

Laser Harp Without Mechanical Strings

Where Photonics Meets Harmony

Group 6



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Table of Contents

List of Tables

List of Figures

1.0 Executive Summary

1.1 Before You Read, An Intro to Music Theory

2.0 Project Description

2.1 Motivation

2.2 Prior Works and Similar Projects

2.3 Goals and Objectives

2.3.1 Overall Goal

2.3.2 Basic Goals

2.3.3 Advanced Goals

2.3.4 Stretch Goals

2.3.5 Objectives

2.4 Optical layout

2.5 Project Requirement Specifications

2.5.1 Engineering Requirement Specifications

2.5.2 Component Performance Specifications

2.5.3 Marketing Requirements

2.6 House of Quality

2.7 Project Block Diagrams

2.7.1 Hardware Block Diagram

2.7.2 Software Block Diagram

2.8 Project Blueprint

3.0 Relevant Technologies and Components Research

3.1 Integrated Circuit

3.1.1 Main Integrated Circuit

3.1.2 Microcontroller Overview

3.1.3 ATMEGA328P-PU

3.1.4 MSP430FR6989IPZR

3.1.5 STM32C031F4P6

3.1.6 STM32L010R8T6

3.1.7 STM32C031C6T6

3.1.8 ESP32-WROOM-32

3.1.9 Development Boards

3.1.10 Microcontroller Selection

3.2 Audio

3.2.1 Audio Storage

3.2.2 Audio DAC

3.2.3 Audio Amplifier Design

3.2.4 List of Amplifiers

3.2.5 Speaker

3.2.6 Volume Control

3.3 Photodetection Device

3.3.1 Overview

- 3.3.2 Types of Photodetection Devices
- 3.4 Stepper Motor
 - 3.4.1 Stepper vs Servo
 - 3.4.2 Overview
 - 3.4.3 Types of Stepper Motors
 - 3.4.4 Advantages and Disadvantages
- 3.5 Laser
 - 3.5.1 Overview
 - 3.5.2 Wavelength Selection
 - 3.5.3 Type of Laser
 - 3.5.4 Laser Diode Driver
- 3.6 Other Laser Harp System Options
 - 3.6.1 Overview
 - 3.6.2 Transmission Diffraction Grating Configuration
 - 3.6.3 Reflection Diffraction Grating Configuration
 - 3.6 Operating Console
- 3.7 Compiling/Uploading Software
 - 3.7.1 Xilinx Vivado & Vitis IDE
 - 3.7.2 Code Composer Studio
 - 3.7.3 Arduino
 - 3.7.4 STM32 Cube IDE
- 3.8 Communication Protocols
 - 3.8.1 Universal Asynchronous Receiver/Transmitter
 - 3.8.2 Inter-Integrated Circuit Communication
 - 3.8.3 Serial Peripheral Interface
- 3.9 Motor Controller
 - 3.9.1 Overview
 - 3.9.2 Types of Motor Controllers
 - 3.9.3 TB6600 and DRV8825
 - 3.9.4 Advantages and Disadvantages of Selection
- 3.10 LCD Screen
 - 3.10.1 Objectives
 - 3.10.2 Comparison of LCD Screens
- 3.11 Power
 - 3.11.1 Battery
 - 3.11.2 Lithium-Ion
 - 3.11.3 Lead-Acid
 - 3.11.4 Nickel-Metal Hydride
 - 3.11.5 Nickel-Cadmium
 - 3.11.6 Battery Comparison and Selection
 - 3.11.7 Wall Power
- 3.12 Regulators
 - 3.12.1 Linear Regulators
 - 3.12.2 Switching Regulators
 - 3.12.3 Regulator Comparison
 - 3.12.4 Linear Regulator Selection

3.12.5	Switching Regulator Selection
3.13	Diffused surface material
4.0	Standards and Design Constraints
4.1	Safety and Regulatory Standards
4.1.1	Laser Standards
4.1.2	Lithium-Ion Battery Standards
4.2	Technical Constraints
4.3	Economic Constraints
4.4	Time Constraints
4.5	Environmental Constraints
4.6	Human Factors and Ergonomic Constraints
4.7	Thermal Constraints
4.8	Manufacturability and Assembly Constraints
5.0	Comparison of ChatGPT or Similar Platforms
5.1	Background Information of ChatGPT
5.2	Pros of ChatGPT
5.3	Cons of ChatGPT
5.4	How ChatGPT Was Implemented
5.5	ChatGPT Applications and Analysis
6.0	Hardware Design
6.1	Laser String Unit (LSU)
6.2	Main Processing Unit (MPU)
6.2.1	User Interface
6.2.2	Power On/Off and Reset
6.2.3	Volume Control
6.2.4	Foot Buttons
6.3	Power Supply Unit
6.4	UART to Serial Converter
6.5	Optical Design
6.5.1	Collimating Lens
6.5.2	Beam Expander
6.6	Electronic Hardware Design After Final Demo
7.0	Software Design
7.1	Coding Run-through and Logic
7.2	DFPlayer File Management
7.3	Function and Class Diagram
7.4	Use Case Diagram
7.5	In-Depth Flow Chart
7.6	Data Transfer Interface
8.0	System Fabrication and Prototype Construction
8.1	General PCB Layout
8.2	Laser String Unit Design
8.3	Laser Harp Assembly and Housing
9.0	System Testing and Evaluation
9.1	Safety Procedures
10.0	Administrative Content

10.1 Budget and Financing	
10.2 Work Distribution and Milestones	
11.0 Conclusion	
Appendix A: Citation	
Appendix B: ChatGPT Prompts and Outcomes	

List of Tables

Table 1 - Engineering Requirements	11
Table 2 - Component Performance	13

Table 3 - Marketing Requirements	14
Table 4 – Comparison of Main Processors	24
Table 5 - Comparison of Microcontrollers.....	29
Table 6 - Comparison of Microcontrollers.....	30
Table 7: Table comparing the different amplifier classes	36
Table 8 - Table Comparing Amplifier Options.....	39
Table 9 - Comparison of Speaker Options	43
Table 10 - Comparison of Photodiode	47
Table 11 - Comparison of Stepper vs Servo Motor.....	49
Table 12 - Comparison of Stepper Motors.....	53
Table 13 - Comparison of Laser Diodes	58
Table 14 - Comparison of Motor Controllers.....	69
Table 15 - Comparison of TB6600 vs. DRV8825 Stepper Motor Drivers	71
Table 16 - Comparison of LCD Displays.....	76
Table 17 - Battery Comparison.....	79
Table 18 - Lithium-Ion Batteries Comparison	80
Table 19 - Comparison of Wall Converters.....	81
Table 20 - Regulators Comparison	84
Table 21 - Comparison of Linear Regulators	84
Table 22 - Comparison of Switching Regulators	86
Table 23 - Chat GPT Examples of Physical User Interfaces (PUIs)	104
Table 24 - Specifications of Collimating Lens.....	115
Table 25 - Specifications for Plano-Concave Lens	119
Table 26 - Specifications for Plano-Convex Lens.....	119
Table 27 - Collection Lens Specifications	120

Table 28 - Budget for Laser Harp Project	145
Table 29 – Bill of Materials	145
Table 30 - Senior Design 1 Milestones	147
Table 31 - Senior Design 2 Milestones	148

List of Figures

Figure 1 - Optical Layout.....	10
Figure 2 - House of Quality Diagram.....	15
Figure 3 - Hardware Block Diagram	16
Figure 4 - Software Block Diagram	18

Figure 5 - Front View of Laser Harp	19
Figure 6 - Top-Down View of Laser Harp.....	19
Figure 7 - Diagram of Note Timing	21
Figure 8 - Diagram of reflection Transmission Grating.....	60
Figure 9 - Diagram of Transmission Diffraction Grating.....	60
Figure 10 - Transmission Diffraction Grating Laser Harp Configuration	61
Figure 11 - Reflective Diffraction Grating Laser Harp Configuration	62
Figure 12 - Diffused Reflection Test Set-Up for Paper	89
Figure 1314 - Schematic of Laser String Unit	106
Figure 15 - Schematic of Laser Diode Driver	107
Figure 16 - Main Processing Unit Schematic	108
Figure 17 - Power System Diagram.....	110
Figure 18 - Schematic of 3.6V, 5V, and 20V Regulators Respectively	111
Figure 19 - USB to UART Converter.....	112
Figure 20 - Keplerian Beam Expander	116
Figure 21 - Galilean Beam Expander	116
Figure 22 - Zemax Lens Prescription.....	123
Figure 23 - Zemax Optical Layout	123
Figure 24 - Zemax of Beam Diameter After Collimating Lens.....	124
Figure 25 - Zemax of Beam Diameter After Beam Expander	125
Figure 26 - Zemax Spot Diagram.....	125
Figure 27 - Use Case Diagram of the Software	130
Figure 28 - In Depth Flow Chart.....	131
Figure 29 - Signal Connection Between Memory and Microcontroller	132
Figure 30 - I2C Interface Connection Between the LCD And Microcontroller	133

Figure 31 - PCB of the Main Processing Unit.....	135
Figure 32 - PCB of Power Supply Unit.....	136
Figure 33 - PCB of UART-USB Converter... 137	Figure 34 - PCB design of the Laser Diode Driver..... 138

1.0 Executive Summary

The Laser Harp project is an interdisciplinary engineering initiative that reimagines a traditional stringed musical instrument using photonics, embedded systems, and electromechanical design. Unlike classical harps that rely on physical strings, our design replaces these with laser beams that are interrupted by a user's hand. These interruptions are detected by photodiodes, which then trigger corresponding musical notes through a microcontroller-based audio playback system. The harp is designed to be frameless, prioritizing accessibility and inclusivity for users with limited physical dexterity. The project not only seeks to preserve the musical versatility of the harp but also expand its use into educational environments. This report documents motivations, research, hardware, and software implementation, as well as feasibility studies to validate the robustness and safety of the Laser Harp.

This unique approach combines the fundamentals of optics with practical electronics and embedded control, resulting in an instrument that bridges music and engineering in a tangible way. The Laser Harp also highlights the potential of photonics as an interactive tool, giving students and general users a chance to engage with concepts like light detection and analog signal processing in a hands-on format. Beyond its technical novelty, the design emphasizes portability, allowing it to be showcased in classrooms, science museums, or community events without extensive setup or calibration. As a team, we recognized the challenge of transforming this idea into a functional system that remains user-friendly and safe, pushing us to make thoughtful design decisions around components, power management, and optical layout. Our shared goal has been to keep the harp approachable while ensuring it meets the rigorous standards of an embedded system that people can trust and enjoy.

While the Laser Harp takes inspiration from prior laser-based instruments, our version stands apart by focusing on contactless interaction and intuitive feedback. Unlike many stage-focused laser harps that rely heavily on MIDI connections and dramatic lighting effects, our prototype integrates the audio system directly, producing realistic harp sounds without needing external synthesizers or computers. This all-in-one concept adds value for casual users who may not have experience with digital audio equipment. To achieve this, careful research went into selecting lasers with safe output levels, mirrors with high reflectivity, and photodiodes with fast response times. This synergy between components and software logic ensures that when a user breaks a beam, the system responds quickly and plays the intended note without noticeable delay.

As part of our senior design experience, this project has also served as an opportunity for every team member to apply and improve their technical skills. Tasks ranging from PCB design and motor control to coding, signal conditioning, and optics alignment have required each discipline to collaborate and adapt. We

have balanced our roles to handle challenges such as system latency, power constraints, and signal processing, while keeping our project within a strict budget. The commitment to good engineering practice extends to safety standards as well, especially considering the use of visible lasers. The team has adhered to relevant laser classifications, planned appropriate protective measures, and documented all procedures to ensure safe operation for users and demonstrators alike.

Looking ahead, this report lays the groundwork for transforming our detailed research and subsystem prototypes into a complete, tested Laser Harp. While the final prototype is still under construction, our design choices, feasibility studies, and documented plans show a clear path forward. The outcome will be an interactive instrument that makes music accessible in new ways, serves as an engaging STEM demonstration, and demonstrates the practical fusion of photonics and embedded electronics. Through this effort, we hope to deliver a project that not only meets our technical goals but also leaves a lasting impression on everyone who experiences it.

This report spans two semesters but was primarily composed during Senior Design One. Any changes to the design, implementation, and manufacturing of the project would be at the end of their respective sections.

1.1 Before You Read, An Intro of Music Theory

A traditional harp, like pianos, uses strings to provide sound, and they would have strings for a wide range of notes. Each string would be tuned to a specific note. And every note has an octave, which is a series of eight notes that represent the notes in between two notes, in this case the note C to C. For our harp, we will not be having the forty-seven strings that a traditional harp has, but instead it will be having seven strings for the range of notes, A to G. But a standard octave, for consistency with a standard piano, starts on note C. And starting on C, each string would be going up the octave by a whole step or two half steps. Now a half step is the smallest interval between two notes in music theory. An example would be the interval of A to A-sharp would be a half up from note A. So, when jumping from A to B, this would be two half steps, or a whole step, and each string of our laser harp would be going up the octave by a whole step. And also, with the introduction of half steps and whole steps, bring sharp, flats and naturals of notes. A natural is just the core note, so an A-natural is just an A. But a flat is down a half step, so an A-flat is just a half-step down from A-natural. A sharp is instead up a half-step, so A-sharp is just a half-step above A-natural. And this would be why sometimes a note would have multiple names. For instance, A-sharp is the same as B-flat, E flat is the same as D-sharp, and F-double sharp (which is a real music notation) is the same as G-natural.

Another thing of music theory that we will be trying to implement in our harp will be keys. A key to music is the specific group of notes that will be used in the

piece, essentially it forms the foundation for the piece of music. Now for simplicity, the standard key with no flats or sharps would be the key of C-major. But for a stretch goal, we would like the user to be able to set the harp to a specific key, like A-flat major, or G-sharp minor, or B-flat major diatonic scale. This foundation setting for the harp will allow for the user to have more range in musical playability.

In addition to being able to play keys, we want the harp to be able to play chords for an advanced goal. Chords are a very common thing in polyphonic instruments like the harp. A chord is simply multiple notes, usually three or more, played simultaneously to achieve a harmonious sound that you simply can't get from playing an individual note. This gives the harp the ability to add some dimensions to its musical prowess, because chords allow for pieces to gain more emotion in a single action. Thus, giving our harp the ability to play chords will make this harp more like a real traditional harp.

2.0 Project Description

This project is the result of a collaborative effort among four students, each bringing their own unique backgrounds and experiences in electrical engineering, computer engineering, and photonics. Despite our different areas of expertise, we came together with a shared interest in music, hands-on design, and innovative technology to create the Laser Harp. This chapter will outline the full scope of our project proposal, including our motivation for choosing this concept, the technical and user-centered goals we aim to achieve, and the steps we've taken to begin transforming this idea into a working prototype. The proposal includes a detailed breakdown of what we want the final product to be capable of, how we plan to build and test it, and how we have researched and planned for the challenges ahead.

The following sections will provide a deeper understanding of the Laser Harp by covering the reasoning behind the project, what makes our approach unique, and how we aim to stand out from previous designs. We will explain the specific design objectives we've set for ourselves, the features we're working to implement, and the standards and constraints we must follow to ensure the system is safe, functional, and user-friendly. Our research and early prototyping have helped shape the technical decisions that form the foundation of our work, and this chapter sets the stage for the detailed engineering work described throughout the rest of this report.

2.1 Motivation

The motivation behind the Laser Harp project stems from our team's shared passion for both music and engineering. Many of us have had experience performing or engaging with music throughout high school and college, which has deeply influenced our desire to develop a project that bridges creativity and

technical innovation. Traditional harps, while elegant and expressive, are also often large, fragile, and physically demanding to play. By replacing physical strings with laser beams, our design seeks to preserve the essence of the harp while reimagining it through modern technology. This innovative approach merges optics, electronics, and embedded systems into a frameless instrument that emphasizes both accessibility and creative expression.

A major driving force behind this project is the desire to make musical interaction more inclusive. The Laser Harp's contactless design removes the physical barriers associated with conventional string instruments. Instead of requiring users to apply pressure or pluck strings, our system allows them to simply interrupt a laser beam with a hand gesture to trigger a note. This creates opportunities for individuals with limited mobility or fine motor control to engage with music in a meaningful and empowering way. In doing so, the harp also doubles as a learning tool, introducing users to basic concepts in photonics, analog and digital electronics, and real-time embedded control through an intuitive, hands-on experience.

We also see the Laser Harp as an opportunity for community outreach and STEM education. Its visually striking design and interactive interface make it an ideal candidate for demonstrations in classrooms, science museums, maker fairs, and other public environments. The harp serves not only as a musical instrument but also as an educational platform that can inspire curiosity in young learners. By showcasing how light can be used to generate sound and how sensors interpret gestures as musical input, the harp naturally encourages exploration of engineering principles in a fun and engaging way.

In contrast to many existing laser harp implementations that prioritize theatricality and stage lighting effects, our design focuses on practicality and ease of use. We are committed to building a device that is not just visually impressive, but also technically sound and musically functional. Every decision in our design, from component selection to software architecture, has been made with the user experience and reliability in mind.

Ultimately, the Laser Harp is more than just a senior design project—it's a creative fusion of engineering skills and artistic expression. It represents our team's commitment to building something that is not only technically impressive but also meaningful, inclusive, and engaging. By merging the worlds of music and technology, we hope to produce a product that resonates with a wide audience, both literally and figuratively.

2.2 Prior Works and Similar Projects

Over the past decade, numerous variations of the laser harp have been developed in both academic and commercial environments. These projects have explored a wide array of design concepts that replace traditional mechanical strings with laser beams, offering a futuristic, touchless approach to musical

interaction. Many commercial and theatrical laser harps emphasize spectacle over functionality, projecting vibrant laser beams vertically in a fan-like pattern and relying on gesture recognition to trigger musical notes. These systems typically use infrared or photodiode-based detection methods and interface with standard MIDI outputs to drive external synthesizers or DAWs. While these models are visually striking and effective for live performance, they are often large, require a power outlet, and are not intended for portable or educational use. Additionally, these designs tend to prioritize visual aesthetics, occasionally at the expense of musical nuance or ergonomic accessibility [1].

Notably, the University of Central Florida (UCF) has previously developed a senior design project in 2020–2021 called the "Expressive Laser Harp." That project featured 15 laser strings, MIDI output, and advanced features such as distance sensing to interpret the location of hand interruption for dynamic pitch or velocity control. The harp was designed to be mounted on a surface and included user interface elements like preset tuning scales, octave shifting, and semitone control. It is also connected to external synthesizers and DAWs via USB MIDI, enabling extensive music production capabilities. However, this project was relatively large in form factor and was intended for stationary use, limiting its portability [2].

Another relevant project was developed at the University of Texas at Arlington (UTA), where students created a frameless laser harp featuring vertically projected laser beams and reflection-based sensors. Their system included ultrasonic distance sensors that modulated sound pitch based on how far a user's hand was from the base of the beam. This added an extra layer of expressiveness to the playing experience by introducing continuous control over frequency rather than discrete note triggering. However, the design was heavily dependent on the vertical orientation of the laser beams, limiting its practicality as a handheld or easily repositionable instrument. The need for accurate reflection angles and environmental stability also posed challenges in terms of usability outside controlled indoor settings. While innovative, the project highlighted the trade-offs between expressive potential and ergonomic flexibility [3].

In public-facing environments, institutions like the Museum of Arts and Sciences in Daytona Beach have hosted large-scale, interactive laser harp exhibits. These installations are primarily designed for educational and entertainment purposes, allowing users—particularly children and museum visitors—to interact with laser beams in a playful, intuitive manner. The systems are typically mounted to the floor or large platforms and utilize visible laser beams combined with simple tone generators to provide immediate feedback when beams are interrupted. Although engaging and effective for introducing the concept of light-based instruments to the general public, these models are not optimized for precision, musicality, or real-time performance. Their focus is more on interactive display than refined musical execution [4].

Our laser harp project builds upon the insights and lessons learned from these prior works. We aim to create a more portable, battery-powered, and frameless instrument that maintains essential musical functionality while enhancing user mobility and accessibility. Rather than anchoring the harp to a fixed platform or requiring external MIDI controllers, our design will support onboard sound generation, intuitive foot controls for sharps/flats and octave adjustments, and a simplified, self-contained interface. By focusing on mobility, ease of use, and a more approachable user experience, our laser harp is intended to appeal to both casual users and aspiring musicians. It represents a shift from spectacle to substance, delivering a functional, expressive, and portable laser-based instrument tailored for modern users and on-the-go creativity.

2.3 Goals and Objectives

The Laser Harp project is centered around creating a modern, accessible, and musically expressive instrument that combines optical technology with digital sound generation. By using lasers as strings, the project seeks to eliminate physical barriers and provide a futuristic interface for musical performance. These goals are structured in basic, advanced, and stretch tiers to allow phased development while ensuring a strong functional core and the flexibility to integrate enhancements such as pitch variation and recording capability. The design emphasizes functionality and portability, supporting creative expression in a compact, user-friendly way.

2.3.1 Overall goal

The primary goal of this project is to design and build a frameless laser harp in which beams of light replace the traditional strings found on a physical harp. Each laser beam will act as an individual string, and when interrupted or “plucked” by the user’s hand, it will trigger the playback of a corresponding musical note.

2.3.2 Basic goals

- Establish complete control over all electronic and photonic subsystems, including the laser drivers, photodiode detection, sound output, and microcontroller communication.
- Configure the Laser Harp to emit 7 evenly spaced laser beams (“strings”) across a 30-inch span with clear beam spacing for player interaction.
- Design and implement a battery-powered system capable of running the entire laser harp (lasers, microcontroller, audio output, and display) for at least 30 minutes of continuous operation per full charge, to enable portable use.
- Integrate a functional display screen that updates in real-time to show the current octave and volume level.

- Calibrate the laser harp's detection system to reliably identify hand interruptions and trigger corresponding notes with a response time of <0.25 seconds, verified through repeated testing.
- Ensure the complete laser harp system, including all electronics, housing, and battery, is light weight, to support easy portability.

2.3.3 Advanced goals

- Laser beam will be collimated using aspheric lenses to maintain a beam divergence.
- Laser beams will be expanded using beam expanding optics to ensure beam size is big enough for easy playability.
- Laser will be allowed to play pre-recorded sound and notes with interaction with an external device
- Laser harp will have synchronization between laser diode and stepper motor, ensure constant string output.

2.3.4 Stretch goals

These goals represent additional features and innovations that may be implemented if the core functionalities of the project are completed ahead of schedule and with remaining resources. Unlike the basic or advanced objectives, these stretch goals are not essential for the initial prototype but are intended to significantly enhance the harp's versatility, interactivity, and user experience. They focus on broadening the system's capabilities beyond its foundational operation and include visual enhancements. Overall, these goals push the boundaries of what the device can do and serve as aspirational benchmarks that could elevate the Laser Harp from a basic functioning prototype into a sophisticated musical instrument.

- Implement recording functionality to playback a performance.
- Create a basic sound engine that allows toggling between different instruments or synth profiles.
- Allow multistring sound.
- Integrate distance-sensing capability to allow each laser to produce multiple notes (natural, sharp, flat) based on user interface.
- Laser harp is able to communicate with external devices wirelessly.

2.3.5 Objectives

To guide the development of the Laser Harp, we have divided our project goals into three categories: basic, advanced, and stretch objectives. This structure helps us prioritize essential features while identifying opportunities for future

improvement. The basic objectives focus on core functionality such as generating laser strings, detecting user input, managing power, and ensuring safe operation. Advanced objectives aim to improve user interaction and performance quality through refined controls and enhanced sound features. Stretch objectives include more innovative additions that could further expand the harp's capabilities, such as wireless communication, multi-string playback, and integration with external music platforms. This tiered approach provides a clear roadmap for development while leaving room for growth and exploration.

Basic Objectives

- Use a stepper motor with a mirror to create the 7 “strings”. Photodetectors will be used to detect changes in intensity. The combination of intensity detection and the position of the stepper motor will ensure the correct harp note is played.
- Develop and simulate PCB designs. Fabricate the successfully simulated custom PCB. With this PCB, we would have to test it with power and components to see if it worked properly, documenting all the qualities and features.
- There will also be an foot pedal/buttons implemented to allow users to shift the octave of the harp up or down, giving them greater expressive control over the instrument. Both the foot pedals for the harp will have two buttons on them.
- The user will have the option via switch to power the device using a standard 120V AC wall outlet or a rechargeable battery. Step-down regulators will be used to convert the wall voltage to a manageable DC voltage level. The device will also have a separate switch to turn the laser individually on or off.
- Optimize the angular spread of the laser beams by ensuring the steps on the stepper motor are at a big enough angle.
- Optimize the dwell time (how long the beam will be at that position on the stepper motor) by utilizing the stepper motor at the correct frequency and by calculating how many times per second the stepper motor will cycle.
- Conduct a trade study on photodiodes and chose one with a fast response.
- The device will have a display that will show the user the volume level and octave of the notes. We also will need to design a boot up screen for the LCD display to show the user that the device has booted up properly. And we will have a booting down screen for it as well.
- Ensure the system falls under ANSI Z136.1 standards.
- Optimize the weight by carefully selecting parts with low weights.

Advanced Objectives

- Design a lens system to collimate the diverging beam from the laser diode and then expand the beam to create a bigger beam size for easier play.
- Design device user interface using the starting values of the stepper motor that allows the user to reset the laser harp and have it start from the beginning.
- Design laser harp so that the stepper motor and the laser are in sync. When the stepper motor turns to a new position, the laser will momentarily turn on and off and back on to maintain the illusion of seven individual light sources.
- The device will have a separate memory storage element that contains pre-recorded musical notes from a real harp or sound. When a string is plucked, a corresponding note will be taken from the storage and played.

Stretch Objectives

- Design a multicolored laser system by coupling the colors into the same beam path.
- Implement interface into laser that allows a connection between the laser harp and music device like synth through MIDI or allow sound integration using music application like Apple's Garage Band.
- Develop multistring functionality, when two strings are played simultaneously, both of the corresponding notes will be played simultaneously. Implement sound mixing so two distinct notes are played either simultaneously or in rapid succession from each other.
- To enhance realism and simulate the experience of playing a real harp, users will be able to modify notes to sharps or flats using a foot pedal. Foot pedals will be bidirectional; harp will play sharps and flats depending on the direction of the pedal.
- Integrate Wireless Communication using an external WIFI module or an onboard module to communicate between the harp and an external device to upload specific sounds into the board's storage element.

The goals and objectives mentioned above were decided during the completion of Senior Design 1. After the completion of Senior Design 2, the scope of the project was changed. The first major change to the design of the project was the decision to alter the beam fan creation. Instead of pulsing a laser diode on and off during the rotation of the stepper motor, the laser diode would now be left continuously on as the stepper motor rotates. There would be a "filter" of seven evenly spaced slits on the roof of the casing that would create the seven strings. The rotation of the stepper motor would create the illusion of seven continuous strings.

2.4 Optical layout

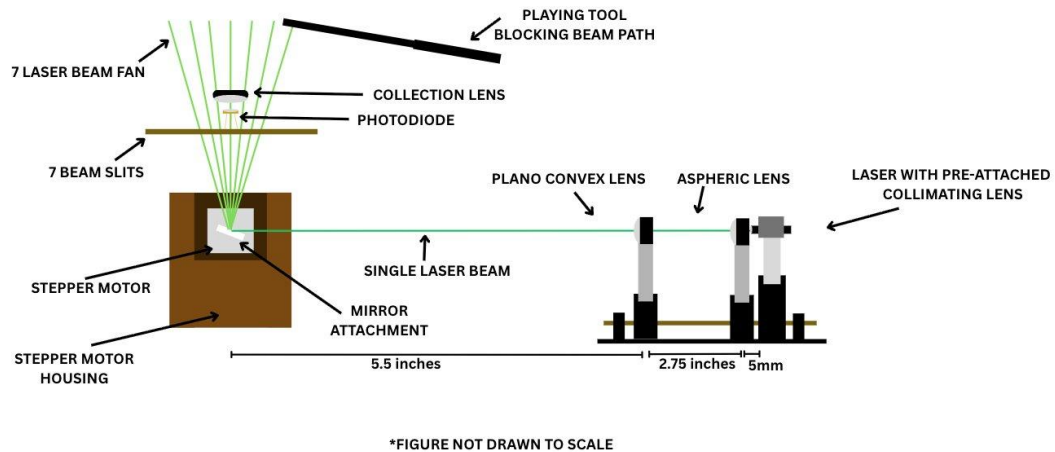


Figure 1 - Optical Layout

2.5 Project Requirement Specifications

The purpose of this section is to outline the key functional, engineering, and marketing requirements necessary to successfully design, prototype, and demonstrate the Laser Harp. These requirements serve as a guideline throughout the development process to ensure the project remains on track in terms of performance, safety, usability, and affordability. By establishing detailed criteria in advance, the team can evaluate progress, identify technical trade-offs, and prioritize core functionalities during both the design and testing phases.

The Laser Harp integrates subsystems from optics, electronics, mechanical design, and embedded software, and therefore demands a multidisciplinary approach to requirement setting. Performance targets were determined through a combination of prior art research, component datasheet analysis, and team simulations. Realistic thresholds were selected based on physical limitations, user interaction models, and system response constraints. Particular attention was given to power consumption, response time, beam detection accuracy, and safety compliance, since these parameters directly impact the instrument's usability in public environments such as classrooms or stage demos.

Marketing requirements, while not purely technical, are equally important in shaping the final user experience. Considerations such as intuitive controls and device cost all play a crucial role in the instrument's accessibility and usage. As this project is intended for both demonstration and educational applications, specifications were chosen to support reliable operation and ease of use while still maintaining the aesthetics and interactive feel of a musical instrument.

The tables below summarize the critical engineering metrics, component-level benchmarks, and marketing expectations that must be satisfied for the project to

be deemed successful. These specifications were reviewed and updated as prototyping advanced, allowing the team to remain flexible while adhering to a structured and measurable development framework.

2.5.1 Engineering Requirement Specifications

This section outlines the key engineering requirements that define how the Laser Harp must perform to meet its intended functionality, user expectations, and practical design constraints. The table presents measurable targets for critical factors such as system response time, memory capacity, note accuracy, power consumption, and physical dimensions. These requirements serve as concrete benchmarks that guide design decisions, component selection, and system integration throughout the project. Establishing clear engineering specifications helps ensure that the final prototype not only works as designed but is also cost-effective, safe, and user-friendly. By setting quantifiable limits for performance, size, cost, and efficiency, the team can systematically test and validate that the system operates within acceptable boundaries. Ultimately, these requirements form a foundation for verifying that the Laser Harp meets all functional goals and delivers reliable and responsive user experience.

Table 1 - Engineering Requirements

Engineering Parameters	Requirements specifications	Units	Description
Response Time	<0.25	Seconds	The response time of the unit shall be less than 0.25 seconds
Number of Strings	7	Strings	The unit shall have a total number of 7 laser “strings”
Memory	<80	GB	The unit shall have a memory up to 80 gigabytes
Cost	\$100-\$500	Dollars	The unit shall be affordable
Spacing between the strings	At least 0.5	Inch	The string spacing of the unit shall be no less than 0.5 inches
Detection Accuracy	90-99	%	The unit shall have a detection accuracy between 90% to 99%
Power Consumption	<200	Watts	The unit shall consume no more than 200 watts
Clock Speed Processing	<10	MHz	The unit shall have a clock speed less than 10 MHz
Weight	5-25	Pounds	The unit shall weigh between 5 to 20 pounds
Size	1-2	Cubic feet	The unit shall be a size between 1 to 2 cubic feet

There was a modification of the engineering specifications for the project, specifically the specifications that were going to be demo on the final. First, the response time specification was clarified to be the time between beam disruption and sound playing, and that the response time of the unit should be less than 0.25 seconds. Detection accuracy was lowered from the 90-99% range mentioned above to 70-75%. The description of the specification was also modified to be How often the beam disruption will be detected. The unit shall have a detection accuracy between 70% to 75%. Finally, the power consumption specification was lowered, from 200W to 25W.

2.5.2 Component Performance Specifications

This section defines the essential performance requirements that each major hardware component must meet to ensure the Laser Harp system functions as

intended. The accompanying table presents a clear overview of key parameters such as electrical ratings, optical properties, mechanical performance, and audio characteristics for the components selected. By establishing these specifications in advance, the project team can carefully evaluate and compare parts to confirm they align with the system's operational needs and design constraints. This level of detail also helps identify any potential limitations or mismatches early in the development process, reducing the risk of performance issues during testing and final implementation. Documenting these requirements promotes consistency across design, assembly, and troubleshooting phases, ensuring that all components integrate smoothly and perform reliably under expected conditions. Overall, this section serves as a critical reference point that guides component selection, procurement, and verification throughout the project lifecycle.

Table 2 - Component Performance

Component	Parameter	Specification	Unit
Laser	Wavelength	520	nm
Mirror	Reflectivity	90	%
Photodiode	a. Spectral response b. Active area size c. Rise/fall time	a. 500-570 b. 13 c. 10	a. nm b. mm^2 c. ns
Stepper Motor	a. Revolution Speed b. Steps in a Revolution	a. 50 b. 200	a. RPM b. Steps per Revolution
Rechargeable Battery	Battery Capacity	30	Minutes
Microcontrollers	Clock Speed	<10	MHz
Speakers	a. Total Harmonic Distortion b. Frequency Range capable for the speaker c. Max Volume	a. 0.5-1% b. 30 - 2000 c. <100	a. Percentage of Distortion b. Hz c. dB
Display Screen	Resolution	128x64	Pixels

2.5.3 Marketing Requirements

This section identifies the primary marketing requirements that guide the design and development of the Laser Harp to ensure it meets user expectations and stands out in the market. The table outlines essential qualities such as portability, sound quality, affordability, safety, and ease of use. These factors reflect what potential users value most and directly influence decisions related to materials, size, usability, and overall product appeal. By clearly defining these requirements, the project team can align technical and design choices with what makes the device practical and desirable for everyday users. This alignment helps position the final product as accessible, safe, and engaging for a wide audience, supporting its potential for success in educational, recreational, or performance settings. Incorporating these user-focused considerations early in the design process ensures that the Laser Harp is functional.

Table 3 - Marketing Requirements

Requirement	Description
Portable	The device should be lightweight and doesn't require a lot of space for use
Good Sound Quality	The quality of the device should be recognizable and have a taper to the sound.
Eye Safe	The laser used for the device should be eye-safe
Low Cost	The device should be affordable for the average person
Easy to use	The device should be portable as well as easy to play and learn from.

2.6 House of Quality

In the development of our Laser Harp, it is essential to strike a balance between engineering performance and user-centered design expectations. Our House of Quality framework helps to evaluate and quantify the trade-offs between technical specifications such as signal latency, power consumption, component cost, and reliability, and the marketing or end-user requirements, including

portability, ease of use, visual appeal, and educational value. By carefully analyzing the interactions between these parameters, we can identify areas where technical enhancements can directly improve the user experience or, conversely, where excessive technical complexity may reduce practicality or inflate costs. This structured approach allows the team to prioritize design features that not only meet performance benchmarks but also support broader project goals such as accessibility, interactivity, and appeal to educational institutions. In doing so, we ensure that our final product is both functionally sound and aligned with the needs and expectations of our intended user base. Through iterative evaluation and thoughtful decision-making, we aim to create a product that maximizes value, minimizes unnecessary complexity, and delivers a compelling, innovative musical experience.

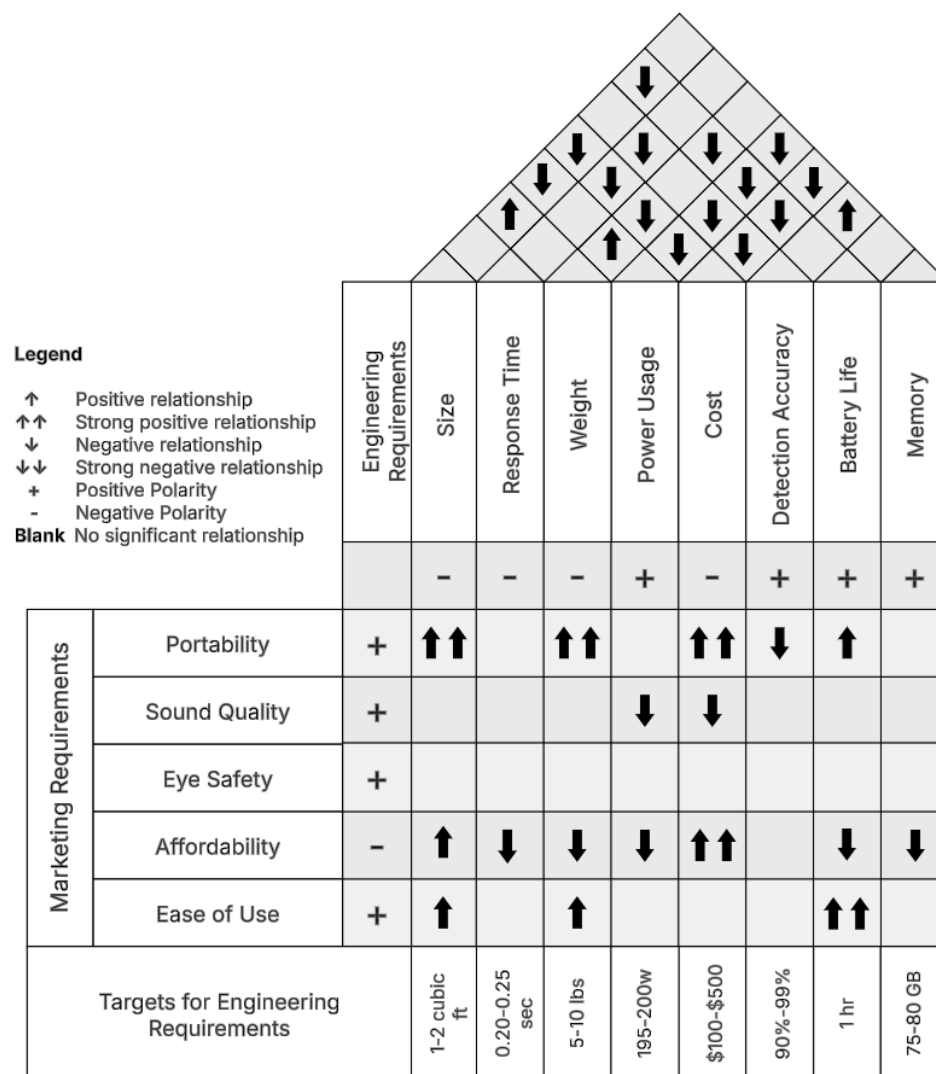


Figure 2 - House of Quality Diagram

2.7 Project Block Diagrams

The project block diagrams provide a high-level visual representation of the Laser Harp system's structure, outlining how the major hardware and software components interact with one another. These diagrams are essential for understanding the overall system architecture, including data flow, power distribution, and control logic. By breaking the project down into functional blocks, we are able to clearly define the roles of each subsystem and illustrate how they work together to achieve the desired performance. The block diagrams serve as both a planning and communication tool, guiding the design process and ensuring that all team members share a unified understanding of the system's layout and functionality.

2.7.1 Hardware Block Diagram

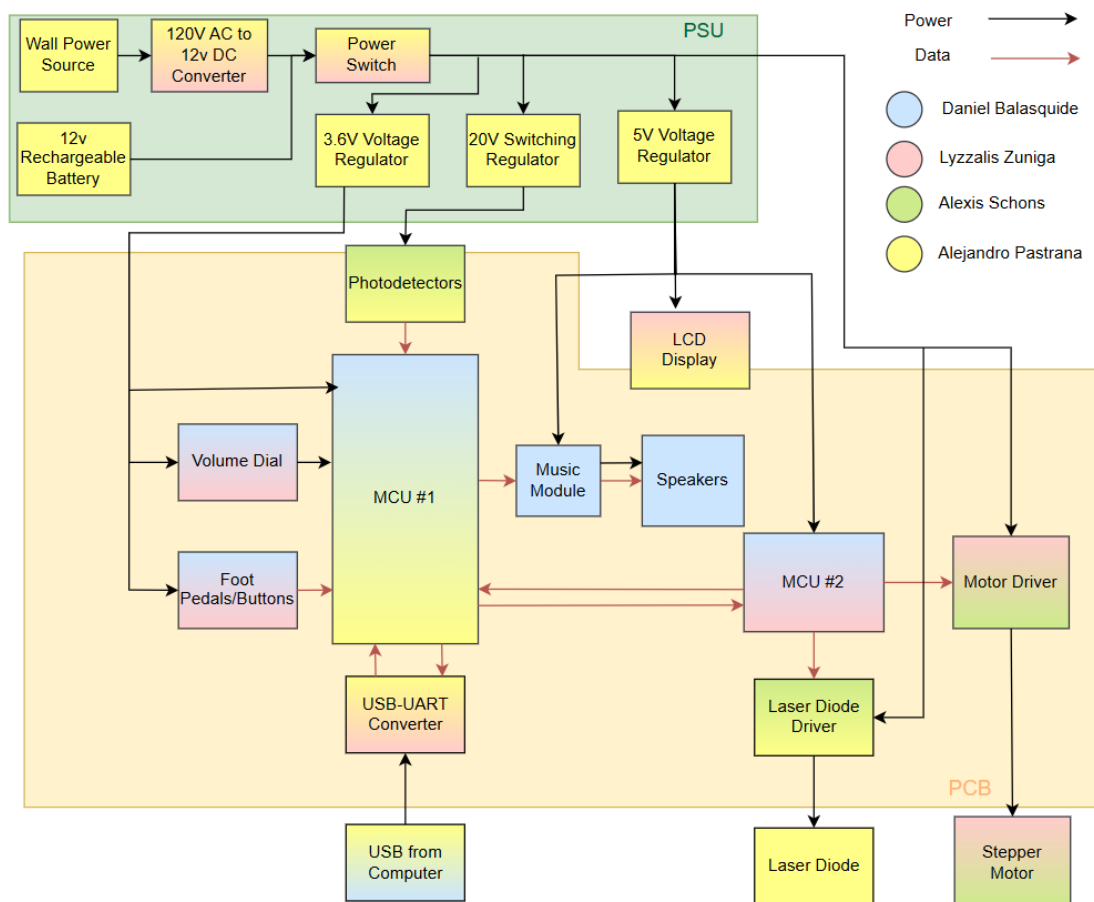


Figure 3 - Hardware Block Diagram

The block diagram shown above shows all the different blocks in our project and how they interact with each other. The PSU section shows how the device is going to be powered. As part of our basic and advanced goals, the harp can alternatively be powered via a wall outlet or a rechargeable battery. The PCB section contains

microcontrollers, which will be used to program the device. Microcontroller #1 will be tasked with sound production, taking the information received by the photodetectors and foot pedals to produce the desired note. This MCU will also be tasked with handling all the user inputs via buttons and dials and pedals. Microcontroller #2 will be tasked with controlling and collecting data pertaining to the stepper motor and managing the laser. This information will be sent to the MCU #1 for processing, the position of the stepper motor is pivotal to determine what note will be played. To summarize, the stepper motor and the laser/optics will produce the strings, as shown in the prototype. When a laser beam is obstructed, the photoresistors will notify the microcontroller that a string has been plucked. The photodiodes, in tandem with the information from the stepper motor, will determine which string has been plucked. All this information will be sent to the microcontrollers and used to play a note corresponding to the string. The notes that are played when the strings are plucked are pre-recorded and saved in a storage element; the notes will not be generated by a synthesizer nor computer.

