Senior Design 2

Laser Musical Instrument

Figure 1: Cover Image [1]

{copyrighted image and design by Glenn J. Hill of Laser Harps LLC /Mountain Glen Harps LLC}

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1. Executive Summary

Throughout human history, music has been a vital part of self-expression. From joyful to sorrowful, momentary to reflective, or solo to communal, music has expressed a wide range of our emotions and thoughts. To do so, the main vehicle for music has been the instrument. As new music evolves so too does the instrument. Being musicians, our team wanted to delve into this concept by doing a laser instrument. Our Senior Design is a chance for us to explore the merge of light with sound.

With feasibility and entertainment in mind, the laser musical instrument consists of lasers diodes, photodetectors, a microcontroller, a speaker, and a power supply. The instrument will have the laser beams act as strings. Each laser will emit to a photodetector that will act as an on/off switch to initiate the emission of sound for that string. The sound is on when a user interrupts the beam and it is off when the beam is not interrupted. The reflections of light will go to second photodetector that determines what note to play out of a range of predetermined notes for that particular string. All of this will be processed by a microcontroller that will sort and assign a note to the incoming signals from the photodetectors. Those notes will be sent to a speaker that will be able to amplify the electrical signal from the microcontroller and convert it into an audible sound.

This report documents the design process for the laser musical instrument. It starts off by presenting the project motivation. Then it goes over the goals and objectives set to be accomplished by our instrument. After that there is a comparison of existing products and design. The requirements and specifications are then shown to see what a user could expect from our instrument with the engineering feasibility of meeting those expectations. Next are constraints that deal with health and safety, economics and time, societal concerns, environmental issues, and manufacturability and sustainability. There are also standards that are given to ensure the necessary steps and procedures are conducted in order to have a safe operation of the instrument. The primary standards this report focuses on are for lasers and battery safety. Block diagrams, schematics, flowcharts, music theory, code logic, necessary design parameters, component comparisons, and chosen parts are expressed in research and design sections of the document. The report will describe in detail the design for the hardware and software portions of the instrument. It would include the implementation of the components and concepts in the device as well as how the different parts and processes of the instrument will work together. After that there is the prototyping and testing of the device in which a single string will be tested to achieve sound and a range of notes. From there the single string can be replicated to multiple beam that each have a different range of notes. Lastly, there is an administrative portion that describes the milestones, overall budget of the project, the tasks the team members are responsible for, and the trade–off between users' predicted needs to the engineering feasibility of said needs.

2. Project Narrative

2.1. Project Motivation

Music is one of the oldest and most fundamental ways to showcase human expression and creativity. It reaches deep into the human mind pulling on feelings, memories, and dreams. It is for this reason that for thousands of year's mankind has been making music with no end. All music that is created requires two things, the musician and the instrument. As time has progressed so has the sounds of music. Part of the reason for the change in sounds is because new instruments have emerged from musicians chasing new sounds and means to express themselves. These new means of expressions also change the experience for any listener of the music. It is for this reason that we have chosen for our project to explore a fairly new type of instrument – laser instruments. From hobbyists who have created laser guitars to professional musicians who use laser harps in their concerts [2], the interest in using light – particularly lasers – as a median to create music has grown. Providing both a visual and auditory stimulation unique to its design, laser instruments captivate audiences in a fascinating way through its detection system. Our project seeks to engage music from an engineering perspective that is novel, feasible, and entertaining.

The goal for our laser instrument is to be able to produce a range of sounds, create an audio/visual experience, and be inexpensive while keeping the instrument versatile. A challenge for all electronic based musical instruments is the replication of natural acoustic harmonics. For our case it is where a string is plucked and vibrates emitting a decaying resonance after the string has been plucked. Another challenge that has appealed for us to take on is to implement a means for a musician to create vibrato variations in the pitch of the notes. Traditionally this is done on a string instrument by using one hand to lightly vibrate the string while the other plucks the string or vibrates the string by means of a tool such as a bow. On top of that it would be interesting to implement a detection system to determine how loud a note is to be played, that would signal the microcontroller to alter the decibels of the output signal. This it to replicate how hitting a sting harder creates a louder sound.

By combining these sounds with the visuals appeal of laser beams, the user can feel as if they are controlling sound with light. The observer can feel as if they can see sound. These sensations are unique to this type of musical instrument as the senses of sight and hearing are merged into one incredible experience. For this instrument to have significant impact on a sizeable amount of people the costs will have to be reasonably inexpensive. By keeping the price as affordable as possible, the average music consumer can enjoy the excitement of having a laser instrument in their home or studio.

Key functions for this to happen are being able to have an intensity detection system, a soundboard to appropriate each laser beam with a specific sound and having a sufficiently audible system. There are several ways to detect how a broken laser beam can correspond to a sound. First is to have the lasers pointed at a photosensor across from it. Once the laser's beam is interrupted the system will trigger the microcontroller to produce a pre-programed note to send to the output speaker. This will be a primary or alpha interruption for the system. Once an alpha interruption is detected the system will engage an intensity detection system located near the source of the lasers. This will be our beta detection. This will measure the intensity of light being reflected back toward the emitting end of the laser. The closer a hand is to the base the more intense the reflection of light will be. This variable intensity allows us to give more variability to the output sound produced. For example, higher reflection intensities could give off higher volume or higher pitches than a lower reflection intensity would.

To make this a reality a microcontroller can be used to create a soundboard. The role of the soundboard is to take the incoming signals from the detection system and interpret what sound to allocate to each broken beam. With this sorting mechanism, variability in sound can be achieved since a constantly changing live-feed of intensity signals can provide new information to emit new sounds. To prevent the reflections of one beam from triggering the intensity detection of another beam, a turn-on detector can be placed where the beam is incident. When the beam is broken, the turn-on detector can send a signal to the soundboard that a specific beam is ready to emit a sound and the soundboard will determine what sound to allocate to that beam. If reflections hit another beam's intensity detector that has not been broken, the soundboard will read that the turn-on detector is off and would not emit a sound to it. In the end what is heard is only possible with the use of a speaker. The speaker will receive the sound determined by the soundboard and audibly emit it. The challenge for using the speaker will be ensuring that the respective sounds are emitted correctly and that they are appropriately audible to the human ear. By controlling the behavior of the circuitry, we believe we can achieve the audio amplification needed.

The project will start with the building and testing of a single string prototype during the first semester. This single string prototype will also serve the purpose for any preliminary demos. This is because once a single has been perfected all the other strings will be replications of the original. The purpose of starting the building and testing of a single string is to better select components for the final build and gaining a better understanding of what is feasible for the instrument to contain in its final prototype. This single string build serve as a controlled system that can be used for all testing before adding to the instrument itself. This is to help protect our prototype during testing so that we can minimize any damage to hardware that can arise from testing procedures.

The laser instrument is intended to provide an interesting and new way of approaching music. While there are many challenges to overcome, there is great potential to engineer light to do wonderful things. To hear light as a range of sounds as it is being played in real-time and at a reasonable price would be an achievement for us. The world of light is coming, and it can be heard.

2.2. Goals and Objectives

Our goal in this project is to create a new kind of musical instrument that is interactive, immersive, and entertaining to play and watch. This new kind of musical instrument will use lasers and detectors as its medium to create tones meaning you do not have to feel or see the instrument to play. There are very few instruments that exist that can be played without the physical perception of touch by the musician.

The instrument should be technologically complex and advance while maintaining a simple appearance and use. The instrument needs to be more than just technologically appealing in its hardware but also appealing to its audio capabilities since after all it is an instrument. This means that each member of the team will need to build an understanding of musical aspects. This will help us create an instrument that better reaches out to a possible target audience.

An objective for this project is to display each team member’s abilities and understanding of electrical and optical engineering. Each team member shall receive valuable experience in the engineering practice of designing and testing while working on a team. The knowledge and experience gained throughout the time spent working on the project shall be at an in-depth level that it can be applied to future professional goals.

We have broken down our major goals for the project down into primary, secondary, and stretch goals. They can be seen in table 1 below. We have limited our goals to three categories with three goals under each category to keep the project realistically viable in our given time period. These goals focus around marketable features we want the instrument to have.

Table 1: Goal Set

Goals		
Primary Goals	*Secondary Goals*	*Stretch Goals*
Intensity detection to determine how loud to make a note	Replication of a vibrato sound	The ability to change the note tuning for each laser
Intensity detection for variability in pitches	Laser beam to be visible	Replicate the feel of playing a real string instrument
To be played from a table top or stand	Protection circuit design for reverse voltage and overcurrent	Replication of sound decay that occurs when a string is plucked

If given more time to work on the designing and testing of the instrument there are lot of features, we would like to add to the instrument. One such feature would be the integration of MIDI communication so that the tones produced can be altered in real time. Another extended goal to be to make the instrument more astatically appealing to increase its ability to entertain an audience. These extended goals and others remain outside a reasonable scope of the project because of the time and team member skill set constraints. For this reason and because the list is extensive, we have excluded from listing them in this report.

