Photonica – A Laser Harp Without Mechanical Strings

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***Abstract* — The Photonica Laser Harp replaces the mechanical strings of a traditional harp with laser beams that can be "plucked" by interrupting light paths. This instrument demonstrates the integration of optical sensing, analog signal processing, and embedded control in a compact, self-contained design. A single green laser diode is reflected by a rotating mirror to form multiple virtual strings that are detected by a photodiode–amplifier circuit and interpreted by a microcontroller. The system generates corresponding musical tones using an onboard audio module and amplifier. The project illustrates how interdisciplinary engineering, spanning photonics, electronics, and software, can be applied to create an interactive and educational instrument that bridges art and technology.**

***Index Terms* — amplifier, embedded systems, laser, optics, photodiode, processing, regulator**

I. Introduction

Traditional harps use tensioned strings that are large, delicate, and require regular tuning and maintenance to produce consistent sound. The Laser Harp offers a modern take on this classic instrument by replacing the strings with visible laser beams that can be "plucked" simply by moving a hand through them. This creates a contact-free and visually engaging way to make music, blending art, technology, and science. In addition to being an interactive instrument, the Laser Harp also serves as an educational tool that demonstrates how concepts from photonics, analog electronics, microcontroller programming, and system integration can come together in a single design. By combining these fields, the project showcases the capabilities of modern embedded systems in handling precise, real-time control within a compact and efficient platform. The main goal of the Laser Harp was to develop a frameless, self-contained, and portable device that detects beam interruptions and plays the correct note instantly. To achieve this, the system uses a single laser-photodiode pair synchronized with a rotating mirror to generate multiple virtual strings, which helps reduce cost and simplify alignment while keeping detection reliable. Design priorities focused on achieving good sensitivity, fast response time, stable power regulation, and safe operation within laser safety standards. The project was a collaborative effort between photonics, electrical, and computer engineering students, with each discipline contributing to optical design, circuit development, and software integration. Through simulation, breadboard testing, and PCB fabrication, each subsystem was refined to ensure performance and consistency. The final prototype demonstrates accurate optical detection, synchronized control, and a creative use of engineering to make music, showing how technology can make instruments both more expressive and accessible.

II. System Components

The system can be most effectively described through its key components that work together to form the complete instrument. This section provides a semi-technical overview of each subsystem and its function within the overall design.

A. Microcontroller

The inclusion of microcontrollers into the project is essential; it is what converts a collection of loosely connected components into a fully functioning laser harp. As alluded, the microcontrollers will be responsible for integrating the seperate subsystems of the project together. We will be using two separate microcontrollers responsible for separate tasks: an ATMEGA328, and an ESP-WROOM-32.

The ATMEGA328 is equipped with a clock speed of 20MHz, with 23 GPIO. The chip reliability is what is attractive for this project, as it will be tasked with simultaneously controlling the stepper motor, and detecting obstructions in the strings from the photodiode via the transimpedance amplifier. 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.

Our second microcontroller is an ESP-WROOM-32. This unit will be communicating with the ATMEGA, receiving information of which string has been played, and playing the corresponding note using the DFPlayer SD card module. It will also be tasked with user interfacing, adjusting volume levels, changing octaves and displaying information through an LCD Display. 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. These features can allow for a very responsive and functional system.

Using one microcontroller would require a more powerful and expensive chip due the memory draw that having a continuous quick stepper motor and continuous responsive note playing. To fix this, two microcontrollers can allow for the stepper motor to be always running while detecting user input, and the audio nor other features of the project won't be affected by other tasks.

B. Stepper Motor

The motion required to scan the laser across multiple positions is achieved using a NEMA 17 bipolar stepper motor. This motor was selected for its precision, torque reliability, and ease of control through digital pulses. It rotates a front-surface mirror that reflects the laser beam to form the fan of virtual strings. The motor operates at 12 V and provides 1.8° per full step, but by enabling microstepping, much finer angular resolution is achieved. This allows smoother and quieter motion, reducing vibration that could cause beam flicker or misalignment. A custom 3D-printed mirror mount was designed to couple the mirror to the motor shaft securely while keeping the overall weight low to minimize inertia. Several iterations were printed and tested to improve balance and rigidity. During testing, the stepper demonstrated stable, continuous operation for extended periods without losing alignment or generating noticeable noise. Its consistent performance ensured that the laser beams appeared evenly spaced and stationary, creating the visual illusion of real harp strings.