Final Hardware Design

After the completion of Senior Design One and during the completion of Senior Design 2, changes to the overall hardware design were made. There were changes to the MCU; one MCU was dropped from the overall design, during the fabrication of the PCBs. After it was decided that one wouldn't be enough, another MCU was added. This MCU, like before, would control the stepper motor, but now would read the analog signals from the photodiode.

There were major changes to the photodetection subsystem of the project. A transimpedance amplifier was designed and manufactured to convert and amplify the current produced by the photodiode into a voltage. Additionally, the 20V regulation used to create a reverse bias voltage for the Photodiode was dropped; using a separate 3.3V regulator with an input of 5V for the reverse bias.

During the testing phase of photodetection, it was found that the stepper motor was creating noise that was affecting the photodetection. It was decided to use the 12V rechargeable battery as an isolated power supply for the stepper motor and driver. The wall power was the only power supply shown for the final demonstration.

2.7.2 Software Block Diagram

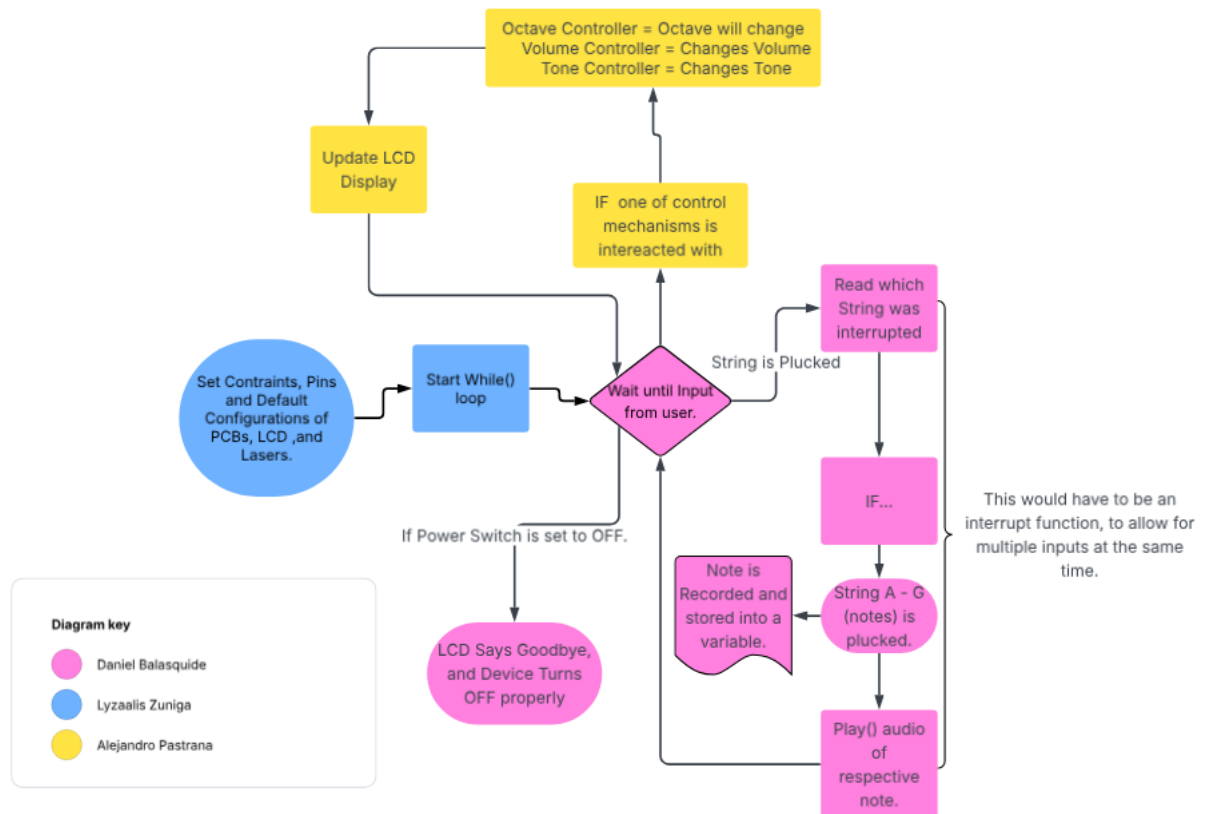


Figure 4 - Software Block Diagram

The software design of the project shouldn't be too sophisticated when it comes to a computer science perspective. Essentially, it will be coded iteratively to save memory and processing power. The method that we will use will most likely be a straightforward approach involving IF statements and switch cases to read the user input and decide accordingly which note to play. The diagram shows that the software will be looping to keep the device functional. In addition, there will be interrupts implemented into the project to allow for the device to handle multiple notes at the same time, essentially allowing the harp to play chords. In addition, the other controlling mechanisms of the harp will be implemented into the code, by just also just using interrupts and if statements. The coding language of the project will be done in C and C++ due to the speed of these languages.

2.8 Project Blueprints

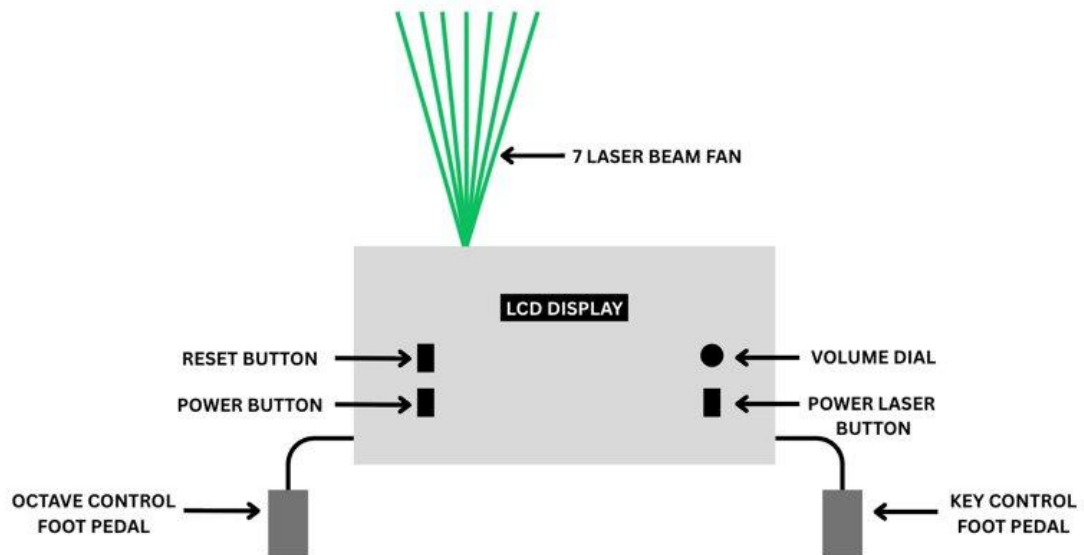
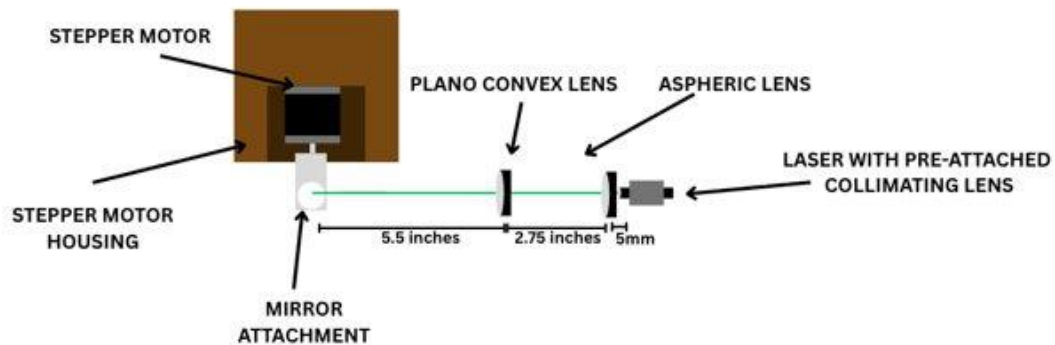
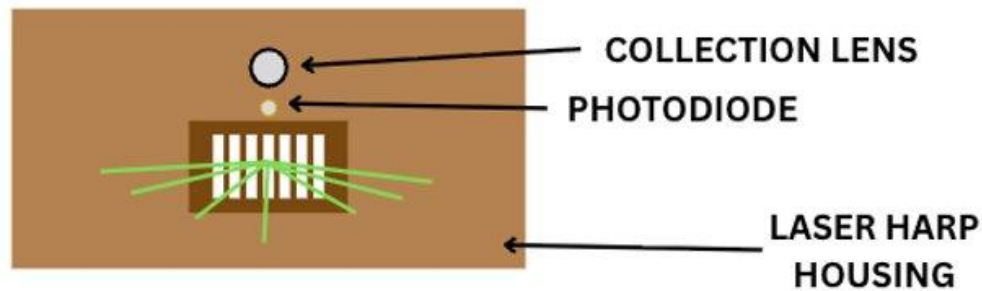


Figure 5 - Front View of Laser Harp



*FIGURE NOT DRAWN TO SCALE

Figure 6 - Top-Down View of Laser Harp with Lid Off



***FIGURE NOT DRAWN TO SCALE**

Figure 7 - Top-Down View of Laser Harp with Lid On

In figure 5 the schematic is of what the laser harp will look like when looking at the front of the Laser Harp. On the front of the housing there will be an LCD display. The LCD screen will display the current volume level and octave. Using the dial to the right of the LCD display the user will be able to adjust the volume of the harp. There will also be four foot pedals. The 1st foot pedal on the left will control the octave up, and the 2nd foot pedal will control the octave down. The foot pedals on the right will control the sharps and flats. These are nice features for the harp user since the Laser Harp will only have seven strings. These pedals will ensure the user will be able to play a variety of songs.

In figure 6 the schematic shows what the Laser Harp will look like from a top-down view. The schematic includes electrical and optical components. All the hardware will be inside the Harp Housing. In figure 6 we chose to highlight the optical/laser portion of the Laser Harp. A laser diode will be mounted inside the fixture and pointing at a mirror that is mounted to a stepper motor. In the beam path to the mirror there will be a collimating lens. This will collimate the beam coming from the laser diode which is extremely important because the beam coming from a diode is very divergent. After the collimating lens there is a set of two lens, these lenses will make up the beam condenser. The beam condenser is important for the playability of the laser harp. With a smaller beam going through the slits the user will be able to see the beams easier and there will be more surface area hitting the user's playing tool therefore making more scatter into the laser diodes. When the stepper motor is on it will rotate the mirror and scan the constant wave beam at a frequency fast enough to where seven beams will be displayed through the slits. A photodiode with a collection lens to aid the light into the photodiode will be placed facing up toward the ceiling. The photodiode will capture the scattered light from when the user blocks a beam with their hand (aka "plucks" the beam). The system will see the increase in light intensity and know the position of the stepper motor and be able to play the correct note corresponding to the beam that was "plucked".

The Laser Harp system will use one photodiode. The original plan was to have 5 photodiodes. The use of more than one photodiode is extra cost and unnecessary. One photodiode with a collection lens will be able to receive all the light necessary to run. In order to understand how the correct note will be detected let's simplify the system. Refer to figure 7. The simplified system will consist of 3 beams and one photodiode with the collection lens (photodiode not pictured in diagram below). The stepper motor will move one step per second. A hand is placed blocking beam number two, but the stepper motor is on beam number one. Looking at the diagram (square 1) below you can see the hand in position to play note two. But the beam is in position one. Therefore, note two will not be played yet. In square two the hand is in position and the stepper motor is in position two. Therefore, note two will be played. In square three the hand is still in position two and the stepper motor has move on to position three. Note two will stop being played.

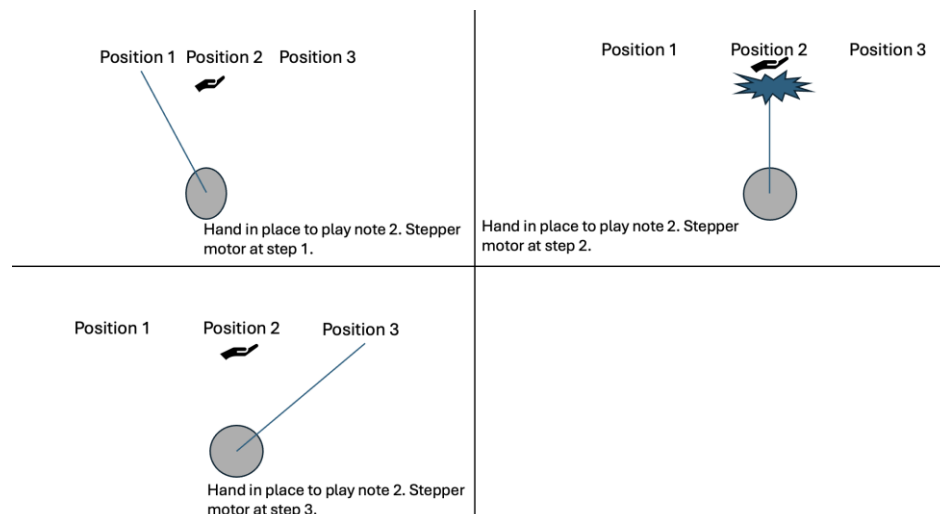


Figure 8 - Diagram of Note Timing

In conclusion the correct note will be played when the stepper motor is in that corresponding position. However, for the Laser Harp system we want to see multiple beams at the same time. In order for this to occur the speed of the stepper motor needs to be increased dramatically. Once, the speed is increased to the correct speed all the beams will be seen at the same time. The only reason we see the multiple beams is because of an optical illusion called the persistence of vision. Persistence of vision is when the human eye sees the continued presence of an image after the image is gone out of view [5]. The brain keeps the impression of the light for about a 10th to a 15th of a second after the image is moved from view [6]. Therefore, the user will be able to see all 7 beams but in reality, there is only one beam present at a time. The system works the same as the above scenario.

3.0 Relevant Technologies and Components Research

The success of the Laser Harp relies heavily on the seamless integration of its core components. Each component was carefully selected based on specific performance metrics and compatibility requirements. This section elaborates on the research conducted for the major components, highlighting the rationale behind each selection and the trade-offs considered during the design process.

3.1 Integrated Circuit

The PCB of the laser harp is possibly the most important part of the entire device. It will be the primary decision-making part of the entire harp. It is responsible for managing all the components and communicating between devices to achieve the intended results. The PCB is responsible for processing analog signals from the photodiodes, which determine if a string is being played. The PCB will also be communicating with an external Arduino, which is in turn controlling the stepper motor that produces each individual string from the laser harp. Taking the position of the stepper motor, the PCB, integrated with a sound storage module and a speaker, will produce the intended harp notes. The PCB will also be integrated with multiple other peripherals like foot pedals that will increase or decrease the notes by a semitone, dials that will be used to control the volume and octave level, and a display that will show octave and volume level. It is essential that the PCB is designed and integrated in such a way, with adequate components, that it will achieve its task in an efficient, and orderly manner.

3.1.1 Main Integrated Circuit

Many components will be featured and integrated in the PCB; however, there will only be one main integrated circuit. This integrated circuit will be the brains of the entire laser harp; managing and controlling every function that we wish to implement in our PCB. This is why it is imperative that we choose a component that will meet the needs for processing, and it is able to do it efficiently as possible, at the lowest price and complexity possible. There are many different components that could fill the role as the main processor of the laser harp, but we choose to only consider three different types of integrated circuits: microcontrollers (MCUs), field programmable gate arrays (FPGAs), and application-specific integrated circuits (ASICs). All three have advantages and disadvantages that can be compared and used to determine the optimal type of integrated circuit for the laser harp.

The primary consideration when deciding which integrated circuit would fit best for the laser harp is the flexibility and utility of the circuit. The main integrated

circuit will be the brains of the entire laser harp, so it would have to perform many different functions at task, usually in a short amount of time. When it comes to MCUs, they are a good match. Usually, microcontrollers come with a set architecture; fixed with predefined components like CPU, memory elements, oscillators and other peripherals all in a single board. Depending on the board chosen, one chip can be used in a wide array of applications. While they can be used to perform a wide range of tasks, they do lack the ability to change hardware configurations. FPGAs: on the other hand, offer greater flexibility in their hardware. FPGAs are a versatile type of integrated circuit that are designed to be reprogrammed to achieve different tasks. This versatility is achieved through an array of fixed programmable logic blocks and flexible interconnects. These interconnections can be rearranged to allow the FPGA to perform tasks of varying intensity. This is in contrast to ASICs. An ASIC is designed and manufactured for a specific purpose and cannot be reconfigured. Its internal transistors are arranged in a fixed structure with fixed and unchangeable interconnectedness. This allows them to be extremely efficient at performing their tasks, while lacking the flexibility to perform anything else. This means that if a specific application does not require certain functionality, like analog conversion for example, it would not be included in the chip. ASICs are the opposite extreme to FPGAs, which are programmable and reprogrammable after fabrication. MCUs are in the middle, they lack chip re-programmability but make up for it by allowing specific chips general versatility, including elements like CPU, memory and other peripherals that allow them to perform different tasks.

Another consideration is ease of use, and feasibility of the use. Microcontrollers are known for their ubiquity, not only for their use in a wide range of applications and products, but in amateur and academic electrical systems. MCUs are the primary integrated circuits that electrical and computer undergraduates are trained and taught on. They are also used heavily by amateur engineers and hobbyists for projects. This is due to their high ease of use. MCUs require a relatively basic amount of knowledge in embedded systems to be used effectively. They, due to their historic usage and ubiquity, have a plethora of information in books and on the internet on how to use them, functionality, use in different applications, and troubleshooting. Any information regarding any specific MCU chip can be found, either provided by the manufacturer themselves or by third-party users. MCU chips are usually programmed using an integrated development environment created by the manufacturer using well known languages like C/C++ and Java, with the occasional instances of hardware language like Verilog. All of this is in contrast to FPGAs which require a higher level of knowledge and expertise to use and integrate into a project. FPGAs require the extensive use of standard hardware description language (HDL) like Verilog or VHDL to configure and reprogram its interconnections. They require a different way of thinking and a deeper understanding of hardware concepts. Information about their usage is often supplied by manufacturer and vendor, but since they are used less by students, amateurs, and hobbyists, they have less amount of information to use. ASICs are at the same end as FPGAs. Since they are manufactured for specific tasks and purposes, they require an even greater

amount of knowledge in integrated circuits and embedded systems to design and use.

The final consideration is physical capabilities and economics. Due to their absolute ubiquity in electronics, MCUs have been tried and tested, and proven to be effective and reliable at processing information. They often; however, are only able to execute one instruction at a single time. This is offsetted by being capable of high processing speed that can create the perception of multiple instructions at once. MCUs are often inexpensive and have low power consumption. FPGAs are more efficient and high performing than MCUs. Due to them being an array of logic blocks, they are able to perform multiple instructions at once. FPGA hardware; however, is often more expensive and due to its relatively high processing, consumes more power and produces more heat than your average MCUs. ASICs, in contrast to both MCUs and FPGAs, are relatively expensive due to their being designed and manufactured for a specific task. Due to their specific design; however, they are more efficient and less power consuming than FPGA.

With all the present information considered, it would be advantageous to the project if the main integrated circuit on the PCB were an MCU. The MCUs offer a low barrier of entry, are relatively inexpensive, and have a huge repository of information in books and on the internet that could be used. Any advantages of both FPGAs and ASICs compared to MCU are unneeded; the efficiency and processing of both integrated circuits would simply be unnecessary to the point of extravagance.

Table 4 – Comparison of Main Processors

Parameters	Microcontroller (MCU)	Field Programmable Gate Array (FPGA)	Application-Specific Integrated Circuit (ASIC)
Processing	Medium	High	High
Efficiency	Medium	High	High
Ease of Use	High	Low/Medium	Low
Flexibility	Medium	High	Low
Cost	Low	Medium/High	High
Power Consumption	Low	High	Low

3.1.2 Microcontroller Overview

For the PCB design, we would need to choose a proper Microcontroller that can handle all the necessary interactions and procedures of the whole project. The requirements that we were looking for in the microcontroller were:

- Capable of Analog to Digital Conversion
- Capable of Digital to Analog conversion
- Capable of reading Photodiode/Sensor output
- Capable of being uploaded with C/C++
- Capable of SPI data transmission

For this project we had to find a couple of microcontrollers that would be able to handle all of these requirements and be relatively compatible with our project and skills. So, we made a list of microcontrollers that would be suitable for our project. Now at first, to select these microcontrollers we would start by looking at the specifications, and qualities that a normal piano keyboard would have. Going off this would be a good start due to a normal keyboard generally having more power (in terms of processing prowess and consumption) than our laser harp, so over-shooting is better than under-shooting.

With some of the microcontrollers, we found that some of them used the same processor, and because of that, we found it would be best to just select three from our list to test. Essentially, selecting three microcontrollers will allow us to get a chance to test the variety of the processor prowess. The four microcontrollers that we have decided to test were the ATMEGA328P-PU, the MSP430FR, the STM32, and the ESP32-Wroom. These four microcontrollers give us the ability to see how powerful the processors are and if we need to select a microcontroller with a higher clock speed or if we need more I/O pins. Generally, testing the microcontroller will give a better picture of what the final product needs to be functional.

3.1.3 ATMEGA328P-PU

The ATMEGA series of microcontrollers are typical microcontrollers used for Arduino boards, but our project will not be using only Arduino for the coding. This board is also able to be coded in C and C++, both of which will be needed for our project because of their compilation time. The ATMEGA328P-PU is a 32-bit core sized microcontroller from ATMEL, designed with an AVR processor.

With twenty-three input/output lines that are programmable, we will be able to have a microcontroller that can take all the necessary inputs from the user, including the controlling mechanisms like the foot pedals, and volume dial. In addition, the microcontroller will also be able to provide the necessary output for the speaker of the system. Having the ability to do Analog to Digital Conversion and Digital to Analog conversion will allow for the microcontroller to be able to

take the inputs from the photodiode and make an output signal necessary for the speaker to output.

This microcontroller provides an ideal balance between feature count, simplicity, and cost. This is functional for developing the complexity of the embedded systems of our project. Its extensive array of peripherals and Arduino/C/C++ coding support makes this microcontroller a very promising decision for use in our prototyping and maybe even our final product design.

3.1.4 MSP430FR6989IPZR

The first and only MCU board from Texas Instruments that we are investigating is the MSP430FR6989. The board is based on the high-performance 16-Bit MSP430 CPUXV2 core. The board offers a clock speed operating at up to 16 MHz frequency. According to the manufacturers, they are used in a wide range of applications in consumer, industrial and appliance domains and are used, according to the manufactures, in home appliances that utilize water and heat meters. They are also used in portable medical meters. The board scores a wide range of peripherals. The board has 86 pins, with up to 83 fast mappable I/Os. Some digital peripherals possible in the board are 32-Bit Hardware Multiplier, Three-Channel Internal Direct Memory Access, and five different 16-Bit Timers With up to 7 capture/compare registers each. For reading analog signals, the board utilizes a 12-Bit Analog-to-Digital Converter with internal reference and Sample-and-Hold, and capable of utilizing up to 16 external input channels used to read analog signals. It includes multiple low-power modes and incorporates a memory protection unit, a 128-Bit or 256-Bit AES Security Encryption and Decryption Coprocessor, and embedded memory elements like 128 Kbytes of FRAM, 2 Kbytes of SRAM. The board scores UART, I2C, and SPI communication use to interact with peripherals and other boards.

3.1.5 STM32C031F4P6

The first MCU board by STMicroelectronics that we are investigating is *STM32C031F4P6* board is based on the high-performance Arm® Cortex®-M0+ 32-bit RISC core. The core has a speed of up to 48MHz with both an internal and external oscillator. The board uses a memory protection unit (MPU), Up to 32 Kbytes of flash memory with protection, and 6 Kbytes of SRAM with hardware parity check.

It has four separate Low-power modes: Sleep, Stop, Standby, and Shutdown, which are good for power consumption, and it also has programmable brownout reset. The board has 20 pins, with up to 18 fast mappable I/Os. For analog readings, the board has a 12-bit, 0.4 μ s Analog-Digital Converter up to 13 channels with a conversion range: 0 to 3.6 V. It uses a supply voltage of 2V ~ 3.6V. To communicate with the separate Arduino board and the storage module, it has one I2C-bus interface, one SPI (24 Mbit/s) with 4 - 16-bit programmable bit

frame, and two USARTs with master/slave synchronous SPI. This MCU offers a lot of versatility and functionality that is needed in the project but is modest in its ability.

3.1.6 STM32L010R8T6

The second MCU board by STMicroelectronics that we are investigating is the. The board is used for a wide range of applications like gas/water meters and industrial sensors, remote control and user interfaces, PC peripherals, gaming, GPS equipment and alarm systems, wired and wireless sensors, video intercom.

The board is based on the ultra-low-power 32-bit MCU Arm®-based Cortex®-M0+ core. The core has a speed of up to 32MHz, which is less than the 48 MHz of the STM32C031F4P6. The board has internal and external oscillators that can vary the speed of the board from 32 kHz to 32 MHz. For memory, the board utilizes 64-Kbyte for Flash memory, 8-Kbyte for RAM, 256 bytes of data from EEPROM, and supports 20-byte memory in a backup register. The board only supports seven low-power modes: Sleep mode, Low-power run mode, Low-power sleep mode, Stop mode with and without RTC, and Standby mode with and without RTC. The board has up to 51 fast mappable GPIOs. For analog readings, A native 12-bit, extended to 16-bit through hardware oversampling, analog-to-digital converter is embedded into the board. The ADC has up to 16 external channels. Three channels are considered fast channels while the others are standard.

For communication, it has a 7-channel DMA controller, supporting ADC, SPI, I2C, and USART/UART. This MCU offers a greater ability in handling larger and more complex operations. Compared to the STM32C031F4P6, it has a larger number of GPIO pins, with larger memory elements; however, it has a slower max clock rate.

3.1.7 STM32C031C6T6

The third MCU board by STMicroelectronics that we are investigating is the *STM32C031C6T6*. The board is based on the high-performance Arm® Cortex®-M0+ 32-bit RISC core. The board offers a clock speed operating at up to 48 MHz frequency. According to the manufacturers, they are used in a wide range of applications in consumer, industrial and appliance domains and often used for systems that require communication between the board and other devices.

The board incorporates a memory protection unit MPU, embedded memory elements like a 12 Kbytes of SRAM and up to 32 Kbytes of flash program memory, and DMA. The board integrates 45 General Purpose Input-Output pins, where most of the pins are shared with special digital or analog functions. The board integrates multiple standard communication interfaces like one I2Cs, one SPI and two USARTs. For analog processing, the board has one 12-bit, 0.4 µs

ADC with up to 21 channels. The board contains multiple different timers: a low-power RTC, an advanced control PWM timer, four general-purpose 16-bit timers, two watchdog timers, and a SysTick timer. The board also supports four different low-power modes: Sleep, Stop, Standby, Shutdown.

Compared to the two previous MCU boards, it has the functionality of both of the MCU. It has the same max clock speed as the first, but larger memory elements, and more GPIO pins. For Potential prototyping, Stm32 also sells a predesigned development board with the *STM32C031C6T6* integrated on it.

3.1.8 ESP32-WROOM-32

The final board that we will consider for the laser harp is the ESP32-WROOM-32 made by the manufacturers Espressif Systems. The ESP32 is quite different from every other microcontroller examined, as it has a powerful, generic Wi-Fi + Bluetooth® + Bluetooth LE MCU module, that allows it to communicate with devices wirelessly. This has implications for the project and its stretch goals as the module could be used to upload sounds and songs onto the board through an external application on a phone or computer. The module uses a 40-MHz crystal oscillator. The board scores 38 total pins, with 35 of them being multipurpose GPIO pins that can be configured to a specific purpose. The board utilizes 18 separate channels for a 12-bit Analog to Digital converter, and two channels for a 8-bit Digital to Analog converter. The board utilizes multiple communication protocols like UART, SPI, I2C. The board also has embedded memory elements like 448 Kbytes ROM, 520 Kbytes SRAM, and a 16 Kbytes SRAM in RTC. To compare with all the other microcontrollers discussed above, the ESP32 doesn't have much in the way of hardware peripherals, as it lacks the number of timers and oscillators, and it lacks the storage size and elements of the other controllers like the STM32's. However, the board makes up for it with a large number of GPIO pins and two ADC channels that can be used with 18 different analog channels. The ESP32 is also quite energy efficient, making it one of the most powerful boards for the lowest consumption out of the ones investigated. The ESP32 comes with multiple configurations and is integrated in many different development boards that can be used for prototyping.

3.1.9 Development Boards

A part of the project that has been discussed frequently up to this point is the inclusion of a development board into the laser harp. A development board is an integrated, designed, preconfigured microcontroller board with peripherals that are used to develop hardware and software projects. They are heavily used by students, engineers, and hobbyists as they are easy to use, and already configured for specific tasks. We decided to include an external development board separate from our chosen microcontroller due to multiple reasons. To start, as explained above, they are easy to use, with a wide range of resources on the internet that can help us use them. Additionally, the development will see

extensive use in the early part of design, destiny, and implementation of the project. With a development board it is easy to test devices and code at a small or large scale without having to boot load code onto a bare microcontroller chip. Since the development board is separate from the main MCU chip, the board takes some of the processing load away from the chip, allowing for faster processing. This opinion is supplemented by the fact that we will use the development board to supervise two very important devices in our project, the stepper motor and its driver, and the laser diode and its driver as well. We chose to keep these together as the action of the stepper motor will in turn influence the action of the laser diode. The inclusion of both of these components into one board ensures that there is no delay between them. Apart from this, like stated above, both the stepper motor and laser diode will have a driver that will control their voltage and current draw. This will cause these components to be separate from the larger PCB design, so it would be best if these were controlled by an external board.

We decided to select one development board, apart from the main MCU chip, to be used for our project. Above, we looked at six separate MCU chips that could be used for the project. Out of the six, four of them, the STM32C031C6T6, ATMEGA328, MSP430FR6989IPZR, and ESP32-WROOM32, can be bought integrated as the development boards NUCLEO-C031C6, ARDUINO UNO R3/R4 Board, MSP-EXP430FR6989, and ESP32-DevKITC. respectively. We decided to use the NUCLEO-C031C6 by STMicroelectronics. We choose this as it allows us to program and control the stepper motor and laser with relative ease. The Integrated development environment for the board, CUBEIDE, is also a reason why we chose this board, as it allows us to configure the pins individually, and the IDE generates the code for the given configurations automatically.

3.1.10 Microcontroller Selection

Table 5 - Comparison of Microcontrollers

Microcontrollers Parameter	STM32C031F4P6	STM32L010R8T6	STM32C031C6T6
Processor	ARM® Cortex®-M0+	ARM® Cortex®-M0+	ARM® Cortex®-M0+
Clock Speed	48MHz	32MHz	48 MHz
Number I/O pins	18	51	45

Core Size	32-bit	32-bit	32-bit
Max Input Current (mA)	100mA	100mA	100mA
Input Voltage (V)	2V ~ 3.6V	1.8V ~ 3.6V	2V ~ 3.6V
Max Possible Power Consumption (mW)	360	360	360
Cost	\$1.01	\$2.25	\$1.43
Development Board Available?	NO	NO	Yes- NUCLEO-C031C6

Table 6 - Comparison of Microcontrollers

Microcontrollers Parameter	ATMEGA328P	MSP430FR6989IPZR	ESP32 WROOM 32
Processor	AVR	MSP430 CPUXV2	2 Low-Power Xtensa® LX6 Microprocessors
Clock Speed	20MHz	16MHz	40 MHz
Number I/O pins	23	83	36
Core Size	8-bit	16-bit	32-bit
Max Input Current (A)	200 mA	200 mA	500mA
Input Voltage (V)	1.8V ~ 5.5V	1.8V ~ 3.6V	2.7V ~ 3.6V
Max Possible Power Consumption (mW)	1100	720 mW	1800
Cost	\$2.74	\$8.34	\$6.56
Development Board Available	Yes (Arduino Uno R3-R4)	Yes (MSP-EXP430FR6989)	Yes (ESP32-DevKitC)

After consideration, we decided to utilize the ESP32 as our primary microcontroller chip. We decided to choose this board as it includes a good number of general-purpose pins. It also handles multiple communication protocols, having multiple channels for each one of them. The board also includes multiple ADC channels, whose pins can read and record analog signals; two pins accommodate DAC processing. The board also can communicate with devices wireless via WIFI; this is important for the stretch goals. The board is fast, small, and includes a large repository of information on the internet and in books. For the development board, we decided to go with the Arduino UNO R3-4 boards, which accommodates the ATMEGA328 chip. We chose this board as it is easy to use, easy to program, and members of the group already have some experience with it. Like the ESP32, it also has a large repository of information available.

3.2 Audio

The audio system is one of the most essential parts of the Laser Harp because it converts user interactions into musical output. Unlike a traditional harp that produces sound through the vibration of strings, this system relies on digital signals, embedded processing, and small-scale amplification to reproduce realistic harp-like tones. When a user's hand interrupts a laser beam, the signal is processed by the microcontroller, which determines which note to play and immediately triggers the sound output circuit. This design makes the instrument completely electronic yet still expressive enough to mimic the experience of plucking actual strings. By integrating the sound system directly into the harp's frame, our goal is to create a self-contained instrument that does not require extra plug-ins or a subwoofer. A well-implemented onboard sound solution will help demonstrate the project's practicality during its use.

Another important aspect of the audio system is its role in enhancing the harp's overall usability and user experience. Without clear, consistent, and responsive sound output, the Laser Harp would not feel intuitive to play. Because this is a contactless instrument, there must be minimal delay between the moment a beam is broken and the moment the corresponding note is heard. If the audio system introduces noticeable lag or distortion, it would reduce the musical quality and limit the harp's effectiveness in demonstrating real-time embedded control. Our team's design approach aims to keep the audio chain as simple as possible while still delivering a pleasing sound that resembles a real harp. The plan is to store high -quality pre-recorded samples in onboard memory, which will be triggered immediately when a beam is interrupted. This keeps processing demands low and ensures that the audio output matches the users intended note to play.

From the input to the speaker output there are multiple steps in between to allow for the input to produce the proper output with the appropriate volume level. The levels of this connection would be from the input of the user to the

microcontroller, then the microcontroller would grab the respective audio file from the memory space. With this audio file, the microcontroller will make a digital to analog conversion that will then be sent through an amplifier that will amplify the signal for the speaker to produce clean audio.

3.2.1 Audio Storage

The audio in the entire system will need to be stored somewhere the microcontroller can access with ease. Some microcontrollers have built in flash memory storage to allow for media storage and outputs, but this memory storage can be very limited so external memory storage may need to be used for the audio to be properly stored. The qualities of the external storage device will need have the following qualities:

- Capable of storing multiple types of audio files (like MP4, WAV etc.)
- Capable of providing quick data reading
- Compatible with microcontroller of choice.

We found the best device that would work for this would be the DFPlayer mini, and using this with a 32 GB micro SD will allow for enough space for the audio files, and libraries for the microcontroller and systems.

DFPlayer mini and Micro SD

For the sound storage of the project, we plan to use the DFPlayer mini manufactured by DFRobot. This device offers multiple features that will be necessary for the Serial Peripheral Interface between itself and the microcontroller. This can support up to 32 GB of storage, this will be enough storage to hold all the audio files for our project and libraries we may need to install for the microcontroller. The DFPlayer mini also has its own amplifier and DAC installed on the module, but we may not be using these features because of their limitations that can make them incompatible with our project. This device only needs a DC voltage of 3.2V – 5.0 V to operate, so it has a flexibility that will be good for our project. This with a 32 GB micro SD will allow for an efficient storage system for our project.

3.2.2 Audio DAC

In order for the system to provide a signal that can be outputted on the speaker, an analog signal will need to be outputted from the microcontroller. The digital analog converter will take the audio signal of the sound file from the audio storage and convert to an analog signal that can be amplified by the amplifier. The digital to analog converter will need to be efficient enough for the user to not notice a significant delay in the sound of the harp. That is why we find that an

external component for DAC will not be needed because we want everything to be concise and efficient. The Audio DAC will be a feature of the microcontroller that we choose because of conciseness, ease of implementation, and efficiency.

3.2.3 Audio Amplifier Design

From the microcontroller, there will be an analog signal that will be the audio signal for the string. The signal will have to go through an audio amplifier so the speaker can provide clean audible sound. The design of the amplifier will depend on the compatibility the type of amplifier has with the system and the specifications of its design. There are countless types of amplifiers that are used for audio, because of that we decided to just stay focused on a few classes of amplifiers that are more commonly used.

The four classes of audio amplifiers that will be handy for understanding are Class A amplifiers, Class B amplifiers, Class AB amplifiers, and Class D amplifiers. Class A, B, and AB are very similar but understanding how they work will show the flaws that each one is able to fix of each other but also show which one has the ideal specifications for our project. Class D works very differently from those but understanding it can allow us to find out which class of amplification will be ideal for our project.

The specifications that will be ideal for this project would be an amplifier that is able to:

- Handle the power that will be provided to it
- Compatible with digital or physical potentiometers that will be used for volume control
- Minimal distortion to output signal
- Minimal power consumption
- Compatible with the speaker that we will select
- Minimal release of thermal energy.

Throughout the analysis of these classes, we will be looking out for these specifications to see which one will provide the best compatibility with our system. Understanding all the specifics will allow for proper installation and troubleshooting in the event we run into problems.

Class A Amplifier

A class A amplifier is a very simplistic class of amplifier that uses at least one transistor with biasing to output an amplified signal for the audio of the system. The simplistic approach can be good to use, because of the amplifiers cost effectiveness and ease of troubleshooting.

The way class A amplifiers work is by having a transistor or a vacuum tube always on to conduct current throughout the entire input signal cycle. The way the amplification occurs is by having the bias point set so that the active components operate continuously in its linear region. So with a transistor, the signal input causes the current of the transistor to vary, and the transistor never turns off, it just conducts more or less current from the input, thus creates an amplification of the signal [7].

A noticeable problem with the class A amplifier would be that the amplifier is always on, which introduces more thermal energy into the system. In addition, the amplifier is not very efficient in the sound and has higher power consumption. But because of the linearity of the amplifier, and the fact that it is constantly on, it picks up all the qualities of the audio signal so there is no distortion in the amplifier. It offers a very high sound quality because it picks up everything on the audio signal, but it is not efficient. Quite a bit of the power that is inputted into the amplifier gets converted into thermal energy.

Class B Amplifier

The class B amplifier fixes the efficiency problem of the class A amplifier but introduces distortion because of the configuration of this amplifier. This amplifier, like class A, is also a linear analog amplification, but it also introduces less thermal energy in the system.

The way this works is by having two transistors work in tandem to amplify the analog input. Typically, one transistor, which will be an NPN transistor, will handle the upper region of the analog input, and the other transistor, which will be a PNP transistor, will handle the lower region of the analog input. This removes a significant amount of thermal energy, making a class B amplifier a more power efficient amplifier. However, due to limitations of transistors, in other words, transistors are never ideal, there will be an interval in the output wave where the input was being transferred. This pause introduces a new problem with amplification and distortion. This distortion can cause a very noticeable unclear audio output from the speaker [7].

Class AB Amplifier

The Class AB amplifier compromises the design of the Class B and Class A ways of amplification. The way this amplifier works is by doing the same way that

class B amplifiers take the input signal, where the transistors will take upper and lower parts of the signal, and fix the issue that class B amplifiers have with this. The way this fixes the problem of distortion is by having each of the transistors conduct a small extra portion of the upper part of the signal. This reduces the distortion because the area where none of the signals would get conducted by the transistor would become noticeably smaller. This also fixes the thermal energy and power efficiency problem with class A amplifiers [7].

This amplifier offers solutions to both the problems that Class A and Class B amplifiers faced but introduce some disadvantages when compared to the previous amplifiers. One problem would be that this amplifier can be more specific and expensive than Class A and Class B amplifiers. Another problem, would be that class AB amplifiers do experience similar problems from both class A and Class B, but they are significantly less problematic.

Class D Amplifier

Unlike the linear approaches of the previous amplifiers, the Class D Amplifier works almost in a completely different way. The other classes of the amplifiers work solely on the analog signal, and just amplified this signal, but in the Class D amplifier, the amplification is done through pulse width modulation. Class D amplifiers fix a lot of problems that the previous classes have but introduces complexity issues as well, due to its differing approach to amplification.