2.3. Existing Products and Designs

There are about three major categories for light sensing musical instruments that can be found on the market currently. Professional instruments, simple projects you do yourself, and kits you can order from overseas that typically require lots of soldering work. The professional products work well but they are few and have large costs to go with them that can easily be in the thousands of dollars. The simple projects can potentially be of good quality but depend on your skill set and the components you use. They are attractive because they typically low-cost and give you some in-depth understanding of the instrument. Then the kits are commonly the lowest cost option where they can be less than five US dollars from an online vender.

Two specific light sensing instruments that have similar concepts are the laser harp, which can be framed or frameless, and the optical Theremin. Our design is to work to combine the framed laser harp and the optical Theremin to create a new instrument. There are also projects that work off of similar concepts, some of which do not have a name.

2.3.1. Laser Harps

As mentioned before there are two designs for laser harps framed and frameless. While the function and purpose for these instruments are similar, they have major variations in their designs and how they work. A framed laser harp has a surrounding body that houses the lasers and their detector circuits. The lasers continuously shine onto photodetectors that will detect when the laser is blocked. They are simpler in concept and design than a frameless laser harp. Frameless designs typically only have a single laser with a high-speed rotating lens to deflect the laser in different directions. Broad framed cameras are used to detect when a beam is interrupted. With a high enough frame rate on a camera it can be seen that the beams are not continuous. This design is more complex than the framed design because video detection software is needed instead of a simple photo detection circuit. Frameless laser harps are mostly used in professional laser shows because the instrument is visibly large as how far the lasers shine which provides for greater entertainment.

2.3.2. Optical Theremins

Optical Theremins are designed to replicate the musical instrument Theremin, where a person’s capacitance with two antennas is used to create sound. A person hovers one hand over each antenna, where the distance from one antenna controls the pitch and the other controls the volume. An optical Theremin replaces the two antennae with optical sensors that detect the variation of light by a person moving their hand over the sensor in a similar fashion someone would with a Theremin. Optical Theremins are much cheaper and simpler to design and build than a Theremin because they do not need a powerful amplifier to generate sound. Both can come in either a single antenna or single sensor design that only allows for variation in the pitch. There are also simple affordable kits for optical Theremins just like there are for laser harps.

2.3.3. Simple Projects and Kits

There are an abundant of simple projects for musical instruments that depend on light detection. Many are unique in their own way but nearly all of them only require using a breadboard, microcontroller and provide any coding for you. The advantage these projects have are their low costs and simplicity. The downfall of these kind of projects are the program is typically sloppy and has errors and they are of hobbyist complexity and therefore lack professionalism. Many of the projects can be done within a day or few.

There are also kits that can be found online for less than five dollars for both framed laser harps and optical Theremins. These kits have done all the design work for you. They mostly come with instructions in a foreign language and cheap components they may be recycled from somewhere else. When you receive a kit all the components are in the same bag so leads tend to be bent out of shape or broken. Then there is lots of assembly required with lots of soldering to the PCB it comes with. The greatest down fall for these kits is that the sound that is produced is poor at best and lack the ability to be altered.

Doing a more detailed investigation on the internet it can be found that a few high-level designs pop up. These high-level designs include PCBs and extensive testing. But most lack any kind of instructions or schematics and they become abandoned by their creators.

2.4. Requirements and Specifications

In this section we present our specifications and technical requirements. Each specification must have a measurable output from our musical instrument. The requirements stem from our goals and marketable approach. The project will require a strong understanding of power supply and power ratings for components. This because we need to make sure we do not over power or under power any components.

Table 2: List of Specifications

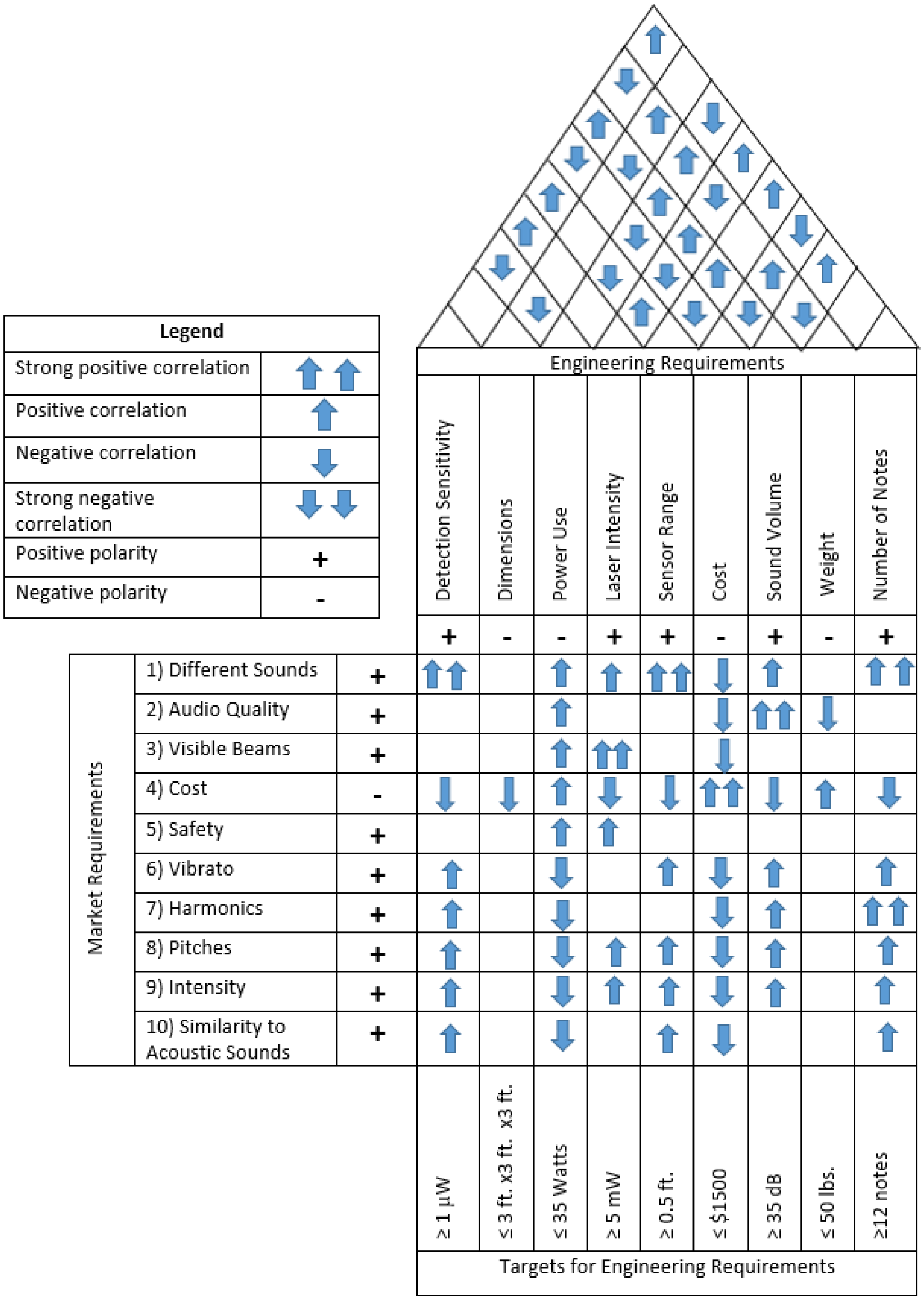
Specifications
Audio output with a range of 65Hz to 3951Hz
Weigh less than 20lb
Run off no more than 13 volts from a battery supply
No greater than 36 inches in any single dimension
Have a response time of less than half a second to play a note from an interrupt
Have an audio output greater than 35 decibels
Have a minimum run time of 30 minutes

Table 3: List of Requirements

Requirements
Battery Powered
Portable so that the instrument can be moved when not being played
PCB design
Ignore ambient light for photodetectors
Minimum of four lasers
Microcontroller for signal processing (DAC)
Interrupting a beams path to produce a sound
Provide entertainment through visibility and sound of the instrument
Cooling system for the lasers to continually run without overheating

2.5. House of Quality

To consolidate the needs of the market with the realistic capabilities of the engineering team, as well as evaluate the tradeoffs amongst the engineering requirements, a house of quality was made. Below is an illustration of these tradeoffs.



Legend	
Strong positive correlation	⬆⬆
Positive correlation	⬆
Negative correlation	⬇
Strong negative correlation	⬇⬇
Positive polarity	+
Negative polarity	-

Market Requirements		Detection Sensitivity	Dimensions	Power Use	Laser Intensity	Sensor Range	Cost	Sound Volume	Weight	Number of Notes
		+	-	-	+	+	-	+	-	+
1) Different Sounds	+	⬆⬆		⬆	⬆	⬆⬆	⬇	⬆		⬆⬆
2) Audio Quality	+			⬆			⬇	⬆⬆	⬇	
3) Visible Beams	+			⬆	⬆⬆		⬇			
4) Cost	-	⬇	⬇	⬆	⬇	⬇	⬆⬆	⬇	⬆	⬇
5) Safety	+			⬆	⬆					
6) Vibrato	+	⬆		⬇		⬆	⬇	⬆		⬆
7) Harmonics	+	⬆		⬇			⬇	⬆		⬆⬆
8) Pitches	+	⬆		⬇	⬆	⬆	⬇	⬆		⬆
9) Intensity	+	⬆		⬇	⬆	⬆	⬇	⬆		⬆
10) Similarity to Acoustic Sounds	+	⬆		⬇		⬆	⬇			⬆
Targets for Engineering Requirements		≥ 1 µW	≤ 3 ft. x3 ft. x3 ft.	≤ 35 Watts	≥ 5 mW	≥ 0.5 ft.	≤ \$1500	≥ 35 dB	≤ 50 lbs.	≥12 notes

Figure 2: House of Quality

3. Design Constraints and Related Standards

This section details the constraints of the project and any related standard that we are aware of. Both constraints and standards explored in this section helped to guide the project’s overall path and design. The constraints and standards listed in this section worked in conjunction with the requirements and specifications, listed previously in chapter 2, to guide any decision making for the project.

