Photonica- Laser Harp Without Mechanical Strings

SENIOR DESIGN 2-GROUP 6

FALL 2025

Meet the Team

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Motivation and Background

- Traditional harps are large, fragile, and difficult to play.
- Lasers replace strings → accessible to those with limited mobility.
- Frameless design emphasizes portability and inclusivity.
- Combines optics, embedded systems, and electronics in one device.
- Intended for:
  - STEM outreach (classrooms, museums, maker fairs).
  - Musical exploration (contactless play, visual appeal).
- Different from existing laser harps:
  - Compact, battery-powered, onboard audio system.
  - Not dependent on MIDI/computer synthesizers.

Goals and Objectives

Overall Goal

- Build a frameless harp where lasers act as "strings."

Basic Goals

- 7 beams across ~30-inch span.
- LCD shows octave/volume.
- Battery operation $\geq$30 minutes.
- Detection latency <0.25 s.

Advanced Goals

- Use collimating + beam expander lenses
- Sync lasers with stepper motor.
- Pre-recorded audio.

Stretch Goals

- Wireless communication (ESP32). Recording/playback.
- Multi String notes & chord support.

Goals and Objectives

Overall Objectives

- A frameless harp will be constructed using a laser diode and stepper motor to produce seven individual strings; and obstruction of the strings will be detected by as photodiode. A voltage reading of a specified level, will trigger a musical note that is saved in an SD card.

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.
- 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.
- 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.

Goals and Objectives

Advanced Objectives

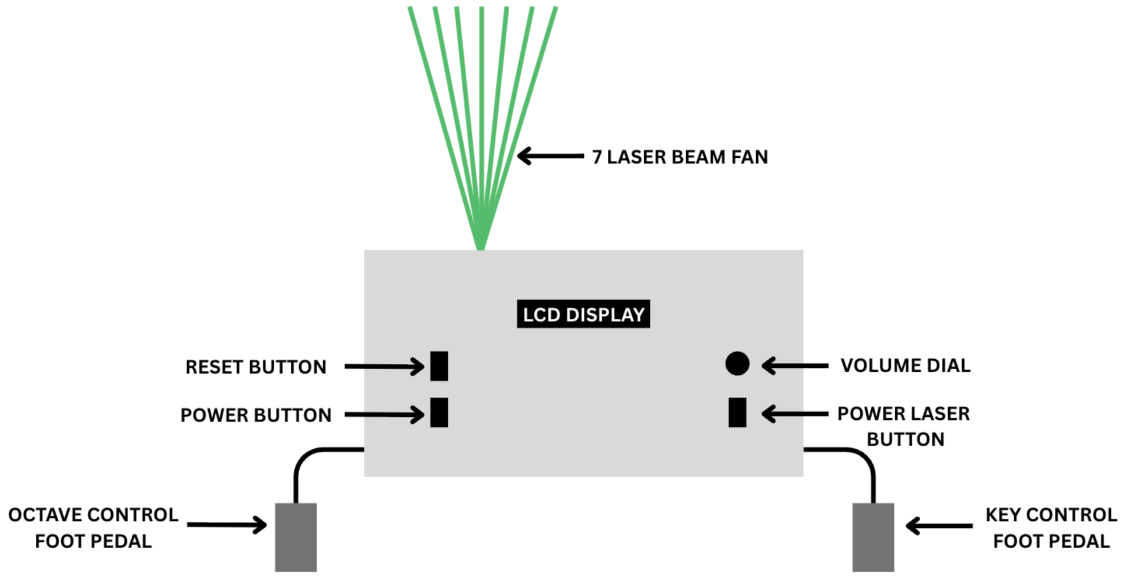
- Design a lens system to collimate a diverging beam from the laser diode and then expand the beam to create a bigger beam size for easier play.
- Design laser harp so that the stepper motor and the laser are in sync. When the stepper motor turns to a new position, the laser will momentarily turn on 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

- 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.
- 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.

Schematic of System

FRONT VIEW OF LASER HARP SYSTEM



TOP-DOWN VIEW OF INSIDE LASER HARP SYSTEM

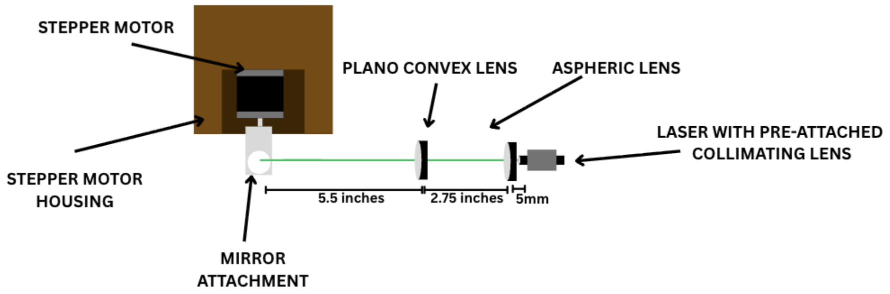
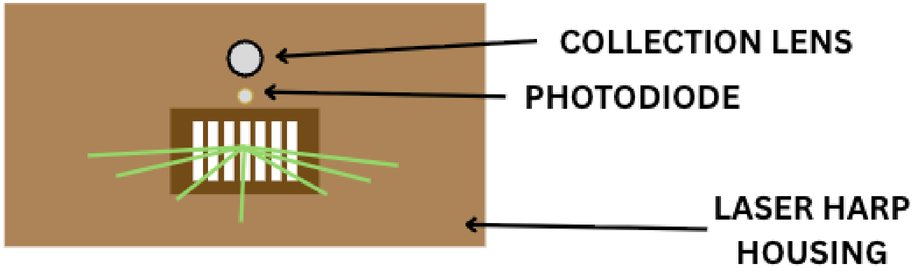


*FIGURE NOT DRAWN TO SCALE

Schematic of System



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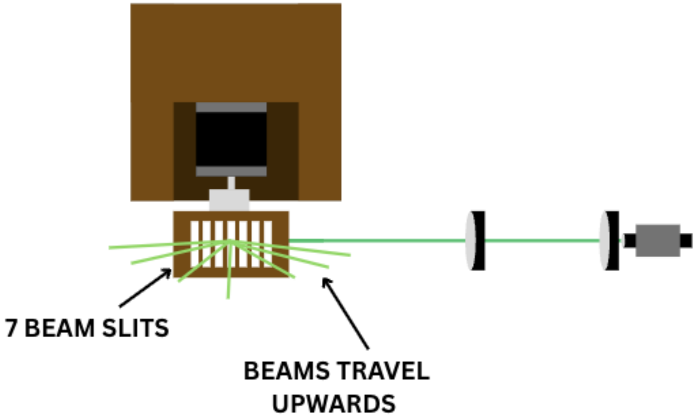

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Lens System

- Collimate light coming from laser diode
- Ensure beam size is small enough to fit through the 7 slits
- Collect reflected light into photodiode

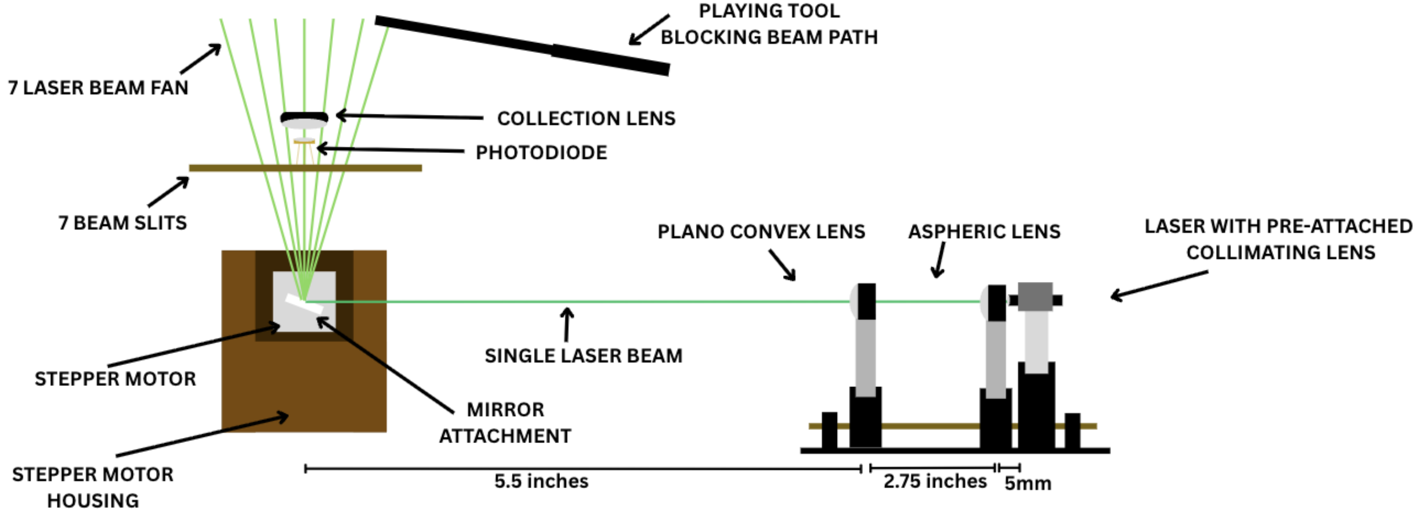


*FIGURE NOT DRAWN TO SCALE

Playing Tool

Type of surface:

- The reflection surface needs to be diffused reflection and white.
- Paper is the perfect surface
    - Paper is easily obtainable for any user
    - Paper reflects the correct amount of light into the collection lens

Width of surface:

- The beam coming out of the slits is thin therefore the surface/tool needs to be thin.

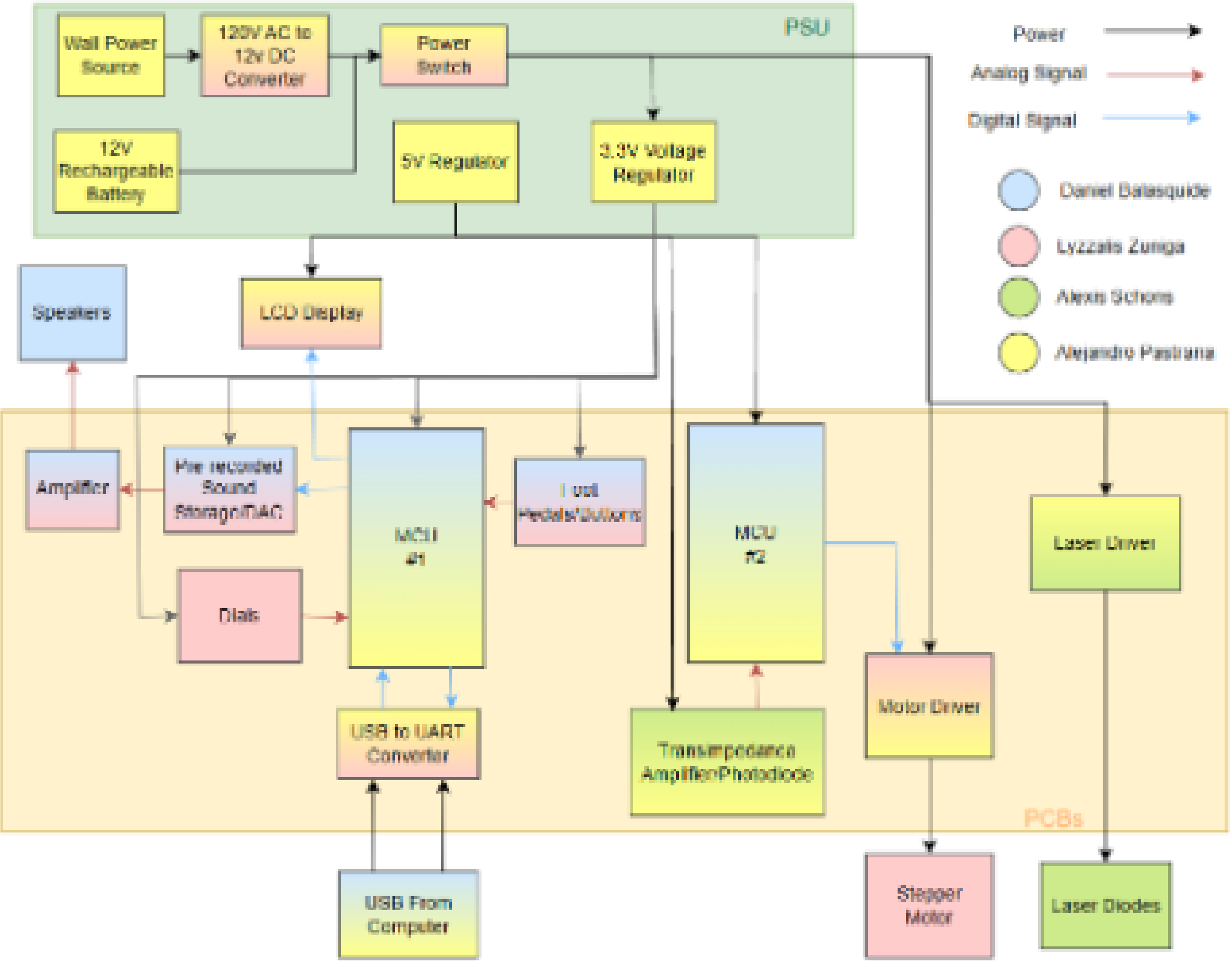
Engineering Requirements

Engineering Parameters	Requirements specifications	Units	Description
Response Time	<0.25	Seconds	Time between beam disruption and sound playing. 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

