Laser Instrument

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***Abstract* – The Laser Instrument aims to provide a portable and cost-effective alternative to other generic instruments such as the electronic keyboard, and technique dependent instruments such as the violin or flute. This system can be used in educational settings to demonstrate the fundamentals of music or for personal use by all musical proficiencies. The system utilizes a laser diode and phototransistor configuration to replace physical keys used on electronic keyboards.**

***Index Terms* – Laser Diodes, Phototransistors, MIDI**

I. INTRODUCTION

Music can be one of the most influential aspects of many people's lives. The sound of music is so powerful that it can elicit many types of emotions. The history of music can be traced back to ancient times, and the evolution of music today reflects the enormous progressive development of this history. Music can be produced from a myriad of instruments or objects. The classical piano is a prime example of an instrument that has developed over many generations. In modern day, the piano can be seen in many different forms, such as a grand piano or electronic keyboard. Even with an instrument such as a piano that has evolved for many hundreds of years, there are people still inventing ways to create instruments that build upon this foundation. This project's goal is to further expand the foundation that current instruments provide.

The laser instrument is designed with the intention of making an instrument that is versatile and can appeal to a larger audience, whether that is by a favorable design or capabilities of the instrument. In this project, the instrument establishes a twist on modern electronic instruments by introducing laser diodes. The act of breaking a laser beam causes the musical note to be played through speakers on the instrument. This is a simple action which is good for listeners of all audiences. It makes playing the instrument much easier, in contrast to someone learning how to play a guitar, for example. In order to maintain a greater user experience, the instrument has a portable design such that the users could play the instrument in whichever environment they choose. The instrument also provides the users with a visual aide in the form of a graphical display. This would speed up the process of learning the instrument by corresponding the laser diodes to the notes that will be played via the display. Instead of taking the time to learn which note a string or key is, for example, the user will be able to play in real time and see which notes are being played.

Another feature to make this instrument different than a typical electronic instrument is the ability to connect to a mobile application via Bluetooth. The laser instrument has a Bluetooth interface that allows users to connect to an application which provides extra functionality that can enhance user experience without impeding on the physical design of the instrument. The main feature is the ability to record the music while the user plays the instrument and then playback the notes the user played. Recording software can be very expensive so having a mobile application that has the ability to record music could potentially save consumers money. Although there may be alternatives such as synthesizers, some of the alternatives can easily cost thousands of dollars. The laser instrument should be a nice variant that is less expensive to own, easy to play, portable enough to carry anywhere, and provide a fun aspect to the electronic instrument.

A. Use Cases

The laser instrument is expected to be applicable in both professional and casual settings alike. The learning curve for playing the instrument is no higher than the average electronic harp, and it meets many of the needs of professional users with high quality audio output, volume, portability, and adjustability. The engineers in this project are not considered musical professionals, and so the demonstration of the final product is most applicable to the casual community. This offers a more proof-of-concept demonstration rather than one of fully marketable quality.

II. CORE TECHNOLOGY

The core technologies utilized in this project are the two types of musical file types, MIDI (Musical Instrument Digital Interface) and .wav files, and the connection between the lasers and phototransistors.

A. Musical Instrument Digital Interface

One of the core technologies used in this project is a technical standard called Musical Instrument Digital Interface (MIDI). MIDI is not actually music, does not contain any sound, and does not function like a standard music file. MIDI is a set of instructions that describe the "communication protocol, digital interface, and electrical connectors" (Swift, 1997) that can be generated and read by a large variety of instruments and devices.

Recording music to a .MID file saves the list of instructions for another device to follow. As long as a device has synthesizer software, it can read the messages to know which key to play, the velocity at which it is played, and for how long. There are other optional pieces of information that can be stored such as key pressure, a change in a controller device (like a pedal or knob), or change in note pitch.

Within this project, MIDI is utilized to record what the user plays on the device by sending the MIDI files to the phone application to be saved. This allows for playback on the phone with minimal storage required to save the recording files. The files taking up the most space on the app will be looped note files that are used to recreate the instruments chosen for playback.