Table 4: List of Constraints

Constraints
The frequency range of a human can hear (20Hz-20kHz)
The lowest level of decibels a human can hear so the instrument can be heard
Max voltage rating of microcontroller (5V)
Limitation of programming language selection and use for microcontroller
The Restriction of Hazardous Substances Directive (RoHS)
On board memory capacity of the microcontroller

3.1. Constraints

This section covers the multiple categories of constraints we encountered for this project. The purpose of constraints for our project are to bind the project so that it maintains safety, environmental, social, and economically sound. All constraints must be realistic and relatable to the project to hold any value. Many constraints work off or from each other as well. Such as the cost of using a stronger material needed for the project but the cost of the material will push the project past its budget so there has to be a compromise in the constraints or even the requirements and specifications.

3.1.1. Health and Safety

Health and safety constraints related to the project go beyond just the safety of the team members but also to anyone who will be operating the instrument. These constraints must always be taken seriously to prevent harm to anyone or anything. The team will face many safety constraints because we will be using lasers that could potentially harm or blind a person. This safety constraint must be taken seriously even after building and testing. If the instrument is ever to be mass produced and sold as a consumer product precautions would have to be made to mitigate the potential threat the lasers have of harming anyone. Besides the lasers we also face safety constraints with using lithium-ion batteries. Because lithium-ion batteries are fragile and highly dangerous if misused or mishandled we have to include precautions when testing and handling the batteries.

This project involves working with electricity which means there is a potential for electric shock. Electric shocks come in different magnitudes from small enough that we may not feel it, to burns, to death or paralysis. Regardless of the magnitude of electric shock they should all be treated with the same respect and regard. Along with electricity the project will require soldering to make electrical connections. Soldering has its own safety constraints such as only soldering in well ventilated area with a fan. This is because there are harmful fumes released into the air when soldering. Just like electric shock soldering can burn a human or other material. How harmful soldering is also depends on the type of solder being used. Where using solder with lead in it will be more harmful than using lead-free solder.

Health constraints are very similar to safety constraints and are the usual reason why safety constraints are made. In the case of soldering fumes, if not conducted properly these fumes could cause long term health issues to anyone who breathed in the fumes. Since our project retains to producing sounds, we may run into a health constraint of hearing damage. Health constraints for the project for the most part can be handled by following all of the safety constraints.

There is no shortage of health and safety constraints that relate to this project. Because there are so many, we could not include them all in this document. Even though they are not listed here they should be taken seriously, and the team always needs to be conscious of them. Ignoring a health or safety constraint for the project could lead to serious permeant damage to person or property and could mean fines or worse for the team.

3.1.2. Economic and Time

Economics and time are always constraints for any project. These constraints are what limit the financial and time frame of the project. We grouped economics together because time is money after all. Both time and money are very limiting factors because neither can be stretched or worked around. A real economic constraint for the team is that the project is self-funded, so we will be working with a limited budget with no room for a slight overflow in the total cost. This fact means that we will be limited by the components, materials, testing equipment, and services that we can use for making the instrument. This constraint can also lead to internal team conflicts if another member uses the team funding to buy parts without approval since this money will also be coming from the other members of the team.

In many cases economic constraints have direct interactions with other forms of constraints where a way to work with an environmental or manufacturing constraint my conflict with the team’s economic constraints, and vice versa. This is a conflict of constraints that will always be met as long as there is an economic constraint.

The time constraint that the team faces is similar to all of the other senior design teams in that we have two semesters to research, design, build, and test our project. While each time also has slightly different time constraints such as team members work and course loads. We have created a milestone table that can be found in chapter 7 of this document that includes the dates of sub-deadlines we created to keep the project on course for the final completion deadline of April 2019. Beside deadline constraints we will also encounter time constraints regarding shipping times to receive material and parts. This can take away a lot of time from the project if orders are not placed in an organized manor. Scheduling and maintaining a calendar will help keep the team on top of all of the time constraints.

3.1.3. Social, Ethical, and Political

Social constraints some of the hardest constraints to define. They can vary drastically by region. The biggest social constraints we have identified for our project are those that relate to music and the social connection that music provides. We want our instrument to be appealing to those that have an interest in music and those whose have an education of musical concepts. These constraints cannot be easily defined in quantitative values because they are mostly perceptive.

Ethical constraints are important to consider because they relate to the betterment or worsening of society, life, and health. Since our instrument will be using potentially dangerous components, we have social, ethical, and political constraints. The ethical constraints we face tie into our health and safety constraints. This is because it is an ethical practice to verify that our instrument will pose as little as a safety threat to a user although it uses lasers and lithium-ion batteries. There is also the risk of creating too intense of sounds with our instrument. It would not be ethical for the team to create an instrument with the intent to bring joy and entertainment to people to only have it create sounds that damage people’s ears. We plan to keep the maximum power driven to the speaker much lower than a level that is capable to damage a person’s hearing.

The political constraints we face vary depending on the country you choose to look from. Political constraints come from laws which in many cases relate to a health, safety, social, ethical, or environmental constraint as well. We will only be considering political constraints regarding the United States because that is the country that we are creating the instrument in. In the United States there are restrictions on the testing that regards lasers. This political constraint relates back to safety. Since our project is only planned to make it to the prototype stage, we do not face many political constraints. If we wanted to take the instrument to a commercial level, then we would face many different political constraints relating to manufacturing and selling of a good.

3.1.4. Environmental

The environmental constraints exist to help prevent and maintain the world we live in. In many cases environmental constraints are related to political, health, sustainability, and manufacturing constraints. Materials such as batteries or those that contain lead all have environmental constraints on how they can be used and how they must be disposed of. Many of our components in our instrument have an environmental impact in their manufacturing process because of the harmful chemicals and energy dependency of the process. There is a popular compliance when it comes to electronic devices and components, the compliance is the restriction of hazardous substances directive (RoHS). To meet this compliance, you must not use any of their restricted substances. If the instrument was to make it to market it would be important to meet the RoHS compliance to make the instrument more marketable. The radiation levels of the lasers will be low enough that they pose no major threat to the environment. If we were to increase the power of the laser to meet our goal of having them visible, then we would have to reinvestigate this aspect of the project to see if we face any environmental or health constraint with the increase power.

3.1.5. Manufacturability and Sustainability

Manufacturability constraints for the team to consider are the supply of each components, the ease of use/implementation, and if any aspect of the project requires any special tools. Since we are only making a single prototype it is not practical to have any fragile components that can break easily even if they are perfect for the job. Each component for the prototype has to be subjected to trial and error testing. This limits the team on the type of components we can use. Thus, means components must be low cost, durable, and abundant so that we can order large quantities for lower cost and not worry so much about breaking components often. Since we do not have access to any special equipment, we are not able to work with any components that are too small to be worked on by hand. This will lead to us needing a larger PCB design. This is manageable for one instrument but to move to mass production of the instrument we would need to minimize the size of the PCB to drive the cost down per board.

The project will require soldering where the heat from the soldering iron can damage some of our components. This constraint means we have to be careful when soldering any components that are easily affected by heat such as our photodetectors. Aside from just burning components we can also overpower and fry components if any shorts are made or if current spikes. Such an occurrence could set the team back a week or more if we are not prepared if any components are parts break. This constraint along with the burning lead us to over order all of our components. This does conflict with our economic constraint of budget but is required at such early stages in a products development.

Sustainability constraints that relate to the team and the instrument are run time, low cost, and physical durability. The run time constraint for the project comes from our choice of batteries and heating. As it would be inconvenient to run out of power while playing our instrument. Batteries have a limited life span meaning once they run out of charge meaning they are no longer capable of powering what they once did. To mitigate this aspect, we have chosen to go with secondary batteries for recharging and to investigate high density batteries. Heat is also a limiting factor when it comes to our instruments run time. Because lasers tend to generate excess heat the longer the instrument runs the more heat it will generated. Some of our components can be drastically affected by this heat. For this reason, we have designed our frame to be well ventilated and have even included fans into our design if they are needed for cooling. The low-cost sustainability ties back into the economics of the project. In order to keep the project moving forward we must maintain the team’s expenses and budgeting. The physical durability constraint is because it would not be good to have a fragile prototype for testing as it would always be breaking and need replacing or rebuilding which would add up costs and take away from time.

3.2. Standards

Standards are important when it comes to engineering and business because they aid in the design and versatility of projects, services, and goods. A standard could be an organized way of formatting a document to a way of how to perform a task to a defining words, symbols, and language. In most cases standards serve as a universal or common way to do a task. In some cases, standards can even be backed by legal means making them to be required for a market good. Some standards require a payment to have access to or to be used while some are also free.