The way class D amplifiers work is by instead of linearly outputting the audio signal through an analog waveform, the class D amplifier would use pulse width modulation to represent the audio signal and rapidly switch the output transistors of the amplifiers to fully on or fully off. So, after the signal goes through a modulator and the switching output transistors, the signal would go through a low pass filter to remove the high frequency switching components, which would leave the audio-frequency content for the speaker, and this reconstructs the original waveform. The low-pass filter also helps reduce electromagnetic interference and thus helps the speaker by preventing the speaker from having too much high frequency energy. In order for the audio to not have distortion or loss of audio parts, the transistors must be very quick, the pulse width modulation uses a powerful amount of pulses of the audio, and the filter has to be lossless [8]. All these parameters allow for a functional and effective class D amplifier. This amplifier removes a lot of problems from the previous classes of amplifiers because it doesn't have a constant output going through, in other words, this amplifier consumes less power than the other classes.

Class D amplifiers have two different implementations for amplification, the single-ended and fully-differential. The implementation that will be best to use for our project would be the fully differential method because of the approach having a preferred use for average speakers. The other approach is mainly used for headphones. The reason for the fully differential approach is because of the

methods of access to its own ground and the amplifiers' ability to provide a significant amount of output power with the same single supply that the single ended approach would run with [9].

Amplifier Class Comparison

Table 7 - Table comparing the different amplifier classes

	Class A Amplifier	Class B Amplifier	Class AB Amplifier	Class D Amplifier
Power Efficiency	Around 25%, Not power efficient	Theoretical efficiency of 78.5%	<78% but >25%	<90%
Output Quality	Very clean, amplifies every part of the audio input	Has distortion in the output signal, but very little safeguard to it	Has distortion in the output signal, but has multiple safeguards for it	Depends on the pulse width modulation, and filters to minimize distortion
Amplification Process	Linear Amplification	Linear Amplification	Linear Amplification	Switching Amplifier via Pulse Width Modulation
Cost	Low	Low	Moderate	Moderate
Problem With Amplifier	Low power efficiency and high thermal energy	Distortion	Distortion and complexity with filter implementation	Distortion and complexity with pulse width modulation

3.2.4 List of Amplifiers

This will be a list of amplifiers that we found on throughout the research that we will be looking into and researching. We will try to select a variety of amplifiers to gain a wide perspective for what to choose. Mainly the goal is to choose multiple amplifiers of different power requirements to allow for flexibility in design changes or compatibility issues.

Mini Digital DC 5V Amplifier Board By NYBG

This amplifier is a good class D amplifier that will not need a lot of power to operate and will provide an output power that can power speakers that need 2-8 Watts of power. The voltage need for this amplifier is 5V, and it is surface mountable, so we can apply female headers to this board to directing solder it into our bigger PCB. This being a class D amplifier will provide that the amplifier will have good power efficiency for our system. In addition, the class D amplifier will also provide a clean audio output signal for our speaker. In addition, another feature about this amplifier would be that this amplifier is able to provide support for a stereo setup in system, in other words we can have two speakers connected to our amplifier to achieve left/right sound. In addition, this module offers a power efficient amplifier chip, specifically the PAM 8403 amplifier. With this chip the module is able to provide 90% power efficiency [10].

This speaker is optimized for lower power consumption and handle stereo speaker set up in our system but there are some disadvantages with this amplifier. One noticeable problem with this amplifier would be the amplifiers' low power output and handling. This amplifier may not be able to handle speakers that can have the range that we want with our harp, specifically going down to low notes. A range of the audio can depend on the quality of the speaker set up, and the wider range of speakers will require more power to function. Another problem with this amplifier would be the amplifiers lack of safeguards from noise from other components and thermal energy like a heat sink. Though these problems may be minimal they are still probable to come up in the further steps of the prototyping in this project.

Walfront Tpa3118 Bluetooth Amplifier Board

This amplifier fixes the problem that the previous amplifier had, which was the power output and the simplicity of the previous amplifier. This Walfront amplifier would require a minimum of 8 Volts DC, and it is surface mountable on our final PCB. This speaker offers safeguards for noise introduced by other components in our system. This being another class D amplifier does provide some benefits that will be optimal for clean audio for the harp [11].

This amplifier, as mentioned above, offers superior power output, which can be necessary for having range with our speaker when it comes to playing low notes. This amplifier will be able to power versatile speakers. Next would be the wide operating voltage ranges that this speaker gives, 8V to 26V, which can allow for flexibility in implementation of this amplifier in PCB design. The sophisticated design of this speaker allows for safeguards to connectivity and noise in our harp. This board also offers Bluetooth connectivity. This can be useful for possible advanced goals in the future, but most likely this feature will not be used in this project [11].

These amplifiers do have some problems that can make implementation possibly difficult in this harp. On disadvantage of this board would be its power requirements, there may be a possibility that a higher voltage than the minimum may be needed for the speaker to operate properly and with range for notes. This power consumption may be slightly difficult to accommodate if we are trying to optimize power consumption for efficiency and quality.

TDA2050 Mono Audio Amplifier Module

This amplifier will be used for the higher end speakers that will be able to play a very high range of notes for the audio system. This amplifier is an AB class amplifier, and it is designed to have low distortion, high power capability and a versatile operating voltage range. In addition, this module is able to be mountable on bigger PCBs. One problem with this module is that it only supports mono audio, so incorporating chords or polyphonic music may be difficult with this amplifier.

The reason this speaker would be a good option for this would be because it is able to play a variety of notes. But this speaker would be able to operate with the low-wattage speakers as well. The operating voltage range of the amplifier module is 5V – 24 V and with this voltage range it can output a power range of 5W to 120W [10]. These ranges can allow for flexibility with our audio system and power that can be allotted into the audio system. Due to the amplifier's compatibility with higher quality speakers, it can also provide higher quality amplification with minimal distortion as well. This module also makes for a quite affordable amplifier in the audio system, by only being around \$11.49 for a 2-piece set on amazon [62]. This would allow for experimentation with the speaker even when we wouldn't be using this final board in the end due to its experimentation.

Some of the problems that this amplifier may introduce is some of the problems that an AB amplifier introduces, such as the problem with distortion and thermal energy. But this module seems to have multiple safeguards with these problems, one being the big capacitors and properly biased transistors to allow for smooth audio amplification. The next thing would be that the amplifier has a sizeable heatsink that can help with the thermal energy problem, but introduction a fan or bigger heat sink can help with that as well. The amplifier chip that it uses is a TDA 2050 amplifier. The AB amplifier chip used on this board, TDA 2050, offers a reasonably high-power efficiency but it is notably lower than the other amplifiers. Only ranging from values less than 67%, according to its respective datasheet from STMicroelectronics, this offers a lack in power efficiency [12]. Despite having this limiting factor, it makes up to have a very versatile operating voltage and outputting power for a variety of systems and speakers.

This amplifier represents a very reasonable priced amplifier that can provide the necessary amplification for the audio system. Understanding the specifications

and limitations of this amplifier can allow for the proper implementation of this amplifier in the audio system of our project.

TPA3110D2 Amplifier Board

This audio amplifier from Texas instruments is a class D amplifier that can allow for a very powerful audio signal to go into the speaker. This amplifier operates from 8-24V and can output 15W signals for both the right and left. This module targets low-cost audio amplification with very optimal low distortion.

The benefits of this module would be the cost efficiently, on amazon, it's around seven dollars, and offers a very ideal amplification. The total harmonic distortion of this module is 0.1% and when testing the device, the amplified sound is very clean and audible. The operation voltage of this amplifier from 8 to 24V offers a very ideal compatibility with our project because of the 12V power source of our project. In addition to that, this module offers a very compact form that can be integrated into the project.

The negatives of this module would be the sensitivity it may have from noise with the DC input signal. If poor regulation is used, then the audio amplifier can produce audio that can be noticeably distorted. With this negative, the module offers a strong choice for this project due to its compatibility and quality of output sound.[64]

Amplifier List Comparison

Table 8 - Table Comparing Amplifier Options

	Mini Digital Amplifier	Walfront TPa3118 Board	TDA Mono Audio Amplifier	TPA3110D2
Amplifier Class	Class D	Class D	Class AB	Class D
Operating Voltage: Min - Max	5V- 5V	8V – 26V	5V – 24V	8V – 26V
Type of Input Voltage	DC	DC	AC/DC	AC/DC
Power Output range	2W – 8W	30W – 60W (30W per speaker port)	5W – 120W	15W

Manufacturer	NYBG	Walfront	HiLetgo	Texas Instruments
Mounting Type	Surface Mount	Surface Mount	Surface Mount	Surface Mount
Audio Channel	Stereo	Stereo	Mono	Stereo, Left and Right channels
Ohm Load for Output	4 Ohms	4 – 8 Ohms	4 – 16 Ohms	8 Ohms
Power Efficiency	90%	>90%	<67%	90%
Amplifier Chip	PAM 8403	TPA 3118	TDA 2050	TPA3110
Cost	\$5.97 for a pack of 5	\$11.02 for one	\$11.49 for two	\$6.17 each
Total Harmonic Distortion	Minimal from Class D amp.	Minimal from Class D amp.	Moderate from Class AB amp	Minimal from Class D Amp

3.2.5 Speaker Specifications

The type of speaker depends on the compatibility of it with the amplifier and other components of the project. The speaker will be taking an output signal from the amplifier to produce the sound of the respective string that was read from the user input.

The specifications of the speaker will be that it would need to be able to output notes as low as 65.41 Hz, and notes as high as 3951.07 Hz. This range is similar to the range of a typical piano, but our range will have to start an octave above the lowest note of a piano. The reason we can not have a speaker reach down to this is because this would call for a much higher quality audio system, by either having a subwoofer implemented in the system, or having an expensive system. Having a range of seven octaves would be consistent with other elements of our project and would make the implementation of the audio more straightforward.

Having this range will also give the final product flexibility with any tweaks or limitations that the system will have in the end. In addition, to having a flexible frequency output, it will need to have minimal power consumption. These are a few options that we find to apply with our amplifier and project.

Douk Audio 2.5" inch 8 ohm Hi-Fi Desktop Full Range Speaker

The Douk Audio speaker provides an affordable speaker for our project that also provides a decent range as well for the system. This speaker is a sizeable speaker as well, which can allow for an audible output of sound in our speaker.

One nice trait about this speaker would be its ability to operate with low power inputs and have a decent range with it as well. The speaker also has a desirable sensitivity, or volume potential, capable of reaching volumes of up to 88 dB, which is a very audible volume. With this sensitivity, the speaker has a good power handling that is quite compatible with our project, 8W – 15W [13]. This will be able to fill up the room very audibly for the user.

One problem with this speaker would be the frequency range, although it is a decent frequency range, the lower band of the range will most likely struggle playing the low octaves of our harp. The frequency response range is 150 Hz – 20kHz, which can play most of the notes that a typical harp can play [13]. What will most likely happen will be that the speaker will have a noticeable drop in audio cleanness when struggling to play thing C2 octave and a few notes of the next octave. The drop will be seen in fuzziness in output, drop volume and possibly unable to produce the note. The solution to this problem would be to include a subwoofer to the system, which fortunately can be implemented with the amplifier of our laser system.

Another advantage about this speaker would be that the speaker is affordable. By only \$13.99 on Amazon [13], this speaker can be doubled up in our system to allow for a stereo system or even allow our harp to play polyphonic tones. In addition to adding mor speakers, we would be able to give our audio system more sensitivity, or volume.

Tang Band W3-881SJ

The Tang Band W3-881SJ is bit of a pricy speaker but offer multiple features that make it a well-suited match for our project. This speaker is \$34.98 on Parts Express [14], so doubling it to make our audio system stereo will be more costly compared to other speakers. This speaker offers a range that will be almost a perfect match with our harp but offers good power consumption.

This speaker offers minimum power handling for operation is 15W and a maximum of 30W [14], which is desirable in our audio because it can allow for

flexibility between low Wattages and a little higher. It is around the middle of our power that can be allotted for our audio system. Next would be the speaker's ability to be audible and clean with audio output. The sensitivity with this speaker is 88 dB as well, so it will be quite audible for our harp.

The frequency response range for this speaker is 100 Hz to 20 kHz [14], this is a better range than the previous speaker but is still not able to produce a clean sound of the C2 octave, but it may be able to produce some sound better than the previous speaker. Due to this speaker being close it may be able to produce sounds that low with reduced distortion or problems. And it can produce sounds in the frequency range with a sensitivity/volume of 86 dB [14]. This volume is also a very powerful volume which is perfect for our harp to be

The Tang Band speaker is a well-designed speaker that prioritizes compact size but still maintains reasonable audio quality. This speaker offers power requirements that are flexible and a frequency response range that is compatible with our project. This speaker is a reasonable option to use for speakers in our project, even despite the slightly high price of the speaker.

Dayton Audio RS100-4 4"

Now this being another Dayton Audio speaker has a few similarities to the previous speaker, but this one is optimized in a way that fits our specifications more than other speakers. This speaker was able to have a more specific frequency range that is closer to the desired frequency range that we want with the speaker in the system.

The frequency range in this speaker according to the datasheet is 80Hz – 20 kHz, which is close to the desired frequency on the low end of the specifications. The desired note, C2, has a frequency of 65.41 Hz and this is quite close to the low end of the frequency range for this speaker. Although it is not in the range, the speaker will still be able to produce sounds down to 65.41 Hz, but they will not be of high quality when produced. When looking at the frequency response chart, we found that this speaker will be able to produce sounds down to 65.41 Hz with around 78 dB, which is quite audible [15]. Problems this may present are that when lowering the volume to certain levels, and playing down to the range, it may be a little difficult for the user to hear or difficult for the speaker to produce. A solution to this would be to implement a subwoofer into the audio system, but this would add another level of complexity and connections. That would be unnecessary since this speaker should be able to produce this note at an audible level on its own.

Speaker Comparison

Table 9 - Comparison of Speaker Options

	Douk Audio Speaker	Tang Band W3-881SJ	Dayton Audio RS100-4 4"
Manufacturer	Douk Audio	Tang Band	Dayton Audio
Model Number	LB020	W3-881SJ	RS100-4
Size, Diameter of Speaker	2.5 inches	3 inches	4 inches
Frequency Response Range	150 Hz – 20 KHz	100Hz – 20 KHz	80Hz – 20 KHz
Power Handling range	8W – 15W	15W – 30W	30W – 60W
Sensitivity/Volume in Decibels	88 dB	86 dB	87.5 dB
Impedance	8 Ohms	8 Ohms	4 Ohms
Cost	\$13.99	\$34.98	\$36.98

Audio System Selection

With careful analysis of the speakers and amplifiers and their compatibility with the entire project, we will plan the following combination. For the amplifier module, we plan to use the TPA3110D2 Audio Amplifier Module. This amplifier boasts a very versatile operating voltage and outputting power which is ideal for our harp. For the Speaker we plan to use the Dayton Audio RS100-4 4" speaker because of its frequency range and sensitivity. This also has power handling that will be compatible with our amplifier and can provide a strong sound that can

have clarity as well. Though the operating power is a little high, we believe adding some edits to the power distribution will make this audio system very functional and effective in our project. In addition, the mono audio system will allow for conciseness with the system and give straight clear sound for audio mixing if we try implementing chords to be playable in our project.

3.2.6 Volume Control

There are several ways to implement volume control from the user input. We will be analyzing three ways to implement this. One way will be through Digital Volume Control which will involve just having the microcontroller take the audio sample, applying volume scaling to it than sending it for the output. Another way would be to do an analog volume control approach, which will involve using digital potentiometers that would be controlled by the microcontroller. The next one would be an amplifier-based control approach, which will involve digitally controlling the amplifier in the system. In all three approaches, the microcontroller needs to have an ability to read some form of volume level in order for it to write it on the LCD screen. The approach will also need to be optimized enough for the entire project to remain efficient without delay.

Digital Volume Control

The digital Volume control involves full control of the digital audio signal before it reaches the digital to analog converter. This would be done through a processor that is capable of digital signal processing. This process can allow for a more precise signal that is capable of amplifying the audio signal with very fine adjustments.

The way digital volume control would work is by using a mathematical approach to adjusting the volume of the audio signal. When the audio is a digital signal, it is not a continuous time function but instead a function with disconnected values of time. This can be best described as a graph that just has thousands of numbers that represent the instantaneous value of the audio signal [13]. Now with these thousands of values that are organized by time, we can use the microcontroller that is capable of digital signal processing to apply the mathematical change to the numbers to adjust the volume of the audio signal. Then with this adjusted digital signal, it would be converted to an analog signal then sent to an amplifier for the speaker to produce.

This implementation of volume control has a high degree of precision and accuracy for the adjustments, but it does introduce new strain and computational necessities for the general processing of the system. Introducing new processing components to a single microcontroller can overwork the component and create latency, depending on precise we want the volume adjustments, and how much processing power is being used for the other parts of the project.

Another problem that one may face with implementing this control is that the microcontroller will need some form of digital signal processing. A simple digital to analog conversion may not be enough, another component may need to be added to allow for the mathematical adjustments of the samples in order to adjust the volume.

Analog Volume Control

The analog volume control is a relatively simple approach to adjusting volume. When the audio signal is leaving the microcontroller to be amplified by the amplifier for the speaker, the analog signal can adjust before it reaches the amplifier. This would be done by using a potentiometer before the amplifier. This approach is a straightforward, and simple way to adjust volume because it is directly adjusting the audio signal, so there is no digital signal processing in this approach. Thus, removing the processing strain that the digital volume control approach introduced.

The potentiometer is a variable controlled resistor, that will be able to be controlled by a dial. This dial is the volume control that the user will use. The biggest benefit of using this approach would be that the audio signal maintains its full audio resolution, so the output will not be distorted from this volume control.

There are multiple potentiometers that we can use for this. There are physical potentiometers that are controlled by a physical dial, with no digital input. And there are potentiometers that can be controlled digitally. Sometimes even both. For this system, a potentiometer that is controlled by the microcontroller would be the best approach, because the system would be able to read the volume level and have a precise control of the volume.

Despite the simplicity and functionality of analog volume control, potentiometers can suffer from wear, and possible channel imbalance over time. But one notable problem of potentiometers would be that they can introduce noise in the system, specifically in the low volume ranges, but a solution for that would just be to know the capabilities of the potentiometer and work around it to prevent problems. Other than that, analog volume control can be a very effective approach to adjusting the volume.

Amplifier-Based Volume Control

This approach involves control of the volume through the amplifier instead of using the microcontroller or an extra component. Instead of changing the input signal, the signal would be amplified to the level that the user sets for it. This approach would require a specific amplifier that is capable of variable control of the amplification, which can be possibly costly.

This approach would eliminate some problems from the previous approaches, such as not having a potentiometer that would introduce more thermal energy in the system and not giving the microcontroller more processing strain. But it does have its own problems as well. With this approach, the amplifier will need to be able to have variable control, preferably through a dial. In addition, we want the volume level to be constantly read and shown on the LCD, so the amplifier will have to be able to be controlled with the microcontroller to achieve this. This can introduce some problems with compatibility, because the microcontroller must have this feature, and can possibly increase the price.

The approach can also produce a cleaner audio signal for the speaker and minimize noise in the system and has promising signal-to-noise advantages. But the problem with this approach would be the specifications that we will need with the amplifier and microcontroller (which can increase price), and this approach can be possibly complex with its implementation. This method introduces a variable configuration of a crucial component of the audio system, which can possibly have unpredictable outputs in the implementations which would require software design that will attenuate to that.

Volume Control Selection

Because of the capabilities of the microcontroller, we believe that the Digital volume control will be the best way to implement volume control. The reason for this is because this approach allows for direct readings of current volume control for the microcontroller to output on LCD. In addition, this approach will use features that are integrated into the microcontroller and its coding libraries, so this approach will be perhaps the most efficient and concise. Implementation of this approach will also be easier to implement because it would just involve coding the microcontroller and dial to work together.

3.3 Photodetection Device

3.3.1 Overview

A photodetection Device is needed because there needs to be a trigger for the harp to play the sound. Because we are using a light source the detector needs to react to light. Hence the photodetection device. The device will need to be able to see the scatter of light. The scatter will be reflected back down onto the device. Therefore, the device needs to follow specific parameters.

3.3.2 Types of Photodetection Devices

When choosing a photodetection device there are two main options to consider. A photoresistor or a photodiode. Photodiodes also have a broader spectral response which means it will be capable of reacting to 520nm [16]. However, a

photoresistor has a narrower spectral range but can see 520nm very well. A graph from reference 15 shows that spectral response of a photoresistor. As you can see 520nm is near the peak of the graph. The graph from reference 14 shows the spectral range of a silicon photodiode. In this graph 520nm is not near the peak of the graph. Meaning the photodiode will still respond to the 520nm but its response to wavelengths closer to 950nm better.

However, photodiodes tend to have faster response times while photoresistors tend to have slower response times [17]. For the application of the Laser Harp a faster response time is more desirable. Due to this we have chosen to use a photodiode for our project.

Some other key factors that need to be taken into consideration when choosing the right photodiode. The first key parameter is wavelength sensitivity. This is determined by what the photodiode is made from. For a range of 180nm to 1100nm [16]. This is great for our application because the wavelength we chose is 520nm.

The second consideration is the active area of the photodiode. Because the light is diffused light and not going directly into the photodiode it would be most desirable to have a larger active area. With a larger active area there is an increase in response time and an increase in cost. The third consideration is the dark current. A low dark current is important to reduce the noise. With a larger active area there is an increase in dark current. A fourth consideration is the capacitance of the photodiode. For a faster response a lower capacitance is needed [18]. For the purpose of this project the photodiode selected is the FDS100 by Thorlabs. This photodiode has a wavelength range of 350 nm -1100 nm. A larger active area of 13 mm^2 and a rise/fall time on 10 ns [19]. In the decision the second-place contender was the FDS1010. The FDS1010 has a very large active area of 100 mm^2 [20]. However, the area in which the diffracted reflection reflects onto is a large area. Meaning we would possibly need more than one photodiode. The FDS1010 cost \$65.46 for one photodiode. It is a cheaper and equally good option to use the FDS100 for the Laser Harp.

Table 10 - Comparison of Photodiode

PN	FDS100	FDS1010	1125-1419-ND	751-1015-ND
Product name	FDS100	FDS101	MTD3910PM	BPW34
Manufacturer	Thorlabs	Thorlabs	Marktech Optoelectronics	Vishay Semiconductor Opto Division

Wavelength range	350 – 1100 nm	350 – 1100 nm	400 – 1100 nm	430 – 1100 nm
Active Area	13 mm ²	100 mm ²	1.21mm ²	7.5 mm ²
Rise/Fall Time	10 ns	65 ns		100 ns
Packaging	TO-5	un-housed ceramic wafer	TO-18	Top view
Dark Current	1 – 20 nA	600 nA	10 nA	30 nA
Capacitance	24 pF	375 pF	12 pF	40 pF
Cost	\$17.55	\$65.46	\$5.61	\$1.23

Some major changes were made for the photodetection subsystem. The primary change would be the inclusion of a transimpedance amplifier that would convert the generated current into an amplified voltage. A reverse bias of 3.3V will be used for the photodiode, and a TL08X series operational amplifier was used for the TIA.

3.4 Stepper Motor

3.4.1 Stepper vs Servo

Choosing the right motor for the Laser Harp's rotating mirror is a key design decision that affects how accurate and responsive the instrument is. The motor's main job is to spin a lightweight mirror at a steady speed so it can split a single laser beam into several beams, creating the virtual strings the player interacts with. To do this well, the motor needs to rotate precisely and consistently while keeping vibration and noise low to avoid messing up the beam alignment. It also has to work smoothly with the microcontroller and sensors, which rely on perfect timing to match each beam with the right photodiode. If the motor drifts or misaligns, it could trigger the wrong notes and ruin the playing experience. Because of this, the motor must stay stable over time, handle different loads, and run efficiently on limited power. To meet these needs, our team compared different motor types and carefully balanced cost, control, and reliability.

After comparing stepper and servo motors, our team decided that a stepper motor is the best fit for the Laser Harp's mirror system. Stepper motors are great for precise, step-by-step rotation and are easy to control with a microcontroller. We chose a standard NEMA 17 stepper motor, which is common in 3D printers. It offers 200 steps per full turn, or 1.8 degrees per step, giving us the accuracy we need to split the laser beam into clear, predictable positions. This smooth, controlled motion helps keep the beams steady and reduces any jitter that could throw off the alignment. Unlike servos, stepper motors don't need extra feedback hardware, which keeps costs and complexity down. They also hold their position firmly when stopped, so the mirror stays locked in place even when the system is idle but powered on.

By comparison, a servo motor allows for continuous rotation and has built-in positional feedback thanks to its encoders and control electronics. This makes servos a good choice for projects that need variable speeds, quick acceleration, or exact positioning when loads change, like robotic arms or machines that need to change directions often. However, for the Laser Harp, the scanning mirror only needs to spin in one direction at a steady, predictable speed to keep the fan of beams stable. Since there aren't any sudden load changes or direction switches, a servo's advanced features aren't really needed. Using a servo would also mean we'd need more complex PWM signal generation, tuning control loops, and calibrating encoder feedback just to reach the same accuracy a simple stepper motor can already provide. This would make the software side more complicated and create more potential points of failure, which doesn't make sense for what this project actually requires.

In summary, after looking closely at all the performance needs, costs, and how everything fits together, our team decided that a stepper motor is the best choice for the Laser Harp's rotating mirror. It gives us the precise positioning, steady rotation, and easy control we need without adding extra hardware or making the software more complicated than it has to be. By using a standard NEMA 17 stepper motor, we can control the beam positions accurately and still have the flexibility to adjust the speed and step settings as we test and fine-tune the system.

Table 11 - Comparison of Stepper vs Servo Motor

Feature	Stepper Motor	Servo Motor
Control Type	Open-loop (no feedback by default)	Closed-loop (uses feedback via encoders)

Precision	High (especially with microstepping)	Very high (due to feedback control)
Holding Torque	Excellent (maintains position without movement)	Depends on control; usually requires active power to hold
Speed Range	Lower to moderate speeds	High-speed capable
Complexity	Simpler control circuitry	Complex; requires encoder and PID tuning
Noise/Vibration	More vibration, especially at high speeds	Smoother and quieter operation
Power Efficiency	Less efficient (draws constant current)	More efficient (draws current as needed)
Suitability for Laser Harp	Excellent: accurate, simple, cost-effective	Overkill: too complex for fixed, predictable motion

3.4.2 Stepper Motor Overview

A stepper motor is a specialized type of brushless DC motor that divides full rotation into a number of discrete, equal steps. Each pulse sent to the motor causes the shaft to rotate by a fixed step angle, allowing for highly controlled motion without the need for feedback systems such as encoders. This makes stepper motors ideal for open-loop control systems, where simplicity and cost-effectiveness are priorities. They are widely used in printers, CNC machines, 3D printers, camera platforms, and robotics [21].

Unlike traditional DC motors, which rotate continuously as long as voltage is applied, stepper motors move incrementally and maintain position at each step

when powered. This feature is particularly advantageous for applications requiring precise positioning and repeatable movement. Since the position is determined by the number of input pulses, software control becomes easier and more predictable [22].

In the Laser Harp, the role of a stepper motor can vary depending on the complexity of the design. It may be used to reposition mirrors that reflect the laser beams, rotate beam-splitting prisms, or even create a dynamic "scanning" effect where the beams move across a user's hand to simulate multiple strings. These applications benefit from the stepper motor's precise control and ability to hold position without drifting.

Stepper motors are categorized by their step angle, torque characteristics, and phase configuration. They are typically controlled using stepper drivers that translate control signals from a microcontroller into the correct sequence of coil activations. These drivers can operate in various stepping modes to increase smoothness and resolution [23].

The simplicity, affordability, and availability of stepper motors make them a go-to solution for many embedded and mechatronic applications, especially in educational or prototyping environments. However, understanding their limitations and correct usage is key to achieving optimal performance.

3.4.3 Types of Stepper Motors

There are three main categories of stepper motors used in electromechanical systems: Permanent Magnet (PM), Variable Reluctance (VR), and Hybrid Stepper Motors. Each type is distinguished by its rotor design, construction method, and performance characteristics, which directly impact how they perform in real-world applications [24]. These motors convert digital input pulses into mechanical rotation, offering open-loop control without the need for encoders or feedback systems. The differences between the three types mainly involve step resolution, torque output, speed characteristics, and overall complexity. Understanding these distinctions is crucial in selecting the right motor for specific applications such as 3D printing, CNC machines, robotics, or, in our case, a laser harp. Each motor type offers its own trade-offs between precision, power, and cost, which must be weighed against the design requirements and constraints of the system. In this section, we will explore each motor type in detail, discussing how they work and how they compare in terms of reliability, efficiency, and ease of integration. This foundational understanding helped our team justify the use of the NEMA 17 hybrid stepper motor for the harp's scanning mechanism. Our decision was based not only on theoretical evaluation but also on practical industry component availability. Proper motor selection plays a pivotal role in the harp's performance and stability, especially when driving mirrors for laser projection with precision and consistency [25].

Permanent Magnet (PM) stepper motors utilize permanent magnets in the rotor and typically have a lower step resolution, offering larger step angles such as 7.5° , 15° , or even 18° . These motors operate based on magnetic attraction between the stator's energized coils and the rotor's permanent magnets. While they are mechanically simpler and more cost-effective than other types, PM motors provide limited torque and less precision. As a result, they are generally used in low-end consumer electronics, such as printers, toys, and simple automated devices, where fine control is not critical [26]. Their reduced manufacturing complexity makes them an attractive choice for applications constrained by budget rather than performance. However, in projects requiring precise motion control or smooth rotation, such as musical instruments or scanning systems, PM stepper motors fall short due to their inherent limitations in resolution and torque consistency. Another limitation is that PM motors can suffer from increased vibration and audible noise at low speeds due to their coarser step angles. This makes them less desirable for applications that demand silent operation or high-frequency response. For the Laser Harp project, where beam accuracy and repeatability are essential, PM stepper motors would not meet the system's precision requirements. Nonetheless, they serve as an important baseline in understanding stepper motor evolution and are still widely used in teaching and entry-level prototyping.

Variable Reluctance (VR) stepper motors differ from PM types in that they do not contain any permanent magnets in the rotor. Instead, the rotor is composed of soft iron with multiple projecting teeth, which align with stator poles as current is sequentially applied to stator windings. This type of motor relies on the principle of minimum magnetic reluctance, causing the rotor to move to the position where magnetic resistance is lowest. VR stepper motors tend to offer high stepping rates, making them responsive and capable of quick motion changes [27]. Their simple rotor design results in low inertia, allowing for fast acceleration and deceleration, which can be advantageous in certain automated systems. However, VR motors typically produce less torque than PM or hybrid motors and suffer from increased operational noise and mechanical vibrations. They also tend to lack the smoothness and positional accuracy required for high-precision tasks. As a result, they are more suitable for applications where speed is prioritized over resolution, such as basic robotic actuators or textile machinery. The lack of a magnetic field in the rotor also limits their holding torque, reducing their effectiveness in systems that require static holding positions without energization. In the context of our Laser Harp system, these drawbacks outweigh the benefits, as the goal is to maintain stable and repeatable angular positions for accurate laser beam placement [25].

Hybrid Stepper Motors combine the key advantages of both PM and VR technologies. These motors incorporate a toothed rotor structure similar to VR motors and embed a permanent magnet along the rotor shaft to enhance magnetic coupling with the stator. This combination results in significantly finer step resolutions, typically around 1.8° per step (200 steps per revolution) and even down to 0.9° in some higher-end models [28]. Hybrid steppers offer higher

torque density, smoother rotation, and more accurate positioning than the other two types. Because of these qualities, hybrid stepper motors have become the standard in modern applications that require precision and stability, including 3D printers, CNC machines, and lab automation equipment. Their compatibility with microstepping drivers also allows smoother motion profiles, further reducing vibration and improving mechanical response. One drawback is that they are typically more expensive than PM and VR motors due to their more complex manufacturing. However, the performance gain in terms of resolution and reliability often justifies the cost for applications where performance matters. The hybrid stepper's robust torque and precision characteristics make it especially well-suited for controlling rotating mirrors in optical scanning systems like our Laser Harp. Their ability to hold position without feedback or closed-loop control makes integration simpler while still achieving professional-grade performance. Additionally, they are widely supported in both hardware and software ecosystems, making them a convenient and scalable choice for development and future upgrades [24].

In most modern embedded or electromechanical applications, hybrid stepper motors like the NEMA 17 are favored for their optimal balance of performance, standardization, and accessibility. The NEMA 17 form factor (1.7 inches wide flange) is a de facto standard in the maker and research communities, making it easy to source, mount, and replace [29]. These motors typically offer a step angle of 1.8° , with torque ratings that are suitable for rotating lightweight components like mirrors or discs. The availability of compatible stepper drivers, such as the A4988 or TMC2209, allows for advanced control features like microstepping, current limiting, and silent operation. This level of control is crucial for minimizing jitter and maintaining laser alignment accuracy across performance sessions. In addition, the physical dimensions of the NEMA 17 are compatible with compact hardware designs, fitting well into the form factor of the frameless harp. It also simplifies integration with existing 3D-printed brackets or aluminum frames used in the construction of our prototype. Ultimately, the selection of a hybrid stepper motor ensures both consistency and expandability, aligning well with the project's long-term goals and technical demands. Its widespread use also means the team can rely on extensive documentation, community support, and vendor availability, reducing risk throughout the development cycle [28].

Table 12 - Comparison of Stepper Motors

Feature	Permanent Magnet (PM)	Variable Reluctance (VR)	Hybrid Stepper Motor
Rotor Composition	Permanent magnet rotor	Soft iron rotor with teeth	Soft iron rotor with teeth + permanent magnet

Step Angle	Larger (7.5°, 15°)	Moderate to small (typically 7.5°–15°)	Fine (typically 1.8°, can go as low as 0.9°)
Torque	Low	Low to moderate	High
Resolution	Low	Moderate	High
Speed Response	Moderate	High (fast acceleration/deceleration)	Moderate to high
Vibration & Noise	Moderate	High	Low (especially with microstepping)
Control Complexity	Simple	Moderate	Moderate to high
Power Efficiency	Low to moderate	Low	Moderate to high
Holding Torque	Moderate	Low	High
Drawbacks	Low resolution, noisy operation at low speeds	Noisy, low torque, less smooth motion	More expensive, slightly more complex control circuitry

3.4.4 Advantages and Disadvantages

Stepper motors offer several key advantages that make them ideal for precision motion control in embedded applications. Their ability to rotate in precise increments without feedback simplifies the control system and reduces cost. This is especially beneficial in applications like laser harps, where precise control of visual or sound elements is necessary [30].

The inherent "holding torque" of a stepper motor means that it can maintain its position firmly when powered, without the need for brakes or external locking mechanisms. This makes it ideal for applications requiring static positioning, such as a laser harp scanning mechanism that must stop at exact angles. Another major advantage is the ease of control. Unlike servo motors, which require feedback and closed-loop systems, stepper motors can be controlled with simple

digital signals. This reduces system complexity and is ideal for beginner-to-intermediate level embedded systems projects.

However, stepper motors are not without drawbacks. One major limitation is their efficiency. They draw current regardless of load, resulting in wasted power and heat generation. Without proper current limiting or sleep mode management, they can overheat in idle states [31]. Additionally, stepper motors lose torque as speed increases. At high RPMs, their performance drops significantly, making them unsuitable for high-speed applications. They also risk "losing steps" if overloaded or poorly driven, which can lead to positional inaccuracies in critical applications.

3.5 Laser

3.5.1 Overview

The type of laser used to create the strings is extremely important. For the user to play the laser harp well, they need to be able to see the strings (laser beams). In order to do that, we are using a wavelength within the visible section of the electromagnetic spectrum. The electromagnetic spectrum spans from $10^{-15}nm$ to 10^9nm . The spectrum is broken down into seven different bands. Radio waves, microwaves, infrared, visible, ultraviolet, X-rays, and gamma rays. Each band has a different name and a corresponding frequency range. For our system, we need a wavelength in the visible frequency range. The visible spectrum falls between the wavelength range of 380 nm to 700 nm [32].

3.5.2 Wavelength Selection

The sensitivity of the human eye to light at certain intensities varies throughout the visible spectrum. The luminous efficiency function shows the average spectral intensity of humans' perception of light [33]. In the reference number 2 there is a graph that shows the human eye's response to all the wavelengths in the visible spectrum. On the graph the peak wavelength is the green spectrum. The average normal sighted human is most sensitive to green light [34]. Green light falls in the range of 500 nm to 570 nm. From this you can conclude that green light is the brightest and therefore easiest color for the human eye to see. The peak wavelength the eye can perceive for light conditions is 555nm and the peak wavelength the eye can see for dark conditions is 507 nm. However, we are choosing to use a wavelength of 520 nm, which is a good middle ground, in our laser harp system.

3.5.3 Type of laser

The most common green laser source is a laser diode. When picking a laser diode there are important things to consider. One of them is the packaging style. There are many different packaging styles for laser diodes. Two for example are cylindrical module packaging and TO (Transistor Outline). A cylindrical module packaging is a complete laser diode module. Unlike the TO can which is the raw laser diode. Another thing to consider when picking a laser diode is thermal management. Laser diodes can get really hot when operating so it is important to pick a diode that is good at dissipating heat or use heatsinks to dissipate the heat. Raw laser diodes like the TO can do not cool well on their own and need a cooling system. For example, a heat sink would work well. To operate the TO can it is possible to also need a driver. A laser diode module already has a cooling system and driver in the device.

The power of the laser diode module average around 5mW. The power of the photodiode is based on how much photocurrent the electoral system needs from the photodiode. After deliberation it has been determined that we need μA of current. For the FDS100 that was chosen the math is as follows.

$$I_{ph} = R * P \quad \text{Equation 1}$$

Where I_{ph} is the photocurrent

R is the responsivity

P is the optical power

Directly going into the photodiode, the photocurrent is

$$I_{ph} = 0.27 * 0.005 = 1.35mA$$

However, the Laser Harp system is using diffused reflection into the photodiode and not a direct laser beam. For than 1% of the laser power reaches the photodiode the photocurrent is as follows.

$$P = 0.01 * 0.05 = 0.0005 W$$

$$I_{ph} = 0.27 * 0.0005 = 13.5\mu A$$

Therefore, 5mW of power will be enough power for the laser diode and the laser diode module could be used. However, there is another factor that comes into play when picking how much power the laser diode should have. In order for the Laser Harp system to be played easily the beams need to be visible. The more power the laser diode has the more visible the laser beams "strings" will be. Once you get above 5mW of power the laser diode becomes a class 3B laser. There are certain safety measures that will need to be taken into account. Those measures will be in the safety and regulations section of this document. Since we know that a minimum of 5mW can get us the proper amount of current needed

for the electrical portion we know that increasing the power can only benefit the photocurrent value. Therefore, how much photocurrent that gets generated is no longer a concern. So, the main factor that needs to be focused on is the visibility of the strings.

An experiment was held to see how visible the laser will be if the power is increased. The experiment consisted of a high-powered fiber coupled laser with a collimator at the end. The power of the laser was able to be varied. Therefore, the power was varied from 10mW to 25mW. When looking at the 10mW beam it was pretty much invisible to the eye. The only thing that was able to be seen was the beam spot. As the power was increasing the 25mW the beam was still invisible to the eye. The Laser Harp system will be played in a darker room. To make the experiment more accurate to the users setting the lights were turned off on the room. When the lights were turned off the beam became slightly visible. The conclusion of the experiment is that the more power the better. For the Laser Harp system it is best if a 100mW laser diode is chosen. The laser diode does not have to operate at the max output power. The team will be able to vary the power and select which output power gives that gives the best-looking beam. The team will also use a fog machine to aid the user to be able to see the beam better. Another benefit of a high power is the more intense the reflection will be on the photodiode which will increase the amount of photocurrent.

Something not technical that is really important to think about is the lead time on parts. Because of this it is necessary to think about where you are buying the part from. This lead time data was from when the TO can option was considered. The data in this paragraph was taken when the 10mW power option was being considered. The website that was looked at was on was DigiKey. For PLT3 520FB there is a lead time of 16 weeks and for PLT5 520DB_P there is a lead time of 10 weeks. The 10-week lead time is a better option however when looking at the scope of this senior design project 10 weeks is too long to wait for the laser diode to come in. Especially because the laser diode is key to get the laser harp to function properly. Therefore, other websites had to be looked into. The PLT5 520DB_P was found on electromaker with 217 in stock. With 217 in stock the lead time should be shorter than DigiKeys' lead time. The laser diode actually selected is from Amazon and will be here within 4 days of ordering with Amazon prime. In the table below the amazon listing does not have a complete datasheet. Because of that it does not have all the specifications the other laser diodes have. That is why the operating current is marked n/a.

When integrating the components together and trying to pulse the laser to make the beam fan, we were having a bit of trouble. The laser diode would drop in intensity, or the laser diode would burn. Because of this we decided to switch to not pulsing the beam and have it constant wave. Then the beam would propagate through 7 slits. We also realized that we could use a less powerful laser. Therefore, we decided to try a laser module off Amazon. The Qiaoba says that it is 5mW however when measuring the power, it ended up being 10mW.

After using both the laser diode and the laser module we ended up sticking with the laser module. As a bonus, the laser module only costs \$16.77.