C. Motor Controller Driver

The stepper motor is driven by a DRV8825 microstepping driver that interfaces directly with the ESP32 microcontroller. The driver receives digital step and direction signals and translates them into precise current pulses for the motor's two phases. Current limiting was adjusted through an onboard potentiometer to 0.35 A per coil to prevent overheating. The DRV8825 supports up to 1/32 microstepping, which was selected to achieve the fine angular precision required for seven discrete beam positions. Protection features, including thermal shutdown and under-voltage lockout, ensure safe long-term operation. Decoupling capacitors and flyback diodes were added to the PCB to mitigate voltage spikes and electromagnetic interference.

D. Audio Subsystem

The audio system is one of the most essential parts of the Laser Harp, serving as a bridge between the user's physical interaction and the musical output produced by the instrument. In order to do this, we have selected the following components for the audio system of this project. The DFPlayer Mini, with quality sounds loaded on an SD card, will be the device that will be sending the audio signal to the rest of the audio system. This will be an audio amplifier to allow the speaker to make a louder and cleaner sound for the user. The amplifier selected for the audio subsystem is the TPA3110 Audio Amplifier, which is a class D amplifier that can reproduce a clean audio signal with minimal distortion and minimal power requirements. This amplifier we find to be effective in our project because of it informative documentation and compatibility with our audio system.

The amplifier will be amplifying the audio signal for the speaker, and the speaker we selected was the Dayton Audio RS100-4 4”. This speaker offers many qualities that are important for our project. It offers a volume that can be very audible and clean, almost as loud as a standard piano. The frequency range of this speaker also offers 80Hz – 20 KHz, which means it can relatively reach all the notes that we will want this product to produce, and with strong quality to the sound as well. The volume for the audio will be controlled by the user with a dial that will be connected to one of the microcontrollers. This dial will be a 10k pontentiometer and the microcontroller can adjust the volume based on the position of this dial.

In short, the Laser Harp's audio subsystem integrates digital playback, amplification, and speaker output into an effective arrangement. The DFPlayer Mini will provide audio playback and storage, the TPA3110 amplifier will amplify that signal while introducing minimal distortion, and the Dayton RS100-4 speaker will provide a full-bodied, clear sound over a wide range of frequencies. Together, these will make the Laser Harp functional and pleasing to listen to, adding an important dimension to the visual and interactive design of the instrument. Such is the well-thought combination of components that allows for reliable performance, expandability, and a quality sound system for the user.

E. Transimpedance Amplifer

Arguably, the most important part of the laser harp will be the transimpedance amplifier. This is because the TIA is tasked with detecting any disruption in the beams of light; detecting any reflection of the light strings from the hand of the user. This will indicate to the microcontrollers that a string has been played, oin turn playing a note corresponding to the specific string played. The amplifier is constructed using TL02 chips, and functions as a current-to-voltage converter. It will take current produce from the photodiode, converting it into a voltage, and amplifying it to a level that will be easily read by the microcontroller. It is important that the TIA has a low output impedance, ensuring that output voltage is sufficiently read by the microcontroller's Analog-to-Digital converters.

F. Optical System

The optical system is a very critical part of Photonica. A laser harp is nothing without a laser. To ensure the laser will be visible and easily playable, a laser diode that is the color green (520nm) was chosen. Also, to ensure playability, the beam needs to be wide enough for the user to block the beam with the playing tool. This ensures the user will accurately block the intended beam. The second most important part of the optical system is light detection. The light detection portion of the optical system consists of a collection lens and a photodiode.

III. SYSTEM CONCEPT

To understand the basic concept of Photonica see the diagrams below.

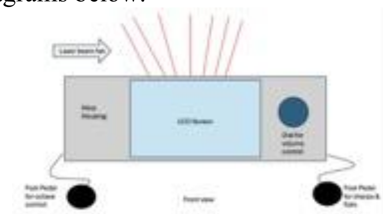

Fig. 1. Front view of Laser Harp system.