There are many standards that relate to our project, such as the classifications of lasers [3]. We will only list a few that we think are important and that we could gain access to. As stated, before since our project includes lasers and lithium-ion batteries we come across many safety concerns. For this reason, we have put top priority to include standards that relate to the safe use and testing of such equipment. In table 5 we have listed all of the related standards to our knowledge. We will go into more detail on standards we think are particularly important in the sub-sections following the table. In search of standards related to the project we referred to organizations such as, but not limited to, IEEE, ANSI, ISO, IEC, UN, AMEI, and U.S. government agencies. Some the standards presented in the table are not given in any detail because we did not deem them to be important enough to be presented in detail in this report. Or because they would take up too much space in this report. Standards are also listed in our reference section along with where we accessed them. We are including them in the table so that others can know we are aware of the standards. A standard being listed in table 5 does not mean that it was used in our project, only that it has relevance to our project.

Table 5: List of Standards

Standards
ANSI Z136.1 Safe Use of Lasers General [4]
ANSI Z136.5 Safe Use of Lasers in Educational Institutions [5]
ANSI Z136.6 Safe Use of Lasers Outdoors [6]
ANSI Z136.7 Testing and Labeling of Laser Protective Equipment [7]
ANSI Z136.8 Safe Use of Lasers in Research, Development, or Testing [8]
ANSI Z136.9 Safe Use of Lasers in Manufacturing Environments [9]
ISO 11145:2018 Optics and photonics -- Lasers and laser-related equipment -- Vocabulary and symbols [10]
IEC 60825-1:2014 Safety of laser products - Part 1: Equipment classification and requirements [11]
ISO 11252:2013 Lasers and laser-related equipment -- Laser device -- Minimum requirements for documentation [12]
ISO 11146-1:2005 Lasers and laser-related equipment -- Test methods for laser beam widths, divergence angles and beam propagation ratios -- Part 1: Stigmatic and simple astigmatic beams [13]
ISO 11146-2:2005 Lasers and laser-related equipment -- Test methods for laser beam widths, divergence angles and beam propagation ratios -- Part 2: General astigmatic beams [14]
ISO/TR 11146-3:2004 Lasers and laser-related equipment -- Test methods for laser beam widths, divergence angles and beam propagation ratios -- Part 3: Intrinsic and geometrical laser beam classification, propagation and details of test methods [15]
ISO 11553-1:2005 Safety of machinery -- Laser processing machines -- Part 1: General safety requirements [16]
IEC 62133-2:2017 Secondary cells and batteries containing alkaline or other non-acid electrolytes - Safety requirements for portable sealed secondary lithium cells, and for batteries made from them, for use in portable applications - Part 2: Lithium systems [17]
UL 2054 Standard for Household and Commercial Batteries [18]
UL 1642 Standard for Lithium Batteries [19]
UN Transportation Testing (UN DOT 38.3) for Lithium Batteries [20] [21]
ANSI C18.3M, Part 2-2017 American National Standard for Portable Lithium Primary Cells and Batteries—Safety Standard [22]
Musical Instrument Digital Interface (MIDI) [23]
ANSI/ASA S1.1-2013 Acoustical Terminology [24]
TRS Audio Jack and socket 3.5mm and 6.35mm(1/4 inch) [25]

3.2.1. Laser Standards

The American National Standards Institute (ANZI) is an organization of experts that has the purpose of setting industry consensus standards in several fields of interest through the use of committees [26]. In the laser world, there are a couple of standards that the ANZI Z136 Committee has established. The foundational governing standard is ANZI Z136.1 which states the different classes of lasers and how to operate them correctly to avoid unwanted damage. The different classes of lasers are Class 1, Class 2, Class 3R, Class 3B, and Class 4. Class 1 laser systems are considered eye-safe under all operation conditions. Lasers with Class 2 ratings are typically considered safe unless a person are stares directly in the laser beam or with the aid of an optical device. They cover visible lasers as well. Class 3R are for lasers that are potentially hazardous but low risk. This Class is about five times the limit of Class 1 lasers and typically cover continuous wave visible lasers with emissions of 1 to 5 milliwatts of power. Laser pointers would be under this classification. Class 3B are highly likely to be hazardous to the eye and skin as they can put out a maximum limit of 500 milliwatts into the eye. Diffuse reflections are safe for viewing. Class 4 lasers are the most dangerous types of lasers as they can be hazardous for viewing either directly or diffused. They can light materials on fire and can interact with metals to give off toxic gas in the surrounding atmosphere. Special care must be taken when handling these lasers. For our project, since we are essentially using laser pointers to create the beams, we will be focused on taking precautions for Class 3R laser systems.

One of the standards is the ANZI Z136.6 standard which outlines how to safely use a laser outdoors [27]. It includes using a buffer zone angle for the laser beam. When aiming a laser at an object it is normally thought that the beam is a straight line that maintains its optical path. However, light can behave in unexpected ways and a portion of the light can deviate or “walk out” of its optical path. The beams that deviate called stray beams and can cause issues with alignment, targeting, and can pose harm to an unexpected observer. Using a buffer zone accounts for any stray beams that might walk out of the normal path of incidence and not cause unwanted harm. The concept of a laser safety officer is also formed in this standard in which a Class 3B and Class 4 laser operations done outdoors should be designed to oversee that the product is safe. In our case that is taken care with University personnel. This is important to understand this standard for our project because if we are to make our prototype portable, then that means it can be taken outdoors and be used. It is therefore critical for the prototype to be safe to use if it were to be taken outdoors.

3.2.2. Lithium-ion Battery Safety and Protection Standards

Safety standards for lithium-ion batteries are important for companies who wish to manufacture, sell, or use the batteries or cells. Including safety standards with a potentially dangerous device increases it's potential to sell and market. MET laboratories, a global service leader in safety approvals for electrical products list a top three standards for lithium battery safety testing [28]. On this list of top three is the UN DOT 38.3 along with IEC 62133-2:2017 and UL 2054 2nd Edition. All three standards test for mechanical and electrical stresses. We have included these standard because we plan to use lithium-ion batteries in our project.

The IEC 62133 standard only includes four tests. Mold case stress, external short circuit, free fall, and overcharging battery. Compared to the other two safety standards IEC 62133 is considered to be the easiest to pass because of few tests and low requirements. This standard is important because it is widely commonly used on an interannual level. Similar testing included in the UN DOT 38.3 standard is not required to be repeated to pass the requirements for the testing of IEC 62133. This is because the UN DOT 38.3 testing requirements are much stricter and more rigorous.

The UL 2054 standard is considered to be the hardest of the three standards because it includes the most testing. The standard includes seven electrical tests, four mechanical tests, four battery enclosure tests, one fire exposure test, and two environmental tests. Compliance with UL 2054 is only mandated by a number of U.S. end device standards. UL 2054 works alongside many other standards such as UL 1642 and IEC 62133. To pass requirements for the tests included in UL 2054 are strict. Many of the tests look at single faults, worse-case operation, and abusive conditions. UL also presents a similar standard, UL 62133, but has different requirements from UL 2054.

Below is a detailed table of the eight standardized tests in UN DOT 38.3 [20] [21]. The standard is required for all lithium-ion batteries that are going to be transported. We believe the UN DOT 38.3 is the most important of the three because it is required by the United nations, has a broad testing, and is detailed. This why we chose to only include a detailed table for this standard. UN DOT 38.3 is a self-certifying standard that can be done by the manufacture themselves or they can also be performed by third part test labs. Depending on the type of cell to be tested not all the tests are required to pass the requirements set by the standard. Specifically test seven is only required by secondary batteries. The table includes the type of cells and/or batteries that are required to for each of the tests to pass the standards requirements.

Table 6: UN Transportation Testing (UN DOT 38.3) for Lithium Batteries

Required Test	Test Description
Test 1: Altitude Simulation (Primary and Secondary Cells and Batteries)	Low pressure testing that simulates unpressurized conditions at an altitude of 15,000meters that could be experienced in an aircraft's cargo hold. A sample is stored under low pressure at ambient temperature for at least six hours. To pass the test, the sample must not leak, vent, disassemble, rupture or ignite. In addition, the open circuit voltage of the tested sample must not drop more than 10% of its pre-test voltage.
Test 2: Thermal Test (Primary and Secondary Cells and Batteries)	Covers rapid and extreme changes in temperature from -40°C to +75°C. Batteries are stored for 10 cycles of 6 hours at -40°C, then 6 hours at +75°C. Same pass criteria as Test 1.
Test 3: Vibration (Primary and Secondary Cells and Batteries)	Simulates potential vibration experienced during transportation. Testing lasts for 3 hours with varying vibrations from 7Hz – 200Hz. Same pass criteria as Test 1.
Test 4: Shock (Primary and Secondary Cells and Batteries)	Simulates possible G-forces that could be experienced during transportation. Same pass criteria as Test 1.
Test 5: External Short Circuit (Primary and Secondary Cells and Batteries)	Simulates an external short circuit with <0.1Ω at 50°C for at least one hour to determine the ability of a cell or battery to withstand a maximum current flow without adverse consequences. Pass criteria is that temperature does not exceed +170°C and no disassembly, rupture, vent or ignite within 6 hours of test.
Test 6: Impact (Primary and Secondary Cells)	For cylindrical cells >20mm diameter, it simulates impact to case of cell. For cylindrical cells <20mm diameter and all other cell constructions, it simulates crushing of a cell. Pass criteria is: Case temperature does not exceed +170C & no disassembly or fire within 6 hours of test.
Test 7: Overcharge (Secondary Batteries)	Simulates an overcharge condition on a rechargeable battery where two times the manufacturer's recommended charge current is applied for 24 hours. To pass the battery must not disassemble or ignite within 7 days of testing.
Test 8: Forced Discharge (Primary and Secondary Cells)	Simulates a forced discharge condition on a battery at the manufacture's maximum specified discharge current. To pass a battery must not disassemble or ignite during testing or within 7 days after the test.