Table 13 - Comparison of Laser Diodes

PN	475- PLT3520FB- ND	720-PLT3520D	475- PLT5520DB_P- ND	Laser Module 520nm Green Laser Dot Laser Diode
Product name	PLT3 520FB	PLT3 520D	PLT5 520DB_P	B0D35Y419W
Manufacturer	ams-OSRAM USA INC.	ams-OSRAM USA INC.	ams-OSRAM USA INC.	Qiaoba
Packaging size	3.8mm x 2.5mm	3.08mm x 2.15mm	5.6mm x 2.3 mm	12mm x 35mm
Operating current	110mA-130mA	225mA – 60mA	43mA -60mA	N/A
Output intensity	50mW	110mW	10mW	approx. 5mW
Class	3B	3B	3B	3B
Cost	\$33.89	\$41.56	\$14.73	\$15.69

3.5.4 Laser Diode Driver

A big part of the project, which is reliable on to effectively implement our frameless laser harp is effective control of the laser diode. The laser diode will be controlled by a microcontroller, toggled on and off at certain times as the stepper motor is turning to produce the seven individual strings. But due to the specific specifications of the laser diode, this cannot be achieved by directly connecting

the laser diode to the microcontroller. The Arduino does not supply enough current nor produce enough voltage to operate the laser diode. Another quality of the laser diode that must be addressed is operational limits. If the current or the voltage increases above the operational limits, it could damage the diode. The diode has a tendency to increase in conductivity when it increases in temperature; improper control of this new current level will damage the diode. This is why the diode must be controlled by a laser diode driver. The driver is a device that will regulate the current and the voltage drop of the diode, preventing it from being damaged.

For this project, we chose not to buy an external laser diode driver. Most diode drivers that are sold on the market do not meet the specification asked by the laser diode's datasheet; either too little voltage is produced, or not enough current is produced by the source. The laser diode drivers that do meet the required operational voltage and current are too expensive, and too complicated to effectively implement in our project. They are too large, or produce too much heat, or are rated for a stronger diode. That is why we decided to design, and manufacture our own diode driver for the project, meeting our specific specifications to effectively control the laser diode.

3.6 Other ways to do the project

3.6.1 Overview

We have decided for the final design that the system will use a stepper motor and a laser diode to produce the laser beam fan. The stepper motor will move in steps at a frequency fast enough to see the 7 beams. However, we did consider other options before finalizing our decision.

One of the ways that was debated was using a diffraction grating to create the 7 beams. This option totally cuts out the need for a stepper motor. Before we go into that approach to the Laser Harp it is important to know what a diffraction grating is. A diffraction grating is an optical component that contains microscopic and periodic groove structures. This splits the incident light into multiple beam paths (by phase changes). With diffraction gratings different wavelengths propagate at different angles. You can think of a diffraction grating to be similar to a dispersion prism. A prism separates the different wavelengths of light and makes a rainbow (if using a white light source). Where the grating splits the light into multiple beam paths. The prism depends on refraction where the grating depends on diffraction [35].

There are two types of diffraction gratings. One type of grating is a transmission grating where light transmitted forms the phase change pattern. The most common type of diffraction grating is a reflection grating. A reflection grating is when a reflecting surface has the microscopic periodic structures on it and the

reflected light forms the phase change pattern [36]. Something important to note about diffraction gratings is that the output angle changes with different wavelengths. The grating separation also contributes to the output angle [35]. The image below on the left is a schematic showing a transmission grating and how the beam goes through the grating and then is split into the different angles. The image below on the right shows a reflective diffraction grating and how the incident light is reflected and split into multiple beams.

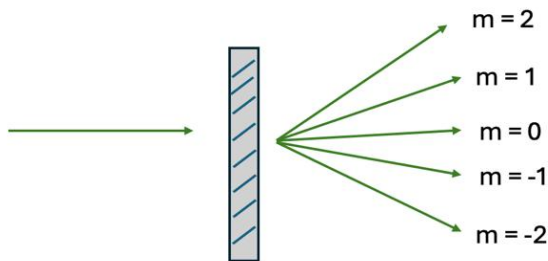


Figure 9 - Diagram of reflection Transmission Grating

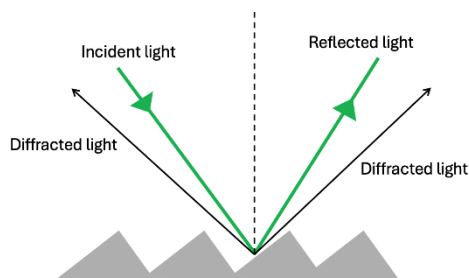


Figure 10 - Diagram of Transmission Diffraction Grating

3.6.2 Transmission Reflection Grating Configuration

For the Laser Harp we would have used a transmission diffraction grating. The set up is shown in figure 10 below. The set up would have been a laser diode with a collimating lens and beam expander pointed at a mirror which would turn the beam upward into the diffraction grating. Then the light would propagate through the grating and create the different beams. The user would then block the light with their hand and the photodiode with a collection lens would catch the reflection of the light. Which would then trigger the electronics to produce the corresponding sound. The main problem with this configuration is that you cannot easily vary the angle in-between the beams. The output angle is determined by the wavelength of the light and the size of the grating. In order to use the Laser Harp easily it is important that there is enough space in between the beams for a person's hand to fit. When using a stepper motor it is easier to program and vary the angles the beams propagate. By choosing the stepper motor we have more control over the system as a whole.

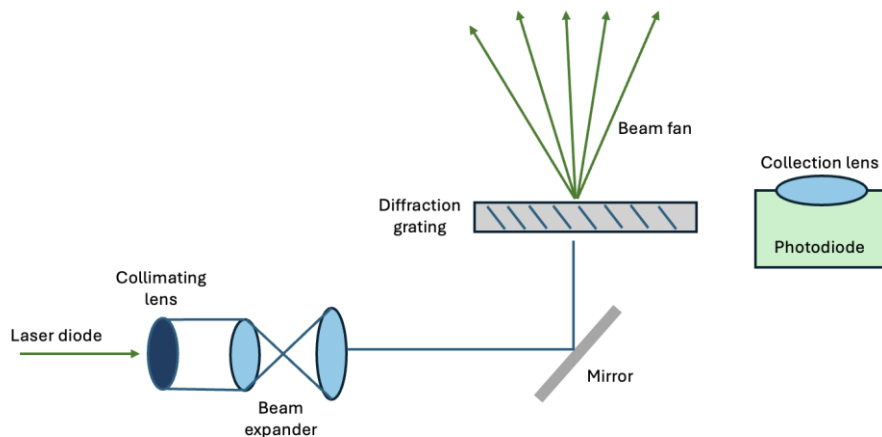


Figure 11 - Transmission Diffraction Grating Laser Harp Configuration

3.6.3 Reflection Diffraction Grating Configuration

Another option that was considered was the use of a white light source and a diffraction grating to create a rainbow. The image below contains the set-up of this version of the Laser Harp. The source would have been a white light source. This way the diffraction grating would create a rainbow output. The white source needs to be collimated. A pin hole with a focusing lens would be placed in front of the source. After, the pin hole and lens the light would be collimated. Though it is collimated the size of the beam would be bigger than needed. Therefore, a beam condensing system would be put in place. The beam condensing system would consist of a negative lens followed by a positive lens. Now that the beam is collimated and condensed it gets sent to a mirror which angles the beam on the reflective diffraction grating. The diffraction grating takes the incident white light and outputs a rainbow of light. At the end of the rainbow a CCD is put in place. The CCD would have been used to detect the absence of light when the users hand blocks a portion of the rainbow.

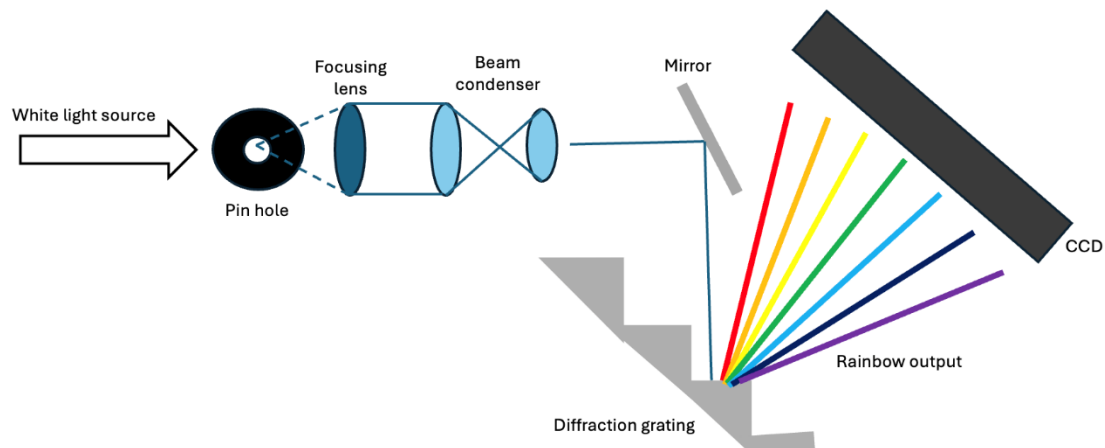


Figure 12 - Reflective Diffraction Grating Laser Harp Configuration

After looking into CCD versus photodiode for the Laser Harp system. We discovered that using a photodiode would be best for our application. Charged-Coupled Devices or CCDs are used more for high quality imaging. For example, CCDs are used a lot in astronomical telescopes, microscopes, and medical equipment. Photodiodes are used for high-sensitive responses to light and have many specialized applications. One application that they are generally used for and that is particularly important for the Laser Harp applications is their use in reflectance or scattering measurements [37]. One big factor in choosing the Laser Harp configuration that we did is the cost. CCDs are also generally more expensive than photodiodes. The average cost for a CCD is over \$100. Where the photodiode we chose for the Laser Harp is \$17.55.

3.7 Compiling/Uploading Software

This project utilizes embedded systems, and in order to properly apply the systems in the components of the project, development environments and compiling software will have to be used in this project. There are multiple development environments, and compiling software and in this section will analyze and compare the software's to see which would fit the best for our project.

3.7.1 Xilinx Vivado & Vitis IDE

The Xilinx products provide multiple applications in embedded systems, from its ability to use Verilog to having its own Development environment that run C++ code on boards for more complex situations.

Xilinx Vivado is very powerful when used effectively, because the whole suite is able to synthesis and perform analysis of PCB designs and Field Programmable Gate Arrays (FPGAs). This software is very extensive in its capabilities because it is able to visualize the embedded systems schematic. It is also able to do High-Level Synthesis for C/C++ designs and also implement the code directly onto the board. The software can also provide detail about the pins, inputs, outputs and behaviors of the components of the system. This allows for us to gather some essential information that can allow for effective debugging.

In addition to Vivado, Vitis IDE is a powerful development environment that can be used to debug the C/C++ designs of the microcontrollers. Vivado and Vitis IDE are able to work together to allow for effective development and implementation of the software system. Compiling with these tools can be very powerful due to their efficiency and functionality.

However, these tools do have a couple of drawbacks with their powerful applications. One big problem with these tools would be that these tools have

some noticeable learning curves and complexities. Specifically, it can be very difficult for people not accustomed to Xilinx tools to use them for individual projects. Usually, Vivado is used with an established board manufacturer, like Xilinx, due to the master files that are made public for use of Vivado on the board. Using our own PCB would create problems immediately for this, because we would have to create our own constraints, and master files. Due to the complexity may take to creating this, it will make the development of the software much longer, and less straightforward than if we were to use other Development environments.

3.7.2 Code Composer Studio

The next development environment that can be used for the software design of our project would be Code composer studio. This Integrated development environment created by Texas Instruments is designed for developing and debugging embedded systems on microcontrollers and other applications. This development environment provides multiple benefits that can make it better than Vivado.

One noticeable benefit would be the simplicity of this development environment. Code Composer is very applicable to a wide range of real-time systems, especially original projects using real-time systems. When it comes to the coding, it requires knowledge of the pin layouts and knowledge of how components will interact with each other. With these pillars, Code Composer Studio can be a very powerful IDE for uploading code onto the Microcontroller due to the straightforward nature. Texas Instruments usually makes products that are quite accessible, for example, Code Composer studio is free to use which makes this software very cost efficient

Code Composer Studio, like Vivado, provides rich visualization and analysis tools for the embedded system. Features like, variable viewing, signal graphing and performance analyzers, these can be very useful tools for debugging and optimizing.

Another powerful quality of Code Composer would be its capability to handle C/C++ designs. With this we can keep to a very efficient coding language that can handle the input and output variables in the system. Another thing about these designs in Code Composer studio, would be the coding design's capability to handle interruptions in the loops, and have measures to deal with input noise.

A big problem with Code Composer Studio, is its lack of compatibility with Microcontrollers, specifically that it can only interact with Texas Instruments Microcontrollers, which can be limiting for our project. Another problem would be that Code Composer can be resource intensive for large projects, but the coding in our project will not be big so this will not be much of a problem.

3.7.3 Arduino

The integrated Development Environment of Arduino is a very accessible and simplistic. The software is the primary platform for programming Arduino microcontrollers and compatible boards, so the versatility of this software is quite limited to select microcontrollers. There are many positives about this development environment and compiler but there are couple drawbacks with it as well.

One big positive about this software would be its simplicity, it has a very simplistic interface and syntax. It can handle C/C++ designs, which can make our system run efficiently. Advance features like code analysis and pinout visualization are not present in this Development Environment.

Arduino development environments have multiple support communities and documentation that can help with optimization and sophistication of software design. It can lack some form of project management, which may be necessary for complex projects. But with this project that will not be much of a necessity due to the simplicity of the coding and software design that will be implemented.

The development environment of Arduino is more of a straightforward, or hobbyist software, while it can be used professionally, it can be quite limiting in complex projects because of its lack of advanced coding capabilities but for this application it may be very powerful because of its ease of use.

3.7.4 STM32 Cube IDE

This development environment is for the use of the stm32 series of boards. Which automatically makes this software limiting in its compatibility, but it is quite accessible to the public (By being free to download). The software is built on an Eclipse CDT framework. The microcontroller that we would be using with this development environment would be the stm32 series, such as the Nucleo boards. And it being able to handle C/C++ designs makes it able to be compatible with this project.

The interface of this development environment can allow for a good visualization of the microcontroller that is being coded. The development environment can also be able to be efficient in the start of software project because of its ability to generate code and configurations from the pin out. One disadvantage of the development environment would be that it can be a little overwhelming for beginners because of the number of options and menus on the interface. A way around that would be to familiarize ourselves with the interface and the fundamentals of the development environment.

This development environment can be relatively straightforward for the embedded systems, but it can still be a little limited in its capabilities because of

the development environments lack of advanced features for more complex and sophisticated projects. But our project being relatively simple in the software design, this problem shouldn't be much of a problem and the implementation of the software through this development environment should work smoothly.

Coding Language Selection and Comparison

There are various coding languages to select such as C, C++, Python, Verilog, etc. We found that C remains a very common use in the industry, but the language can have some limitations when it comes to embedded systems. Python, on the other hand, has a very simple syntax and fast development and testing cycles procedure to it, but the language does have slower execution and higher RAM and flash usage. This can prove not the most suitable for this project. The Arduino C++ provides balance between ease of development and hardware-level capability, making it suitable for rapid prototyping in embedded systems. The language is object oriented, so sophistication and capabilities of the language is very optimal for this project. In addition, the language is C based language, so it is faster to run and uses less memory to operate and compile due to its similarity in level to assembly.

In the end, Arduino C++ was picked because it combines accessibility, flexibility, community support, and enough performance for typical microcontroller applications, providing both easy development and understanding of libraries and professional-grade control where needed.

Integrated Development Environment Selection

We believe that Arduino will be the best fitted development environment for our project. This environment is compatible with many types of microcontrollers, which can allow for flexibility in our project. This development environment is also a software that we are familiar with, and it is software that many other engineers at UCF are familiar with as well. So having the community support will help with making designing the software much smoother and efficient. Despite Arduino being a basic development environment, its simplicity is what makes it very compatible with our project. Our project is not very complex when it comes to software design, so simplicity can help with implementation.

3.8 Communication protocols

One of the most important parts of the project, integral to its functionality, is the communication between devices, and peripherals. Besides communication between components like displays and storage elements and the microcontroller, but communication between the main microcontroller and the arduino board that will be used to control the stepper motor and the laser diode. Effective

programming of these communication protocols will ensure that every component is in sync with each other, doing the functions they are designed to do. Below, we will go over some of the communication protocols that we might be using in this project.

3.8.1 Universal Asynchronous Receiver/Transmitter

The most basic communication protocol that could be used in the development and implementation of this project is the Universal Asynchronous Receiver/Transmitter (UART) protocol. This protocol might be the simplest and easiest way for a MCU, or Arduino board to communicate with each other or with the computer. It involves the communication of UART modules between each other, using a single wire to transmit data. The data is transmitted serially, one bit at a time, with the data bounded by a start and stop bit. Unlike most other communication protocols, UART utilizes asynchronous communication, as each device generates its own clock signal, relying on a predetermined baud rate to read the incoming information. We will be utilizing UART primarily in prototyping, testing, and implementation; using UART to communicate between the MCU/arduino and the computer to display reading on a terminal display like Putty. We will also use UART when using the development board as a bootloader for the MCU chip that we will select.

3.8.2 Inter-Integrated Circuit Communication

To communicate between chips, or between components in a project over relatively short distances, Inter-Integrated Circuit Communication (I2C), is used. Unlike UART which uses one wire, I2C uses two wires, serial data (SDA), and serial clock (SCL), using a synchronized clock to communicate between devices. The protocol is very effective as it could be configured in a way that supports communication of one singular master device and multiple slaves. This is possible because data, when transmitted over the SDA wire, contains within it the destination address of the slave receiving the data. The data message also contains a read/write bit, which indicates to the receiver if the data is meant to be read and stored, or written. This protocol will likely be used extensively during implementation, and production of the laser harp, as I2C is used when displaying text on a LCD screen, or reading data from a memory card, as we will in the implementation of the project.

3.8.3 Serial Peripheral Interface

One most widely used communication protocol, and one that we'll most likely be utilizing in this project will be the Serial Peripheral Interface (SPI) communication protocol. Just like the I2C protocol, SPI utilizes a master-slave relationship between the devices. The master, controlling the clock signal between devices,

sends data bits synchronized with the clock to the slave device. Unlike I2C, the protocol utilizes a total of four different pins to communicate between devices. The first two are MISO (Master Input Slave Output) and MOSI (Master Output and Slave Input), which are the wires that the data physically travel through; MISO is meant for communication from the slave to the master, and MOSI is used to send data and instruction from the master to the slave. Two more wires are used, Slave select (SS), which is used to select and ready the slave device that is meant to receive data. The other wire controls the serial clock (SCLK), which drives the clock of the slave devices. There are a lot of advantages that we will take advantage of in our project. The first is that, since MISO and MOSI are two separate wires, the master can send and receive information simultaneously. This is important as it ensures quick communication between devices. As reiterated before, the primary MCU will be communicating with an arduino board, which is driving the stepper motor and laser diode, and exchange information about the position of the stepper motor. This operation has to be done quickly so sound can be played correctly. Another advantage is that the data transfer rate is faster than I2C, since it doesn't utilize start/stop bits and acknowledgements between slave and master.

3.9 Motor Controller

3.9.1 Overview

The objective of a motor controller or driver in the laser harp project is to regulate the electrical input to the stepper motor, ensuring it operates accurately and safely within its specifications. A stepper motor driver converts low-power digital control signals from a microcontroller, such as the ATmega328P, into high-power voltage and current signals suitable for driving a stepper motor. This allows for precise control of the motor's rotation, position, and speed—essential for maintaining consistent laser alignment in the harp's optical array. The driver ensures that each step signal corresponds to a specific degree of rotation, translating software-based control into real mechanical movement.

Stepper motors, unlike DC motors, require phased input signals to rotate, which makes a driver circuit indispensable. A basic motor driver takes care of this phasing logic, enabling the motor coils in the correct sequence and duration. Without a driver, the microcontroller would be incapable of supplying the necessary current and might even be damaged attempting to drive the motor directly. Furthermore, modern stepper drivers support advanced control features such as microstepping, which subdivides motor steps into finer increments for smoother motion and reduced vibration. This feature is particularly beneficial in the laser harp, where beam jitter or misalignment would negatively affect sound mapping and user experience.

In our application, the controller must allow for real-time updates to the motor's position, as the rotating mirror assembly will be used to fan out laser beams at

fixed angular intervals. The precision of the motor driver directly correlates with the accuracy of beam spacing and the responsiveness of the system to user interactions. Additionally, we must ensure that the driver can handle the rated current and voltage of our chosen NEMA 17 stepper motor, typically around 1.2 to 2.0 A per phase. The motor controller also contributes to system stability and power efficiency, making it a core component in the hardware architecture.

Another key objective is system reliability. The laser harp must operate consistently over extended periods without overheating or introducing jitter into the laser pattern. Therefore, thermal performance and protection features, such as overcurrent and thermal shutdown, are critical attributes of any motor controller we consider [38]. The selected controller must also be compatible with the PWM (Pulse Width Modulation) or step/dir interfaces commonly used with microcontrollers. This will allow seamless integration with our embedded software system and simplify the process of writing control routines.

Lastly, the motor driver must be cost-effective and readily available to meet our project timeline and budget constraints. While industrial-grade motion controllers offer extreme precision, they tend to be overkill for small-scale projects like ours. We prioritize a balance between affordability, ease of use, and performance. By clearly defining these objectives, we can confidently narrow down our motor driver selection to a device that supports our overall goal of creating an interactive, visually appealing, and functionally reliable laser harp.

3.9.2 Types of Motor Controllers

There are several categories of motor controllers suited for stepper motors, each with different capabilities, form factors, and levels of complexity. The most common types include discrete transistor-based circuits, H-bridge drivers, chopper drivers, and intelligent motion controllers. For laser harp applications, we focus on stepper-specific motor drivers, as they are tailored to control the unique pulsing nature of stepper motor coils. Each of these types has specific trade-offs regarding cost, complexity, efficiency, and precision.

Discrete transistor drivers consist of individually wired transistors or MOSFETs arranged to form logic-controlled switches. While this method provides learning opportunities and customization, it lacks current regulation, microstepping, or thermal protection. This makes it unsuitable for the precise and delicate control required in a laser harp. H-bridge drivers, while ideal for DC motors, can also be used in full-step mode for bipolar stepper motors. However, they typically lack advanced stepper-specific features like microstepping, leading to jerky motion and audible noise during operation.

Chopper drivers are among the most common and effective solutions for stepper motors. These drivers use current chopping and pulse-width modulation to regulate the current in each coil, preventing overheating and maintaining torque at various speeds. Popular examples include the A4988 and DRV8825, both of

which support microstepping and come with onboard current limit settings. These are widely used in 3D printers, CNC machines, and robotic applications for their balance of simplicity, functionality, and cost. They are well-documented and widely supported in open-source hardware communities [38].

Digital motion controllers go a step further by integrating advanced features like trajectory planning, encoder feedback, and communication protocols such as SPI, UART, or CAN. While powerful, these controllers are often expensive and over-engineered for small embedded applications like ours. They are typically reserved for high-end automation systems or robotics where adaptive control and closed-loop feedback are required. For our purposes, a simpler driver with manual or digital configuration is more appropriate.

Finally, some hybrid motor drivers combine traditional stepper control with simple feedback mechanisms. These hybrid systems offer improved position accuracy and fault detection without the complexity of fully closed-loop systems. However, they are relatively new and costlier than basic stepper drivers, with limited availability in the market. Thus, for a reliable and practical solution that matches our needs, we focus on open-loop chopper-style stepper drivers that have been field-proven in comparable applications.

Table 14 - Comparison of Motor Controllers

Category	Discrete Transistor	H-Bridge	Chopper Driver	Digital Motion Controller	Hybrid (Semi-closed-loop)
Precision	Low	Low–Moderate	High	Very High	High
Current Control	No	Limited	Yes	Yes	Yes
Microstepping	No	No / Full-Step	Yes (1/8–1/32)	Yes	Yes
Ease of Use	Complex (manual setup)	Moderate	Easy	Complex	Moderate

Cost	Low	Low–Moderate	Low–Moderate	High	Moderate–High
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3.9.3 TB6600 and DRV8825

Precise control of the stepper motor is essential for the successful operation of the laser harp, as it directly affects the alignment and positioning of the laser beams that simulate the strings. Any inconsistencies in rotation or stepping could lead to misalignment of the beams, ultimately impacting sound accuracy and user interaction. After carefully reviewing a variety of stepper motor driver modules, we identified two promising candidates that matched the electrical and performance requirements of our system: the TB6600 and the DRV8825. Each driver was evaluated based on criteria such as current output, microstepping resolution, ease of integration, footprint, and thermal performance.

The DRV8825, developed by Texas Instruments, is a widely used stepper motor driver known for its compact form factor, cost-effectiveness, and microstepping capabilities of up to 1/32 step resolution. These features are especially beneficial for applications that require fine motion control and smooth operation—qualities that are critical in the operation of our rotating mirror, which is used to fan out the laser beam into multiple playable strings. The DRV8825 operates over a voltage range of 8.2 V to 45 V and can handle up to 2.2 A per coil with proper heat dissipation. Additionally, its simple STEP and DIR control interface is highly compatible with our ATmega328P-based control system. It also comes with built-in protection features such as thermal shutdown, under-voltage lockout, and overcurrent protection, which enhance its reliability in embedded applications. Its popularity within the maker community has also resulted in extensive documentation, libraries, and troubleshooting resources—reducing the development time significantly.

In contrast, the TB6600 is a more robust, industrial-grade stepper motor driver capable of delivering up to 4.5 A of current. This makes it especially well-suited for high-torque motors or situations requiring prolonged operation under moderate to high loads. The module includes a larger PCB footprint and an integrated heat sink, making it more resilient under thermally stressful conditions. The driver also features a DIP switch configuration interface that allows for quick adjustments of microstepping modes (from full step up to 1/16 microstepping) and current limits without any software changes. This ease of hardware configurability was particularly useful during early prototyping when we needed to quickly experiment with different motor behaviors. However, the size and external wiring requirements of the TB6600 make it less suitable for final integration in a compact, battery-powered musical instrument. Nonetheless, its rugged performance and ease of tuning made it a valuable tool in the early phases of hardware development.

For our initial prototype, we decided to use the TB6600 due to its proven stability, ease of setup, and higher current-handling capability. These qualities allowed us to focus on validating the motor control system and mirror movement without needing to address heat dissipation or fine-tuned voltage settings early on. Its forgiving thermal and electrical tolerances provided a safe testing environment while we refined other aspects of the system. As we transition toward Senior Design 2 and prepare to build a more compact and fully integrated version of the laser harp, we plan to shift to the DRV8825. Its smaller footprint, lower cost, and PCB-friendly design make it better suited for our final implementation. We will conduct thorough durability and performance testing of the DRV8825 to ensure it can handle continuous operation while delivering the microstepping precision required to align the laser beams reliably.

By using the TB6600 in the early development stages and the DRV8825 in the final design, we are taking a phased approach that balances reliability, scalability, and system optimization. This approach not only allows us to meet immediate functional requirements but also gives us the flexibility to fine-tune motor behavior and performance as the design evolves. Both drivers have played and will continue to play an important role in helping us meet our goals of building a precise, responsive, and user-friendly laser harp.

Table 15 - Comparison of TB6600 vs. DRV8825 Stepper Motor Drivers

Feature	TB6600	DRV8825
Microstepping Support	Up to 1/16	Up to 1/32
Max Current Output	Up to 4.5 A	Up to 2.2 A (with heatsink)
Operating Voltage Range	9V – 42V	8.2V – 45V
Form Factor	Large, bulky module	Compact, PCB-mountable module
Built-in Protections	Overheat, overcurrent, short-circuit	Overcurrent, undervoltage, thermal shutdown
Cooling Requirements	Built-in heatsink (generally sufficient)	Requires heatsink or external cooling

Cost	Higher (~\$10–\$15 per unit)	Lower (~\$3–\$5 per unit)
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3.9.4 Advantages and Disadvantages

Selecting the appropriate motor driver for the laser harp was a critical decision that required balancing performance, size, cost, and long-term integration. Both the TB6600 and DRV8825 drivers offer unique advantages that made them valuable to different phases of our project. Their combined use during prototyping and final implementation provides both stability in testing and flexibility in system optimization.

The TB6600 driver has several compelling advantages, especially for early-stage development. Its high current-handling capacity (up to 4.5 A) and built-in heat dissipation via an integrated heat sink make it ideal for stress-free prototyping. The simple DIP switch interface allows for rapid adjustments to microstepping and current settings without requiring code modifications, saving time during tuning and experimentation. Additionally, the TB6600 offers excellent thermal reliability, with built-in protections against overheating, short circuits, and overvoltage. These features were especially helpful during initial system trials, where unknowns about power draw and load conditions made stability a top priority. Its ability to interface with most standard microcontrollers, including the Arduino Uno and ATmega328P-based boards, also ensured wide compatibility during testing.

However, the TB6600 also comes with some disadvantages. Its physical size is significantly larger than that of the DRV8825, making it impractical for compact or portable systems. It is designed more for industrial or bench-top environments, not lightweight embedded applications like our laser harp. Additionally, while it supports microstepping up to 1/16, this resolution is lower than the DRV8825's 1/32 capability, resulting in slightly less precise motor control. This lower resolution is acceptable during early testing but may introduce minor inconsistencies in final beam alignment. Finally, its higher power requirements and wiring complexity make integration into a custom PCB more challenging, which is why it was not chosen for the final design.

The DRV8825, in contrast, is well-suited for compact embedded systems. Its main advantages include a smaller form factor, higher microstepping resolution, and integration-friendly pin layout. It supports microstepping up to 1/32 steps, allowing smoother and more precise motor rotation—an essential feature for ensuring clean laser beam alignment and minimizing vibration. The wide voltage range (8.2 V to 45 V) and current-limiting capability (up to 2.2 A per coil) provide flexibility in power supply selection while maintaining motor safety. The DRV8825 also includes onboard protection features such as overcurrent protection, undervoltage lockout, and thermal shutdown. These safeguards increase the system's robustness and reduce the risk of hardware failure due to environmental

stress or user error. Its compatibility with many existing software libraries also accelerates development, as it can be quickly implemented without requiring custom low-level drivers.

Despite these strengths, the DRV8825 is not without its challenges. Its maximum current output is lower than the TB6600, and reaching 2.2 A requires excellent thermal management through external heat sinks or fans. Insufficient cooling could lead to thermal shutdowns or degraded performance over time. Additionally, setting the current limit on the DRV8825 requires manual tuning via a potentiometer, which introduces a slight learning curve and potential for user error. While its microstepping performance is excellent at moderate to high speeds, some inconsistencies arise at very low step frequencies, which could require extra calibration in precision uses. Furthermore, the DRV8825 is generally more sensitive to poor wiring or noise compared to more rugged drivers like the TB6600.

In conclusion, both drivers serve distinct but complementary roles in our design pipeline. The TB6600 provides a reliable and forgiving platform for early-stage experimentation and functional validation, especially where space is not a concern. On the other hand, the DRV8825 offers the fine motor control and compact size necessary for final system integration. By leveraging the strengths of both drivers at different phases of development, we were able to reduce risk, streamline prototyping, and prepare for a successful transition into a polished, portable, and efficient final product. This dual-driver strategy reflects our broader design philosophy: begin with reliability, finish with refinement.

3.10 LCD Screen

3.10.1 Objectives

The inclusion of an LCD screen in the Laser Harp project is central to the user interface and overall user experience. As the instrument operates in real time and requires feedback about current musical parameters, the LCD will serve as the main output for displaying system states. Specifically, it will show the current volume level, octave, and musical key being played. This enables the user to quickly verify how the harp is configured without needing to rely on audio cues alone. In interactive educational settings, this feedback becomes even more essential, as users may not be trained musicians and need visual support. Having these parameters available at a glance encourages experimentation and hands-on learning. The LCD also helps in situations where external sound levels are high or the user cannot distinguish musical intervals clearly. By reinforcing auditory information with visuals, the instrument becomes more accessible and intuitive. This aligns with one of the core goals of the project: to create a harp that is inclusive, educational, and easy to use for both novices and experienced users.

From a technical perspective, the LCD screen serves as a point of convergence for user input and system response. When a user presses a button, adjusts a knob, or activates a foot pedal, the LCD can immediately reflect the change in system state. This creates a real-time feedback loop that reinforces the functionality of the controls and validates system responsiveness. Without the LCD, users would need to guess which octave or key is selected until they begin playing, which could result in confusion or unintended output. By making these changes immediately visible, the LCD increases usability and reduces the cognitive load required to operate the instrument. It also supports the implementation of additional control features in future versions, such as menus for tone selection or system diagnostics. The screen becomes a communication bridge between the embedded system and the human user, which is critical for any interactive musical instrument. This objective goes beyond convenience—it directly affects how learnable, responsive, and user-friendly the device will be.

The LCD also plays a role in enhancing the aesthetic appeal and professionalism of the final product. While the Laser Harp is an engineering prototype, it is also a musical instrument designed for demonstration in public and academic settings. Including a neatly mounted LCD display gives the device a more finished and high-tech look. It signals to observers and users that the device is not just a collection of wires and sensors, but a functional, thoughtfully designed system. In STEM outreach events or public exhibitions, this kind of polish makes a strong impression. When potential users see system values updating in real time, it adds a level of credibility and intrigue to the interaction. This objective may seem secondary compared to technical performance, but it plays a key role in user perception and engagement. Ultimately, design is not just about what a system does, but how users feel when they interact with it and the LCD will be a major part of creating that experience.

Lastly, the LCD fulfills a critical objective in terms of user accessibility. The frameless nature of the Laser Harp already removes many physical barriers to playing an instrument, but the LCD extends this accessibility into the visual and cognitive realm. For users with hearing impairments, seeing the musical key or octave visually may provide additional context that audio alone cannot. For children or users without musical training, the display can guide learning and exploration. This reinforces the harp's role as an educational and inclusive tool. It also allows the development of modes that respond differently depending on the user's preferences, such as "learning" versus "performance" modes. In either case, the LCD makes it easier to switch contexts without confusion. As the Laser Harp evolves, this screen could even support multilingual or icon-based displays for universal design. Including the LCD ensures the harp is more than just playable—it becomes teachable, understandable, and welcoming to a broad range of users.

3.10.2 Comparison of LCD Screens

LCD (Liquid Crystal Display) technology includes a variety of display types, each designed to meet specific performance and integration needs. One of the most basic and reliable forms is the Character LCD, commonly available in 16x2 or 20x4 configurations. These modules display fixed alphanumeric characters using an HD44780 controller and are often used in embedded systems for their low power consumption and simplicity. While they lack graphical capability, they are highly effective for presenting real-time system status like selected musical key, octave, or volume on the Laser Harp. Character LCDs are also easy to integrate using either parallel or I²C communication and are supported by a wide range of development tools. Their affordability and reliability make them ideal for entry-level projects, though they fall short when advanced UI or custom graphics are required. Nonetheless, for projects like the Laser Harp where clarity and low complexity are prioritized, they offer an efficient and user-friendly interface.

Monochrome Graphic LCDs provide greater flexibility by allowing pixel-level control, which enables the display of charts, icons, and animations. A standard 128x64 pixel model with an ST7920 controller can render both text and simple graphics, making it ideal for interfaces that require more than basic status reporting. In comparison to character LCDs, these displays support visual feedback elements like volume bars or waveform indicators. However, they require more microcontroller resources and more complex code, which can present challenges in embedded systems with limited memory. Their use in the Laser Harp could enhance interactivity but may not justify the added complexity given the project's current scope. Despite their moderate cost and accessibility, they introduce a learning curve and require external libraries for smooth integration. Nonetheless, they remain a versatile mid-range option for embedded applications where visual output is essential but full-color display is unnecessary.

TFT LCDs represent the high end of embedded display technology, offering full-color graphics, high resolutions, and often touchscreen capabilities. Modules such as the 1.8" ST7735 or 2.4" ILI9341 displays provide dynamic interfaces suitable for rich graphical UIs, animations, and user settings menus. These displays can elevate the user experience in the Laser Harp by supporting real-time note visualizations or interactive control panels. However, they require a faster microcontroller, more memory, and significantly more power. Their complexity also extends to firmware development, where GUI libraries and optimized drivers are necessary. The physical footprint and increased cost further limit their practicality in compact or budget-conscious projects. While aesthetically superior, TFTs may exceed the functional needs of the Laser Harp, especially in its prototyping phase. They are best reserved for applications where advanced user interaction is critical and supported by suitable hardware resources.

OLED displays offer an appealing alternative due to their high contrast, fast refresh rates, and low power consumption when displaying minimal content. Unlike LCDs, OLEDs emit light at the pixel level, resulting in sharper visuals and better readability in various lighting conditions. The common 0.96" 128x64 OLED with SSD1306 controller is widely used in small, battery-powered embedded systems. It supports both graphics and text, making it versatile for real-time displays like octave indicators or waveform icons on the Laser Harp. While these displays are compact and efficient, they may suffer from burn-in over long-term use and can be slightly more expensive per inch than LCDs. They are ideal for minimalist interfaces but may not offer sufficient screen real estate for detailed interaction. OLEDs are a solid choice for clean, modern designs where space is limited, and brief dynamic updates are the norm. Their strengths lie in visual clarity and power efficiency, making them a valuable option in embedded projects with constrained physical and electrical footprints.

In summary, selecting an appropriate LCD display requires careful evaluation of visual needs, system complexity, and available resources. Character LCDs offer simplicity and clarity for essential data; graphic LCDs provide moderate flexibility; TFTs deliver advanced interactivity at a higher resource cost; and OLEDs offer crisp visuals in compact packages. For the Laser Harp, a 20x4 I²C Character LCD provides an optimal blend of clarity, integration ease, and sufficient screen space to display volume, octave, and key data effectively. It aligns with the project's goals of accessibility, simplicity, and efficient system design, while leaving room for future upgrades if a richer user interface is ever required.

Table 16 - Comparison of LCD Displays

Feature	Character LCD	Graphic LCD	TFT LCD	OLED
Display Type	Alphanumeric only	Monochrome graphics + text	Full-color graphics	Monochrome graphics (some color)
Common Sizes	16x2, 20x4	128x64 pixels	1.8"–3.5" (128x160 to 320x480)	0.96" (128x64), 1.3" (128x64)
Controller	HD44780	ST7920, KS0108	ILI9341, ST7735	SSD1306, SH1106
Interface	I ² C or Parallel	SPI or Parallel	SPI (often), Parallel (sometimes)	I ² C or SPI

Power Consumption	Low	Moderate	High	Low to Moderate
Graphics Capability	None	Basic	Advanced (images, animations)	Basic (sharp contrast)
Ease of Use	Very easy	Moderate	Complex	Moderate
Ideal Use Case	Simple text output	Custom symbols, simple UI	Rich GUI, menus, touch control	Compact status display

3.11 Power Supply

The power supply is what ultimately powers the harp. There shouldn't be any external power supply, and every component should be powered by this single supply. The power supply, and by extension the entire Power Supply Unit should generate a stable DC voltage of manageable ~12V that can be further decreased using regulators. The power supply. A major design consideration for this project is its portability. The laser harp is supposed to be easy to use, carry, and store. The harp should have a base capability of being powered from a wall outlet. This is important in the design, testing, and prototyping parts of the project, but also for the final project, as a matter of convenient charging. However, the ultimate goal is to have the harp charge via a rechargeable battery.

3.11.1 Battery

There are some considerations that should be given when choosing a potential rechargeable battery. The type of battery, and its chemistry is very important to know. There are many different types of battery that use different mechanisms to store and discharge energy. These types are used for different applications, so they will have differing performances. We would like our battery to be efficient, to have minimal energy loss in use and idle. The battery should be temperature stable; it should increase its temperature an unreadable amount. The battery shouldn't become less efficient over time after multiple charge/discharge cycles. The battery should also be energy dense; a major consideration of the battery is its size. Portability is a major project specification, so the battery shouldn't take up much space, and it shouldn't be very heavy.

3.11.2 Lithium-Ion

Lithium-Ion batteries are one of the most popular types of batteries used in commercial and industrial applications, often used in electronics. They work by ionizing lithium atoms in the anode of the battery. The lithium ions are pushed from the anode and through the electrolyte to the cathode where they recombine with their electrons. There are many different lithium batteries, but we are only investigating lithium-ion batteries that contain cobalt. Due to lithium being one of the smallest elements in the periodic table, Lithium-Ion batteries can generate very high voltages and produce a large charge storage per unit mass and unit volume. Lithium-ion batteries have a relatively small discharge rate, with a charged battery discharging 1.5–2% of its total charge per month in some cases. They also have a relatively long cycle life; multiple discharge and recharge cycles will not impact much of the battery's capacity. Lithium-ion batteries; however, are temperature sensitive, and have a tendency to overheat, and possibly explode.

3.11.3 Lead-Acid

Lead-Acid batteries is another highly popular battery, often used in the automotive industry, and often used as a backup power source. Energy is produced and stored in the Lead-acid battery by the controlled reaction between elemental lead and sulfuric acid.

Lead-acid batteries are relatively cheap, being cheaper than most other types of batteries in the market. These batteries have a high discharge rate, producing high current. Lead-Acid batteries are also very durable, working in relatively high and low temperatures. These batteries do have some well-established downsides. They have a large self-discharge rate, as well as a relatively short cycle life, reducing its capacity the more it is recharged. Lead-Ions are also very large and heavy, compared to other rechargeable battery types.

3.11.4 Nickel-Metal Hydride

Nickel–Metal Hydride are another type of rechargeable battery often seen in commercial settings. It works by the reactions that occur between a cathode of nickel oxide-hydroxide and anode of a hydrogen-absorbing alloy. They are often seen as a great alternative to other types of battery due to their relatively high energy efficiency. This leads them to have a long battery life, and it requires fewer charging periods. They are also very affordable compared to other battery types like lithium-ion batteries. While they are quite efficient, they also have a lower energy density compared to other battery types like lithium-ion batteries. When not in use, they also have a tendency to discharge at a higher rate than other types of batteries

3.11.5 Nickel-Cadmium

Nickel-Cadmium is the final type of rechargeable battery investigated. Battery chemistry works by the reactions that occur when a cathode contains nickel oxide-hydroxide, an anode that is composed of metallic cadmium and an alkaline electrolyte solution of potassium hydroxide. Nickel-Cadmium batteries are quite energy dense, able to store significant amounts of energy. They have a long cycle life, able to be discharged and recharged a large number of times before it starts affecting its capacity. They also are able to be charged at a higher rate than many other battery types. They, however, have some notable downsides. First, they experience the memory effect where they may develop a reduced capacity if not fully discharged before recharging. They also have a tendency to discharge on their own and have a lower energy density than other battery types like the Lithium-ion. And due to the use of Nickel-Cadmium, they are quite dense, and heavy for the amount of energy they store.

