optical instruments.
Class 3B	Medium to high-power lasers that can cause severe eye and skin injuries. Additional safety measures required, such as engineering controls, restricted access, and proper use of personal protective equipment (PPE).
Class 4	Highest level of laser hazard. Can cause severe eye and skin injuries, as well as pose fire hazards and other risks. Stringent safety protocols necessary, including laser interlocks, controlled access, extensive training, and specialized PPE.

Another standard implemented in laser safety is Maximum Permissible Exposure (MPE). MPE is the maximum amount of radiation produced by a laser that an individual can be exposed to without suffering effects. Standards provide MPE tables that specify which levels of laser radiation. These tables take into account the class of the laser, wavelength, and specific considerations for different body parts. It is important to follow this standard along with other standards to keep everyone safe.

Engineering and Administrative controls are crucial standards to operating lasers. Engineering Controls include the use of interlocks, beam stops, laser enclosures, and safety shutters. Interlocks make sure that the laser operates safely by preventing accidental bumps into the laser. Beam stops absorb and dissipate the laser energy and reduce the risk of accidental exposures. Laser enclosures are very similar by keeping the laser workplace enclosed thus preventing accidental exposures. Safety shutters are barriers that block laser beams when not in use. Administrative controls are standards that are not physical items like training programs, hazard assessments, and standard operating procedures. Training procedures are essential to educate laser operators about all potential risks, emergency procedures, and safe practices. Standard operating procedures (SOPs) make rules and guidelines to ensure safe use and consistent steps with organization. A combination of both of these controls protects all workers in the industry.

Test/ Label equipment: ANSI Z136.7

Personal Protective equipment (PPE) when working with lasers is one of the most important standards when preventing any sort of accident. PPE when working with lasers are mostly equipment to protect your eyes from a stray beam. These protective eyewear are designed to absorb specific wavelengths of light.

They use filters and different optical densities to reduce the intensity of the laser beam. Protective clothing is also a common form of PPE to minimize the risk of skin exposure to laser radiation. The clothing is also specific based on the lasers class, power, and wavelength.

Warning signs and labels are integral to laser safety standards, effectively communicating laser hazards. They display essential information, such as laser class, associated risks, and precautions. These signs control access to laser areas, emphasizing restricted entry and the requirement for personal protective equipment. They also provide emergency details and promote safety training and awareness. Compliance with warning signs and labels ensures a safe environment, conveying risks, managing access, and fostering a culture of laser safety.

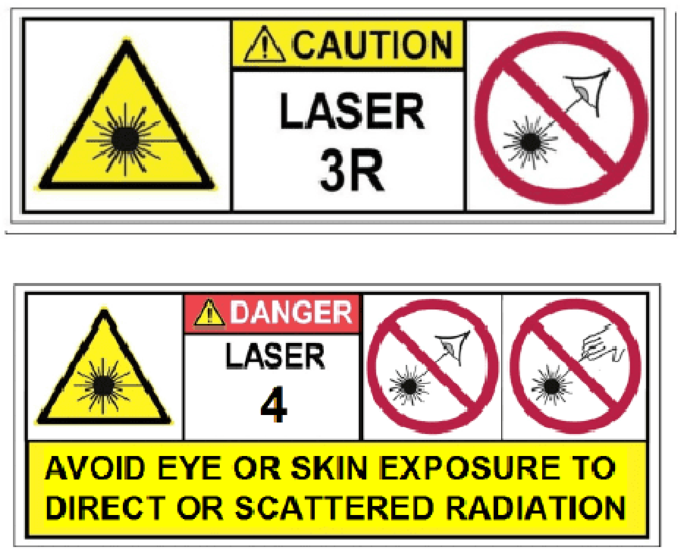


Figure 29: Comparison of Warning signs of Class 3R and Class 4. Images used from IEC 60825-1 [98]

In conclusion, laser safety standards are indispensable for promoting the safe and responsible use of laser technology. These standards encompass various aspects such as laser classification, maximum permissible exposure limits, engineering and administrative controls, personal protective equipment, and the use of warning signs and labels. By adhering to these standards, organizations and individuals can effectively mitigate risks, prevent accidents, and prioritize the well-being of those working with or exposed to lasers. Laser safety standards are essential in creating a secure working environment and ensuring the advancement of laser technology is accompanied by the highest standards of safety.

IEC 60825 - Safety of Laser Products

An international standard published by the IEC describing safety precautions of laser products emitting laser radiation within the range of wavelengths 180 nanometers to 1 millimeter.

4.1.2. Acceptable Electronic Design

The Institute for Printed Circuits (IPC) is the leading standards organization for the electronic interconnection industry [99]. They offer standards for all natures of PCB development, from microelectronics to large power equipment, and for every stage of development along the way. There are far too many standards which are not relevant to this design, so an IPC tool sheet was used to identify the standards relevant to the PCB design for this project. This sheet can be seen below, with the standards related to this project highlighted in red.

Each standard in each subsection was reviewed to ensure that each relevant standard was identified. Most of these standards relate to the large-scale manufacturing of the PCB itself, as well as the more intricate standards for nanoscale electronics. However, a select few offered great guidance to several key steps of the PCB development process for this design. Unfortunately, most of these standards are only available at individual prices of over $100, so could not fit the budget for this project. Where materials were made available for free, those materials were more heavily included. Where materials were paywall locked, they were researched outside of the official document in order to understand how they could be useful, if they were made available.

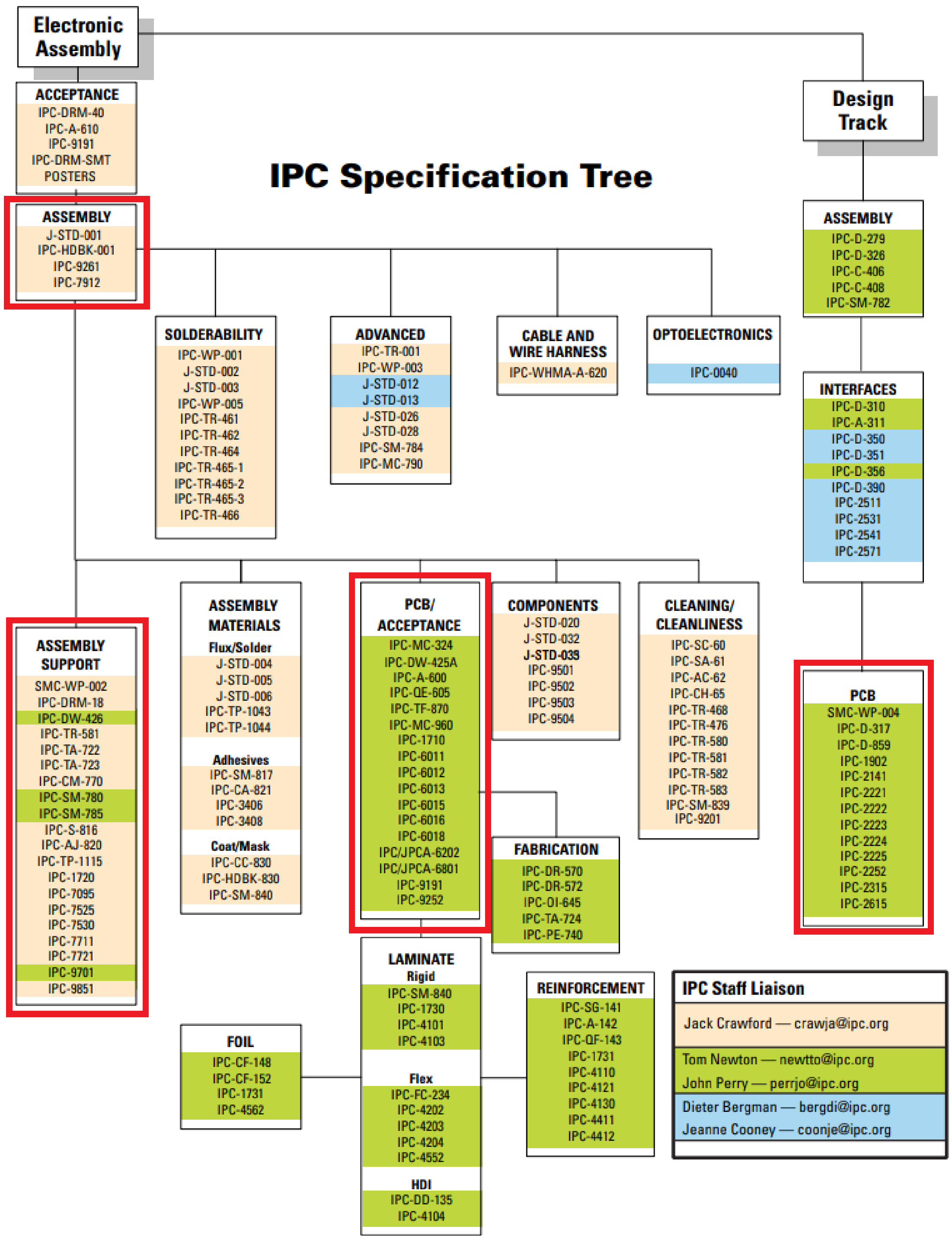


Figure 30: IPC Specification Tree. Image used from IPC standards guides and documentation with modification by the Lazer Pong project team [99].

Soldering: IPC J-STD-001 and IPC-AJ-820A

These two standards comprise the extent of the soldering and assembly standards related to this design. The assembly and joining committee for the IPC (IPC-AJ) is responsible for the standards set for component joining techniques and technologies [100]. The standard (J-STD-001) offers exact details as to the standard for each variety of component assembly, while the assembly and joining handbook (AJ-820A) covers these technologies in greater detail [101]. An additional handbook is available, IPC-HDBK-001, which offers further detail into the requirements for quality component assembly and connection [102].

To summarize, the IPC recommends the following precautions be taken into account when assembling PCB components via soldering [102]:

1. All surfaces, materials and tools must be free of debris.

2. Soldering temperature rates and duration must conform to the part manufacturer's standards.

3. The pin should be fully wetted, and the conduction pad should be fully covered.

If these steps are followed and the solder is carefully examined to be free of debris before component assembly, the end result should be a high quality joining.

Rigid PCB Design: IPC-2222

The IPC standard that most directly applies to this design is IPC-2222, the standard for rigid design. This standard offers insight into "optimal component placement, routing density and electrical performance" for small scale, rigid PCB implementations [103]. The guidance this standard could offer may be invaluable to this design, as the PCB design complexity for this task is sizable.

The main insight offered by this standard for the end-user, who is designing and ordering a custom fabricated PCB, is in the choice of board dielectric and thickness, as well as methods for fixing components to the board. As per the standard, the FR4 board dimensions will offer the minimum in capacity as far as dielectric thickness and operating temperature capacity [103]. In the VLSI development industry, this board type is often used to model functional prototypes for systems validation testing. For this reason, and the lower cost of producing a board with less dielectric material, this designation will be used for the PCB components of this project.

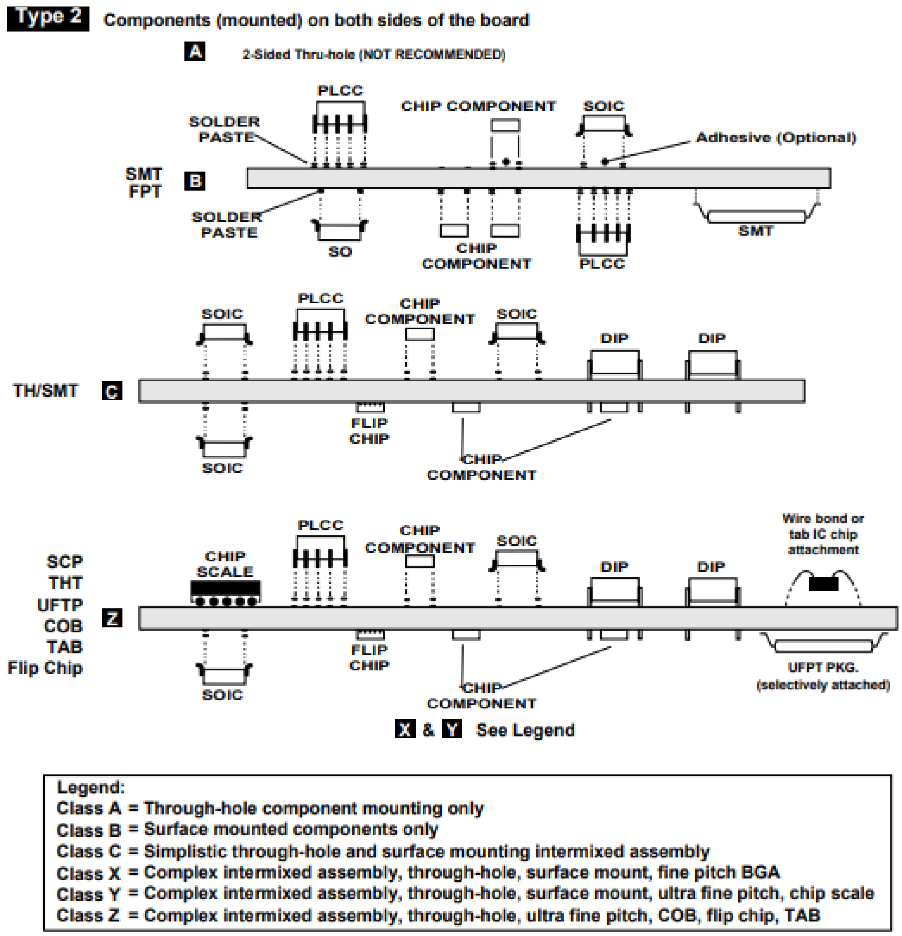


Figure 31: IPC-2222 standard for mounting components on both sides of the PCB. Image used from IPC-2222 [103].

Additionally, components will be mounted on both sides of the PCB. This will be required for the MCU decoupling capacitors, which must be placed at and underneath the VDD and VSS pins [36]. Most components will be surface mounted, but the I/O pin headers for the laser receivers may need to be through-hole mounted if more than three layers of PCB are needed. For this, the component assembly for this design will be considered Class C.

Acceptability: IPC-A-600 and IPC-6012

These two standards documents outline the key factors to identify when qualifying acceptable PCB. They offer ways engineers can measure manufacturing quality for PCB products to classify the quality, and potentially verify or validate a product [89, 90]. Additionally, the document labels common PCB nonconformities, and offers standards for acceptable levels of board distress. By classifying electronics into three classes, each with their own escalating set of acceptable standards, the documents clearly define what the minimum standards are for holistic board quality as it relates to the purpose of the electronic products [89, 90].

Table 27: Electronics Classifications for Acceptable Standards. Table information pulled from IPC-6012 [89, 90]

Class	Description
1	General electronics, which include most consumer products. These products are focused on simple task completion and reliability, with the potential for occasionally interrupted service.
2	Dedicated service electronics, which include communications, industrial, and enterprise equipment. These products are focused on extended life, low/efficient cost, and rarely interrupted service.
3	High reliability electronics, which include life support systems and flight control/vehicle control systems. These products require the highest level of quality assurance, as well as truly uninterrupted service.

As a class 1 electronic, also known as a “General Electronic Product”, this design will be held to the standards therein as described by these documents. Electronic products of this class generally require correct functionality, but leave provision for the potential for error [104]. PCB designed for this class of electronics may have some level of physical distress and still be acceptable for use, while the same cannot be said of class 3 electronics [104]. Ergo, it may be acceptable for a nick in the PCB of a microwave controller to cause a short and produce a failure, but the same could not be said for the PCB of a flight control system, or an emergency dispatch radio.

Most of the inspection information is provided in IPC-A-600, which assesses in great detail each observable defect that the PCB may experience and how the scale of those defects impacts the acceptability of the board [105]. These defects include edge damage, such as burrs, nicks and haloing, as well other common defects with the board surface, subsurface, contacts, solder, and through-holes [105]. This document will be used to validate the PCB received in the prototype build stage of this project. All board defects will be labeled, measured and compared to the class 1 acceptability standards provided to validate the board quality before and after assembly.

4.1.3. Hazards and Protections from Energy and Power

For any engineer working closely with electricity or power, it is of utmost importance that they understand the potential dangers and hazards of electronic devices, especially in settings where those devices rely on mains power, which as discussed earlier, flows through outlets at relatively high levels of voltage. Luckily, following the established standards set by organizations like the IEC can ensure the well-being of the designers, users, and equipment.

IEC 60950: Information Technology Equipment Safety

This international standard addresses specific safety requirements for electrical equipment in many sectors of the engineering environment. Applicable to mains-powered and battery-powered equipment with a rated voltage less than 600 V, this means that this standard is also relevant to the design of the Lazer Pong Table. IEC 60950 provides a comprehensive framework of safety guidelines, recommendations, and criteria that manufacturers and users should adhere to, aiming to ensure that the equipment operates safely while minimizing risks such as electric shocks, electrical fires, radiation, chemical hazards and more [106].

Looking further into the details of the standard, its scope covers a broad range of common Information Technology devices, including computers, routers, switches, etc. It also provides details of where certain harms can originate from. For instance, contact with bare parts that normally run hazardous voltages. Here, the standard then provides many helpful examples of measures to take in order to reduce this risk: “To prevent the user from having access to these hazardous voltages, the exposed parts should be behind locked covers or safety interlocks.” [106]. Many instances like this example span a large portion of the IEC 60950 standard document, with various potential harms and their associated techniques that can ensure equipment and user safety.

Florida Electrical Code

The Lazer Pong Table was originally designed in the state of Florida, so it was important to also consider the standards that govern electrical installations and practices within the state of Florida. While mostly designed for the larger electrical systems installed in residential, commercial, and industrial buildings, there are also many sections that describe furnishings and smaller appliances that are relevant to the the design of the Lazer Pong Table.

The purpose of the Florida Electrical Code is for the practical safeguarding of persons and property from hazards arising from the use of electricity [107]. It contains several considerations that are necessary for safety, including wiring methods, circuit protection, power distribution, communication systems and more.

4.1.4. Accessibility

Since the Lazer Pong Table seeks to attract a wide range of users, who will all come from many walks of life, it will be equally important to consider factors that relate to how accessible the overall design needs to be. The Americans with Disabilities Act (ADA) statute identifies who is a person with a disability, who has obligations under the ADA, general non-discrimination requirements and other basic obligations [108]. The federal ADA has issued regulations and design standards that respect the rights of people with disabilities, and these standards will provide valuable design criteria that will be important to consider when trying to make the Lazer Pong Table an accessible product.

Guide to the ADA Standards for Acceptable Design

This guide, developed by the US Access Board in cooperation with the Department of Justice and the Department of Transportation, helps to give simplified explanations of the requirements within the ADA Standards. The guide also provides clearly labeled diagrams, figures, and measurements for best practices. For example, Chapter 3: Clear Floor or Ground Space and Turning Space is especially relevant to how the Lazer Pong Table can follow the ADA's standards, as it provides helpful measurements and diagrams for average allowable clear space and average reaching zones [109].

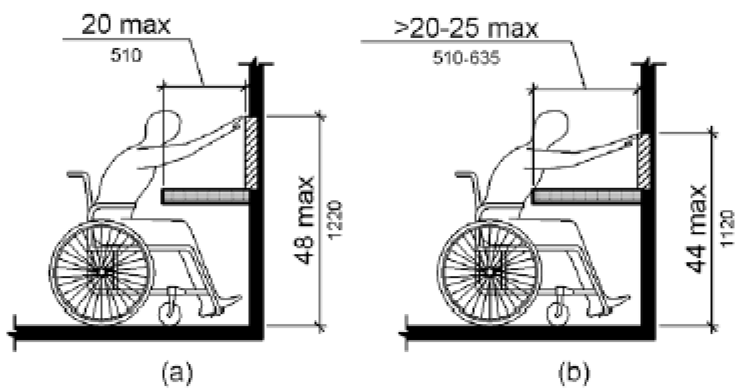


Figure 32: ADA measurements for obstructed high forward reach. Provided by the U.S. Access Board [110]

Figure 32 is just one example of these important measurements to follow, detailing the average high forward reach for wheelchair users. As a product that will encourage reaching for objects like cups and ping pong balls on a tabletop, the final design will be much more useful to end users if these are followed, further enhancing their overall experience. These measurements will be useful for the physical build of the table and its supporting structures. Adhering to the standards set by the ADA will ensure that our final design is as accessible as it can possibly be for all persons.

ICC A117.1: Accessible and Usable Buildings and Facilities

Developed by the International Code Council (ICC), whose primary goal is to establish and promote a set of comprehensive building safety and sustainability codes, the ICC A117.1 standard is intended to describe how persons with physical disabilities can independently get to, enter, and use a facility or building element [110]. Similar to the Guide to the ADA Standards, this standard provides many useful design measurements and recommendations for building appliances and furnishes. Chapter 9 particularly gives recommendations for clear floor space, heights, approach methods, and more. For instance, in Section 907.1, it states that: "Gaming machines and tables shall have… clear floor spaces required… [and] shall be permitted to overlap" [110]. The measurements for clear floor spaces were provided in Section 305.3 as 52 in. minimum in length and 30 in. minimum in width [x].

Assistive Tools for Design Activity in Product Development

This is a research paper written by E. Zitkus, P. Langdon, and J. Clarkson and published by the Proceedings of the International Conference on Sustainable Intelligent Manufacturing [111]. While not necessarily considered as a conventional standard, it does provide an incredibly detailed guide on how to analyze the needs of a project's end users from the start, as well as techniques to start integrating those needs in the middle of the project's lifetime. For instance, the paper suggests using user trials or self observation early in the project's conceptual phase, using similar products to gather information on which needs are met. Then, after the project has kicked off, simulation tools like CAD models can be used to further test how these needs can be integrated and how achievable they may be. Overall, it is a significantly useful resource to treat as a standard, enabling the design to not only meet the needs of its expected wide audience, but to also make the process of developing those solutions much more efficient and assured through the use of researched techniques.

4.2. Constraints

In the development of any product or idea there are always limitations to what can be done to accomplish what is desired. The Lazer Pong table is no different, and also has constraints that will need to be considered in its conception. These limitations range a wide variety of different subjects that all contribute together to what can be done for the project. Within the design of the Lazer Pong table there are economic and time constraints, which are imposed from the fact that this is a project for a college course and the members of the group have finite money. There are also environmental, social, health, safety and ethical constraints that come from what the project is intended for and what it is composed of. Manufacturability and sustainability constraints are also key factors in the design which plays a role in the feasibility of the project as a whole.

4.2.1. Economic and Time Constraints

The economic and time constraints are two of the most limiting factors to the Lazer Pong project. On the time side of the project there is a large limitation due to the fact there is a strict schedule that must be abided by. This schedule is set by the fact that the project is for the senior design I and senior design II courses. For the first part of senior design as a whole, the project is in a planning phase. There is a large amount of research that is done to facilitate the goals and objectives of the project during this phase of senior design. Given that our group's senior design project started in the summer term there is even less time. Summer class terms only go for 12 weeks, while the typical fall and spring terms are 16 weeks. Assuming one spends the recommended 9 hours of time working on coursework outside of class, and senior design is seen by many previous students as having the workload of 3 classes in one, then 27 hours out of the week should be spent on working on the senior design project. With 5 people in the group and 4 weeks less time than a standard semester, this project is deprived of a total of 540 hours for the planning phase. The project has some small builds and tests that are constructed to ensure different systems in the build will operate as intended. However, the construction of the project all together does not come until the second phase of senior design.

For senior design II, the actual construction portion, it will be during the fall semester, so there will be 16 weeks to work on the project. This is unfortunately still a limited amount of time for the project build. In senior design II the PCB will have to be designed and tested, and this can take weeks to arrive after it has been ordered. Because of this, there are only so many attempts and prototypes that can be built before the final design must be submitted. With all of the research and small test runs during the planning phase of the project, this should not be an issue, but that does not mean that unforeseen problems will not arise. There are also issues with availability of products during the time frame that the senior design project will be taking place. If a certain product that would be otherwise ideal for the build of the project is unavailable or would take too long to manufacture or ship, then it would unfortunately have to be disregarded for the actual build of the project.

Along with the time constraints that are instilled just by the senior design course, there are also time constraints that come from outside the realm of senior design. The group consists of 5 college students that are also taking or will be taking other courses that cannot be disregarded. These other courses will have time that must be dedicated to them in class, as well as outside of the classroom. There are also factors such as jobs outside of schoolwork that sometimes take precedence in order for bills and food to be paid for. In an industry scenario, the project would be given by the job, so this constraint on time would not be present.

In regards to the economical constraints for the project there are personal constraints as well as constraints for the viability of the project itself. Personally, since there are no sponsors for this project, the Lazer Pong table will be fully funded by the group members of the project. All of us are college students and do not have access to an excessive amount of disposable income to use on the construction of the project. Despite the limited budget for the project, the overall integrity of the project design will not be compromised.

With the economic constraints of the project as a whole there are many ideas to take into consideration. A major constraint is that the project intended use is eventually to be for the public. This implies that the price it would be listed to the market must be acceptable and affordable. For comparison the Chexal Technologies RaveTable mentioned in section 3.1.3 goes for a market price of

$3,195.00 - $4,145.00, depending on selected features. Similarly the Bay Tek's Beer Pong Master from section 3.1.5 is currently on the market for $4,995.00. The economical constraint set here is to compete with these comparable market products, while also providing better features. To be able to achieve this it is crucial to incorporate the most cost-effective parts when selecting the methods for the designs of the different systems of the project. This will give the Lazer Pong table the highest overall quality build while retaining its marketability.

4.2.2. Environmental and Social Constraints

The environmental and social constraints of the Lazer Pong table are vital concerns to take into account. These will play large roles in the overall design of the project. The environment that the Lazer Pong table will ideally inhabit is where the constraints will be drawn from, as using it outside of this scope will not provide or will interfere with the goals of the project. The social constraints will mostly stem from the marketability of the project and how it will be received by the public.

Firstly, for the environmental constraints of this project, it is likely that there will be liquids near or on the table such as beverages from the users, given the table will be mainly intended for social gathering uses. This being commonplace for the table means that it is very important that the table is waterproofed. There will be many electrical components in close proximity to the play area, and spills are more than likely to happen considering the nature of the game to be played with the table. Implementing ideas such as clear acrylic over the top of the LEDs or in front of the laser diodes and photodetectors will help in the waterproofing of the Lazer Pong table. Also ensuring that any wiring is held within the structure of the table will help in preventing any water damage from compromising the system. If water damage were to occur to one piece of the system it could easily cause the entire functionality of the table to fail.

Another crucial environmental constraint is the overall durability of the Lazer Pong table. Considering the party-like environment that the Lazer Pong table will normally be situated in, the sturdiness of the table is a vital concept to incorporate in the design of the project. With the likelihood of alcoholic beverages being consumed while the table is in use it is very possible that the table could undergo bumps and shakes. The game of beer pong is also competitive in nature, so this adds to the level of intensity that some might play, which would in turn lead to the players' disregard for the table itself. For example, if a bounce shot is attempted, then the other player(s) can attempt to swat the ball. The swatting motion could easily lead to the table being hit if the player is solely focused on the ball and winning.

Where the game will be played or where it will operate the most effectively is an environmental constraint that plays a role in the project. For the goal of ball tracking, this project will use infrared light sensitive photodiodes. Because of the use of these photodiodes, and their purpose for the game, it would be unwise to attempt to use the Lazer Pong table in an outdoors environment. This is because of the light spectrum emitted from the sun. The sun emits all frequencies of electromagnetic waves excluding gamma rays [112]. This would then include infrared emissions, which if the Lazer Pong table were to be used outside during the day, then the photodetectors could end up reading this signal radiating from the sun and not function as intended. Therefore, it is a constraint set by the way in which the laser grid will operate that the project will not be able to be used properly outside.

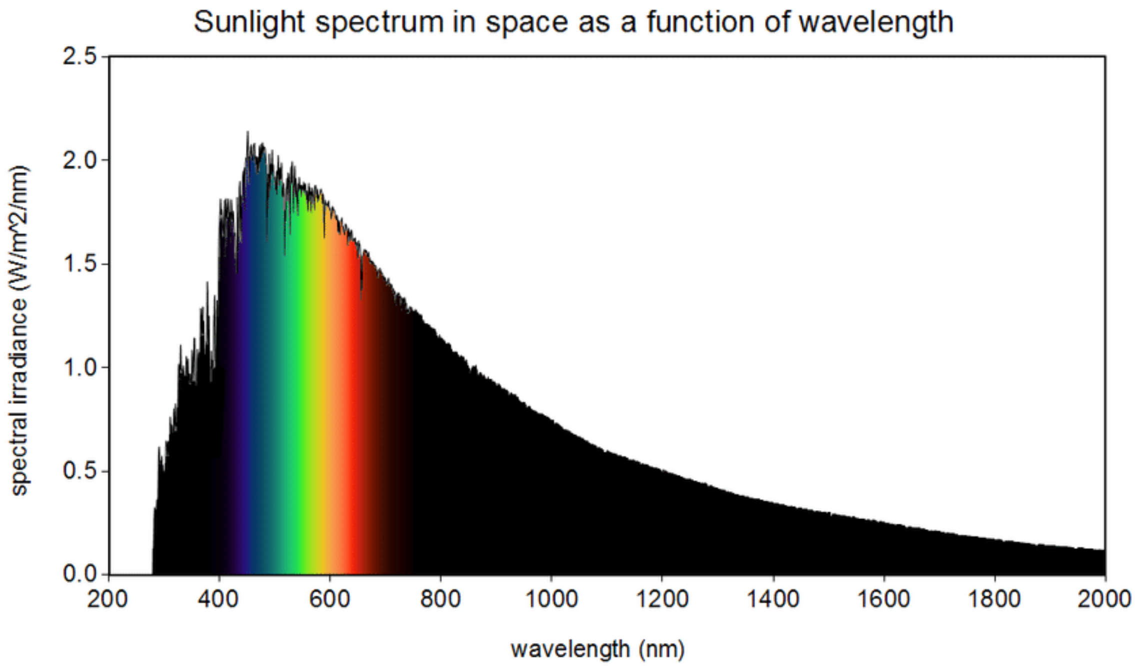


Figure 33: Image showing light spectrum in wavelength units emitted from the sun. Public domain image from [112].

4.2.3. Health, Safety and Ethical Constraints

Health, safety and ethical constraints could be viewed as the most important constraints to ensure they are considered, because they are for the well-being of everybody. If these are neglected then those making or using the Lazer Pong table would be at risk of hurting themselves or others. There will be many parts to the Lazer Pong table, and of those parts there are many that can potentially cause damage to people. The implementation of lasers and LEDs needs to be considered, as well as all of the wiring that will be going along with it. Also the game that is meant to be played with the Lazer Pong table implies alcohol consumption, which must be something that is addressed.

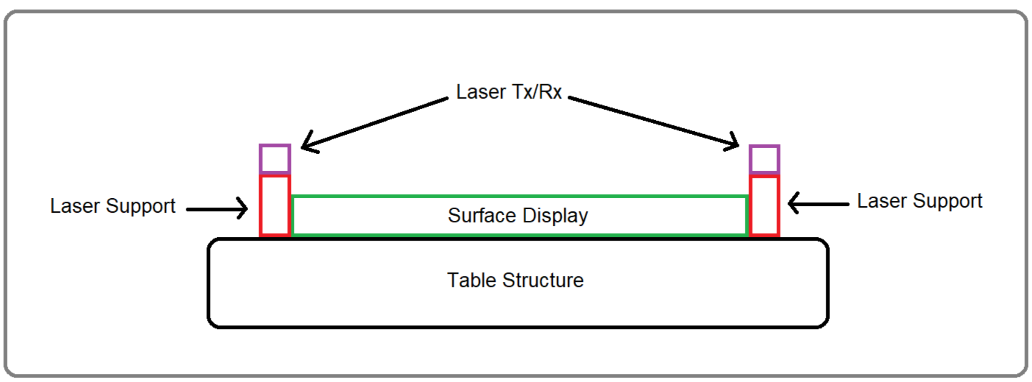
Firstly, the laser diode modules that will be used for the laser grid will be a potential danger to health and safety. Laser's are inherently more dangerous than other types of light sources because of their narrow beam emission, which is easily focused onto a small spot on the retina [113]. Therefore it is crucial that the output power of the lasers are low, to minimize the potential harm that they could cause. The LEDs are less hazardous than the lasers, but because of the design of the table they will be facing directly upwards. This could cause damage to the eyes of the players if they were to play like this for extended periods of times, so constraints on how this can be mitigated will need to be employed. Also, with all of these parts there will be lots of wiring to power them. Exposed wires pose a threat of electrocution, which of course would be unacceptable. This means that there will need to be design considerations on concealing these wire from the players.