B. .wav Files and Note Looping

A common method of recreating instruments is using synthesizers, particularly from timers to re-create the wave functions of instruments and change frequencies and amplitude to change the note and volume. However, this method means that the device could only produce the instruments recreated through analog devices. These circuits would also have to go through manual manipulation to correctly synthesize instruments. Even after this implementation, the audio would not sound quite like the instrument. Instead, to allow for customization and additional instruments, the team chose to go with the method of looping recorded instrument notes.

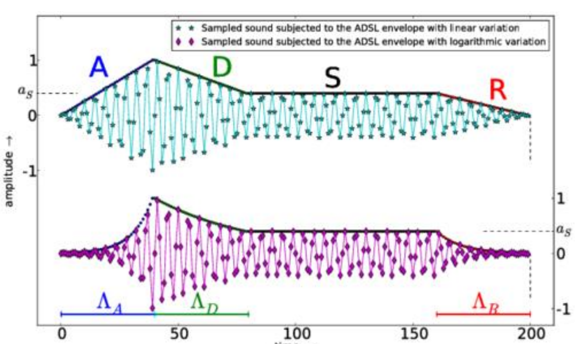

Figure 1 Attack, Decay, Sustain, Release (ADSR Envelope, 2019)

Initially for each note for each instrument, two different parts of the note were kept, the portion of sustain that was looped, and the initial attack and decay that was only played once at the beginning. Figure 1 shows the parts of notes when they are played at t = 0 until t = 150. The decay portion of notes were omitted from this project. These two pieces for each note were saved as .wav files that were read as chars by the MCU. Then they are played on the DAC output from the MCU out to the audio circuit. This choice allowed for the customization of the included instruments. Such customizations include changing the types of instruments and the octave ranges allowed.

After rigorous testing and review, each instrument available for playback with the laser instrument has been assigned its own method of playing or looping notes. For certain instruments the output sounds much clearer without looping and including all note portions. This includes the attack, decay, sustain, and release of each note in the available octave. This method applies to instruments like the piano and drumkit where typical usage would not include any looping. Other instruments still use the method that involves looping the sustain portion of a note that is described in the paragraph above. All of the files for each playback method are saved to an SD card read by the MCU.

C. Laser Diodes and Phototransistors

The secondary core technology utilized within this project is the method of mimicking keys with the usage of lasers. Red laser diodes emit light in the red spectral region with a wavelength ranging from about 625 nm to 700 nm. Hobby level red laser diodes typically come in wavelengths of 635 nm, 650 nm, and 670 nm. Shorter wavelengths overall provide easier visibility to the human eye but can potentially pose more difficulties when it comes to efficient generation of the laser (Paschotta, n.d.).

The team chose to use a small, red laser for the needs of the project. The 6 mm diameter, 18 mm length lasers are rated for about 5 mW for the 650 nm wavelength. Although most phototransistors are better in the green spectrum, these laser diodes work fine for this application. Chosen for the small size and being much cheaper than green, the red lasers give the flexibility for more notes at a reduced price.

To read the signals from the lasers, phototransistors with a flat-head design were chosen due to their ease of use and sensitivity of light. Phototransistors are an easier sensor to use compared to photodiodes because phototransistors do not require an additional component to amplify current output. A flat-head design was implemented because it allowed a larger receiving angle for light emitted onto the sensor, and this as a result consequently increased the accuracy of the instrument's sensor configuration.

III. SOFTWARE DESIGN

The software for this project is broken up into two main parts: the main device and the mobile application. The device is the main part of the project and is the portion of the project with the majority of the software. Being that the device is intended to be used without the app as well, the focus has been the integration and testing of what was written for the components of the instrument. The laser instrument uses an ESP32-WROOM-32-D for the MCU because of its memory size and the included Bluetooth features. With the device's popularity, the team was able to purchase chip development kits and develop code separately on the different subsystems. The MCU software was developed within the Arduino IDE using C/C++, and the application code was developed within Android Studio using Java.