3.11.6 Battery Comparison and Selection

Table 17 - Battery Comparison

Parameter	Lithium-Ion	Lead-Acid	Nickel–Metal Hydride	Nickel-Cadmium
Energy Density (Wh/kg)	150-190	30-50	60-120	45-80
Internal Resistance (mΩ)	150-300	<100	200-300	100-200
Cycle Life (80% Capacity)	500-1000	200-300	300-500	1000
Self-Discharge Rate (per Month)	<10%	5%	30%	20%
Overcharged Tolerance	Low	High	Low	Moderate
Typical Cell Voltage (V)	3.6	2	1.2	1.2

Charge Temperature	0 to 45°C	-20 to 50 °C	0 to 45 °C	0 to 45 °C
Discharge Temperature	-20 to 60 °C	-20 to 50 °C	-20 to 65 °C	-20 to 65 °C

After comparing four different types of battery chemistry, we decided that the best choice for our rechargeable battery will be a Lithium-Ion rechargeable battery. This is due to its high energy density, high efficiency and stable and long battery life. Lithium-ion batteries are also one of the most used battery types in electronics, so there are many resources that we can look through to ensure proper usage. Now we have to make choice between several different Lithium-Ion batteries:

Table 18 - Lithium-Ion Batteries Comparison

Parameters	KBT 12V 1200mAh Rechargeable Li-ion Battery	Rapthor Rechargeable 12V 5200mAh Lithium ion Battery Pack	Seasider 12V 2600mAh Rechargeable Li-ion Battery Pack
Voltage (V)	12	12	12
Capacity (mAh)	1200	5200	2600
Max Current Output (A)	3.6	3	5
Weight (Ounces)	7.3	16.8	10.5
Price	\$15.99	\$32.89	\$20.99
Power for One Hour (W)	14.4	62.4	31.4

3.11.7 Wall Power

Besides having a rechargeable battery that serves as the primary form of power generation, we decided to add the possibility of the Laser Harp to be powered via a wall outlet. The user will be allowed to switch between the battery pack and the wall outlet using a simple three-way switch, one for each power source, and one for off. The reason why we decided to have a separate module for wall power

and not just directly plug the battery pack to the wall and have that act as wall power is because of the battery's property. The Lithium-Ion battery chosen is the right fit for the project, due to its reliability and energy density. The big drawback is that Lithium-Ion batteries have a low tolerance for overcharging. Another reason is that the battery also has a tendency to degrade when experiencing pass through charging, or current being drawn out from a continuously charging battery. A pivotal part of the PSU of the laser harp would be a possible wall converter that could convert a wall voltage of 120 AC to a suitable 12V DC voltage. The converter should also be able to draw enough current to power the entire laser harp. Below, we weigh different wall converters against each other to determine which would be best.

Table 19 - Comparison of Wall Converters

Parameters	SanSun 12V 5A Power Supply, AC 120V to DC 12V	COOLM 12V Power Supply 7A 84W Security System Power Adapter	ALITOVE 12V Power Supply 6A 72W AC to DC Adapter
Max Current (A)	5	7	6
Max Wattage (W)	60	84	72
Weight	0.64 Pounds	0.6 Pounds	0.66 Pounds
Output Connector Size	5.5 x 2.1mm	5.5mm x 2.5mm	5.5mmx 2.5mm
Cord Length	9ft	7.2ft	6ft
Cost (USD)	\$9.99	\$16.69	\$15.99

Above, we looked at three possible choices for a wall voltage converter. The main parameters that we are investigating for possible selection is max supply, and the max wattage of the converter. It is important that the converter can supply enough power to turn on and run our laser harp. When looking at possible converters, we looked at cables that could supply differences in max current. Since the three converters supply the same voltage, we want to make sure that the current supplied will be enough to power the laser. In this case, since the voltages supplied are the same, and there isn't much difference in size and weight of the cable, it could be best to choose the cable that can supply the largest possible current. So in this case, we could choose the 84W, 7A COOLM converter, as the amperage in this current isn't forced, so it wouldn't be detrimental to us to pick a converter with the possibility to supply more current than we actually need. Instead of the COOLM, we could also pick the SanSun converter, as it is the cheapest of the three. While the lowest in max current, it can still achieve 5A with a total wattage of 60 W, which is more than enough for the project. Upon consideration, I decided to go with the 12V, 5A wall converter of SanSun.

The primary power supply was changed for the final project. As stated above, the initial idea was to have two power supply options, wall power from a cable and a rechargeable battery. Due to unforeseen changes in the design, the battery was used to power the stepper motor and driver exclusively, and wall power was made the only power option shown for the final prototype. The Sansun wall power was used.

3.12 Voltage Regulator

Voltage Regulation is an important part of any Electrical Engineering project. It ensures that if there is a change in an input voltage, or if there is noise being applied on the input, that the project and its component will still receive a constant DC source. If there is change in the amount of power being drawn by the devices due to a fluctuation of the total load on the source, it can guarantee a stable voltage to ensure it protects electrical equipment. This means that the regulator must be reliable to ensure that it doesn't compromise any devices. There are two types of voltage regulators: linear regulators and switching regulators. We will consider both types of regulators, and all the forms they come as.

3.12.1 Linear Regulators

Linear Regulators are the first type of voltage regulator. In both types of regulators, the most important part is a voltage feedback mechanism that corrects for a change in voltage. In linear regulators, this correction is possible by using a bypass device, like a BJT or MOSFET, either in series or in parallel with the load, which acts as a variable resistor. The regulators then adjust the pass

device variable resistance by using feedback to compare the output voltage with a predetermined reference voltage. The regulator releases excess voltage through heat. In general, linear regulators are simple, but are very inefficient, especially if there is a large change in voltage. Linear voltage regulators only come with a buck, or step-down, topology; linear regulators can only achieve voltage regulation by decreasing an input voltage to a smaller output voltage.

3.12.2 Switching Regulators

The second type of regulator that we are investigating is switching regulators. Switching voltage regulators work by bypassing devices like MOSFET or diodes and high frequency switching and energy storage elements like inductors and capacitors to regulate voltage. They quickly and efficiently cycle between on and off to regulate the voltage of the output. This in turn leads to a decrease in heat, as excess voltage is being dissipated using the capacitors and inductors. This also leads to switching regulators being smaller than linear regulators, as they don't need space for heat dissipation. Switching regulators come with different topologies: Step-down (Buck), Step-Up (Boost), and Step-Up/Step-down (Buck-Boost). Buck regulators take a larger input and decrease it, boost does the opposite, increasing the voltage of the input, and Buck-Boost, using the switching elements, can do both. Switching regulators offer design flexibility as one regulator can generate multiple stable output voltages from a single input. Switching regulators are, however, usually more complex than linear regulators, using more components to regulate voltage. Switching regulators also increase the amount of noise from high frequency switching of the energy storage elements, requiring further components, and increase complexity to reduce noise.

3.12.3 Regulators Comparison

One of the primary goals of our project is to build a laser harp that is easily portable. To achieve portability, it would be optimal to reduce the size of parts whenever possible. While not always true, switching regulators are usually more complex than linear regular, leading to a larger PCB size. Switching, due to lack of heat, is usually smaller; however, we would like the PCB to be adequately large to be able to solder, and test individual components effectively, leading to a larger PCB. Regulators will be used mainly for the power source, and as voltage source for photodetectors, ensuring that both the component and devices are being powered with a stable voltage, but also that there is no outside interference with the photodetectors and the analog readings from the MCU. Noise prevention is a huge consideration when choosing a type of regulator. After consideration, it would be beneficial if the laser harp utilizes both types of voltage regulator. The voltage source used for the project will be 12V, but depending on the component, that voltage would either decrease or increase.

Table 20 - Regulators Comparison

Parameter	Linear Regulator	Switching Regulator
Topology	Buck	Buck, Boost, Buck-Boost
Efficiency	+	++
Heat	-	++
Complexity	++	-
Noise	++	-

3.12.4 Linear Regulators Selection

Given the components, our original power supply voltage of 12V will be decreased to accommodate the components used. That being said, a step down regulator that is capable of producing an output that can be adjusted using resistors to divide voltage is ideal. The linear regulators will regulate input voltage for the two MCUs. While the MCUs probably already have built-in voltage regulators, it is advised to still use an external regulator to prevent damage or malfunctions. For the laser harp, we will ultimately use two linear regulator instruments, The First regulator will be around step-down the power supply voltage of 12V down to 3.6V. This regulated voltage will be primarily used to power the primary MCU, and the arduino. This voltage will also be used to power some of the other components like the LCD screen, and storage element. We are looking to use two of the same type of regulator, one that can produce enough current and a high enough voltage to power both components. We will consider three possible regulators that will possibly be used for the project below.

Table 21 - Comparison of Linear Regulators

Parameters	7805	LM317	LM350
Max Output Voltage (V)	5	37 (Adjustable)	35 (Adjustable)
Max Input Voltage (V)	35	40	36

Dropout Voltage (V)	2	3	3
Max Output Current (A)	1.5	1.5	3
Line regulation @ 22°C	50 mV	0.01% of Output	0.02% of Output
Load Regulation @ 22°C	10 mV	0.1% of Output	0.3% of Output
Price	\$0.50	\$0.56	\$1.86

In a linear regulator, we are looking for one that can generate the desired voltage but generate enough current to power all the components adequately. We are also looking for a regulator that doesn't produce enough heat to damage the PCB or any other part of the circuit, as well as being able to accommodate a heat sink if need be. The regulator should also be affordable and available to be bought in bulk. After consideration, we decided to go with the LM317. This is due to an adequate voltage source that can be adjusted if need be. It also is able to produce a max current of 1.5A, which should be enough for the components. Alongside its affordability, the regulator is also able to be housed in a TO-220 package, which is able to accommodate a heat sink.

3.12.5 Switching Regulators Selection

The primary use of a switching regulator will be to increase our power supply of 12V to a larger voltage. The primary application on the laser harp for this regulator would be to supply the photodiodes with a relatively stable bias voltage to increase sensitivity and performance of the photodiodes when observing light. It would be best if the regulator could vary its output voltage using resistors. This regulator will be used for two very important purposes. The first is to supply a bias voltage to the photodiodes, as a larger bias voltage will lead to a better, more efficient, and higher responsivity photodiode. The second purpose would be to power the stepper motor driver in order to achieve a desired speed for the

stepper motor. The ultimate goal of this regulator is to produce an output voltage of at least 15V, but at with the goal of 20V. We would like to use a regulator that is adjustable and can and is relatively simple, so that it doesn't take much space.

Table 22 - Comparison of Switching Regulators

Parameters	TPS61046YFFR	LMR64010XMFx	LM27313XMFx
Max Output Voltage (V)	28	40	28
Max Current (A)	1.2	1	0.8
Max Input Voltage (V)	5.5	14	14
Typical Efficiency @ ~500 mA load current	85% @ 3.6Vin and 12Vout	90% @ 10Vin and 20Vou	90% @ 10Vin and 20Vout
Output Voltage Accuracy	±2%	±1%	±1%
Price	\$1.09	\$1.62	\$1.62

The main purpose of this regulator, as said before, is to generate a relatively large bias voltage for the photodiodes, in order to increase their responsivity and efficiency. The regulator must be able to generate a voltage between 15-20V , as this is adequate to produce the best results for the diodes. It will also be used to power the stepper motor driver. Upon consideration, we find that the regulator better suited for this design is the LMR64010XMFx. This is due to its affordability, high maximum current. It also has a relatively simple design, which is good as it will reduce possible space in the PCB.

There were major changes made to the overall usage of voltage regulators in the final project. The number of voltage regulators changed. In the final prototype, four different regulators were used. Two LM2576 Regulators were used for the primary regulation, one 3.3V and the other 5V. Additionally, for the photodetection subsystem, two additional regulators were used. One LM1117 was used to supply the photodiode with a reverse voltage of 3.3V. A LM2664 negative voltage converter was also used to supply the transimpedance amplifiers used with the photodiode a negative voltage if -5V.

3.13 Diffused Reflection Material

For the Laser Harp to function properly the light has to get reflected into the laser diode. If the light does not reach the photodiodes correctly the light will not be collected into the photodiodes. There are different types of reflection that need to be considered. Before we go into the different types of reflection it is important to know what reflection is. The law of reflection states the angle of reflection is equal to the angle of incidence. The law works at any angle if the incident light is 45 degrees the reflection angle will also be 45 degrees [39]. Reflection is the change in direction of a wavefront at an interface between two different media so that the wavefront returns into the medium from which it originated. In simpler terms reflection is something bouncing back after hitting a surface. For example, a mirror or an echo [40].

For the purpose of the Laser Harp, it is important to talk about light reflection. In the case of light reflection there are two types. The light reflection is either specular or diffused. The first way of reflection is specular reflection is the reflection off of a mirror or off a calm body of water. Specular reflection is when all the incoming light reflects in a predictable way. If parallel rays of light hit a plane mirror they are all reflected in the same direction [39].

There are more than just smooth surfaces. Therefore, the question arises what happens when light rays hit a rough surface. Well, every ray of light has to follow the law of reflection, the reflected light has the same angle as the incident light. So, when light hits a rough surface, the light will go in different directions. This is due to the fact that every bump within the rough surface will have a different incident and reflected angle. Overall, specular reflection is the reason we see clear images where diffused reflection is why the image may look dull [39].

When researching which type of reflection would be beneficial for our use in the Laser Harp we looked into both types of reflection. The first type of reflection we looked into was specular reflection because it is the most common and well-known type. The group decided to run an experiment. The experiment consisted of setting up the photodiode on a breadboard with the proper electrical components (i.e. resistors and capacitors). The circuit we created was hooked up to a multimeter and the photodiode was pumped using a function generator. A Helium Neon laser was used as the light source and a pair of gloves was placed on the hands of one of the group members. On the gloves aluminum reflective tape on the palms of the gloves was used as the specular reflecting surface. The function generator was turned on and set to 12v pumping into the photodiode. The max voltage allowed for the type of photodiode we selected is 25v. The more voltage that is pumped into the photodiode the better the photodiode accepts the light. However, it is not a good idea to pump the photodiode at the max voltage. This can leave to frying the photodiode and making it unusable.

The Helium Neon laser was turned on and pointed up toward the ceiling and the photodiode/bread board were down on the table. The group member wearing the makeshift specular reflecting glove held their hand in the path of the laser beam. A reflection on the breadboard was present. However, the specular light only reflects at the same angle the light goes in. This caused a problem, the reflected light was in a thin curve line with the brightest point in the middle of the curved line. Because of the reflection only being in the shape of a line it was very hard to get the light into the photodiode. The glove wearing group member had to angle their hand at a very specific angle in order to direct the light into the photodiode.

Even though a portion of the reflected line of light was in the photodiode there was not much output on the multimeter. This was because towards the end of the line of reflected light the intensity of the light grew smaller and smaller. The most amount of light needed to go into the photodiode. This meant that the center of the reflected line of light needed to be precisely positioned into the photodiode. The angle that achieves the peak intensity going into the photodiode was very hard to do. When operating the Laser Harp, the user needs to easily be able to guide the light into the photodiodes. The user cannot play the harp and hit the perfect reflecting angle at the same time. Therefore, the conclusion of the spectral reflection experiment was that spectral reflection is not the most suitable option for our Laser Harp application.

After this experiment we knew that diffused reflection would be the best option of the Laser Harp application. This then brings up the question what type of material would give us the most intense reflection. The material needs to be rough and not shiny. The group immediately thought of white cloth. We then conducted an experiment using a white cloth to block the laser beam.

The experiment was set up very similarly to the experiment with the specular reflection. However, instead of using the makeshift reflecting glove a white cloth was used. Just like above the laser was turned on and pointed at the ceiling and the photodiode was set to 12v. A group member placed the white cloth in the path of the laser beam, and we got an output we did not expect. There was not an intense reflection on the breadboard. In fact, the reflection was barely there. Therefore, the photodiode did not get enough reflected light to register anything more than noise on the multimeter. From this experiment we concluded that a white cloth was not the right choice for the Laser Harp application. But why? It is a diffused reflection. We came to the conclusion that the white cloth was too porous and that too much other laser beam light was going through the cloth instead of being reflected by the cloth.

When looking into what the best diffused reflection surface is a few materials come up. For example, some of the materials are non-absorbing powers like plaster, paper, or a polycrystalline material such as white marble. Another experiment was done to test these research findings and more specifically test paper.

This experiment consisted of a higher power laser. Before the laser that was being used was 5mW HeNe laser. This laser was not only too low of a power but the wrong wavelength for the application of the Laser Harp system. It has been determined that a 50mW – 100mW laser will be used for the Laser Harp system. Disclaimer: the exact laser that will be used in the project was not used during this experiment. However, a laser with an output power of over 30mW was used. This laser was also the correct wavelength (520nm) for the Laser Harp system. The experiment also consisted of a power meter and a collimating lens. As shown in the figure below the set up was as follows. An optical post was mounted onto a magnetic mount. The magnetic mount was set on an optical table. Two angled post clamps were used. Angled Post Clamp A was used to hold an optical post with the collection lens attached to it. Angled Post Clamp B was attached to an optical post with the laser diode module mounted to it.

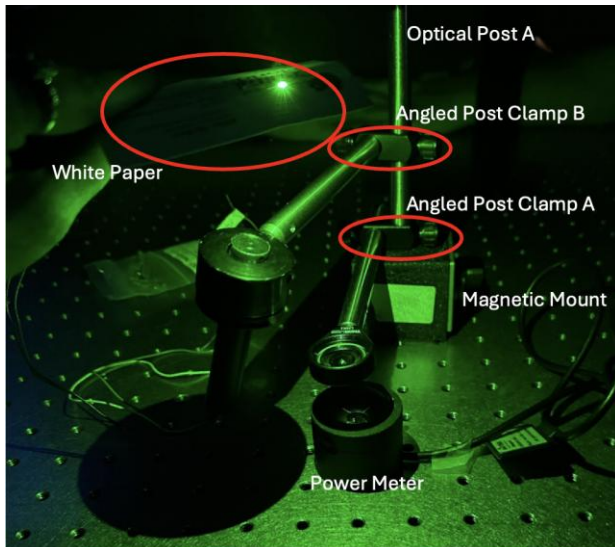


Figure 13 - Diffused Reflection Test Set-Up for Paper

In order to conduct the experiment, the laser module was plugged in and turned on the collection lens was then moved up and down optical post A. Moving the lens up and down the optical post was done to ensure that the focus of the lens was in the active area of the detector. A piece of white paper was then used to interrupt the beam path. The collection lens collected the diffused reflection into the photodiode. The ambient output on the detector was $2.2 \mu W$. Once the white paper was put into place the power meter read $23 \mu W$. We also ran the test with just a hand interrupting the beam. There was little to no output reading on the detector when this was done. In order to know if the paper produced enough diffused reflection there is some math to be done.

We know that the electrical team needs μA in order for the electronics to work and properly play a note.

Formula to convert watts to amps:

$$A = \frac{W}{V} \quad \text{Equation 2}$$

A = amps
W = watts
V = Volts

From above we know that the watts being outputted were $23\mu W$. The laser was plugged into a standard wall outlet. In the United States the standard wall outlet is 120V.

$$A = \frac{23\mu W}{120} = 0.19\mu A$$

Therefore, the electrical team will have enough current to work the electronics. To conclude the experiment the paper was a success and a great contender for the material to be used for the diffused reflection.

4.0 Standards and Design Constraints

An important part of engineering research, design, and development is to be aware of the limitations that engineers will face before manufacturing. Some of the limitations are constraints that are caused by factors that will impede development, but that engineers will have to endure. These constraints are caused by economic, environmental, social, political, ethical, health, and safety factors that hinder development, but will also ease engineering into designing a product that is realistic to their circumstances. However, other hinders that engineers will face are standards that they will have to abide by to ensure production is safe and efficient as possible.

4.1 Safety and Regulatory Standards

Standards will be present at all stages of development in the engineering process. They are ubiquitous in the process because they ensure engineers are producing a product that is consistent with safety, performance, and characteristics that are expected when releasing it to a market. Some of these standards are required, and others are optional, but they are all important the same.

4.1.1 Laser Standards

Due to the Laser Harps main feature being laser beams at the strings of the harp it is extremely important for our system to follow the proper safety regulations. Different lasers are broken down into different classes. Each class has their own set of safety requirements. Class 1 lasers are considered safe under all

conditions. They are as safe as an everyday light. Some higher-powered lasers can fall under this class if the laser is fully enclosed and cannot be opened without turning the laser off. Class 1M the laser is safe to view directly in the eye but can be hazardous if viewing with an optical aid, like a microscope or telescope. The class 2 classification only applies to visible lasers with an accessible output of $>1\text{mW}$. This is because class 2 lasers are considered safe due to the fact that our blink reflex limits the exposure of the beam to approximately 0.25 seconds. If the beam was not visible that blink reflex could not happen. Class 2M is like class 1M as the laser can be hazardous if viewed with an optical aid. Class 3R is for visible continuous wave laser. These lasers can produce around 5 times more power than a class 1 or class 2. But they cannot exceed 5mW . For class 3B lasers it is considered hazardous if the eye is exposed directly to the beam. However, a diffused reflection of the beam is not considered dangerous. A continuous wave laser cannot exceed 0.5 W . While a pulsed laser cannot exceed 125mJ in 0.25 seconds. According to Perdue University's laser safety guide the continuous wave and pulsed wave can be between 5mW – 500mW . Lastly, is class 4 which is the most dangerous classification. These lasers are considered hazardous to view at all the time and can cause extreme and devastating damage. They can not only damage your eye but can also ignite materials, cause skin damage, and they may produce hazardous fumes. For continuous wave lasers the output starts at 500mW . For Pulsed lasers they can produce 125mJ in 0.25 seconds [41].

The laser that was chosen for the laser harp is a 110mW green laser diode. This falls under the classification of a class 3B laser. As stated above class 3B lasers are considered hazardous when exposed directly into the eye. But the diffused reflection is not harmful. Because it is dangerous we will follow the safety guidelines very carefully.

There are a couple laser safety guides that are used nationwide. The IEEE 2066 – 2021 and the ANSI Z136.1. The IEEE 2066 – 2021 is a guide for Safety Specification of Laser Transmission in High-Power Industrial Laser Systems. This guide's main goal is to help keep passive optical elements and optical fiber cables used in high power industrial laser systems from being affected by optical, opto-machines, and related effects [42]. We will mainly follow the ANSI Z136 guide of laser safety due to it having more variety in fields and optical elements. The ANSI Z136.1 is the American National Standard for Safe Use of Lasers. This standard is used in all fields in the United States including industrial, military, medical, and educational for use of laser systems. The ANSI Z136.1 provides guidance for lasers and laser systems that operate at wavelengths between 180 nm – 1000 nm [43]. When reading the standard, it says the laser safety officer should decide if the system needs goggles or not. However, I have been informed that the university does not have a laser safety officer. So, I will be going off of the procedures we take when doing labs for undergrad classes. When working with the class 3B lasers in class laser goggles are not enforced. If someone feels uncomfortable, they are welcome to wear them. Therefore, for the

Laser Harp system laser goggles will not be enforced. However, it is important to not look directly into the beam.

Laser warning signs are used when dealing with different class lasers. The warning signs are there for people to know what type of protection they need to use when dealing with that laser system. Because the Laser Harp will be using a class 3B laser it will be important to have a label to inform users. Most laser warning labels consist of bright yellow and orange. They also say warning in large letters with the class of the laser. The label needs to be on the outside of the Laser Harp housing to ensure the users can easily see the laser classification and take the appropriate laser safety precautions.

If someone still feels uncomfortable with using the laser they can use the appropriate laser goggles. The Laser Harp system does use diffused reflection to scatter the laser light into the photodetectors. However, the design of the laser harp being an unframed harp (the beams pointing directly up into the air) puts the user at risk for injury. To combat this the use of eye goggles can be used if the user feels uncomfortable. There are some very important factors that need to be considered when choosing the correct laser safety goggles. The first thing when picking out the correct laser goggles is checking to see what wavelengths the goggles will cover. For the Laser Harp system we will need safety goggles that cover the green spectrum. It is also important to know the Optical Density of the goggles. Optical density refers to how much light is being attenuated, or blocked, by the goggles. Depending on the Optical density it can also be hard to see any light at all. When picking laser goggles it is good to also make sure there is a balance so the user can still see around them and not be harmed by the light [44]. The image in reference 25 shows different styles of laser safety goggles. The goggles in the image have an optical density of 6+ which covers the wavelength range of 190nm - 532 nm. The goggles in the image also have visible transmission of 50%. Meaning they will be easy to see out of and be able to protect the eyes from the green laser light [45].

4.1.2 Lithium-Ion Battery Standards

There are many different standards that are implemented to ensure safety and proper performance when using Lithium-Ion batteries in projects. There is an innate risk in the use of Lithium-Ion batteries, as they can be dangerous and pose risks for the manufacture of a product containing batteries and the consumer who is meant to buy this product. Lithium-Ion batteries are energy dense, so they have a tendency, when improperly used or stored, to catch fire, or possibly explode. This can occur when the battery is overcharged or recharged with an incompatible charger. It experiences overheating or exposure to heat or extreme temperatures, it can endure physical trauma that may damage the individual cells of the batteries or any electronic component, short-circuiting, battery cell malfunctions or caused by defects or contamination during fabrication. Lithium-Ion batteries also contain toxic materials that, when placed

under stress or heat, may leak toxic acid or release toxic gases like hydrogen fluoride. One of the standards that deal with Lithium-Ion batteries for general use is *UL 1642*. This regulation was developed to regulate and ensure Lithium-Ion batteries manufactured and sold at a suitable standard that ensures safety for the consumer. The standard deal switches battery at the cell level, ensuring they are designed for safety for whatever application they are used in. *UL 1642* is directed specifically at Lithium-Ion battery cells being used in user-replaceable applications. It is a test focused standard where the cells are passed a multitude of tests to ensure safety and sturdiness. *UL 1642* tests consist of short-circuit, abnormal charging, forced-discharging, crush, impact, shock, vibration, heating, temperature cycling, and fire exposure. This standard has implications for us as it will determine the ways we use and handle the battery. A way that this standard might affect the design and use of the battery is on the matter of overheating. It is important that we use the battery in a way that prevents possible overheating, which can cause damage to the battery, and cause harm to us and the project as a whole. We must use the battery in accordance with the parameters set by the standard. This standard also affects how we transport, and overall manner we take care of the battery. We must make sure that during testing and assembly, that we are causing the battery physical stress that may exceed the stress endured during the physical tests the standard *UL 1642* has highlighted.

For proper use of batteries for industrial and commercial application, standards *IEC 62619* and *UL 2271* are used to ensure this. *IEC 62619* deals with the use of Lithium-Ion batteries in industrial applications. It not only utilizes stress tests like the ones discussed to ensure battery sturdiness, it also ensures battery safety while in use. One main safety concern discussed in this standard is thermal runaway, when an overheating cell causes a chain reaction of heat dissipation. This is tested using a propagation test, to ensure how an overheating cell might affect all the other ones. The standard also focuses on battery use design; how batteries are implemented into battery systems, insulation and wiring, venting, and temperature/voltage/current measurements. *UL 2271* is another standard, it deals with commercial appliances. This standard focuses on how to safely design batteries suited for different, and changing loads, as well as appliances that draw a larger load. It runs tests like the ones previously mentioned to ensure the battery is suitable enough for come personal commercial applications. These two standards have implications on our design as it will affect how the battery will power the components. One major aspect of the standards that we will have to address is making sure the battery is being used correctly and safely. We got to make sure that the circuit is not drawing more current than what the battery can take, as it could damage the battery. Another thing is to make sure that there is a quick change of load, that may cause sudden change in the current and wattage going out of the battery. Like *UL 1642*, *IEC 62619* and *UL 2271* make sure to highlight proper battery storage; how a battery is stored in a device when in use. This has implications in heat, and how to store a battery without having it overheat. It also has implications in measurements, as it is important for us to have an easy and safe way to measure voltage and current if need be.

4.2 Technical Constraints

Designing the Laser Harp required meeting a number of technical constraints to ensure performance, safety, and usability. One of the primary constraints is power consumption. Since the harp is designed to operate on battery power, all subsystems must consume less than 200 watts in total. To meet this constraint, the team selected energy-efficient components, including voltage regulation and low-power microcontrollers. Additionally, the stepper motor's duty cycle was optimized to run only when beam scanning is active, thereby conserving energy during idle states.

Another key technical constraint is system latency. For the harp to feel responsive and natural to play, the delay between a user interrupting a laser beam and the corresponding sound being produced must be less than 0.25 milliseconds. This requires synchronization between the photodiode input, microcontroller processing, and sound playback. Interrupt design and efficient analog-to-digital conversion are critical to maintaining this real-time responsiveness.

Physical constraints also play a significant role in the hardware design. The complete device must weigh under 20 pounds and fit within 2 cubic feet of volume. This ensures portability and ease of use in a variety of environments such as classrooms, public exhibits, and live performances. To meet these constraints, internal components are arranged to optimize space without compromising performance or accessibility.

Thermal management is another critical consideration. Lasers, stepper motors, and microcontrollers can generate significant heat during prolonged use. The internal housing design includes passive ventilation paths where necessary to maintain operational temperatures. Component placement on the PCB is also arranged to minimize thermal hotspots.

4.3 Economic Constraints

Cost management is a critical constraint in the development of the Laser Harp. As an undergraduate senior design project, the team set a strict budget limit of \$600 for the entire system. This constraint guided every component choice, encouraging the use of cost-effective materials, open-source hardware, and efficient sourcing strategies. To meet these goals, the team prioritized components to reduce the need for costly replacements or redesigns.

Manufacturability was another economic constraint. The PCB will be designed as a two-layer board to reduce fabrication and assembly costs. Surface-mount components were limited to those that could be reliably hand-soldered to avoid the need for specialized equipment. This decision made in-house prototyping feasible and reduced dependence on external fabrication services. Another

constraint that must be addressed and work around is economic uncertainty, financial strains we might face when it comes to possible tariffs. A lot of products that could be and are used are partly or fully manufactured in a foreign country. Any tariff or fee implemented on countries that supply electronic equipment to the United States will cause prices increases for said equipment. It is important that when choosing equipment and components to use, that we must account for price changes.

In summary, economic constraints shaped every phase of the project from component selection and circuit design to manufacturing methods and energy efficiency. By carefully managing the budget and making informed trade-offs, we plan to build a fully functional, high-performance prototype without exceeding the financial limits of the project.

4.4 Time Constraints

Time management is a critical factor in any engineering project, and our Laser Harp design is no exception. As a senior design team working within the confines of a university semester, we are operating on a fixed timeline with hard deadlines for major deliverables. These include documentation drafts, design reviews, a working prototype demonstration, and the final written report. With the summer semester running approximately 12 weeks and fall 16 weeks, our available time to research, design, build, and test the project is extremely limited, especially when accounting for exam weeks, holidays, and personal responsibilities. This constraint requires the team to not only maintain a consistent pace but also to prioritize essential tasks in the correct order to prevent delays. Missing just one milestone could result in a cascade of issues that affect future stages, which emphasizes the need for strict adherence to our project schedule. As a result, planning buffer time for troubleshooting, procurement delays, and unexpected design changes is essential to meeting our goals. The time constraint does not just pressure us to finish, it also forces us to think critically and make efficient, strategic engineering decisions.

One of the primary challenges tied to time constraints is component procurement and assembly. While we can complete theoretical designs and simulations early in the semester, many hardware components, such as the stepper motor, laser diodes, photodiodes, and custom PCBs, require time for shipping and manufacturing. Delays in delivery, especially with overseas orders, can disrupt the integration timeline and shorten the available testing window. To mitigate this, the team established a purchasing timeline as early as possible and prioritized ordering long-lead-time items first. However, even with these precautions, certain components may arrive later than expected, requiring parallel work on software development or circuit simulation in the meantime. In addition, soldering and assembling a custom PCB is a time-intensive process that must be done carefully to avoid mistakes. Any hardware issues discovered during testing may require rework or redesign, which can take several days to weeks, depending on

the severity. These kinds of setbacks are typical in hardware projects, and being prepared for them is part of our risk management strategy.

Another significant constraint arises from the testing and debugging phase, which typically takes longer than anticipated. Even with a carefully designed system, it is common to discover unexpected behavior or performance issues during integration. For example, noise in the photodiode signals, misalignment of laser beams, or motor jitter could require circuit modifications or firmware tuning. Testing must be conducted not only on individual subsystems but also on the complete system working together under real conditions. This integration testing is where many time-related bottlenecks occur. To handle this, we have scheduled progressive validation checkpoints after each hardware subsystem is completed. This allows the team to detect and correct issues before full system assembly begins. However, with limited time, there is pressure to fix problems quickly without compromising quality or safety. Balancing thorough testing with available hours requires discipline and effective communication within the team.

Time constraints also place a heavy emphasis on documentation and reporting, which are essential components of the senior design course. In addition to building the prototype, we must also write formal reports, give presentations, and maintain organized design documentation throughout the semester. This includes the D&C, midterm report, final report, block diagrams, test procedures, and more. Writing detailed reports takes considerable time and coordination, especially when merging contributions from multiple team members. Each member has other academic and personal responsibilities as well, so scheduling group meetings and writing sessions has required flexibility and strong communication. In some cases, we have had to divide documentation responsibilities while cross-checking each other's work for consistency and accuracy. Managing this part of the project has proven just as time-sensitive as the engineering work itself and is critical to the overall success and evaluation of our project.

Despite these limitations, the team has responded to the time constraint by using clear task delegation, weekly meetings, and milestone tracking. Each team member has been assigned responsibilities based on their strengths to reduce overlap and avoid unnecessary delays. We've also maintained a shared folder and calendar to centralize communication, file sharing, and scheduling. When challenges arise such as shipping delays or debugging setbacks the team meets to reassess the schedule and redistribute tasks if necessary. Time constraints have pushed us to be more adaptable and disciplined, which are valuable skills in both engineering practice and team-based project environments. While the pace of development has been demanding, the pressure has also helped us maintain momentum and focus on producing a high-quality, functional Laser Harp prototype within the academic timeframe.

4.5 Environmental Constraints

The Laser Harp is intended to function reliably across a variety of environments. As such, environmental constraints must be thoroughly considered during the design process to ensure component durability and system stability. Factors such as temperature, humidity, dust, and ambient light levels can affect the performance of key subsystems, particularly the optical and electronic components. For instance, laser beam visibility and photodiode detection accuracy can degrade under bright sunlight or excessive ambient lighting. To mitigate this, the system was designed to perform best under indoor lighting conditions, with shielding around sensors and a beam expander to improve laser visibility.

Temperature variation is another key consideration. The operating range for most components is between 0°C and 40°C, which covers most typical environments, but excludes extreme outdoor conditions. Stepper motors, microcontrollers, and lithium-ion batteries all have maximum temperature ratings that must not be exceeded to avoid thermal failure. To ensure safe thermal margins, the team conducted testing in a range of simulated environments, including warm indoor spaces and cool air-conditioned labs. Ventilation slots in the enclosure allow for passive cooling, while materials were selected for thermal stability. In extreme cases, such as outdoor exhibitions, additional shade or cooling accessories may be needed to ensure proper operation.

Humidity and moisture also present risks to the system, particularly for exposed PCBs, connectors, and the speaker module. High humidity could lead to corrosion of contacts or signal degradation due to condensation. To reduce susceptibility, all internal electronics are enclosed within a semi-sealed housing, and any exposed solder joints are covered with protective coatings or heat shrink tubing. The laser optics and photodiode face upward and are shielded from splashes and debris using transparent acrylic panels, which also serve to protect users from direct laser exposure. Although the current prototype is not fully waterproof, it is moisture-resistant enough for typical indoor use.

Lastly, dust and particulate matter must be considered, especially since the harp includes open optical paths and moving mechanical parts. Dust accumulation on the mirror, lens, or photodiode can scatter the laser beam and reduce detection reliability. The mirror and lenses are enclosed in a shrouded compartment with minimal airflow to reduce the risk of contamination. By addressing these environmental constraints proactively, the team ensures that the Laser Harp can be deployed in diverse conditions without performance degradation.

4.6 Human Factors and Ergonomic Constraints

When designing an interactive musical instrument such as the Laser Harp, human factors and ergonomics play a critical role in ensuring usability, comfort,

and accessibility. The harp is designed to be frameless and contactless, meaning users will rely entirely on hand gestures and foot controls to operate it. The height and positioning of the laser beams must accommodate users of various heights and arm lengths. If the lasers are too close together or mounted too high or low, it may cause strain or prevent users from effectively interacting with the instrument. Therefore, beam placement was optimized to create a natural hand reach zone, roughly between waist and chest level, to support comfortable play over extended periods.

Foot pedal spacing and layout were also carefully considered. Many traditional instruments, like electronic keyboards or harps, utilize pedals for expressive control, so the harp's foot buttons need to mimic this familiarity while remaining intuitive. The pedals for octave control and sharp/flat toggling are placed apart to prevent accidental double presses, and each pedal is designed with a low actuation force to assist users with reduced leg strength or dexterity.

Accessibility was a core design principle throughout development. By avoiding physical strings and enabling gesture-based interaction, the harp becomes more inclusive for users with mobility limitations, such as those with arthritis or fine motor impairment. Furthermore, the lightweight and compact frame allows the harp to be transported and set up by a single person. No special tools are needed to assemble or operate the device, further simplifying interaction for novice users. All controls are labeled with icons or short descriptors to support non-English speakers and younger users, ensuring broad accessibility. By keeping user experience at the center of the design process, the team aimed to create an ergonomic instrument that anyone could learn and enjoy with minimal training or prior musical knowledge.

4.7 Thermal Constraints

Thermal constraints represent a critical consideration in the design and implementation of the Laser Harp, particularly as the system incorporates a range of active electronic and electromechanical components that generate heat during normal operation. Although the final integrated prototype has not yet been assembled, we have developed and tested the core subsystems individually—each with its own thermal behavior and challenges. These include the laser diode, stepper motor, audio amplifier, power regulators, and microcontroller. Each of these subsystems introduces localized heat, and without proper mitigation, their combined thermal output in a fully enclosed system could lead to component degradation, signal instability, or even system failure. This uncertainty, caused by the lack of full integration at this stage, led us to take a cautious approach and consider worst-case thermal scenarios based on manufacturer datasheets, laboratory measurements, and simulation tools.

Heat-producing components will require adequate spacing and positioning to avoid the buildup of hot spots and to minimize thermal coupling between

sensitive parts. Passive cooling techniques, such as heat sinks, thermally conductive mounting surfaces, and strategically placed ventilation openings, will be explored to ensure a balanced thermal profile throughout the enclosure. While none of the subsystems tested so far have exhibited dangerous temperature levels under short-term operation, prolonged use may change the system's thermal dynamics, especially once all elements are working in unison. During the integration phase, we will monitor system temperatures during extended operation and adjust our layout and cooling strategies as needed to prevent overheating. These measures are critical for maintaining safe and stable conditions for all internal components.

Thermal behavior is also important when considering signal stability and user safety. Excessive heat near optical or sensing components may alter performance characteristics or introduce measurement inaccuracies. In particular, systems involving light detection or sound processing can become unreliable if exposed to fluctuating or elevated temperatures. Even moderate thermal drift can affect calibration settings, sensor readings, and timing sequences. Additionally, thermal stress over time can cause solder joint fatigue or physical warping of the circuit board, both of which could compromise reliability. To avoid these issues, we aim to distribute heat-generating components away from temperature-sensitive circuits and materials, and ensure that adequate clearance and airflow are available around higher-wattage sections of the design.

As we transition into the next phase of development, thermal testing will become a larger focus. Once all hardware components are assembled into a single system, we plan to perform continuous runtime tests to identify any unforeseen thermal issues. This includes monitoring for heat concentration zones, measuring surface temperatures, and determining whether any active cooling methods may be necessary. Should passive methods prove insufficient, we may incorporate low-power fans or other compact thermal management solutions. Overall, addressing thermal constraints early in the design process contributes significantly to the overall reliability, longevity, and safety of the final product. With thoughtful layout and material selection, we are confident that we can maintain a safe and thermally stable operating environment for the Laser Harp.

4.8 Manufacturability and Assembly Constraints

Manufacturability and ease of assembly are critical factors in the successful development and realization of the laser harp project. As a student-led engineering project, we face several practical limitations in terms of equipment, resources, and fabrication capabilities. Unlike commercial environments where automated pick-and-place machines, reflow ovens, and multi-layer PCB fabrication are standard, this project required design choices compatible with manual assembly and testing. As such, the team prioritized a two-layer PCB design to simplify the fabrication process, reduce costs, and ensure the feasibility

of soldering components using standard lab tools. The layout was carefully arranged to avoid complex trace routing and to minimize the need for vias, which can increase both manufacturing complexity and the potential for signal degradation if poorly implemented.

Manufacturability remains a top consideration as the team transitions into Senior Design II. One major constraint that lies ahead is the physical alignment and integration of components such as the stepper motor, mirror mount, laser diodes, and photodiodes. These components require precise spatial orientation, meaning that the mechanical housing must be both rigid and adjustable to maintain optical alignment without sacrificing portability. Designing custom mounts or enclosures may become necessary to address noise and vibration, especially for the rotating mirror that must maintain consistent angular accuracy to produce seven discrete laser "strings." These mechanical elements must be manufacturable using tools readily available in the university labs, which restricts our material choices and design complexity.