For the ethical side of the constraints, it is important to realize the game that will be played. The Lazer Pong table will be facilitating the game of beer pong, which, as the name of the game states, entails alcohol. Beer pong is a party game, and to put a product onto the market that promotes playing the game can be seen as an ethical issue. That is because then it could be said that the project is also supporting the drinking of alcohol. To combat this, it will be necessary to tell the potential buys to ensure they drink responsibly.

5. Hardware and Software Design

When approaching the design stages of this project, it is important to consider the high-level direction of the project. The entirety of this design up to this point has been approached from the perspective of four main subsystems: The laser grid, the surface display, the microcontroller embedded system, and the power delivery system. Each of these subsystems has been individually, carefully analyzed by one of our team's relative experts, and the design criteria of each has been prepared in the form of a list of necessary components. What remains is to determine what support these components needed to function within the project requirements, how they were assembled and connected, and how the subsystems themselves were combined to form the overall design.

First, it is at this stage that two of the subsystems were joined. Since the physical components of both the laser grid and surface display were required to complete the table surface, these two subsystems are hitherto referred to together as the optical subsystem as displayed in the image below. This design component was constituted by the physical table structure, the surface display built into the play area in the center of the table structure, and the array of laser grid transmitters and receivers placed around the perimeter of the play area. The design of these components needed to be secure and precise to ensure proper alignment of the transmitters and receivers is maintained during approved device use.



Composite Optical Subsystem

Figure 34: Composite optical subsystem overview showing combination of laser grid with surface display. Image provided by the Lazer Pong project team.

With this subsystem designed, it then became necessary to design the two supporting networks for these key operating components: The embedded microcontroller system and the power supply system. These supporting systems provide the logic necessary to interface the laser grid with the surface display, as well as the power required for all systems. These two systems operate together to support the goals and objectives of the project.

5.1. Optical Design

The optical design for the laser pong table will consist of two primary optical systems. These will be the laser grid and the LED surface display. The laser grid's design will serve to provide a solution for ball tracking during the gameplay, while the LED surface display will assist in tracking scores, cups in play, and other various visual effects. Overall these two systems will be designed to work in conjunction with each other to achieve the goals of this project. However, each system contains their own relative designs which need to be considered. The next few subsections will highlight the key features in the construction of these different optical systems, as well as describe why certain design choices were made.

For the laser grid, careful design considerations are needed to provide the best experience for the users of the table. The laser grid will be designed to encompass the entire table surface to provide the goal of ball tracking anywhere on the table. It is important to consider the restrictions that will come with the designing of the laser grid. For instance, the laser grid will obviously be a part of the table, but for the purpose of the game it can not interfere with the play area. This would make the game of beer pong not able to be played properly, which would undermine the entire purpose of the project. Therefore, a way to attach the laser grid to the perimeter of the table needs to be designed. The design of this perimeter will need to take into account the dimensions of the parts that it will hold, and in addition to that the specifications that the laser grid must meet to operate correctly.

The LED surface display also has many design strategies that will need to be discussed. While the laser grid itself is connected to the basic table design, the LED surface display will be built into the table itself. In this sense, it is crucial to design how this is going to work so that it can operate the best for the table. Choices such as the materials that will be used in the construction of the table are critical to LED surface display, as the LEDs will have to be mounted on this material. Also understanding the way in which the LEDs will be spaced and individualized inside of the table will be necessary. Additionally, the play area will be on the table itself, so the LEDs will need a way to be protected from damage while the game is being played. These are all vital parts to the LED surface display and its design.

5.1.1. Laser Grid

The laser grid is the first major optical system in the project's optical design as a whole. There will be two major components that will facilitate the goal of the laser grid. Those two components are the laser diode module, which will serve to establish an optical signal, and the photodetector, which receives the optical signal from the laser diode and converts it into an electrical signal. This signal that is converted will ultimately be sent to the LED surface display to communicate whether or not the signal has been tripped or not. The major goal that the laser grid will accomplish in this project is tracking where the ball is by the means of this signal. When a ball interrupts an established signal, the coordinates will be known and this information will be relayed to the LED surface display. The laser grid will be able to detect the ball anywhere on the table, including inside of a scoring cup.

With the design of the laser grid there will be a few aspects to keep in mind. The overarching concept that will determine the specific optical design is the method in which we choose to build the photoelectric sensors. The method that was chosen for this project was previously stated in section 3.2.2 as being the through-beam sensor. Having this method selected, the focus now shifts to how the laser transmitters and receivers will be oriented to achieve this and the other goals of the project. Through-beam sensors establish a signal by sending a direct beam path from the emitter to the detector. The main idea behind a through-beam detector is that when an object passes through this beam path a change in the signal occurs. This change in signal is how the laser grid will be able to detect where the ball is along the table.

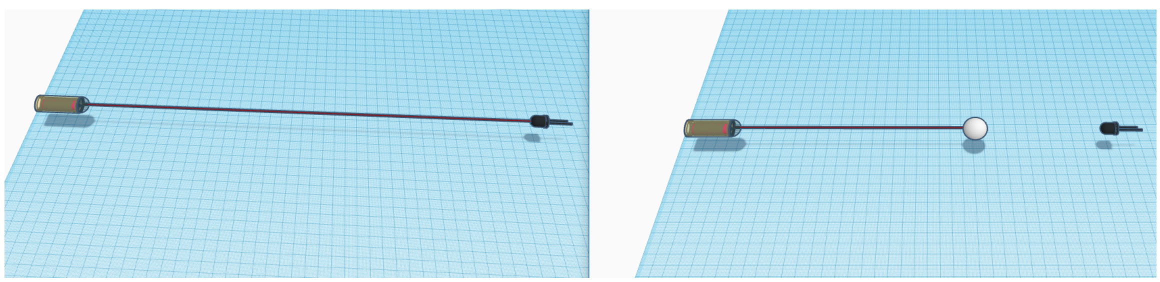


Figure 35: Diagram showing how the through-beam sensors will be used for the laser grid (components in image not to scale). Image provided by the Lazer Pong project team

To design the through-beam sensor for the laser grid, the laser transmitters and receivers must both be positioned parallel to the surface of the table. From this parallel position, the two will be placed opposite of each other. They will also be raised 20 mm from the table in order to detect the ball when it passes the beam path. This height was chosen because the diameter of a standard ping pong ball is 40 mm, and with this the when the ball comes into contact with the table the beam would be positioned at the center of the ball, which is where the ball is the thickest.

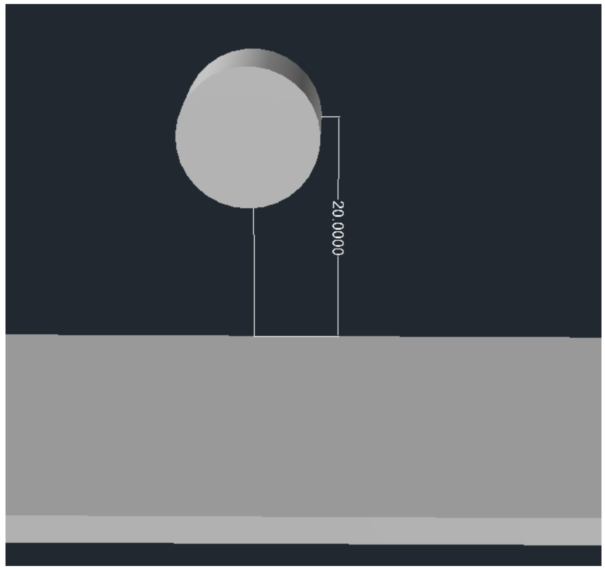


Figure 36: Simple diagram showing center of laser diode module being 20mm above table surface. Image provided by the Lazer Pong project team

The table itself will be 2 feet by 4 feet, so to detect the ball everywhere over this surface there will be a total of 48 laser transmitters and receivers. The transmitter will be split into two directions, with 16 along the 2 foot side and 32 along the 4 foot side. In this setup the laser transmitters and receivers would be spaced evenly apart giving individual separations of approximately 38 mm between the centers of each module. Along with this, the laser transmitters and receivers will be securely mounted in custom holders. This will ensure the design of the laser grid will have the highest possible stability. These holders will be attached to the perimeter of the play area. This is done so as to not interfere with the integrity of the game.

Laser diode modules

For the laser diode modules, they are made of a brass house casing with a pre-built collimating lens. The brass house casing is of a cylindrical shape having a length of 10 mm and a diameter of 6 mm. Along with this, the collimating lens on the output side of the laser diode module has a diameter of 3 mm. Having these small dimensions for the laser diode modules is good because it will be easier to hide them from the players, which then in turn will not take away from the visual appeal of the table. The laser diode modules come with a pre-built driver as well to control the laser’s output. There are also red and black leads extending from the driver to which the power will be supplied. The operating voltage for the laser diode modules is 3 VDC with an operating current of 100mA. The center wavelength of the laser’s output is approximately 780 nm. They also have a low optical power output of around 3 mW, which is emitted in a dot shape after the collimating lens. This collimating lens can be adjusted a total of 2 mm, 1 mm in each direction, but for the design of this project the lens will be kept in its original position to maintain the highest collimation.

For the holders it is crucial for them to be able to tightly and securely hold the laser diode modules as well as the photodetectors. The best way to make sure that this is so is by custom designing the parts using a sturdy material such as plywood. This ensures that there will be minimal error in the positions in which the parts will go. While this does add potential risk of human error, plywood is a relatively cheap option with the ability of being customized to the laser grid's needs. Issues such as making the holes too large, uneven spacing between the holes or even slight vertical shifting of the holes could arise during the fabrication of these holders. Because of this it is crucial to ensure precise measuring and cutting to reduce the chance of any of these issues arising.

Considering the fact that there are two different parts with different dimensions, there will also need to be two different types of holder designed and fabricated. To make the holders for the laser diode modules and photodetectors the previously mentioned design measurements must be accounted for. This means for the laser diode modules the center of the emission side must be 20 mm above the table's surface, so the hole for the holder will start at 17 mm above the surface of the table. This is because the radius of the laser diode module is 3 mm. The reason 17 mm is to allow for the device to slot in nicely, and also tight enough that it will not move too much once inserted. The width of this holder will be made from plywood of ¼ inch thickness or approximately 6.35 mm, which is almost as long as the device itself, but this will leave enough room for the laser diode module to be removed more easily should it need to be serviced or replaced. The holder must also have a height tall enough to be able to attach to the perimeter of the play area. The Lazer Pong table's thickness will be approximately 32mm. Therefore, it is necessary for the holder to have an extra 32mm below where the table surface will start in order to be attached to the plywood that the LED surface display will be on.

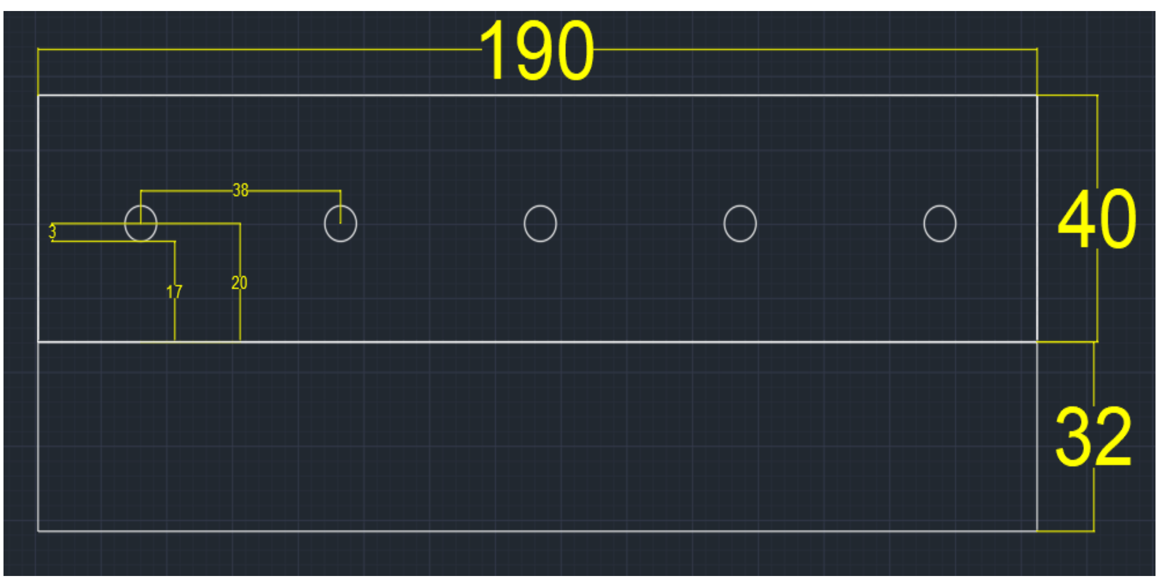


Figure 37: 2D Front view of a portion of Laser diode holder with dimensions. Image provided by the Lazer Pong project team.

Photodetectors

Next in the design of the laser grid is the photodetectors. The photodetectors are in size a smaller piece of the puzzle that is the laser grid, but are just as important. The photodiode itself is encased in a black epoxy that is in the shape of a half capsule. This black epoxy covering is crucial to the photodetector as it will block visible light from reaching the photodiode. With the LED surface display being so close to where the photodetectors will be, this factor was a major concern. The dimensions of the encapsulant are 8.6 mm long and a diameter of 5 mm. After this there are the anode and cathode leads which have been pre-soldered onto a small board with the LM393 Dual differential comparator. This will be what amplifies the signal for the MCU.

For the photodetectors the same general ideas apply but with different dimensions. Given their slightly smaller diameter of 5 mm the hole will start 17.5 mm above the table's surface. Similarly to the holder of the laser diode module, with a slightly smaller length of 8.6 mm, the holder will also be made with ¼ inch thick plywood. The hole diameter for the photodetectors was chosen to also allow the lip of the photodetector to act as a natural block from it going too deep as well. Again, the holders must extend an extra 32mm past the table surface in order to ensure the ability for them to be attached to the table. The holders will be connected to the outside perimeter of the table by screws to help ensure stability.

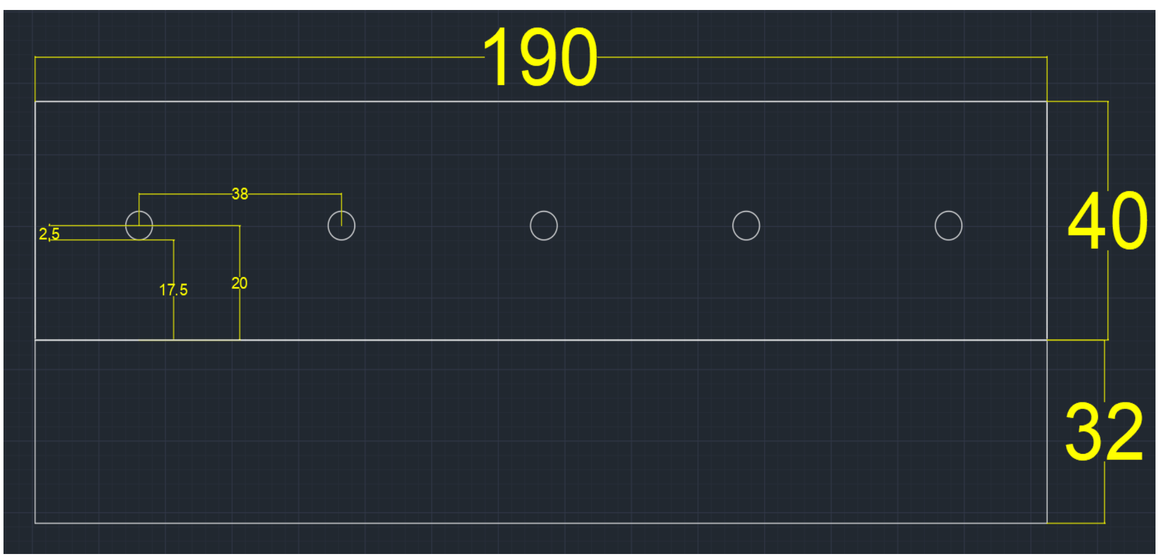


Figure 38: 2D Front view of a portion of Photodetector holder with dimensions. Image provided by the Lazer Pong project team.

In addition to the holders for the laser diode modules and photodetectors, there will also need to be a way to shield them from the play area. With just the holders the components will be exposed to the outside environment on the side facing the play area. This is an issue as it will make it more likely for the parts to be touched or hit after alignment. To prevent this a barrier must be placed between them and the play area, but one that would not interfere with the optical signal being transmitted. A great choice for this would be a clear acrylic sheet. There are many options for these and will serve as a great protector against the outside play area. This was also chosen due to the low cost and the fact that it can be clear, which will affect the laser transmitter or photodetector minimally. The chosen thickness is approximately 2mm, which is very thin, but will provide a layer of protection from the parts being directly interacted with. The clear acrylic will be attached to the plywood by the means of CA glue, which is better known as a type of superglue. This is commonly used by woodworkers as a means of attaching things together. Christophe [114], a woodworker and blogger, states “To glue plexiglass to wood, make sure the surface is clean and dry. To prepare the surface and eliminate any debris, sand it using sandpaper. As a bonding agent, you can use CA glue, hot glue, or epoxy glue”. This is the method that will be utilized to add the clear acrylic to the front of the holders.

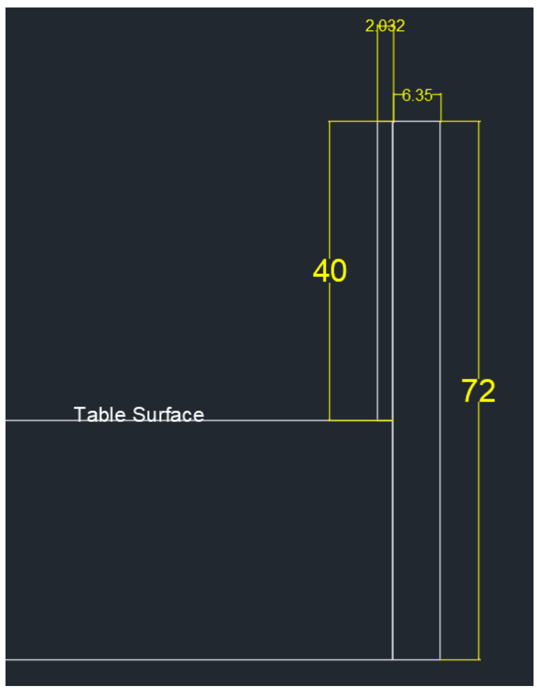


Figure 39: 2D side view of clear acrylic added to front of holders. Image provided by the Lazer Pong project team.

It is also important to consider how the laser diode modules and photodetectors will both receive power to operate. Luckily, both components come already fabricated with leads to connect the power required for them. Because there are 48 of each component, consideration for how they will all be powered is slightly more difficult than if there were only one of each. The laser diode modules will all be connected on a single line to the 5V-3V regulator, while the photodetectors will be connected to another single line to the 5V-3.3V regulator, which will both be on the PCB.

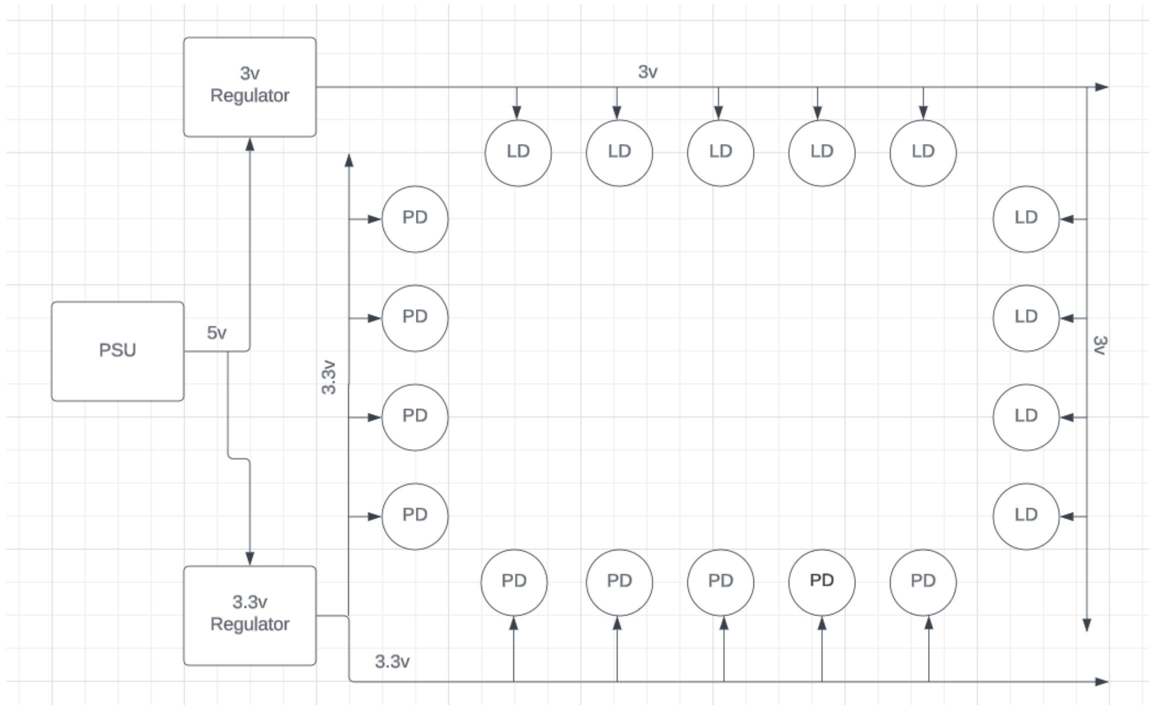


Figure 40: Flowchart representing power delivery method to the laser diode modules (LD) and photodetectors (PD). Note that a subset of the full 32x16 array is shown. Image provided by the Lazer Pong project team.

All together these different factors and components will be used to construct the laser grid design. The design will create a 32x16 grid that will allow for 512 unique coordinates across the table. With this it will be possible to track the ball wherever it lands on the table. This will complete the main goal of the laser grid, and also contribute to help achieve the other goals of this project.

5.1.2. LED surface display

To fulfill the objectives of displaying game events recorded by the laser grid and providing captivating music visualization, a panel of individually addressable LEDs was strategically positioned on the table surface. This LED array served multiple functions, including indicating player scores, illuminating active cups, tracking and displaying the overall score, and synchronizing lighting patterns with the rhythm of surrounding sounds. Advanced features such as ripples upon ball bounces can be implemented if full-table ball detection is achieved. For the LED surface display there are four major components: A solid foundation, prefabricated LED strips, pixel isolation grids, and a light diffusing table surface. With these components properly designed and integrated, this simple table surface was transformed into a beautiful two foot by four foot display encompassing the entire surface of our beer pong table.

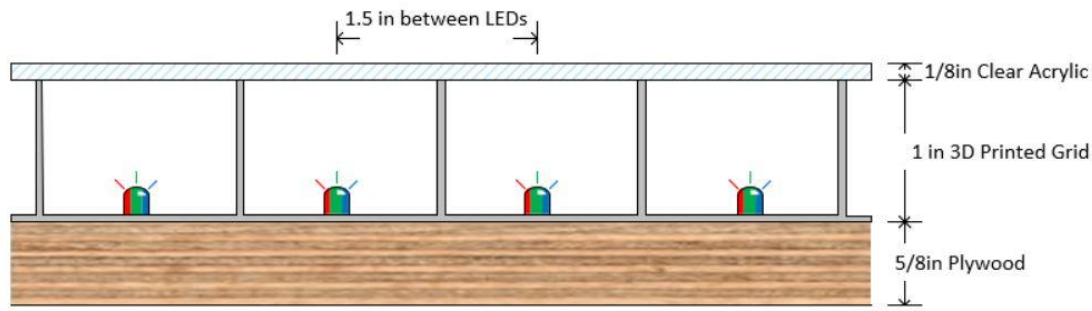


Figure 41: Cross Sectional of Table top Display. Image provided by the Lazer Pong project team.

The very first element when designing this table in the actual structural foundation of this table. This could arguably be one of the most important elements for this table. Without the actual build of a “table”, there is nothing but a simple board game. This foundation must be able to stand up properly and support the weight of our design. Another important factor is having the table foundation be lightweight so it is easy to transport but still structurally sound. A strategic choice of design is crucial for having a solid base for Lazer Pong.

The LED display design incorporates a pre-manufactured LED strip spliced into an LED array. These LED strips will be the main attraction to our surface display. Providing the vibrant colors and animations to make the consumers gameplay that much more dynamic than traditional beer pong. The layout of the LED strips is essential for creating a smooth and unified display.

Each LED is a pixel for the display. The design must achieve a way to isolate each pixel from one another to prevent unwanted blending of colors. Creating grid pieces is an optimal solution for isolating these LED pixels and will act as dividers. The grid pieces must be integrated into this design to produce the desired display. These grid isolators will be placed directly on top of the LEDs

To create a seamless pixel display and reduce light intensity, a light-diffusing acrylic was placed on top of the panels.This is needed to create a softer and consistent brightness of light produced by the LEDs. This light diffuser will also act as the table's top level and smooth surface.

This design offers numerous advantages, making it an ideal solution for enhancing the gaming experience and displaying game events with flair. The table surface is effectively covered with a manageable pixel count, effortlessly controlled through a simple microcontroller. This seamless implementation ensures efficient operation and precise management of the LED display, resulting in a visually captivating spectacle during gameplay. The LED surface served as the centerpiece for showcasing visual effects and the game score. It is carefully crafted to exhibit specific colors and animations corresponding to the game state relayed from the laser grid to the MCU. The communication protocol and single digital output line further streamline the process, solidifying the LED surface's practicality and contributing to an engaging and immersive gaming atmosphere that leaves players enthralled.

Table Foundation

When it comes to designing the LED display, selecting a suitable base is essential, and plywood stands out as an excellent choice for numerous reasons. Plywood offers a combination of durability and strength that makes it ideal for this application. One of the primary advantages of plywood is its remarkable durability. Crafted by layering multiple thin sheets of wood with their grains positioned perpendicular to one another, plywood exhibits superior strength and resistance to bending, warping, and cracking [115]. This structural integrity ensures that the LED display's base remains intact even under heavy use, providing a reliable foundation for the entire setup.

In addition to its durability, plywood boasts excellent dimensional stability. This means it is less susceptible to changes in shape caused by fluctuations in humidity or temperature. This is because the tendency of the layers are greatly restricted by the longitudinal stability of the adjacent layers [116]. As a result, the plywood base will remain stable and flat over time, ensuring the LED display maintains its desirable and consistent form and functionality. Cost-effectiveness is another key benefit of plywood.

Compared to other materials available in the market, plywood offers an affordable option without compromising quality. Its efficient manufacturing process and wide availability in various thicknesses and grades make it a cost-efficient choice for constructing the LED display's base. Plywood has a widespread availability in a diverse range of thicknesses and grades. A thick and sturdy cut for added robustness or more of a lightweight and portable option, with an abundance of choices ensures an ideal fit for this design.

To achieve a stable and solid tabletop and considering the other elements of the display, selecting a ⅝” plywood cut is optimal. This thickness strikes a balance between strength and weight, providing a sturdy surface capable of supporting the LED strips and other components of the display. By opting for plywood, the LED display can be constructed with a robust base that meets the required specifications. This design will be a 4’x’3 cut of the plywood while the actual display was still 4’x2’. There will be an extra 6” buffer on each side of the display to allow for a designated location to put the cups once they have been scored.

LEDs

The core of the LED display design revolves around seamlessly integrating pre-manufactured individually addressable BTF Lighting Fairy LED strips spliced into a dynamic LED array. These LED strips take center stage, becoming the main attraction of our surface display. With their brilliant hues and captivating animations, they elevate the gaming experience to new heights, imbuing traditional beer pong with a thrilling, dynamic twist. The meticulous arrangement of the LED strips becomes a critical element in crafting a cohesive and visually stunning display, ensuring every pixel plays its part in painting a smooth and unified canvas of light.

The construction of the 4’x2’ LED display will require a total of 32x16 LEDs to create each of the pixels in the 32x16 display. Since each LED strip provides 50 LEDs, we will require a combination of multiple strips to achieve our target. To be precise, 11 LED strips will be necessary to fulfill the requirement for 512 light sources. In order to create a single 512 LED strip out of these smaller strips, each will be connected to the next by the included male and female connectors. These connectors will enable the strips to seamlessly link together, creating a unified and integrated display system.

The ⅝ inch thick plywood base, measuring 2 feet by 4 feet, served as the foundation for the LED display tabletop. Initially, it was anticipated the need to individually cut and solder each row of LED strips. However, it was opted for a more convenient solution using LED strips that can be arranged in a series snaking pattern, forming a 32x16 pixel array.

This comprehensive arrangement provided the necessary illumination to create a captivating and visually appealing LED display. To ensure the stability of each LED light source, they were affixed by applying hardware staples on each side of the light source. With a spacing of 1.5 inches between each light source, we encountered a slight challenge due to the LED strip's design, which separates each light source by 4 inches. Consequently, we had excess wire between the light sources on the plywood base.

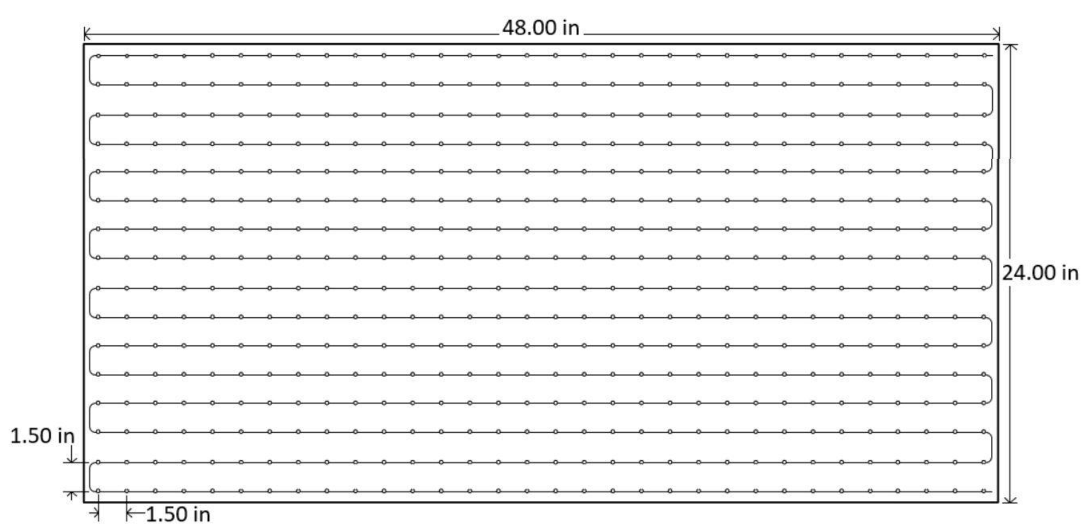


Figure 42: LED strip pattern on table surface. Image provided by the Lazer Pong project team.

To address this issue, the design discreetly manages the extra wire by concealing it underneath the tabletop. By strategically creating holes in the plywood, corresponding to the spacing between the light sources, we will effectively route the excess wire out of sight. This approach not only maintains the visual appeal of the LED display but also ensures practical wire management, with no loose wires visible to the viewer.

Pixel Isolation Grid

The next step in the LED display construction process involves designing the grids to isolate the individual pixels. To accomplish this, we will utilize Autocad to design the grid and a 3D filament printer for the actual printing. There are numerous benefits to producing our own grid pieces. One key advantage is the ease and cost-effectiveness of replicating each piece. By utilizing 3D printing, we eliminate the need for expensive manufacturing methods such as molds or tooling commonly found in traditional manufacturing. This not only reduces costs but also allows for rapid prototyping and customization. Such flexibility is crucial during the testing phase as it saves substantial time and material expenses, enabling us to swiftly address design flaws. Moreover, the accessibility of 3D printing has significantly improved in the last decade. Utilizing the printers in campus labs accelerates production processes, making them more efficient.

The printed grids have dimensions of 6 inches by 6 inches, forming a 4x4 pixel arrangement. Each of these grid pieces have a thickness of approximately 1 inch. This thickness ensures durability and provides a stable foundation for the display. Since the grid is the thickest part of the display with an inch between the light source and the light diffuser it might consequently make the table surface brightness slightly lower than if we go with a thinner grid, but not low enough to change the thickness of the grid. Once all 32 grid pieces were printed, they were affixed above the LED strips using a two part epoxy. This secure attachment ensured that the grids remain in place, maintaining the integrity of the display. With the grids in position, the next step was to define each pixel for the display. This involves programming the LED strips to correspond to the desired patterns and colors, allowing for the creation of vibrant and dynamic visuals.

Light Diffusing Surface

The final stage of the construction process involves placing the frosted acrylic light diffuser on top of the 3D printed grid. The frosted acrylic panel is 48’’x24’’ and ⅛ inch thick. For this single 4’x2’ display we needed 1 panel of this frosted acrylic. This single frosted acrylic will be fixed to the 3D printed grids using the same two part epoxy used to attach the grids to the plywood. Since this is one single panel the table top is smooth so that does not affect the game in any way.