A. Main Device Software

The main instrument's software is four different portions that have been worked on by separate members of the team. These four subsystems are the sensor configurations containing the lasers and phototransistors, the Bluetooth connectivity, the LCD screen, and the audio subsystem with the SD card. The software itself works as shown in Figure 2.

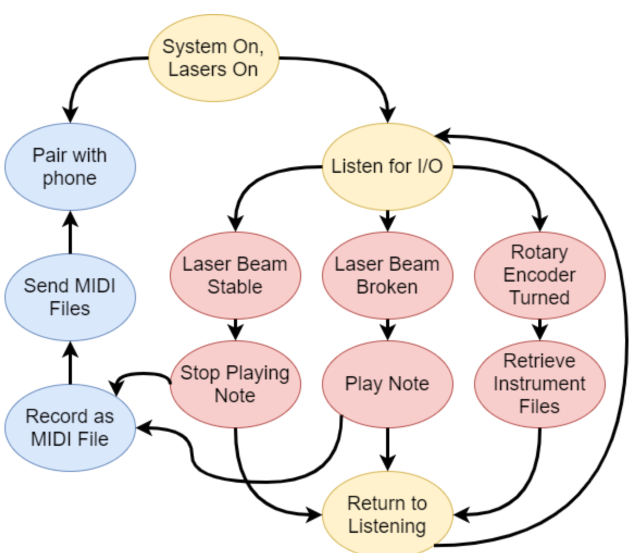

Figure 2 Physical Device Logical Flow

The lasers and phototransistors are key components to the operation of the laser instrument. When the laser beam between a laser diode and a phototransistor is broken, a key is "pressed", and when a phototransistor begins to receive light emitted from a laser diode or has a stable connection, the key is then "released". The code of this subsystem revolves around the MCU reading the voltage change from the phototransistors as they receive light beams emitted from the laser diodes or the beams are blocked.

In regard to Bluetooth, the instrument uses Bluetooth Low Energy to preserve power from the LiPo battery. The instrument itself acts as peripheral device which advertises itself for a central device, or the mobile application, to connect. The mobile application will connect to the instrument and the instrument utilizes the information from the lasers and phototransistors to transmit MIDI data. This portion of code handles the handshake with the connecting phone and maintains that connection.

The LCD screen is used as a tool for notifying the user what instrument is being used and which note is being played. To minimize GPIO pins usage of the MCU, the LCD receives its instructions using an I2C interface that acts as a midpoint between the MCU and the LCD. The I2C interface reduces the pin count for the MCU from 16 to only 4. The LCD changes when notes are played using the lasers, to display the key name as a music symbol. When the instrument type changes because the rotary encoder was turned or pressed, then the LCD displays the name of the newly selected instrument.

The last major subsystem is the audio system. Each of the music files are stored on the SD card. Each instrument setting has its own group of associated notes so that the laser instrument can differentiate between flute, trumpet, percussion, piano, and violin. These instruments were the ones selected by the team behind this project but are interchangeable to allow for user customization. When a note is played, the MCU retrieves the loop portion that is played over and over until the note is released. The note is played by using the DAC pin that is part of the ESP32 out to an audio amplifier. From there, using a potentiometer to control volume, the audio is sent to the speakers, located in the front of the device to play towards the user.

When the device is turned on using the power switch on the side of the frame, the ESP32 turns on along with all other components directly connected to power. The ESP32 will try to pair with a phone if it can. Startup will then have the device load an instrument to be ready to play for the user. The default startup instrument is a piano. From there, the device will listen to input from the user. The three types of input are a beam is broken between a laser diode and phototransistor, a beam is emitted from a laser diode to a phototransistor, or the rotary encoder is turned.