Engineering Requirements

Engineering Parameters	Requirements specifications	Units	Description
Detection Accuracy	70-75	%	How often the beam disruption will be detected. The unit shall have a detection accuracy between 70% to 75%
Power Consumption	<25	Watts	Power Consumption of the entire unit. The unit shall consume no more than 25 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

Hardware Block Diagram



Optical Engineering Specification

Component	Parameter	Specification
Laser diode	a) Wavelength b) Power	a) 520nm b) 110mW
Collimating Lens	a) Focal Length b) Lens Shape c) Diameter	a) 7.5mm b) Aspheric c) 12mm
Positive Lens	a) Focal Length b) Lens Shape c) Diameter	a) 48mm b) Plano-Convex c) 12mm
Mirror	a) Wavelength Range	a) 380-750nm
Collection Lens	a) Focal Length b) Lens Shape c) Diameter	a) 25.4mm b) Plano-Convex c) 12mm
Photodiode	a) Spectral Response b) Active Area c) Responsivity	a) 500-570nm b) 13 mm^2 c) 0.65 A/

Photodiode

	FDS 100	FDS1010	MTD3910PM	BPW34
Spectral Bandwidth	350 - 1100 nm	350 - 1100 nm	400 - 1100 nm	430 - 1100 nm
Active Area	13 mm^2	100 mm^2	1.21 mm^2	7.5 mm^2
Rise/Fall Time	10 ns	65 ns		100 ns
Cost	$17.55	$65.46	$5.61	$1.23

- Middle range for cost
- Larger active area without costing as much as the FDS1010
- Smaller rise/fall time
- Easily sees 520nm wavelength

Laser Diode

	PLT3 520FB	PLT3 520D	PLT5 520DB_P	Qiaoba Laser Module
Output Intensity	50 mW	110 mW	10 mW	5 mW
Cost	$33.89	$41.56	$14.73	$16.99

The Qiaoba Laser Module was bought off Amazon. That being said the datasheet was incorrect, and the laser actually produces about 10mW.

Photocurrent Calculation:
-Need 5μA

$$I_{ph} = R * P = 0.65 * 0.01 = 0.0065A$$

- Easy to use compared to raw laser diodes
- Cheaper than the other higher-powered options
- Short lead time

Laser Driver

- Laser Diodes are sensitive components; operating the diode exceeding its operating values would lead to short life span, or complete damage.
- Laser Diodes tend to increase in conductivity and increase current drawn when it increases in temperature.
- Laser Diode Driver will be used to ensure that Laser Diode is limited to its operational values. Diode will be turned on and off using a switch connected to the PSU
- Constant Current Driver based on the LM2596S will be use to as a laser diode.

Microcontrollers

	ATMEGA328 P	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
Input Voltage (V)	1.8V ~ 5.5V	1.8V ~ 3.6V	2.7V ~ 3.6V
Cost	$2.74	$8.34	$6.56

- Primary Components, responsible for controlling entire harp; added buttons, dials for user interface
- MCUs must have a large number of GPIO pins, able to use pins to read, and output digital and analog signals
- Fast clock speed, good amount of storage
- Must be easy and widely used; available resources online
- Two MCUs will be used to divide tasks appropriately

Microcontrollers

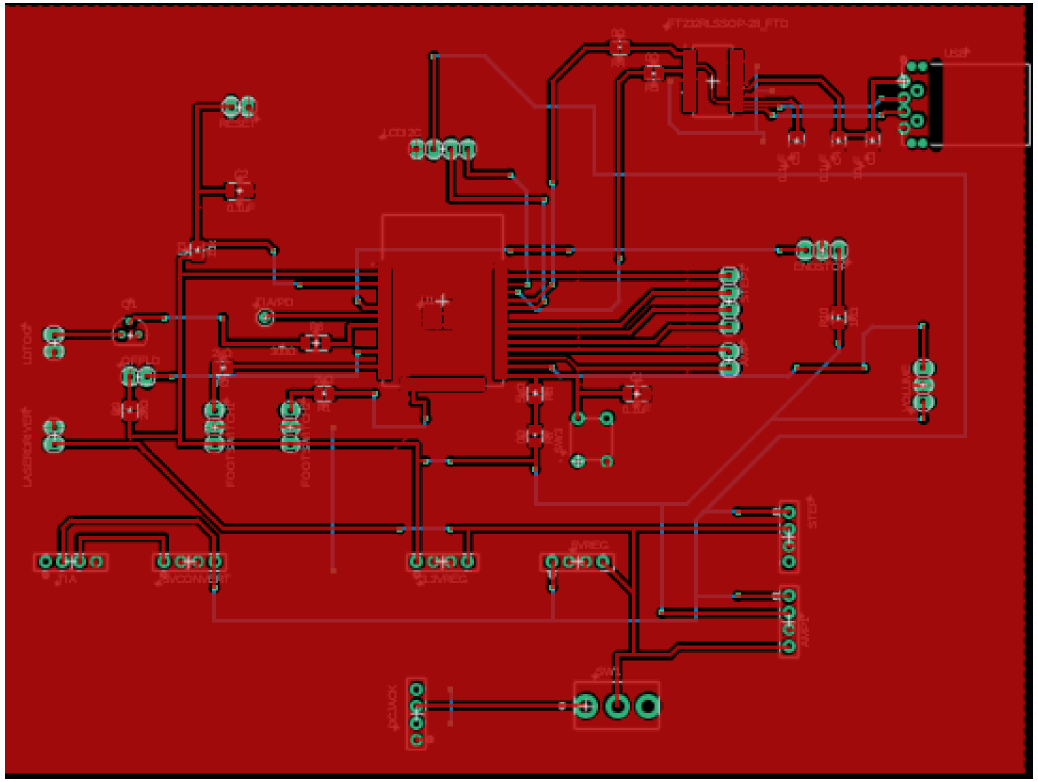
ATMEGA328PU:

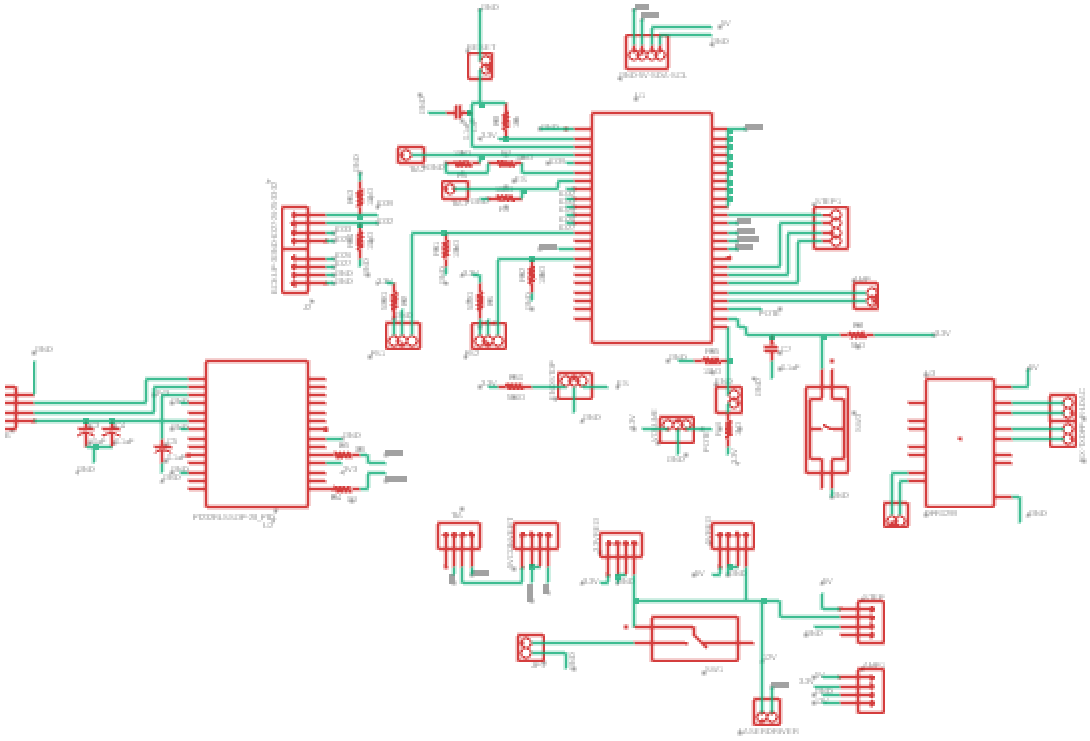
- Tasked with controlling Stepper Motor and Driver
- Reads Analog readings from Photodiode
- Communicating steps of disturbance to ESP32

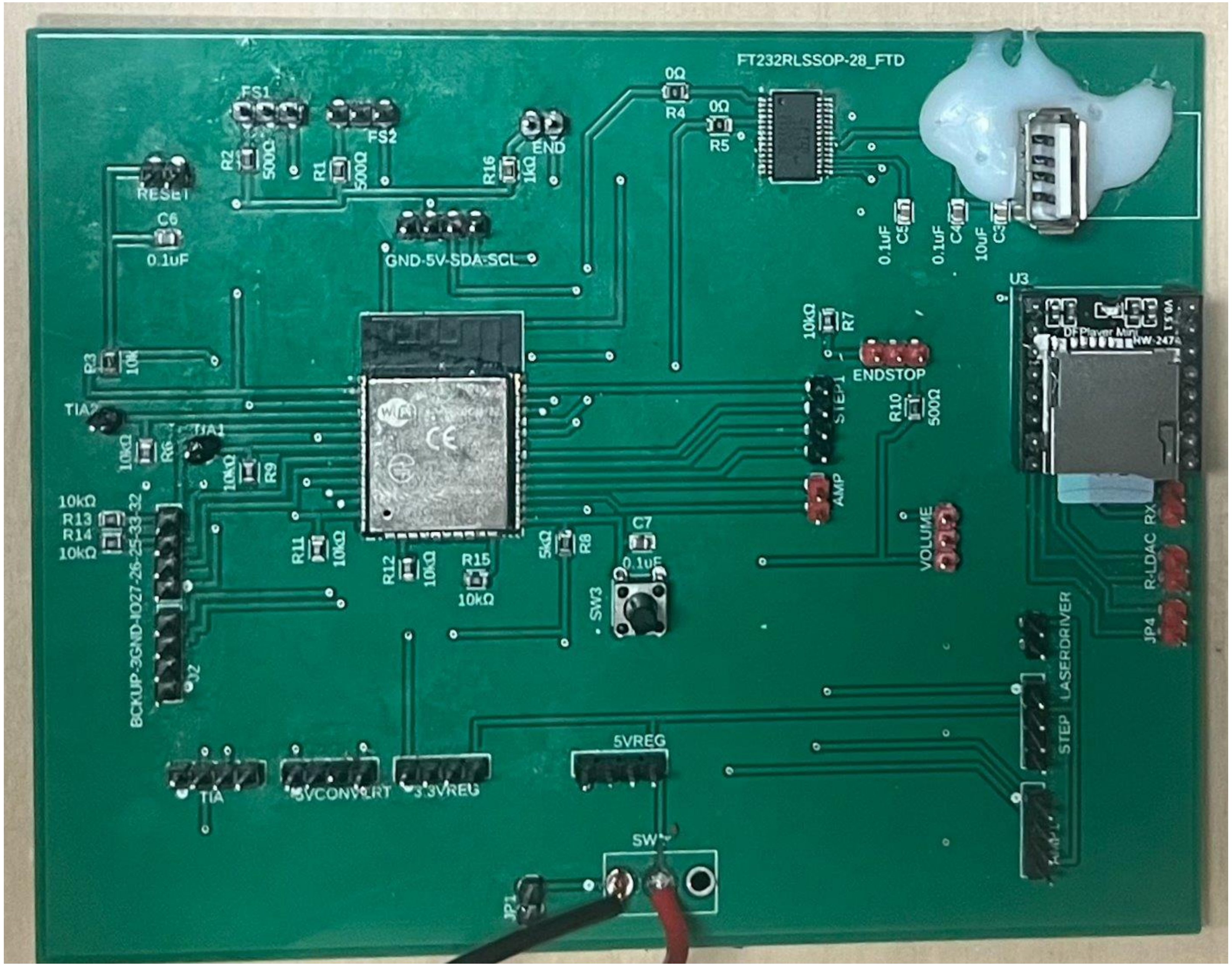
ESP WROOM 32:

- Tasked with playing music for string; info received from ATMEGA
- Controls User Interfaces
- Sends reset command to ATMEGA328
- Has onboard USB-UART Converter for programming

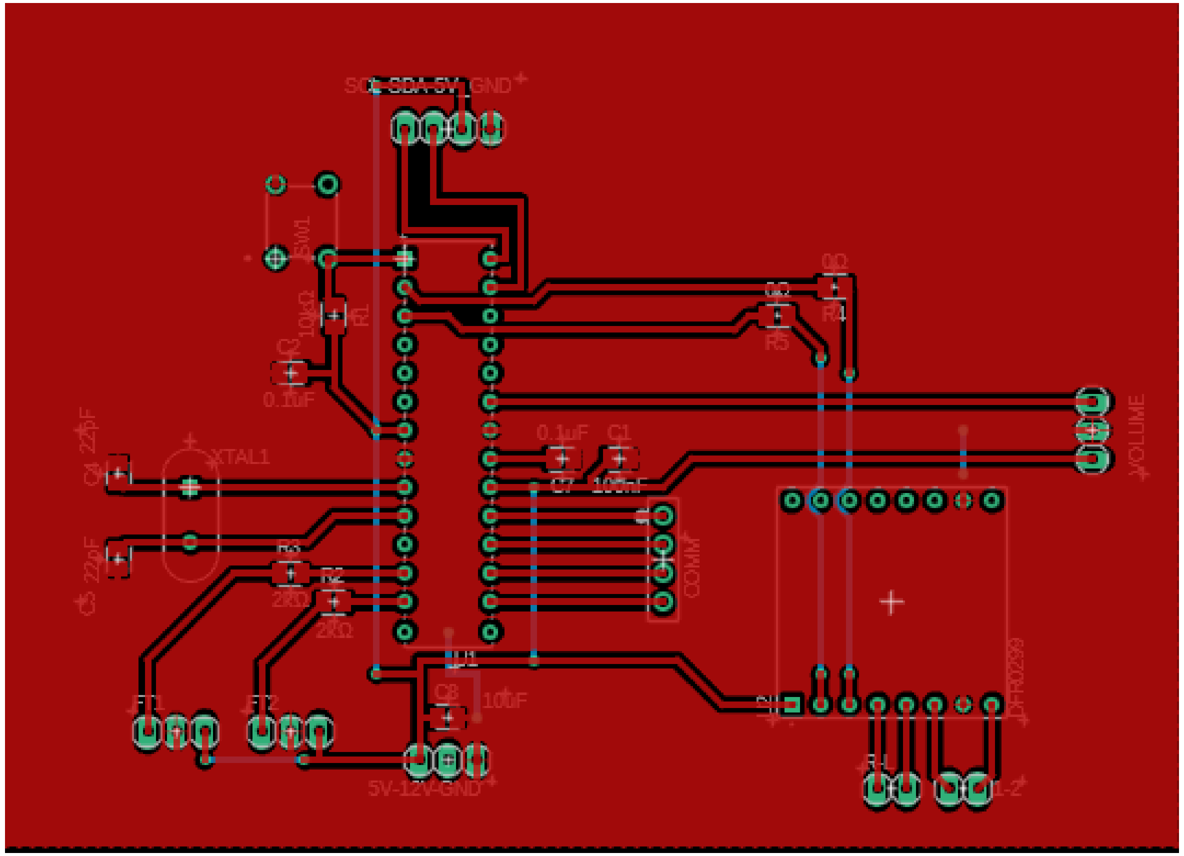
PCB Design – ESP32 Board

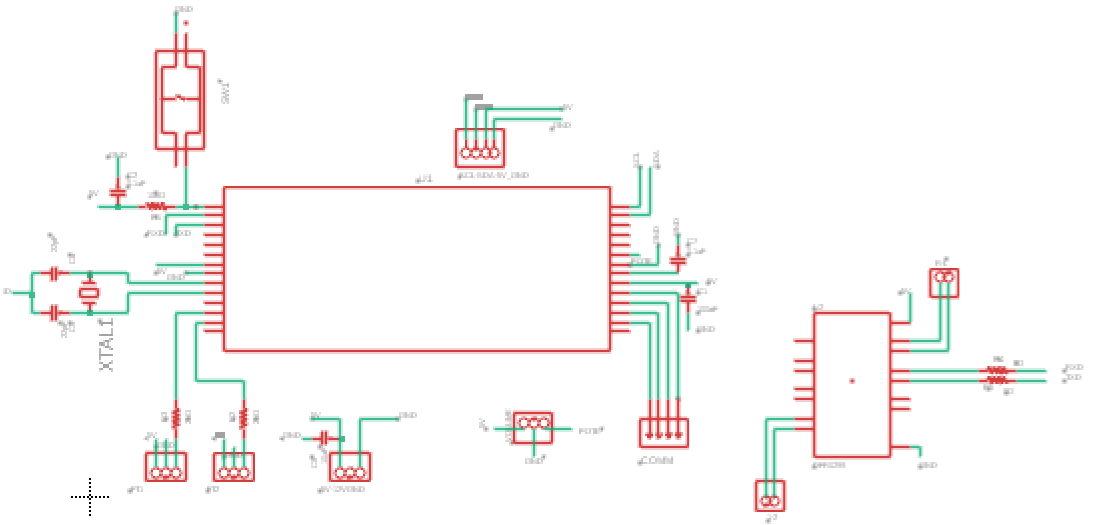


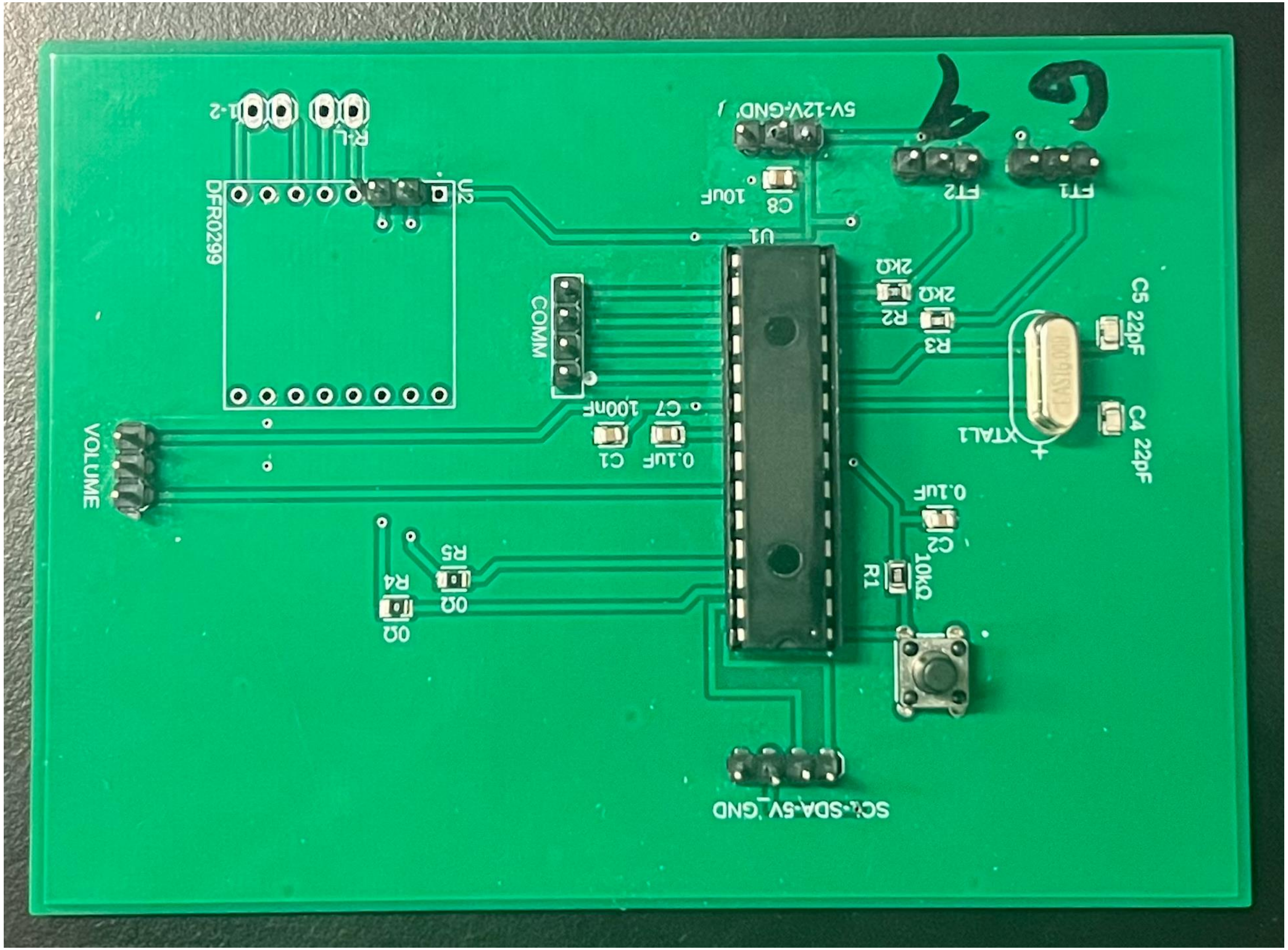



FT232RLSSOP-28_FTD
0Ω
R4
0Ω
R5
FS1
FS2
END
R2
500Ω
R1
500Ω
R16
1kΩ
RESET
C6
0.1uF
GND-5V-SDA-SCL
0.1uF
C5
0.1uF
C4
10uF
C3
U3
DFPlayer Mini
10kΩ
R7
ENDSTOP
STEP1
R10
500Ω
AMP
VOLUME
RX
R-LDAC
JP4
LASERDRIVER
STEP
R3
TIA2
TIA1
10kΩ
R6
10kΩ
R9
10kΩ
R13
R14
10kΩ
BCKUP-3GND-IO27-26-25-33-32
J2
R11
10kΩ
R12
10kΩ
R15
10kΩ
5kΩ
R8
C7
0.1uF
SW3
TIA
5VCONVERT
3.3VREG
5VREG
JP1


PCB Design- ATMEGA328 Board






DFR0299
U2
COMM
VOLUME
U1
5V-12V-GND
C8
10uF
FT1
FT2
R2
2kΩ
R3
2kΩ
C5
22pF
C4
22pF
XTAL1
C7
100nF
C1
0.1uF
R1
10kΩ
R4
R5
SCL-SDA-5V_GND

Stepper Motor

Feature	Permanent Magnet (PM) Stepper	Variable Reluctance (VR) Stepper	Hybrid Stepper (e.g., NEMA 17)
Cost	Uses permanent magnets in rotor	Reluctance-based, no magnets	Combines PM + VR designs
Precision	Low (large step angles ~7.5–15º)	Moderate (step angles ~5–15º)	High (small step angles ~0.9–1.8º)
Torque	Moderate	Low torque	High torque, stable at standstill
Speed	Good at low speeds	Moderate	Balanced torque & speed
Cost	Low (cheapest option)	Low–medium	Medium, most common in projects