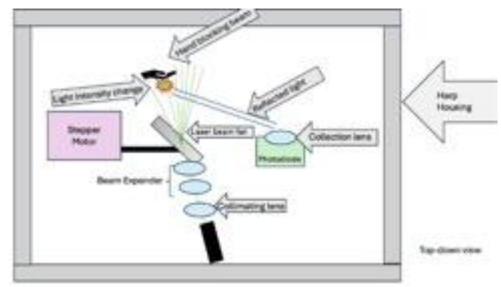

Fig. 2. Inside view of Laser Harp System

From the figures above you can see the basics of how the Laser Harp will work. The beam will come from the laser diode. The laser diode is driven by the laser driver, ensuring the laser gets reliably constant current, ensuring safe laser operation. The light will then get collimated, and then the beam will get expanded. After the desired beam is created, the beam will get reflected off a mirror. The mirror is attached to a stepper motor that is driven by a stepper driver and controlled by the first microcontroller, the ATMEGA328. On the top of the casing of laser harp, where all the components are stored in, there are seven open slits with some separation between each other. The stepper motor will turn back and forward, shining light through each slit. The motor will be turning back and forward with such a frequency that it will appear to the human eye as if seven individual strings are emanating from the instrument simultaneously. The desired beam is then blocked by a user, and the reflected light gets sent into the collection lens which focuses the light onto the photodiode. The photodiode is connected to a transimpedance amplifier, converting the current into a voltage that will be read by the first microcontroller. The microcontroller will note the position of the stepper motor at the moment when the photodiode detects a string being played, and determine which slight that position corresponds with. This information is sent to the second microcontroller, the ESP32, and the information received will play the note that corresponds with the string played. The note will be played by the audio module, the DFPlayer, controlled by the microcontroller, and played through our chosen speaker. This microcontroller will also be tasked with managing user interface and configuring the settings the user has input. Two foot switches will be used to increase and decrease the octave of the harp, a button will change the key, and a dial will be used to increase and decrease the volume of the harp. An LCD will display this information back to the user.

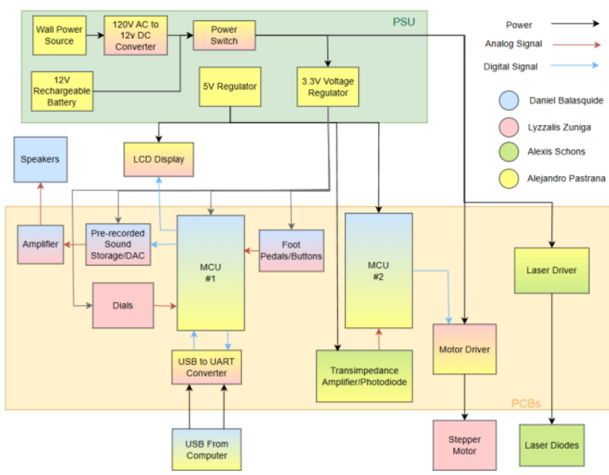

Fig.3 Hardware Block Diagram

IV. Hardware Details

A. *Optical Components*

Laser diode: to ensure the enough light will get reflected into the photodiode a 110mW laser at a wavelength of 520nm was chosen. This will not only ensure enough light reflection but also make it easier for the user to see the beam. Additionally, an LM317 regulator is used to create a constant current laser driver for the laser diode, ensuring that the laser is getting constant and stable current from its power source.

Photodiode: Some key factors when choosing a photodiode are the wavelength sensitivity and the size of the active region. Therefore, choosing a photodiode 520nm needed to be in the wavelength range. When playing the laser harp the reflected light will not always come from the same angle. To ensure the light always makes it into the photodiode we need a larger active area. The FDS100 was chosen because 520nm is in the wavelength range and it has an active area of 13.

Lens system: For this system, a collimating lens, beam expander, and collection lens are needed. Using equations 1 and 2 the focal length and numerical aperture for the collection lens was calculated.