If the beam connection between a laser diode and a phototransistor pair is broken, then a note is played by retrieving the file from the SD card and playing it through the audio circuit. This begins a loop of the file that will continue to play until the beam is regained between the laser and the phototransistor. The resulting MIDI message is created which takes into account the "time" the note was played and the note itself. If connected to a mobile device, the message is sent via Bluetooth. The device then listens for the next input.

If the beam connection between a pair of a laser diode and phototransistor is a solid connection, then the looping note being played is stopped. The stop is recorded by a timestamped MIDI message that is sent to a connected phone if applicable. The device goes to a listening state for the next input.

Finally, the last possible input from the user is from rotating the rotary encoder. This changes the instrument type to be played by the instrument. The display will also change to show the current instrument chosen. Once the rotary encoder stops moving, the instrument continues to listen for the next input.

C. Application Software

The mobile application is a supplemental aspect of this project and is not needed in order to operate the laser instrument as intended. However, it is meant to be used to enhance the user experience further than the standalone laser instrument by allowing the user to record the notes they play.

The application has been designed in a way that is easily navigable and which maximizes the functionality in conjunction with the laser instrument. The primary functions of the application are to connect to the instrument via Bluetooth and to view, edit, or play past recordings. An active connection to the instrument is not required in order to access all functions related to past recordings, and the connection is only used to create more recordings for use in these functions.

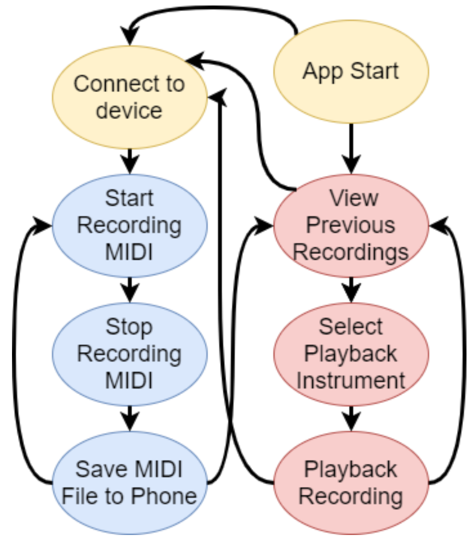

Figure 3 Mobile Application Logical Flow

The information retrieved from the laser instrument is not actual audio, but it is a standard audio instruction set in MIDI format (Swift, 1997). The average user's mobile device is expected to contain synthesizer capabilities, and the engineers in this group were therefore able to rely on these devices to generate the audio recorded from the instrument. While the audio generated by the laser instrument and the audio generated by an average mobile device may be different, they are similar enough to be recognized. A user with this application is able to alter the properties of the notes in a past recording such as instrument type. The laser instrument has the audio files that are accessed by the MIDI instructions, and an average mobile device has even more audio synthesizing capabilities. Then all of the recorded instructions, edited or not, can be played back by the user's mobile device or saved separately. These functions are the core of the application's software in this project. The connection to the physical device via Bluetooth provides access to more recorded instructions that can be used by the core functionality.

IV. HARDWARE DESIGN

The internal hardware and frame had extensive research and design done to find products that were inexpensive and safe for consumers in order to create a device meant to be cheap and available to the public.

A. Electrical Components

The electrical design for the system was based on four main needs for power: the ESP32 chip, the LCD screen, the laser diodes and the audio system. Only two different voltages were needed for this system: a 3.3V rail and a 5V rail. Between the battery and the voltage regulators located on the board, a single throw, single pole switch was placed as the systems main on/off switch to preserve power and act as an emergency off switch.