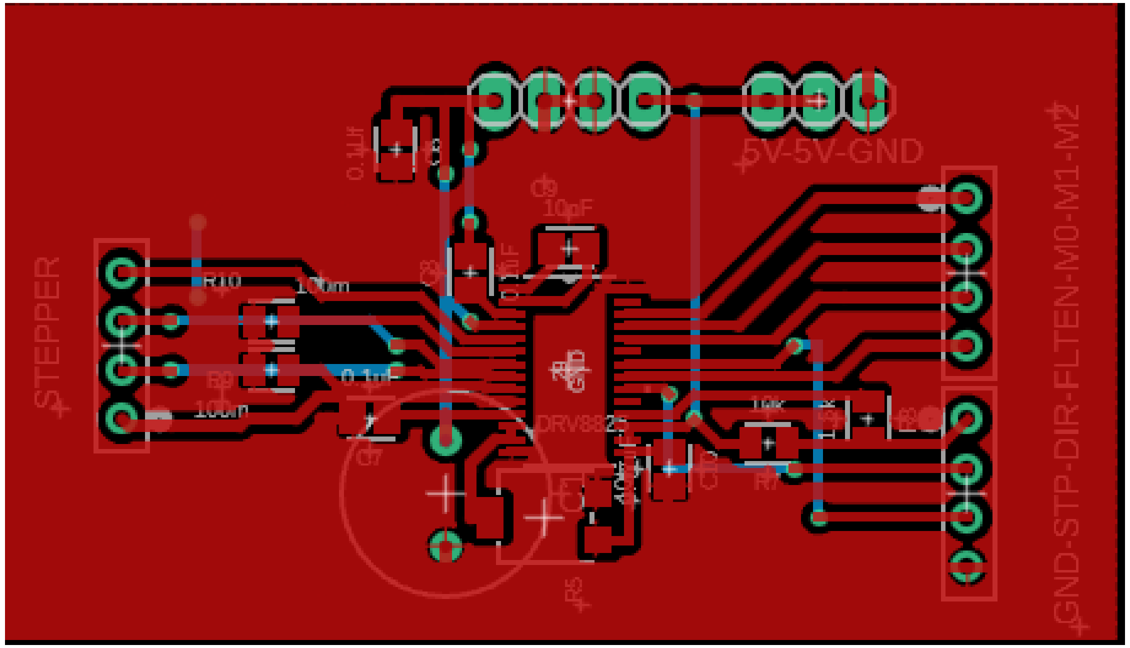
- Best balance of precision, torque, and reliability compared to other stepper types.
- Combines the advantages of both, allowing for smaller step angles (around 0.9–1.8°) that are ideal for accurate positioning of the harp's moving components.
- Offers high torque and good stability at standstill, which ensures smooth performance during operation.

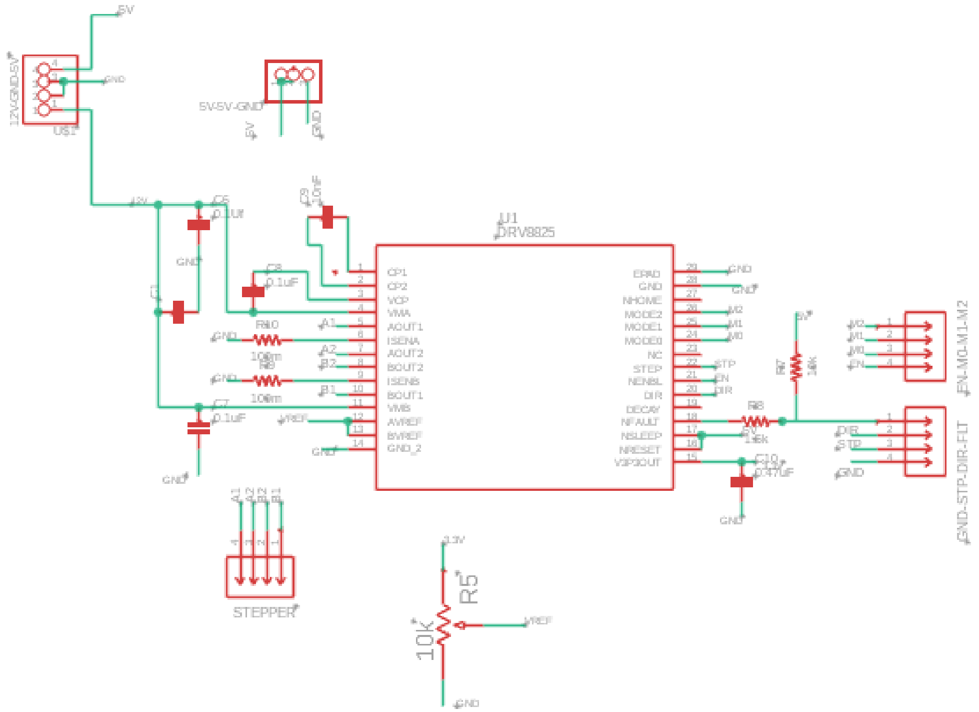
Motor Drivers

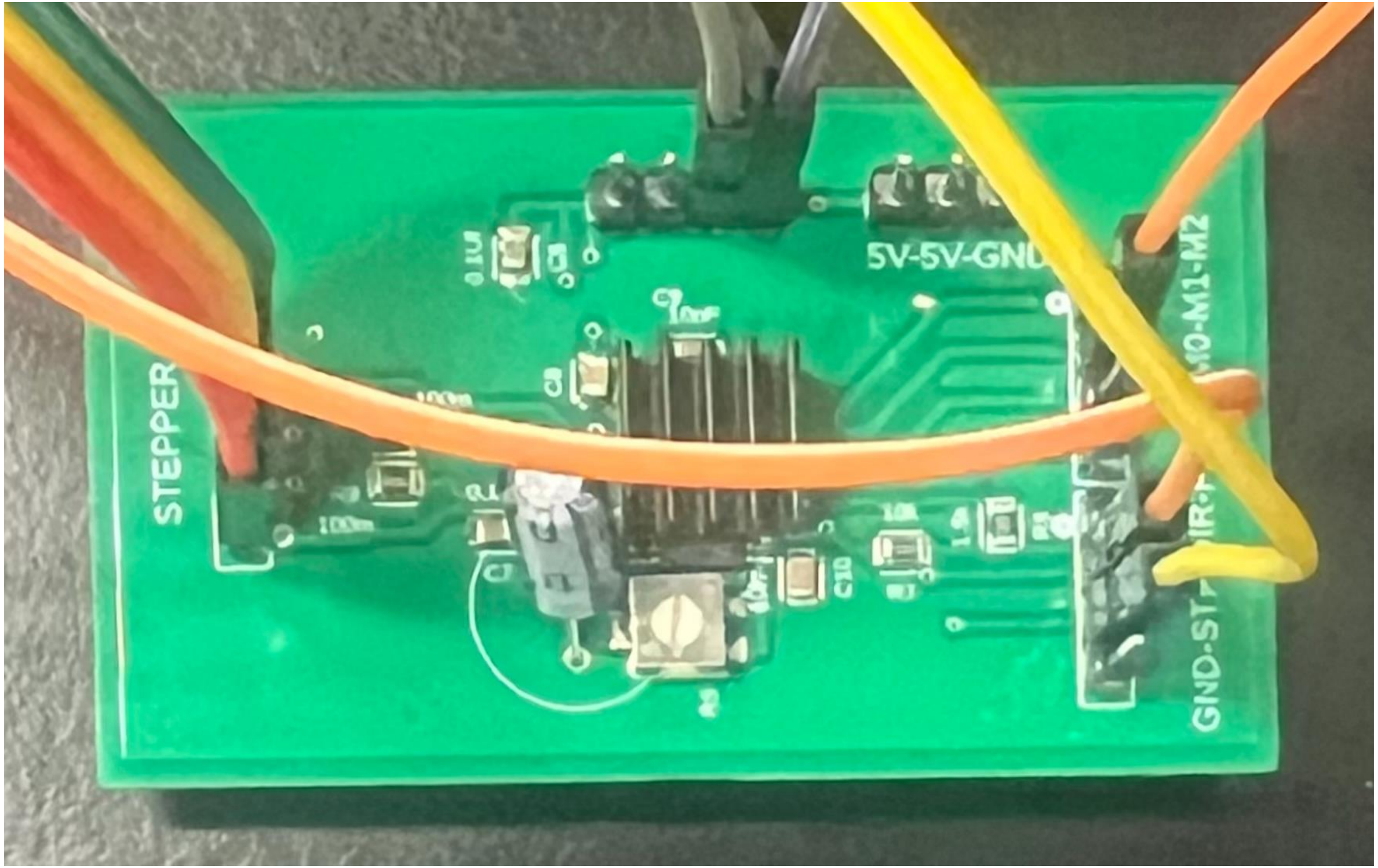
Feature	TB6600 Driver	DRV8825 Driver
Current Capacity	Up to ~4.5 A per phase (high power)	Up to ~2.2 A per phase (lower power)
Voltage Range	9–42 V	8.2–45 V
Size	Larger, external module	Compact, small breakout board
Complexity	Requires wiring & setup	Easy to integrate, simple to use
Cost	Higher (~$15–25)	Lower (~$5–10)
Use Case	Heavy-duty motors, CNC, robotics	Small to medium stepper motors

- Offers precise microstepping control, which allows for smooth and accurate movement of the rotating mirror in our laser harp.
- Its compact size makes it easy to integrate into our PCB layout, while its low power consumption aligns with our efficiency goals.
- cost-effective and widely available, making it an ideal choice for both prototyping and final implementation.
- Overall, the DRV8825 provides reliable performance for driving our NEMA 17 stepper motor and supports the project's focus on precision and simplicity.