4. Research and Background Information

Before beginning detailed design work the team researched background information on important concepts and components. In this chapter we introduce important aspects from music and audio signals, relating them to the teams understanding of electrical engineering and physics. We discuss major theories behind the project coming from optics and electronics as well as important functions and programming style for our code. Then we investigate important components and perform comparisons between the ones we looked at and our selection.

4.1. Music Theory

This section goes into the musical aspect and technicality of the project. We will go over some important terms, our understandings, and our approaches to handle the musical aspect of the project. The purpose of this project is not to be musicians but to be engineers that create an instrument for musicians. So, it is important for the team to have and understanding of what music is on a physical level. For this project we only are looking at the acoustic range of sounds since it is the range that a human can hear. It is important to note that sound is a vibration through air on a physics level. This makes understanding music on a mathematical level an easier approach to relating the physics and electronics than to the musical theories. Both music and electronics use the same terms to represent the same concepts such as frequency and harmonics, whereas the understanding and approaches to these concepts are what separates the two fields.

4.1.1. Musical Notes and Tones

Notes and tones are similar when it comes to sounds. Notes are the building blocks of written music, they are defined by a pitch and duration. Tones are steady periodic sounds that are characterized by their pitch, duration, intensity and their timbre. A way to differentiate the two is to think of notes the as a written word while tones are the physical sound that is produced when speaking the word. Tones can be either a pure tones comprising a single sinusoidal waveform or be a complex tone that comprised of multiple pure tones. Pure tones are rare in nature and no instrument creates a pure tone [29].

4.1.2. Pitch and Frequency

Pitch is the frequency property a sound wave. The frequency of the sound wave is how often the particles that make up the wave are vibrating [30]. The units for frequency are hertz which one hertz is one vibration per second. In music pitches are given the names of the letters A, B, C, D, E, F, and G. The letters are also the names of notes when in regards of their pitches. Pitch of a sound can only be determined in sounds that have clear and stable frequencies. The pitch of a note is its fundamental frequency. There are also ten octaves that make up the acoustic range of sound. Notes are fixed to an exponential scale so that the A in the third octave has double the frequency of the A in the second octave and the A in the second octave has double the frequency of the A in the first octave. For this reason, music intervals can be represented on a logarithmic scale in cents where a music interval is the difference in pitch between two sounds.

4.1.3. Loudness, Intensity, and Volume

The volume or how loud a sound is the intensity sound pressure from a sound wave. This relates to the amplitude of the signal. Sound intensity is defined as the sound power per unit area [31]. The commonly used unit of measurement is decibel. A decibel scale is a logarithmic scale of the amplitude of the signal. This means a 30-decibel sound is ten times louder than a 20-decibel sound [32]. Because of the scaling to increase to volume by three decibels it requires double the power. To go down three decibels, it requires reducing the power by half. There are different meanings and measurement standards of loudness depending on the industry or what it is a noise from. This is because loudness is perceptive and has to be relative to another sound level. The greater the decibels of a sound wave the louder it is. Interesting is that zero decibels does not mean there is no sound. Zero decibels for sound is referenced as the hearing threshold of the human ear [33]. Zero decibels can also mean that there is zero difference in a system.

4.1.4. Scale, Octave, and Musical Interval

A scale is an organization of a set of notes by their pitch. Scales typically cover an entire octave with either a higher or lower octave as well [34]. Scales are used to help with forming melodies and harmony in music. An octave is the interval between one musical pitch and another with half or double its frequency [35]. There are a total of ten octaves in the acoustic range of sound. An octave is also a unit of frequency level as defined by ANSI. Similar to an octave being the interval between two similar notes a musical interval is the difference between any two pitches. There are interval ratios, such as a perfect fifth, they help with relative pitch comparisons and matching. Scales, octaves, and musical intervals are all aspects that relate to different notes and tines frequencies and how they relate to each other [36]. Musical intervals also relate to degrees of notes. In many cases they aid in the creation and composing of musical work.

4.1.5. Timbre and Vibrato

Timbre is the perception of sound quality of a note. It is what differentiates two sounds of the same frequency [37]. It is also how humans are able to distinguish different types of sound such as vocals, a string instrument, or a wind instrument.

Timbre is related to a signal’s spectrum an envelope. There are many ways that musicians can alter the timbre of the notes they are playing. Implementing such a feature into our instrument would greatly increase its versatility. Typically, in electrical instruments the use of effect units and graphic equalizers are used to alter the timbre. While not being directly related to timbre vibrato is an important effect in music. Vibrato is a musical effect where there is a periodic frequency change in a soundwave. Vibrato can also be thought as pulsating variations in the pitch of a note. Vibrato has a magnitude in its pitch variation and the rate of the pulses. Vibrato detection is one of the team’s goals for the instrument. The implementation if vibrato varies among different instruments and vocals. Most string instruments vibrato is created by rocking the finger that holds the string down while it is being played while in vocals it is created by slight variations in the vibrations of the vocal chords. Figure 3 below shows the waveform of vibrato on a violin [38].

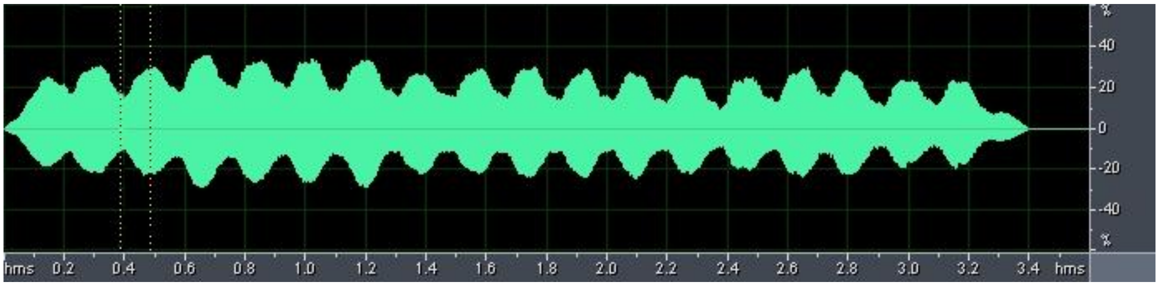


Figure 3: Waveform of a Vibrato sound from a Violin
{Permission granted by Joe Wolfe of University of New South Wales}

4.1.6. Relation between Music Theory and Signal Processing

In simple terms the musical characteristics of an audio signal come from music theory. Each musical characteristic relates to physical of the audio signal. This means that an audio signal can be treated like any other signal. Knowing the terminology in music theory is import for the team to understand so that we can have a good understanding of the non-engineering side of the project. Ideally an audio signal will be a sinusoidal or in other words an analog signal. This means analog signal processing is more important especially for the output of the instrument. While for the instrument most of the signal processing will be digital because it will be handled by the micro controller.

4.2. Relevant Electrical Components and Concepts

In this section we will discuss any import electrical components or concepts. We will not discuss any specific models or the different types there are for each component that there may be. Rather this section is only for introducing any major components and the concepts that go with them that serve as a foundation for our design.

Laser diode and Photodetector:

Two major components for our design are the laser diode and the photodetector. Both of which the user for our instrument will be interacting with directly to play the instrument, therefore they are fundamental components to our design. A laser diode is a special type of diode that can generate a laser beam. A photodetector is a light dependent resistor, meaning the intensity of light that shines onto the photodetector determines how conductive the component becomes. In our design the laser diodes we be aimed to shine on the photodetectors constantly unless something blocks the laser beam from reaching the photodetector. A way to think about this aspect of our project is that the laser is a transmitter and the photodetector is a receiver.

Voltage divider:

Alone a photodetector is not enough to create a detection circuit. This is where the concept of voltage divider comes in [39]. Here we will put another resistor in series with the photodetector then probe the common node between them. The voltage at this node is dependent on the values of the two resistors and the voltage input. The equation for the voltage divider circuit is given below in equation 1. Either R1 or R2 can be the photodetector and the other would be a fixed value. The signal created at V_{out} is an analog signal as it instantaneously changes with the value of the photodetector. This concept is crucial to our instrument because this is the detection circuit need for each laser for us to replicate a string. Each laser will need to have its own voltage divider circuit to correlate to it.

$$V_{out} = V_{in} \cdot \left(\frac{R_2}{R_2 + R_1}\right)$$

Equation 1: Voltage divider

Comparator:

From the voltage divider the generated analog signal will be sent to a comparator to determine if a referenced threshold voltage has been reached due to a laser being intercepted. A comparator is a digital component that will either send a digital 1 if the threshold has been reached and a digital 0 otherwise. This will digitize the detection signal so that it can be processed by the microcontroller. Each laser will need its own comparator as well so that the processor knows which laser has been interrupted.