For the beam expander, a Galilean design was chosen. The Galilean beam expander will allow for smaller distances between the lenses which is optimal for the portable design of the laser harp. To find the magnification and radius of the negative and positive lenses that create the beam expander, the following equations were used.

A collection lens is the same make up of a collimating lens, therefore equations 1 and 2 were also used for the collection lens calculations.

TABLE 1

Lens System Specifications

	Collima-ting Lens	Negative Lens	Positive Lens	Collection Lens
Focal Length	7.5 mm	-24mm	48mm	25.4mm
Lens Shape	Aspheric	Plano-Concave	Plano-Convex	Plano-Convex

B. *Photodetection and Amplification*

As previously discussed, photodetection is very important when implementing the instrument. The current produced by the photodiode when it detects the reflection from the strings being played will be comparatively very low, in the microamps level. The first goal would be to convert this small current into a comparatively larger voltage that can be effectively read by the microcontroller. A simple load resistor will not suffice, as the load resistor must be very large, in the megaohms range, way larger than the impedance of the microcontroller, causing current going into the microcontroller, causing a faulty reading from the photodiode. A transimpedance amplifier with a low output impedance will be needed to ensure a stable and large reading for the microcontroller. The photodiode will be reversed bias with a voltage of 3.3V. This increases the responsivity and sensitivity of the photodiode when detecting light. Using the transimpedance amplifier, the current will be converted into a voltage, linear relationship, where the voltage will be equal to the product of the output current and the feedback resistor used in the amplification circuit. The amplifier, the TL02, will then be used again to convert the output voltage, which is negative, into a positive voltage that can be read by the microcontroller. Additionally, if a second photodiode is needed, a single-rail operation amplifier, the OPA340, can be used to sum the voltages from both transimpedance amplifier, ensuring a larger physical range that light can be detected, and a larger range of voltage that can be used to detect the strings being played.

C. *Stepper Motor Assembly*

Beam scanning is achieved using a NEMA 17 bipolar stepper motor that rotates a front-surface mirror mounted directly to the shaft. The stepper was selected for its torque stability and fine angular control. It operates from a 12 V supply and provides 1.8° per full step; with microstepping enabled, this resolution increases to fractional degrees, resulting in smooth motion and minimal vibration. A lightweight, 3-D-printed mirror hub couples the mirror to the shaft and was optimized through several iterations to balance weight and stiffness. During continuous operation, the motor maintained stable alignment for over 30 minutes of runtime without noticeable drift. Proper motion control was essential for ensuring the beam reflections remained evenly spaced and visually stable for the user.

D. *Motor Driver Module*

The stepper motor is controlled by a DRV8825 microstepping driver connected to the ESP32 microcontroller. The driver translates logic-level step and direction signals into current pulses for the motor's two phases. Current limiting was calibrated to 0.35 A per coil using the onboard potentiometer, balancing torque and thermal performance. The DRV8825 provides up to 1⁄32 microstepping capability, which was used to achieve precise angular spacing between virtual strings. Additional decoupling capacitors were placed near the power pins to suppress switching noise, and flyback diodes were used to protect against back-EMF. The driver's integrated thermal and over-current protection allowed reliable operation even under continuous rotation during demonstrations.

E. *DFPlayer Mini Audio Module*

Audio generation is handled by the DFPlayer Mini, a compact MP3 decoder with an integrated DAC and serial interface. The module stores digital audio files on a 32GB micro-SD card and can play them directly through a UART connection from the ESP32. Each note on the harp corresponds to a pre-recorded file labeled and indexed for quick access. When the microcontroller detects a beam interruption, it sends a play command to the DFPlayer, which outputs the corresponding tone almost instantly. The simplicity of the DFPlayer allowed the design to remain lightweight without requiring complex external DAC circuitry. Its onboard volume control and reliable file indexing made it ideal for embedded musical playback applications.