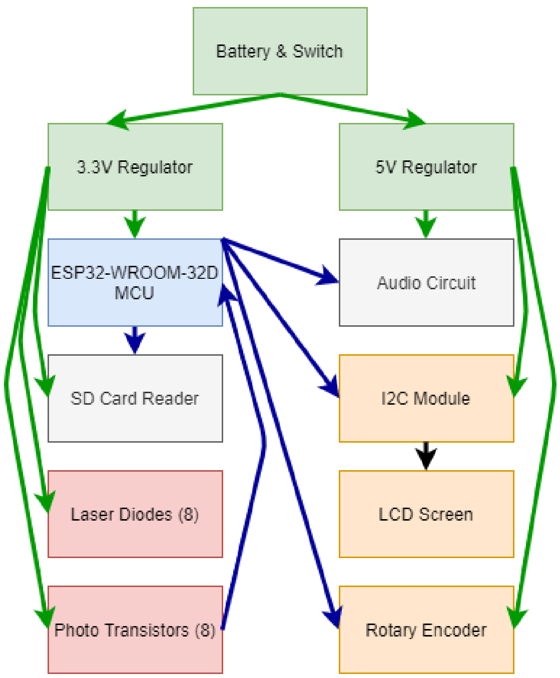

Figure 4 Block Diagram with Power Needs

On the board, the power was sent to the two STMicoelectronics LDO Voltage regulators. Both with a maximum of .8 A, one regulator output 5V, the other output 3.3V. Devices using the 3.3V regulator are: the ESP32 chip, the SD card reader breakout board, and the phototransistors. There are two devices using the 5V regulator: the audio amplifier and the I2C interface that talks to and powers the LCD. The overall system is shown in Figure 4 above as both power needs and the communication between the devices. The green arrows represent power distribution from the battery to the device. The blue arrows represent the communication between the ESP32 and the different devices, as well as the direction the communication occurs.

With a requirement to be portable, rechargeable batteries were a necessity for this project. The battery also needed to handle 1 Ampere hour to satisfy the requirement of an hour of instrument play. To handle the needs of the components, the required time to play, and the capability for recharging, a 7.4V Lithium Polymer battery was chosen. It offered a charge of 1600 mA/h, and up to 3000 charge cycles, making it perfect for a device with portability and reuse in mind. Considering the laser diodes needed about 100 mA, the ESP32 needed up to about 400 mA, and the LCD needed about 130 mA, the battery gave the device the possibility for more than the hour minimum play time before a recharge would be required. If the device is not connected to Bluetooth, the laser instrument could run for much longer, possibly 2 hours.

To maintain an order and uniformity, two different daughter boards were created for the needs of the project, as can be seen in Figure 5. The first board, shown on the left of the image, is for the laser diodes. To achieve some stretch goals, the design includes a MOSFET that would control turning individual lasers on and off without using power from the board. Although no longer necessary, this was included in the daughter boards, along with a resistor, and holes for the 3.3V rail, ground, and the laser diodes themselves. These small boards were only 0.99 x 0.80 inch.

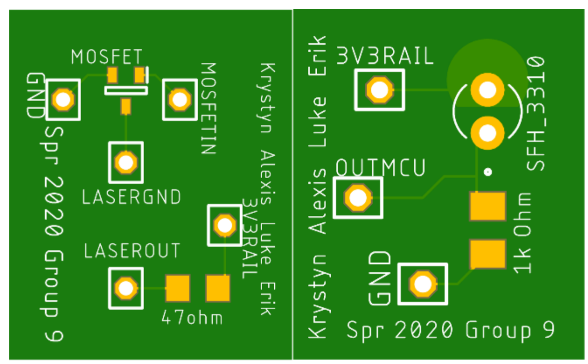

Figure 5 Daughter Boards for the laser diodes and phototransistors, respectively

The board created for the phototransistors has space for the phototransistor, a necessary resistor, and three holes: 3.3V, Ground and the signal out to the MCU. These boards were only 0.69 x 0.82 inches. Both daughter boards were originally designed a little larger but redesigned to remove blank space to significantly reduce the price of manufacturing. But due to COVID19, the team ordered from OSH Park which charged by size of the board. Given the uniformity of these boards, the team was able to mount these more effectively to the frame than individual laser diodes and phototransistors. Long boards with all the components spaced evenly were considered, but the spacing between lasers was not decided as well as the number of boards. The small boards gave the team many more options, although the decision required more wiring.