In terms of the layering of the LED display, the order will be as follows: starting from the bottom, we have the 5 ⁄ 8 inch plywood serving as the sturdy base, followed by the LED strips which provide the illumination being attached by hardware staples. On top of the LED strips, we positioned the 3D printed grids, providing a defined structure for the pixels that is fixed with a two part epoxy. Finally, the frosted acrylic will be placed on top using the same two part epoxy, serving as both the light diffuser and the solid surface of the table. The frosted acrylic layer plays a dual role in the display. The entire system was protected by a transparent pane, allowing the ball to bounce while safeguarding the delicate components. Not only does it diffuse the LED light evenly, creating a soft and pleasing glow, but it also acts as a durable tabletop surface. It possesses the strength and stability required to support the weight of cups and withstand gameplay activities, ensuring a robust and reliable construction.

Designed Layering

The design of the LED surface for our beer pong table encompasses a carefully curated combination of components that result in a visually captivating and highly functional display. The sturdy ⅝ inch plywood base ensures long-lasting durability and stability, preventing any warping issues. The integration of LED strips, connected through specialized connectors, enables precise illumination to showcase game scores and mesmerizing visual effects. The 3D printed grids offer the advantages of customization and easy replication, providing a structured layout for the individual pixels. Furthermore, the frosted acrylic light diffuser serves a dual purpose as a resilient table surface and a means to evenly distribute the LED light, enhancing the overall aesthetic appeal. The end result is a stunning 4’x2’ LED display that elevates the gameplay experience and adds an impressive visual element to the beer pong table. This meticulously designed LED surface is sure to captivate players and onlookers alike, creating a dynamic and immersive atmosphere.

5.2. Power Design

Arguably the most important aspect of the overall design, the power supply needs to be constructed in a way that ensures every major component receives the appropriate voltage and current levels. The LED panel, laser diodes, and MCU all have specific and unique power requirements in order to operate correctly, so it is crucial to establish a sufficient power supply design that can adequately address each component’s requirements. Determining how the power design can be consistent, reliable, and adequate requires knowledge of certain techniques and methods of power distribution. Some of these techniques include parallel connections and voltage regulation, both of which will be used heavily throughout the design. The following figure summarizes how each component will be connected with respect to how power will be distributed from the main unit.

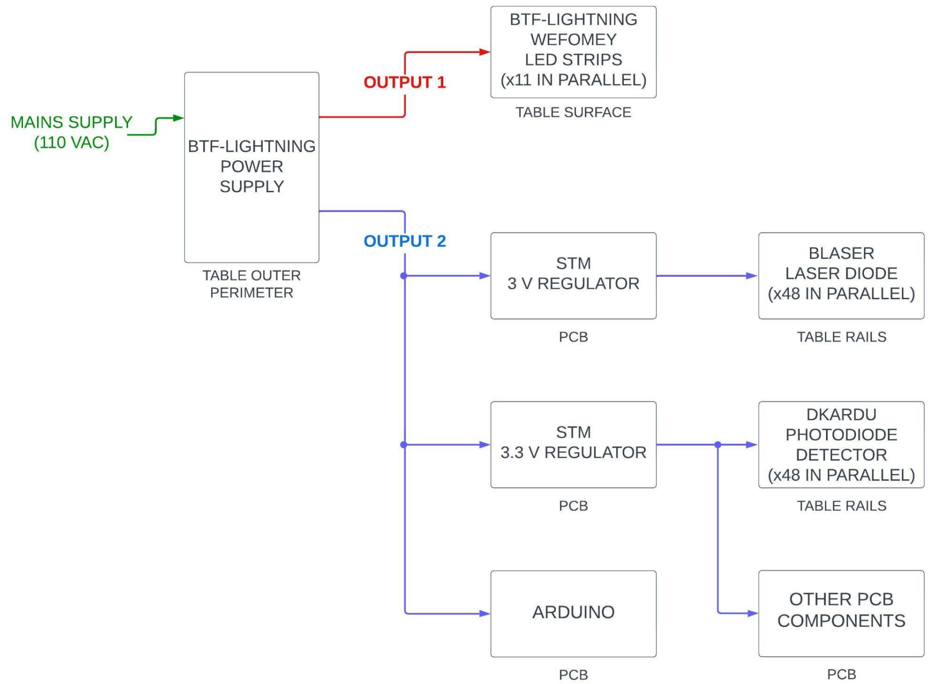


Figure 43: Power Distribution Wiring Diagram. Image provided by the Lazer Pong project team.

To ensure a well-organized power distribution system, careful consideration will be given to the connections and routing of every wire. From a high level, the overall power distribution will include: A main central unit that will take in the mains supply from a local outlet located under the table to discourage tampering from end users, a branch going from the first output of the central unit out into the LED strips on the table surface, and finally another branch from the second output of the central unit going to the voltage regulator circuits located on the PCB, which will then be routed to the laser diodes and photodiodes on the table surface, as well as the other PCB components, such as the MCU.

The subsequent sections are dedicated to the key parts of the overall setup, and will go into depth on exactly how each of those components are provided their necessary power. It all starts with the main power supply, showing how that unit is able to be plugged into a local outlet, transform that power into usable levels of DC voltage, then distribute that voltage to each branch at a certain level of current. The branch dedicated to the LED strips mainly demonstrate the usefulness of parallel connections, while the second branch dedicated to the laser modules and controllers will showcase how the implementation of precise voltage regulators further tailor levels of power to adequately suit the devices' requirements. By applying such techniques and power management strategies, the whole of the power distribution design is allowed to be significantly efficient, with each component operating at an optimal level, minimizing energy losses and promoting sustainability by reducing power consumption.

5.2.1. The Main Power Supply Unit

The main power supply of the Lazer Pong Table will be provided by the BTF-LIGHTNING Power Supply Unit (PSU). This unit will be connected to a standard local outlet to take in the mains supply of 110 VAC at 60 Hz. A notable feature of the BTF-LIGHTNING PSU is that it has the capability to accommodate both standard values of the mains supply, which is controlled by an external switch on the device. This switch allows for easy adjustment of the input to be either 110 V/60 Hz or 220 V/50 Hz, depending on the available power source of the local outlet. This serves as a simple way for the end user to plug in the Lazer Pong Table practically anywhere in the world, as the implemented PSU is flexible in its ability to input the worldwide standards of power.

A standard three-prong power cord will be used to connect from the local outlet to the live, neutral, and ground terminals of the PSU. A three-prong cord consists of three wires, typically denoted by color. The live terminal, or left prong, connects to the unearthed conductive part of an AC mains supply, while the neutral terminal, or right prong, must connect to the earthed conductive part. The final middle prong is the ground terminal. The purpose of this setup in many applications is for protection against blowout and electric shock [117]. The PSU has input terminals dedicated to a live connection, neutral connection, and ground. These are clearly labeled on the unit by the symbols “L”, “N”, and “Earth Ground” respectively.

There are then two output terminals on the BTF-LIGHTNING PSU. These are labeled on the unit by two sets of the symbols “V+” and “V-”, with the former representing the positive node of the load and the latter representing the negative side. From the 110 VAC input coming from the local outlet, the PSU has internal circuits that convert that input into a voltage level of 5 VDC. Each output on the PSU then provides this constant 5 V voltage level to up to two loads, with the outputs capable of providing a maximum current of 30 A. It is worth noting that both outputs of the BTF-LIGHTNING PSU are only capable of providing the same level of voltage. There is no way on the unit itself to control or switch the voltage or current levels. This means that if other levels of voltage are desired, an external, separate circuit will need to be incorporated to take in the PSU’s voltage level and step that up or down to the new level.

5.2.2. The First Branch - LED Strips

Efficiently managing how power is distributed to multiple components will be a critical aspect of designing the Lazer Pong Table, as many of its systems involve numerous duplicate parts that all need to receive some amount of power. A prime instance of this happening is with the LED strips. These strips are composed of several individual LEDs, with each strip requiring some amount of power. Since the design involves many duplicates of these strips adjacent to each other, power will need to be distributed somehow to all of the parts efficiently.

The first output terminal of the PSU will solely be dedicated to the LED strips, as they will by far require the most amount of power to operate. Separating them into their own branch ensures that this relatively high amount of power is provided consistently without interruption from other devices. Each subsequent strip will then be connected in parallel. This is one of the main techniques applied when attempting to manage power distribution to many separate components.

A system that is setup using parallel connections allows for each of the connected parts to receive the same level of voltage [118]. If five identical devices were connected in parallel with a 5 V source, then each device would receive 5 V. This is in opposition to the other method of using series connections, where a single level of voltage is divided across the number of parts connected. If five identical devices were connected in series with a 5 V source, then each device would receive about 1 V. The parallel method is more desired in this case as it allows for the voltage source to remain at a low level without sacrificing how much is distributed to each connected device. However, this comes at the cost of the flow of current. In the parallel method, current is divided among the connected devices, while in the series method, current is shared throughout each device [118]. Since the parallel method is still preferred in terms of keeping a low voltage source, compensating for the distributed current means will thus involve making sure that the level of current that is provided by the source is sufficiently large enough to be divided across the components. For the LED strips, each LED is expected to draw approximately 30 mA, for a total of 15.36 A for all 512 planned LEDs. As discussed previously, each output on the PSU can provide a maximum of 5 V at 30 A, so both parameters are met for the first branch.

The chosen LED strips, the BTF-LIGHTNING Wefomey LED strips, require a 5 V power supply to operate, the voltage does not need to be regulated on this terminal. This is of course because the PSU already provides this 5 V level of power. Knowing that a regulation circuit is unnecessary for this branch, and instead using a configuration of connections directly from the first output of the PSU, simplifies the overall design of the power distribution system and reduces the need for any additional components along this first output branch. The strips contain 50 individual LEDs each, with simple positive and negative terminals located at both ends of the strip. These terminals will be connected to the first output terminal directly using wires, with each additional LED strip being connected in parallel to the same output terminal, for a total of 11 strips to provide 512 individual LEDs. These wires will have connectors crimped to the ends to allow for safe and easy connecting to the end devices. The parallel connections on the wires will be done using special wire splitter connectors.

5.2.3. The Second Branch - Laser Modules

The second output terminal of the PSU will host two systems: the laser diode modules and the MCU. Discussing the laser modules first, they will also be connected in parallel for each subsequent module. These laser diode modules operate at a voltage level of 3 V, meaning that a linear voltage regulator will need to be implemented to regulate the PSU's 5 V output down to the required 3 V. This regulation is necessary to ensure that the laser diode modules receive a stable and appropriate voltage supply, preventing hardware damage from an excessive input voltage level [38].

The STMicroelectronics LM317T is an adjustable linear voltage regulator integrated circuit (IC), which lets the designer control its output from a range starting at 1.2 V all the way to 37 V with a steady current of 1.5 A. This adjustability is determined by two resistors connected in series with the output terminal of the LM317T and connected in parallel with the ADJ terminal. The values of these resistors will determine the regulated output voltage, which can be modeled by the following equation that was provided by the datasheet [104] for the LM317T:

$$V_o = V_{REF} * (1 + R_2/R_1) + (I_{ADJ} * R_2)$$

Where V_o is output voltage, V_{REF} is the voltage drop between the output terminal and ADJ terminal, R_1 and R_2 are resistors of some arbitrary value, and I_{ADJ} is the current that flows through the ADJ terminal. The LM317T is designed in such a way that it maintains I_{ADJ} to a significantly small value, so the term $I_{ADJ} * R_2$ can be safely ignored. The LM317T also is designed to provide an internal reference voltage of 1.25 V between the output and ADJ terminals. That simplifies the relationship between the output voltage and the resistor values to:

$$V_o = 1.25 * (1 + R_2/R_1)$$

Note that R_1 tends to be some fixed resistor value, while R_2 tends to be a variable resistor value, akin to a potentiometer, to provide even more flexibility and control over the regulation. So, in order to achieve a regulated voltage of 3 V, then the resistors must be chosen in a way that satisfies the simplified equation described above. Values that would accomplish this goal would be R_1 = 1 kΩ and R_2 = 1.4 kΩ. Some additional diodes and capacitors will be implemented as well, as the LM317T documentation recommends the use of both components. The capacitors will be used for improving transient responses, allowing the entire circuit to provide more stable voltage levels to the load, which are the laser modules. The diodes will be used to protect against short circuiting from either the input side or the output side [104].

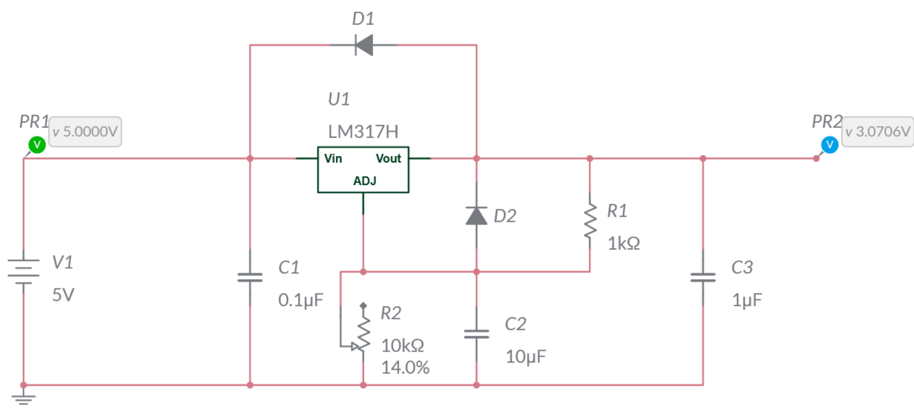


Figure 44: 5 V to 3 V voltage regulator with protection. Schematic provided by the Lazer Pong project team.

Figure 44 shows how the regulator circuit will be set up. The value of R_1 will stay constant through the use of a 1 kΩ resistor component, while an Arduino 10 kΩ potentiometer will be used for R_2. A potentiometer is a circuit component that allows the designer to more precisely adjust its resistance, which will be useful in ensuring that the regulated output voltage is finely tuned to the desired level. Recalling the previous expression describing the relationship between the output voltage and the two resistor values, since the value of R_1 is constant, that means that the output voltage is directly proportional to the value set on R_2. The greater the resistance across the potentiometer, the greater the output voltage will be regulated two, and as the resistance approaches a lower value, so will the output voltage. The two diodes will be the 1N4148 model, a commonly used version of the diode that is widely applicable in many electronics. There will be three capacitors implemented, each at different values of capacitance. Shown in the figure are the values recommended within the LM317T's datasheet.

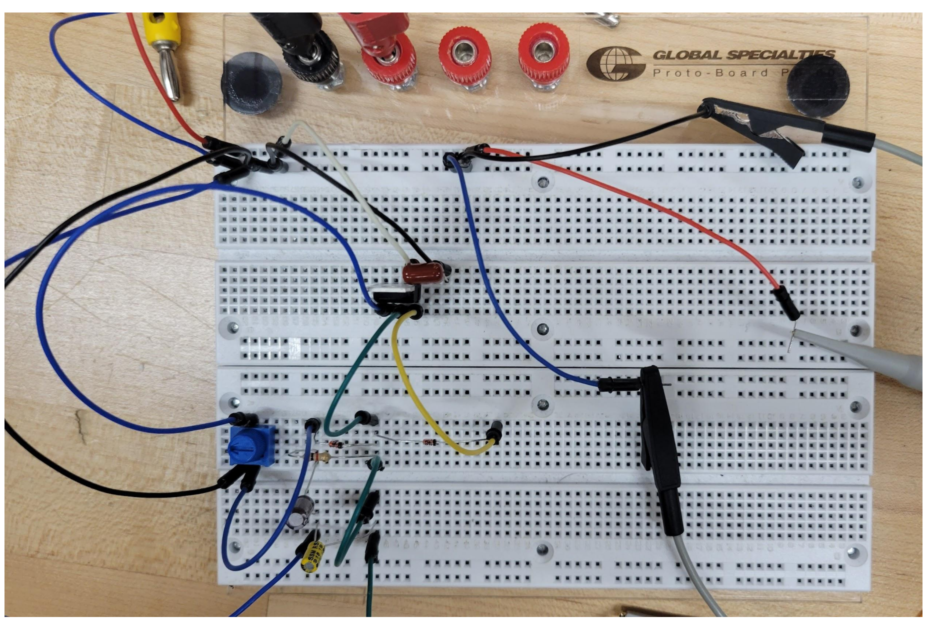


Figure 45: Constructed breadboard test for regulator circuit shown in Figure 44. Image provided by the Lazer Pong project team.

The regulator circuit shown in Figure 44 was constructed and tested on a breadboard using a Keithley 2230-30-1 Triple-Channel DC Power Supply. After building the circuit, the signals shown in Figure 45 were then displayed using the Tektronix DPO4034B Mixed Signal Oscilloscope.

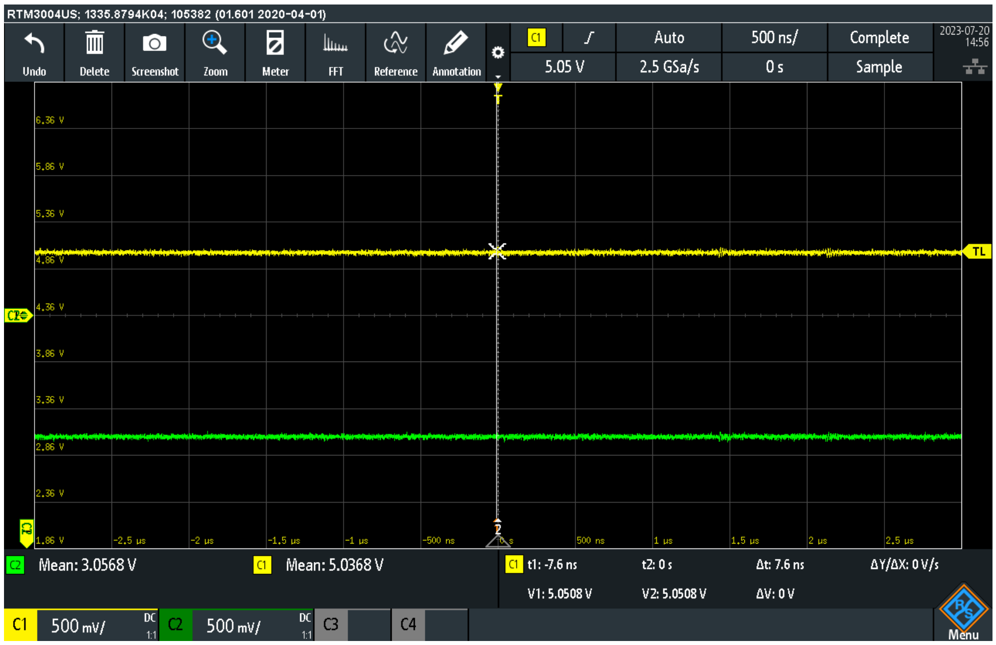


Figure 46: Waveforms of input voltage and output voltage of regulator circuit in Figure 44. Image provided by the Lazer Pong project team.

Figure 46 showcases the waveform signals of the input voltage, colored yellow, compared to that of the output voltage, colored green. Knowing that both signals should represent DC voltages, the constant waveform for both input and output is expected. It is also of note that there is little variation in the signals, with few to none spikes of unexpected levels. Measurements of the mean value of the voltages were taken, and it is clear that the regulator circuit is functioning correctly. The yellow signal measuring the voltage level of the input shows a mean value of around 5.0368 V, and the green signal displays a measurement of a mean voltage level of 3.0568 V. Taking a closer look at the output voltage, the measured value is well within range of the level that was calculated, having a very minimal percentage of error between the measured value and the theoretical desired value. Percent error is a simple quantity that describes how different an expected value is from the actual value, expressed as a percentage using the following expression:

$$\delta = \frac{|V_A - V_E|}{V_E} * 100\%$$

Where V_E is the expected value and V_A is the actual value. Plugging in the measurements found for the output voltage, the resulting percent error is only 0.736%. A percent error as close to zero is very desirable, as that implies that the actual value does not significantly differ from the expected value. Having a quantified percent error of less than 1% demonstrates that the design for the voltage regulator functions properly and can thus be implemented into the greater power distribution system for the purpose of converting the PSU's 5 V level to the required 3 V power level for the laser modules.

5.2.4. The Second Branch - Laser Photodiodes & MCU

In addition to powering the laser diode modules, the second output terminal of the PSU will also host connections to the Lazer Pong Table's microcontroller. The MCU requires two different voltage levels: 5 V and 3.3 V. Since the PSU is able to already supply a 5 V voltage level, this connection will not require a voltage regulator to be implemented. Like with the LED strips, this allows for a more simple design. But in order to provide both of these levels, including the 3.3 V level, another voltage regulator will need to be used to regulate the initial 5 V from the PSU down to a stable 3.3 V level. Again, this ensures that the MCU receives the precise voltage levels it needs to operate effectively and safely, reducing the possibility of hardware failure. The STMicroelectronics LDL1117 regulator will be used here as well, similar in setup to the first branch. This same 3.3 V regulator will be used for the laser photodiodes as well, as those operate at a similar level as the MCU. For more details describing the setup of the 3.3 V regulator, as well as its schematic, see Section 5.3.2.

5.2.5. Determining Power Requirements

An important consideration when planning these power distribution circuits is how much current is expected to be drawn from each of the connected devices. This quantity is usually provided to the designer in the respective component's datasheet. From knowing parameters such as the device's input current and operating voltage, the designer can also calculate the expected power consumption of that device. It is important to know how much power will be potentially consumed so that the designer can ensure that the PSU itself is outputting enough power to distribute across the entire system. Since the PSU's output voltage and maximum output current are known, 5 V and 30 A respectively, then it is known that the BTF-LIGHTNING unit is capable of providing a maximum of 150 W. To determine whether this amount of power is sufficient enough for every major component of the Lazer Pong Table that will need to be powered, the following power schedule was created to find the total expected power consumption of the LED array, laser diode modules, and MCU controllers.

Table 28 shows a power schedule for the Lazer Pong Table's major components that require power. A power schedule is a technique that allows an engineer to consider the operating voltage of a part, how much that part draws in current from a source, and consequently how much total power that part will need from the source. Power consumption is directly proportional to the product of a device's voltage and current level, so it is important to obtain those specifications from the relevant devices. Other specifications, such as power factor, heat load, and so on can be included on a power schedule, but the essential value that can be determined from a power schedule is the total expected power consumption.

Table 28: Power Schedule.

Device	Operating Voltage (Volts)	Current Draw (Amps)	Power Cons. (Watts)
BTF-LIGHTNING Wefomey LEDs (x512)	5.000	0.030 (per LED) 15.36 (for 512 LEDs)	76.800
Blaser Laser Diode (x48)	3.000	0.100 (per Module) 4.800 (for 48 Modules)	14.400
DKARDU Laser Receiver (x48)	3.300	0.015 (per Module) 0.720 (for 48 Modules)	2.376
STMicroelectronics STM32F205RE	3.300	0.120	0.396
	Totals:	21.000	93.972

From this power schedule, it can be seen that the total expected current draw of the whole system is approximately 21 A, and the expected power consumption of every major component is 93.972 W. Both of these values fall within the range that the BTF-LIGHTNING PSU is able to provide, so the power supply unit itself is certainly capable of distributing power to the Lazer Pong Table's systems.

By carefully configuring the wiring connections between components, using correct connection schemes implementing voltage regulator circuits where necessary, and factoring in expected values of power consumption, the power supply is able to efficiently and reliably distribute power to every major device on the Lazer Pong Table. Steps will be taken to scrutinize these wiring connections, ensuring they are properly, securely, and safely designed. This attention to such detail in the power supply design will contribute heavily to the overall performance and longevity of the operation of the Lazer Pong Table.

5.3. Microcontroller Board Schematic Design

Thinking of the design like a living being, the digital electronics can be viewed as the nervous system, with the MCU as the brain at its core. Laser sensors, no different than eyes, ears or nerve endings, are at the periphery of the system. They produce signals that propagate down to the brain, which processes them and decides on an appropriate response. This response is then translated to different nerve endings, alike to the sensors, except they deliver signals instead of receiving them, activating other cells to certain action. In this way, the LED surface is the muscle of this design: It acts when instructed by the brain.

This analogy represents the core idea of the overall design: Take in optical data from a sensor array, calculate the position of an obstructing object in the array, then translate this positional data to a potential game state change, and finally represent this change on the LED surface. This game state change could be a menu option selection, a score, or simply an object touching the table surface. In any case, the system needs to be aware of the change from the sensors, know what that change means for the game state given the constraints of the design, and be able to represent it with LEDs. While all three of these steps happen in different parts of the design, they will all pass through the MCU, the nexus of the entire design.

To understand the way this objective translates to electronic design, each step of the process needs to be viewed as a high-level object–A black box. The actual design and implementations inherent in these black boxes are completely obscured such that only the overall purpose of each can be gleaned. Each black box has four defining features: A set of inputs, a set of outputs, a purpose, and a name. Using this model, the needs of each subsystem within the digital electronics system can be easily defined, making subsystem design, organization and optimization as streamlined as possible.

5.3.1. Overview

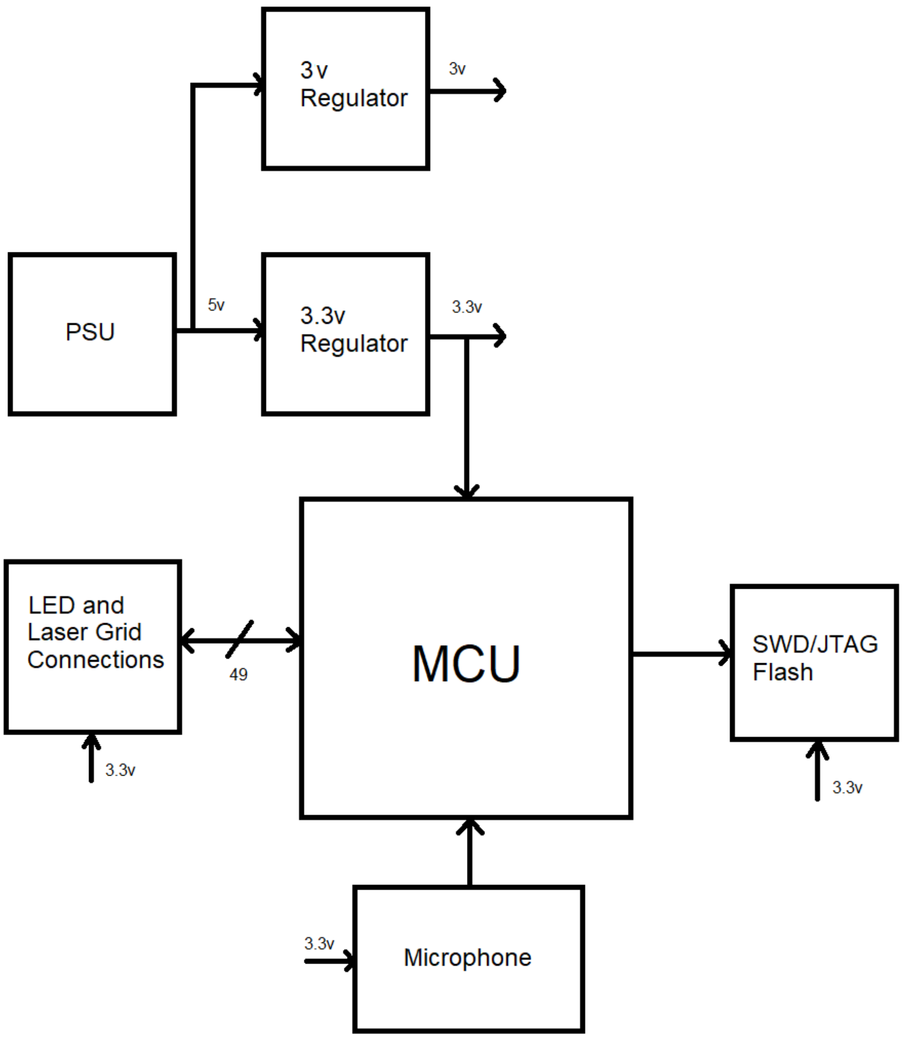


Figure 47: PCB Block Diagram. Image provided by Lazer Pong project team.

Each black box within the PCB design is shown above, with names and I/O drawn to represent the way they will interact in the PCB. If an arrow is drawn towards a block, it is an input. Likewise, an arrow drawn away from a block is an output. Text next to the arrows shows the nature of the output: The number of output lines, the voltage level if power is being delivered, and the data protocol if data is being delivered.

The Regulator

The PSU is the source of power for the entire design, and the PCB is no exception. Since the surface LEDs require a 5v power supply, this is the level at which power is delivered from the PSU. However, the PCB and all of its components need to be powered at 3.3v DC, so a box will be needed to regulate the power down further. This box, the regulator, will take 5v DC power from the PSU as input, and output steady 3.3v DC power to the whole PCB. While most of the connections to this output will be with the MCU itself, other ICs will need power as well.

In addition, another 3.0v regulator is needed to supply power to the laser diodes. The laser diodes do operate just fine at 3.3v, but the specifications for these diodes require that they operate at 3.0v, so this second, slightly lower voltage regulator is included to ensure proper function of these devices.

Laser Grid Connections

Though the laser sensors are located outside of the PCB, the connections from these lasers to the MCU need to be considered as a separate box in the PCB. While these connections perform no operation other than simply facilitating proper I/O signal transfer from the laser all the way down to the pins of the MCU, it is critical that these connections are able to produce clean signals. Without a steady DC signal at the proper logical levels for the MCU, the system could raise false flags or read the incorrect logical value from the sensors.

Update: SPI Connection

Instead of a single GPIO pin for output to the LED display, the final design required an SPI port to communicate with an Arduino, which then communicates with the LED display. This connection needs to be close to the MCU to reduce the trace length for the sensitive, high-speed data transmission. If the traces are too long or mismatched in length, EMI could corrupt the data.

MCU

The MCU is surely the most involved box in the PCB, as it has the most inputs, the most outputs, the most complex function, and requires more support than any other subsystem. As a box, the MCU takes in 48 GPIO signals from the laser sensor connections, one ADC signal from the microphone, and 3.3v power from the regulator as input. It calculates where the break on the table surface is due to these inputs, then transmits these coordinates to the Arduino. While most of the intricacies of this box are tied up in the inner workings of the MCU and are irrelevant for this abstraction, there will be much complexity in the connection of 49 inputs to a single device. It will be important to take the limitations provided by these inputs into consideration when deciding the placement of the MCU in the PCB design.

Microphone

A single, analog microphone would be required to measure the ambient music for the purpose of informing dynamic entertainment lighting on the LED surface. This box will take in the ambient sound, and output this sound as data on a single analog output.

When viewed from a high level, the whole system is not comprised of too many moving parts. Few constitutional subsystems are needed to represent the whole system, so those systems will have as much freedom as they can when it comes to implementation. This will be very important, because some of these subsystems will require careful design to avoid overcomplicating the PCB.

5.3.3. MCU Schematic Design

(See Appendix B for the final PCB schematic.)

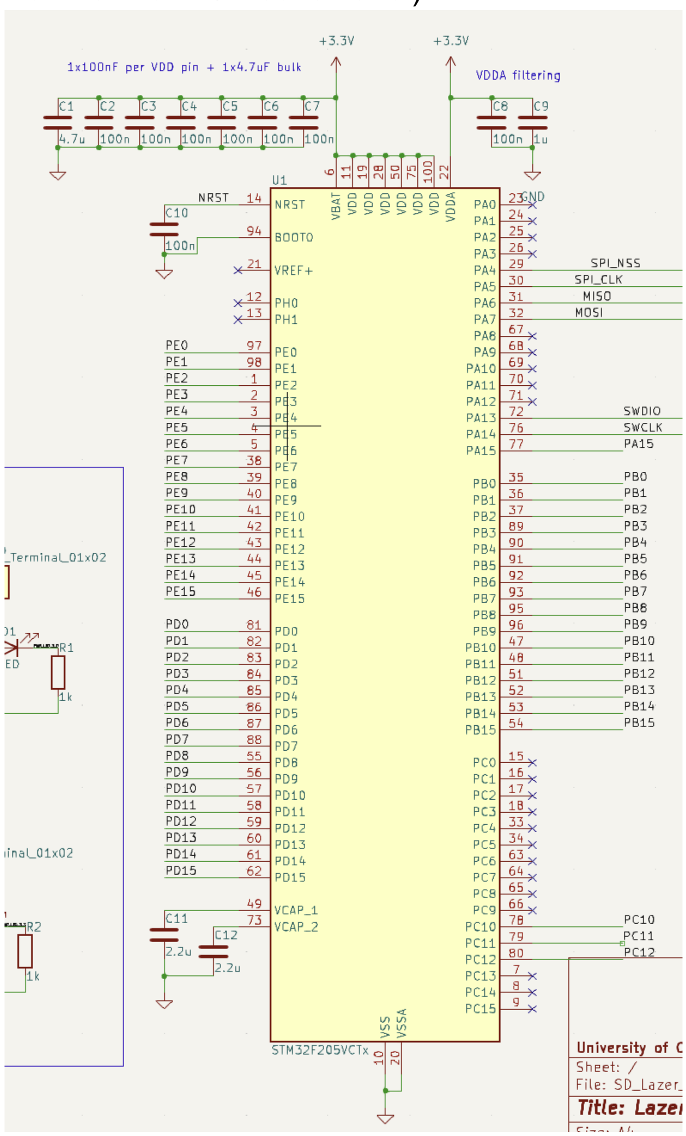


Figure 48: MCU Schematic. Image provided by Lazer Pong project team.