Finally, another important factor to keep in mind as we move into the next phase of the project is how we'll actually put everything together. Since the harp includes a lot of different parts—like the stepper motor, laser, photodiodes, and display—we're planning to build and test each of these sections separately before fully assembling the system. To make this process easier, we're designing our PCB and wiring layout to be modular, so we can connect and disconnect individual components without damaging anything. This means using simple, accessible connectors like JST or header pins that allow parts to be swapped or adjusted during testing. It also helps in case we need to troubleshoot issues or replace components later on. Our goal is to create a system that's flexible and easy to work with—not just for testing, but for future upgrades as well. This approach will also give us a smoother path to debugging since we can isolate each section and verify it before moving on. Ultimately, this level of planning should save us time and reduce the chance of major setbacks once we begin the full assembly in Senior Design 2.

5.0 Comparison of ChatGPT or Similar Platforms

In today's academic and engineering environment, students have easier access than ever before to advanced artificial intelligence tools like ChatGPT. These AI models have become highly capable and can assist with a range of tasks, including explaining technical ideas and organizing research in a clear way. For our Laser Harp project, we found that ChatGPT was especially useful during the early stages of research. Since our project brings together different areas of engineering, having a tool that helped us explore ideas, compare different approaches, and answer general technical questions was especially useful during the early phases of development.

At the same time, it is important to recognize that tools like ChatGPT have clear limitations. While it can clarify and explain concepts, it cannot physically test circuits, align optical components, or confirm that our hardware meets safety standards. All information generated by the AI needs to be cross-checked against data sheets, official standards, and real-world test results. For a project like ours, which involves laser safety requirements and real-time detection, relying solely on an AI model would not be practical or responsible. Instead, we view it as an additional resource that supports, but does not replace, the hands-on and research-based work that our team must do.

In this section, we will discuss how ChatGPT specifically contributed to our Laser Harp project and highlight the ways in which it added value during our research and documentation phases. We will also explain some of its drawbacks, especially when compared to other tools like GitHub Copilot or standard online search engines. By looking at both the advantages and the limitations, we aim to show how AI tools can be helpful in a senior design project when used properly and with good engineering judgment.

5.1 Background of ChatGPT

ChatGPT is a conversational artificial intelligence tool created by OpenAI that uses advanced language models to understand and generate text that feels natural and human-like. According to OpenAI, ChatGPT is designed to answer questions, provide explanations, and help users learn about a wide range of topics through simple, interactive dialogue. It works by predicting what words should come next in a sentence based on patterns it has learned from massive amounts of training data. For students and researchers, ChatGPT can be used as a flexible tool to help explore ideas, check general information, or get quick overviews of unfamiliar topics. Unlike traditional search engines, ChatGPT focuses on generating conversational responses rather than just providing links. While it is not perfect and does not always have the latest information, its accessibility and ease of use have made it a popular choice for students working on complex, interdisciplinary projects. OpenAI continues to update ChatGPT to improve its accuracy and expand what it can help users accomplish [46].

5.2 Pros of ChatGPT

ChatGPT provides multiple aspects and approaches to the goals and objectives of our project. This AI source gave us a good glimpse, and a general idea of how our project will be developed. We can take the ideas that we learn from ChatGPT and work on them to improve them, to better suit our project. The use of ChatGPT is mainly because of this, but also because of the numerous advantages that this tool provides.

One pro of ChatGPT would be the availability of this tool. Generally, we are able to ask this AI source about anything at any time, which can be very handy for real-time situations in this project, from research to design decisions. Also, the instant response of the tool makes it even more handy in the whole process of our research and development.

Another strength would be the versatility of ChatGPT. This AI source has a possible application to almost every aspect of our project, including brainstorming, coding, researching, and even summarization of complex ideas in our project. One specific situation would be when needing a starting point for where to research microcontrollers, the tool can provide us with a list that we can do our individual research on to find the ideal microcontroller. This can be really helpful overall, as a good starting point can allow us to make very valuable research for our project.

Another pro of ChatGPT, can be found in its ability to help us with making things sound sensible or a “sanity check.” To review our work so far, to get an unofficial verification that the stuff in our project is functional, but this should not be taken 100% accurately because this would be one of the main cons of ChatGPT.

5.3 Cons of ChatGPT

Despite the multiple benefits of ChatGPT, it has very noticeable limitations to its knowledge and applications. In this project, we are very aware of these drawbacks and respond to them in a proper manner.

The major drawbacks of ChatGPT would be AI's lack of true human understanding and cognitive function. Because of this, the AI will lack an ability to provide human responses to aspects of the project that require professionally human advice and assistance. An example of this would be that when we make responses to ChatGPT, we have to be very specific about the problem, and even then, the response from the AI can be inaccurate or misleading. That is why using ChatGPT for very specific problems would be counterproductive to our project, and that this tool should be used from broad topics and problems.

Another drawback of ChatGPT, would be the risk of over-reliance. Using only ChatGPT can make the work in this project inaccurate and unoriginal. Throughout the project, we strive to keep a standard and focus for designing our project with functionality and originality. This focus can allow us to really understand all the aspects of our project and learn how to optimize the project properly. This can be seen through research done on our project, if the research is read thoroughly and not reliant on ChatGPT, our knowledge of the systems in this project will improve substantially.

5.4 How ChatGPT was Implemented

Despite these potentially damaging drawbacks of ChatGPT, it can still be properly used to develop our project effectively. The way we would use ChatGPT would be to keep the standard and focus of the functionality and originality in mind while using this tool. The way to do that, would be to read everything that the AI source provides and understand it to the best of our knowledge. Then with that, do our own independent research, by reading outside and credible sources (like research journals) to thoroughly understand the information ChatGPT provides. This would allow for us to see any inaccuracies in the information provided by ChatGPT and work around it. This would be the ideal situation. The main way to keep ideal would be to keep applications of ChatGPT for broad situations, like starting points for our research.

We believe that ChatGPT is a cutting-edge machine learning tool that can make our research efficient and effective. It can be used for its spontaneous responses that can provide foundations for our brainstorming and provide an opinion on our project that can be helpful. The main part of implementation of ChatGPT is to make sure that due to the possible inaccuracies that this tool can provide, it should be used properly and the information provided should be double checked and researched. Avoiding using ChatGPT for very specific tasks will allow for proper implementation, and keeping a need for research and avoidance of overreliance of the tool can allow for a functional project overall.

5.5 ChatGPT Applications and Analysis

One major advantage of using platforms like ChatGPT is the ability to quickly access accurate and relevant information tailored to specific needs. Although traditional search engines have long allowed users to look up almost any topic, the results are often broad or only loosely related to the original query. This can make it time-consuming to sift through forum discussions, lengthy articles, or outdated web pages just to find a clear, concise answer. In contrast, ChatGPT provides responses that are directly aligned with the question asked, making it much easier to find exactly what you're looking for.

A practical example of this comes from our senior design project, where we needed to identify specific industry components related to our design constraints and ideas. Initial internet searches led us to general information or unrelated documents, but using ChatGPT allowed us to pinpoint the relevant standards quickly and understand how they applied to our project. This not only saved time but also helped us move forward with greater confidence in the accuracy of the information. Tools like ChatGPT have become invaluable in academic and engineering settings for enhancing productivity, supporting research, and clarifying complex technical topics.

Prompt: Give me physical user interface

ChatGPT Response: Sure! A Physical User Interface (PUI) refers to any tangible way a user interacts with a device or system. Here are examples of physical user interfaces:

Table 23 - Chat GPT Examples of Physical User Interfaces (PUIs)

Type	Description	Examples
Buttons	Pressable components to trigger actions	Power button, keyboard keys, elevator buttons
Switches	Toggle or change system state	Light switches, mode selector switches
Knobs/Dials	Rotatable controls for tuning or adjusting	Volume knob, thermostat dial
Sliders	Move along a path to change a setting	Audio mixing boards, brightness sliders
Touchscreens	Display that responds to finger/stylus	Smartphones, ATMs, tablets
Joysticks	Directional control using a stick	Game controllers, drone remotes
Touchpads/Trackpads	Flat, touch-sensitive areas	Laptop trackpads, drawing tablets
Rotary Encoders	Infinite rotation input devices	Digital menu selectors, control knobs in cars
Sensors	Detect presence or movement	Proximity sensors, gesture sensors
Levers	Move up/down/sideways to control mechanism	Gear shifter, arcade machine levers

Key Characteristics of a PUI:

- **Tangible:** You can physically touch or manipulate it.
- **Direct feedback:** Often provides tactile or visual response (e.g., clicking sound, LED blink).
- **Durability:** Designed to handle repeated interaction.
- **Ergonomics:** Must be intuitive and comfortable to use.

As demonstrated, our prompt to ChatGPT yielded a direct and relevant response that aligned closely with the information we were seeking. Had we relied solely on a standard internet search, we likely would have spent considerably more time sifting through unrelated results, vague forum posts, or lengthy articles to find the same level of clarity. ChatGPT streamlined this process by presenting us with clearly defined examples of Physical User Interfaces, which we were then able to research further and incorporate effectively into our project report.

6.0 Hardware Design

The hardware design of the Laser Harp integrates multiple subsystems that work together to deliver a functional, safe, and interactive musical instrument. Each part of the system has been selected to balance performance, cost, and simplicity while ensuring that the final prototype stays within the project's physical and budget constraints. The main components of the hardware include the power supply unit, dual microcontroller units, the optical beam system, photodetectors, user interface controls, audio playback circuitry, and the stepper motor assembly. Together, these elements form a cohesive design that connects optics, embedded electronics, and real-time signal processing in a single device. For the schematics and the PCB boards shown in Chapter 8, the program FUSION 360 was used to produce the schematics for the components that are going onto a PCB board. FUSION 360 also allows for the integration of the schematics into PCB designs, which we also have done. For the system that contains the stepper motor, stepper motor driver, and laser, we use Digikey's schematic creator SCHEME-IT to produce the schematics.

6.1 Laser String Unit (LSU)

The laser harp will be a culmination of a lot of different parts coming together; assembled to create the instrument that we seek to make. As stated previously, what some would call the harp, and its strings, will be produced by the reflection of a laser diode's light from a mirror that is being turned at a fast frequency by a stepper motor. The stepper motor and the laser diode are both controlled by the Arduino Uno board. These two are located and controlled by the same board to ensure synchronization, as the laser must turn on and off at specific times to ensure that the device creates the illusion of individual strings. The stepper motor will require high current to operate, so a TB6600, or equivalent, stepper motor driver will be used to drive the motor. The driver is used to control and determine the right current needed to drive the motor, and how many micro steps are in each revolution. As the motor turns, the Arduino will record the values of the relative position of the stepper motor, and send these values to the main ESP32, located on the main board, for processing. The Arduino and the ESP32 communicate via the SPI protocol, with the Arduino acting as the slave device. The devices, besides the stepper motor and the TB6600 driver will be powered by regulators, which will be discussed later.

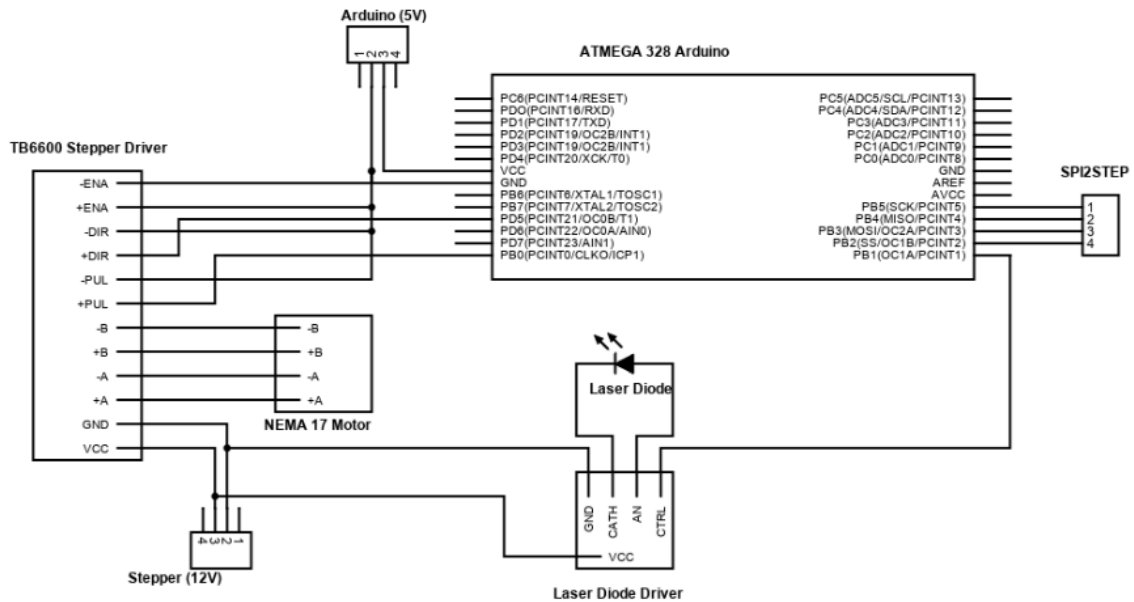


Figure 14 - Schematic of Laser String Unit

The laser module is a very important part of the LSU and the laser harp as a whole. The laser diode can not be controlled directly by the Arduino due to it's the diode's properties. First, the Arduino would not be able to produce enough current to power the diode by itself. Second, if we used a NPN transistor to act as a gate, and power the laser diode with the 12V, it still wouldn't be enough. As stated previously, the diode has a set rated operational voltage and operational current. The laser diode is very delicate, and any increase in the current and voltage above the operational limit will damage the diode. Another property that must be accounted for is the tendency of laser diode to increase in conduction when temperature increases. So, we are forced to regulate the voltage and the current to effectively control the laser diode and increase its lifespan. This was done by designing a laser diode driver. The diode includes a linear regulator that will act as a constant current source. The driver will also use a Zener diode to regulate any increase in voltage, and a gate is used to toggle the laser on and off from the Arduino.

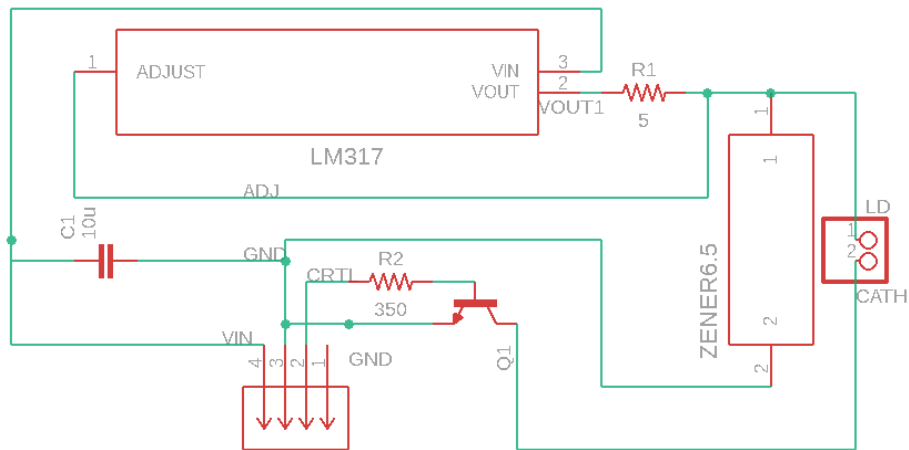


Figure 15 - Schematic of Laser Diode Driver

6.2 Main Processing Unit (MPU)

The main processing unit is the largest part of the laser harp, and the main section of the PCB. The primary task of the main processing unit is to detect the disturbances in the laser strings produced by the Laser String Unit; process information given by the Arduino and play the intended musical note. The MPU, and the entire laser harp for that matter, by the ESP32 board. The ESP32 will be tasked with the processing of the information given by its peripherals and outputting the intended sound. The ESP32 detects the playing of the strings by the three (or five) photodiodes that are in the MPU. The photodiodes are tasked with detecting the reflection from a user hand when they play a string. This information will be passed through an analog pin on the ESP32 to be processed. Cross-referencing the stepper motors position given by the Arduino, the ESP32 can play the intended sound. In the MPU includes a music module, the DFPlayer Mini, which has an SD module attached. The DFPlayer uses a DAC module and a Class D amplifier to produce the notes stored in the SD card. The ESP32, when it detects a string, will communicate with the DFPlayer via UART to produce the give sound via a speaker connected to it. Additionally, the main processing unit includes the user interface; the dials and buttons that will influence the notes being played.

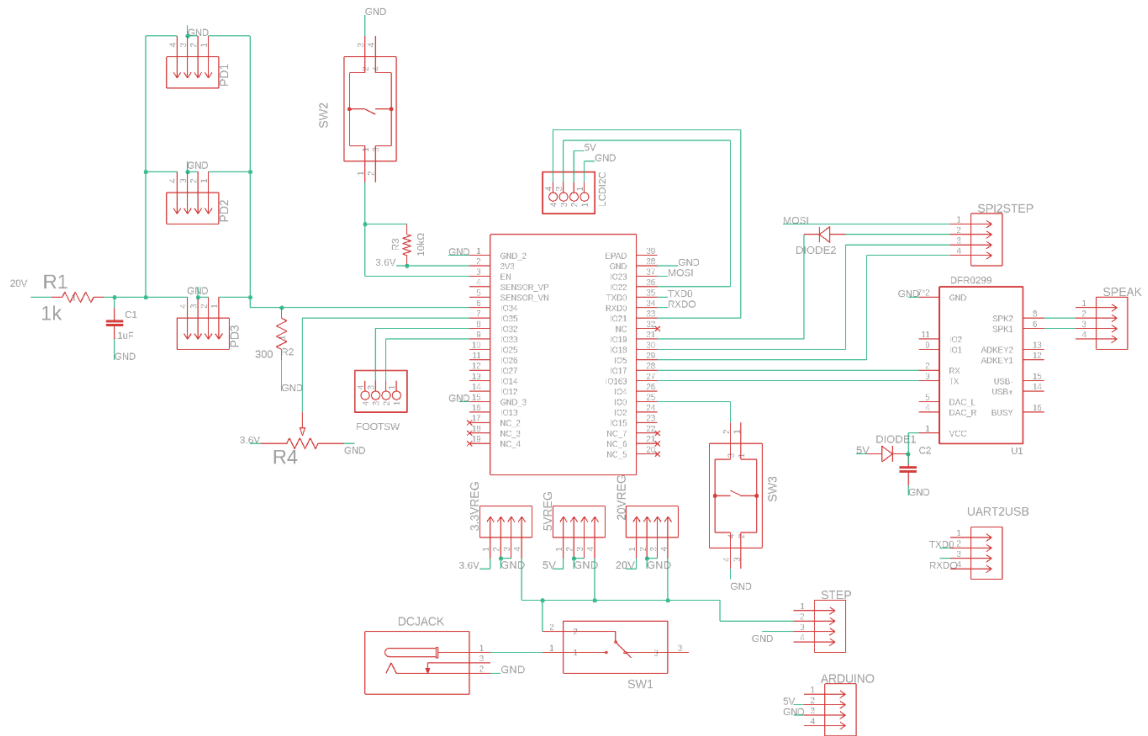


Figure 16 - Main Processing Unit Schematic

6.2.1 User Interface

An essential aspect of the laser harp system lies in its user interface—the way in which the player engages with and controls the instrument. Unlike traditional instruments, the laser harp integrates both physical and digital inputs that enhance interactivity and provide a more versatile user experience. The most immediate point of interaction is through the laser “strings,” which are broken by hand gestures to produce musical notes. However, the user interface extends far beyond just playing the harp.

Users will have access to several control features that enhance usability, safety, and customization. These include a main power switch for system activation, as well as the option to toggle between power sources, either a rechargeable battery or an AC-to-DC wall adapter. In addition, users will be able to activate or deactivate both the laser array and the rotating stepper motor that controls string placement. This ensures safe startup conditions and allows for precise motor alignment. Volume controls will also be provided to tailor the sound output to the user's environment or preference. Furthermore, users will have access to tuning and note selection settings, enabling them to shift notes by half step or entire octaves, mimicking the key-shifting functionality found in electronic keyboards. The integration of these control systems ensures a responsive, intuitive, and flexible experience suitable for both novice users and advanced performers. The design and implementation strategies for these controls are detailed in the following sections.

6.2.2 Power On/Off and Reset

The power control system of the laser harp is designed to give the user full autonomy over how and when the device is activated, as well as to ensure operational safety. At the heart of this system is a three-position selector switch that provides three distinct modes: OFF, Battery Power, and Wall Power. This switch acts as the main gatekeeper for the power supply unit (PSU), controlling whether power is sourced from an internal battery pack or an external AC-to-DC converter. This dual power system gives users the flexibility to use the harp in portable or stationary settings. The laser harp will be equipped with a 5.5mm x 2.5mm power jack that can accommodate the wall converter and the battery.

To maintain musical consistency, the system also includes a reset button that, when pressed, sends a signal to return the stepper motor and laser to a predefined “home” position. This ensures the harp always begins operation in a calibrated state, avoiding desynchronization between the beam and the sensor grid that could disrupt note accuracy. Safety, predictability, and ease-of-use are the guiding principles behind this control design.

6.2.3 Volume Control

Sound output is a critical component of the laser harp experience, and users must be given control over the volume to suit different environments, from quiet rooms to live performance settings. To provide this control, the harp integrates an analog volume adjustment system using a potentiometer in conjunction with an audio amplifier circuit.

When a laser string is interrupted, the corresponding note signal is routed through a sound amplifier. This amplifier uses variable gain, which can be modified by adjusting resistance within the feedback loop. A user-accessible dial connected to a potentiometer allows the user to dynamically vary this resistance. Turning the knob increases or decreases the gain, which in turn affects the volume of the sound output. This intuitive analog approach is both cost-effective and reliable, making it ideal for an embedded musical system. Detailed schematics and performance considerations for the audio amplification system are discussed in the Audio Output section of this report.

6.2.4 Foot Buttons

To further enrich the hands-free playability of the laser harp, the design incorporates foot buttons inputs. These buttons serve as auxiliary controls that enable real-time musical adjustments without interrupting the playing motion of the user’s hands. The buttons will likely be made out of pressure sensitive resistor that change resistance when pressure is applied. This change in pressure can be detected by the ESP32 and processing is made accordingly.

One button may serve as a sustain function, holding a note even after the hand is removed from the beam, much like a traditional piano pedal. Other buttons can be used to change octaves or shift musical scales mid-performance, allowing for live improvisation and flexibility. The buttons will operate using standard momentary switches, interfaced with the microcontroller through digital I/O pins. Pressing a button sends a signal to the control logic, which then executes a predefined software routine. Integrating foot buttons not only frees up the user's hands for expressive play but also brings the laser harp closer in functionality to professional-grade musical instruments.

6.3 Power Supply Unit

The laser harp is intended to have the possibility of two different sources of power, a wall power converter and a rechargeable battery. Both devices will be able to power the laser harp with a voltage of 12V; however, there are some implications on how this is done. To ensure the safety of the components used and the laser harp, regulators will be used to control and regulate the voltage and load current of each device.

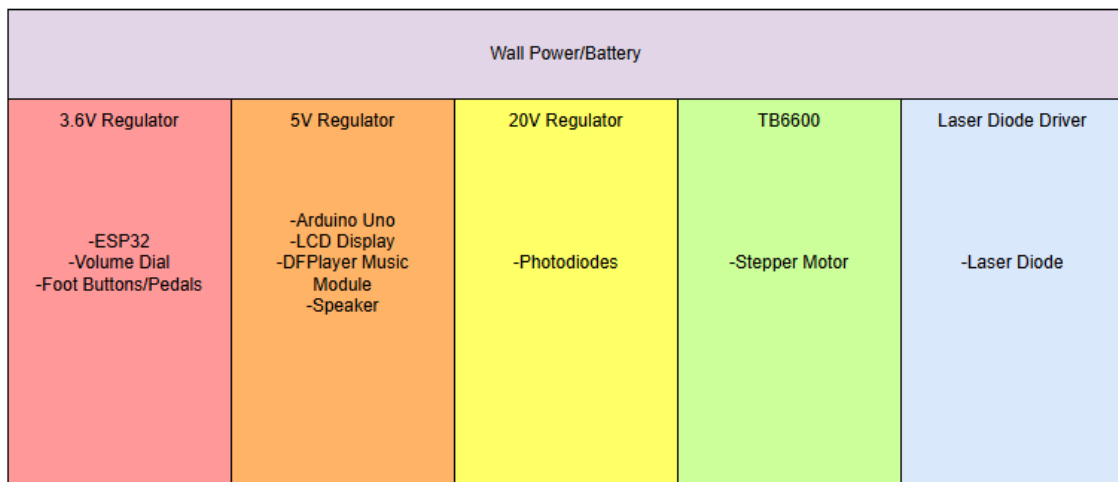


Figure 17 - Power System Diagram

Due to the different voltage ratings of the devices, it would be best for the laser harp to utilize both types of regulators, linear and switching regulator. The primary purpose would be to generate a stable voltage source for both microcontroller and photodiodes. A stable voltage source ensures that the microcontroller does not experience any malfunction or isn't damaged by any sudden change in the voltage. A stable voltage is also important for photodiodes, as having a low-noise voltage source is imperative to an accurate reading. Three different regulators were used in this project, one 3.6V linear regulator, one 5V linear regulator and one 12V to 20V switching regulator. Both linear regulators

were used to power every component besides the stepper motor. Linear regulators were used to ensure each component gets a stable voltage, ensure that none of the components get damaged by any sudden change in load or power output. As shown in Figure 12 above, most of the components will handle voltages of either 3.6V or 5V. Linear regulators were used to ensure stable voltages through its run time. The 20V switching regulator is used to supply a bias voltage to the photodiodes to ensure high efficiency and high responsivity when detecting light from the strings. Figure 13 shown below shows the schematic of the three regulators. The stepper motor does not need a regulator, as the TB6600 stepper driver acts like a buck regulator, taking the large 12V and reducing it to a more manageable voltage.

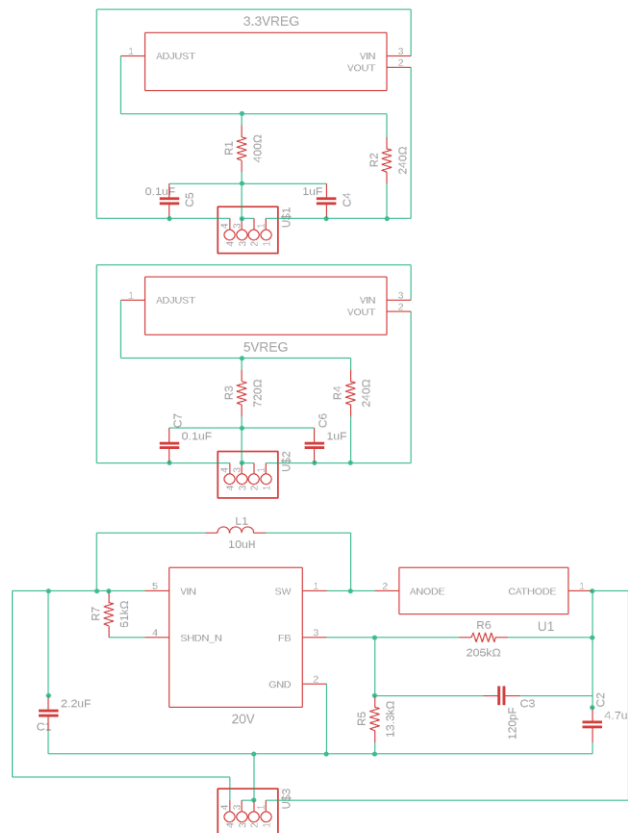


Figure 18 - Schematic of 3.6V, 5V, and 20V Regulators Respectively

6.4 UART to Serial Converter

A small inclusion to the overall design of the laser harp is the addition of a small USB to Serial converter. The converter, in conjunction with the two buttons mentioned above in the main processing unit, is used to upload code into the ESP32 without the use of a development board or any sort of shield. This allows the choice to easily program and reprogram the board after the board has being soldered into the PCB. The converter involves a USB shield connected to a

FT232RL chip. The chip is powered by the USB cable connected to the board, with the boards UART going into the ESP32. When the previously mentioned buttons are pressed, (One is held down, then the other pressed, and both released), the board can save code from the USB and save it to its flash memory.

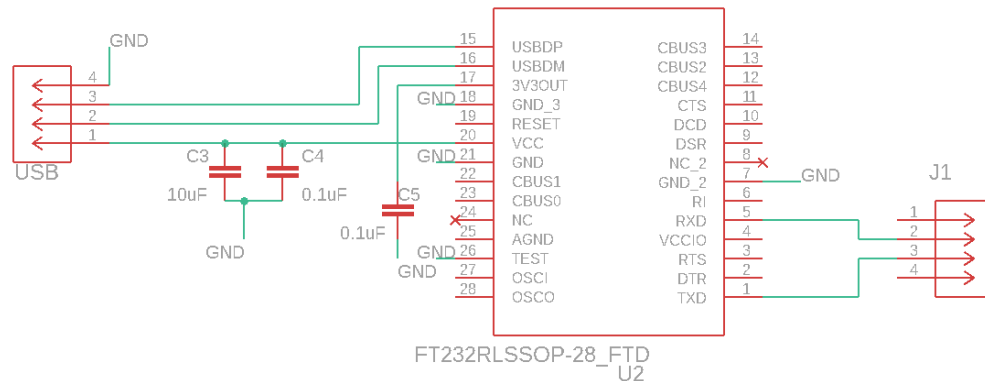


Figure 19 - USB to UART Converter

6.5 Optical Design

6.5.1 Collimating lens

There are three main optical components that need optical design. The collimating lens, beam expander, and the collection lens. There are many important factors that go into each of these components.

Starting off with the collimating lens. Important specifications when designing the collimating lens are focal length, numerical aperture, lens diameter, lens type/shape, and material. Laser diodes produce strongly diverging light. This is due to the size of the emitting area of the laser diode. For laser diodes the emitting area is normally very small. The small emitting area means a more diverging beam. Also, because of the shape of the emitting area of laser diodes the beam is elliptical shaped. To fix the large divergence a collimating lens is used to collimate the light. The most common lens type/shape used for collimating light from a laser diode is an Aspheric lens. The reason for this is it reduce the spherical aberrations that come from the laser diode. For good collimation the numerical aperture should be much larger than the numerical aperture of the laser diode [47].

It is also very important that the distance between the collimating lens and the laser diode is exactly the focal length. If the distance does not equal the focal length, then the beam will either converge or diverge after the collimating lens [47]. In order to calculate the proper focal length needed the beam divergence angle is needed and the desired beam diameter.

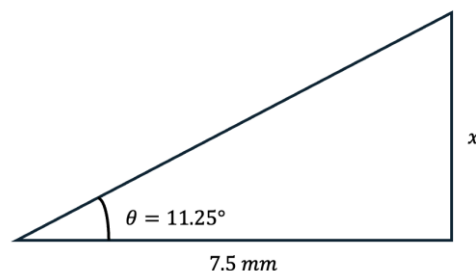
It is also very important that the distance between the collimating lens and the laser diode is exactly the focal length. If the distance does not equal the focal length, then the beam will either converge or diverge after the collimating lens. In order to calculate the proper focal length needed the beam divergence angle is needed and the desired beam diameter.

$$f = \frac{\frac{d}{2}}{\tan\left(\frac{\theta}{2}\right)} \quad \text{Equation 3}$$

The formula for finding the focal length is equation 3 above. In the focal length equation d is the wanted beam diameter (beam diameter desired after the lens) and θ is the full divergence angle coming from the laser diode [48]. Laser diodes have fast, and slow axis and the fast and slow axis diverge at different angles [47]. When calculating the focal length, the axis with the larger divergence angle is used for a single aspheric lens configuration [49]. The collimated beam shape will be more elliptical. To get a more circular beam shape using a mounted prism pair is a good option [50]. For the purpose of the Laser Harp one aspheric lens to collimate the light will be acceptable. Using the equation 3 I have found that I need a focal length of 7.7mm.

$$f = \frac{3}{2 * \tan\left(\frac{22.5}{2}\right)} = 7.7mm$$

Checking my work:



$$x = 7.5 * \tan(11.25)$$

$$x = 1.5mm$$

$$\text{total beam size} = 2 * 1.5 = 3$$

The numerical aperture is also very important when designing the lens. The numerical aperture is a dimensionless number that identifies a range of angles the system can accept or emit light [51]. For a collimating lens for a laser diode a high numerical aperture is recommended. This is because the light coming from the laser diode has a very big divergence angle. Therefore, the bigger the numerical aperture the more light from the laser diode can be captured into the collimating lens. The equation for numerical aperture is below in equation 4.

$$NA = n\sin(\theta) \quad \text{Equation 4}$$

Where n is the refractive index of air ($n=1$) and θ is half the divergence angle [51]. Like in the focal length formula the larger divergence angle is used. This is to ensure that as much light as possible is going into the collimating lens.

$$NA = \sin\left(\frac{22}{2}\right) = 0.2$$

When calculating the numerical aperture for the laser diode we get $NA = 0.19$. When designing a collimating lens, you want the numerical aperture of the lens to be larger than the numerical aperture of the laser diode. If the numerical aperture is too small, then the collimated beam can be distorted. For our system it is recommended that the numerical aperture of the lens be $\geq 2 * NA \text{ of laser diode}$. Which means the numerical aperture of the lens needs to be ≥ 0.4 [49]. An aspheric lens is also a great choice when collimating a laser diode because they have larger numerical apertures.

The diameter of the collimating lens should be big enough to capture the light from the divergence angles. For our system we have chosen to choose a diameter that is roughly the diameter of the laser diode. Therefore, the diameter of the collimating lens will be greater than 12mm. An option for a diameter could be around a 6mm lens. However, 6mm lenses are hard to work with because they are too small. When it comes to the material of the lens glass, or plastic would work well for our application. Due to the cost of the lenses plastic is typically the better option for the Laser Harp system. However, through doing a lot of research and looking through different lens catalogs a glass lens has been selected. The price of the glass lens is around \$30. Which is not very expensive for a lens.

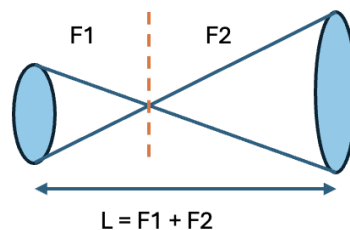
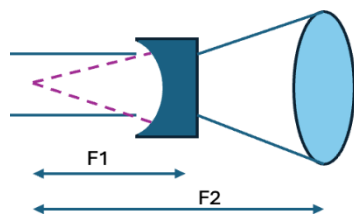
From the math done above we know we need a focal length around 7.5mm, a large numerical aperture (greater than 0.4mm), and a diameter larger than 12mm. Because we are not using custom parts off the shelf lenses need to be looked at. When looking at the lenses available the following lens was found on Edmund optics.

Table 24 - Specifications of Collimating Lens

Diameter	12mm
Clear Aperture	9.50mm
Focal Length	7.5mm
Numerical Aperture	0.8
Substrate	LIBA2000+
Cost	\$33.92

6.5.2 Beam Expander

After the lens is collimated the diameter of the beam will be around 3mm. 3mm is a small beam. In order for the laser harp to be easier to play a bigger beam diameter is preferred. A bigger beam diameter will help the user see the beams better, but it will also cause there to be more reflection back into the photodiodes. Which will make it easier to capture the reflection and trigger the photodiodes. There are two main types of beam expanders Keplerian and Galilean. The Keplerian beam expander is shown below in figure 20 on the left. The Keplerian beam expander consists of two positive focal length lenses. The space between the lenses is the first focal length plus the second focal length. In figure 21 below on the right the Galilean beam expander is shown. Because one of the lenses is negative the distance between the lenses is shorter than the Keplerian configuration [52].



**Figure 21 - Galilean
Beam Expander**

**Figure 20 - Keplerian
Beam Expander**

For the Laser Harp system we are choosing to use the Galilean beam expander configuration because the space between the lenses will be smaller which is most desired for our setup. The Galilean beam expander consist of a one negative (concave) and one positive lens (convex) [52]. We have decided that we want to expand the beam with 2x magnification. In order to figure out the focal lengths necessary to do so the equations below were used.

$$M = \frac{f_2}{|f_1|} \quad \text{Equation 5}$$

$$5 = \frac{48}{|-24|}$$

Because we are not making custom parts for the Laser Harp system off the shelf focal lengths were investigated. For the diameter of the lens, we are going with 12mm. This is due to the fact that the diameter of the negative lens needs to be bigger than the incoming beam diameter. The incoming beam diameter is 3mm. There are off the shelf lenses that are smaller than 12mm however the smaller the lens the harder it is to handle. When going through the catalog of lenses from Edmund optics we found a 48mm positive lens and a -12mm negative lens. These two focal lengths give us the 2x beam expansion.

$$D = f_2 - |f_1| \quad \text{Equation 6}$$

$$48 - |-24| = 24mm$$

Therefore, the distance between the lenses needs to be 20mm.

Each lens in the beam expander has their own specifications that need to be followed. For the negative lens (concave) the parameters are focal length (determined above), diameter, coating, lens type, and curvature. The use of a negative lens is to diverge (expand) the incoming light. The focal length was determined above as -24mm.

When creating a Galilean beam expander, it is best to use a plano-concave lens for the negative lens. The flat side of the lens (aka plano side) helps to improve the wavefront of the beam. For the best wavefront it is recommended to place the lens with the plano side facing the incoming beam. This will help balance out of some of the spherical aberration that might be occurring [53]. The curvature of the concave side of the lens is calculated using the lens makers equation [54].

$$\frac{1}{f} = (n - 1) \left(\frac{1}{R_1} - \frac{1}{-R_2} \right) \quad \text{Equation 7}$$

f = the focal length of the lens

n = refractive index

R_1 = Radius of the plano side of the negative lens

R_2 = Radius of the concave side of the negative lens

$$\frac{1}{-24mm} = (1.5 - 1) \left(\frac{1}{\infty} - \frac{1}{-R_2} \right)$$

The refractive index used in the equation above is that of Polymethyl methacrylate. Polymethyl methacrylate is a type of plastic (also known as acrylic) [55]. The reason plastic is being used instead of glass is because it is normally cheaper than glass. This makes $R_2 = -12mm$. The company I found to make the plastic plano-concave lens is in Europe. Due to the state of our tariffs, it might be cheaper to buy glass lens from Thorlabs. A BK-7 plano-concave lens from Thorlabs averages at around \$24 - \$25 plus shipping [56]. If we have to use BK-7 here is the curvature for the concave side.

$$\frac{1}{-24mm} = (1.517 - 1) \left(\frac{1}{\infty} - \frac{1}{-R_2} \right)$$

In the BK-7 case the curvature comes out to $R_2 = -12.408mm$. This curvature is not that much different from the Polymethyl methacrylate. This is due to their close refractive indexes.

The diameter of the lens is determined by the incoming beam diameter. The incoming beam diameter is chosen value determined by the optical engineer on the team. That value is 3mm. Therefore, the diameter of the negative lens needs to be larger than 3mm. The final diameter value will be determined by the diameter of an off the shelf part I can purchase.

Since we are using a 520nm (green laser) the lens should be AR coated for the green spectrum.

When designing the positive (convex) lens of the beam expander there are parameters that need to be met. For example, some of the parameters are focal length (determined above), diameter, coating, lens type, and curvature. The reason a plano-concave lens is needed for the beam expander is that the lens will collimate the expanded light coming from the negative lens [57]. Just like the plano-concave lens the plano side is there to help improve the wavefront quality. Also, placing the lens in the system with the plano side facing the input beam with further improve the wavefront by helping eliminate the spherical aberrations [53]. Therefore, the lens type we will be using for the positive lens will be a plano-convex lens.

Another parameter that is important when doing the optical design for the positive lens of a beam expander is the curvature of the lens. The formula for calculating the curvature of the plano-convex lens is below.

$$\frac{1}{f} = (n - 1) \left(\frac{1}{R_1} - \frac{1}{R_2} \right) \quad \text{Equation 8}$$

Just like the negative lens the parameters are:

f = the focal length of the lens

n = refractive index

R_1 = Radius of the plano side of the negative lens

R_2 = Radius of the concave side of the negative lens

Notice that the formula is very similar to the formula to find the curvature for the negative lens. However, the radius of curvature number two is positive. This is due to the fact that we are doing the calculation for a positive lens.

$$\frac{1}{48mm} = (1.5 - 1) \left(\frac{1}{\infty} - \frac{1}{R_2} \right)$$

Using the same refractive index as above (Polymethyl methacrylate) the radius of curvature for the convex side of the plano-convex lens is $R_2 = 24$. The reason the R_1 goes to infinity is because that is the plano side of the lens. When a lens is flat the radius of curvature is infinity. Also like the negative lens another alternative to the plastic lens is using BK-7. Once again, the refractive index for BK-7 is $n = 1.517$.

$$\frac{1}{48mm} = (1.517 - 1) \left(\frac{1}{\infty} - \frac{1}{R_2} \right)$$

The radius of curvature for the convex side is $R_2 = 24.816$. As you can see the radius of curvature value is not far off from the Polymethyl methacrylate. It is important to calculate each radius of curvature even if they are going to be similar values because that little difference in curvature could make a difference in the final output.

The diameter of the positive lens depends on the input beam size and the desired expanded beam size. It is very important that the diameter is bigger than the desired beam size. For example, the Laser Harp system after the collimating lens will have a 3mm beam size. A 2x magnification beam expander the expanded beam size will be 9mm. Therefore, the diameter of the convex lens should be larger than 9mm. Another parameter that will be similar to the negative lens is the coating. The coating will need to be AR coated for the green wavelength range.

The beam expander lens specifications are as follows.

Table 25 - Specifications for Plano-Concave Lens

Diameter	12mm
Focal Length	-24mm
Numerical Aperture	0.25
Substrate	N-BK7
Cost	\$31.80

Table 26 - Specifications for Plano-Convex Lens

Diameter	12mm
Focal Length	48mm
Numerical Aperture	0.13
Substrate	N-BK7

Cost	\$20.00
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Collection Lens

A collection lens is essentially a collimating lens. A collimating lens is placed after the laser diode and takes the diverging light from the laser diode and straightens/directs the light. The collection lens will be placed before the photodiode it will take in the scattered light and straightens/directs the light into the photodiode. There will be one collection lens for the one photodiode.