The main motherboard, seen in Figure 7, exists mainly for power out to components and the connections from the ESP32 chip out to the components. These connections are completed in two different ways. The large rectangles are for terminals broken up into groups of 8. The terminals are spring tension which allow for easier changes than connections that are screwed in. The other connections are made with header pins or by simply soldering wires to the holes where the headers would go. The headers were helpful for attaching the SD card breakout board to the motherboard. The back of the PCB is a ground plane, helpful for maintaining a consistent ground for all components. The board also needed to be sized to fit within the bottom portion of the device, only allowing for a maximum of about 4 inches in any direction.

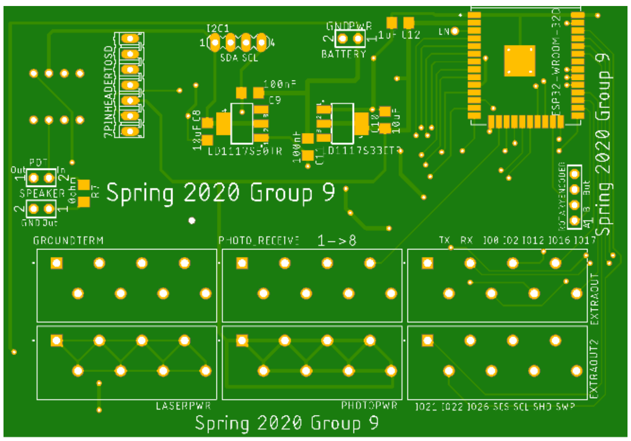

Figure 6 Front of the Motherboard

Although an audio circuit was created on the back of the board, it underperformed in comparison to the Adafruit Class D Audio Amplifier. The motherboard amplifier has been bypassed to use the Adafruit amplifier instead. As a secondary major change, the board was made with one more regulator, a 3.45V regulator, for the laser diodes. This was because the regulator had been purchased before all research was completed, but the team planned to use it. Due to a technical error with the footprint, the 3.45V regulator was not included and the laser diodes receive power from the 3.3V regulator using wires on the back to extend the power traces to the phototransistors. This "green wire modification" did not affect the project too dramatically, the laser diodes were dimmer than planned, but the lasers could still be registered by the phototransistors. Had the laser diode boards not been developed and printed first, the resistor on the board would have been changed to compensate for the voltage change.

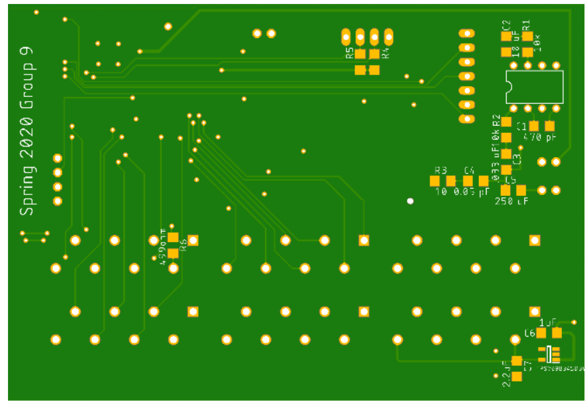

Figure 7 Back of the Motherboard

B. Physical Frame

To be able to properly give users an accessible design to the lasers but minimize possible injury from lasers, a few different models for the frame were created. The final design was laser cut from acrylic to save the time and cost of 3D printing. The overall shape is a rectangular prism with a cutout for playing space within the frame as can be seen in Figure 8. The frame holds the laser diodes above the cutout area, and the phototransistors are placed under the bottom of the cutout, directly under the laser diodes.