The complete schematic for the MCU is shown above, with all connections either labeled or directly placed in the schematic. 3.3v power is connected to the power trace, and GND is connected to the ground plane. IO labels represent trace connections between the GPIO pins and pin connectors placed on each side of the MCU. Component values and part numbers can be found in the table below.

Table 29: MCU Schematic Parts and Values.

Part	Number	Value
MCU	STM32F205VC	100-pin LQFP
C1	C0805C475K3RACAUTO7210	4.7uF
C2	08055C104KAT2A	100nF
C3	08055C104KAT2A	100nF
C4	08055C104KAT2A	100nF
C5	08055C104KAT2A	100nF
C6	08055C104KAT2A	100nF
C7	08055C104KAT2A	100nF
C8	08055C104KAT2A	100nF
C9	C0805X105K5RACAUTO	1uF
C10	08055C104KAT2A	100nF
C11	C0805X225K3RACAUTO	2.2uF
C12	C0805X225K3RACAUTO	2.2uF

The purpose of the microelectronic components is to implement an algorithm, as defined by a series of logical and mathematical operations, to create the effects that fulfill the objectives of the design. Therefore, the best way to design the microelectronic systems would be to begin with the computational component responsible for those operations: The MCU. Beginning with the MCU creates a wheel-and-spoke model for the schematic design, where the MCU sits at the center and all of the supporting subsystems sit at the periphery. These supporting subsystems will be designed to first facilitate the proper operation of the MCU, with simplicity and cost efficiency as the next highest priorities.

Power Supply to the MCU

Before the MCU can perform the required logical operations, it needs to be able to turn on. The STM32F2 family of microcontrollers operate at a VDD of 1.8 to

3.6 volts, with a recommended VDD of 3.3 volts [36]. This voltage needs to be delivered to the MCU at all of the labeled VDD ports, as well as the VDDA port for ADC function [36]. Double width power traces were run to deliver this 3.3v power between the power regulators and the MCU. Similarly, ground needs to be delivered to the MCU at all of the labeled VSS ports, again including the VSSA port for ADC function [36]. A ground plane was instituted on the bottom layer of the final design, with vias to bring ground connections down to the plane [36]. This 3.3v power and ground are supplied by a power subsystem designed to supply reliable and noise-free power, so that ADC function will not be compromised.

While a clean power signal is ideal, it may not be a guarantee at all times. Different operating temperatures, thermal buildup, and power surges and dips may complicate the power signal, regardless of the integrity of the local power delivery system [36]. The image below demonstrates the signal clarity gained by decoupling power. With that in mind, STMicroelectronics recommends decoupling capacitors be placed between each pair of VDD/VSS pins, as well as the VDDA/VSSA pins. Isolated VDD pins will also need to be decoupled to ground, along with the voltage regulator VCAP pins [36]. The decoupling capacitors are demonstrated in the schematic above, with all of their values as prescribed by the relevant datasheets in the table below the schematic. All decoupling capacitors were placed as per the datasheet, and as close to the pin as possible. By the manufacturer’s standards, these capacitors must be placed in these locations to ensure proper operating conditions of the microcontroller [36].

Figure 49: Two Different Inverter Signals, Displaying the Difference Between Decoupled and Not Decoupled Signals. From left to right and top to bottom, the signals are: Signal one untreated, signal one decoupled, signal two untreated, signal two decoupled. Image used from Hackaday.com [119].

In addition to stabilizing the power source, the decoupling capacitors at VCAP_1 and VCAP_2 provide necessary stability to the microcontroller's voltage regulator [36]. Power on and power off transitions can cause damage to sensitive components within the microcontroller, so the use of the built in voltage regulator is required to avoid this issue [36]. With the voltage regulator enabled and in main regulator mode (MR), the voltage rise time is given as 20us/V, which should provide ample adjustment time in the transient state for all of the internal components [36].

I/O Connections

Most important to the overall purpose of the microelectronic systems of this design, 48 total I/O devices are connected to GPIO pins on the microcontroller. The central design considerations in planning these I/O connections was the ease with which those traces could be laid in the PCB design, and the software limitations that will be outlined later in the chapter. To summarize these limitations: The 48 I/O connections to the laser receivers will be organized in groups of 16, each of which must share a single I/O port on the microcontroller. Thus, for 48 connections, 3 of the 5 I/O ports must be selected to accept these sensor signals.

Looking at the GPIO pin distribution for the STM32F205VC in the 100-pin LQFP package, most of the GPIO port pins are distributed such that they could be fairly easily assigned to a few pin connectors [36]. The only two ports that do not easily fit this model are ports B and C, which are haphazardly arranged on 3-4 sides of the package [36]. This means that using ports A, D and E for the laser sensor connections would be the cleanest way to provide a reasonable number of pin connectors and to simplify the process of laying this wide, dispersed datapath. However, port A is unusable because of the need for a JTAG/SWD debugger. The datasheet for this microcontroller has port A14 as the CLK and port A15 as the data for the debugger, so those ports must be left open [36]. This means that port B must be used instead of port A, since it has a marginally better layout than port C. Additionally, port C has a large number of the microcontroller's ADC pins, so leaving those open for the microphone will ensure that the component has access to a viable ADC I/O pin [36].

The pin assignments to the connectors, and the space of the pin connectors themselves, were designed to eliminate the need for running traces over or under each other. A 2-layer PCB was employed: One top layer for most of the components and traces, and a bottom layer as a ground plane. This means that these I/O traces have to run together to nearby pin connectors, with the power trace weaving around them to the perimeter of the board. In the end, two large pin connectors in 2x13 pin packages were placed at the bottom and to the left of the MCU. Along these sides of the MCU, the pins were broken out in exactly the order in which they appeared on the pinout. While this complicated the connection to the laser receivers themselves, since the pin connectors for each port are scattered around the device, it ensured PCB complexity is minimal. In the end, it was easier to reorder the wires to the receivers than it would have been to complicate the trace routing.

Finally, several additional auxiliary pins were needed: One SPI connection for the Arduino and one ADC pin for the condenser microphone. Since SPI1 was the only SPI connection to have all of its pins available, given the high GPIO usage, these pins were assigned for SPI communication and broken out in full-duplex. That is, each of the chip select (CS), controller-out-peripheral-in (COPI, or MOSI), peripheral-out-controller-in (CIPO or MISO), and SPI clock connections were broken out into a 4-pin SPI connection. This was done to ensure that, in the event that our SPI scheme needed to change, we would have full SPI capability. For the ADC connection for the microphone, it was determined that no connection to the MCU was required. Since the LED display calculations must be made on the Arduino side of this electronic system, a breakout pin for data from the microphone to the Arduino was included alongside the four SPI pins. These five pins for data to the Arduino were broken out together, at the top of the PCB.

Table 30: GPIO Pin Assignments.

Port	Px0	Px1	Px2	Px3	Px4	Px5	Px6	Px7
B	J2_1	J2_2	J2_3	J1_13	J1_14	J1_11	J1_12	J1_9
D	J1_21	J1_22	J1_19	J1_20	J1_17	J1_18	J1_15	J1_16
E	J1_8	J1_5	J1_6	J1_3	J1_4	J1_1	J1_2	J2_4
Port	**Px8**	**Px9**	**Px10**	**Px11**	**Px12**	**Px13**	**Px14**	**Px15**
B	J1_10	J1_7	J2_13	J2_14	J2_15	J2_16	J2_17	J2_18
D	J2_19	J2_20	J2_21	J2_22	J2_23	J2_24	J2_25	J2_26
E	J2_5	J2_6	J2_7	J2_8	J2_9	J2_10	J2_11	J2_12

JTAG/SWD Flash and Debug Connection

From the two port A pins A13 and A14 discussed in the previous section, a flash device connection was established. This device allows a ST-LINK style debug tool to be used to analyze hardware and software details, as well as to flash the software routine to the microcontroller. It interfaces with the microcontroller using only these two pins, so they are the only consideration to be made here. The only design complication created by this device was to reassign port A I/O connections to port B, though both devices could potentially have been assigned to port A. If a 3-pin jumper were connected to each of these two port A pins, with one input from port A and two outputs to the laser receiver I/O connection and the JTAG/SWD device, the devices could share the pin. The operating engineer would simply have to move the jumper to the desired two pins to make the connection to the proper device.

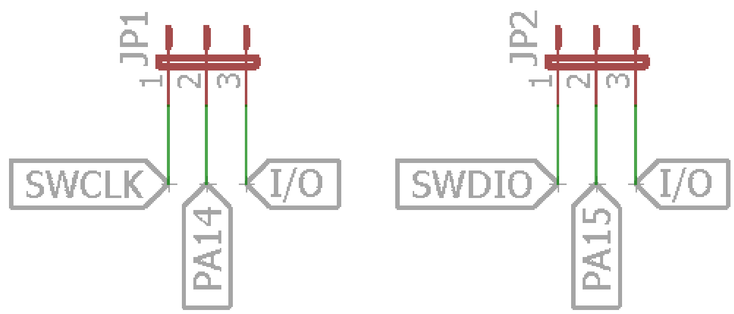


Figure 50: Jumper connection for SWDIO port. Image provided by Lazer Pong project team.

The connections listed above represent the entirety of the necessary schematic design. With power supplied and stabilized, and GPIO connections secured, there is nothing else that must be designed to support the microcontroller. If it were decided that a battery would be helpful to the PCB design, a connection could be made to VBAT to drive that auxiliary power [36]. NRST was not needed, so it was simply connected to a capacitor, connected to ground. These unnecessary peripheral systems will be kept in mind moving forward, but they were not implemented in the final PCB.

5.3.2. Regulator Schematic Design

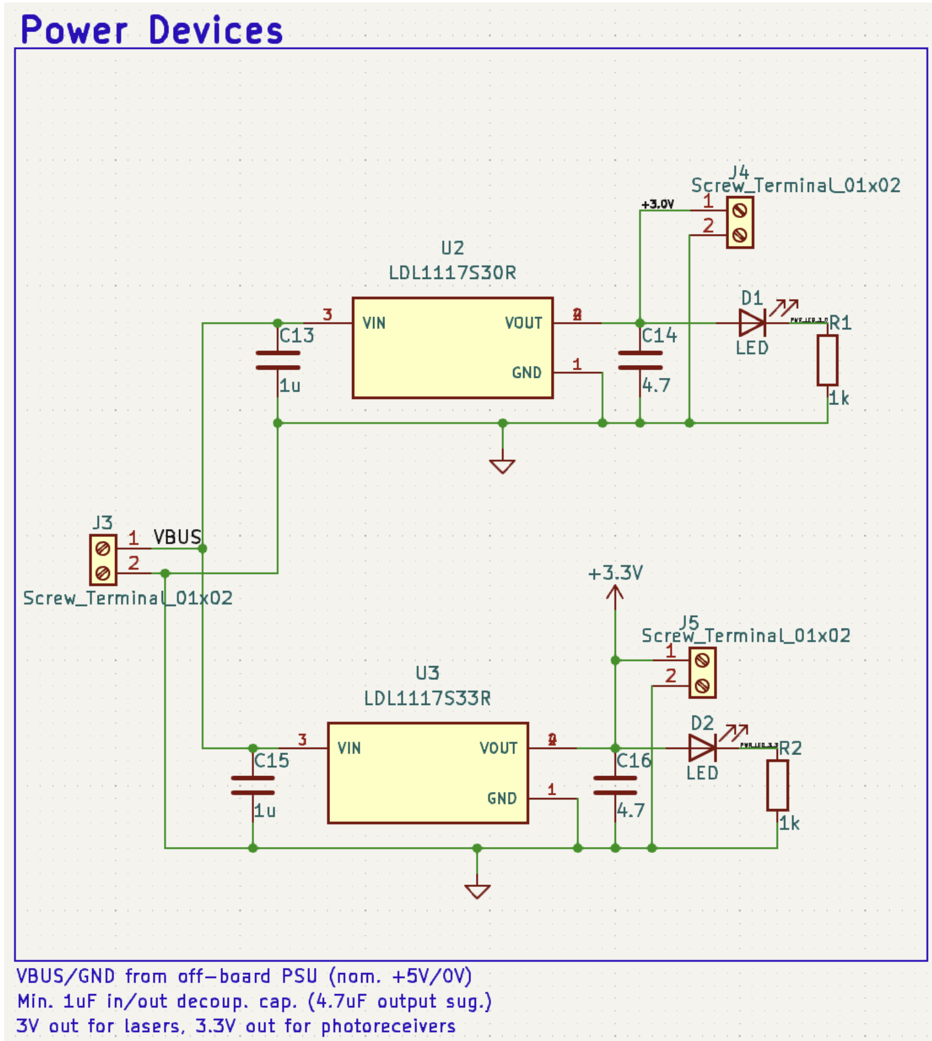


Figure 51: Regulator Schematic. Image provided by Lazer Pong project team.

Table 31: Regulator Schematic Parts and Values

Part	Number	Value
U2	LDL1117S30R	3.0V
U3	LDL1117S33R	3.3V
C13, C15	C0805X105K5RACAUTO	1uF
C14, C16	C0805C475K3RACAUTO7210	4.7uF
R1, R2	CRCW08051K00FKEAHP	1 kOhm

The technical design of the electronic subsystems within the PCB began with the power delivery system, the foundation of the entire board. A power trace at 3.3v was necessary to provide power within acceptable ranges to the MCU, as well as the microphone. This power is delivered by a 5v-3.3v regulator, which takes 5v DC power and common ground from the electronic system's power network, provided by the PSU. After down-regulating this power using a low-dropout (LDO) linear regulator, steady 3.3v power is delivered to the PCB.

An LDO was selected to handle the DC voltage regulation because of the relatively small-scale needs of this project. Not only are LDOs small and simple, but their limits on voltage regulation are well within the specifications for this design [66]. This specific part was selected because it has roughly double the current capacity as could be drawn by the MCU, even with substantial current draw on the GPIO connections. Additionally, since this application requires such low power draw, the excessive heat build-up of the LDO should be completely avoided. This known complication with LDOs can cause low power efficiency and unreliable output, but should not be a concern with this application.

To connect the LDO part in the schematic, 5v power from the PSU must be supplied to the IN pin to provide the pre-regulated voltage, and common ground must be provided to the ground plane [69]. In order to activate the device, the same 5v power must also be supplied to the EN pin to bring it HIGH when power is supplied [69]. On the other end, 3.3v power out is provided by the OUT pin, ready for distribution to the rest of the board. Finally, the GND pin must be connected to the ground plane [69].

In order to stabilize the resulting power signal, the ST LDL1117 series of LDO linear regulators require a decoupling capacitor to be placed near the output of the device [69]. This capacitor should be a ceramic capacitor due to their low variance and equivalent series resistance (ESR), and must provide at least 1uF effective capacitance when taking bias voltage and temperature into consideration [69]. Since little transience is expected in the power signal, aside from some noise, a higher capacitance part was chosen for this capacitor. This higher capacitance part should ensure that no oscillation is observed in the power signal.

Additionally, it is recommended to place another decoupling capacitor at the power input side of the LDO. This is not required by the device, but will improve what little transient response is present, as well as further smooth out any ripple or noise [69]. Since this capacitor is less necessary for the stability of the power signal, a lower capacitance part will suffice [69]. For both this and the previous decoupling capacitor, the device is placed as close to the pin as possible, and is connected directly to the GND pin on the LDO, not just through the ground plane [69]. This will ensure that signal stability is provided directly to the regulation device and not dispersed through the ground plane.

The end result of this application of an LDO linear regulator was a very stable and reliable 3.3v power signal for the microelectronic systems of this design. While the benefits of reliable and efficient power should be relatively straightforward to appreciate, the design needs of this electronic system further require high quality power delivery. Since ADC computing would be used to process the analog output from the condenser microphone, stable power will be necessary to ensure clean measurements are made by the ADC. With 12 stages of voltage comparison at Vmax=3.3v, the ADC would be sensitive to voltage changes on the scale of microvolts. This means that even small amounts of noise in the power signal could significantly alter the ADC readings for this design, and should be avoided as much as possible.

Note that another linear voltage regulator circuit will be hosted on the PCB. That one will provide a 3 V power signal that will only be routed to the laser photodiodes. It will not have any connections to any of these microelectronics. Since that regulator will be used to power the sensitive optical equipment, it will require greater power analysis than can be provided here. For additional information, as well as the schematic diagram, see Section 5.2.3.

5.3.4. I/O Connection Schematic Design

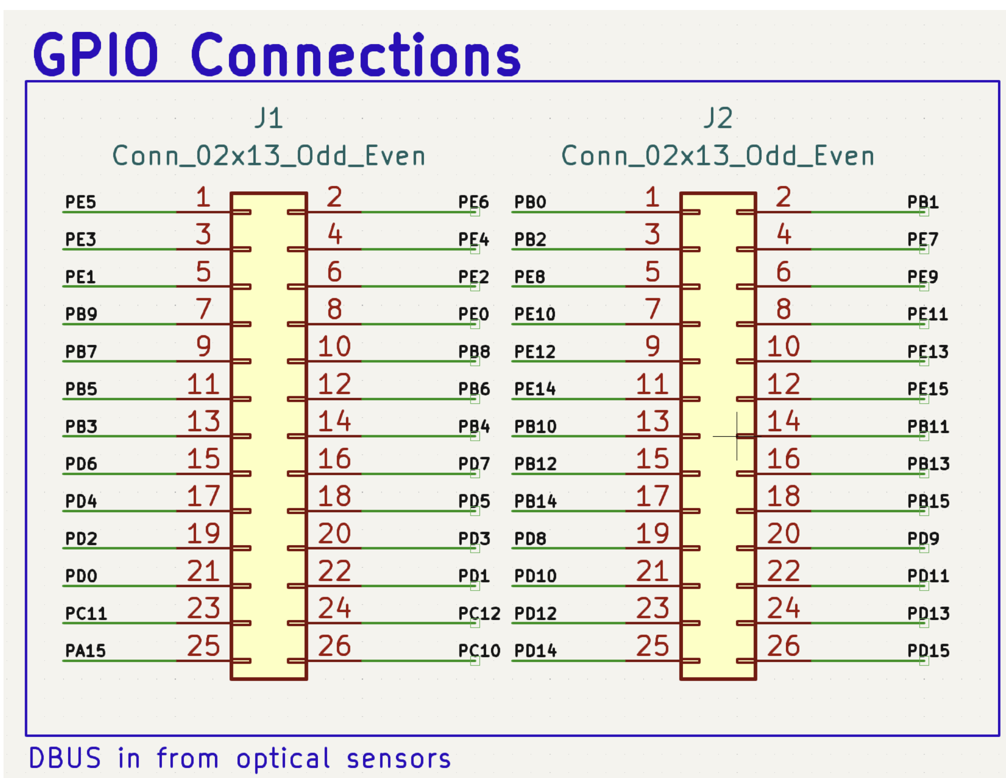


Figure 52: I/O Pin Header Configuration. Image provided by Lazer Pong project team.

Now that the port assignments for the multitude of GPIO devices has been decided, the pin designations for the data lines from these pins must be determined. The goal with the organization of these pin connectors was to conflict as little as possible with the most naturally attainable trace configuration for the PCB. The assumption was made that no signal processing would be necessary, though there is provision for that eventuality.

The schematic and table above represent the ideal pin layout: Roughly one pin header is assigned to each side of the microcontroller, with two lanes of I/O traces running to two rows of pin on either side of the header. Unfortunately, due to the need to avoid routing traces around each other and the spread nature of the pins on the microcontroller, each header will be supplied by mostly nonconsecutive photodiode receivers, which will complicate the wiring scheme for that part of the design. With power to the photoreceiver parts being delivered by the 3.3v out header, it was unnecessary to include power connections for the receivers here.

While the photoreceivers should provide a signal of significant quality to suffice for the simple GPIO needs of this design, there was potential for the need to amplify or clean these signals. If that became the case, a transimpedance amplifier would have to be added to the data path for each data line from the photoreceivers. While these transimpedance amplifiers could all be placed directly on the PCB, the schematic design would become incredibly complex, not to mention the consequences for the PCB design itself. If this step becomes necessary, rows of amplifiers will have to be placed on intermediary PCB components between the photoreceivers and these I/O pin connectors. In this eventuality, power will certainly have to be delivered between the two PCBs, and so to the photoreceiver units as well.

This I/O datapath constitutes the single greatest challenge we faced in the design of the PCB. The huge number of connections at the microprocessor pins, at the pin connectors, and at the receivers themselves left ample room for both human error and machine error. More than this, the potential for the need to postprocess all 48 signals was a daunting one. If a significant issue was found with the quality of the photoreceiver signal, it could have been necessary to revisit the laser and photoreceiver technology selected for this design. Fortunately, while the signal quality from the receivers was less than ideal, it was sufficient to interface mostly as intended with these electronics.

5.3.5. Microphone Schematic Design

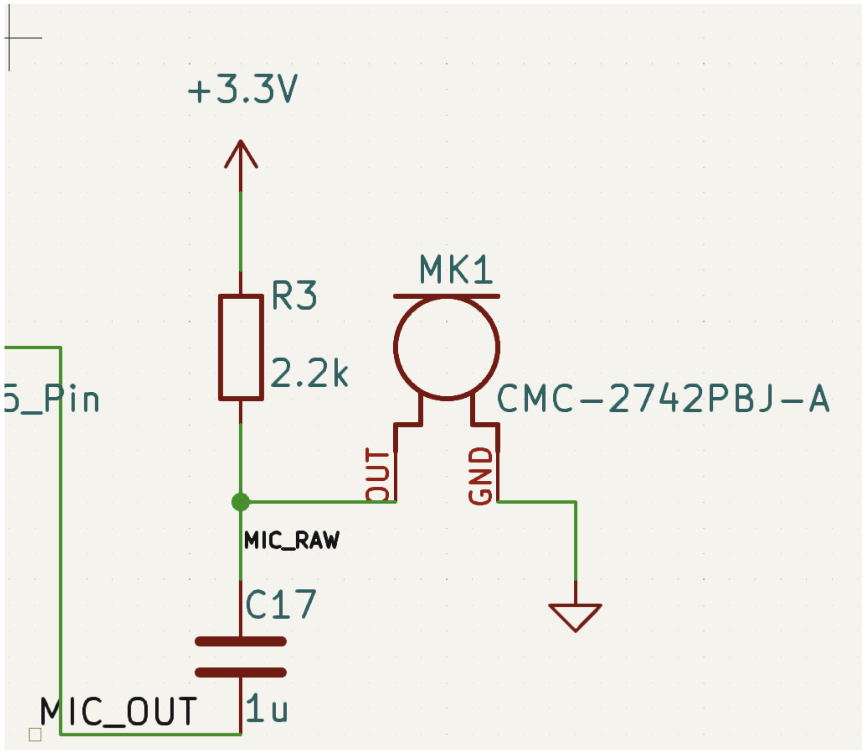


Figure 53: Microphone Schematic. Image provided by Lazer Pong project team.

Table 32: Microphone Schematic Part Description

Part	Number	Value
Electret Condenser Microphone	CMC-5044PF-A	-47 to -41 dB 100 to 20,000 Hz
R3	CRCW08052K20FKEAHP	2.2 kOhm
C17	C0805X105K5RACAUTO	1uF

In order to inform the reactive lighting on the surface display, an analog condenser microphone was employed to measure the volume of any noise around the table. This microphone works by utilizing a pickup placed over a FET impedance converter to produce an analog signal on the scale of GND to VDD (no more than -47 to -41 dB) that reflects the sound signal at the microphone [73]. This analog signal is then delivered to the Arduino at a breakout pin, where it would have been included in the display data calculation, if time had permitted.

As per the manufacturer's requirement, a single 1uF capacitor must be placed at between the output pin of the microphone and the ADC pin of the microcontroller [77]. The purpose of the capacitor is to shield the ADC input from the DC voltage level from VDD [77]. This way, the ADC only receives the analog signal from the microphone. Additionally, a 2.2 kOhm resistor must be placed between the VDD voltage source and the output pin [77]. This resistor will act as the load for the microphone, producing the necessary power to provide function to the internal FET electronics [77].

5.3.6. SWD Flash Connection

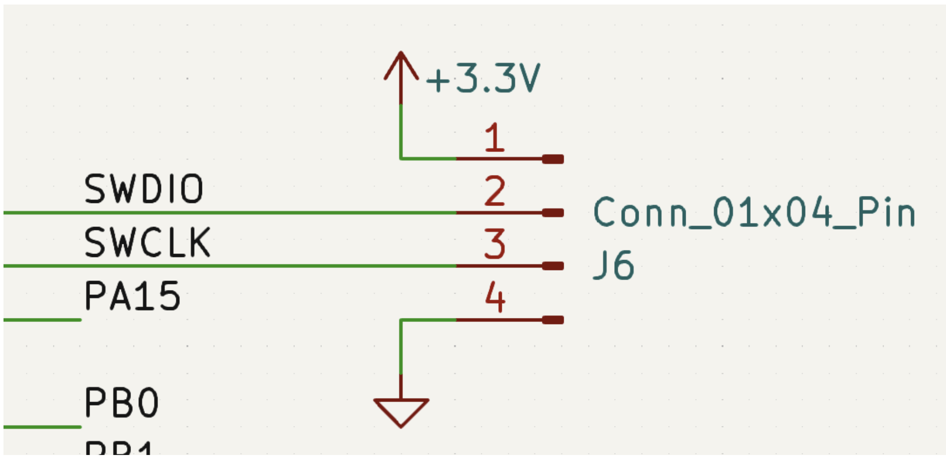


Figure 54: SWD Flash Connection Schematic. Image provided by the Lazer Pong project team.

While the industry standard for hardware and software debug is typically implemented through a JTAG connection, the complexity of that flash and debug capability far exceeds the needs of this design. Flash functionality ws necessary to load the software routine onto the microcontroller, and some debug capacity was needed to ensure complete functionality of the design. However, this represents the limits of the debug needs of this design. Additionally, JTAG requires a 20-pin header, which would take up additional space on the already crowded PCB. By choosing a SWD connection for debug and flash, the device operates with exactly the required debug services, and none more.

5.4. PCB Design

The PCB design process went through three stages throughout the end of Senior Design 1 and the duration of Senior Design 2. First, our first draft was designed. This draft mirrored the above schematics, with the exception that the device did not include an SPI connection. Instead, at that time, the plan was to address the LED display via our electronics, without the need of an Arduino device. Unfortunately, it was discovered that our electronics could not be compatible with the drivers for the LED display. We attempted to preserve our hardware and fix the issue on the software side, but could not create a solution, given the short duration of this project. It was determined that the best solution would be to include an Arduino device for communication with the display, which would be interfaced with via SPI.

The second PCB version included a half-duplex controller-transmitter SPI connection, instead of a GPIO connection for the LED display. The goal with this SPI connection was to include a smaller Arduino platform locally on our PCB, soldered directly to the device. Our electronics would act as the controller, transmitting graphics commands via SPI to the Arduino, which would act as the peripheral and display controller. It was discovered that placing this section of the datapath over SPI was a very inefficient design, and was very prone to error in SPI transmission. We determined that the simplest part of the datapath to communicate over SPI would be the break coordinates, as those could be transmitted solely as two 8-bit numbers (X-break and Y-break). Unfortunately, this version of the PCB could not support this SPI transmission, as it required reversing the controller-peripheral designations, as well as which data line was used (COPI vs CIPO). A new revision had to be made, with expanded SPI capability.

The final PCB version replaced the old SPI communication scheme with a full-duplex, peripheral-transmitter scheme. This not only had enough capability to support our new proposal for this leg of the datapath, but included full SPI capability, should another change to the SPI transmission arise. Additionally, since issues arose with the form factor of the embedded Arduino system, these connections were broken out to generic 2.54mm pins. This allowed us to utilize any Arduino platform we so chose.

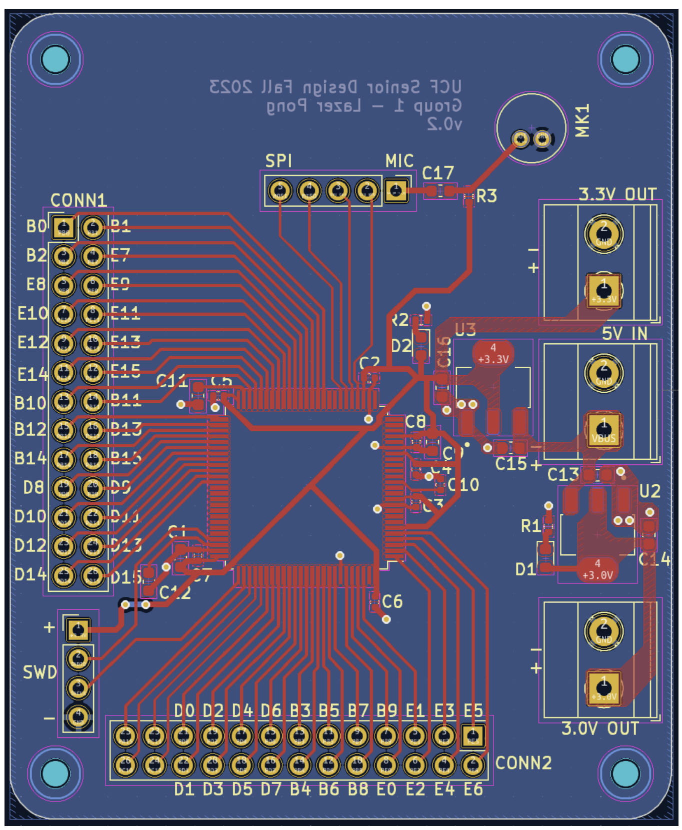


Fig 55: PCB Overview. Image provided by the Lazer Pong project team.

5.4.1. PCB Design Overview

Most of the important design features were discussed in the schematic design subchapter, so this subchapter will focus on copper routing and component placement design choices. The overall strategy in placing these components was to section the PCB into distinct groupings: The power subsystems were placed along the right side of the device, the GPIO breakouts were placed along the bottom and left sides of the device, the MCU was placed at the center, and the Arduino connections and analog devices were placed at the top. With the exception of the power subsystems, all of the subsystem locations were determined by the relative location of the required MCU pins. This allowed for sensitive data traces to be as short as possible, and removed the need for 4+ layers of PCB or a significant number of via routes.

5.4.2. PCB Design: Power

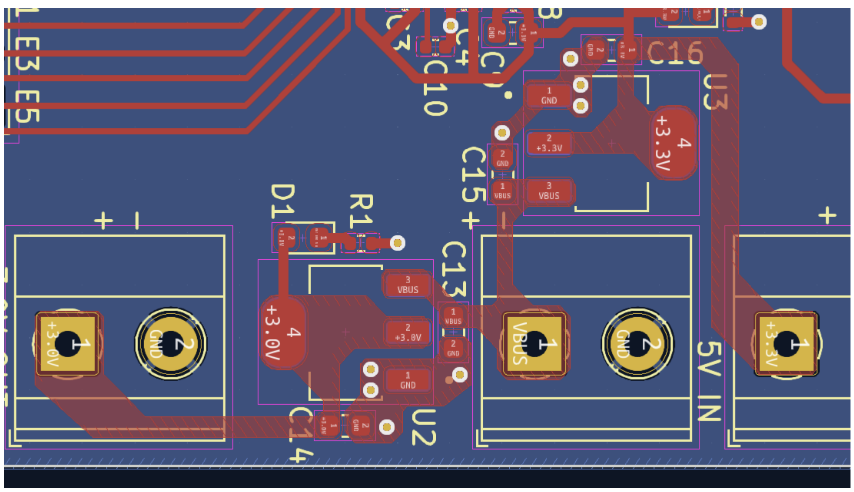


Fig 56: PCB Power Subsystems, rotated 90 degrees for convenience. Image provided by the Lazer Pong project team.