The active area of the photodiode is 13mm^2 . 13mm^2 are the dimensions $3.6\text{mm} \times 3.6\text{mm}$. When doing research for the photodiode I found the $3.6\text{mm} \times 3.6\text{mm}$ was on the larger side for photodiode active areas. Because the active area is larger the diameter of the collection lens will need to be larger as well. Therefore, the diameter needs to be larger than 3.6mm . It is easiest and cheaper to look for off the shelf parts instead of making a custom part. When looking into common diameters we found a 25.4mm lens [58].

The scattered light will be very large. Therefore, a wide acceptance angle will be very important. In order to achieve a large acceptance, angle a large numerical aperture is needed. This will be similar to the laser diode. The laser diode has a big divergence angle and needs a numerical aperture greater than or equal to 0.4. For the collection lens we will assume that the divergence of the scattered light will be large. Therefore, we will use a numerical aperture size of greater than or equal to 0.4.

When choosing the lens type for the collection lens a lens shape that has a high numerical aperture is recommended. A type of lens that has a high numerical aperture is an aspheric lens. However, after doing further research a plano-convex lens will work great for a collection lens.

Now that we know the diameter and the numerical aperture, we can figure out what focal length will be needed for the collection lens. When looking for common off the shelf parts we found a lens that has a bigger diameter (25.4mm), is plano-convex, and has a focal length of 25.4. This focal length will work great for the purpose of the laser harp. Because it is not too far from the photodiode. We want a focal length that is not really far and not too close.

Table 27 - Collection Lens Specifications

Diameter	25.4mm
-----------------	--------

Focal length	25.4mm
Lens shape	Plano-Convex
Material	N-BK7
Cost	\$63

System losses

When creating a system, it is important to know what losses there will be in the system. It would be beneficial to have all the optical AR coated to 520nm. However, buying optics that are coated making them very expensive. To know how much loss will be in the system the following math is done.

We need to go lens by lens. The first lens we will start out with is the collimating lens. We need to calculate the Fresnel losses.

$$R = \left(\frac{n_1 - n_2}{n_1 + n_2} \right)^2 \quad \text{Equation 9}$$

R = reflectance

n_1 = refractive index of incident medium (air)

n_2 = refractive index of lens material

$$R = \left(\frac{1 - 1.52}{1 + 1.52} \right)^2 = 0.0426$$

For the collimating lens the lens material is LIBA 2000+ the index of refractive of LIBA 2000+ is 1.52 [59].

Now that we have R we need to find the total Fresnel loss. The equation for total Fresnel loss is given below.

$$\text{Fresnel loss} = 1 - T_{total} \quad \text{Equation 10}$$

$$T_{total} = (1 - R)^2 \quad \text{Equation 11}$$

Calculating the total loss for the collection lens:

$$T_{total} = (1 - 0.0426)^2 = 0.916$$

$$Fresnel\ loss = 1 - 0.916 = 0.0833$$

Therefore, the total loss for the collection lens is 0.0833

Now calculating the loss for the beam expander. The list loss that is needed is the plano-concave lens.

$$R = \left(\frac{1 - 1.5168}{1 + 1.5168} \right)^2 = 0.0422$$

$$T_{total} = (1 - 0.0422)^2 = 0.917$$

$$Fresnel\ loss = 1 - 0.917 = 0.0825$$

Plano-Convex lens is made with the same material so math will be the same.

$$R = \left(\frac{1 - 1.5168}{1 + 1.5168} \right)^2 = 0.0422$$

$$T_{total} = (1 - 0.0422)^2 = 0.917$$

$$Fresnel\ loss = 1 - 0.917 = 0.0825$$

The total Fresnel loss of the beam expander is

$$0.0825 + 0.0825 = 0.165$$

Now we need to calculate the Fresnel loss of the collection lens. The collection lens is made from BK-7. Therefore, the math will be the same as above.

$$R = \left(\frac{1 - 1.5168}{1 + 1.5168} \right)^2 = 0.0422$$

$$T_{total} = (1 - 0.0422)^2 = 0.917$$

$$Fresnel\ loss = 1 - 0.917 = 0.0825$$

To calculate the total loss of the lens system all the Fresnel losses need to be added together.

$$0.0825 + 0.165 + 0.0833 = 0.3308$$

As you can see there will be about 33% loss in this lens system. The loss would go down considerable with all the optical AR coated at 520nm. However, this project is student funded, and the optics would cost a lot more with the AR coating. For a future improvement to the Laser Harp system all the optics should be AR coated for 520nm.

Zemax modeling

To verify the math that was done above I have simulated the optics in Zemax.

The image below is the lens prescription for each of the three lenses.

Configuration 1/1													
	Surface Type	Comment	Radius	Thickness	Material	Coating	Clear Semi-Dia	Chip Zone	Mech Semi-Dia	Conic	TCE x 1E-6	Par	
0	OBJECT	Standard	Infinity	6.491			0.000	0.000	0.000	0.000	0.000		
1		Standard	Infinity	0.000			0.970	0.000	0.970	0.000	0.000		
2	STOP (aper)	Even Asphere	4.831	5.500	LB2000		4.800 U	1.200	6.000	-3.065	-		
3	(aper)	Standard	-12.700	25.000			4.800 U	1.200	6.000	0.000	0.000		
4	(aper)	Standard	Infinity	3.500	N-BK7		5.500 U	0.500	6.000	0.000	-		
5	(aper)	Standard	12.400	-23.994			5.500 U	0.500	6.000	0.000	0.000		
6		Standard	Infinity	45.500 V			5.094E-03	0.000	5.094E-03	0.000	0.000		
7	(aper)	Standard	Infinity	2.500	N-BK7		5.500 U	0.500	6.000	0.000	-		
8	(aper)	Standard	-24.820	48.000			5.500 U	0.500	6.000	0.000	0.000		
9		Standard	Infinity	0.000			2.210	0.000	2.210	0.000	0.000		
10	IMAGE	Standard	Infinity	-			2.210	0.000	2.210	0.000	0.000		

Figure 22 - Zemax Lens Prescription

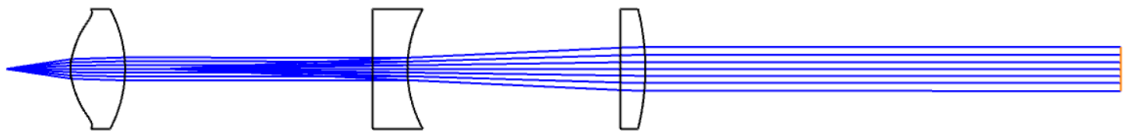


Figure 23 - Zemax Optical Layout

Looking at the figure 23 above starting from the left is the collimating lens. As you can see the light comes in as a point source the lens then takes in the light and collimates it. You can see the light is collimated because of the parallel rays after the lens. The beam diameter is now 2.25mm, as shown in figure 24 below.

The now collimated light goes into the negative lens and the beam gets expanded. You can tell the beam is expanding by the diverging rays after the negative lens. The now expanded beam goes into the positive lens to get collimated again. The beam size after the lens is approximately 4.4mm. Refer to

figure 25 to see the beam size after the beam expander. It is also important to look at the spot diagram after the system as a whole. This is to ensure a clean spot. In figure 26 you can see the clean beam in the spot diagram.

Overall, the lens system that was designed above works exactly as planned. Except for the distance between the plano-concave and plano-convex lenses. For my calculation I expect the lens spacing to be about 25mm. However, in the Zemax simulation to get a collimated beam from the beam expander the distance between lenses is 45.5mm.

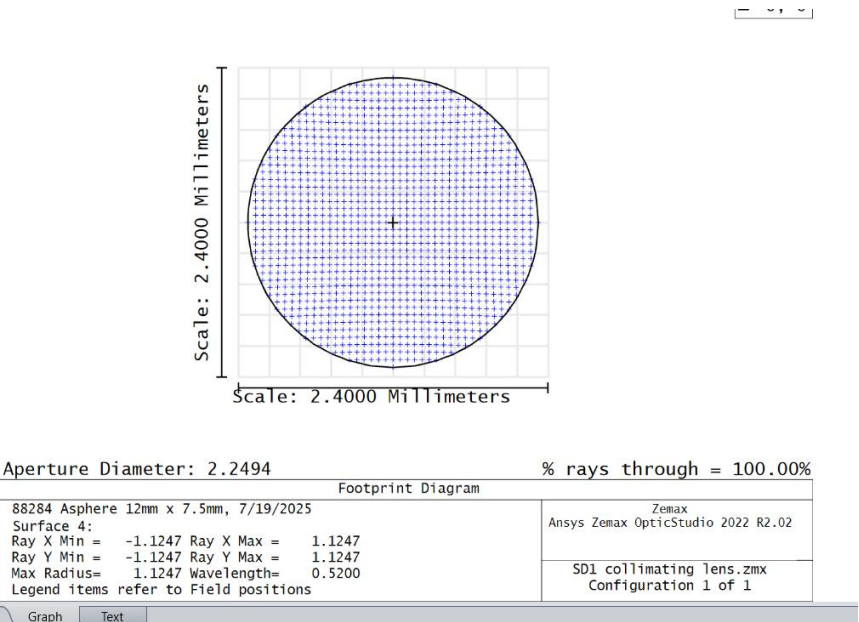


Figure 24 - Zemax of Beam Diameter After Collimating Lens

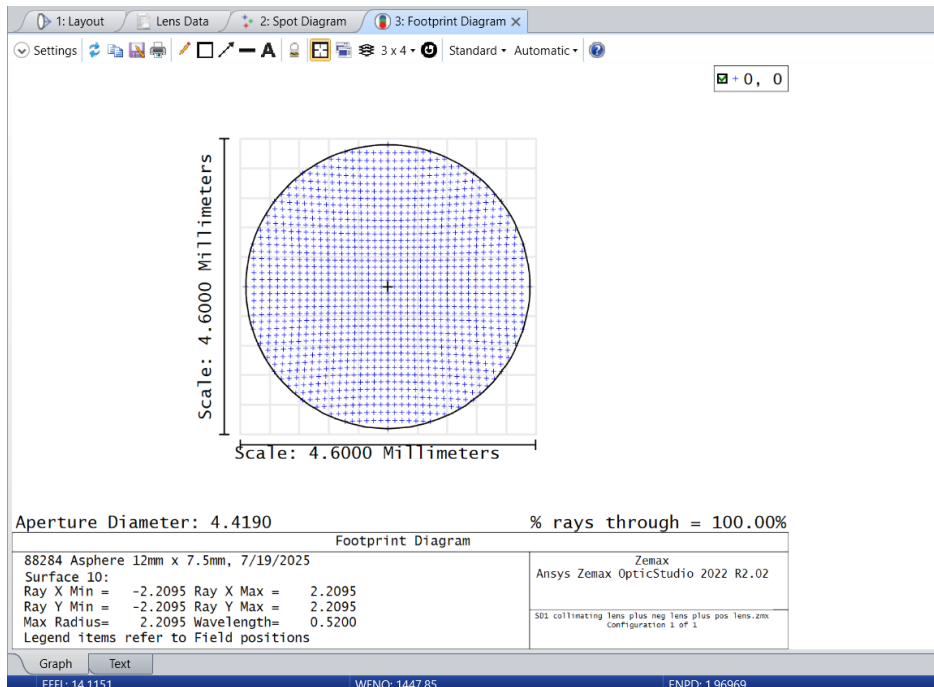


Figure 25 - Zemax of Beam Diameter After Beam Expander

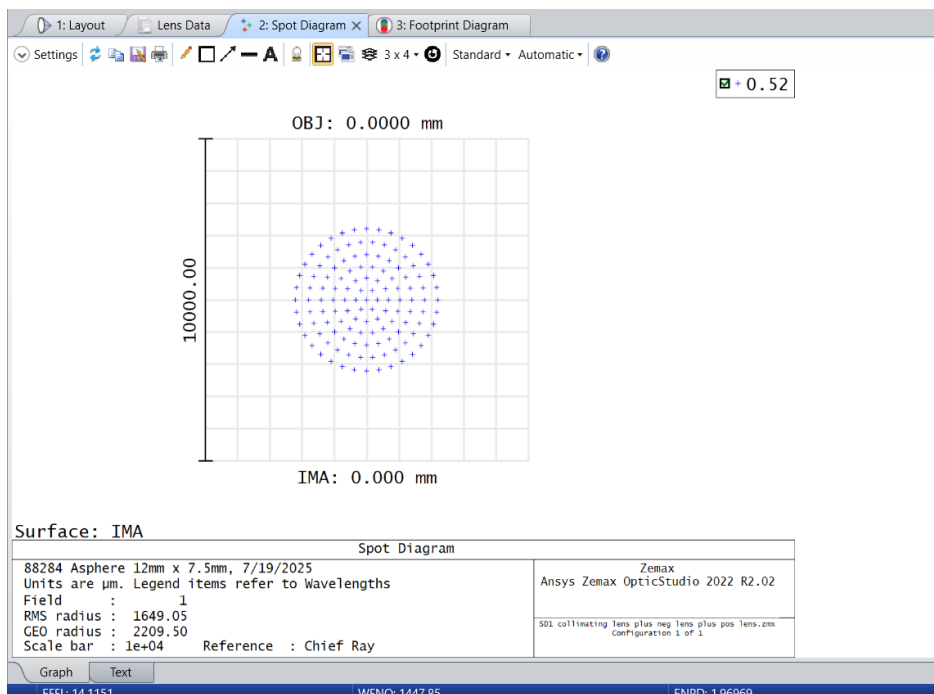


Figure 26 - Zemax Spot Diagram

After needed to change the system to be constant wave instead of pulsed it was aperient that this optical system focuses the beam at the desired width 18 inches away. With the goal of the laser harp to be portable and easy to carry 18 inches is too far for our system. A solution to this is to take out the negative lens. This

works because the laser diode module already has a collimating lens pre-attached. The Aspheric and the plano-convex lens achieve the desired thin width at 5 inches away. Which is a better option compared to the 18 inches away. Therefore, the final optical system is the same except the negative lens has been taken out.

6.6 Electronic Hardware Design After Final Demo

As mentioned throughout the report, major changes were made to the project, diverging from the original ideas that were established by the end of Senior Design 1.

The number of MCU used for the project changed throughout production but ultimately remained unchanged by the end. An Esp32 was used to control all of the UI in the project and to play music when it received information from the ATMEGA. The ATMEGA now would control the stepper motor and read voltage reading from the photodiode. The ATMEGA would send information of the position of the stepper motor when it read a reading to ESP32. To create the voltage reading, a transimpedance amplifier was made. It was constructed using a TL08X series operation amplifier to convert and amplify the current to a voltage.

The PSU had some changes done to it. First, the 20V Boost regulation to apply a reverse bias to the photodiode was dropped. The two primary regulators, the 3.3V and 5V were also changed. Instead of using a LM317 LDO regulator, the LM2576 switching regulator was used to produce both voltage levels. We decided as it could produce the voltage while reducing heat produced. Additionally, the stepper motor was also changed. Instead of the TB6600, the DRV8825 was used, with a custom PCB board being constructed to drive the NEMA 17 motor. For the laser driver, a premade board made from the LM2596 voltage regulator was used to generate constant current. No MCU would now be controlling the laser, as it wouldn't be pulsed anymore.

7.0 Software Design

For the software design, this project will involve relatively basic iterative software architecture for the multiple peripherals and systems. This can be seen from the need to optimize both memory usage and processing power within the constraints of budget and typical microcontroller environments.

Another reason for simplicity, by choosing a lower level of coding language like C is because of its efficiency. This coding language is powerful when it comes to their runtimes. In this part of the project, we are favoring a simple and efficient approach, not using too much memory but also being as quick as possible. Throughout the whole design process of the code, we will be debugging with a readable and thorough coding philosophy.

7.1 Coding Run-through and Logic

The iterative approach was favored for its optimization and efficiency. For most of the project, the decision-making logic will be implemented through a combination of conditional statements (IF statements) and switch-case operations. These would be used in conjunction of the inputs sensed by the user. We also need storage to hold all the sounds that the harp can play, so a micro sd will be used to fulfill this role. So essentially IF this laser was “plucked” by the user, then this sound will be played off the speaker, and the sound would be grabbed from the sound file provided by the DFPlayer Mini sound storage. This would be done for all the strings of the device.

Next would be when the user wants to change the octave of the harp, the volume of the harp, if the user wants the note to go up a half-step or go down a half step, and if the user wants the harp to be set to a certain key. All these changes will be made through a couple of control mechanisms, like pedals, dials and buttons. The way to do this would be to do IF statements with these inputs. So essentially, IF this control mechanism is interacted, then the code will read the input signal and do the respective change in accordance to the respective control.

The system is constantly running, which means it is constantly checking and waiting for the inputs. Even if the user is not plucking a string or interacting with the harp, then harp is still on and updating and reading inputs. This is to have the harp consistently active, and the way to do that would be to have while loop running the whole time to keep the entire system running. But because it is a while loop, having all the if statements in the loop would make the sluggish and make the harp noticeably delayed. So, inputs would have to be organized within the while loop, and within another part of the code. This part will be the interruptions of the code, using interrupts will allow for the code to continuously check the strings while also providing the respective output at the same time. This would allow for our advanced goal of the user to play chords to happen.

In order for the system to figure out which sound to play for the respective string this would involve multiple parts of the project to function. For the first part, the user input will be detected by the analog input for the photodiode detecting a reflection off the user's hand. With that, the microcontroller would read the current position that the stepper motor was in and transmits this information to the other microcontroller for next the next step of processing. With the information received by the other microcontroller, it would read it and would grab

the respective sound in accordance with the user input and the settings already set. With that, the microcontroller would output the audio signal to the audio system for audible output.

The interrupt mechanism provides support for simultaneous processing of several notes to input, which is necessary for chord play back. If several strings are triggered within a very short time interval, interrupt handlers will coordinate to provide harmonious multi-note output. This requires good timing control and resource allocation to ensure that all the notes begin and end at appropriate times without audio artifacts or system overload. But this interrupt mechanism will also provide support for the user to change the note up a half step or down a half step, or to change the octave of the harp. This would allow for smooth playability for the user and efficiency for the whole system.

7.2 DFPlayer File Management

The microSD was organized with folders and files. The folders will be named 001, 002, and 003. Each folder will represent sharps, flats, and naturals. The files within the folders will be named with 0001 to 0050. Each of these files will represent a sound for the harp to play. The software will be by default set to natural, folder 002, because naturals are the notes that the user will play most often. Using the pedals to change to sharps or flats, the user will have to hold the appropriate pedal, and when they let it go the system will revert back to the default folder.

The code will have a function that will have global variables for the octave, and pitch (for sharp, natural and flat). When the folder is selected, the code will multiply the octave by seven, representing the shift of octave in the respective folder, and this will allow for the system to select the correct note.

7.3 Function and Class Diagram

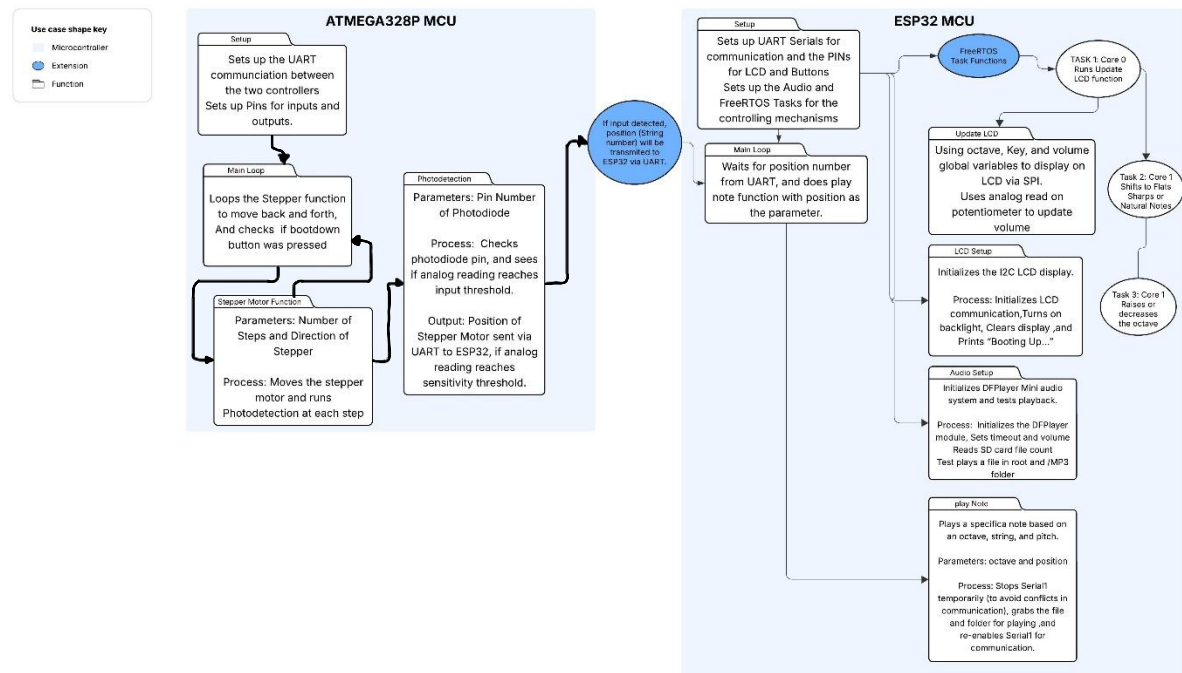


Figure 27 – Function and Class Diagram

This is a Function and class Diagram. This will show the connections between the main and setup, and the communication function between the two devices. The chart shows all the functions for the respective microcontrollers that were used for the project. The connections show what the functions are used in the code, specifically if it was used in a main loop or the setup function. The Esp32 will handle all the controlling mechanisms of the project and the audio for the project. Because of this, this controller can have some overhead and delay because this isn't time sensitive. But the Arduino is time sensitive, so very little blocking statements are used in it because the stepper motor is moving really fast and stutter can be very noticeable. This is why the two controllers have different levels of complexity in their software design.

7.4 Use Case Diagram

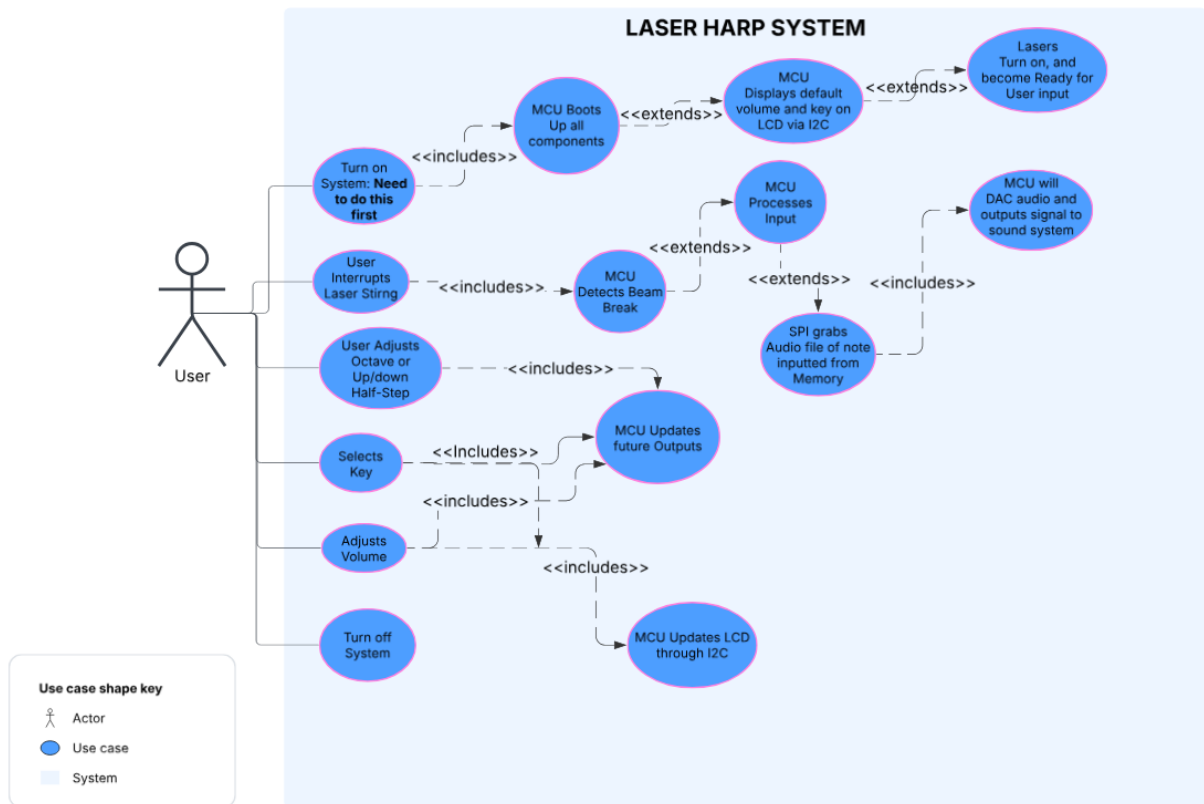


Figure 28 - Use Case Diagram of the Software

The use case diagram is a visual representation of the interactions between the users, and a system. In this diagram above, there is only one actor interacting with the system, so the use case diagram is straightforward. It would just involve all the possible inputs that the user can interact with. The first input the user would have to do would be to turn on the system. With that the system would initiate boot up procedures and turn on all components of the system. Then display the default volume and key of the system on the LCD via I2C, then turn on the lasers and stepper motor for user input. After all that, the user can now pluck the strings, and the microcontroller will detect these inputs and grab the respective audio file of the note in the specific octave that the user inputted (and this would include any half-step input from the user). Through SPI, the audio will be transferred from the storage device and output from the microcontroller into the audio system as an analog signal by using the DAC on the microcontroller. The key and volume will be detected by the microcontroller and updated on the LCD through I2C as well.

All the use cases involve a function that extends from the input of the user. This straightforward design allows for quite understandable implementation on the

microcontroller and its connections. The architecture, data transfer interface, and code tests are crucial for the implementation of this design.

7.5 In-Depth Flow Chart

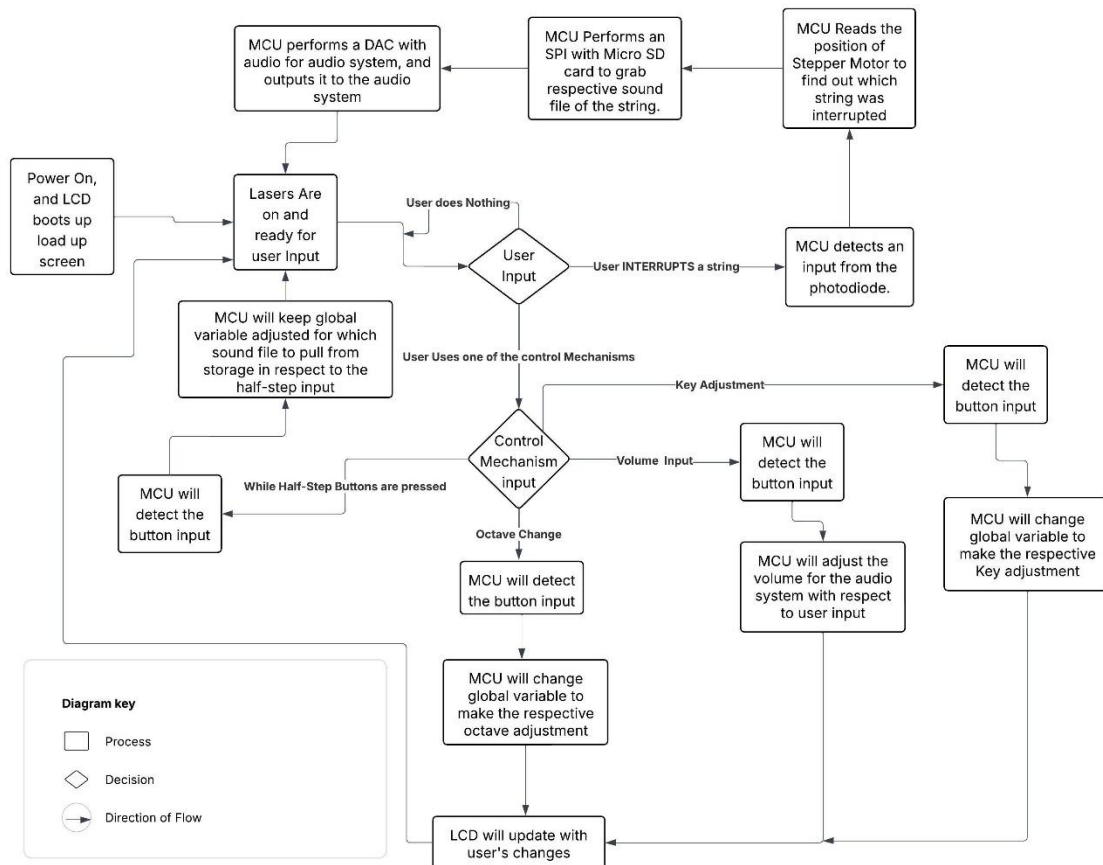


Figure 29 - In Depth Flow Chart

In this flow chart, it goes into a deeper analysis of the processes and decisions that will be going through the software design of the project. Specifically, the connection that we can see that the microcontroller will have between the other systems. One note would be that the MCU, will be two MCUs, one for most of the connections of the systems and one to set up all the devices of the project.

In this flow chart, we can see that at the beginning of the whole project will be the boot up process of the entire system. The LCD will give a loading process and let the user know that the product is booting up and starting up the lasers. Then the lasers will turn on and be ready for user input. In the flow chart, the software then has a decision that will branch into multiple possibilities for what the what product will do, but at the end of all the decisions, it will loop back to the system being ready for user input. Then when the system detects a user input from the lasers it will perform the necessary processes to grab the audio file from the storage

device for the sound file that represents the string that the user interrupted and the correct key and octave that the string is set to.

The other inputs are the controlling mechanisms, these would include the volume control dial, the octave changing buttons, key adjustment button, and the half-step up/down adjustment. The volume would be directly adjusting the volume for the audio signal, and this would be detected through the input of a dial. The octave change would be two buttons that represent going up and going down an octave, and the software would be an if statement for these buttons. The variable that will represent the current octave will be changed from the octave buttons. The key change would then be the next button on the interface, this would detect the input and then change a global variable to represent the different keys and let the MCU which sound files to grab from. At the end of the volume dial, the octave buttons, and key change buttons; the LCD will be updated with the respective change, to let the user know what the current settings are. For the Half-step buttons, this would work by having two buttons for the user input. While pressed the user can make another input on the string and the input will respectively shifted up or down a half-step. The way to do this would be to have an interrupt that will change a global variable representing whether the note is shifted up or down a half-step.

7.6 Data Transfer Interface

The data files from the external memory storage will be mainly the audio files for the speaker system. The microcontroller will need to have access to this storage and be able to read the audio files and output them as analog signals. The way we will incorporate this data transfer will be via Serial Peripheral Interface.

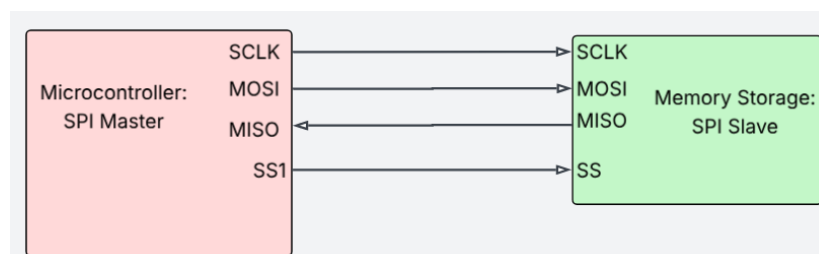


Figure 30 - Signal Connection Between Memory and Microcontroller

SPI offers a very quick and reliable way to transfer data in the entire system, and is even more applicable in this situation due to the fewer number of devices in the system. The way SPI works is by having a master device transfer data and instruction to one or more slave devices via four different signal lines. The Full-Duplex formation of SPI can allow for flexibility in the system. On the left is a figure diagram that shows how the microcontroller and memory storage will be connected in an SPI formation. The SCLK is the serial clock, that allow for the

data transfer between the master and slave devices to be in sync. The next is the MOSI signal, which is an acronym for Master Out Slave In, and it is the data line used to transmit data from the master to the slave device. The next is MISO, which is another acronym for Master In Slave Out, which is used to transmit data from the slave to the master device. The last line is the SS, which is another acronym for Slave Select, and this is used by the master device to activate and deactivate communication with a particular slave device in a multi-slave SPI system. But in this situation, there would only be one SS signal. One device will allow for efficient data transfer with SPI, which excels at small quantities of device connections.

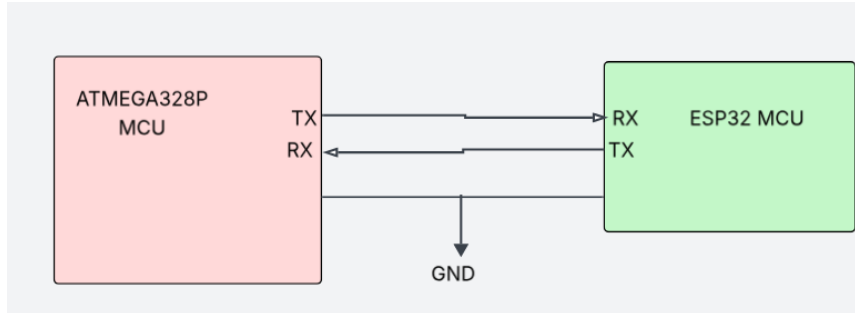


Figure 31 – UART Connection between the two microcontrollers

The UART connection between the two microcontrollers will be used in this project. Above is a diagram showing the communication between two microcontrollers. The UART connection is only for transmitting the position or string of the stepper motor for the esp32 to know which sound file to grab from the microSD. The RX for the ATMEGA328P will be used to safely stop the stepper motor to its beginning position to allow for the user to turn off the system safely.

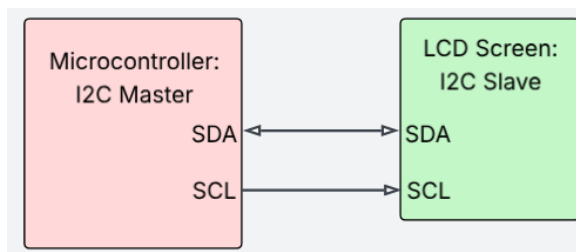


Figure 32 - I2C Interface Connection Between the LCD And Microcontroller

The next data interface that will be used in the project will be the interface between the LCD screen and the Microcontroller. This display will not be very crucial for the user experience, so this does not need to be really efficient because that would be a waste of power and processing. The decision for data interface between the LCD and Microcontroller is between the I2C protocol or parallel. Parallel will mean each pixel will require its own GPIO, which can be impossible to implement with microcontrollers when GPIOs are limited, therefore,

parallel connection will not work in our system. So an I2C connection will be used in displaying items on the LCD screen. An I2C connection is name for Inter-Integrated Circuit, and it involves a two-wire serial communication that is half-duplex. The connections of the two wires are the SDA and SCL. The SDA is the serial data of the transfer, it's the line used for transmitting data between devices. SCL is the serial clock, and it is for the clock signal that synchronizes the data transfer on the SDA line. With this interface, we can achieve a reliable and lossless data transfer. This, is optimizing reliability and ease of implementation over efficiency because this will only be displaying volume, the key, and boot up visuals.

8.0 System Fabrication and Prototype Construction

In this chapter, we will show the preliminary designs for the PCB boards that we will produce. We will provide an overview of the general design of the laser harp hardware, and how it will be assembled when the final prototype is constructed in Senior Design 2. We will go over the relative placement of the board and any implication and design considerations that we will consider when it is time to build the final prototype. The PCB designs were generated using the program FUSION 360 from the schematics produced in Chapter 6. FUSION 360 has limitations as it is unable to produce symbols and schematic icons for components that aren't included in its library or components that don't have electronic models that are compatible with FUSION 360. The primary example is the photodiodes. We choose the FDS100 photodiode as are light detection components; however, they don't have models that are compatible with either FUSION 360 or any other modelling application that is available to us. In a case like this, this component is represented often by a female pin located on the board.

8.1 General PCB Layout

Currently, one major consideration that we have been following as we design the schematics and PCB design of the project is ease of assembling and use. For us, who are relatively new to PCB design and assembly, it is important for us to design our PCB in a way that allows us to assemble it quickly, test it easily, and troubleshoot it with ease if need be. One way this was achieved was by separating the main components of the laser harp into separate PCBs. The main processing unit, where the primary MCU and audio processing are located, will be on a single PCB board, the largest of all the board. This board, like previously stated, will contain the main processing component, taking the interaction with the strings, and producing the adequate sound. The board will include most of the user interface, the ones concerning music, and the notes being played. The board will also include the location of the photodiodes. In the schematic and the PCB shown below, the mount where the photodiodes will be placed is represented by female pins. The PSU, and the USB-to-UART converter are also

made into aspirate PCBs for ease of access and ease for troubleshooting. It will be easier for us to test and troubleshoot the components of the laser harp, if the components are separated. If we must redesign or replace components, it will also allow us to do this without reordering a PCB for the entire laser harp project. As shown in the schematics above and PCB below, the individual PCBs will be connected using jumper wires.

The general assembly of the laser harp will ultimately be influenced by the final implementation of all the components together; we will only know how the laser harp will look like once we design, manufacture, and assembly every component together. However, there are assumptions that we can still make about how the final prototype might look like. When assembling the laser harp, we would like the PCBs to be as small as possible, compacting them to a small area to make the laser harp as small and as portable as possible. Another consideration we will have to make is heat. We are using linear regulators, and drivers to power and control components in our project, so a lot of heat will be produced, so it is imperative that we design our harp in such a way that it will allow space for heat sinks and ventilation, and space between PCB boards to ensure that the components don't overheat. Since batteries will be used, it is also assumed that the batteries will be outside of the actual device once we build it in SD2.

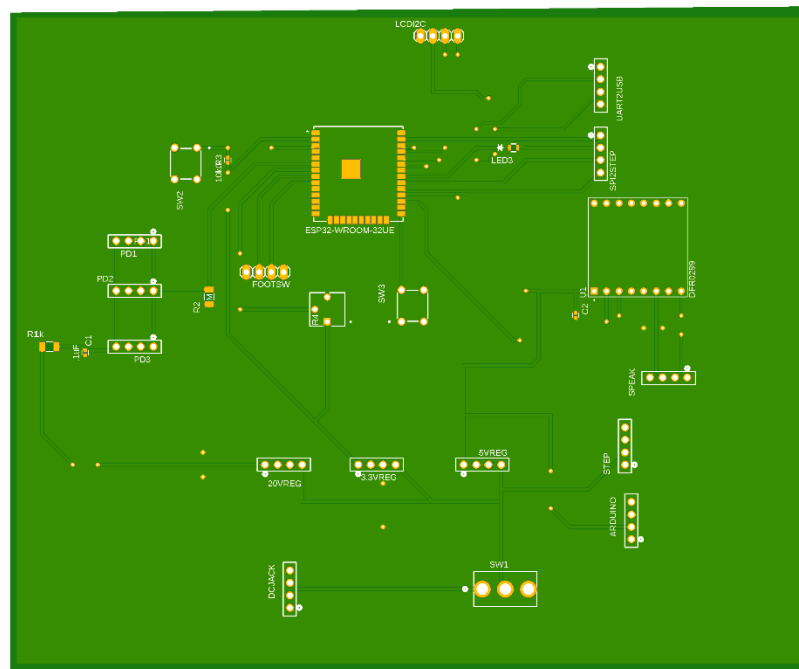


Figure 33 - PCB of the Main Processing Unit

The figure shown represents the MPU with all the components attached to it. The MPU contains the ESP32, our primary and main microcontroller, that will be our main processor. The MPU PCB also include five sets of female pins in the lower half of the board. The three horizontal pins are the input and output of the regulator, coming from the PSU board. The two vertical pins represent the power

inputs for the Arduino board and the Stepper motor located in the LSU section of the laser harp.

The MPU PCB also includes mostly all of the user interfaces that the user will interact with to control and operate the laser harp. There is a potentiometer, pins for pressure buttons used to control the notes, and an LCD to display the volume for the user. There is also a switch that will be used to turn the harp on and off. On the top right side of the PCB board includes the DFPlayer mini, the SD card module that will store and play the notes corresponding to the strings on the harp. The module is connected to pins that will go to a speaker and output the sound played.

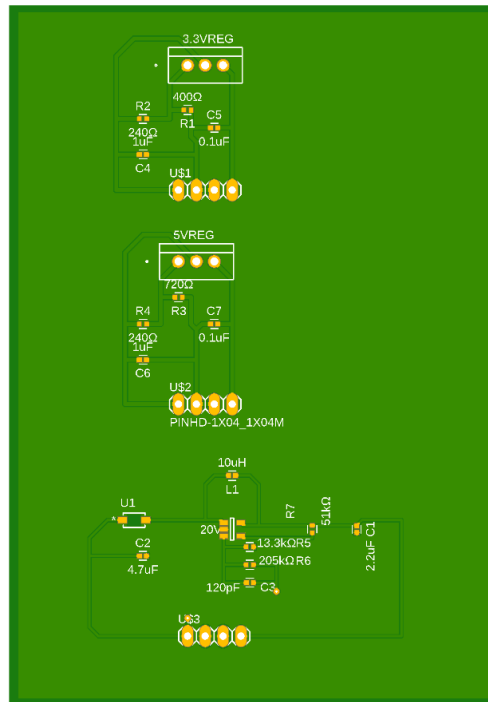


Figure 34 - PCB of Power Supply Unit

The Figure shown above shows the three regulators that will be used to power the laser harp. From top to bottom, the board includes the 3.6V regulator, the 5V regulator, and the 20V switching regulators. A consideration when assembling the laser harp, as previously stated, is heat. The PSU, through its two linear regulators, will produce quite a bit of heat, that might affect the operations and performance of the components and laser harp as a whole. So, it is imperative that there is enough room to ventilate heat, and allow for the inclusion of heat sinks and other heat dissipation components.