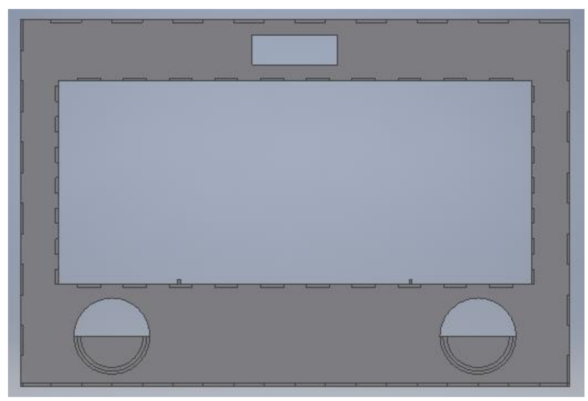

Figure 8 Front of the Frame

The frame has supports for where the phototransistors sit under. This prevents the weight of player's hands from putting too much load on the frame. The supports are the two vertical back pieces. There are supports for the two speakers behind the cutouts for the speakers at the bottom of the frame. The speaker supports were added to help hold the heavy magnets used in creating a better sound within the speakers compared to smaller, cheaper speakers. Also placed in the front is a rectangular cutout for placing the LCD for the user to view which note is being played by the user. Intentionally placed at the top, the LCD is not blocked by the user's hands while being played.

Finally, on the bottom also sits a holder to prevent the main PCB from moving, with clearance for the ESP32 antenna. On one side of the frame, there is space for the power switch to be pushed into place. On the other side is space for both the rotary encoder for instrument selection and the potentiometer that controls the volume. The frame was designed in AutoCAD Inventor with the intention of being 3D printed because the resulting frame would not have had sharp edges and would have had a more professional than the clear dovetailed acrylic. A 3D printed frame would have also been lighter and had the ability to better secure all the PCBs. Furthermore, the print material would absorb light better than the clear acrylic, which reflects and refracts the light. Unfortunately, due to COVID19, the team didn't have the time or resources to print a final frame.

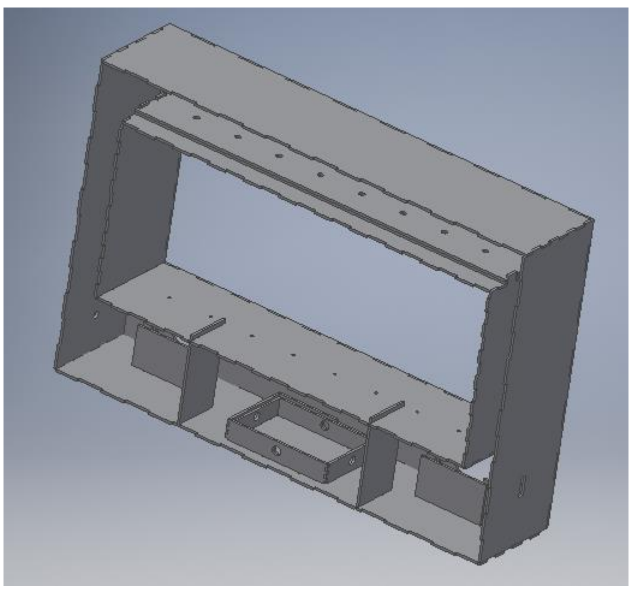

Figure 9 Back of the Frame

The device is 18 inches wide, 12 inches tall, and 4 inches deep. The width size allows for a wide playing space and adequate spacing between lasers for different hand sizes. The height provides space for potential future versions to support multiple octaves, but ultimately it is for user comfort and to allow spacing for the tall LCD screen and speakers. The frame's depth allows for a heavier base and space for all components, particularly the motherboard. Moreover, the depth allows for a sturdier bottom to prevent a likelihood of the device falling over. The final prototype also has a back piece that snaps into place similar to the front to prevent harm to the user. This was intended to be demonstrated when the device was displayed during the senior device showcase.

V. COMMUNICATION

There were a variety of methods used in communicating to the different components within the project. Bluetooth was used in communicating between the ESP32 and a mobile phone, SPI between the SD Card and the MCU, and I2C between the MCU and the LCD.