PCB Design- Stepper Motor Driver



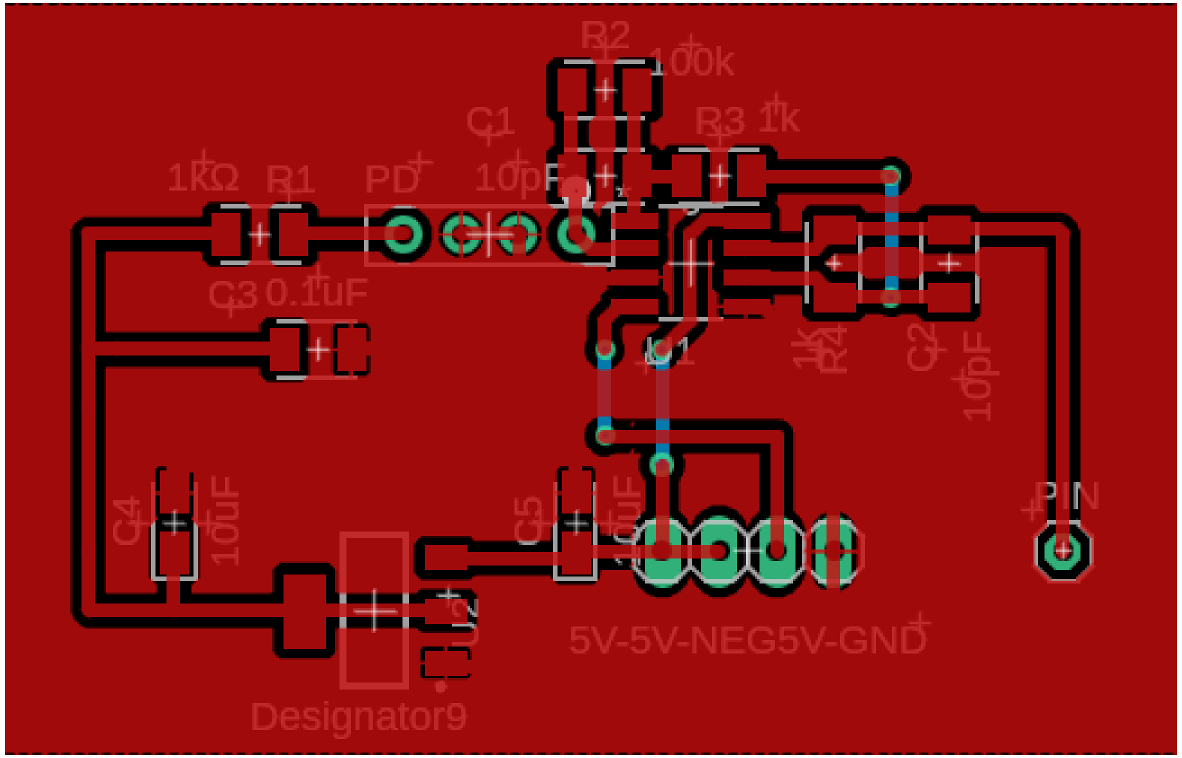


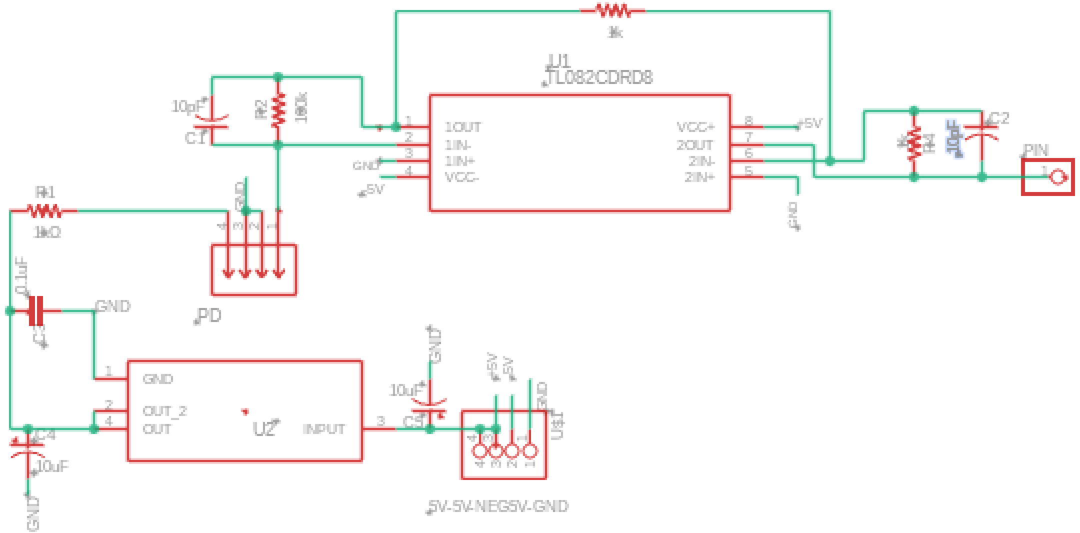

STEPPER
5V-5V-GND
GND-ST

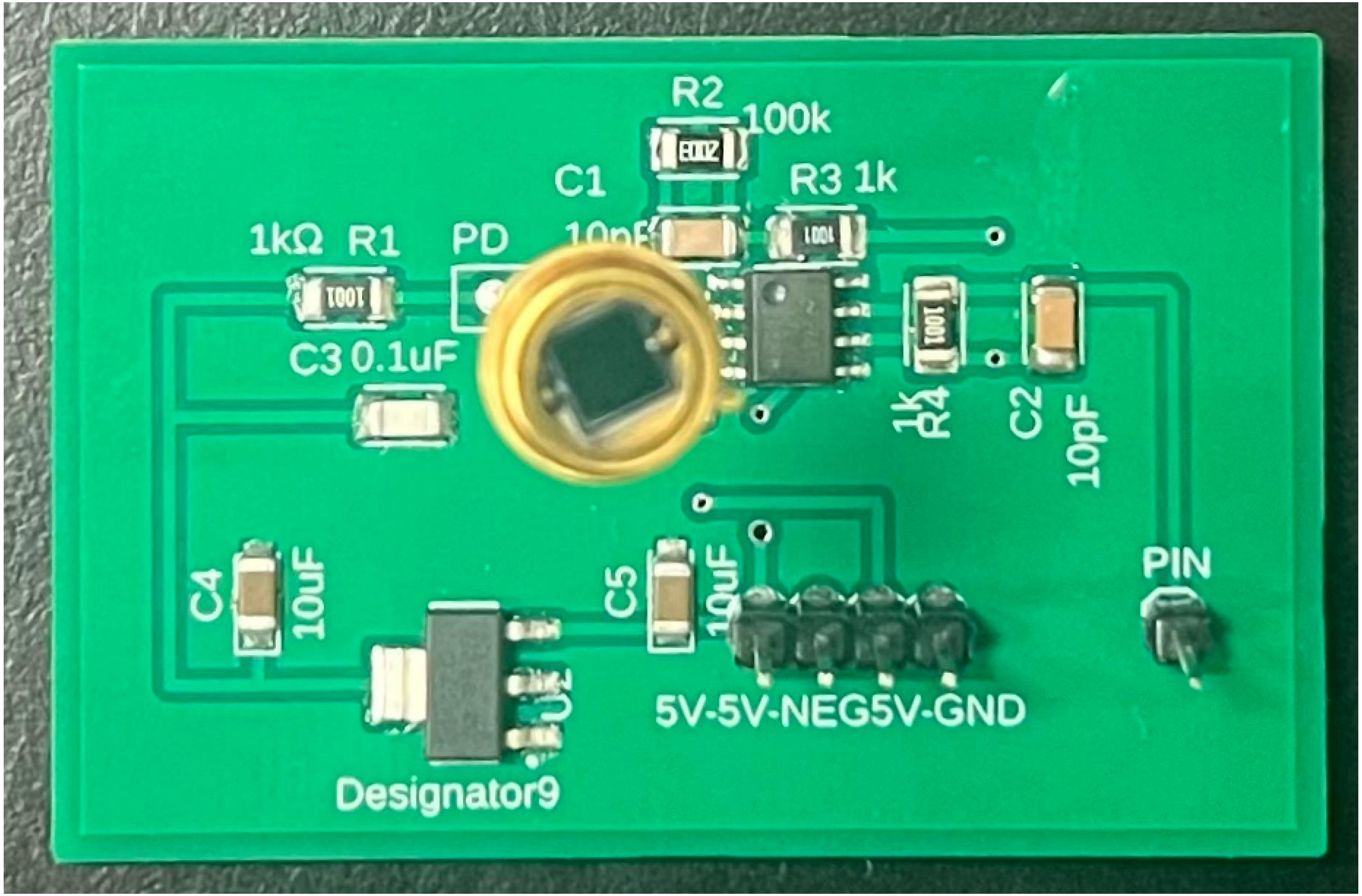
Transimpedance Amplifier

- A Transimpedance amplifier is a low input and low output impedance current-to-voltage converter used for photodiodes.
- Circuit uses operational amplifier to convert and amplify relatively small, and sensitive current into measurable voltage.
- Output voltage of the amplifier will measure by the MCU to detect "plucking of strings.
- TL08X Series Op-Amp used as the amplifier for the TIA.

PCB Design- Transimpedance Amplifier



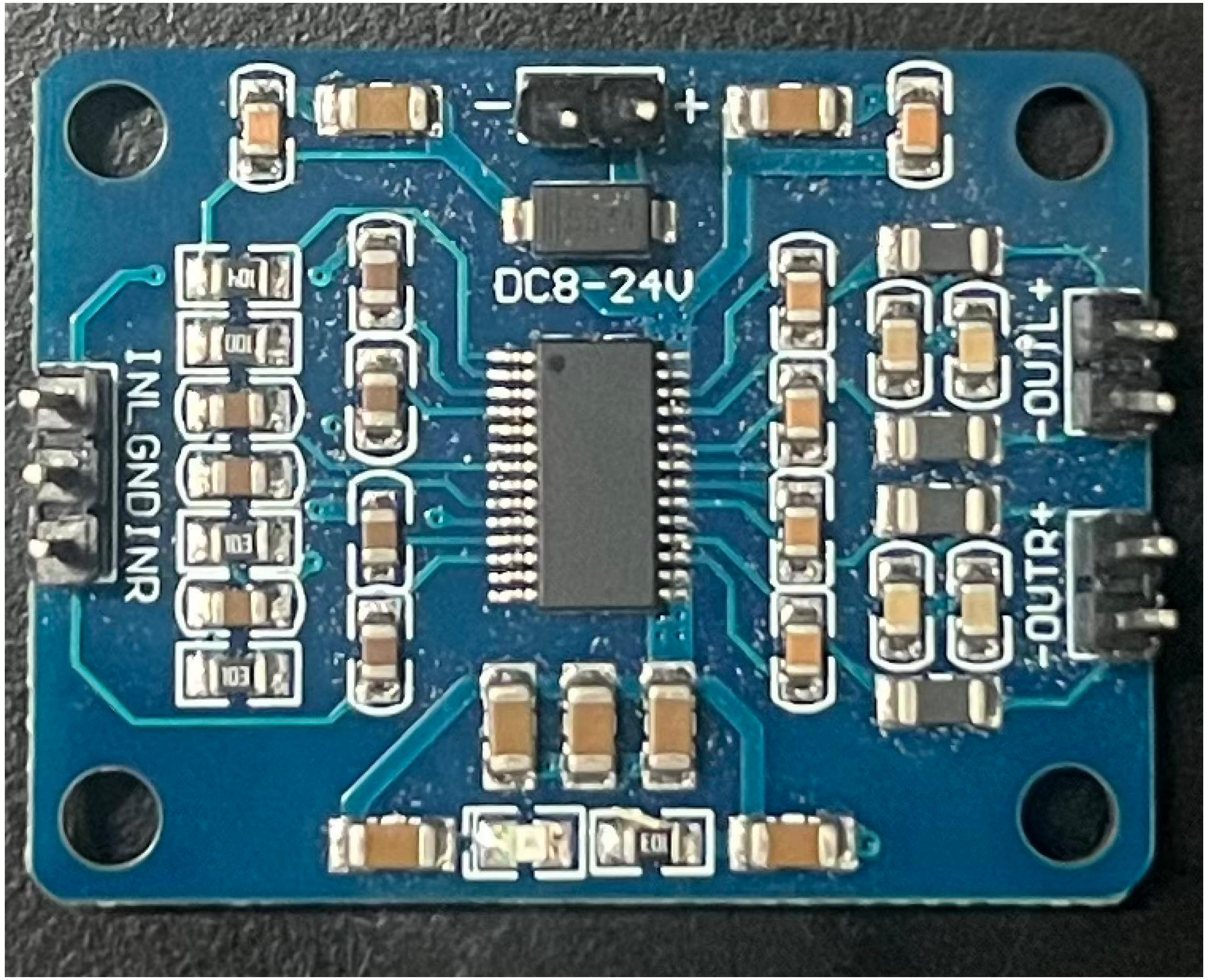



R2
100k
C1
10pF
R3 1k
1kΩ R1
PD
C3 0.1uF
R4
1k
C2
10pF
C4
10uF
C5
10uF
U2
PIN
5V-5V-NEG5V-GND
Designator9

Audio Amplifier

	TPA3110	Mini Digital Amplifier	DFPlayer Audio Amplifier	TDA Mono Audio Amplifier	LM386 Low Voltage Audio Power Amplifier
Amplifier Class	Class D	Class D	Class D	Class AB	Class AB
Operating Voltage Min-Max	8V - 26V	5V-5V	3.3V-5V	5V-24V	5V - 12V
Type of Input Voltage	AC/DC	DC	DC	AC/DC	DC
Total Harmonic Distortion	Minimal from Class D amp, 0.1% THD	Minimal from Class D amp, 0.15% THD	Minimal from Class D amp	Moderate for a Class AB amp, 10% THD	Very minimal for a Class AB amp, 0.2%
Cost	$3.52 each	$5.97 for a pack of 5	$5.90 each	$11.02 for a pack of 2	$1.05 each

- The Audio Amplifier will be needed because of the size and requirements of our speaker
- The two amplifiers that we will be using for the Audio will be the amplifier built into the DFPlayer mini, and the other amplifier will be the TPA3110 audio amplifier.