F. *Power and Regulation*

In the instrument, there are many different components that require differing power needs, components that must function with specific voltage and current levels. It is important that these needs are met accordingly; this ensures that the components are able to function properly, safely, and for as long as possible. To meet every possible need, the base voltage level that the instrument will use will be 12V. This will be supplied by two possible needs, a rechargeable lithium-ion battery or a wall cable. These two can be interchangeable and will be chosen by the user and their needs. This 12V level will be used to power the stepper motor driver, laser driver, and any additional component that can be added like a fan to cool the components or an audio amplifier that can be used to augment the sound level. For the other components, two LM2576 regulators will be used to step the voltage down to a manageable level. This level will be 3.3V and 5V as these voltages will be used by all the rest of the components. Additionally, one LM2664 voltage converter will be used to supply –5V to the transimpedance amplifiers. A LM1117 is also used to supply a 3.3V reverse bias voltage for the photodiode, and one LM317 to be used as a constant current driver fot the laser diode.

G. *LCD Screen*

The LCD screen serves as the main user interface for the Laser Harp, providing real-time visual feedback to the player. A 128×64 I²C LCD module was chosen for its clarity, low power consumption, and ease of communication with the ESP32 microcontroller. The display shows key information such as the current octave, selected musical key, and volume level, ensuring the performer can make precise adjustments during use. Communication between the LCD and ESP32 is handled via the I²C protocol, which only requires two data lines (SDA and SCL), reducing wiring complexity within the enclosure. The LCD updates dynamically based on user inputs from the rotary volume dial and foot pedals. These inputs are read through the ESP32's analog and digital pins, processed in software, and translated into updated display values. The decision to use an I²C-based LCD instead of a parallel interface minimized pin usage and allowed better integration with the other peripherals running concurrently on the ESP32. The LCD backlight brightness was also tuned for indoor and low-light demonstrations to ensure visibility without excessive power draw. Overall, the display enhances user experience by providing a responsive and easy-to-read interface that complements the harp's optical and audio systems.

V. PCB Design

Besides the DFPlayer audio module, LCD display, stepper motor and the possible inclusion of an audio amplifier, all of the components will be implemented on PCB boards designed by the team. Most components mentioned above will be installed into their own sperate PCB boards. This ensures components are isolated into their own low-noise environment. It also ensures that if there is a fault in the design or construction of one of the boards, a full replacement will not be needed for the rest of the boards. The separate boards will be connected using wires, which will introduce some noise, but these will be maintained as short as possible to reduce noise to as small as possible. Board size was kept small, but still large enough to work with confortably.

VI. Software Detail

For software design this project will involve relatively basic iterative software architecture for the multiple peripherals of the project. This can be seen from the need to optimize both memory usage and processing power within the constraints of budget and typical microcontroller environments. The main format of it should be compatible with a dual microcontroller project.

Another reason for the simplicity, by choosing a lower level of coding language like C++ is because of efficiency. This coding language is powerful when it comes to its runtime. C++ gives software architecture an object oriented perspective which can allow for a more optimized and organized code. 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. So C++ will be used in the project. The development environment for will be Arduino because of it's versatility and simplicity in implementing embedded systems. Throughout the whole design process of the code, we will be debugging with a readable and thorough coding philosophy. Below is the basic diagram of the software design.

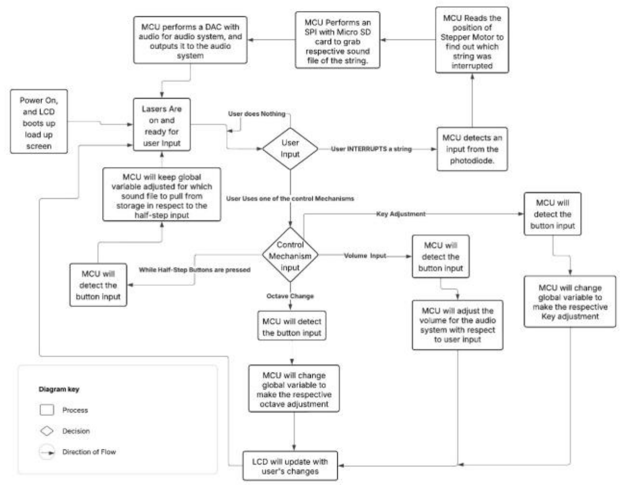

Fig.4 An In-Depth block diagram of software design

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. And to make sure everything is working smoothly and quickly, we will be using a two microcontroller system with synchronous tasks set up for the microcontrollers.