A. Bluetooth and Bluetooth Low Energy

Due to wanting to connect the device to a phone, the team investigated several Bluetooth communication modules and MCUs before deciding on the ESP32 module. The ESP32 offered its own antenna and internal Bluetooth capabilities. Running Bluetooth v4.2, the module would be able to communicate from a reasonable distance and allow the possibility of Bluetooth Low Energy, or BLE.

The team decided on using Bluetooth Low Energy. To define the components, the ESP32 acted as a peripheral device waited to be connected with and a server where data can be read or written. The mobile application acted as the central device that connects to a peripheral and a client that reads or writes to the server. When connected, the mobile app reads data from the instrument and compiles the MIDI file.

B. Serial Peripheral Interface (SPI)

In order to give the device plenty of memory for music files, an SD card was chosen. To read the SD card, the ESP32 communicated to the card using SPI, a synchronized serial communication protocol. The ESP32 was master for this case, communicating to the single slave device with SCLK, SS, MISO and MOSI lines. The SCLK line is to synchronize communication to the main clock generated by the master. Even with only one device, the SS, or Slave Select line, is necessary to select and enable the device that the MCU is talking to. The MISO, or Master In Slave Out, is the communication from the SD card to the MCU. The MOSI, or Master Out Slave In, is what the MCU communicates to the SD card. This interface allowed for the MCU to fetch a music file from the SD card to then read and play the file in real time. Playing files was a requirement of the project, and with the speed and compact size of the SD card, the device could hold many more notes and instrument types than 5 instruments with 8 natural notes.

C. Inter-Integrated Circuit (I2C)

To reduce the connections between the LCD and the MCU, an I2C interface was used to reduce the total number of connections out from the MCU from 16 to 2. I2C is a protocol is a bi-directional synchronized protocol with the ability to have multiple master devices and multiple slave devices. Utilizing only two lines of communication, the Serial Data Line, or SDA, and the Serial Clock Line, or SCL, the devices can talk at speeds of 100 kbit/s. This option was perfect for quickly changing the LCD screen to show what notes are being played by the user at the correct time.

VI. CONCLUSION

Overall, the project in its completion accomplished the main goal: a portable device that uses lasers to replicate other instruments. As a reflection of the applicability in both a casual and professional case, the device offers the 8 natural notes for an octave rather than all 13 notes with accidentals. The standalone laser instrument has features that allow the user to customize the audio output with instrument selection, note selection, and volume. It offers a display on the front that shows the selected instrument and the current note being played. The device is mobile with a lightweight design and adequate battery life for extended use. As an addition to the primary focus of the project, the laser instrument is accompanied by a mobile application that allows notes to be recorded.

VII. BIOGRAPHY

Krystyn Wikoff is a Computer Engineering Student. Within the project, her primary roles were designing the 3D models, mechanical design, and electrical design, including the design for the PCB. She plans to pursue a masters while working after graduation at L3Harris as a Software Integration & Test Engineer.

Alexis Lamb is a Computer Engineering student. Her roles for the project focused on the sensor configuration of the instrument, the integration of all components, firmware of the instrument, and assistance with the frame and mobile application. She plans to continue working with Lockheed Martin in the Engineering Leadership Development Program after graduation while pursing her masters degree.

Erik Lim is a Computer Engineering student. For this project, he was in charge of the power subsystem, graphical user interface, and implemention of Bluetooth Low Energy communication. He also assisted with electrical design and mobile application.

Luke Hazelton is a Computer Engineering student. His roles in the project included mobile application design, audio file editing, and assistance with frame and PCB design. His plan after graduation is to work as a Software Computer Tools Engineer with CAE. This is a transition to a full-time position from his current co-op position.

ACKNOWLEDGEMENT

The engineers would like to express their gratitude to FamiLAB Makerspace for allowing the team to cut their final prototype frame from acrylic on the lab's laser cutter.

The engineers would also like to acknowledge Dr. Samuel Richie and Dr. Lei Wei for their assistance, support and guidance.

The engineers would like to thank the faculty review team for offering their time and expertise for the final examination of this project.

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