DC8-24V
INL GND INR
-OUTL+
-OUTR+


Speaker

	Douk Audio Speaker	Tang Band W3-881SJ	Dayton Audio RS100-4 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
Sensitivity/Volume in Decibels	88 dB	86 dB	87.5 dB
Sound Quality	Clean Audible Sound, with low distortion	Clean Audible Sound with low distortion	Balanced Audio, with minimal Distortion
Impedance	8 Ohms	8 Ohms	4 Ohms
Cost	$13.99	$34.98	$36.98

- The Frequency Response shows the range of notes that the speaker will be able to reach, low wider ranges means the speaker will be able to produce lower notes with appropriate volume and cleanness
- We found the Douk Audio Speaker to be the best because of its clean audible sound, and operable frequency response, and the operating voltage

LCD Display

Feature	LCD Display	OLED Display	TFT Display
Visibility	Limited viewing angles, lower contrast	High contrast, wide viewing angles	Bright colors, wide viewing angles
Power Use	Low	Very low (efficient for text/UI)	Higher power consumption
Resolution	Basic text/characters	Moderate (clear text/graphics)	High resolution, detailed graphics
Cost	Very low	Moderate, affordable	Higher
Integration	Easy, basic control (I2C/parallel)	Easy, I2C supported	More complex, requires more pins

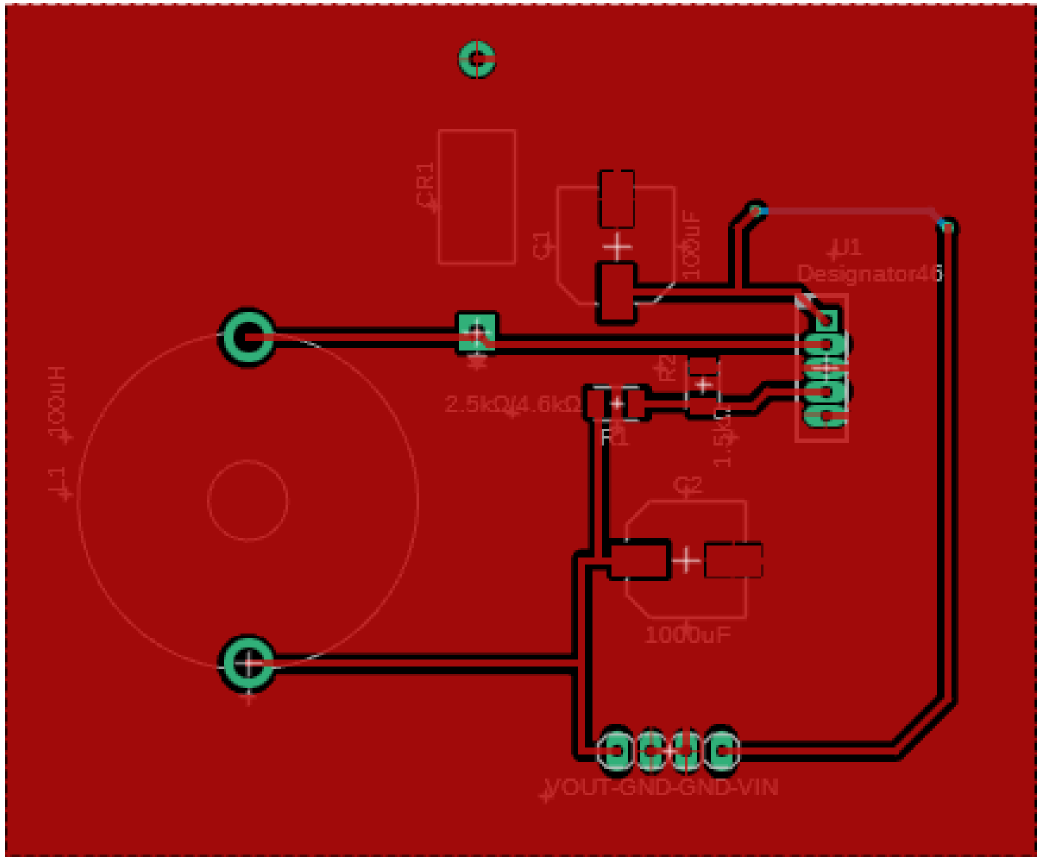
- Low cost compared to OLED or TFT
- Displays simple information like volume, octave, and key
- Uses very little power, efficient for long operation
- Easy to connect with I2C or parallel interfaces

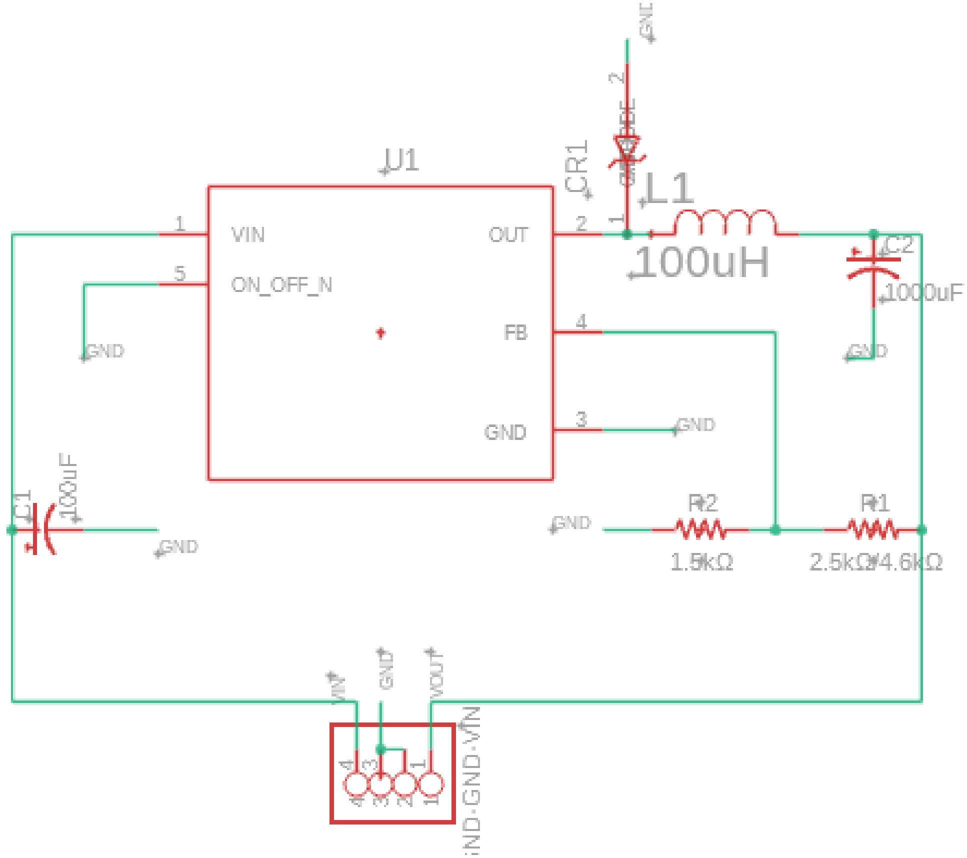
Voltage Regulator

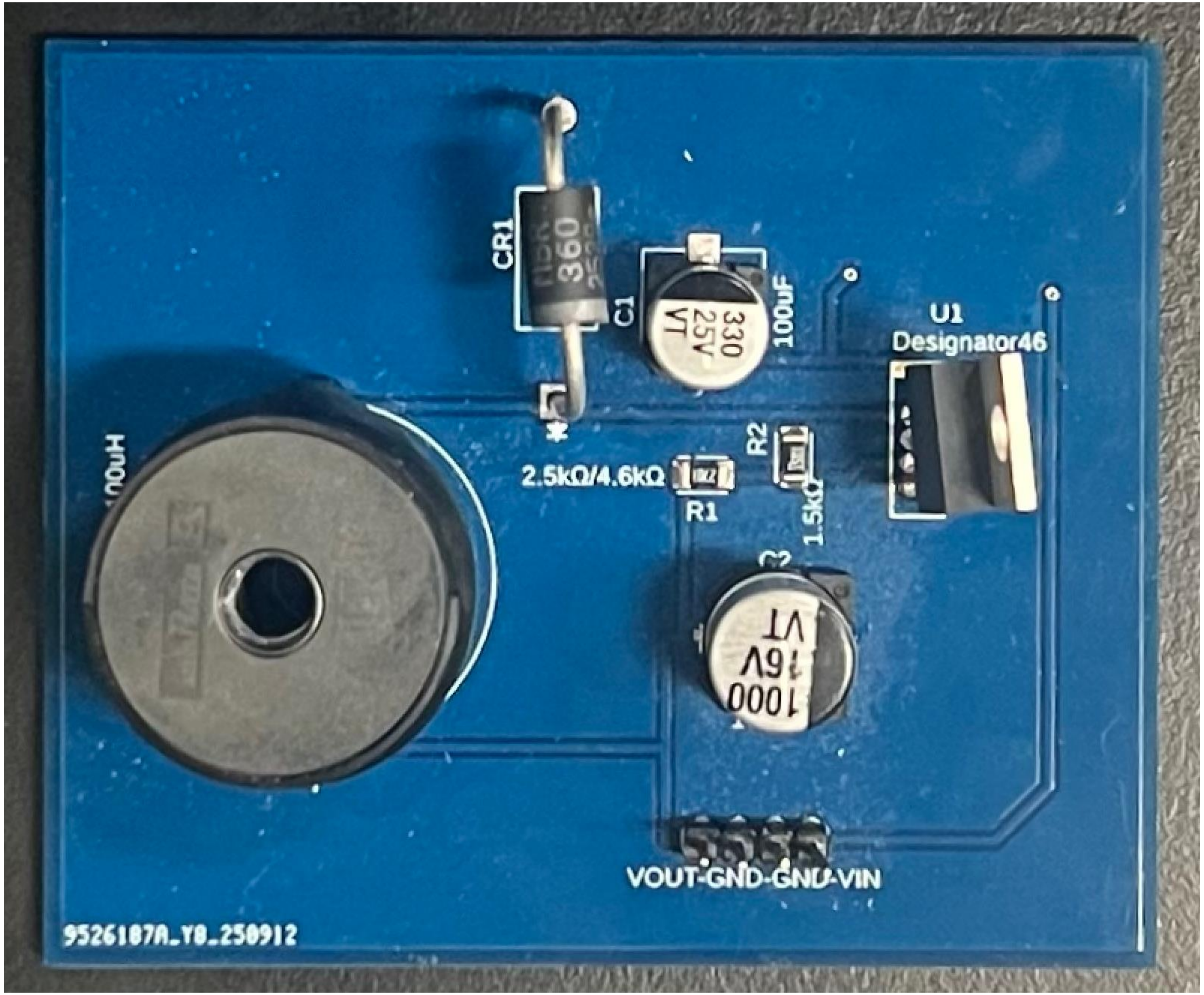
	LM317	LM2576	AP62150Z6
Type	Linear	Switching (Buck)	Switching (Buck)
Max Output Current (A)	1.5 A	3 A	1.5 A
Dropout Voltage (V) @ 1 A	2 V	1 V	2 V
Efficiency	~50%	75%	70-90%
Switching Frequency	0 Hz	52kHz	1MHz
Price	$0.53	$1.75	$3.54

- PSU will include of two main voltage regulators, a 3.3V and a 5V regulator.
- When looking at possible choices, efficiency, and loss as heat of regulators were considered.
- Possible EM Interference, and design flexibility was also considered when choosing regulator.
- Regulators were compared on having decently high output current, high efficiency, and low EMI.
- Other, smaller, voltage regulators/converters were used for in the project like the LM1117 for TIA and an additional negative voltage converter

PCB Design- Regulators






CR1
C1
100uF
U1
Designator46
R2
2.5kΩ/4.6kΩ
R1
1.5kΩ
VOUT-GND-GND-VIN
9526187A_Y8_250912

Power Supply

- Primary Voltage source will come from will power; SANSUN 12V 5A Wall Cord chosen.
- Wall Power will be fed to the regulators to power components using 3.3V and 5V
- Wall Power used to power directly the laser driver; audio amplifier and fan for cooling
- Rechargeable 12V battery used to power stepper motor driver; motor caused interference on the Transimpedance amplifier, motor and driver isolated.