For the Arduino microcontroller of our project, it will be handling the stepper motor steps and photodiode detection of the project. The position, which will be the string that was detected, will then be communicated via UART to the ESP32 microcontroller. The esp32 microcontroller will be handling the communication input of the detected string to play the corresponding note of the string off the DFPlayer and audio system. The DFPlayer library that is provided on Arduino Can allow for us to change the volume and to access specific notes that will be stored on the micro-SD.

The ESP32 microcontroller will also handle all the controlling mechanisms, like volume, octave changer, Key change, and LCD updates. Because of the ESP32's dual core design it will have much more capability to run synchronous tasks. The LCD will be using an I2C communication between the microcontroller and the LCD screen. I2C communication is reliable but not the quickest, but for this communication it doesn't need to be quick, just reliable. The display does not require rapid data transfer, so reliability and simplicity take priority over speed in this case. This would be implemented into the ESP32 by using the LCD library that is provided on the Arduino Development environment. Through I2C, the LCD will receive updates such as the currently octave, key, or volume level, ensuring the user interface remains informative and responsive.

In addition to using UART for data communication between the two microcontrollers, we will be using it as well to run instructions on the DFPlayer, and then the DFPlayer will be running SPI between itself and the microSD module. This communication needs to be quick, so UART and SPI will be necessary for the project.

Overall, this software design features structured control logic, proper utilization of synchronized dual microcontrollers, and communication protocols in such a way that it functions smoothly. This can allow for entire product to accurately be interpreting input and deliver responsive, high-quality audio performance.

VII. Conclusion

The Photonica Laser Harp successfully demonstrates how modern engineering can merge photonics, electronics, and embedded control into an interactive and educational musical instrument. Through the integration of a 520 nm laser, precision optical detection, signal amplification, and real-time microcontroller processing, the system converts light interruptions into sound in a way that is both intuitive and visually engaging. The project required extensive collaboration across multiple engineering disciplines — from optical alignment and beam geometry to circuit design, PCB development, and firmware implementation. Each subsystem was carefully tested and refined to ensure stability, responsiveness, and user safety, resulting in a fully self-contained prototype capable of reliable performance during demonstrations.

Beyond its functionality, the Laser Harp serves as a clear example of how engineering principles can be applied creatively to enhance human interaction with technology. It bridges the gap between art and science by using precise engineering techniques to produce expressive, real-time feedback through light and sound. The experience gained from designing and implementing this system strengthened the team's understanding of hardware-software integration, system optimization, and interdisciplinary collaboration.

Future improvements may include expanding the harp's polyphonic capability using multiple photodiodes, adding wireless connectivity for MIDI output, and developing a more compact optical housing for increased durability and alignment stability. Ultimately, the project not only achieved its technical goals but also showcased how engineering design can transform traditional instruments into innovative, accessible, and inspiring forms of expression.

The Engineers

Daniel Balasquide: He is the Computer Engineer and Project Leader of the group. Responsible for developing and maintaining the firmware and software that bring the Laser Harp's subsystems together.

Alejandro Pastrana: He is one of the Electrical Engineers of the group. Responsible for designing the power supply, selecting appropriate voltage regulators and protection circuits, and the PCB and hardware design.

Alexis Schons: She is the Photonics engineer of the group. Responsibilities include selecting the appropriate laser diodes, photonics aspect of the project, and setting up photodiode detection array.

Lyzzalis Zuniga: She is the other Electrical Engineer of the group. Responsibilities include helping develop the custom PCB design, verification of connections between components, motor driver and stepper motor functionality with the project, and hardware assembly of the system.

References

[1] UCF Senior Design Project, *Expressive Laser Harp*, University of Central Florida, 2021.
[2] Texas Instruments, *OPA380 Low-Noise Transimpedance Amplifier Datasheet*, TI, 2022.
[3] DFRobot, "DFPlayer Mini MP3 Module Datasheet," Rev. 1.2, 2023.
[4] C. Poynton, "Persistence of Vision," *Journal of SMPTE*, vol. 102, no. 7, pp. 603–611, 1993.
[5] ANSI Z136.1 – *American National Standard for Safe Use of Lasers*, Laser Institute of America, 2020.