Microcontroller:

The microcontroller will serve as the signal processor, waveform generator, and to memory storage. This will be a bottleneck in our design as all of the signals will have to pass through the microcontroller or be generated by it. Depending on the comparator that is passing a signal the microprocessor will generate a waveform that correlates to a programmed value to determine the frequency of the waveform. The generated waveform will be a square wave with a frequency of the musical note that is to be played. This signal passes to a digital to analog convertor to produce a more desired sound. A few microcontrollers have a built in digital-to-analog converter as well as an analog to digital converter.

Analog-to-Digital Converter:

An analog-to-digital converter (ADC) receives an analog signal such as a sine wave and outputs a signal with a finite number of values. If the input is a sine wave then the output will have the same shape as a sine wave, but it will have steps instead of being a smooth, continuous curve. Most microcontrollers have an ADC connected directly to their analog input pins to convert the analog signal coming in to a digital signal for processing. The number of bits and the sampling rate can impact the quality of the output signal. Having more bits increases the number of possible values that the output signal can take, thereby increasing the accuracy to which the output matches the input. Having a higher sampling rate increases the number of points sampled in one second which allows the output to more closely follow the input, thereby increasing its accuracy. Equation 2 can be used to define the number of conversion bits or to define the voltage per bit for a given voltage range. Where V_h is the highest voltage level, V_L is the lowest voltage level, n is the number of conversion bits of the ADC, and ε_V is the voltage per bit.

$$\varepsilon_v = \frac{V_H - V_L}{2^n}$$

Equation 2: Analog to Digital Conversion

Digital-to-Analog Convertor:

A digital-to-analog convertor does exactly as its name suggests, it takes in a digital waveform and produces an analog waveform out. The purpose of using a DAC is to increase the sound quality of the waveform before it goes to the speaker to make sound. This is because a pure sinusoidal waveform is more appealing of a sound than a square wave which would be the digital signal. In many cases the process of converting the waveform can degrade the signal so the selection of a DAC needs to be thorough to minimize this issue. There are many different ways to on how a DAC can convert a signal a few are pulse-width-modulation, oversampling, and binary-weighted. From the DAC the signal will pass to an amplifier before finally reaching the speaker to output sound.

Amplifier and Speaker:

The last part the signal will reach is the amplifier and speaker. The purpose of the amplifier is to increase the amplitude of the signal before it reaches the speaker so that the sound will be loud enough to be heard. Amplifiers can also be used to increase or decrease the level of the sound. An amplifier may not be needed to produce a sound from the speaker but the implementation of the amplifier stage before the speaker will increase our range volume we can produce from the speaker. A speaker is an electroacoustic transducer meaning it will take the electrical audio signal and convert it into a soundwave. A speaker is crucial in our instrument because without it no one could hear the instrument being played. The audio output of the instrument is the main measurable output that and audience can judge our instrument on.

Power Supply:

Power is energy over time and just like everything our instrument will need a stable supply of power to drive and run the whole system. The power supply needs to be stable meaning minimal drops in spikes of the power level to prevent any components from being harmed. There are many options for a power supply be it from a wall outlet, battery, or another device.

Analog read:

As part of our goals we want to have an intensity detection circuitry meaning we need to have components that can read and write analog signals. The two aspects that would require this are the pitch detection system and the volume controls since we want both to take place while playing the instrument.

Musical Instrument Digital Interface (MIDI):

MIDI is a standard used for digital communication between different audio devices and electronic musical instruments [40]. Including a MIDI capabilities into the instrument would increase the versatility in its audio capabilities since it could be connected to a computer with running editing software, synthesizers, and mixers. This would also mean that less internal memory would be required because the notes would no longer have to be stored and could be generated in real time by a connected device. MIDI is a necessity for the instrument to move further than a prototype because if its wide use and popularity.

Switched mode power supply/switching regulator:

A switched mode power supply consists of a switching regulator to convert electrical power efficiently. This is sometimes referred to as a switching regulator and a buck/boost converter. The way they work is by switching on and off at high frequencies. The output is connected to storage components such as inductors and capacitors to stabilize the output. The application for these regulators is for high power and high efficiency. Because of the high current draw from the laser diodes a switching regulator will need to be used to lower the voltage from the batteries to a stable five volts.

Transimpedance amplifier:

A transimpedance amplifier uses a current input to produce a voltage output. They can be designed using general op-amps or with specialized amlifiers. Since we are using photodiodes, which produce a forward current depending on the light intensity, for the beta sensor we will need to use a transimpedance amplifier so the MCU will be able to have a voltage value for the beta sensors. The transimpedance amplifier is part of our beta sensors.

4.3. Coding

The microcontroller for this project will need to be able to recognize when a beam has been broken, read the voltage from the intensity detectors, and output a sound wave. It also needs to be able to stay in a low power mode when no beams are broken in order to save power. Since we are using an Arduino microcontroller, most of the features such as reading from the analog input pins generating a sound wave output can be accomplished using standard function in the Arduino programming language. The Arduino programming language is a dialect of standard C++ with some functions specific to the microcontroller. The language contains functions for initializing a pin as input or output, reading from an input pin, setting the value of a digital output pin, and generating a square wave signal on a specific digital output pin at a specific frequency.

4.3.1. Coding Style

Since there currently exists no international standard for C++ coding style or format, the style that will be used in this project is the GNU coding standard, which was created especially for C/C++ programming [41]. This standard was created for use in GNU software to which people from all over the world contribute. It is designed to maximize the portability, maintainability, and readability of code.

The GNU coding standard specifies rules for the formatting of source code that, while not necessary for a decent compiler, help standardize the behavior of software within the GNU system to ensure that the software can run on as many CPU types as possible.

Following the standard, the first part of the software should be a comment that quickly but sufficiently explains what the program does. If the program uses multiple source files, “this comment should be at the top of the source file containing the ‘main’ function of the program.” A comment should also accompany every static variable and function as well as the function’s return value to briefly describe its purpose. The standard also states the variable name should be written in ALL CAPS when referring to its value instead of the variable itself in the comment.

When writing the actual source code, there are specific rules regarding the formatting.

- Lines must be no more than 79 columns.
- Names and open braces for functions, structs, and enums should go in the first column.
- Split the list of function arguments to two lines if they don't fin on one line.
- Add a space before an open parenthesis and after a comma.
- If a line must be broken at an operator, make sure that the break is before the operator.
- The open brace for a while or do-while loop should be indented with the contents of the loop indented again.

Making the lines no longer than 79 columns makes sure that the code is as easy to read as possible on as many systems as possible. An exception to the rule about structs and enums is that if the contents of the struct or enum can fit on one line then put the name, open brace, and contents all on the same line.

The GNU standard also has rules regarding making effective use of C constructs to ensure that the code is as clean as possible.

- Variables being declared in the same declaration should all be on the same line. If they don't all fit the break the declaration into two on separate lines.
- Integer constants should be defined with enum instead of #define.
- Variables defined as enum constants should be given names in all
- Braces should always be used for nested if-else statements.
- Assignments should not be performed inside if conditionals. However, this is allowed inside while conditionals.
- An if statement nested inside an else statement should either be written as "else if" on one line or use braces inside the else statement.
- Structure tags should not be declared in the same declaration as variables or typedefs.

When naming variables, it is important to ensure that the name clearly identifies the variable and its purpose as well as not able to be easily confused with another variable. In particular, global variables should be named such that their purpose is clear. While local variables should also have descriptive names, their names may be shorter since they only have a function-level scope and their purpose should be clear from the comments. Although it is not mentioned in the standard, it is important to remember that variables, functions, or anything else cannot be given the same name as a library function or a reserved word, which means that functions and variables can't be called things like "for", "int", or "getchar".

The GNU coding standard also contains rules for topics such as conditional compilation and ensuring maximum portability of code between systems and CPUs. However, since the software used in this project is only targeted towards one specific platform, these actions are not seen as relevant and will therefore be disregarded.

4.3.2. Program Flow

The software used for this project has three main parts:

a. Setup
b. Loop
c. Interrupt Service Routine (ISR)

The setup function is always the first function to be called in the program after the device powers on or after a reset. According to the Arduino documentation, this function “initialize variables, pin modes, start using libraries, etc.” [42]. This is also the function where interrupts are configured.

The loop() function is the main part of the program. It is a continuous loop contains the main algorithm for the program. Any other functions are called from this one. In this project, the loop function is also where the MCU will be put in a low power mode. According to the Arduino documentation, this function “loops consecutively, allowing [the] program to change and respond” [43]. In the case of this project, the loop function will be where the notes are played and the MCU goes to sleep.