Power Consumption

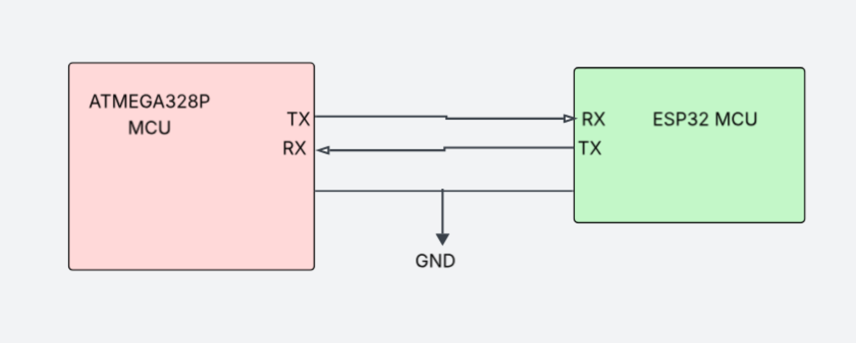
Power Source	Output Current	Output Power
12V Wall Power	130mA	3.48 W
12V Rechargeable Battery	107mA	1.284 W

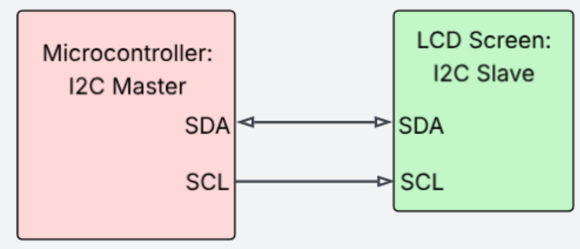
Regulator	Input Current	Output Current	Input Power	Output Power	Efficiency (%)
3.3V	24mV	65mA	0.288W	0.215W	74.5%
5V	95mA	165mA	1.14W	0.825W	72.3%

Components (Voltage)	Current Draw	Power Consumption
Stepper Driver (12V) - RB	107mA	1.28 W
Arduino Board (5V)	109mA	0.545 W
TIA/PD Subsystem (5V)	9mA	0.045W
Laser Driver (12V)	85mA	1.02W

Software Design – Communication Protocols

- The protocols used for this project was SPI, UART ,and I2C
- We use UART between the ATMEGA and the ESP32 for transmitting the stepper motor position, transferring a bootdown to the ATMEGA
- I2C will be used for the LCD display
- SPI will be used for the communication with the DFPlayer



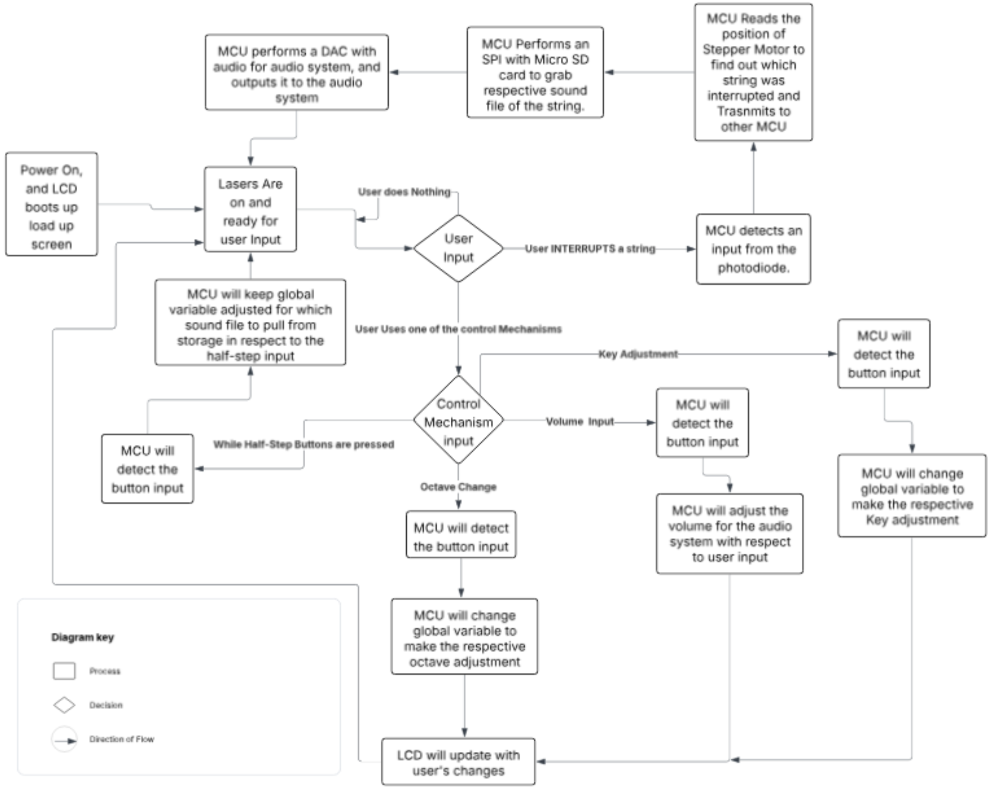


Software Design - Softwares

- The IDE software's that we could have used for this project were Arduino IDE, Espressif IDE, and Visual Studio with Platform IO.
- All these options are viable, but we found that Arduino IDE supports both Microcontrollers and is very user friendly. It also has high community support, and library availability that can allow for us to use the DFPlayer, and LCD effectively and efficiently. So, this will be our choice, and we will use C++.

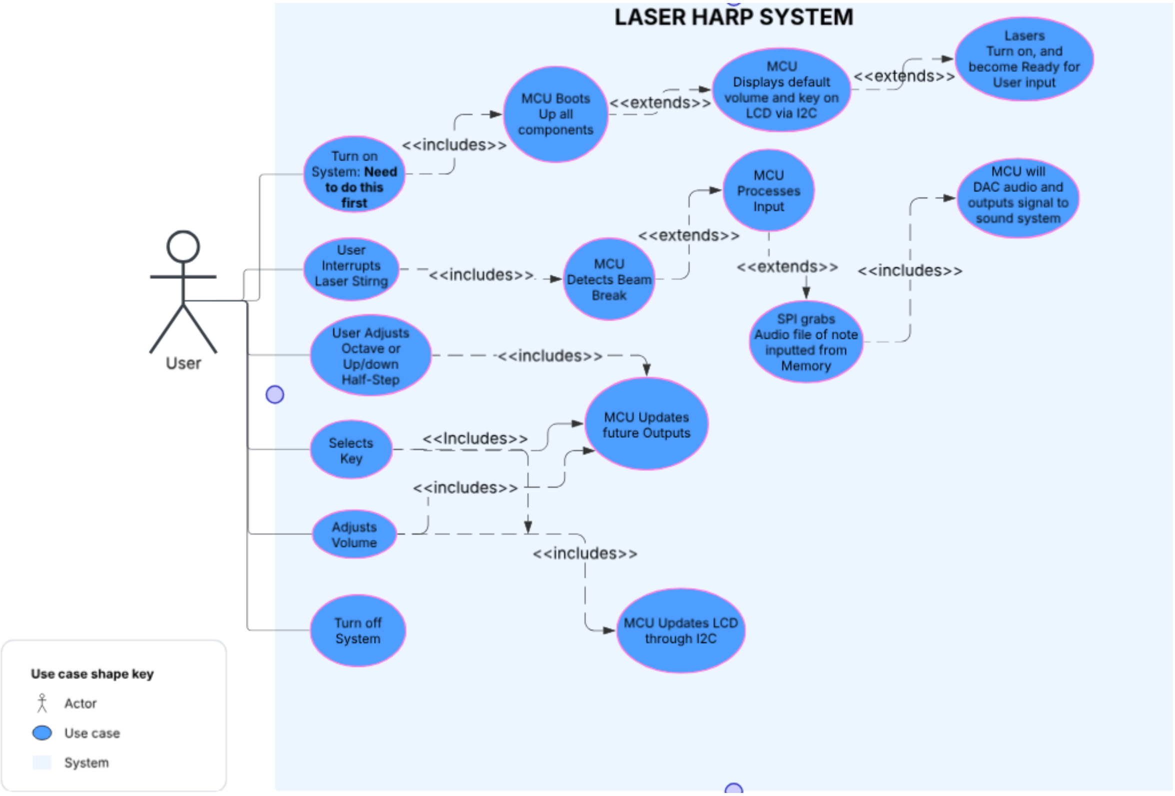
	Compatibility	Complexity	Language Support
Arduino IDE	Both MCUs	Very User Friendly	Primarily C++
Espressif IDE	ESP32 Only with overhead	Challenging due to low level coding	C and C++
Visual Studio	Both MCUs	Can range from complexities due to language use and file management	Supports many Languages and architectures

Software Design – In Depth Diagram



- On the left shows the in-depth flowchart that will demonstrate how the entire software design will flow.
- To create it, we used two MCUs, one for stepper motor and detection, and other for the music playing and user buttons of the project

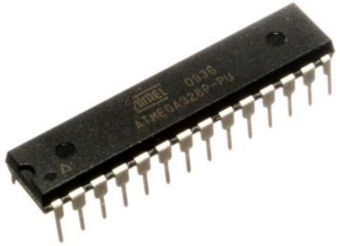
Software Design – User Case Diagram



- This diagram shows the functional requirements of the system
- This provides a high-level overview without technical detail to show what the user input will do and the basic overview of the software.

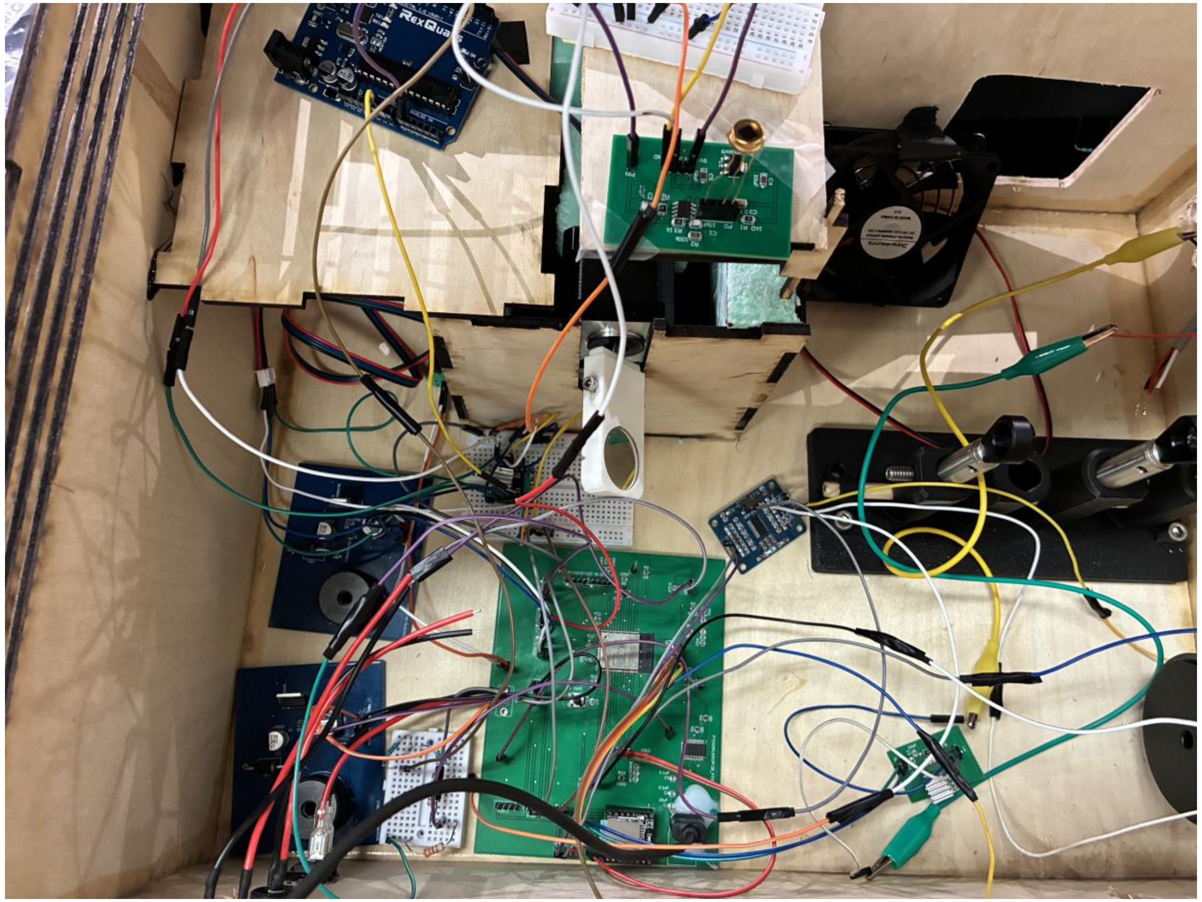
Software Design – MCU Software Tasks

- The Two codes and tasks for the ATMEGA and ESP32 were chosen for specific reason.
- The ATMEGA allows for fast and reliable control of the stepper motor. Because of the speed of the motor and the photodetection task, there is very little room for blocking statements such as reads or writes.
- Esp32 offers multiple cores that can allow for Synchronous tasks with the FreeRTOS, which allow for multiple button inputs and analog reads at the same time.