To ensure that the full 1.2A of power supported by the two voltage regulators would be able to be delivered consistently without burning up PCB traces, “power puddles” were used to deliver power between the off-board inputs and outputs, and the onboard voltage regulators. These puddles, seen above as the large red patches, are simply small sub-planes that deliver HIGH or GND for their respective voltage level. The current supported by these puddles is much higher than what would be supported by a single trace, and well above what could possibly be drawn by the optics systems.

5.4.3. PCB Design: MCU and GPIO

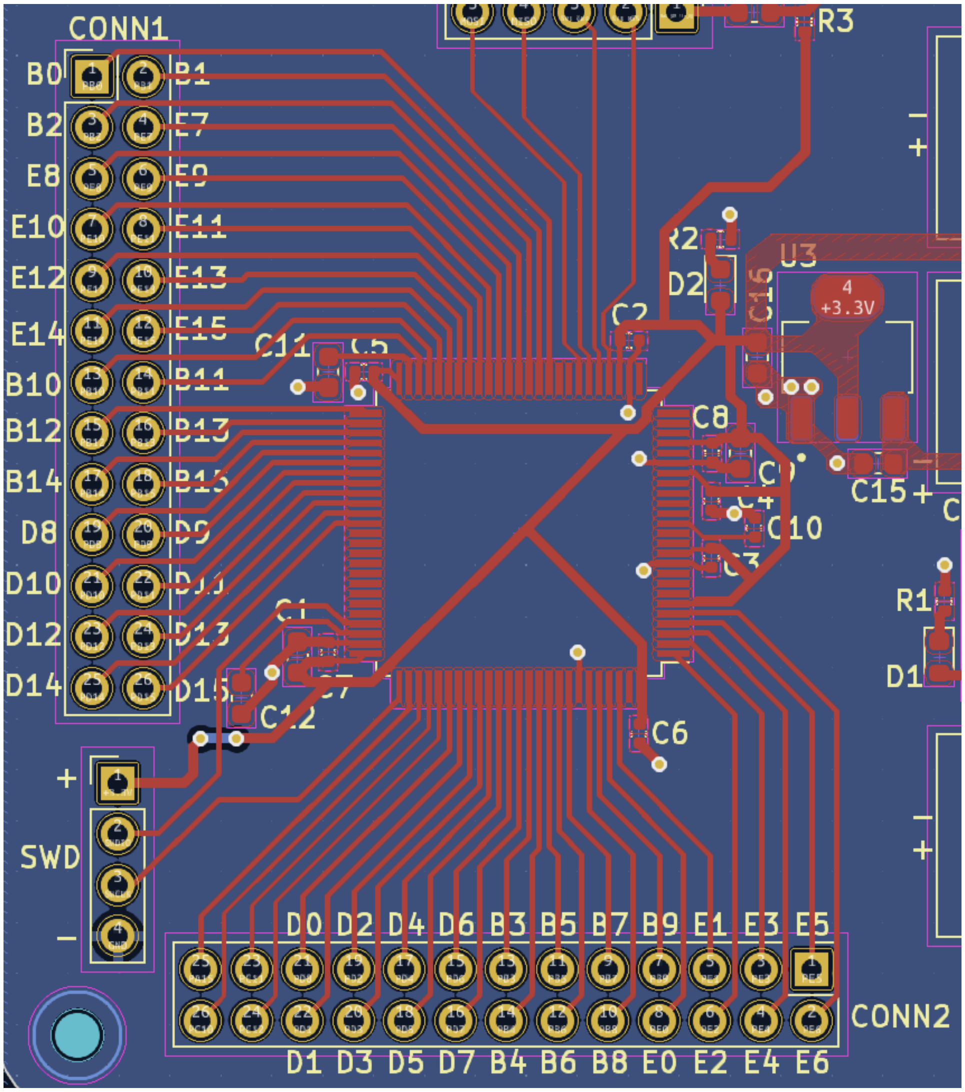


Fig 57: PCB GPIO Subsystem. Image provided by the Lazer Pong project team.

As intended by the schematic design, the GPIO connections were easily broken out directly in the order in which they appear on the pinout of the microcontroller. To minimize parasitic capacitance, the traces were fanned out as much as possible, and as early as possible. Unfortunately, some capacitors needed to be placed in the way of the GPIO traces, though luckily the form factor used for these devices made them small enough as to minimally impede these GPIO traces. In the final product, no issues were found with the GPIO connections themselves.

The SWD header was also broken out in this vicinity, as those were the locations for those SWD pins on the MCU. Since the SWD connection was the last connection to be routed, it became a little cluttered. This was not helped by the V_CAP pins being located directly in between the SWD and SCK pins for this connection, which required routing around two 0603 capacitors.

5.4.4. PCB Design: SPI and MIC

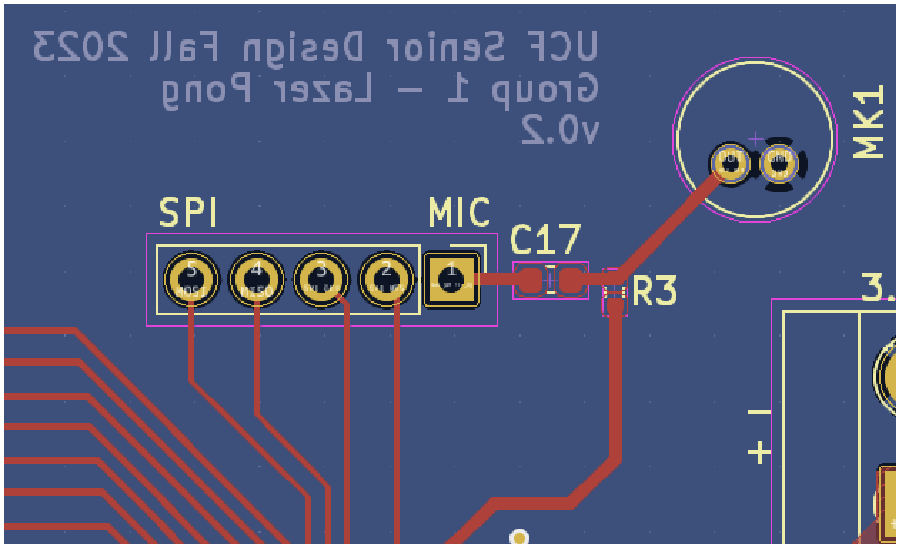


Fig 58: PCB SPI and MIC. Image provided by the Lazer Pong project team.

Finally, the Arduino output connections were placed near the only available set of SPI pins. These connections were broken out directly to this 5-pin header, along with a connection for the microphone data. While these connections were not trace matched, signal integrity issues with the SPI communication were never observed.

5.4.5. PCB Design: Conclusion

Overall, the design of the PCB was relatively straightforward. By doing most of the legwork in the schematic design to ensure that the PCB design would have every advantage it could, our design process made this last stage simple. While it did take several revisions to properly address the issues with communication, the actual PCB revisions were minimal in complexity. In the end, our electronics operated exactly as intended, and at no point in the bring-up stage did we encounter any issues with improper electronic design.

5.5. Software Design

The software that drives the automated functionality of the Laser Pong table is run on a microcontroller on the PCB designed for this project, as well as an arduino to control the LEDs, IR Laser inputs, and game state of the table. The core functionality of the table is automating the game of beer pong which relies on a polling mechanism that continuously checks registers to accurately track the position of the ball during gameplay. This data is then used to trigger appropriate routines ensuring a seamless and engaging gaming experience for the user. In this document, the naming conventions of the STM32 microcontroller will be used for abstract discussion of the software architecture.

When the table is turned on, the software will begin by initializing the SPI and GPIO pins that drive the functionality of the components of the table. SPI is used to transfer the location data gathered by the MCU, which quickly polls the registers reading input from the IR laser receivers, to the arduino, which communicates this data to the LEDs. This communication between the MCU and the arduino facilitates the tracking of the location of the ball during gameplay as well as provides the touch navigation function to the menu. The STM32F205VC microcontroller has 14 different timers to choose from based on the programmer's specific needs [36]. For this design, the general purpose timer TIM2 on the MCU was used. This is because this timer has a max timer clock speed of 60 MHz, which provides the software with a clock speed that is fast enough to accurately track the ball's location as it is moving along the table. A fast clock speed is necessary because the software needs to be able to poll the registers in rapid succession to react to the ball if it has moved from its previous location on the table or is rolling along the table. Another reason for the need for a fast clock speed is because of the music visualization feature of the table. This feature reads in sounds picked up from the microphone and converts them to a signal via the ADC. The software reacts by displaying a light flash that is synchronized to the signal peaks. To accurately respond to the signal peaks, the software must poll the signal received from the microphone rapidly to detect and react to signal peaks quick enough to display the light effect in sync with the peak.

The GPIO registers on the microcontroller must all be set appropriately. The CRH and CRL register are used to control if a pin is initialized as an input or an output, as well as the speed that the pin can output data. This register was used to set the components in the table to either input or output, depending on their use in the system. The pins connected to the LEDs surrounding the table were set as output, with their max output speed set to 2MHz. The speed was set to this lower value because the LEDs did not need to create a strobing light effect where the LEDs flash very quickly. An LED is turned on when the ball is in its location and turns off once the ball leaves the location, which did not occur in multiple fast pulses. The rhythmic LED light pulses that are displayed when the software reacts to music does not exceed 2MHz. Therefore, the output speed is reduced to save power. The pins connected to the IR laser receivers were set as input in the CRH and CRL register. This is to ensure that the software can read the input signal of the receiver and react accordingly when the signal is broken or restored. The pins connected to the microphone were also set as input so the software can read in the signal converted by the ADC and flash the LEDs on the table in sync with the signal peaks. The IDR, or Input Data Register, was used to read in the input of an entire port of 16 pins that were set as input by the CRH and CRL register. The input is accessed as a 32 bit word whose lower 16 bits represent each pin. This register is used to read in the signals produced by the IR laser receivers and the microphone so that the software can react and execute the proper routine related to the state of the input of these components. The pins that the IR laser receivers are set to 0 so they are treated as input. The SPI communication then transfers this data to the arduino which executes the LED light effects by lighting up the LEDs when they are ordered to by a routine in the software.

Once the SPI and GPIO pins are initialized, the software begins its main game state. This state is where all the main functions of the table are done, such as checking for raised flags and executing light effect routines. During this state, the software continuously polls the input received by the IR laser receivers, checking for high signals that indicate the presence of an object on the table. The polling function is controlled by the timer in the MCU. When a high signal is detected, the software begins calculating the location of the ball by using a 2D array of output registers where each bit in the array represents one IR receiver. The software determines in which row and column the signal break occurs and performs an “AND” function on the columns and a 16 bit number with all the bits set to high placed in the row that the signal break occurred. This process gives the software the location of the break in both the X and Y directions. Once the bits in the location of the break are set back to low, meaning the break in signal is no longer occurring, the software reads low signal from the register and begins the process again. The block diagram below describes the software’s behavior during the use of the table.

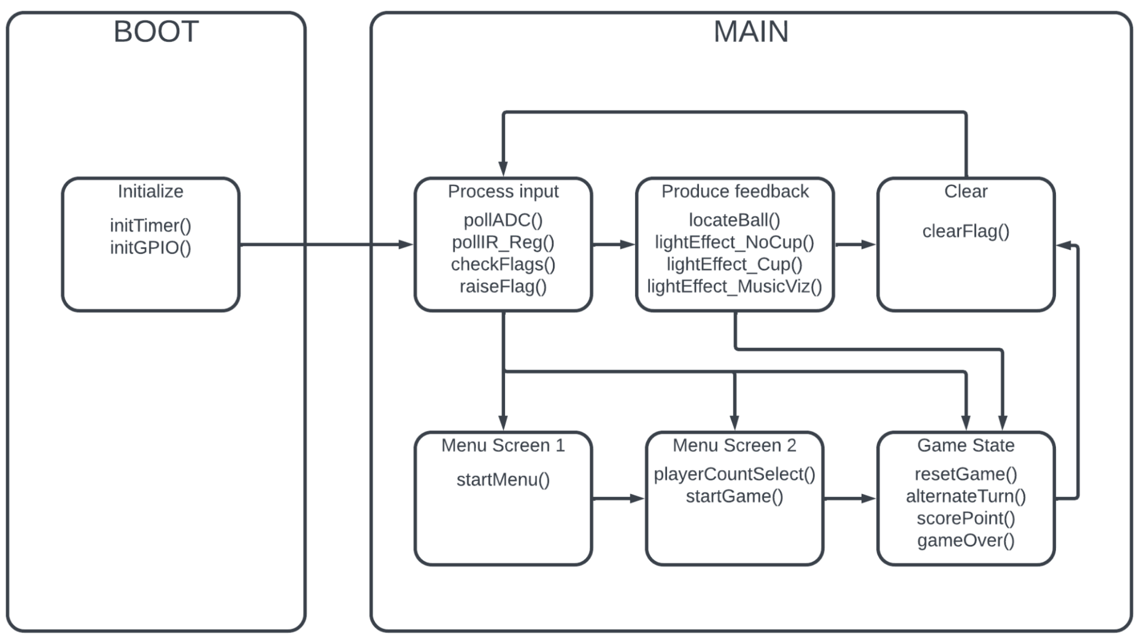


Figure 59: Software Block Diagram. Image provided by Lazer Pong project team.

During this process, the menu is implemented to allow users to operate the table and begin playing. The menu is crucial to the function of the table, as it allows users to choose how many players are participating as well as alternate turns to provide accurate scoring during gameplay. The menu is located on the surface of the table, using the LEDs to display menu options in a 32x16 pixel wide grid. The user operates the menu by touching the surface of the table in the location of their desired selection, which is facilitated by the IR receivers tracking the location of an object on the table. When the user touches the table in the location of a menu selection, the signal of the IR receivers in that location is broken. The same calculation done to locate the ball during gameplay is utilized to determine the position of the signal break as one where a menu selection is located. This triggers the software to initiate the routine related to the menu selection.

The first screen of the menu is a simple start screen, with one option to start the game. Choosing this option brings you to the second screen of the menu. This screen is where the user chooses how many players are participating in the game. The user can choose one to four players to participate. A color is assigned to each player. This color is displayed by the LEDs when they are used to provide visual feedback during gameplay, or when the music visualizer pulses to signal peaks from the microphone. Representing each player as a color will give the players a visual cue that informs them which player’s turn it is. Once the player count is picked, the user selects the start option, represented by a green circle in the menu. This option will begin the game state of the table, where the user can play the game.

The final menu is displayed during gameplay, and allows the user to alternate turns during the game. The user must alternate turns during a game to ensure that when a score is made, the correct player is awarded the point. This menu also has an option to reset the game. This option resets the score and terminates the current game being played. The menu will then return to the first screen, allowing the user to select a player count and start a new game. This option is included so that the user can end a game being played and start a new game at any time, rather than needing to fully complete the game before starting a new game. These two buttons are located in the corners of the table on the edge where the user will stand during gameplay, rather than in the center on said edge. This was done to further differentiate the two selections on this menu, as one is critical for game functionality, and the other simply resets the game state. To keep the user from accidentally pressing the reset option, these selections are spaced as far away from each other as possible.

While the game is being played, the score and progression is handled by the software, accurately rewarding players with points and declaring a winner at the end of the game. When the user selects the number of players participating the software creates an array variable for each player. This variable is used to hold information about each individual player, like their assigned color and score. The rules of the game are as follows: the first player stands at the end of the table opposite from 10 cups placed in a triangle formation. The player tosses the ball and attempts to get the ball to land in the cup. If the ball lands in the cup, the software rewards the current player with a point, and provides a visual cue that a score was made. The player then removes the ball from the cup and presses the next turn button. If the ball does not land in a cup, the player does not receive a point. The player then touches the alternate turn selection on the table, which will switch to the next player and change the color on the board to indicate the switch. The participants continue the cycle until all of the cups have been removed from the table, where the score for each player is compared, and the highest score is declared the winner. The table performs a visual effect to indicate the game is over, and displays the number of the player who won as well as their score. The software then returns to the pre-game state, and displays the start menu to the user once again.

The music visualization feature is powered by the software in the system, and requires the microphone signal to be converted and analyzed to create rhythmic LED light pulses on the table that synchronize to the beat of a song played in the table's vicinity. The microphone's input is first converted from an analog signal to a digital signal via the ADC, which is then analyzed by the software. The software uses polling and check flags to locate the high amplitude signal peaks and responds by flashing the LEDs located on the edges of the table. This makes the LEDs dance to the music and makes the user experience more exciting and dynamic.

The software for the table facilitates the operation of the automated features that enhance the gameplay of cup pong. The game operation, menu, light effects, and music visualization are all handled by the software and the various components communicate to provide the enhanced gaming experience to the user.

5.5.1. Overview

Menu

The menu is used to control the game state of the table. It consists of a small section of LEDs to display the settings to the user, as well as a touch screen functionality to control the menu. The menu communicates with the IR laser receivers to facilitate the touch screen function. The menu appears when the table is turned on, and once the game has started, the menu separates into two sections at the corners of the table near the player, and displays the alternate turns and exit game selections. These options stay during the game and are used to change turns and exit the game before the game has finished.

Laser Configuration

The laser receivers in the table are used to determine the location of the ball, and if a score is made. Within the software, they interact with the MCU and the LEDs to provide feedback for when a score is made or the ball hits the table. Each laser receiver is individually addressable using an array of 16-bit registers where each receiver represents a single bit within the register. The software polls these registers for any bits that have been flipped to a 1, and uses this to determine the location of the receiver that has been triggered. This allows the LEDs to provide feedback in that location, and for the MCU to determine if a score was made. The lasers also facilitate the operation of the menu, providing the touchscreen functionality that allows the user to select menu options.

LED Configuration

The LEDs are configured in a similar way as the laser receivers, with each LED being individually addressable. The LEDs are used to provide feedback for scores and the ball's location, as well as display both static effects and effects that correspond to the sounds captured by the microphone within the table. The LEDs being individually addressable allows a single LED in the location of the ball to light up, providing feedback to the user. There are also static light effects that will play regardless of the ball’s location. These effects are used to provide a visually appealing display on the table. There is a function that uses the LEDs to visualize music or other sounds that are captured by the microphone. The LEDs have multiple routines for visual feedback, each with different light effects and static lighting modes.

Game State

The logic to control the game is simple, only needing to award points when a score is made and control the game state. Starting, resetting, and alternating turns is done by the user with a start menu controlled by touch facilitated by the IR lasers. Programming this functionality only required reading the user selections, and running the appropriate function to complete the task. The game starts with 10 cups on the table. The user selects how many players will be participating and the first player begins their turn. Each player is assigned a color that is displayed via the LEDs to differentiate the players and indicate whose turn it is. Switching turns from player to player is done by the user in the start menu. Because there is only one set of cups, the turns must be switched manually so the program knows which team to award points to. When the ball lands in a cup, a score is awarded, and the ball is removed. The game continues until a score of 5 is achieved by a player. The software then displays the winner's score. A visual effect plays to indicate that the game is over. Then the game state resets, and a new game can be played.

Microphone and Music Visualization

The table was intended to have a microphone embedded inside, which would be used to capture audio from the surrounding area and communicate with the LEDs to create effects that correspond to the captured audio. This process is called music visualization, and would provide a visually appealing effect that moves to the beat of a song. This would have been done using an analog-to-digital converter, or ADC. The ADC would convert the sounds picked up from the microphone to digital signals that can be processed by the MCU. These signals would have been used to communicate to the LEDs when to turn on and how bright to illuminate. A high pass filter would have been used to filter out sounds that are a low volume. This is done to keep the LEDs from visualizing quieter sounds within the room, such as people talking, and only visualize louder sounds such as music.

5.5.2. Menu

The menu plays a crucial role in operating the table during gameplay, providing users with a straightforward and user-friendly interface. The menu serves as the central hub for the user, allowing them to access the functionality of the table. It is designed to facilitate the initiation of a game. The design prioritizes enhanced accessibility and ease of use to ensure that anyone can play with the table effortlessly. The software powering the menu includes a main menu that allows the user to select the number of players and initiate the game. To display the menu, a grid of LEDs measuring 32x16 pixels is positioned on the table surface. This grid serves as the visual interface through which users can navigate and make their selections. To interact with the menu, users simply need to touch the surface of the table. This touch input is facilitated by the IR laser receivers, which track the user's touch and determine which option they have selected. By touching specific areas of the table corresponding to different menu choices, users can navigate through the available options and make their desired selections.

Starting up the table brings the user to the main menu. This menu has an option to start the game. Choosing this option brings the user to a new screen, where they choose how many players are participating in the game. The number of players is important to the functionality of the table because the table must know which player to award a point to when a score is made. The user selects the amount of players and selects the start game option to begin playing. Each player is assigned a different color. This is done to indicate to the user whose turn it is to play by changing the color displayed by the LEDs on the table to the color associated with the player. Once the game is started the software commences the table's game routine. The menu then disappears and is replaced by a small screen with two buttons. These buttons will be used to alternate turns when playing the game and to end the game. This is necessary to track which player is to be awarded a score when one is made during play. The rest of the LEDs dedicated to the menu along with the rest of the LEDs on the table display the visual effects that are used to provide feedback to the user when the ball touches the table or a score is made. A mockup design of the menu can be found below.

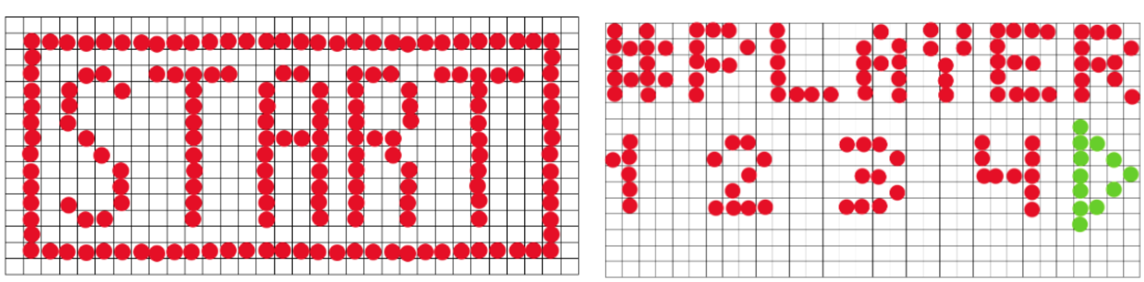


Figure 60: Start menu and player select menu. Images provided by Lazer Pong project team.

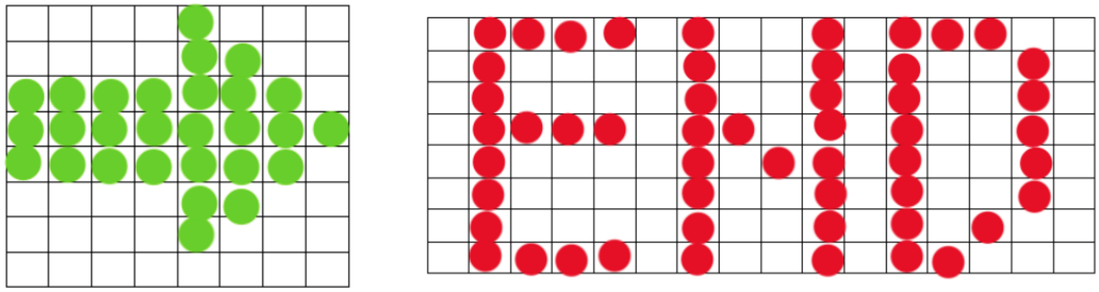


Figure 61: Alternate turns and end game menus. Images provided by Lazer Pong project team.

The menu design of the table is intentionally kept simplistic to enhance accessibility and ease of use for the player during gameplay. The IR lasers, LED visual effects, and music visualization are all automated so the user does not have to configure them using the menu. This ensures that users can focus on the game without the need to manually adjust these elements. The menu consists of 3 individual screens: The main menu, the start game menu, and the alternate turns menu. Given the limited screen space available on the 32x16 pixel LED segment, careful consideration is given to efficiently utilize the available space on each screen. During gameplay, the menu system adapts to maximize the visual effects displayed on the table. The full menu will only be displayed to the user when a game is not in progress. When the game is being played, a more compact menu called the alternate turns menu will appear which will be smaller and split into the corners of the table rather than the full 32X16. This is utilized to save space and allow the LED display to focus on presenting the visual effects without unnecessary obstructions. By carefully managing the menu screens and optimizing the use of limited screen space, the table ensures that users have easy access to necessary options while maximizing the visual impact of the game. The simplified design enhances the user experience by streamlining interactions and placing emphasis on the engaging visual effects displayed during gameplay.

The menu is an integral part of the function of the table. It facilitates the table’s operation by presenting the configuration options to the user, as well as progressing the game by alternating turns. The menu’s simplistic design and touchscreen capabilities provide the user with accessible and straightforward control of the table and its features, while not distracting the user from the gameplay. The menu is conveniently located at the edge of the table where the player stands during gameplay. It is large enough to facilitate the menu operations, but also compact so that the maximum amount of space can be dedicated to displaying the dynamic light effects and music visualization.

5.5.3. Laser Configuration

The IR lasers are used to track the ball’s location and determine when a score has been made. This tracking process is vital for providing accurate gameplay feedback to enhance the overall user experience. The IR lasers are used to track the location of the ball and determine if a score is made. They communicate with the LEDs to provide visual feedback to the user and enhance the playing experience. In the software, the process of tracking the ball and locating breaks in the receiver signal is implemented through polling an array of 16-bit registers. This array holds information about the state of the receivers at different positions of the table. By performing an “AND” function on this array, the software can identify the exact location where the break in signal occurs, both in the X and Y directions. This information is then utilized to coordinate the visual feedback provided by the LEDs, ensuring that the LEDs accurately represent the ball’s location and movement.

A break in signal is processed by the microcontroller using a falling edge trigger, or running the signal in an active high mode and checking for when the signal becomes low. This is because when there is nothing in front of the IR laser receiver, the signal passes from the emitter to the receiver and reads a high signal, or a 1 in binary. When the signal is broken, the receiver does not receive any signal from the emitter, and reads a low signal, or a 0. The check flags in the IFG registers check for a low signal from the receiver, and when one is found, the program responds by setting the corresponding bit in the register to 1.

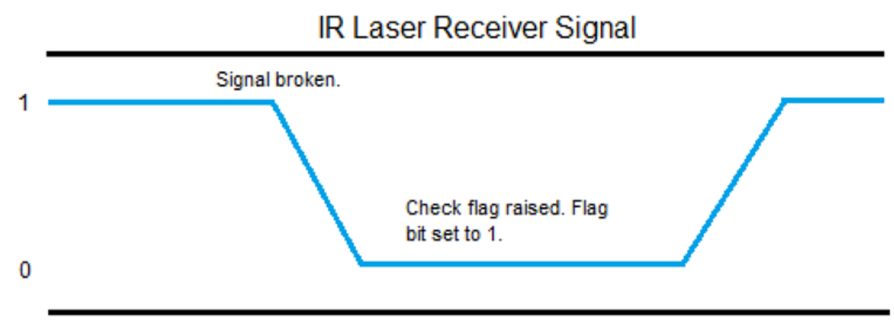


Figure 62: IR Receiver signal falling edge trigger. Image provided by Lazer Pong project team.

Using the breaks in signal alone is not enough to locate the ball on the table. Each laser receiver must be able to be individually addressable so that each break can be processed on their own. To achieve this, each laser is connected to a single pin on the microcontroller. This allows the MCU to react to a break in signal at a single location. To determine the location in both the X and Y direction, the pins are represented in the software as single bits in a 16-bit register. These registers make up a 2D array that represents the surface of the table in a grid.

Each laser receiver is connected to a single pin on the microcontroller. This uses 48 pins: 32 pins lengthwise and 16 pins crosswise. Each port is 16 pins wide, so this configuration utilizes 3 ports total: 2 ports lengthwise and 1 port crosswise. This allows us to create a 2D array of 16-bit registers that correspond to the array of ports, making each pin on the microcontroller individually addressable. In this configuration, we use the 16-bit registers to check for breaks in the receiver signal. Below is a diagram describing the pin configuration of the microcontroller.

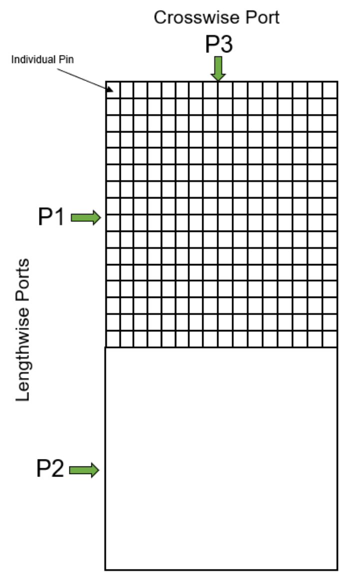


Figure 63: Layout of ports on microcontroller. Image provided by Lazer Pong project team.

With a 2D array of 16-bit registers, we use the technique of masking to find the position at which the ball is located. Each pin in use, which are all connected to the IR laser receivers, takes up a single bit within one of the registers in the array. Each bit in the register has a check flag for if the signal is broken. The program begins by polling the registers to check for a break in the receiver signal. When a break at one of the receivers occurs, a check flag is raised, and the bit in that position goes from a 0 value to a 1. Once the program has confirmed the break, it creates 16-bit values where all bits are the value of the flag at their respective indexes in the lengthwise direction. An “AND” function is performed between this created value and the check flags in the crosswise direction, which results in a value that represents the location of the break in signal. This value is then passed to the LED array, which is organized so that the value given by the operation is the coordinates in the LED array where the proper LED is held. The diagram below is a step-by-step visual representation of this operation. The diagram shows the first 8 bits of the operation for simplicity, however the array will consist of 16-bit words in the software.

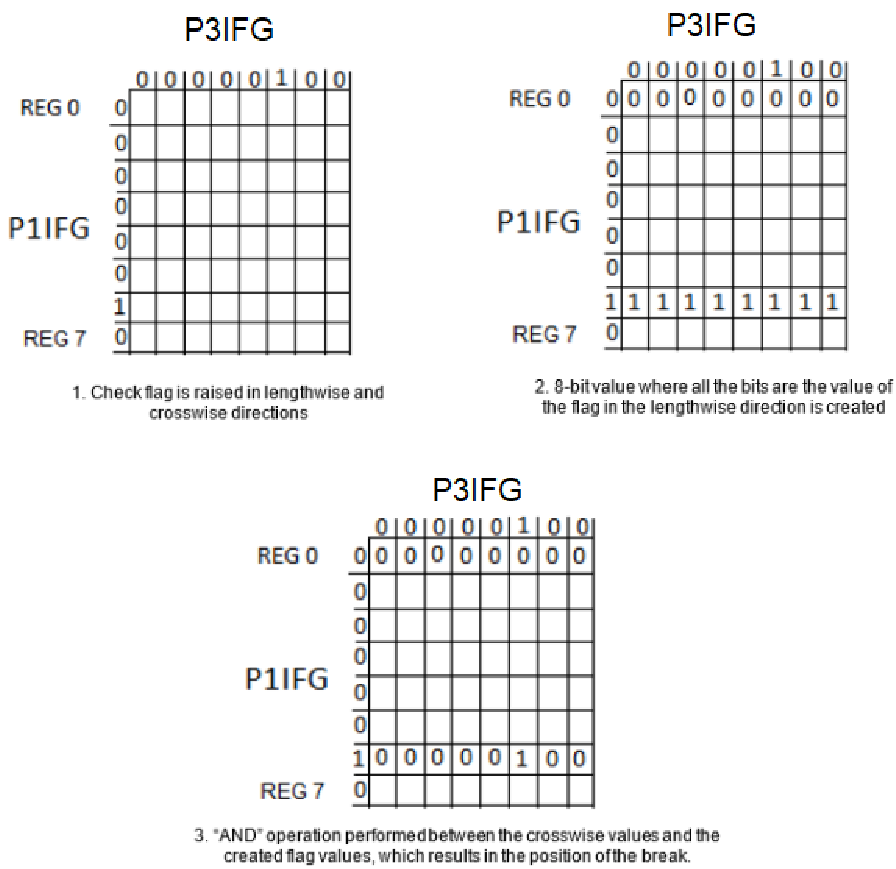


Figure 64: Procedure to determine location of signal break. Image provided by Lazer Pong project team.

We chose to use polling to check for breaks in the signal because it is the simplest solution that enables the program to locate multiple signal breaks at the same time. Using interrupts was the first solution that was considered, but is not viable because only one interrupt flag per port could be raised at one time, making multiple signal breaks at the same time not possible. For example, if a signal break occurred in the intersection of Port 1 and Port 5, as well as another signal break at Port 4 and Port 5, the latter break will not be processed by the program. This is because the check flag for Port 5 would be cleared before the next signal break could be processed, and thus would not appear when checking for a flag when processing the second signal break. The use of polling solves this by constantly checking all flags until one is raised, and once the routine has completed, it continues to check for flags.