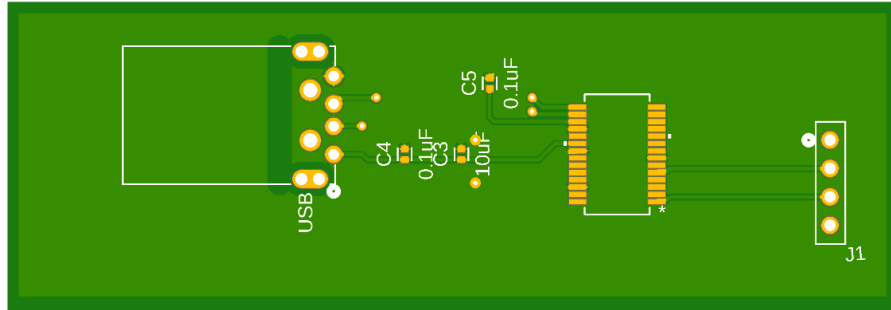


Figure 35 - PCB of UART-USB Converter

Above is the UART-USB converter PCB board layout. The converter is a relatively small part of the laser project; it will allow easy programming of the ESP32 board once it is solder into the board. Having the converter separate from the rest of the board allows for easy troubleshooting and the omission of it from the final design if it is warranted, as it might not see as necessary if the components are well integrated and there is no need to reprogram the ESP32 board.

8.2 Laser String Unit

The Laser String Unit (LSU) is the part of the laser harp that will, mostly, not be composed of PCB boards. As previously stated, the LSU is composed of the stepper motor, the NEMA 17, the stepper motor driver, the TB6600, the laser diode used, the laser diode driver that will manage the laser diode, and the Arduino board that will control all of this. Using jumper cable, the Arduino in the LSU will coordinate with the Esp32 on the Main Processing Unit (MPU) board to generate the notes played. The Arduino will continuously communicate with the main board, relaying the position of the stepper motor as it turns. This is the only form of communication and interfacing the LSU will have with the MPU. The LSU will be powered by the PSU, just like the MPU, with multiple sources going into the LSU.

The laser driver is primary powered by the 12V power supply directly, as it has voltage/current regulator already built into it. The driver will be connected to the Arduino directly, via a Digital output pin. This pin will be use to toggle the laser diode on and off as the stepper motor turn to produce the laser fan effect, with seven strings radiating outwards. The laser diode and its driver will sit across from the stepper motor with no obstruction. The laser driver is probably one of the most important components of the laser harp, as it allows the diode to be safely powered on and controlled by the Arduino. If the laser diode driver was include the laser diode would either not turn on to begin with, or turn on briefly before breaking down from damage to do overcurrent and overvoltage. Below is the PCB design for the laser diode driver.

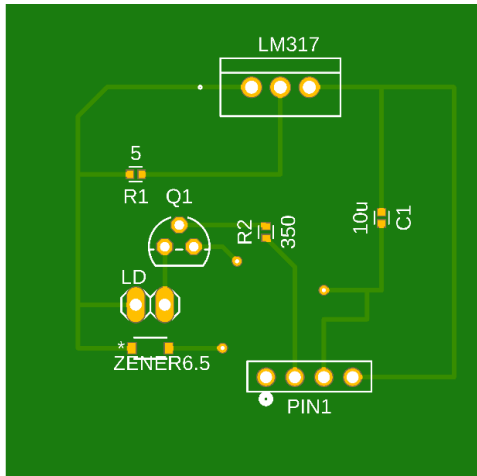


Figure 36 - PCB design of the Laser Diode Driver

8.3 Laser Harp Assembly and Housing

One of the main and final objectives of Senior Design 2 is to design and assemble housing for all of the components of the laser harp, joining all of them together to create our final prototype. Assembly of all the parts is a huge factor in constructing the final prototype. We first need to find an effective way to include every part of the project in the possible housing. One way is to mount the PCB boards on the walls of the housing, allowing for larger footage for the components that aren't on a PCB like the stepper motor and laser. Another consideration is that the components should be assembled in a way that will make it hard, or cumbersome for us to troubleshoot or augment parts of the PCB ones it is constructed. If minor changes have to be made, the harp should be assembled in a way that makes it easy for work to be done on it, or easy to take parts out without much issue.

There are also multiple implications that must be addressed to construct the housing effectively. The first of the implication is, again, heat. Our laser harp and its components will most likely produce a lot of heat, so it is imperative that the housing and the assembly of the boards and components ensure that there is adequate space for ventilation and inclusion of heat dissipation devices. It is also important that the housing itself is able to accommodate ventilation, and that the material used for the harp is able to dissipate heat and not insulate the heat. The other implication is that the harp must be somewhat portable. One of the main specifications that we set out to follow from the very beginning of the project is to make the laser harp as portable as possible. This has an implication on the size of the laser harp, as the housing cannot be so large that it is cumbersome for one person to transport it alone. It should also be able to be transported in a vehicle easily. Other not about the housing, that it should be heavy. The material for the housing shouldn't add any extra weight to the laser, as we wanted it to be not so heavy that it is uncomfortable to carry. The housing should also have a nice look to it, either polish or a matte finish so it doesn't look cheap. Reiterating from

above, the housing should also be easy to come apart or deconstructing for the sake of making changes to the components once the harp is built.

PCB Manufacturing Addendum

PCB design and manufacturing during Senior Design 2 occurred differently to what was expected during the composition of this report. The stepper motor PCB was separated into two sperate boards, one for the DRV8825 stepper driver and the other for the ATMEGA. Additionally, the photodiode was removed from the main board and attached to a transimpedance amplifier PCB board designed during Senior Design 2. The two regulator boards also change. As stated above, instead of LM317, the LM2576 regulators were used for the two boards. A board for the laser driver was not used and a board for the LM2664 negative voltage converter was made.

9.0 System Testing and Evaluation

This section provides an overview of the preliminary testing and implementation strategies for both the hardware and software components chosen for the Laser Harp project. The purpose of this phase is to validate that each subsystem performs as expected when operated independently and to identify any integration challenges that may arise when constructing the final prototype. Our testing efforts focused on core subsystems such as the stepper motor assembly, photodiode-based detection system, and microcontroller integration. By evaluating each component's performance in isolation, we gathered valuable data to inform design decisions for the full system.

Alongside hardware and software validation, we also conducted feasibility testing for the optoelectronic components, which form the core of the Laser Harp's interaction mechanism. Special attention was given to determining how well the photodiodes could detect light variations resulting from user interaction and how accurately these signals could be interpreted by the microcontroller. Our testing results provide a strong foundation for assembling a reliable and functional Laser Harp in Senior Design 2 (SD2). This section concludes with a brief outlook on our SD2 implementation strategy and our approach to system-level integration and testing.

9.1 Component Testing

Component testing was conducted throughout the semester to verify the reliability and effectiveness of the hardware that will be integrated into the final Laser Harp design. Each subsystem was tested independently, using development boards and controlled lab conditions. Our goal was to confirm that each component operates according to specification, and to gather data on how

these components can be synchronized in a full-system context. The focus was placed on repeatability, responsiveness, and electrical compatibility.

The results from this testing phase are instrumental in helping us plan the system integration process in SD2. For each test, we documented power requirements, control logic, and mechanical behavior. We also considered constraints such as thermal performance and analog signal stability to anticipate any future interference issues. These insights will directly guide our final enclosure design, power distribution layout, and user interface development as we continue into the next phase of the project.

9.1.1 Stepper Motor

The first component that we tested was the stepper motor, and all the components that are necessary to operate with. We tested the NEMA 17, stepper motor, and how it will be used for the final prototype of the laser harp. We utilize the TB6600 driver to power and control the stepper motor, and an ARDUINO UNO development board to control the components. Additionally, we used a 12V voltage from a lab bench power supply to power the driver and motor. To start, we tested the basic functionality of the stepper motor by turning it on and uploading simple code onto the Arduino to have the stepper motor rotate. Two digital pins from the Arduino were used to control the direction and speed of the motor. We connected the driver to the 12V supply, and we were successfully able to produce rotation from the stepper motor. Additionally, we configure the stepper motor so that it would make the stepper motor produce 200 micro steps per revolution. After this we configure the code on the Arduino to have the stepper motor produce one full rotation clockwise, stop, then one full rotation counterclockwise. This was done successfully as well. The next part was to rotate the stepper motor at a given faster or slower speed. As previously stated, as the stepper motor revolves, it stops and starts intermittently to produce small micro steps as it revolves around. To change the speed, we will have to increase the time between the start and stop of the micro steps. This was possible by decreasing or decreasing the delay between the starts and stops of the motor; to increase speed, we decrease the delay, and to decrease the speed, we increase the speed. Another way that speed can be changed is by changing the settings in the stepper motor driver, the TB6600, to allow a larger current draw into the stepper motor; however, this was not done for this instance, as it wasn't and will not be necessary to achieve the desired speed.

The final test conducted on the stepper motor was to make the stepper motor produce the right revolution so that it is able to achieve the desired pattern with the strings. The stepper motor, ideally, should start a specific position, turn and travel a certain distance and return backwards to the initial position. This movement, implemented with a toggling laser, should produce the strings of the laser harp. The distance traveled by the stepper motor as it rotates corresponds with the radial width of the fan of strings. This distance corresponds with

approximately 70 degrees of the full 360 of the stepper motor. The stepper motor will travel the distance with 21 individual steps in between. The idea is to have the laser toggling on every third step to produce the seven strings and turn off on the return. We didn't have the laser at the time, but the movement of the stepper motor was achieved successfully.

9.2 Optoelectronics Testing

The main Optoelectronic component used and tested at this point were the photodiodes used to absorb and detect the strings being played. As the stepper motor turns, the laser diode toggles, and the strings are produced, the photodiode absorbs any incoming light from the surroundings. When the string is played, the reflection of the light from the users hand will be detected by the photodiode. The photodiode is connected to Esp32 via an analog pin input, any disturbance from the strings will be detected by the Esp32, where it then will play the corresponding note. This was tested using the same process above. Instead of the ESP32, we again use the Arduino board as it was easier to use at the time. We constructed a small circuit. The circuit included a resistor series and a capacitor in parallel with the photodiode, which is in reverse bias. We applied a voltage of 12V to increase the photodiodes responsivity and a load resistor. The load resistor is set to ground, and a wire is used to measure the voltage going through the load resistor, leading it to the analog pin of the Arduino. Now, using a simple code, we programed the Arduino to read the analog read from that specific pin. Above the photodiode, we added a collection lens to focus the light on the photodiode. We then use a laser, not the laser diode we will use for the final prototype, to simulate one of the strings being played. We used a simple index card to demonstrate the disturbance of the strings. We were successfully able to get a noticeably large analog reading from the photodiode on the Arduino when the index card blocks the light 6 inches above the photodiode. We also verified the Arduino output with a multimeter to ensure that the reading was correct. It is important to make sure we are getting enough voltage into the Laser Harp system

9.3 Coding Tests

In this part, it will go over the necessary coding tests that will need to be taken throughout the software implementation. This will be progressive and gradual, in order to fully understand each step of implementation in the case that we will need to trouble shoot and back track. The tests necessary, will be tests of the analog detection from the photodiode, a progress check of data transfer, outputting of the audio signal to the amplifier and speaker, power distribution, boot up/down process, control mechanisms and inputs, and LCD display tests. There is quite bit of tests that will need to be taken but going through each one reflectively can allow for proper troubleshooting in the case that errors occur.

9.3.1 Analog Detection

Having the microcontroller booted up properly, and having it effectively connected to the integrated development environment is the first step to all of these tests. But the first step to implementation of our software will be to see if the microcontroller can detect an analog input. This can prove that the photodiode is working properly and has an established connection with the microcontroller. The first test will be to have the minimum voltage be detected by the microcontroller in the analog input pin. The minimum voltage that will be detected by the photodiode will be just 1mV.

The code behind this test will involve understanding the pinout of the microcontroller and initializing/setting all the GPIOs that will be used in this test. To know if the test is successful, an LED will be lit on the development board to indicate that a voltage higher than 1 mV was detected. The reason this would be significant would be because it would reveal to us that the photodiode connection is detecting the scattering light from the reflection of the laser on the users hand. This will then also be used as a core function for user input detection in the final product of the software.

The next step to testing the analog input of the microcontroller would be to test the photodiode in connection with the microcontroller, and shining light into it to get inputs. Then when the inputs are detected by the microcontroller and shown on the UART terminal of the integrated development environment, we can move on to integrating the laser detection of the system. Instead of the using basic light, we would be using the reflection of the laser to shine onto the photodiode connected to the microcontroller to detect the input. When the UART reveal a proper reading then we can consider this test successful. This will show that the laser input being detected with reflection from the user hand onto the photodiode is functional and implementable into a grander design.

9.3.2 Data Transfer and Output

This test will involve testing the output of the audio signal and the if the data transfer between the Microcontroller and the memory storage is functional and efficient. This would also give a glimpse into the DAC of the microcontroller by having it output an analog signal for the audio system. This test will involve implementing all the proper GPIOs of the microcontroller and seeing to that the connections are made appropriately. We will be looking for functionality and efficiency, so a timer and LEDs will be used for optimization of the test.

Following the first test, a speaker will be included in the system to get an audible test with the Microcontroller and sound storage. This will prove that sound can be generally outputted from the device. Next from that, will be to introduce the amplifier into the audio system. With the amplifier introduced into the system, we can see how sound can be amplified into a more powerful speaker. The code in

this test would also double up as an audio test for the speaker. This will allow us to see functionality with the amplification and speaker with connection to the microcontroller and sound storage.

When that is all functional, we can try to implement the controlling mechanisms of the audio. First would be the volume dial of the system, coding this would involve an interrupt that will change the volume variable of the software design. If this is all functional, then a test of the half-step, octave, and key adjustments will be tested individually and then together. All of these have a similar format of changing which sound file will be grabbed when inputted. If all of this is working smoothly then it can combine with the laser input of the project to get a proper data transfer between the microcontrollers to output the respective sound file from the sound storage.

9.3.3 LCD Functionality

This test will involve testing the LCD screen in connection with the microcontroller. This will be testing the I2C data interface and seeing if this provides the functionality that we need for it. This will involve testing possibly a few LCDs with the just general operation and then seeing how the refresh rate with this LCDs will operate with our project.

For the first test, it will be basic boot up and have the LCD display that everything is operational and working. This will show us that the connections between the microcontroller and the LCD is operational. Next will be to test the LCD being updated with the inputs of the user such as the volume, key, and octave adjustments. If this is able to work it will show that the product is detecting inputs from the user in the controlling mechanism, and that the LCD is able to show that adjustment.

9.4 Plan for Senior Design 2

As we transition from the prototyping and research phase of Senior Design 1 into the implementation-focused portion of Senior Design 2, the main objective will be to fully integrate all subsystems of the laser harp into a complete and functional final product. This phase will center on building, assembling, and extensively testing the complete system to ensure that the harp performs reliably, safely, and as intended under various operating conditions. While individual components such as the stepper motor, laser module, photodiodes, and LCD interface have already been tested in isolation, in Senior Design 2 we will bring these parts together into one cohesive unit.

The initial weeks of the semester will be dedicated to finalizing the printed circuit board (PCB) design based on our tested breadboard prototypes and simulation data. Once completed, the PCB will be fabricated and assembled with the selected components, ensuring proper connectivity between the microcontroller,

drivers, sensors, and power regulation circuits. After board validation, we will begin mounting the physical structure of the harp, including the housing for the stepper motor, mirror assembly, laser positioning system, and detection array. Attention will be paid to component alignment, cable management, and overall design to ensure both stability and ease of use.

Following physical construction, the team will conduct a thorough integration of the software and firmware, including the control logic for laser timing, note triggering, sound playback, and user inputs. Particular care will be taken to ensure that the stepper motor and laser toggle in precise synchronization to simulate seven distinct “laser strings.” The LCD will be configured to display user-selectable parameters such as volume, key, and octave, while foot pedal input will be tested to verify octave-shift and sharp/flat toggling. Sound output will be refined through amplifier adjustments and speaker testing.

Once the full system is assembled, we will enter a comprehensive testing and validation phase. This includes functionality testing (each string must play the correct note), stress testing (ensuring system behavior under prolonged use), and user testing to evaluate usability and responsiveness. We will document all issues and iterate on both hardware and software as needed. Additionally, we will verify that the design adheres to all applicable safety standards, including laser exposure limits under ANSI Z136.1 guidelines. Power consumption, battery life, thermal performance, and latency will also be analyzed to confirm operational stability.

The ultimate goal of Senior Design 2 is to deliver a working Laser Harp that demonstrates all core functionalities described in our objectives. By focusing on integration, refinement, and validation, we aim to showcase the laser harp in a final presentation and potentially explore further enhancements or applications.

10.0 Administrative Content

In the following sections, we will provide a detailed overview of the key administrative aspects of the project. This includes a clear breakdown of the projected budget, how costs have been allocated for different parts of the project, and an explanation of how responsibilities have been divided among team members to ensure that each area of the project is properly managed. This helps ensure that the project stays on schedule and that each member contributes effectively. Together, these administrative details reflect the careful planning required to turn a complex design concept into a working product.

10.1 Budget and Financing

To simplify and categorize the financial plan, the total estimated cost of the Laser Harp project is grouped into key system components as follows:

Table 28 - Budget for Laser Harp Project

Category	Estimated Cost
Electronics (Microcontroller, PCB, OLED, Audio Output)	\$140
Photonics (Lasers, Sensors, Mirrors)	\$300
Power (Battery Pack, Power Cabling)	\$50
Audio (Speaker, Amplifier, Audio Storage)	\$60
Frame and Structural Materials	\$60
Miscellaneous (Connectors, Mounts)	\$50
Total Estimated Cost	\$660

Table 29 – Bill of Materials

Material	Cost
Plano-Convex Lens (Collection Lens)	\$63.00
Mirror	\$60.20
Laser Diode	\$41.56
Plano-Concave Lens	\$31.80
Plano-Convex Lens	\$20.00
Collimating Lens	\$33.92
NEMA 17 Stepper Motor	\$12.99

TB6600 Driver	\$9.98
DFPLAYER Mini SD Module	\$5.90
ESP32 WROOM 32 Chip	\$6.56
Arduino ATMEGA328 Board R3	\$14.49
12V Rapthor Rechargeable Battery Pack	\$32.89
12V COOLM Wall Power Converter	\$16.69
Integrated Circuits, Regulators, Transistors, <i>etc.</i>	\$30.00
Total	\$379.98

10.2 Work Distribution and Milestone

The following section outlines the primary responsibilities assigned to each team member. The work distribution was decided by taking into account each member's strengths and areas for growth. Our team's goal was to divide the tasks as evenly as possible to maintain fairness and to ensure that every aspect of the project is managed thoroughly and completed to a high standard.

Daniel Balasquide — Computer Engineer

Responsible for developing and maintaining the firmware and software that bring the Laser Harp's subsystems together. Tasks include writing the embedded code for the microcontrollers, setting up real-time interrupt routines for beam detection, integrating the LCD user interface, and ensuring that the audio playback system works smoothly with the hardware. Also, coordinate testing of the software to confirm that the system responds quickly and reliably during live use.

Alejandro Pastrana — Electrical Engineer

Focus primarily on the power system and contributes to hardware design

alongside Lyzzalis. Responsible for designing the power supply, selecting appropriate voltage regulators and protection circuits, and ensuring that the system powers safely. Also, help test and monitor the harp's power efficiency, manage thermal temperature, and assist with the overall layout and assembly of the hardware subsystems.

Alexis Schons — Photonics Engineer

Handle the photonics aspects of the Laser Harp. Responsibilities include selecting the appropriate laser diodes, aligning the mirror and stepper motor system that generates multiple virtual strings and designing the lens systems. Alexis will also set up the photodiode detection array, optimize its placement for accurate beam interruption sensing, and ensure that the optical system operates safely and meets laser classification standards.

Lyzzalis Zuniga — Electrical Engineer

Focus on the hardware design and integration for the Laser Harp alongside Alejandro. Responsibilities include helping develop the custom PCB layout, selecting and organizing key electronic components, and verifying that all wiring and connections between sensors, microcontrollers, and motor driver circuits are properly designed for reliability and efficiency. Assist with the physical assembly of hardware, including soldering, placement of components, test signal paths, and troubleshooting any hardware-level issues that arise during development.

Table 30 - Senior Design 1 Milestones

Task	Start Date	Anticipated End Date	Duration
Divide and Conquer	5/20/25	5/30/25	2.5 weeks
30-page milestone	6/6/25	6/20/25	2 weeks
Midterm demo testing	6/15/25	6/26/25	1.5 weeks
60-page milestone	6/21/25	7/7/25	2 weeks
90-page milestone	7/8/25	7/18/25	1.5 weeks
Final report (120 pages)	7/19/25	7/29/25	1.2 weeks

Table 31 - Senior Design 2 Milestones

Task	Start Date	Anticipated End Date	Duration
Order and Test PCB	8/18/2025	10/15/2025	7 Weeks
Testing Parts Individually	8/25/2025	10/15/2025	8 Weeks
Assembly of Parts	10/1/2025	11/25/2025	7 Weeks
System testing	11/1/2025	TBD*	TBD*
Practice Demo	TBD*	TBD*	TBD*
Final Presentation	TBD*	TBD*	TBD*

*Note: Some dates are TDB due to us waiting on deadlines for Senior Design 2

11.0 Conclusion

The Laser Harp project has demonstrated our team's dedication to combining creativity with practical engineering skills to tackle a unique design challenge. By reimagining a traditional harp using lasers, optical sensing, and embedded electronics, we have laid the foundation for an innovative instrument that expands the ways people can experience and create music. Our goal has been to replace the physical strings of a classical harp with visible laser beams, allowing users to play music through simple hand movements without the physical demands of plucking strings. This approach emphasizes inclusivity and modernizes the instrument while highlighting the value of photonics and real-time

embedded control. From the beginning, our design choices have focused on balancing technical feasibility with usability and safety, ensuring that the final product will be both practical and engaging for a wide range of users.

So far, we have made significant progress in defining the hardware and control systems that will make the Laser Harp possible. Careful research has gone into selecting components that meet our project's technical requirements while staying within the limits of our budget. This includes the decision to use a stepper motor for precise mirror rotation, the choice of photodiodes with fast response times, and the design of a custom PCB that connects all subsystems efficiently. We have also focused on how to manage power safely and reliably, knowing that the harp must function with battery power. These steps reflect our commitment to designing a working prototype that demonstrates professional engineering practice and thoughtful problem-solving.

Equally important to us is the potential educational impact of the Laser Harp. From the start, we envisioned this project as more than just an instrument, it is also a demonstration piece that can introduce others to photonics, embedded systems, and control design. The harp's frameless, portable design supports this goal by making it easy to use in classrooms, outreach events, or science centers where students and visitors can see engineering principles in action. The visible beams and immediate sound response help connect abstract concepts to real-world applications in a way that is interactive and memorable. This focus on outreach and learning adds meaning to our technical work and aligns with our motivation to use engineering to engage and inspire others.

Looking ahead, we recognize that transitioning from research and design to a fully functional prototype will require careful testing and refinement. Aligning the stepper motor, mirror, and photodiodes to produce stable, accurate beam paths is one of our next major tasks. We will need to fine-tune the motor speed, microstepping, and mounting to keep the beams correctly positioned over extended use. Similarly, assembling and testing the custom PCB will allow us to validate our signal pathways, noise reduction measures, and power distribution plans. These steps are necessary to ensure that the harp operates reliably and meets our performance targets when used in real settings. As we test each subsystem, we expect to learn more about how our design choices perform under real conditions and where adjustments may be needed.

Another area of focus in the coming weeks will be finalizing and verifying the audio subsystem. Producing clear, realistic sound within the harp's compact frame will depend on the amplifier's performance, the quality of the speaker, and how well the microcontroller handles playback. We plan to test different audio samples, adjust volume control options, and ensure that the system works consistently at different power levels. We will also test for potential sources of interference or distortion that could affect the sound quality. By addressing these technical details now, we will be in a stronger position to deliver a polished demonstration during our final presentation.

Throughout this project, we have relied on good communication, clear task division, and mutual support to keep progress steady and organized. Each team member's role, whether working on the hardware, firmware, optics, or power design, has contributed to building a complete system that brings together multiple areas of engineering. Regular check-ins and documented milestones have helped us manage risks and stay aligned with our timeline. As we move into full integration and testing, we will continue to share updates, compare results, and make informed adjustments to solve challenges as they appear. This experience has strengthened our technical and teamwork skills, which are just as important as the design itself.

In conclusion, the Laser Harp is more than a creative idea, it is a practical example of how engineering disciplines can be combined to produce something functional, educational, and inspiring. Our midterm progress shows that we have a realistic plan, a clear design strategy, and a motivated team ready to carry this project through to completion. With continued testing, refinement, and careful integration, we are confident that the final prototype will meet our goals for safety, playability, and visual appeal. We are excited to demonstrate the Laser Harp to others and share how our work highlights the real-world possibilities of interdisciplinary.

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Appendix B: ChatGPT prompts and outcomes

Prompt: Give me physical user interface

ChatGPT Response: Sure! A Physical User Interface (PUI) refers to any tangible way a user interacts with a device or system. Here are examples of physical user interfaces:

Table 32 - Chat GPT Examples of Physical User Interfaces (PUIs)

Type	Description	Examples
Buttons	Pressable components to trigger actions	Power button, keyboard keys, elevator buttons
Switches	Toggle or change system state	Light switches, mode selector switches
Knobs/Dials	Rotatable controls for tuning or adjusting	Volume knob, thermostat dial
Sliders	Move along a path to change a setting	Audio mixing boards, brightness sliders
Touchscreens	Display that responds to finger/stylus	Smartphones, ATMs, tablets
Joysticks	Directional control using a stick	Game controllers, drone remotes
Touchpads/Trackpads	Flat, touch-sensitive areas	Laptop trackpads, drawing tablets
Rotary Encoders	Infinite rotation input devices	Digital menu selectors, control knobs in cars
Sensors	Detect presence or movement	Proximity sensors, gesture sensors
Levers	Move up/down/sideways to control mechanism	Gear shifter, arcade machine levers

Key Characteristics of a PUI:

- **Tangible:** You can physically touch or manipulate it.
- **Direct feedback:** Often provides tactile or visual response (e.g., clicking sound, LED blink).
- **Durability:** Designed to handle repeated interaction.
- **Ergonomics:** Must be intuitive and comfortable to use.

Appendix C: Software Code

“Main.ino” fully uploaded onto the ATMEGA328P PCB:

```
#include <math.h>
#include <stdio.h>
#include <HardwareSerial.h>
#include <SoftwareSerial.h> // for DFPlayer or ESP32 communication

// ----- Pin Definitions -----
#define RX_PIN 8
#define TX_PIN 9
#define PHOTO_PIN A0 // Photodiode input
#define LED_PIN 25 // Optional LED indicator (used for testing)

// Stepper and Laser
const int stepPin = 7;
const int dirPin = 6;
const int laz = 4; // Laser diode control pin
int sensitivity = 2; // Photodiode sensitivity threshold
int edges = 1; // Variable for the edges of the laser harp
int sensitivityMOD = 10; // Add to the sensitivity for the calibration
int edgeMOD = 3; // Divides the sensitivity to accommodate for the edges

// ----- Motor and Detection Variables -----
const int counterclockwise = HIGH;
const int clockwise = LOW;
int position = 1;
long currentStep = 0; // <--- Tracks the exact step position of the stepper

// ----- Step Timing (Adjust for speed/smoothness) -----
const int stepInterval1 = 1000; // High pulse time (µs)
const int stepInterval2 = 80; // Laser ON delay (µs)
const int stepInterval3 = 1000; // Delay between steps (µs)
const int DaDelay = 0; // Optional delay between steps

SoftwareSerial myserial(RX_PIN, TX_PIN); // RX, TX for DFPlayer or secondary
MCU

// ----- SETUP -----
void setup() {
  // Stepper pins
  pinMode(stepPin, OUTPUT);
  pinMode(dirPin, OUTPUT);
  pinMode(laz, OUTPUT);
```

```

// Inputs
pinMode(PHOTO_PIN, INPUT);

// Communication
Serial.begin(115200);    // Serial monitor or ESP32
myserial.begin(9600);    // DFPlayer or secondary serial communication
// Set initial direction
digitalWrite(dirPin, clockwise);
Serial.println("Laser Harp System Initialized...");
}

// ----- MAIN LOOP -----
void loop() {
    // Reset position tracking for each full sweep
    position = 1;

    // Sweep clockwise
    digitalWrite(laz, LOW);
    digitalWrite(dirPin, counterclockwise);
    stepMotorForward(35, counterclockwise, DaDelay);

    // Sweep counterclockwise
    position = 7;
    digitalWrite(dirPin, clockwise);
    stepMotorReverse(35, clockwise, DaDelay);
    //Serial.println("num");
    if(Serial.available() > 0){
        Serial.println("STOPPED");
        exit(0);
    }
}

// ----- PHOTODIODE DETECTION -----
void photodetection(int pinNum, long stepValue) {
    int reading = analogRead(pinNum);

    // Optional debugging: print raw reading
    // Serial.print("reading is ");
    // Serial.print(reading);
    // Serial.print("\n");
    //This is nested if that will check for photodetect and acomodates for the edges
    //needs to be tested
    if (reading < sensitivity){
        if((position == 1) || (position == 7)){
            if(reading < edges){

```

```

        return;
    }
    }else{
        return;
    }
}

if (reading < sensitivity) return; // No detection

// If detected:
Serial.println(position);
}

// ----- STEPPER MOTOR FORWARD -----
void stepMotorForward(int steps, int direction, int delayer) {
    int temp = steps / 7; // roughly where each beam is
    digitalWrite(dirPin, direction);

    for (int j = 0; j < steps; j++) {
        // Generate one step pulse
        digitalWrite(stepPin, HIGH);
        delayMicroseconds(stepInterval1);
        digitalWrite(stepPin, LOW);
        currentStep++; // track total step position

        // Every 1/7th of the sweep, check for detection
        if ((j % temp) == 0) {
            delayMicroseconds(stepInterval2);
            digitalWrite(laz, HIGH);
            photodetection(PHOTO_PIN, currentStep);
            position++;
            delayMicroseconds(stepInterval2);
            digitalWrite(laz, LOW);
        }

        delay(delayer);
        delayMicroseconds(stepInterval3);
    }
}

// ----- STEPPER MOTOR REVERSE -----
void stepMotorReverse(int steps, int direction, int delayer) {
    int temp = steps / 7;
    digitalWrite(dirPin, direction);

    for (int j = 0; j < steps; j++) {

```



```

// Generate one step pulse
digitalWrite(stepPin, HIGH);
delayMicroseconds(stepInterval1);
digitalWrite(stepPin, LOW);
currentStep--; // track reverse motion

// Every 1/7th of the sweep, check for detection
if ((j % temp) == 0) {
  delayMicroseconds(stepInterval2);
  digitalWrite(laz, HIGH);
  photodetection(PHOTO_PIN, currentStep);
  position--;
  delayMicroseconds(stepInterval2);
  digitalWrite(laz, LOW);
}

delay(delayer);
delayMicroseconds(stepInterval3);
}
}

```

“Main.ino” fully uploaded onto the ESP32 PCB:

```

//Importante
#include <HardwareSerial.h>

#define one      12
#define two      14
#define three    25
#define Volume_Pin  4
#define OctHigh  25 // For raising the octave
#define OctLower 33 // For lowering the octave
#define delayer   125 // Delay for main loop of code
#define KeyFlat   13
#define KeySharp  14

```

```

HardwareSerial dfSerial(2); // Use UART2

int octave = 1;
int Key = 2;

//for debouncing in the octave task
unsigned long last = 0;
unsigned long debounce = 1000;

// -----
// Setup
// -----
void setup() {
  Serial.begin(9600); // Use Serial for terminal output

  // UART1 communication
  Serial1.begin(115200, SERIAL_8N1, 16, 17); // RX=16, TX=17

  Serial.println("Tasks created!");

  // For controlling mechanisms
  pinMode(OctHigh, INPUT_PULLDOWN); // For octave up
  pinMode(OctLower, INPUT_PULLDOWN); // For octave down
  pinMode(KeyFlat, INPUT_PULLDOWN); // For changing the key
  pinMode(KeySharp, INPUT_PULLDOWN);

  // For volume dial
  pinMode(Volume_Pin, INPUT_PULLDOWN);

  setupLCD();
  AudioSetup();
  update_LCD(Volume_Pin);

  // -----
  // Task 1 - runs on Core 0 - For LCD Update
  // -----
  xTaskCreatePinnedToCore(
    task1Function, // Function to run
    "Task1",      // Task name (for debugging)
    2048,         // Stack size (bytes)
    NULL,         // Parameters to pass
    1,            // Task priority (higher = more priority)
    NULL,         // Task handle (optional)
    0             // Core to run on (0 or 1)
  );
}

```

```

);

// -----
// Task 2 - runs on Core 1 - For Octave Adjustment
// -----
xTaskCreatePinnedToCore(
  task2Function, // Function to run
  "Task2",       // Task name
  2048,          // Stack size
  NULL,          // Parameters
  1,             // Priority
  NULL,          // Handle
  1             // Core 1
);

// -----
// Task 3 - runs on Core 0 - For Key Adjustment
// -----
xTaskCreatePinnedToCore(
  task3Function, // Function to run
  "Task3",       // Task name
  2048,          // Stack size
  NULL,          // Parameters
  1,             // Priority
  NULL,          // Handle
  1             // Core 1
);

Serial.println("Yep set up");
}

// -----
// Main Loop
// -----
void loop() {
  int receivedNumber = Serial1.parseInt();
  if (receivedNumber > 0) {
    Serial.print("\n Something: ");
    Serial.print(receivedNumber);
    playNote(octave, receivedNumber);
  }
  delay(delayer);
}

// -----
// Task 1 - LCD Update
// -----

```

```

void task1Function(void *parameter) {
  while (true) {
    update_LCD(Volume_Pin);
    //Serial.println(" Working");
    vTaskDelay(pdMS_TO_TICKS(250)); // Delay (non-blocking)
  }
}

// -----
// Task 2 - Octave Adjustment
// -----
void task2Function(void *parameter) {
  while (true) {
    int higher = digitalRead(OctHigh);
    int lower  = digitalRead(OctLower);
    int curr = millis();
    int temp = curr - last;
    if(temp >= debounce){
      if (higher) {
        if (octave < 7) {
          octave++;
          last = millis();
        }
      }

      if (lower) {
        if (octave > 1) {
          octave--;
          last = millis();
        }
      }
      // higher = 0;
      // lower = 0;
    }
    vTaskDelay(pdMS_TO_TICKS(125)); // Delay (non-blocking)
  }
}

// -----
// Task 3 - Key Adjustment
// -----
void task3Function(void *parameter) {
  while (true) {
    int sharp = digitalRead(KeySharp);
    int flat  = digitalRead(KeyFlat);
    if(!(flat) && !(sharp)){

```

```

    Key = 2;
    vTaskDelay(pdMS_TO_TICKS(250)); // Delay (non-blocking)
}

if (sharp) {
    if (Key < 3) {
        Key++;
        vTaskDelay(pdMS_TO_TICKS(250)); // Delay (non-blocking)
    }
}
if (flat) {
    if (Key > 1) {
        Key--;
        vTaskDelay(pdMS_TO_TICKS(250)); // Delay (non-blocking)
    }
}
vTaskDelay(pdMS_TO_TICKS(250)); // Delay (non-blocking)
}
}

```

“Audio_LCD.ino” fully uploaded onto the ESP32 PCB:

```

#include "DFRobotDFPlayerMini.h"
#include <LiquidCrystal_I2C.h>

// -----
// Pin Definitions
// -----
#define DF_RX 5 // (RX) Pin 5 on ES32 to TX on DFPlayer (with divider)
#define DF_TX 18 // (TX) Pin18 on ESP32 To DFPlayer RX

// -----
// Global Variables
// -----
int DaVolume = 30;

/*
Key Reference:
001 = C flat
002 = C natural
003 = C sharp
*/
int lcdColumns = 16;
int lcdRows = 2;
int volume = 0;

```

```
LiquidCrystal_I2C lcd(0x27, lcdColumns, lcdRows);  
DFRobotDFPlayerMini player;
```

```
// -----  
// LCD Setup  
// -----  
void setupLCD() {  
  lcd.init();  
  lcd.backlight();  
  lcd.clear();  
  lcd.setCursor(0, 0);  
  lcd.print("Booting Up...");  
}
```

```
// -----  
// DFPlayer Debug Information  
// -----  
void printDetail(uint8_t type, int value) {  
  switch (type) {  
    case TimeOut:  
      Serial.println("DFPlayer: Time Out!");  
      break;  
  
    case WrongStack:  
      Serial.println("DFPlayer: Wrong Stack!");  
      break;  
  
    case DFPlayerCardInserted:  
      Serial.println("SD card inserted.");  
      break;  
  
    case DFPlayerCardRemoved:  
      Serial.println("SD card removed.");  
      break;  
  
    case DFPlayerCardOnline:  
      Serial.println("SD card online.");  
      break;  
  
    case DFPlayerUSBInserted:  
      Serial.println("USB inserted.");  
      break;  
  
    case DFPlayerUSBRemoved:  
      Serial.println("USB removed.");  
      break;
```

```

case DFPlayerUSBOnline:
  Serial.println("USB online.");
  break;

case DFPlayerPlayFinished:
  Serial.print("Track finished: ");
  Serial.println(value);
  break;

case DFPlayerError:
  Serial.print("DFPlayer Error: ");
  switch (value) {
    case Busy:      Serial.println("Card not found / Busy"); break;
    case Sleeping:  Serial.println("Sleeping"); break;
    case SerialWrongStack: Serial.println("Serial Wrong Stack"); break;
    case CheckSumNotMatch: Serial.println("Checksum mismatch"); break;
    case FileIndexOut:  Serial.println("File index out of bounds"); break;
    case FileMismatch:  Serial.println("File mismatch"); break;
    case Advertise:     Serial.println("Advertise mode"); break;
    default:           Serial.println(value); break;
  }
  break;

default:
  Serial.print("Unknown type: ");
  Serial.print(type);
  Serial.print(" value: ");
  Serial.println(value);
  break;
}
}

// -----
// LCD Update
// -----
void update_LCD(int pin) {
  //int volume;
  volume = analogRead(pin);
  volume = volume / 136;
  DaVolume = volume;

  player.volume(volume);

  int Temp = map(volume, 0, 30, 0, 12); // Map to range volume(0-30)

```

```

lcd.setCursor(0, 0);
lcd.print("Vol:");
int i = 1;
for(int j = 1 ; j < 12 ; j++){
  if(i <= Temp){
    lcd.write(byte(255));
  }else{
    lcd.print(" ");
  }
  i++;
}

int lastVolume = volume;
lcd.setCursor(0, 1);
lcd.print("Oct: ");
lcd.print(octave);
delay(125);
//For say flat or sharp on LCD
lcd.setCursor(9, 1);
switch (Key){
  case 1:
    lcd.print("FLAT ");
    break;
  case 2:
    lcd.print("NATURAL");
    break;
  case 3:
    lcd.print("SHARP ");
    break;
}
}

// -----
// DFPlayer Setup
// -----
void AudioSetup() {
  delay(1500); // Let USB enumerate
  Serial.println();
  Serial.println("=== ESP32 + DFPlayer Mini ===");
  Serial.println("Opening UART2 for DFPlayer at 115200...");

  // DFPlayer serial on UART2, remapped to your pins
  dfSerial.begin(9600, SERIAL_8N1, DF_RX, DF_TX);
  delay(300);

  Serial.println("Initializing DFPlayer...");


```



```

delay(700); // Give DFPlayer time to boot after power-up

if (!player.begin(dfSerial)) {
  Serial.println("ERROR: DFPlayer not responding.");
  Serial.println("Check: 5V on VCC, common GND, RX/TX wiring, SD card
    (FAT32).");
  while (true) { delay(1000); } // Stop here so you can read the error
}

Serial.println("DFPlayer Mini online ");

// Be generous with timeouts; some clones are slow
player.setTimeout(1000);

// Volume: 0..30
DaVolume = analogRead(Volume_Pin);
player.volume(DaVolume);

Serial.println("Volume set to ");
Serial.print(DaVolume);
Serial.print(" (max 30).");

// Try to read file count (some clones return -1; that's OK)
int files = player.readFileCounts();
Serial.print("Files reported on SD (may be -1 on some modules): ");
Serial.println(files);

// Try to play from root as 0001.mp3
Serial.println("Trying root file: 0001.mp3 -> player.play(1)");
player.play(1);
delay(1500);

// Also try MP3 folder (/MP3/0001.mp3)
Serial.println("Also trying MP3 folder: /MP3/0001.mp3 ->
  player.playMp3Folder(1)");
player.playMp3Folder(1);
Serial.println("If you still hear nothing: confirm speaker on SPK1/SPK2 and file
  names.");
}

// -----
// Play Note Based on Octave and Position
// -----
void playNote(int oct, int pos) {
  Serial1.end();
  oct--;

```

```

int x = 7 * oct;
pos += x; // Shift position according to octave range
player.playFolder(Key, pos);
delay(delayer);
Serial1.begin(115200, SERIAL_8N1, 16, 17);
}

void changeKey(){
  int temp = octave * 7;
  temp++;
  if(Key == 3){
    Key = 1;
    player.playFolder(Key,temp);
    return;
  }
  Key++;
  player.playFolder(Key, temp);
}

```