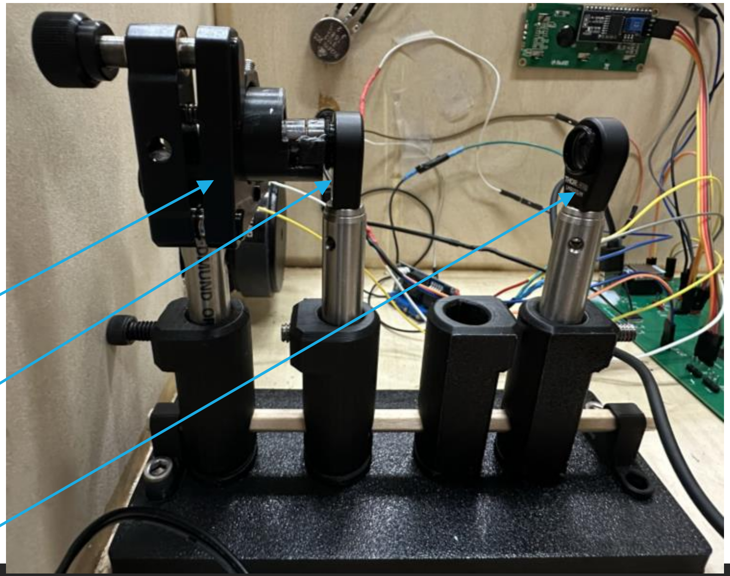
Testing and Prototyping- Entire Design

- Project initially tested with breadboards and development boards
- All components used placed loosely in the casing
- Harp powered using smaller 12V 2A wall power
- Stepper Motor powered first with 12V wall power, then separate 12V power supply

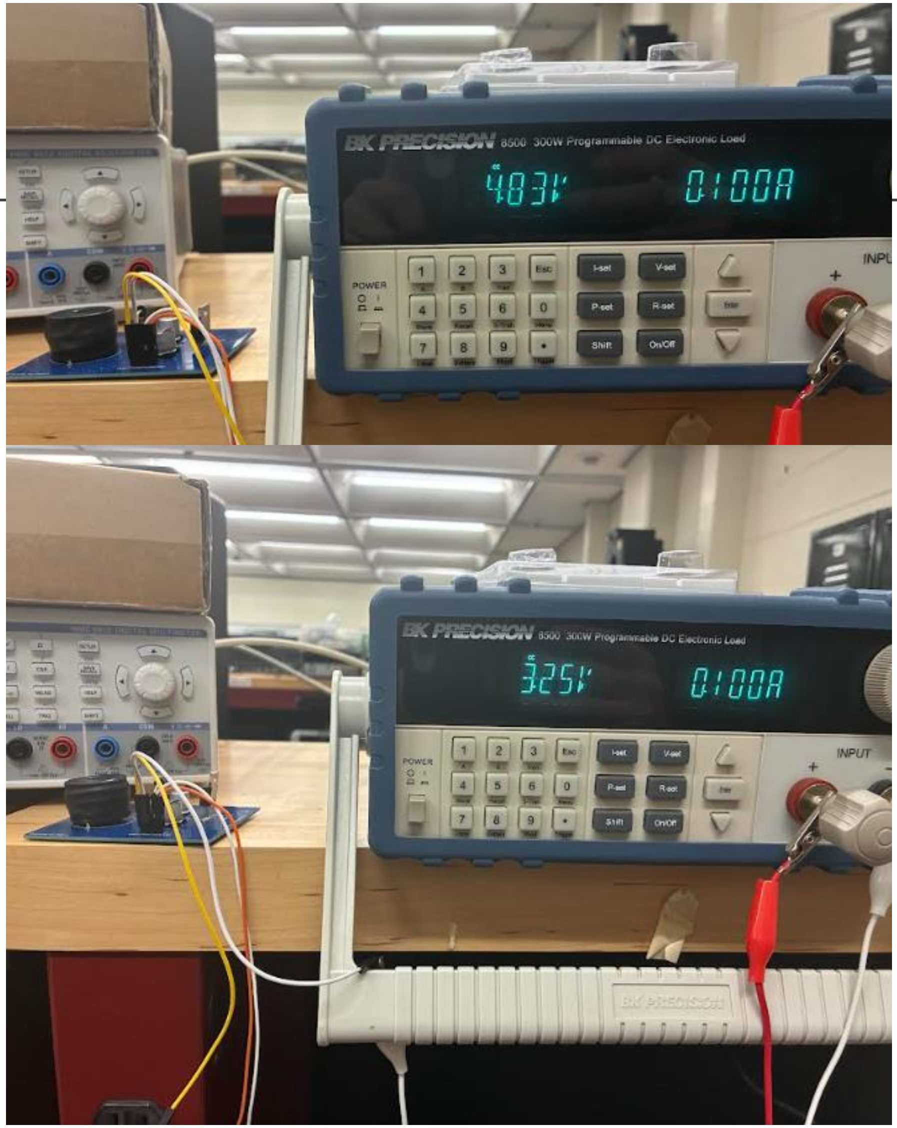


Testing and Prototyping- Laser/Optical System

- Initially the laser diode was going to be pulsed to create the 7 strings
  - Problem: The laser diodes burned
  - Solution: Keep laser constant wave and use slits to create the 7 strings
  - Problem: Original lens design with original diode choice magnified the beam too big to fit through slits
  - Solution: Use diode with smaller emission size, get rid of the plano-concave, keep the plano-convex and the aspheric



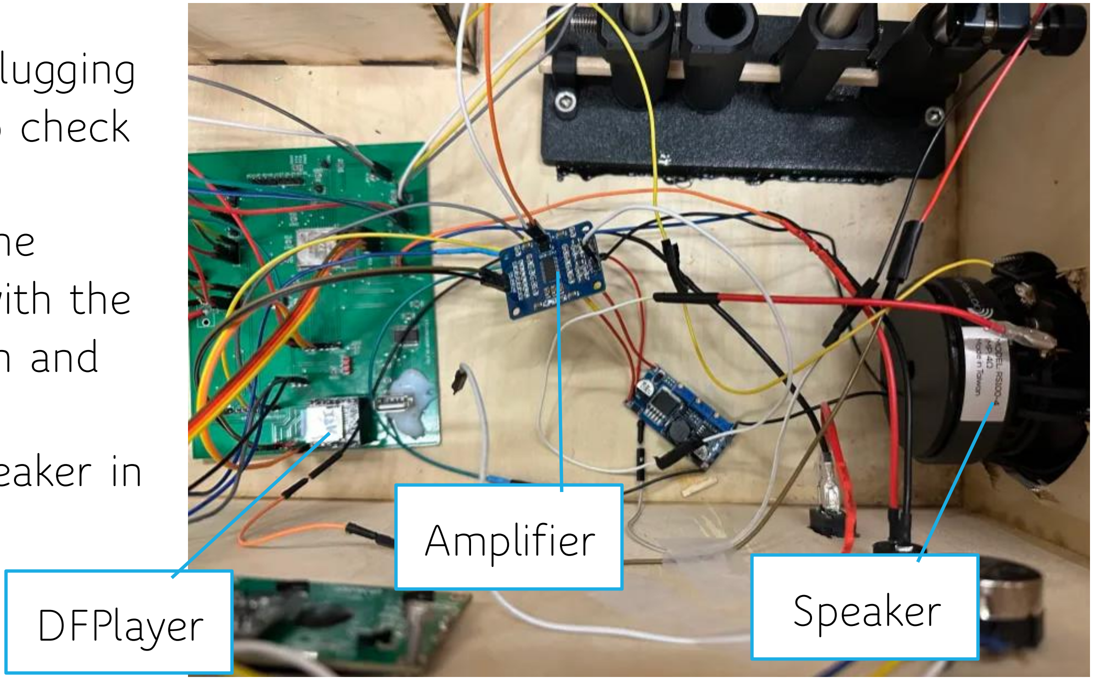
Testing and Prototyping- Voltage Regulation



- Electronic Load was used to measure voltage drop off under load
- As measured, current draw for both voltage regulators does not exceed ~100mA

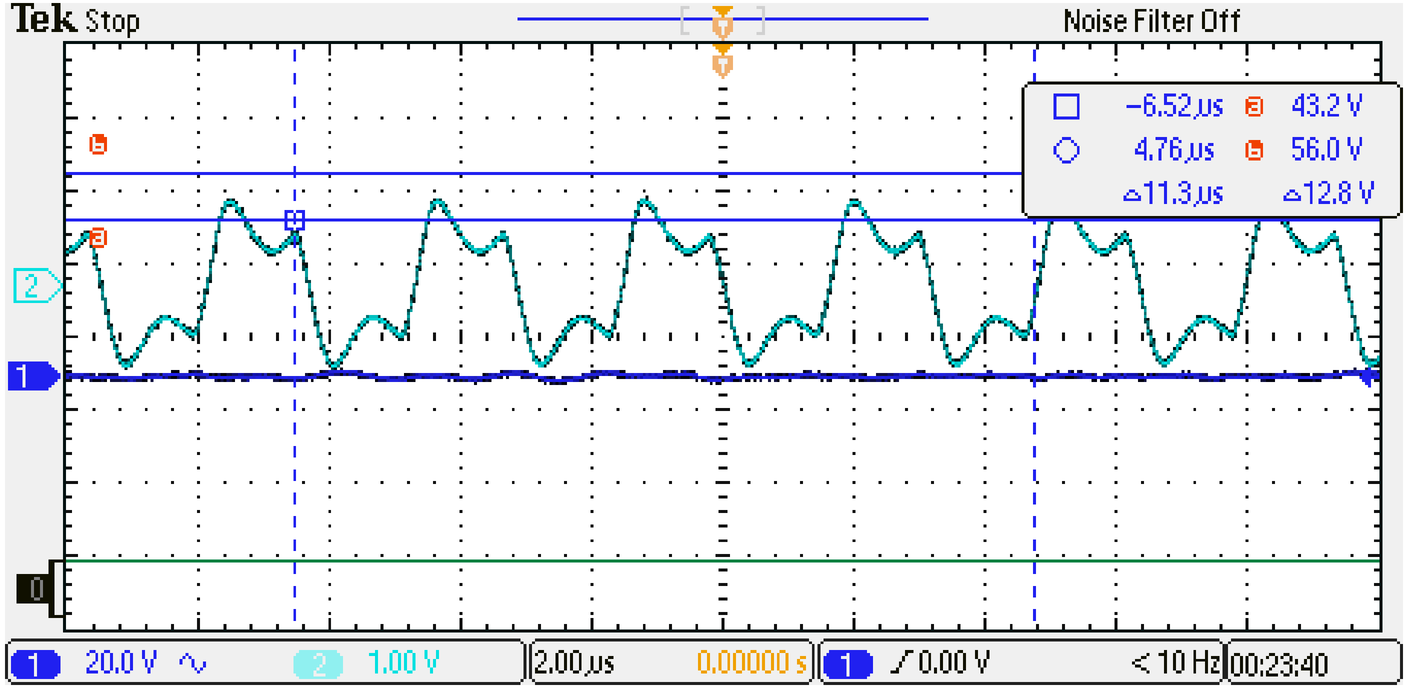
Testing and Prototyping- Audio

- Testing for the speaker to check the audio was plugging in an audio signal to the speaker and amplifier to check the loudness and clarity of the setup.
- Next was to hook it up to the DFPlayer to play the sounds on the MicroSD and then hooking it up with the entire project. All tests showed ideal amplification and clarity to sound.
- On the right is the setup of the amplifier and speaker in the project



Testing and Prototyping- Audio

- The amplification from the TPA3110 audio amplifier was seen on the oscilloscope.
- On the right shows the oscilloscope reading for the amplifier playing a constant note on the Dfplayer.
- The wave labeled 1 is the input to the amplifier and the wave labeled 2 is the output of it.



Problems and Solutions- TIA

Problem:

- Initially, Transimpedance Amplifier was outputting voltage not match expectation; huge spikes in voltage
- TIA tested separated from other components and in tandem; Stepper Motor caused interference

Solution:

- When Stepper Motor was disconnected from system; noise disappeared
- Stepper Motor and Driver were isolated and powered up with separate voltage supply

Problems and Solutions- Delay and Communication

Problem:

- Originally, single ESP32 was used for the harp; used to control every components
- Even when using both cores, ESP32 would cause delay, especially regarding the stepper motor and User Interface

Solution:

- Second MCU was added to the project; ATMEGA328 tasked with controlling the Stepper Motor and measuring TIA
- ESP32controls UI and plays notes for strings; both MCUs communicate via UART to pass information between each other.

Problems and Solutions- Stepper Motor and Driver

Problem:

- Motor driver overheating causing stepper motor to stops randomly; driver enters thermal shutdown.
- The stepper motor rotates more than the programmed number of steps, causing the mirror to pass the intended slit positions and sweep beyond the 35-step range. Even though the code specifies a set number of steps, the mechanical rotation does not match what is expected.

Solution:

- Lowered the current limit via Vref and added heatsinks
- Tuned Vref so the motor has enough torque to hit each step and stop without slipping.