One limitation of this routine is that if multiple signal breaks occur at one time, it will cause the program to turn on LEDs that do not correspond to the location of the signal break. This is because as the program performs the “AND” operation, it would result in a value of 1 being put in every combination of intersections, rather than just the intersections that occurred. This limitation is demonstrated below.

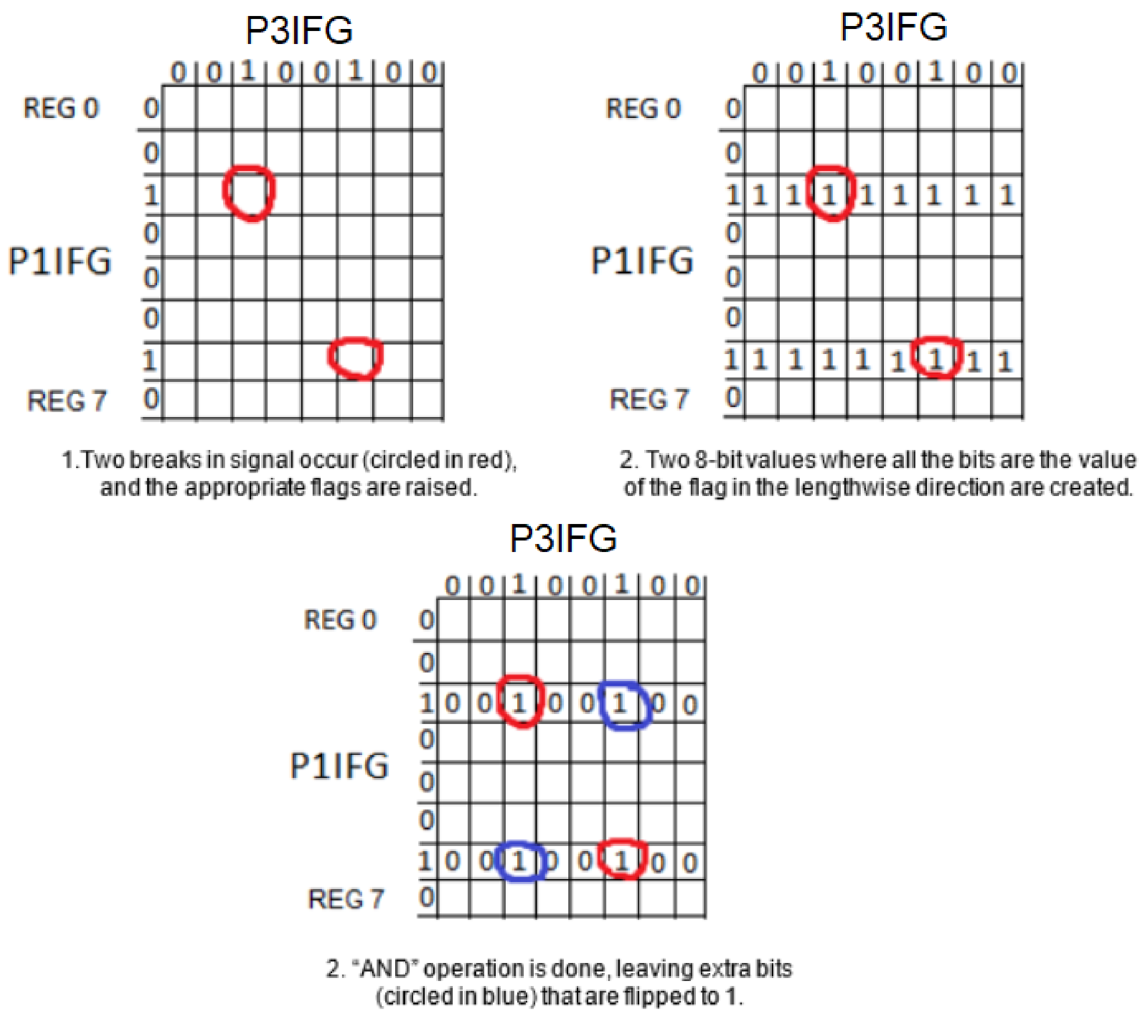


Figure 65: Example of polling limitation. Image provided by Lazer Pong project team.

The software must account for discrepancies in the signal breaks when determining where the ball is located. One discrepancy that may occur is if the check flags for the signal break in the X and Y direction are not raised at exactly the same time. In the event that the signal breaks occur one polling cycle apart from each other, the software would still need to register this as one break and locate the position of the break. To complete this, the software does not clear the flag until the signal returns to reading high, meaning the signal break is no longer occurring. This allows the software to continue polling for a cycle to locate the signal break in the other direction and calculate the location. Once the location is calculated, the LEDs activate in that position until the signal is restored. The flag is then cleared, and the software continues the cycle.

The IR laser receivers in the system facilitate the main function of the table. They provide information about the location of the ball or other objects on the table, which is then used to control the game's score, flash the LEDs at the location, and determine the menu option that the user selects. They are organized in the software to make flashing the LED in the proper location simple and efficient. The ability for the table to locate an object and provide visual feedback is achieved through the use of the IR receivers, and the operations done by the software.

5.5.4. LED Configuration

The LEDs on the table are utilized to display effects and provide visual feedback to the user. These LEDs work in conjunction with the IR laser receivers and the microcontroller unit (MCU) to display the menu and create light effects when certain events occur, such as the ball touching the table or when a score is made. To enable this function, the LEDs are configured as output within the software. This allows the MCU to send signals to the individual LEDs to operate them. When one or more IR receivers detect a break in signal, indicating that the ball has made contact with the table, the software triggers the LEDs to flash in the same location as the ball. This creates a visual effect that enhances the user's experience and provides feedback about the ball's position on the table.

For the software to flash each light independent of the others on the grid, the LEDs must be individually addressable. To achieve this, the LEDs are placed in an array where each LED represents a number in this array. When the software instructs an LED to flash, it calls the specific location in the array that represents the LED. This structure of the array is exactly like the array that holds the location of the IR receivers. This is to make locating the LED in the position of the IR receiver that has a broken signal much simpler, as the X and Y coordinates of the IR receiver in the array are the same coordinates as the LED in its array. The LEDs are addressed so if one were to flash each LED in an incrementing order, the LEDs would travel up and down the board in a snaking pattern. This was resolved by using the 2D array to represent the LEDs in a row and column order. A looping algorithm increments the location in the LED array, setting each LED to the proper location in the 2D array. This will make drawing graphics to the LEDs more straightforward.

[0]	[15]	[16]	[31]
[1]	[14]	[17]	[30]
[2]	[13]	[18]	[29]
[3]	[12]	[19]	[28]
[4]	[11]	[20]	[27]
[5]	[10]	[21]	[26]
[6]	[9]	[22]	[25]
[7]	[8]	[23]	[24]

→

	0	1	2	3
0	[0,0]	[1,0]	[2,0]	[3,0]
1	[0,1]	[1,1]	[2,1]	[3,1]
2	[0,2]	[1,2]	[2,2]	[3,2]
3	[0,3]	[1,3]	[2,3]	[3,3]
4	[0,4]	[1,4]	[2,4]	[3,4]
5	[0,5]	[1,5]	[2,5]	[3,5]
6	[0,6]	[1,6]	[2,6]	[3,6]
7	[0,7]	[1,7]	[2,7]	[3,7]

Figure 66: Conversion from 1D array to 2D for LEDs. Image provided by Lazer Pong project team.

To drive the LED array, a set of functions were programmed into the software and were used to standardize and organize the visual effects presented to the user. The functions were called during the various routines to provide the graphics presented to the user. A standard graphics library was used for drawing effects such as text or simple shapes. For the more intricate effects such as the one that is displayed when a point is scored, this library was used to create simple shapes that were then programmed to perform more intricate designs. An example of this would be using a drawLine command to create a function that produces lines that travel along the board, rather than being static.

The LEDs main function is to provide visual feedback while playing the game. This function lights up an LED when the ball is in its position, and creates a graphic that indicates a score when one is made. When a score is achieved, the software instructs the LEDs to produce a light effect to indicate the score to the user. This light effect will be different from the one used to tell the user the location of the ball. The LEDs surrounding the cup where the score is made will all light up in a pattern. This effectively communicates important information to the user through visual cues, making gameplay more engaging and intuitive.

The other functions of the LEDs are to indicate the score, the end of the game and display the winners score, display the menu, and display the music visualizer effects. During the game, the LEDs display the number and score associated with the current player in the center of the table. If the ball were to land in the location of the score, the LEDs in that location change to the color that indicates the ball location. This effect is prioritized because it is the main function of the table, and the goal is to dedicate most LEDs on the table to this function. When a game has completed, the LEDs then display the end game screen. This is a short dynamic effect to emphasize the game is over, followed by the text “Game Over” displayed on the table. Finally the LEDs display the number associated with the winning player as well as the score of that player. This effect clearly alerts the user when the game is over and informs the user which player won. The menu is used to start and configure a game, and uses the LEDs to display the menu options. The menu uses touchscreen functionality to allow the user to make selections. This feature is facilitated by the IR laser receivers, which track the selections from the user. The menu is located at the edge of the table where the player stands during gameplay, and displays text and shapes to indicate selections to the user. Lastly, the LEDs display the music visualizer effect. This effect uses the LEDs that surround the edge of the table, omitting the location used for the menu. It uses the input of the microphone to flash to the beat of a song being played in the vicinity of the table. When the microphone picks up a high amplitude signal, the software instructs the LEDs to flash in synchronization with the signal peak.

The LEDs in the system create the visual effects of the table which provide the user with a visually appealing and engaging cup pong table. The LEDs are responsible for displaying the visual feedback that informs the user of the current state of the game including the ball location and the score, as well as the menu screens and music visualization capabilities. The software takes advantage of standard graphics libraries like fastLED.h, as well as using custom functions to display numerous different light effects, such as light flashing in a firework effect and text on the table.

5.5.5. Game State

The game state of the table describes the sequence of events that make up the rules of the game. To enforce these rules, the software makes use of the IR receivers to track when a score is made. The software receives the input from the IR receivers and uses it to calculate the location of a signal break. This signal break indicates that the ball or another object is located on the table. Once the program successfully identifies the position where the signal break occurs on the table, it proceeds to execute the appropriate routine, which is contingent upon whether the break is detected within a cup's location. In the event that no cup is present at the identified location, a flag is raised and the program initiates a visual effect using the LEDs in that location. The software continues polling, but does not yet clear the flag. Once the break in signal is restored, it clears the flag. The program then resumes polling for flags and repeats the process. If the program detects a break in signal in a location with a cup, it promptly clears the flag associated with it and proceeds to poll once again, this time monitoring whether the signal remains interrupted. If the signal continues to be broken, it means that the ball has landed in the cup in the location and has not fallen out. This results in a point being scored. The program records the score and provides a visual effect to represent the score. It then clears the flag and resumes the polling process in order to detect any further signal breaks. This procedure is shown in the flowchart below.

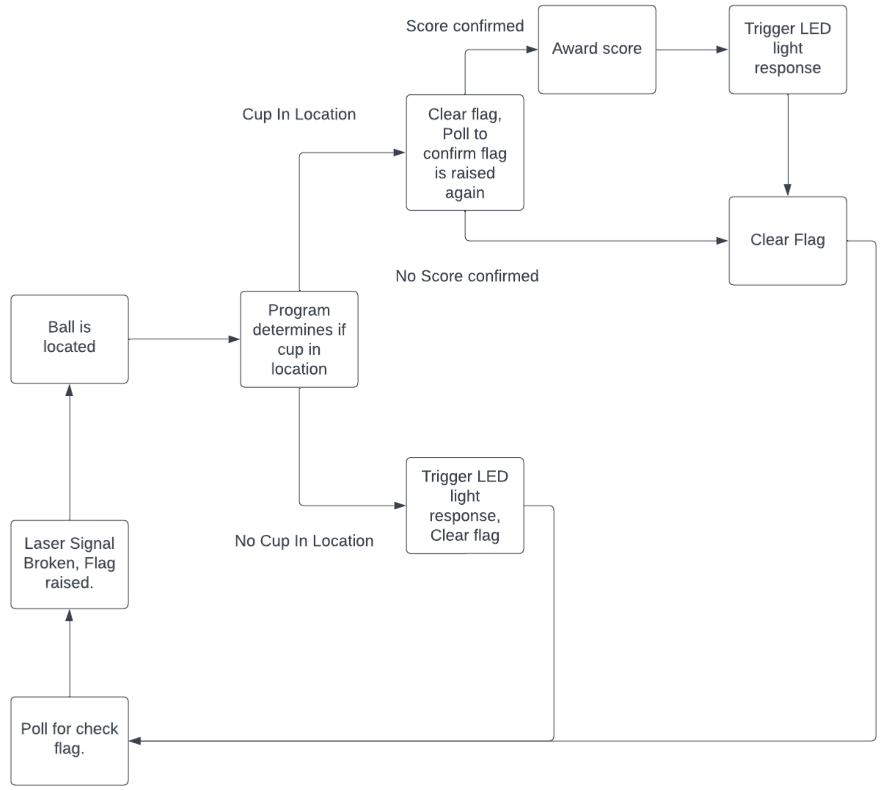


Figure 67: Program block diagram. Image provided by Lazer Pong project team.

To facilitate this process, the software utilizes a series of loops that will keep track of which of the player's turn it is and any related data, as well as the amount of remaining cups on the table. This will allow the software to determine which player will win the game, as well as when the game is over and all the cups are removed. The game state begins when the game is started. The software creates an array that holds the relevant data for each player. This includes the number that represents the player, and their current score. The software then tracks the score of each player as they play the game, alternating players when the alternate turn is pressed. Once the game is over, the scores are compared and the highest score is declared the winner. The game state then resets and the user must use the menu to start a new game.

The software that facilitates the game state of the table relies on the other components to accurately track the progression of the game. It makes use of the LEDs and IR laser receivers to automate the score keeping and flow of the game, as well as informing the user of this information. Using loops to progress through the game, the software identifies the ball location and uses this information to determine the appropriate routine related to the game state, such as rewarding a score or ending the game. This feature makes using the table simplistic, increasing the accessibility for all users by automating game information and progression.

5.5.6. Microphone and Music Visualization

The microphone located within the table would have been used to provide a music visualizer effect. This feature ensures that the table not only facilitates gameplay but also creates an immersive environment by synchronizing dynamic light effects with the sounds captured by the microphone. The software that powers this functionality would capture the input from the microphone and convert it into a signal that can be processed, and trigger LEDs on a segment of the table to flash in sync with the signal peaks. This makes the lights on the table flash to the beat of a song to provide a captivating light show to the user during gameplay. This functionality adds to the table's ability to foster a more social and engaging atmosphere when playing.

The MCU converts the signals received from the microphone from analog to digital signals using the ADC, or Analog to Digital Converter. When the table is turned on, the ADC begins initializing and the software begins polling the signal being received from the microphone. The signal from the microphone is polled quickly so that the software can accurately time the light effect to the beat of the music. The software polls the signal to find signal peaks, which was used to trigger the light response. Only the signal peaks are used to create a light response because the microphone will pick up all the sounds in the vicinity of the table, but the goal is to only visualize music. The music will have a louder, driving pattern that makes the beat of the song. This pattern creates a larger input signal from the microphone, which raises a flag instructing the software to activate the light effect. Below is an example of a signal received by the microphone, and how the software reacts to the signal peaks.

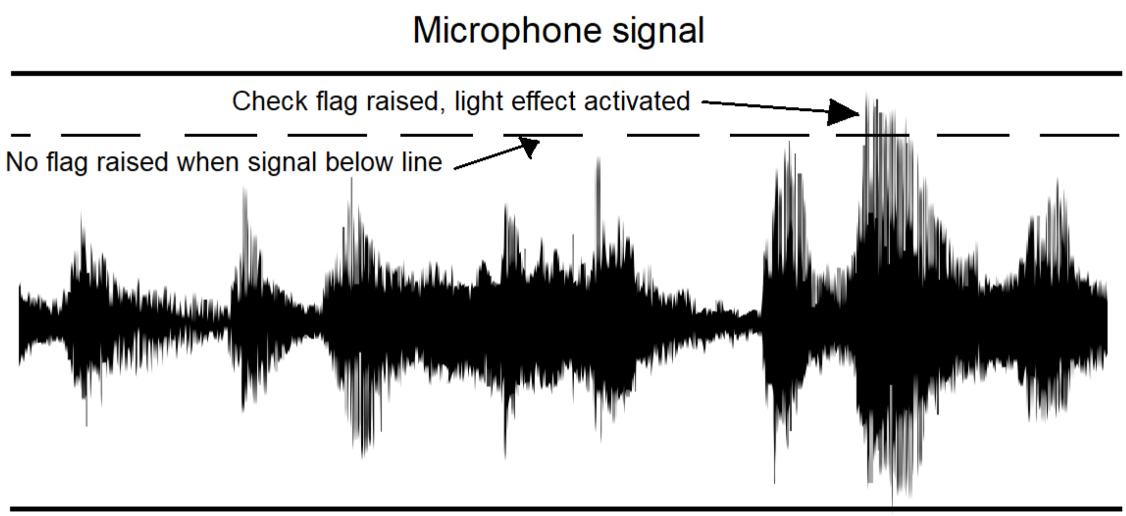


Figure 68: Microphone signal example with check flag. Image provided by Lazer Pong project team.

When this occurs, the LEDs along the edges of the table flash in synchronization with the beat of the song. This provides a rhythmic pulse that enhances the visual aspect of the table. The color of the LEDs that flash will change depending on which player is currently playing. This color will be the color that represents the current player, and will help provide visual feedback describing which player is to play on the current turn.

The music visualization via the microphone is an interesting and visually appealing effect that adds to the social aspect of the table's function. Cup pong is generally played at parties, so this functionality makes the table more suited for social events by making the table react to the sounds of the party, like the music being played. This feature is separate from the gameplay and brings a unique captivating visual effect without distracting from the game to immerse the user into the game and the social gathering.

5.5.7. Stretch Goals

Some of the aspects of the menu could be enhanced to add to the accessibility and overall user experience. The menu allows the user to select player count, start and end a game, and alternate turns during gameplay. This could be expanded to allow for more customization of the various features of the table. More options for configuration could be added to the menu, such as the ability to switch between different lighting patterns or colors. The menu would consist of a main menu which would have multiple options for the user to select from. Each option would bring the user to a new menu that would display the settings that configure a specific function on the table. The light effects would have a menu to change the lighting patterns to add accessibility to users who potentially have a condition that makes them more sensitive to flashing lights.

Another goal to further enhance the configurability of the table would be to add different lighting effects. The user would select one of the lighting effects by using the menu, and it would change the effects produced by the table when the ball is on it or if a score is made. There would be multiple different lighting effects to choose from and each would allow the user to change the color of the effect. The user would also have the ability to turn the lighting effects off entirely. This would add customizability to the table and enhance the accessibility.

5.5.8. Operational Manual

This section will go over the sequence of operations that the user will perform to use the table. The bulleted list describes each step the user takes to turn the table on, navigate the menu, start a game, and play the game.

- Turn the table on by flipping the power switch located on the power supply unit.
- The table will turn on, and the menu will appear along the table surface.
- Locate the menu and operate it by using the table's surface as a touchscreen and pressing the menu selections displayed by the LEDs. Be sure to use two fingers to choose the selection. Small children may need to use their whole hand.

- Touch the start button on the first screen of the menu. This brings the user to the game settings screen.
- On this screen, select how many players are participating by pressing the appropriate number on the screen.
- Then press the green arrow on the game configuration screen to start the game.
- The first player tosses the ball in an attempt to make it land in the cup.
- If the ball lands in the cup, this player receives a score. If the ball does not land in the cup, no point is scored,
- Once the first player's turn is over, press the alternate turns button, located on the left corner of the table near the user.
- The next player then attempts to score a point.
- Each player continues to attempt to score and alternate the turns until a score of five is reached.
- The winner is determined by which player has the highest score.
- The table then returns to the pre-game state, where the user can start a new game.
- At any time during a game, pressing the end game button located on the right corner of the table near the user will end the current game and bring the table back to the pre-game state.
- When the user is finished using the table, turn the table off by flipping the power switch.

The sequence of events that are done to operate the table is intentionally kept simplistic to allow for greater accessibility and ease of use. For a user to start playing the game, they only need to navigate 2 simple menus, select the number of players, and alternate the turns. All other functions of the table are automated by the software to keep the operation as straightforward as possible.

6. Prototype Build and Test Plan

With Senior Design 2 complete, the build, validation and test plan originally outlined here was executed with incredible success. The optics components of the build were completed on schedule, allowing for ample time to test and adjust the electronics during bring-up. This electronics bring-up constituted the large majority of challenging verification work, as we reached several issues that required PCB revision throughout the semester, with the final revision arriving with only three weeks remaining until the final demonstration. However, since we were able to employ our fabrication firm, JLCPCB, to perform our assembly, none of the original PCB validation and assembly plans were necessary. All of these, including confirmation of our conformation to the relevant standards, were performed by JLCPCB.

Validation of the optics components occurred throughout Senior Design 1 and well into the beginning of Senior Design 2. We found that the vast majority of our components operated correctly, with little fallout. This fallout did occur through the remainder of the project, though, as various sensors and transmitters failed. These were simply replaced with other validated components.

Once all of these component systems had been validated, their assembly began. Assembly began with the table structure, starting with the foundation and working up through the surface display and the laser grid. Once this structure was completed, the electronics were brought up, then connected and secured to the solid table structure. With all of these systems in place, the power supply network was connected, and the build was complete.

At that stage, all that was required was to thoroughly test the device. The key distinction between validation and final testing was that the purpose of this testing was to verify proper high-level functionality. That is, does the device perform its routines as required? It was intended to do this by drafting a set of test plans for each key feature of the device, and performing these tests while observing the software process using a software debug tool. Once the prototype has passed all of these tests, it would be ready for final demonstrations. However, due to delays in PCB bring-up, the final testing was limited to ad-hoc live testing shortly before the demonstration. This was done organically, with our entire group thoroughly operating the device to find and resolve any remaining issues.

6.1. PCB Validation and Assembly

PCB validation and assembly was vastly simplified from our original plan. Once it was discovered that our fabricator could verify, assemble and validate our design all for us, we absolved ourselves of that responsibility. The standards defined in Chapter 4 were still employed, however, as those definitions still held true for our design, and JLCPCB compared our final design, boards, components and joinings to these standards.

The final step in confirming proper assembly and function of the PCB environment was to validate the operation of the MCU. Through SWD, simple logical routines were used to test the controller's ability to operate the GPIO devices, and the correct function was validated with the software debug tool. This was done by first connecting a single GPIO connection to an LED, and toggling this LED. Once this functionality was proven, SPI functionality was verified in stages. First, a single known bit of data was transmitted and received. Then, two alternating bits were transmitted, to ensure we could send both coordinates and receive them in the proper order. Once all of this functionality was achieved, the main software was flashed to the MCU, and its functionality was also verified by the software debug tool. With the knowledge that the MCU and its corresponding PCB environment are functioning fully correctly, the entire embedded electronic system was considered validated.

6.2. Component Validation

Next, the optical components were evaluated. In order to validate the optical components, the signals produced by the receiver components were measured and compared to ensure that all optical receiver components are able to produce the correct output signal before inclusion in the build. This was done by applying the IR laser from one of the appropriate transmitters to the receiver at the maximum distance (4 feet), and recording the steady voltage level. If the receiver is unable to produce within 20% of VDD (2.5v) at a steady level as per the GPIO requirements derived from the microcontroller's datasheet, it will be insufficient for this build [36]. Once 48 acceptable receivers were identified, they were prepared for the build.

In addition to the receivers, the lasers were also validated. A test environment was established where a validated receiver was placed at the maximum distance from the laser, and the laser was shone onto the receiver. If the laser was able to be aligned to the receiver and was able to provide a strong enough optical signal to activate the receiver device, the laser was approved for use. Once 48 of these lasers were validated, correct functionality of the optical components was assured.

After the laser transmitter and receiver components had been validated, it was necessary to validate the LED array. It was especially important to validate the array before it was set into the surface display, as it would become quite difficult to remove once installed. Validation of the LED array was done by applying a simple counting program to flash each colored LED at each LED device along the array in order, and in each color. That way, it would be clear if any of the individual diodes were malfunctioning, or if their logical control is faulty. Once this

LED array had been validated, it was ready for installation into the surface display.

Finally, the power supply network had to be validated. Since the regulators were already validated in the PCB assembly stage, all that remained was to ensure that the PSU outputs the correct 5 volt output at a steady level, and that its maximum current draw is acceptable. Once these two things were validated, the wiring for the power supply network was assembled to ensure that it could be validated as well. No nicks or other major defects were found in the delivery network and the correct levels were observed at its termination points, so the power supply network was fully validated.

6.3. Prototype Build Plan

The Build process began at the very beginning of the semester with the design and assembly of the table surface. Matthew constructed the table with help from tools and workspace provided by his family. He used a solid 4’x4’ plywood slab as the foundation, and installed framing for the game surface inset. He then drilled holes in the base to run the wiring for the LED strings, which had excess wiring that needed to be hidden beneath the table. These strings were fabricated in 100 LED sections, so five 100 LED sections and one 12 LED section were soldered together to form the entire surface display. Power was connected every 200 LEDs, as per the manufacturer’s recommendation, and data was connected at one end of the 512 LED string. Finally, this whole string was placed into the table surface in a snaking pattern, starting at the top-right of the table and snaking lengthwise across the table all the way to the bottom.

The LED isolation grid was fabricated next by cutting sections of balsa wood slats to the desired length, then cutting slits in each slat at 1.5” increments so that they could be intersected into a 4’x2’ grid. Then, each slat was painted black to accentuate the LED lights, and the grid was placed over the game surface. Finally, a 4’x2’ fogged acrylic panel was fixed over the top of this grid, and the table surface build was complete.

While this build was ongoing, electronics bring-up began. The second PCB version was already ordered, and bring-up testing with the first version was underway. Once the table surface build was complete and we were looking towards assembling the laser grid, it was discovered that a third version would be necessary. This version was ordered around this time, and would come in with less than a month left in the project. During this month, SPI testing and bring-up occurred, and the final software versions were finished.

With that, the table foundation construction for the prototype was complete. There was discussion of implementation of a full table structure, including legs, but this was deemed unhelpful for the prototype for one main reason: Unless the legs were collapsible, the higher profile of the full table would be very difficult to transport. A flat table top could be transported easily, and it would suffice to set the table surface atop a lab bench. While any final design would surely include legs, they would only hinder the final purpose of this prototype.

Next, the laser grid foundation was assembled. A plywood riser was constructed around the perimeter of the surface display by cutting two 2'x6"x⅝" rails for the crosswise dimensions, and two 4'x6"x⅝" rails for the lengthwise dimensions. These rails were fixed on each side of the game surface to produce a rail for each side of the perimeter of the play area that was plenty tall enough to support our optical components. Additionally, before the laser grid components could be set into the risers, their connections had to be built. The hot/cold connections already on the laser receivers were stripped to ½" and woven to the power network connections. For the laser receivers, connections to both the power network and the digital I/O pins were made. Jumpers were connected to the pins on these devices, which were soldered to an additional length of wire to reach the electronics for power and data connection.

The optical devices were then placed into holes drilled at 20mm above the surface and 1.5" (roughly 38mm) apart from each other. These devices then had to be aligned, which required adjusting the aperture on the lasers until the resulting bead on the other end was within specifications (<20mm in diameter). The receivers were simply placed into the holes made for them. The lights on the laser receivers were checked to ensure that proper reception was made from the lasers.

With that complete, the table construction was finished. All that remained was to fix the PCB and the PSU to the surface and connect all of the components. By pre-drilling holes for posts and fixing these posts to the table surface and the PCB, the PCB was securely fastened to the table surface. The PSU was mounted using its provided mounting equipment. This ensured that the sensitive power and electronics equipment was not disturbed during use or travel. Once both of these components were fixed to the table surface, the connectors were applied to the pin headers on the PCB and to the terminals of the PSU. At this point, the build was complete.

6.4. Prototype Test Plan

Individual component testing was completed through pre-validation, which occurred before the design build, as described in Chapter 6.2. All optical components were verified to function correctly, the PCB was verified to operate with correct electronic characteristics, and the LED surface display was verified to have full range of color and brightness on each LED. This meant that, once the build was complete, all that remained was to test the interconnection of these components and their overall function. During each of the following operations, the microcontroller was set to debug mode with a debug device connected to the SWD port on the PCB and monitoring the software flow. This debug device ensured that operation logs were available should the device fail any test.

Surface Display Operation Testing

The first major feature to test was the operation of the surface display. This required the application of a simple test protocol to the microcontroller, which simply operated each LED in sequence to ensure that proper addressing and function was achieved with the finalized PCB. The finalized PCB, with support from the Arduino, was able to address each LED and apply each of the primary LED colors, sothe surface display passed testing.

Laser Grid Operation Testing

With the surface display known to function, the next task was to test the operation of the laser grid. This required another test protocol, this time designed to simply activate the LED beneath each intersection along the grid when that intersection is broken. Then, a ping pong ball rolled across the table was used to test each intersection of the grid. The breaking of each intersection in the grid caused each LED to activate, so the grid passed testing. This tested not only the proper device operation of both the lasers and the receivers, but also ensured that the signal was being properly delivered to the microcontroller, the operation of the microcontroller GPIO pins was working as intended, and the SPI connection to the Arduino functioned correctly.

Overall Functionality Testing

Overall functionality testing occurred in two stages. The first stage was a deliberate step-by-step walkthrough of each feature of the device operation as outlined in Chapter 5.5. Multiple test plans may have been needed to confirm holistic function was achieved for each individual feature, but time did not permit this extensive testing. The second stage was mass functionality testing through standard, anticipated operation of the device. This required playing through the device game in every possible combination of settings repeatedly, while ensuring that the device was not mismanaged or damaged from repeated use. This “stress testing” should have revealed any hidden quirks or bugs in the system, and allowed the design team to verify that the intention behind the device design was achieved.

Test Plan Documentation

During the course of Senior Design II, it was intended for each stage of the test process to be assigned a “test plan”. This document would outline the purpose of the testing, the features to be validated, what outcomes would constitute success, the observations made during testing, and the final result (pass/fail). However, we did not have time at the end of the semester to document a regimented validation test plan, so live testing to ensure proper operation during the demonstration had to suffice.

The overall goal of device testing was to ensure that the device function is understood as realistically as is possible. Once device quirks, malfunctions, or bugs were identified, it was deliberated as to how these should be handled. Some could have constituted major functional failures and required overhaul of certain design elements, while others were entirely negligible. In the end, while some glitches and nonconformities were observed in the operation of the device, none were so extreme as to hinder its overall function.

6.5. Required Facilities and Equipment

The build and testing stage of this project required the use of advanced diagnostic equipment and optical design facilities. The following equipment and facilities were used in the second semester of this project:

Electrical Equipment

The most important device for the testing of this build was a debugger, the ST-LINK device. This device used a SWD connection to the board to provide diagnostic information about the operation of both hardware and software on the PCB, as well as assist with first-time operation of the PCB to identify potential shorts or other design errors. Additionally, an oscilloscope was required to measure the signal output from the photoreceivers, and for some analysis on the PCB where the debugger proved insufficient. Finally, a digital multimeter (DMM) was very helpful with in-depth debugging.

Manufacturing Equipment

For the construction of the table frame, a circular or table saw was necessary to cut the plywood. All connections were made using wood screws to fix the frame pieces together. The PCB components and power network connections were made using solder, so soldering equipment was required as well.

The Senior Design Lab

Almost all of the equipment described above was made available to this project by the senior design lab facilities. This lab housed the electrical and optical equipment required, with the exception of the debugger, which was provided by this project group.

7. Administrative Content

7.1. Budget

The budget for our project aimed to incentivize low cost solutions for our desired outcomes, but was not allowed to drastically alter the overall systems performance. The funding for our project was solely the responsibility of our group, since we did not have a sponsor. The table below is the final result of the overall cost of the project.

Table 33: Project Budget.

Item Description	**Quantity**	**Total Estimated Cost**
Photoelectric Tx/Rx Device	$250	$200
LED strip	$100	$120
Table Construction Materials	$200	$200
Microcontroller	$30	$400
PCB/Misc Electronics	$150	
Total	$730	$920

7.2. Project Milestones

All project milestones were met on time until June 30th. From that point on, most milestones were met with between 1 and 7 days of delay, due to a miscalculation in the time required to build the necessary proof of concepts. However, the final deadlines were all met, and the project was delivered on time. Project milestones for Senior Design 2 were much more fluid, as delays affected some parts of the build much stronger than others.

Table 34: Project Milestones for Senior Design 1.