An ISR is called whenever an interrupt occurs. It is specific to one interrupt vector and contains whatever procedure the device needs to complete before going back to low power mode. For this project, the ISR is where the device will read the voltage from the beta detectors and play a note. For the ATmega2560, there is a total of 57 interrupt vectors, including eight external interrupt vectors and five Timer1 vectors. Of the eight external interrupt vectors, six can be associated with a digital I/O pin. These available pins are digital pins 2, 3, 18, 19, 20, and 21. The exernal interrupts can be configured to trigger on a rising edge, falling edge, or a low level, as well as on both a falling edge and rising edge, which was the case used in this project, since the voltage on the digital input pins will change depending on if a laser is shining on the alpha detectors or not. When an interrupt occurs, the bit corresponding to that interrupt will be set in the External Interrupt Flag Register (EIFR). This flag bit is used to determine which ISR to call for the current interrupt. Since the flag is cleared automatically when the ISR is called, there is no need to clear the flag in software.

4.3.3. Functions

pinMode(pin, mode)

The pinMode function configures the specified pin to the mode specified by MODE, which can be either “input” or “output”. Digital pins are specified by their number (digital pin 3 is written as 3) and analog pin are specified by adding “A” before their number (analog pin 3 is written as A3).

analogRead(pin)

The analogRead function reads the voltage on the specified analog pin. The value returned will be an integer between 0 and 1023, since each analog input pin is connected to a 10-bit ADC. The range of the returned value can be modified with the map function, which is explained more below. The analogRead function will be used in the interrupt service routine to read the voltage from the intensity detectors in order to determine which note to play.

tone(pin, frequency, duration)

The tone function generates a square wave with a 50% duty cycle with a specified frequency on the specified pin. The duration parameter is optional and determines for how long the tone should be generated. Omitting the duration will generate a tone indefinitely until the noTone function is called. This function can only be used to generate one note at a time. This means that at any given moment, the function can be generating a tone on only one pin, which means that the noTone function must be called to kill the current note before playing a different note.

noTone(pin)

The noTone function kills the note generated with the tone function. This is used when a new note needs to be played, since the tone function can only generate one note on one pin at a time. This means that whenever the voltage from the intensity detector changes enough for a new note to be played, the noTone function must be called before the new note can be generated.

attachInterrupt(interruptNumber, ISR, mode)

This function attaches an external interrupt to the digital I/O pin specified by the first argument. Since a pin’s interrupt number is not the same as its pin number, it is reccomended to use the digitalPinToInterrupt function to get the correct interrupt number for the pin. The second argument is the function that will be used as the ISR whenever the interrupt is triggered. Just like the other ISR for the ATMega560, this function should be declared as type void, take no arguments, and return no values. The third argument determines when the interrupt will be triggered. The four predefined values that can be used are

- LOW: The interrrupt is triggered when the pin’s voltage goes low.
- CHANGE: The interrupt is triggered when the pin’s voltage changes.
- RISING: The interrupt is triggered on a rising edge.
- FALLING: The interrupt is triggered on a falling edge.

sleep_cpu()

This function puts the MCU into power down mode in order to conserve power. When in power down mode, the ATmega2560 draws only .1 µA compared to 500 µA in active mode. This means that power down mode draws 5000 times less current than active mode. In order to enable a sleep mode, first bit 0 of the sleep mode control register (SMCR) must be set to one. Then the correct bits in the SMCR are set according to the table:

Table 7: SM0, SM1, and SM2 Values to Select A Sleep Mode

SM0	SM1	SM2	Desired Sleep Mode
0	0	0	Idle
0	0	1	ADC Noise Reduction
0	1	0	Power-down
0	1	1	Power-save
1	0	0	Nothing
1	0	1	Nothing
1	1	0	Standby
1	1	1	Extended standby

SM0, SM1, and SM2 are sleep mode bits 0, 1, and 2. these correspond to bits 1, 2, and 3 in the SMCR. Note that settings SM0 or SM0 and SM2 is not a valid configuration for enabling a sleep mode. Using the table, this means that to enable power-down mode, SMCR bits 0 and 2 must be set with the others cleared. The sleep_cpu function must be called immediately after these bits are set.

playBeamx()

This function works as an ISR for the external interrupts attached to each beam, where “x” is the beam number. Whenever the voltage on a digital input pin changes, the function associated with that beam will be called to either configure the hardware timer and take an initial reading from the ADC if the beam is broken, or stop any note playing and disable the hardware timer if the beam is no longer broken.

4.4. Power Supply

For our project we need a stable and constant power supply while the instrument is in use. The job of the power supply is power all the components and set all the bias voltages. Components such as the speaker, fans, and the ATmega2560 will be given this supply voltage directly. Using a wall outlet would work but would require an AC adapter to convert to DC power and step the voltage down. Depending on an outlet would also reduce portability of the instrument. For these reasons we have decided to us a battery pack as our power supply. A battery pack has many advantages from a wall outlet in that it can supply DC power directly at a better suited voltage for our components than the 120 volts that a wall outlet supplies, and it adds to the portability of the instrument. The lower voltage supply also aids in the simplifying all our voltage divider circuits that need to be limited to a 5-volt max. We decided later to specify that the instrument needs to be battery powered with a voltage supply less than 13 volts.

4.4.1. Battery

With the selection of depending on a battery pack as our power source we still had to decide on how to implement the batteries into our project. We have performed testing and research to make sure we have a suitable voltage and a good amount of capacity. The limited capacity is the biggest drawback of using a battery pack. This is relived slightly with the implementation of using rechargeable batteries. Doing this will make sure we will not need voltage regulators, current regulators, buck converters, or boost converters unless we have fragile components that have a rated voltage under 3.6 volts. We investigated a few different means of implementing a battery pack by either buying a manufactured battery pack, using commercial battery cells, or creating our own battery pack. The battery pack to be used will be charged and recharged by power from a wall outlet.

Before choosing our implementation method for the batteries we decided it would be best to research the different types of batteries and then look at the pros, cons, and pricing of different types of batteries. When determining the right battery or cell there are a few major characteristics to look at to compare the batteries and cells. How important each of these characteristics are determines on the application and purpose the battery will be used for. Almost needless to say cost is a factor when it comes to anything including batteries. Different battery types have different costs as well as the sizes of the batteries. Some batteries are cheaper at a flat fixed cost while some are cheaper of time where cycle times are a factor. Second is comparing safety of each type of battery. This means comparing how tolerable a cell or battery is to overcurrent and deep cycle drains as well as reactions to extreme temperatures and more. It is important to look into restrictions is important for specific battery types and where they are to be used. Two important factors that should always looked at when comparing batteries and cells are energy density and power density. These factors consider the volume and weight against the capacity and output power. These two factors can also be taken over the cost to better compare batteries and cells. Other factors or characteristics to investigate for batteries and cells are life cycle durability, especially for rechargeable batteries and environmental hazards.

The final battery selection was made to have a nominal voltage of 11.1 volts. The battery system was designed so that further additions can be made to the system. One future addition may be cooling fans to help prevent overheating of regulators and the laser diodes. Cooling fans will require a higher voltage and will also produce current spikes. Although the defined specification for the battery run time needs to be greater than 30 min the final prototype well exceeded this specification. In testing of the instrument, the system was able to run on the battery pack for over two hours. In a future version of the system the battery pack will need to include protection circuitry, battery management system, and built in charging capabilities. All of these systems will help in the safety and marketing of the laser musical instrument.

4.4.2. Battery Technology and Research

Researching into the different types of batteries we discovered there to be two classes of batteries primary and secondary, with many different types of chemical foundations for each battery type. A primary battery is a single use battery where as a secondary battery is one that can be recharged. We focused on secondary batteries as they are the ideal batteries and nearly the ‘norm’ in many current consumer products now. There is a limit for how many times a battery or cell can be recharged. A single charge is commonly referred to as a cycle so any reporting or recording of how many times a secondary battery can be recharged it may be worded as how many cycles the battery is rated for. The main types of commercial batteries are, lead-acid, alkaline, lithium-ion, nickel-cadmium, and nickel-metal-hydride. They each have their own respectful pros and cons. Below are paragraphs going into more detail for each type followed by a table the compare the types of batteries we looked into [44].

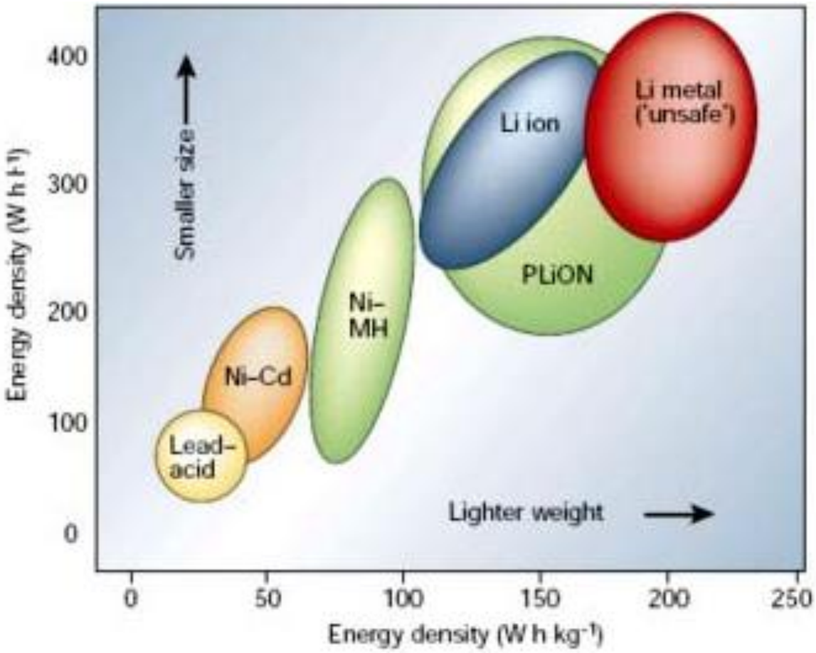


Figure 4: Battery density comparison [45] {Permission pending approval}

Lead-acid:

Lead-acid batteries are one of the most common batteries in use today and have been for some time. They are most commonly used is in automobiles and for backup storage. They do pose an environmental hazard as they include lead. Lead- acid batteries are low-cost, heavy duty, stable, and durable batteries. Their biggest drawback is their weight and size. Lead-acid batteries have low energy to volume and energy to weight ratios, for this reason they are considered to be the least portable battery or not portable at all. Their biggest strengths are durability, they have a large power to weight ratio, and can supply huge surge currents when needed. While durable, lead acid batteries are too heavy to be used for our portable instrument.