Task	Duration	Status
Senior Design 1		
Brainstorming	May 23rd - 30th	Complete
Project Selection	May 30th	Complete
Initial Documentation	May 30th - June 2nd	Complete
Research Component List	June 5th - June 16th	Complete
Prototype and Proof	June 7th - June 30th	Complete
Chapter 3 Draft	June 7th - June 16th	Complete
Chapters 4 and 5 Draft	June 16th - June 23rd	Complete
60 Page Document	By June 30th	Complete
Schematic Capture	By July 7th	Complete
Bill of Materials	By July 7th	Complete
Chapters 6 and 7 Draft	By July 14th	Complete
Complete Final Report	By July 25th	Complete

Table 35: Project Milestones for Senior Design 2.

Task	Duration	Status
Senior Design 2		
PCB Assembly 1	Oct. 2nd - 9th	Complete
Testing and Redesign 1	By October 13th	Complete
PCB Assembly 2	Oct. 13th - Oct. 20th	Complete
Testing and Redesign 2	By November 7th	Complete
Surface Build	By Oct. 25th	Complete
Laser Grid Build	By Nov. 23rd	Complete
PCB Assembly 3	Nov. 7th - Nov. 15th	Complete
Final PCB Testing	By December 1st	Complete

Appendix A - References

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Appendix B - Overall Schematic

Due to the complexity of the overall schematic, the electronics were black-boxed in the schematic. The PCB schematic and design are available in Appendix C.

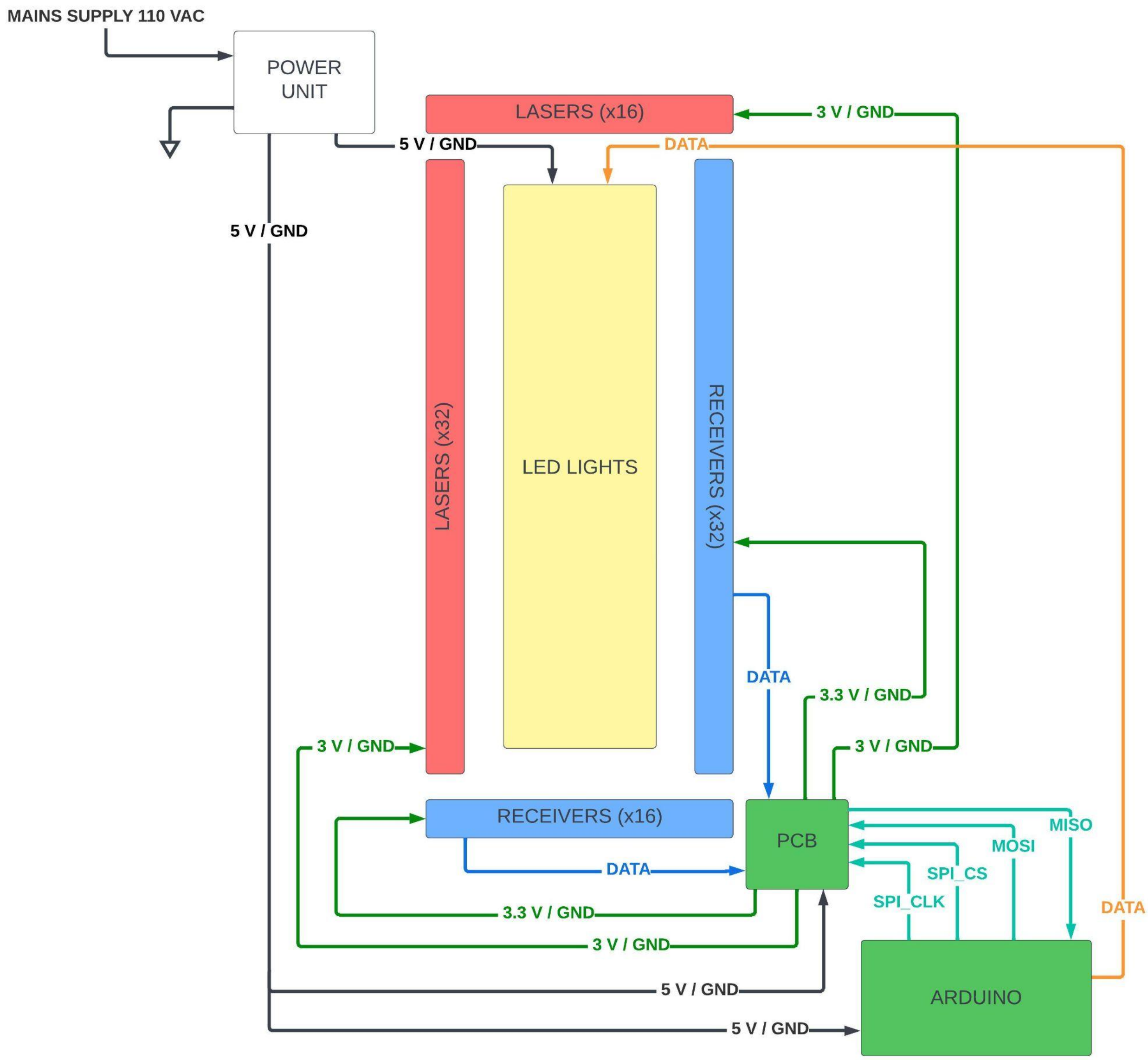

Fig. XX: Overall Schematic

Appendix C - PCB Schematic and Design

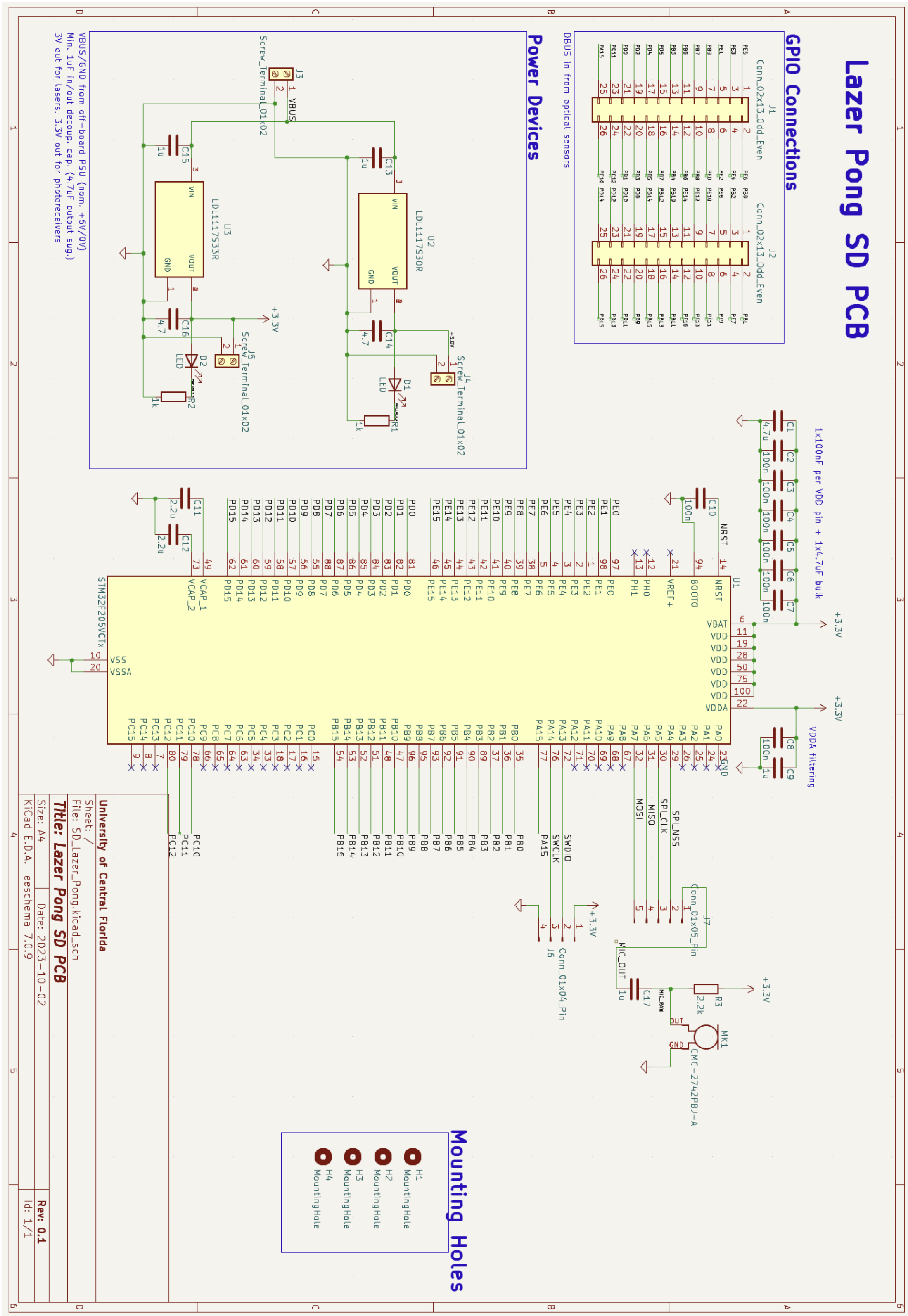

Fig. XX: PCB Schematic. Image provided by Lazer Pong project team.

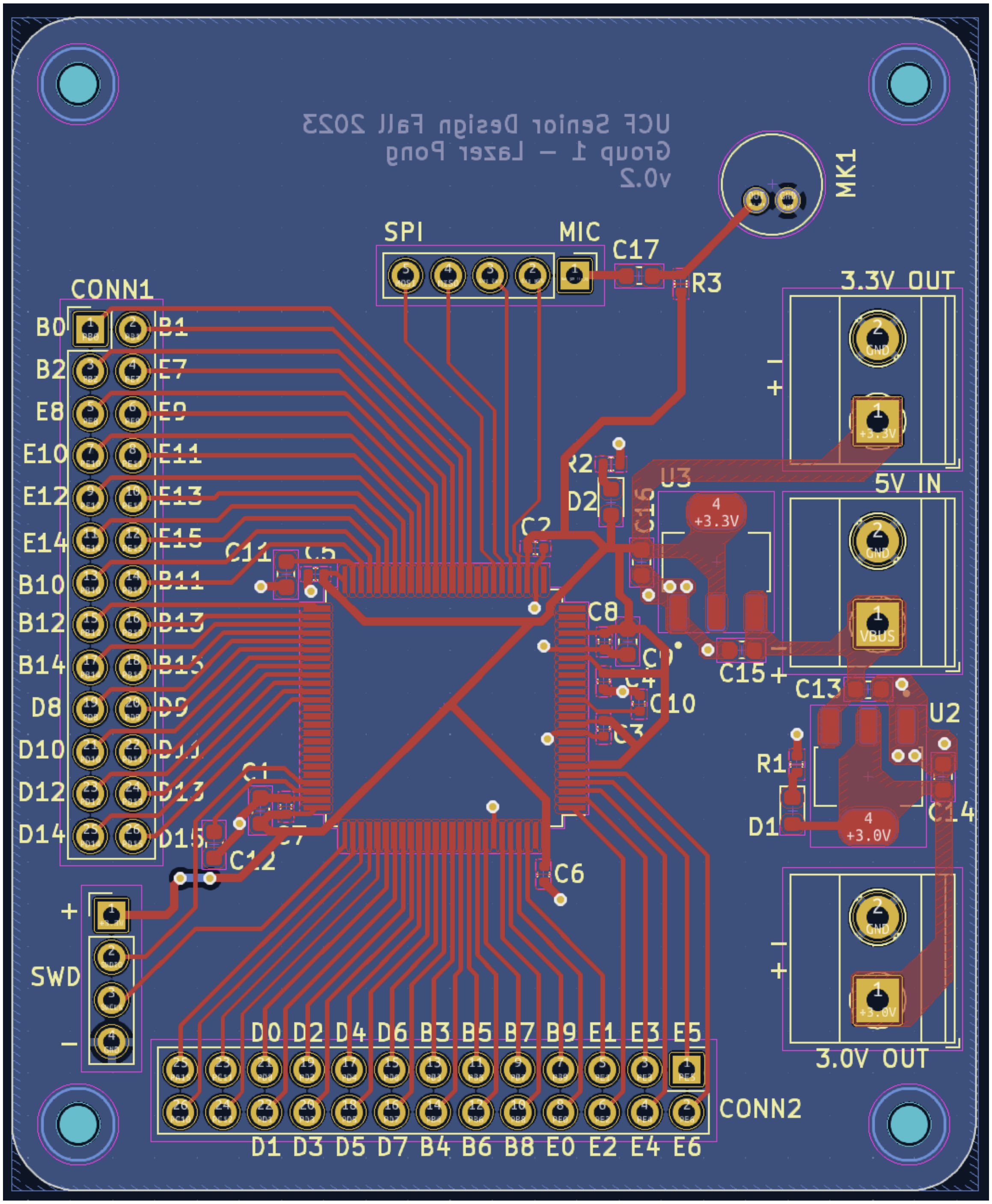

Fig. XX: PCB Design. Image provided by Lazer Pong project team.

Appendix D - Software Code

D.1 Arduino Code

```
//Senior Design 2 Group 1 Fall 2023
//Laser Pong Table Arduino Code
//Handles the graphics and gamestate of the Laser Pong table

#include <FastLED.h>
#include <SPI.h>
#define NUM_LEDS 512
#define LED_PIN 5 //How boring and obvious!
#define COLOR_ORDER GRB //Green (G), Red (R), Blue (B)
#define CHIPSET WS2812B
#define BRIGHTNESS 60
#define VOLTS 5
#define MAX_AMPS 500 //value in milliamps
#define NUMPINS 32

//cup and button locations
#define ENDGAMEBUTTON 450
#define NEXTTURNBUTTON 61
#define STARTGAMEBUTTON 321
#define ONE_PLAYER 454
#define TWO_PLAYER 326
#define THREE_PLAYER 198
#define FOUR_PLAYER 70
#define CUP_1 478
#define CUP_2 350
#define CUP_3 222
#define CUP_4 94
#define CUP_5 412
#define CUP_6 284
#define CUP_7 156
#define CUP_8 346
#define CUP_9 218
#define CUP_10 280

// Params for width and height
```

```
const uint8_t kMatrixWidth = 16;
const uint8_t kMatrixHeight = 32;

//global variables
int buffer[2] = {16, 32};       //initial location data buffer
int breakloc[2] = {16, 32};     //second buffer used to check validity
int valid_index=0;              //Final buffer used to check validity
int numPlayers = 0;             //number of players
int score[4] = {0, 0, 0, 0};    //array to hold player scores
int state=0;                    //current state of table
int x_index = 0;                //x index in breakloc buffer
int y_index = 1;                //y index in breakloc buffer
int currentPlayer=1;            //current player


CRGB leds[NUM_LEDS]; //LED array

//colors for players
CRGB blue = CRGB::Blue; //player1
CRGB red = CRGB::Red; //player2
CRGB purple = CRGB(128, 0, 128); //player3
CRGB green = CRGB::Green; //player4

//function declariations
void registerReset();                                       //reset location
registers
uint16_t XY (uint16_t x, uint16_t y);                      //1d led array to
2d led matrix
void receiveSTM();                                         //receive spi data
from stm
void gameState();                                         //game state
void scoreScreen();                                       //score gfx
void startMenu();                                         //start menu
int playerSelect();                                          //Select num of
players
void gameButtons(int x, int y);                              //next turn and
end game gfx
void numbers(int i, CRGB color, int x, int y);            //number gfx
void scoreBoard(int player, int score, int x, int y);    //scoreboard gfx
```

```
void pointScored(int x, int y);                          //point scored
screen
void gameOver(int x, int y);                         //game over gfx
void winner(int player, int x, int y);                  //determines and
displays winner
void endGameScreen();                                     //displays
gameOver and winner gfx
void firework(int x, int y);                         //firework effect

void setup() {
  //initialize leds
  FastLED.addLeds<CHIPSET,LED_PIN,COLOR_ORDER>(leds,NUM_LEDS);
  FastLED.setMaxPowerInVoltsAndMilliamps(VOLTS,MAX_AMPS);
  FastLED.setBrightness(BRIGHTNESS);
  FastLED.clear();
  FastLED.show();

  Serial.begin(115200);

  //initialize SPI
  SPI.begin(10);
  SPI.setClockDivider(10, 84);

}

void loop() {
  receiveSTM();                        //Receive data from MCU via SPI

  switch (state) {
    case 0:                            //start menu
      score[0]=0;
      score[1]=0;
      score[2]=0;
      score[3]=0;
      currentPlayer=1;
      Serial.println("Start Menu");
      startMenu();
      break;
    case 1:                            //player count select
```

```
      Serial.println("Player Select");
      playerSelect();
      break;
    case 2:                                   //game state
      Serial.println("Game State");
      gameState();
      break;
    case 3:                                   //game over
      Serial.println("Game Over");
      endGameScreen();
      break;
    case 4:                                   //score
      scoreScreen();
      break;
    default:
      break;
  }

  //illuminate break location
  leds[XY_inputArr(breakloc[0], breakloc[1])] = CRGB::White;
  FastLED.show();

  delay(50);


}

//resets registers for holding location data, use after button presses
void registerReset() {
  valid_index = 512;
  buffer[0] = 16;
  buffer[1] = 32;
  breakloc[0] = 16;
  breakloc[0] = 32;
}

//function to convert 2d led array data to 1d index
uint16_t XY (uint16_t x, uint16_t y) {
  // any out of bounds address maps to the first hidden pixel
```

```
  if ( (x >= kMatrixWidth) || (y >= kMatrixHeight) ) {
    return (NUM_LEDS);
  }

  const uint16_t XYTable[] = {
    480, 479, 416, 415, 352, 351, 288, 287, 224, 223, 160, 159,  96,  95,
32,  31,
    481, 478, 417, 414, 353, 350, 289, 286, 225, 222, 161, 158,  97,  94,
33,  30,
    482, 477, 418, 413, 354, 349, 290, 285, 226, 221, 162, 157,  98,  93,
34,  29,
    483, 476, 419, 412, 355, 348, 291, 284, 227, 220, 163, 156,  99,  92,
35,  28,
    484, 475, 420, 411, 356, 347, 292, 283, 228, 219, 164, 155, 100,  91,
36,  27,
    485, 474, 421, 410, 357, 346, 293, 282, 229, 218, 165, 154, 101,  90,
37,  26,
    486, 473, 422, 409, 358, 345, 294, 281, 230, 217, 166, 153, 102,  89,
38,  25,
    487, 472, 423, 408, 359, 344, 295, 280, 231, 216, 167, 152, 103,  88,
39,  24,
    488, 471, 424, 407, 360, 343, 296, 279, 232, 215, 168, 151, 104,  87,
40,  23,
    489, 470, 425, 406, 361, 342, 297, 278, 233, 214, 169, 150, 105,  86,
41,  22,
    490, 469, 426, 405, 362, 341, 298, 277, 234, 213, 170, 149, 106,  85,
42,  21,
    491, 468, 427, 404, 363, 340, 299, 276, 235, 212, 171, 148, 107,  84,
43,  20,
    492, 467, 428, 403, 364, 339, 300, 275, 236, 211, 172, 147, 108,  83,
44,  19,
    493, 466, 429, 402, 365, 338, 301, 274, 237, 210, 173, 146, 109,  82,
45,  18,
    494, 465, 430, 401, 366, 337, 302, 273, 238, 209, 174, 145, 110,  81,
46,  17,
    495, 464, 431, 400, 367, 336, 303, 272, 239, 208, 175, 144, 111,  80,
47,  16,
    496, 463, 432, 399, 368, 335, 304, 271, 240, 207, 176, 143, 112,  79,
48,  15,
```

```
    497, 462, 433, 398, 369, 334, 305, 270, 241, 206, 177, 142, 113,  78,
49,  14,
    498, 461, 434, 397, 370, 333, 306, 269, 242, 205, 178, 141, 114,  77,
50,  13,
    499, 460, 435, 396, 371, 332, 307, 268, 243, 204, 179, 140, 115,  76,
51,  12,
    500, 459, 436, 395, 372, 331, 308, 267, 244, 203, 180, 139, 116,  75,
52,  11,
    501, 458, 437, 394, 373, 330, 309, 266, 245, 202, 181, 138, 117,  74,
53,  10,
    502, 457, 438, 393, 374, 329, 310, 265, 246, 201, 182, 137, 118,  73,
54,   9,
    503, 456, 439, 392, 375, 328, 311, 264, 247, 200, 183, 136, 119,  72,
55,   8,
    504, 455, 440, 391, 376, 327, 312, 263, 248, 199, 184, 135, 120,  71,
56,   7,
    505, 454, 441, 390, 377, 326, 313, 262, 249, 198, 185, 134, 121,  70,
57,   6,
    506, 453, 442, 389, 378, 325, 314, 261, 250, 197, 186, 133, 122,  69,
58,   5,
    507, 452, 443, 388, 379, 324, 315, 260, 251, 196, 187, 132, 123,  68,
59,   4,
    508, 451, 444, 387, 380, 323, 316, 259, 252, 195, 188, 131, 124,  67,
60,   3,
    509, 450, 445, 386, 381, 322, 317, 258, 253, 194, 189, 130, 125,  66,
61,   2,
    510, 449, 446, 385, 382, 321, 318, 257, 254, 193, 190, 129, 126,  65,
62,   1,
    511, 448, 447, 384, 383, 320, 319, 256, 255, 192, 191, 128, 127,  64,
63,   0
  };

  uint16_t i = (y * kMatrixWidth) + x;
  uint16_t j = XYTable[i];
  return j;
}

uint16_t XY_inputArr (uint16_t x, uint16_t y) {
  // any out of bounds address maps to the first hidden pixel
```

```
  if ( (x >= kMatrixWidth) || (y >= kMatrixHeight) ) {
    return (NUM_LEDS);
  }

  const uint16_t XYTable[] = {
     0,  63,  64, 127, 128, 191, 192, 255, 256, 319, 320, 383, 384, 447,
448, 511,
     1,  62,  65, 126, 129, 190, 193, 254, 257, 318, 321, 382, 385, 446,
449, 510,
     2,  61,  66, 125, 130, 189, 194, 253, 258, 317, 322, 381, 386, 445,
450, 509,
     3,  60,  67, 124, 131, 188, 195, 252, 259, 316, 323, 380, 387, 444,
451, 508,
     4,  59,  68, 123, 132, 187, 196, 251, 260, 315, 324, 379, 388, 443,
452, 507,
     5,  58,  69, 122, 133, 186, 197, 250, 261, 314, 325, 378, 389, 442,
453, 506,
     6,  57,  70, 121, 134, 185, 198, 249, 262, 313, 326, 377, 390, 441,
454, 505,
     7,  56,  71, 120, 135, 184, 199, 248, 263, 312, 327, 376, 391, 440,
455, 504,
     8,  55,  72, 119, 136, 183, 200, 247, 264, 311, 328, 375, 392, 439,
456, 503,
     9,  54,  73, 118, 137, 182, 201, 246, 265, 310, 329, 374, 393, 438,
457, 502,
    10,  53,  74, 117, 138, 181, 202, 245, 266, 309, 330, 373, 394, 437,
458, 501,
    11,  52,  75, 116, 139, 180, 203, 244, 267, 308, 331, 372, 395, 436,
459, 500,
    12,  51,  76, 115, 140, 179, 204, 243, 268, 307, 332, 371, 396, 435,
460, 499,
    13,  50,  77, 114, 141, 178, 205, 242, 269, 306, 333, 370, 397, 434,
461, 498,
    14,  49,  78, 113, 142, 177, 206, 241, 270, 305, 334, 369, 398, 433,
462, 497,
    15,  48,  79, 112, 143, 176, 207, 240, 271, 304, 335, 368, 399, 432,
463, 496,
    16,  47,  80, 111, 144, 175, 208, 239, 272, 303, 336, 367, 400, 431,
464, 495,
```

```
    17,  46,  81, 110, 145, 174, 209, 238, 273, 302, 337, 366, 401, 430,
465, 494,
    18,  45,  82, 109, 146, 173, 210, 237, 274, 301, 338, 365, 402, 429,
466, 493,
    19,  44,  83, 108, 147, 172, 211, 236, 275, 300, 339, 364, 403, 428,
467, 492,
    20,  43,  84, 107, 148, 171, 212, 235, 276, 299, 340, 363, 404, 427,
468, 491,
    21,  42,  85, 106, 149, 170, 213, 234, 277, 298, 341, 362, 405, 426,
469, 490,
    22,  41,  86, 105, 150, 169, 214, 233, 278, 297, 342, 361, 406, 425,
470, 489,
    23,  40,  87, 104, 151, 168, 215, 232, 279, 296, 343, 360, 407, 424,
471, 488,
    24,  39,  88, 103, 152, 167, 216, 231, 280, 295, 344, 359, 408, 423,
472, 487,
    25,  38,  89, 102, 153, 166, 217, 230, 281, 294, 345, 358, 409, 422,
473, 486,
    26,  37,  90, 101, 154, 165, 218, 229, 282, 293, 346, 357, 410, 421,
474, 485,
    27,  36,  91, 100, 155, 164, 219, 228, 283, 292, 347, 356, 411, 420,
475, 484,
    28,  35,  92,  99, 156, 163, 220, 227, 284, 291, 348, 355, 412, 419,
476, 483,
    29,  34,  93,  98, 157, 162, 221, 226, 285, 290, 349, 354, 413, 418,
477, 482,
    30,  33,  94,  97, 158, 161, 222, 225, 286, 289, 350, 353, 414, 417,
478, 481,
    31,  32,  95,  96, 159, 160, 223, 224, 287, 288, 351, 352, 415, 416,
479, 480
  };

  uint16_t i = (y * kMatrixWidth) + x;
  uint16_t j = XYTable[i];
  return j;
}

//receive data from stm mcu via spi
void receiveSTM() {
```

```
  //transfer data via spi
 for (int i=0; i<2; i++) {
    buffer[i] = SPI.transfer(10, 0x00);
    delay(1);
  }

  //if x index > 16, flip x and y to resolve timing issues
  if (buffer[x_index] > 16) {
    int temp = x_index;
    x_index = y_index;
    y_index = temp;
  }

  //received buf invalid, keep loc same
  if ((buffer[0] != 0) && (buffer[1] != 0)) {
      //if breakloc does not equal previous breakloc, make new location
breakloc. if that location is still valid, make it = valid_index
          if   ((breakloc[0]   !=   buffer[x_index])   ||   (breakloc[1]   !=
buffer[y_index])) {
        leds[XY_inputArr(breakloc[0],breakloc[1])] = CRGB::Black;   //turn
previous loc led off
      breakloc[0] = buffer[x_index];
      breakloc[1] = buffer[y_index];
      valid_index=512;
    }
    else valid_index=XY_inputArr(breakloc[0], breakloc[1]);

  }

}

//function to control the game state
void gameState() {

    //if player reaches 5 points, game is over
    for (int i=0; i<4; i++){
      if(score[i] == 5) {
      state = 3;
```

```
     }
    }

     //if current player is higher than the number of players, go back to
player one
    if (currentPlayer>numPlayers) {
      currentPlayer=1;
    }

    //show game board
    scoreBoard(currentPlayer, score[currentPlayer-1], 5, 8);
    gameButtons(0, 28);
    FastLED.show();



    //end game button
    if (valid_index == ENDGAMEBUTTON) {
      endGameScreen();
      registerReset();

    }

    //next turn button
    if (valid_index == NEXTTURNBUTTON) {
      Serial.println("Next Turn");
      currentPlayer++;
      FastLED.clear();
      if (currentPlayer>numPlayers) {
      currentPlayer=1;
    }
      scoreBoard(currentPlayer, score[currentPlayer-1], 5, 8);
      FastLED.show();
      registerReset();
      delay(1000);
    }

     //if score made show score screen, increment player score, and player
num
```

```
     if ((valid_index == CUP_1) || (valid_index == CUP_2) || (valid_index
== CUP_3) || (valid_index == CUP_4) ||
     (valid_index == CUP_5) || (valid_index == CUP_6) || (valid_index ==
CUP_7) ||
    (valid_index == CUP_8) || (valid_index == CUP_9) ||
    (valid_index == CUP_10)) {
      Serial.print("Point Scored: ");
      Serial.print(valid_index);
      Serial.println();


      registerReset();

      score[currentPlayer-1] = score[currentPlayer-1] + 1;
         //set score
      FastLED.clear();

      state = 4; //scoreScreen

    }

}

//screen that is displayed when score is made
void scoreScreen() {

      pointScored(0, 8);
      gameButtons(0, 28);
      FastLED.show();

        //end game button
        if (valid_index == ENDGAMEBUTTON) {
          endGameScreen();
          registerReset();

        }

        //next turn button
        if (valid_index == NEXTTURNBUTTON) {
```

```
          Serial.println("Next Turn");
          currentPlayer++;
          FastLED.clear();
          if (currentPlayer>numPlayers) {
          currentPlayer=1;
        }
          scoreBoard(currentPlayer, score[currentPlayer-1], 5, 8);
          FastLED.show();
          registerReset();

           state = 2; //gamestate
          delay(1000);

        }

}

//displays the start menu
void startMenu()
{
  FastLED.clear();
  int x = 0;
  int y = 8;

  //line
  for (int i=0; i<kMatrixWidth; i++){
    leds[XY(i+x, 0+y)]= CRGB::Red;
    leds[XY(i+x, 8+y)]= CRGB::Red;
  }

  //S
  leds[XY(1+x, 2+y)] = CRGB::Blue;
  leds[XY(2+x, 2+y)] = CRGB::Blue;
  leds[XY(0+x,3+y)] = CRGB::Blue;
  leds[XY(0+x, 4+y)] = CRGB::Blue;
  leds[XY(1+x,4+y)] = CRGB::Blue;
  leds[XY(2+x,4+y)] = CRGB::Blue;
  leds[XY(2+x,5+y)] = CRGB::Blue;
  leds[XY(1+x,6+y)] = CRGB::Blue;
```

```
leds[XY(0+x,6+y)] = CRGB::Blue;
//T
leds[XY(3+x,2+y)] = CRGB::Blue;
leds[XY(4+x,2+y)] = CRGB::Blue;
leds[XY(5+x,2+y)] = CRGB::Blue;
leds[XY(4+x,3+y)] = CRGB::Blue;
leds[XY(4+x,4+y)] = CRGB::Blue;
leds[XY(4+x,5+y)] = CRGB::Blue;
leds[XY(4+x,6+y)] = CRGB::Blue;
//A
leds[XY(7+x,2+y)] = CRGB::Blue;
leds[XY(6+x,3+y)] = CRGB::Blue;
leds[XY(8+x,3+y)] = CRGB::Blue;
leds[XY(6+x,4+y)] = CRGB::Blue;
leds[XY(7+x,4+y)] = CRGB::Blue;
leds[XY(8+x,4+y)] = CRGB::Blue;
leds[XY(6+x,5+y)] = CRGB::Blue;
leds[XY(8+x,5+y)] = CRGB::Blue;
leds[XY(6+x,6+y)] = CRGB::Blue;
leds[XY(8+x,6+y)] = CRGB::Blue;
//R
leds[XY(10+x,2+y)] = CRGB::Blue;
leds[XY(10+x,3+y)] = CRGB::Blue;
leds[XY(10+x,4+y)] = CRGB::Blue;
leds[XY(10+x,5+y)] = CRGB::Blue;
leds[XY(10+x,6+y)] = CRGB::Blue;
leds[XY(11+x,2+y)] = CRGB::Blue;
leds[XY(12+x,3+y)] = CRGB::Blue;
leds[XY(11+x,4+y)] = CRGB::Blue;
leds[XY(12+x,5+y)] = CRGB::Blue;
leds[XY(12+x,6+y)] = CRGB::Blue;
//T
leds[XY(13+x,2+y)] = CRGB::Blue;
leds[XY(14+x,2+y)] = CRGB::Blue;
leds[XY(15+x,2+y)] = CRGB::Blue;
leds[XY(14+x,3+y)] = CRGB::Blue;
leds[XY(14+x,4+y)] = CRGB::Blue;
leds[XY(14+x,5+y)] = CRGB::Blue;
leds[XY(14+x,6+y)] = CRGB::Blue;
```

```
  leds[STARTGAMEBUTTON] = CRGB::Blue;

  //location of start button
  if (valid_index == STARTGAMEBUTTON) {
    FastLED.clear();
    registerReset();
    state = 1;


  }

}

//displays player select screen. select how many players are playing
int playerSelect()
{
  FastLED.clear();
  int x = 0;
  int y = 8;

  //Line
  for (int i=0; i<kMatrixWidth; i++) leds[XY(i+x, 5+y)] = CRGB::Red;

  //#
  for (int i=0; i<5; i++) leds[XY(0+x,i+y)] = CRGB::Blue;
  for (int i=0; i<5; i++) {
    if (i % 2 != 0) leds[XY(1+x,i+y)] = CRGB::Blue;
  }
  for (int i=0; i<5; i++) leds[XY(2+x,i+y)] = CRGB::Blue;

  //P
  leds[XY(4+x,0+y)] = CRGB::Blue;
  leds[XY(4+x,1+y)] = CRGB::Blue;
  leds[XY(4+x,2+y)] = CRGB::Blue;
  leds[XY(4+x,3+y)] = CRGB::Blue;
  leds[XY(4+x,4+y)] = CRGB::Blue;
  leds[XY(5+x,0+y)] = CRGB::Blue;
  leds[XY(6+x,1+y)] = CRGB::Blue;
```

```
leds[XY(5+x,2+y)] = CRGB::Blue;

//L
for (int i=0; i<5; i++) leds[XY(7+x,i+y)] = CRGB::Blue;
for (int i=0; i<3; i++) leds[XY(7+i+x,4+y)] = CRGB::Blue;

//Y
leds[XY(10+x,0+y)] = CRGB::Blue;
leds[XY(12+x,0+y)] = CRGB::Blue;
leds[XY(10+x,1+y)] = CRGB::Blue;
leds[XY(12+x,1+y)] = CRGB::Blue;
leds[XY(11+x,2+y)] = CRGB::Blue;
leds[XY(11+x,3+y)] = CRGB::Blue;
leds[XY(11+x,4+y)] = CRGB::Blue;

//R
leds[XY(13+x,0+y)] = CRGB::Blue;
leds[XY(13+x,1+y)] = CRGB::Blue;
leds[XY(13+x,2+y)] = CRGB::Blue;
leds[XY(13+x,3+y)] = CRGB::Blue;
leds[XY(13+x,4+y)] = CRGB::Blue;
leds[XY(14+x,0+y)] = CRGB::Blue;
leds[XY(15+x,1+y)] = CRGB::Blue;
leds[XY(14+x,2+y)] = CRGB::Blue;
leds[XY(15+x,3+y)] = CRGB::Blue;
leds[XY(15+x,4+y)] = CRGB::Blue;

  numbers(1, blue, 1, 17);
  numbers(2, green, 5, 17);
  numbers(3, red, 9, 17);
  numbers(4, purple, 13, 17);

  leds[ONE_PLAYER] = CRGB::Blue;
  leds[TWO_PLAYER] = CRGB::Blue;
  leds[THREE_PLAYER] = CRGB::Blue;
  leds[FOUR_PLAYER] = CRGB::Blue;



//locations of player num select buttons
```

```
  if (valid_index == ONE_PLAYER) {       //one player
    numPlayers=1;
    FastLED.clear();
    registerReset();
    state = 2;
  }
  if (valid_index == TWO_PLAYER) {       //two players
    numPlayers=2;
    FastLED.clear();
    registerReset();
    state = 2;
  }
  if (valid_index == THREE_PLAYER) {       //three players
    numPlayers=3;
    FastLED.clear();
    registerReset();
    state = 2;
  }
  if (valid_index == FOUR_PLAYER) {      //four players
    numPlayers=4;
    FastLED.clear();
    registerReset();
    state = 2;
  }


}

//graphics for game buttons
void gameButtons(int x, int y)
{



  //end game
  leds[XY(0+x, 0+y)] = CRGB::Red;
  leds[XY(0+x, 2+y)] = CRGB::Red;
  leds[XY(1+x, 1+y)] = CRGB::Red;
  leds[XY(2+x, 0+y)] = CRGB::Red;
  leds[XY(2+x, 2+y)] = CRGB::Red;
```

```
  //next turn

  leds[XY(14+x, 0+y)] = CRGB::Green;
  leds[XY(13+x, 1+y)] = CRGB::Green;
  leds[XY(15+x, 1+y)] = CRGB::Green;
  leds[XY(14+x, 2+y)] = CRGB::Green;

}

//graphics for numbers
void numbers(int i, CRGB color, int x, int y)
{


  //0
  if (i == 0)
  {
  leds[XY(1+x, 0+y)] = color;
  leds[XY(0+x, 1+y)] = color;
  leds[XY(0+x, 2+y)] = color;
  leds[XY(0+x, 3+y)] = color;
  leds[XY(1+x, 4+y)] = color;
  leds[XY(2+x, 1+y)] = color;
  leds[XY(2+x, 2+y)] = color;
  leds[XY(2+x, 3+y)] = color;
  }

  if (i == 1)
  {
    leds[XY(0+x, 1+y)] = color;
    leds[XY(1+x, 0+y)] = color;
    leds[XY(1+x, 1+y)] = color;
    leds[XY(1+x, 2+y)] = color;
    leds[XY(1+x, 3+y)] = color;
    leds[XY(1+x, 4+y)] = color;
    leds[XY(0+x, 4+y)] = color;
    leds[XY(2+x, 4+y)] = color;
  }
```

```
if (i == 2)
{
  leds[XY(0+x, 0+y)] = color;
  leds[XY(1+x, 0+y)] = color;
  leds[XY(2+x, 1+y)] = color;
  leds[XY(2+x, 2+y)] = color;
  leds[XY(1+x, 2+y)] = color;
  leds[XY(0+x, 3+y)] = color;
  leds[XY(0+x, 4+y)] = color;
  leds[XY(1+x, 4+y)] = color;
  leds[XY(2+x, 4+y)] = color;
}

if (i == 3)
{
  for (int j=0; j<5; j++) leds[XY(2+x, j+y)] = color;
  leds[XY(1+x, 0+y)] = color;
  leds[XY(0+x, 0+y)] = color;
  leds[XY(1+x, 2+y)] = color;
  leds[XY(1+x, 4+y)] = color;
  leds[XY(0+x, 4+y)] = color;
}

if (i == 4)
{
  leds[XY(0+x, 0+y)] = color;
  leds[XY(0+x, 1+y)] = color;
  leds[XY(2+x, 1+y)] = color;
  leds[XY(0+x, 2+y)] = color;
  leds[XY(1+x, 2+y)] = color;
  leds[XY(2+x, 2+y)] = color;
  leds[XY(2+x, 3+y)] = color;
  leds[XY(2+x, 4+y)] = color;
}

if (i == 5)
{
  leds[XY(0+x, 0+y)] = color;
```

```
    leds[XY(1+x, 0+y)] = color;
    leds[XY(2+x, 0+y)] = color;
    leds[XY(0+x, 1+y)] = color;
    leds[XY(0+x, 2+y)] = color;
    leds[XY(1+x, 2+y)] = color;
    leds[XY(2+x, 3+y)] = color;
    leds[XY(0+x, 4+y)] = color;
    leds[XY(1+x, 4+y)] = color;
  }

  if (i == 6)
  {
    for (int j=0; j<5; j++) leds[XY(0+x, j+y)] = color;
    leds[XY(1+x, 0+y)] = color;
    leds[XY(1+x, 2+y)] = color;
    leds[XY(2+x, 2+y)] = color;
    leds[XY(2+x, 3+y)] = color;
    leds[XY(1+x, 4+y)] = color;
    leds[XY(2+x, 4+y)] = color;
  }

  if (i == 7)
  {
    for (int j=0; j<5; j++) leds[XY(2+x, j+y)] = color;
    for (int j=0; j<2; j++) leds[XY(j+x, 0+y)] = color;
  }

  if (i == 8)
  {
    for (int j=0; j<5; j++) leds[XY(2+x, j+y)] = color;
    for (int j=0; j<5; j++) leds[XY(0+x, j+y)] = color;
    for (int j=0; j<5; j+=2) leds[XY(1+x, j+y)] = color;
  }

  if (i == 9)
  {
    for (int j=0; j<3; j++) leds[XY(j+x, 0+y)] = color;
    for (int j=0; j<3; j++) leds[XY(j+x, 2+y)] = color;
    leds[XY(0+x, 1+y)] = color;
```

```
    for (int j=0; j<5; j++) leds[XY(2+x, j+y)] = color;
  }

}

//graphics for score board and cup locations
void scoreBoard(int player, int score, int x, int y)
{
  FastLED.clear();
  //cup locations
  leds[CUP_1] = CRGB::White;
  leds[CUP_2] = CRGB::White;
  leds[CUP_3] = CRGB::White;
  leds[CUP_4] = CRGB::White;

  leds[CUP_5] = CRGB::White;
  leds[CUP_6] = CRGB::White;
  leds[CUP_7] = CRGB::White;

  leds[CUP_8] = CRGB::White;
  leds[CUP_9] = CRGB::White;

  leds[CUP_10] = CRGB::White;


  //P
  leds[XY(0+x,0+y)] = CRGB::Red;
  leds[XY(0+x,1+y)] = CRGB::Red;
  leds[XY(0+x,2+y)] = CRGB::Red;
  leds[XY(0+x,3+y)] = CRGB::Red;
  leds[XY(0+x,4+y)] = CRGB::Red;
  leds[XY(1+x,0+y)] = CRGB::Red;
  leds[XY(2+x,1+y)] = CRGB::Red;
  leds[XY(1+x,2+y)] = CRGB::Red;
  if (player == 1) {
    numbers(player, blue, x+4, y);
  }
  if (player == 2) {
    numbers(player, green, x+4, y);
```

```
  }
  if (player == 3) {
    numbers(player, red, x+4, y);
  }
  if (player == 4) {
    numbers(player, purple, x+4, y);
  }
  numbers(score, blue, x+2, y+6);

}

//screen played when score is made
void pointScored(int x, int y)
{
  FastLED.clear();
  //S
  leds[XY(1+x, 0+y)] = CRGB::Blue;
  leds[XY(2+x, 0+y)] = CRGB::Blue;
  leds[XY(0+x,1+y)] = CRGB::Blue;
  leds[XY(0+x, 2+y)] = CRGB::Blue;
  leds[XY(1+x,2+y)] = CRGB::Blue;
  leds[XY(2+x,2+y)] = CRGB::Blue;
  leds[XY(2+x,3+y)] = CRGB::Blue;
  leds[XY(1+x,4+y)] = CRGB::Blue;
  leds[XY(0+x,4+y)] = CRGB::Blue;

  //C
  leds[XY(4+x, 0+y)] = CRGB::Red;
  leds[XY(5+x, 0+y)] = CRGB::Red;
  leds[XY(3+x, 1+y)] = CRGB::Red;
  leds[XY(3+x, 2+y)] = CRGB::Red;
  leds[XY(3+x, 3+y)] = CRGB::Red;
  leds[XY(4+x, 4+y)] = CRGB::Red;
  leds[XY(5+x, 4+y)] = CRGB::Red;

  //O
  leds[XY(7+x, 0+y)] = CRGB::Blue;
  leds[XY(6+x, 0+y)] = CRGB::Blue;
  leds[XY(6+x, 1+y)] = CRGB::Blue;
```

```
  leds[XY(6+x, 2+y)] = CRGB::Blue;
  leds[XY(6+x, 3+y)] = CRGB::Blue;
  leds[XY(6+x, 4+y)] = CRGB::Blue;
  leds[XY(7+x, 4+y)] = CRGB::Blue;
  leds[XY(8+x, 0+y)] = CRGB::Blue;
  leds[XY(8+x, 1+y)] = CRGB::Blue;
  leds[XY(8+x, 2+y)] = CRGB::Blue;
  leds[XY(8+x, 3+y)] = CRGB::Blue;
  leds[XY(8+x, 4+y)] = CRGB::Blue;

  //R
  leds[XY(9+x,0+y)] = CRGB::Red;
  leds[XY(9+x,1+y)] = CRGB::Red;
  leds[XY(9+x,2+y)] = CRGB::Red;
  leds[XY(9+x,3+y)] = CRGB::Red;
  leds[XY(9+x,4+y)] = CRGB::Red;
  leds[XY(10+x,0+y)] = CRGB::Red;
  leds[XY(11+x,1+y)] = CRGB::Red;
  leds[XY(10+x,2+y)] = CRGB::Red;
  leds[XY(11+x,3+y)] = CRGB::Red;
  leds[XY(11+x,4+y)] = CRGB::Red;

  //E
  leds[XY(12+x, 0+y)] = CRGB::Blue;
  leds[XY(13+x, 0+y)] = CRGB::Blue;
  leds[XY(14+x, 0+y)] = CRGB::Blue;
  leds[XY(12+x, 1+y)] = CRGB::Blue;
  leds[XY(12+x, 2+y)] = CRGB::Blue;
  leds[XY(13+x, 2+y)] = CRGB::Blue;
  leds[XY(12+x, 3+y)] = CRGB::Blue;
  leds[XY(12+x, 4+y)] = CRGB::Blue;
  leds[XY(13+x, 4+y)] = CRGB::Blue;
  leds[XY(14+x, 4+y)] = CRGB::Blue;

  //!
  for (int i=0; i<3; i++) leds[XY(15+x,i+y)] = CRGB::Red;
  leds[XY(15+x,4+y)] = CRGB::Red;

}
```

```
//displayed when game is over
void gameOver(int x, int y)
{

  //G
  leds[XY(0+x, 0+y)] = CRGB::Blue;
  leds[XY(1+x, 0+y)] = CRGB::Blue;
  leds[XY(2+x, 0+y)] = CRGB::Blue;
  leds[XY(0+x, 1+y)] = CRGB::Blue;
  leds[XY(0+x, 2+y)] = CRGB::Blue;
  leds[XY(0+x, 3+y)] = CRGB::Blue;
  leds[XY(1+x, 4+y)] = CRGB::Blue;
  leds[XY(2+x, 4+y)] = CRGB::Blue;
  leds[XY(2+x, 3+y)] = CRGB::Blue;

  //A
  leds[XY(4+x,0+y)] = CRGB::Red;
  leds[XY(3+x,1+y)] = CRGB::Red;
  leds[XY(5+x,1+y)] = CRGB::Red;
  leds[XY(3+x,2+y)] = CRGB::Red;
  leds[XY(4+x,2+y)] = CRGB::Red;
  leds[XY(5+x,2+y)] = CRGB::Red;
  leds[XY(3+x,3+y)] = CRGB::Red;
  leds[XY(5+x,3+y)] = CRGB::Red;
  leds[XY(3+x,4+y)] = CRGB::Red;
  leds[XY(5+x,4+y)] = CRGB::Red;

  //M
  for (int i=0; i<5; i++) {
    leds[XY(6+x, i+y)] = CRGB::Blue;
    leds[XY(8+x, i+y)] = CRGB::Blue;
  }
  leds[XY(7+x, 1+y)] = CRGB::Blue;
  leds[XY(7+x, 2+y)] = CRGB::Blue;

  //E
  leds[XY(9+x, 0+y)] = CRGB::Red;
  leds[XY(10+x, 0+y)] = CRGB::Red;
```

```
leds[XY(11+x, 0+y)] = CRGB::Red;
leds[XY(9+x, 1+y)] = CRGB::Red;
leds[XY(9+x, 2+y)] = CRGB::Red;
leds[XY(10+x, 2+y)] = CRGB::Red;
leds[XY(9+x, 3+y)] = CRGB::Red;
leds[XY(9+x, 4+y)] = CRGB::Red;
leds[XY(10+x, 4+y)] = CRGB::Red;
leds[XY(11+x, 4+y)] = CRGB::Red;



//O
for (int i=0; i<5; i++) {
  leds[XY(0+x, 5+i+y)] = CRGB::Red;
  leds[XY(2+x, 5+i+y)] = CRGB::Red;
}
leds[XY(1+x, 5+y)] = CRGB::Red;
leds[XY(1+x, 9+y)] = CRGB::Red;

//V
for (int i=0; i<4; i++) {
  leds[XY(3+x, 5+i+y)] = CRGB::Blue;
  leds[XY(5+x, 5+i+y)] = CRGB::Blue;
}
leds[XY(4+x, 9+y)] = CRGB::Blue;

//E
for (int i=0; i<5; i++) leds[XY(6+x, 5+i+y)] = CRGB::Red;
leds[XY(7+x, 5+y)] = CRGB::Red;
leds[XY(8+x, 5+y)] = CRGB::Red;
leds[XY(7+x, 7+y)] = CRGB::Red;
leds[XY(7+x, 9+y)] = CRGB::Red;
leds[XY(8+x, 9+y)] = CRGB::Red;

//R
for (int i=0; i<5; i++) leds[XY(9+x, 5+i+y)] = CRGB::Blue;
leds[XY(10+x,5+y)] = CRGB::Blue;
leds[XY(11+x,6+y)] = CRGB::Blue;
leds[XY(10+x,7+y)] = CRGB::Blue;
```

```
  leds[XY(11+x,8+y)] = CRGB::Blue;
  leds[XY(11+x,9+y)] = CRGB::Blue;




}

//determines and displays winner number
void winner(int player, int x, int y)
{
  //P
  leds[XY(3+x,0+y)] = CRGB::Red;
  leds[XY(3+x,1+y)] = CRGB::Red;
  leds[XY(3+x,2+y)] = CRGB::Red;
  leds[XY(3+x,3+y)] = CRGB::Red;
  leds[XY(3+x,4+y)] = CRGB::Red;
  leds[XY(4+x,0+y)] = CRGB::Red;
  leds[XY(5+x,1+y)] = CRGB::Red;
  leds[XY(4+x,2+y)] = CRGB::Red;

   if (player == 1) {
    numbers(player, blue, x+6, y);
  }
  if (player == 2) {
    numbers(player, green, x+6, y);
  }
  if (player == 3) {
    numbers(player, red, x+6, y);
  }
  if (player == 4) {
    numbers(player, purple, x+6, y);
  }

  //W
  for (int i=0; i<5; i++) {
    leds[XY(0+x, 5+i+y)] = CRGB::Red;
    leds[XY(2+x, 5+i+y)] = CRGB::Red;
  }
  leds[XY(1+x, 8+y)] = CRGB::Red;
```

```
  leds[XY(1+x, 7+y)] = CRGB::Red;

  //I
  for (int i=0; i<5; i++) leds[XY(4+x, 5+i+y)] = CRGB::Blue;
  for (int i=0; i<3; i++) {
    leds[XY(3+i+x, 5+y)] = CRGB::Blue;
    leds[XY(3+i+x, 9+y)] = CRGB::Blue;
  }

  //N
  leds[XY(6+x, 5+y)] = CRGB::Red;
  leds[XY(6+x, 6+y)] = CRGB::Red;
  leds[XY(6+x, 7+y)] = CRGB::Red;
  leds[XY(6+x, 8+y)] = CRGB::Red;
  leds[XY(6+x, 9+y)] = CRGB::Red;
  leds[XY(7+x, 5+y)] = CRGB::Red;
  leds[XY(8+x, 6+y)] = CRGB::Red;
  leds[XY(8+x, 7+y)] = CRGB::Red;
  leds[XY(8+x, 8+y)] = CRGB::Red;
  leds[XY(8+x, 9+y)] = CRGB::Red;

  //S
  leds[XY(10+x, 5+y)] = CRGB::Blue;
  leds[XY(11+x, 5+y)] = CRGB::Blue;
  leds[XY(9+x, 6+y)] = CRGB::Blue;
  leds[XY(9+x, 7+y)] = CRGB::Blue;
  leds[XY(10+x, 7+y)] = CRGB::Blue;
  leds[XY(11+x, 7+y)] = CRGB::Blue;
  leds[XY(11+x, 8+y)] = CRGB::Blue;
  leds[XY(10+x, 9+y)] = CRGB::Blue;
  leds[XY(9+x, 9+y)] = CRGB::Blue;

}

//screen that displays game over and winner graphics
void endGameScreen()
{
  FastLED.clear();
  Serial.println("endGameScreen");
```

```
  int winningPlayer=0;
  int most = 0;
  for (int j=0; j<4; j++) {
    int temp = score[j];
    if (temp>most) {
      most = temp;
      winningPlayer = j+1;

    }
  }
  Serial.println("Winner");
  Serial.println(winningPlayer);
  Serial.print(most);
  for (int i=0; i<3; i++) {
    //FastLED.clear();
    firework(7, 12);
    gameOver(2, 8);
    FastLED.show();
    FastLED.delay(1000);
    FastLED.clear();
    winner(winningPlayer, 2, 8);
    FastLED.show();
    FastLED.delay(1000);
    FastLED.clear();
    }

    FastLED.clear();
    state = 0;
}

//firework lighting effect
void firework(int x, int y)
{


  int j=0;
  for (int i=0; i<10; i++)
  {
    leds[XY(i+x, j+y)] = CRGB::Red;
```

```
    leds[XY(x, j+y)] = CRGB::Red;
    leds[XY(i+x, y)] = CRGB::Red;
    leds[XY(x-i, y-j)] = CRGB::Red;
    leds[XY(x, y-j)] = CRGB::Red;
    leds[XY(x-i, y)] = CRGB::Red;
    leds[XY(x+i, y-j)] = CRGB::Red;
    leds[XY(x-i, y+j)] = CRGB::Red;
    FastLED.delay(100);
    leds[XY(i+x, j+y)] = CRGB::Black;
    leds[XY(x, j+y)] = CRGB::Black;
    leds[XY(i+x, y)] = CRGB::Black;
    leds[XY(x-i, y-j)] = CRGB::Black;
    leds[XY(x, y-j)] = CRGB::Black;
    leds[XY(x-i, y)] = CRGB::Black;
    leds[XY(x+i, y-j)] = CRGB::Black;
    leds[XY(x-i, y+j)] = CRGB::Black;

    j++;
  }
}
```

D.2 STM32 Code

```
/* USER CODE BEGIN Header */
/**

******************************************************************************
*****
 * @file           : main.c
 * @brief          : Main program body

******************************************************************************
*****
 * @attention
 *
 * Copyright (c) 2023 STMicroelectronics.
 * All rights reserved.
 *
 * This software is licensed under terms that can be found in the LICENSE
file
 * in the root directory of this software component.
 * If no LICENSE file comes with this software, it is provided AS-IS.
 *
```

```
**************************************************************************
*****
 */
/* USER CODE END Header */
/*                                                                  Includes
------------------------------------------------------------------*/
#include "main.h"
/*                              Private                             includes
----------------------------------------------------------*/
/* USER CODE BEGIN Includes */
#include <stdio.h>
/* USER CODE END Includes */
/*                              Private                              typedef
-----------------------------------------------------------*/
/* USER CODE BEGIN PTD */
/* USER CODE END PTD */
/*                              Private                               define
------------------------------------------------------------*/
/* USER CODE BEGIN PD */
/* USER CODE END PD */
/*                              Private                                macro
-------------------------------------------------------------*/
/* USER CODE BEGIN PM */
/* USER CODE END PM */
/*                              Private                            variables
---------------------------------------------------------*/
SPI_HandleTypeDef hspi1;
/* USER CODE BEGIN PV */
/* USER CODE END PV */
/*                 Private                 function              prototypes
-----------------------------------------------*/
void SystemClock_Config(void);
static void MX_GPIO_Init(void);
static void MX_SPI1_Init(void);
/* USER CODE BEGIN PFP */
/* USER CODE END PFP */
/*                    Private                  user                     code
---------------------------------------------------------*/
/* USER CODE BEGIN 0 */
/* USER CODE END 0 */
/**
 * @brief  The application entry point.
 * @retval int
 */
int main(void)
{
 /* USER CODE BEGIN 1 */
 /* USER CODE END 1 */
                                  /*                                     MCU
Configuration--------------------------------------------------------*/
  /* Reset of all peripherals, Initializes the Flash interface and the
Systick. */
 HAL_Init();
 /* USER CODE BEGIN Init */
 /* USER CODE END Init */
 /* Configure the system clock */
```

```
 SystemClock_Config();
 /* USER CODE BEGIN SysInit */
 /* USER CODE END SysInit */
 /* Initialize all configured peripherals */
 MX_GPIO_Init();
 MX_SPI1_Init();
 /* USER CODE BEGIN 2 */
 uint8_t data[2] = {16,32};
 /* USER CODE END 2 */
 /* Infinite loop */
 /* USER CODE BEGIN WHILE */
 while (1)
 {
        data[0] = 16;
        data[1] = 32;
        uint8_t dummy;
        uint8_t x = 16;
        uint8_t y = 32;
        for (int i=0; i<16; i++) {
            if (GPIOB->IDR & (1 << i)) {
                  x = i;
                  break;
            }
        }
        if (x != 16){
            for (int i=0; i<16; i++) {
                  if (GPIOD->IDR & (1 << i)) {
                        y = i;
                        break;
                  }
                  if (GPIOE->IDR & (1 << i))  {
                        y=i+16;
                        break;
                  }
            }
        }
        if (x!=16 && y!=32) {
              data[0] = x;
              data[1] = y;
        }
          while(HAL_SPI_Receive(&hspi1,  &dummy,  1,  HAL_MAX_DELAY)  !=
HAL_OK) {}
            HAL_SPI_Transmit(&hspi1, &data, 2, HAL_MAX_DELAY);
       //
        //HAL_Delay(100);
   /* USER CODE END WHILE */
   /* USER CODE BEGIN 3 */
 }
 /* USER CODE END 3 */
}
/**
 * @brief System Clock Configuration
 * @retval None
 */
void SystemClock_Config(void)
{
 RCC_OscInitTypeDef RCC_OscInitStruct = {0};
```

```
 RCC_ClkInitTypeDef RCC_ClkInitStruct = {0};
  /**  Initializes  the  RCC  Oscillators  according  to  the  specified
parameters
 * in the RCC_OscInitTypeDef structure.
 */
 RCC_OscInitStruct.OscillatorType = RCC_OSCILLATORTYPE_HSI;
 RCC_OscInitStruct.HSIState = RCC_HSI_ON;
 RCC_OscInitStruct.HSICalibrationValue = RCC_HSICALIBRATION_DEFAULT;
 RCC_OscInitStruct.PLL.PLLState = RCC_PLL_NONE;
 if (HAL_RCC_OscConfig(&RCC_OscInitStruct) != HAL_OK)
 {
   Error_Handler();
 }
 /** Initializes the CPU, AHB and APB buses clocks
 */
 RCC_ClkInitStruct.ClockType = RCC_CLOCKTYPE_HCLK|RCC_CLOCKTYPE_SYSCLK
                              |RCC_CLOCKTYPE_PCLK1|RCC_CLOCKTYPE_PCLK2;
 RCC_ClkInitStruct.SYSCLKSource = RCC_SYSCLKSOURCE_HSI;
 RCC_ClkInitStruct.AHBCLKDivider = RCC_SYSCLK_DIV1;
 RCC_ClkInitStruct.APB1CLKDivider = RCC_HCLK_DIV1;
 RCC_ClkInitStruct.APB2CLKDivider = RCC_HCLK_DIV1;
 if (HAL_RCC_ClockConfig(&RCC_ClkInitStruct, FLASH_LATENCY_0) != HAL_OK)
 {
   Error_Handler();
 }
}
/**
 * @brief SPI1 Initialization Function
 * @param None
 * @retval None
 */
static void MX_SPI1_Init(void)
{
 /* USER CODE BEGIN SPI1_Init 0 */
 /* USER CODE END SPI1_Init 0 */
 /* USER CODE BEGIN SPI1_Init 1 */
 /* USER CODE END SPI1_Init 1 */
 /* SPI1 parameter configuration*/
 hspi1.Instance = SPI1;
 hspi1.Init.Mode = SPI_MODE_SLAVE;
 hspi1.Init.Direction = SPI_DIRECTION_2LINES;
 hspi1.Init.DataSize = SPI_DATASIZE_8BIT;
 hspi1.Init.CLKPolarity = SPI_POLARITY_LOW;
 hspi1.Init.CLKPhase = SPI_PHASE_1EDGE;
 hspi1.Init.NSS = SPI_NSS_HARD_INPUT;
 hspi1.Init.BaudRatePrescaler = SPI_BAUDRATEPRESCALER_16;
 hspi1.Init.FirstBit = SPI_FIRSTBIT_MSB;
 hspi1.Init.TIMode = SPI_TIMODE_DISABLE;
 hspi1.Init.CRCCalculation = SPI_CRCCALCULATION_DISABLE;
 hspi1.Init.CRCPolynomial = 10;
 if (HAL_SPI_Init(&hspi1) != HAL_OK)
 {
   Error_Handler();
 }
 /* USER CODE BEGIN SPI1_Init 2 */
 /* USER CODE END SPI1_Init 2 */
}
```

```
/**
 * @brief GPIO Initialization Function
 * @param None
 * @retval None
 */
static void MX_GPIO_Init(void)
{
 GPIO_InitTypeDef GPIO_InitStruct = {0};
/* USER CODE BEGIN MX_GPIO_Init_1 */
/* USER CODE END MX_GPIO_Init_1 */
 /* GPIO Ports Clock Enable */
 __HAL_RCC_GPIOE_CLK_ENABLE();
 __HAL_RCC_GPIOA_CLK_ENABLE();
 __HAL_RCC_GPIOB_CLK_ENABLE();
 __HAL_RCC_GPIOD_CLK_ENABLE();
 /*Configure GPIO pins : PE2 PE3 PE4 PE5
                          PE6 PE7 PE8 PE9
                          PE10 PE11 PE12 PE13
                          PE14 PE15 PE0 PE1 */
 GPIO_InitStruct.Pin = GPIO_PIN_2|GPIO_PIN_3|GPIO_PIN_4|GPIO_PIN_5
                         |GPIO_PIN_6|GPIO_PIN_7|GPIO_PIN_8|GPIO_PIN_9
                         |GPIO_PIN_10|GPIO_PIN_11|GPIO_PIN_12|GPIO_PIN_13
                         |GPIO_PIN_14|GPIO_PIN_15|GPIO_PIN_0|GPIO_PIN_1;
 GPIO_InitStruct.Mode = GPIO_MODE_INPUT;
 GPIO_InitStruct.Pull = GPIO_PULLDOWN;
 HAL_GPIO_Init(GPIOE, &GPIO_InitStruct);
 /*Configure GPIO pins : PB0 PB1 PB2 PB10
                          PB11 PB12 PB13 PB14
                          PB15 PB3 PB4 PB5
                          PB6 PB7 PB8 PB9 */
 GPIO_InitStruct.Pin = GPIO_PIN_0|GPIO_PIN_1|GPIO_PIN_2|GPIO_PIN_10
                         |GPIO_PIN_11|GPIO_PIN_12|GPIO_PIN_13|GPIO_PIN_14
                         |GPIO_PIN_15|GPIO_PIN_3|GPIO_PIN_4|GPIO_PIN_5
                         |GPIO_PIN_6|GPIO_PIN_7|GPIO_PIN_8|GPIO_PIN_9;
 GPIO_InitStruct.Mode = GPIO_MODE_INPUT;
 GPIO_InitStruct.Pull = GPIO_PULLDOWN;
 HAL_GPIO_Init(GPIOB, &GPIO_InitStruct);
 /*Configure GPIO pins : PD8 PD9 PD10 PD11
                          PD12 PD13 PD14 PD15
                          PD0 PD1 PD2 PD3
                          PD4 PD5 PD6 PD7 */
 GPIO_InitStruct.Pin = GPIO_PIN_8|GPIO_PIN_9|GPIO_PIN_10|GPIO_PIN_11
                         |GPIO_PIN_12|GPIO_PIN_13|GPIO_PIN_14|GPIO_PIN_15
                         |GPIO_PIN_0|GPIO_PIN_1|GPIO_PIN_2|GPIO_PIN_3
                         |GPIO_PIN_4|GPIO_PIN_5|GPIO_PIN_6|GPIO_PIN_7;
 GPIO_InitStruct.Mode = GPIO_MODE_INPUT;
 GPIO_InitStruct.Pull = GPIO_PULLDOWN;
 HAL_GPIO_Init(GPIOD, &GPIO_InitStruct);
/* USER CODE BEGIN MX_GPIO_Init_2 */
/* USER CODE END MX_GPIO_Init_2 */
}
/* USER CODE BEGIN 4 */
/* USER CODE END 4 */
/**
 * @brief  This function is executed in case of error occurrence.
 * @retval None
 */
```

```
void Error_Handler(void)
{
 /* USER CODE BEGIN Error_Handler_Debug */
 /* User can add his own implementation to report the HAL error return
state */
 __disable_irq();
 while (1)
 {
 }
 /* USER CODE END Error_Handler_Debug */
}
#ifdef  USE_FULL_ASSERT
/**
 * @brief  Reports the name of the source file and the source line number
 *         where the assert_param error has occurred.
 * @param  file: pointer to the source file name
 * @param  line: assert_param error line source number
 * @retval None
 */
void assert_failed(uint8_t *file, uint32_t line)
{
 /* USER CODE BEGIN 6 */
 /* User can add his own implementation to report the file name and line
number,
     ex: printf("Wrong parameters value: file %s on line %d\r\n", file,
line) */
 /* USER CODE END 6 */
}
#endif /* USE_FULL_ASSERT */
```

Appendix E - Copyright

We hereby declare that we have not copied more than 7 pages from the Large Language Model (LLM). We have utilized LLM for drafting purposes.