Table 8: Lead-acid pros vs. cons

Pros	▪ Low-cost ▪ Abundant ▪ Durable physically and electrically ▪ High current supply ▪ Can tolerate overcharge ▪ Low internal resistance
Cons	▪ Heavy ▪ Big ▪ Low cycle count ▪ Toxic/ environmental impact ▪ Slow to charge

Alkaline:

Alkaline are one of the largest batteries on the consumer market. Most are a primary battery because the rechargeable counterparts are a much newer technology. Alkaline batteries are safe, abundant, and low cost. Rechargeable alkaline cells include barium sulfate in the cathode mix to help with the cycling of the cell. They have lower cycles lives from other rechargeable batteries, lower capacities, and lower discharge currents. They are bested used where regular disposable alkaline batteries are also used.

Table 9: Alkaline pros vs. cons

Pros	▪ Abundant ▪ Low-cost ▪ Low internal resistance
Cons	▪ Very low cycle count ▪ Small capacities

Lithium-ion (Li-ion):

Lithium-ion batteries are some of the most popular batteries on the market now and growing. They work by lithium-ions flowing to the positive electrode from the negative electrode while discharging and the opposite flow of lithium-ions when the battery is being charged. Lithium-ion batteries are found in many portable electronics, phones, military, and electric vehicles. They have the highest energy density per weight and volume for any rechargeable battery we looked into. They are commonly called the most portable battery on the market today. Due to the high cycle counts and densities lithium-ion batteries are best used over longer periods to help drive their cost down for their usability. The drawbacks of the lithium-ion battery are the safety concern, cost, and fragility. When using lithium-ion batteries protection circuitry is required because of the safety concerns. The required safety circuitry needs to protect the cells from, overcharge, over discharge, overheating, and venting or rupture. The most popular lithium-ion cell is the 18650, this cell is even used in the Tesla Model S.

Table 10: Lithium-ion pros vs. cons

Pros	▪ Abundant ▪ Great energy density ▪ Great power density ▪ Low self-discharge ▪ High cycle life ▪ Can have low internal resistance
Cons	▪ Dangerous ▪ High initial cost ▪ Can have a moderate internal resistance ▪ Can’t tolerate overcharging ▪ Can’t tolerate deep cycles ▪ Not physically or electrically durable ▪ Temperature issues

Nickel-Cadmium (NiCd):

Nickel-Cadmium is a mature chemical battery that uses nickel oxide hydroxide and cadmium as electrodes. They boast a long service life, stable at high discharge current, and can endure extreme temperatures. The nickel-cadmium battery is the only batter that can handle ultra-fast charging without any issues. Nickel-Cadmium batteries do raise some environmental concerns. The largest drawback of nickel-cadmium batteries is that they suffer from lowering capacity when a partially charged cell is recharged. They are most widely used in power tools, medical devices, and aviation. Because of Nickel-Cadmiums all around inferior properties to its nickel-metal-hydride counterpart we have omitted it from our final comparison. This battery chemistry may be one of the worse possible choices due to the memory effect that will decrease the life span of the cells.

Table 11: Nickel-Cadmium pros vs. cons

Pros	▪ Able to ultra-fast charge ▪ Good performance at extreme temperatures ▪ High cycle count ▪ High current discharge ▪ Low internal resistance ▪ Lightweight
Cons	▪ High self-discharge ▪ Suffers from memory effect ▪ Toxic/ environmental impact ▪ Not as good as lithium or nickel-metal-hydride batteries

<u>Nickel-Metal-Hydride (NiMH):</u>

Nickel-metal-hydride are similar to their counterpart the nickel-cadmium battery but use a hydrogen storing metal in the in the negative electrode. A nickel-metal-hydride battery has a higher energy density per volume and weight meaning it has a higher specific energy. Their applications are in medical instruments and hybrid cars. The nickel-metal-hydride is nearly an overall improvement from the nickel-cadmium battery.

Table 12: Nickel-Metal-Hydride pros vs. cons

Pros	▪ Not toxic like nickel-cadmium ▪ Able to ultra-fast charge ▪ Good performance at extreme temperatures ▪ Can have a high cycle count ▪ High current discharge ▪ Low internal resistance ▪ Lightweight ▪ Much higher energy density than nickel-cadmium
Cons	▪ Can have a low cycle count ▪ Suffers from memory effect ▪ Low overcharge tolerance

4.4.3. Final Battery Comparison

The table below covers many aspects when comparing all of the batteries together. When the final decisions came to pick a battery, it came down to the lithium-ion. We picked to use a lithium-ion battery because they have extremely large energy and power densities and how widely used the technology is. Currently lithium-ion cells are used in many consumer products from laptops, cars, and cellphones. The popularity of lithium-ion batteries has been steadily increasing in recent years bring down their costs as well. The costs of lithium-ion cells are on the same level as all of the aforementioned chemistry types besides lead acid. The increase of the popularity also has grown rise to many retailers who are will provide bulk orders of many different cell types of lithium-ion cells. The largest drawback of this selection is the protection and precautions that come along with the its use. That being stated we are well aware of safety precautions and protections that need to be taken and implemented into our instrument for our safety and everyone else's safety that comes into contact with our instrument.

Table 13: Battery specifications comparison [46]

	NiCd	NiMH	Li-ion	Alkaline	Lead Acid
Gravimetric Energy Density (Wh/kg)	45 - 80	60 - 120	110 - 160	80	30 - 50
Internal Resistance (mΩ)	100 to 200	200 to 300	150 to 250	200	< 100
Cycle Life (to 80% of initial capacity)	1500	300 to 500	500 to 1000	50	200 to 300
Overcharge Tolerance	Moderate	Low	Very low	Moderate	High
Self-discharge/ Month (room temperature)	20%	30%	10%	0.3%	5%
Cell Voltage (Nominal)	1.25V	1.25V	3.6V	1.5V	2V
Peak Load Current	20C	5C	>2C	0.5C	5C
Operating Temperature (discharge only)	-40 to 60°C	-20 to 60°C	-20 to 60°C	0 to 65°C	-20 to 60°C
Maintenance Requirement	30 to 60 days	60 to 90 days	Not required	Not required	3 to 6 months
Typical Battery Cost	$50	$60	$100	$5	$25
Cost per Cycle	$0.04	$0.12	$0.14	$0.10-0.50	$0.10
Commercial use since	1950	1990	1991	1992	1970

4.4.4. Lithium-ion 18650

We decided to create our own battery pack because we can better select our supply voltage, capacity, and weight. A battery pack or battery bank is comprised of cells; these cells can be combined in series to increase the voltage and in parallel to increase the capacity. A commercial battery pack would come with protection circuitry already in place which would be convenient and safe, but we would still be limited to more fixed values that wouldn't be high enough to power everything. From this we decided to use the lithium 18650 as our cell. We chose the 18650 cell because of its popularity and abundance creating lower prices from them. Our battery pack will be comprised of four 18650 cells in a three series two parallel arrangement. This will give us double the voltage meaning 11.1 volts is being supplied and doubles the capacity from a single cell. Each cell will be placed in holders with metal plates at the end, these plates will be soldered and connected to make our battery pack where the batteries can be placed in and removed out from.

The 18650 is a cylindrical cell named for its physical dimensions, 18mm in diameter and 65mm in length, not from its voltage or capacity ratings. We selected the 18650 because it is abundant, rechargeable, efficient, lightweight, low cost, has a good capacity, and gives us a desired voltage output. We will build a pack of four cells for our final design. An 18650 supplies 3.6 volts and depending on the specific cell the capacity can range from 1500-3600mah. It is worth noting that the varying capacities can be harmful if different capacity cells are combined to make a battery bank. Using a lithium-ion battery is also attractive because of its large commercial use and applications.

4.4.5. 18650 Cell Selection

When picking a cell the team considered five different versions, the Samsung INR18650-30Q, Samsung INR18650-25R, LG HG2 18650, Panasonic NCR18650BD, and the Lishen 21700. Table 14 below shows the cells with their characteristics for the two may factors, capacity and continuous discharge rating, for comparing cells. Since initial estimation for current draw of the system was near three amps and the team wanted to design the system so that future additions could be made, we only considered cells that have at least a ten amp continues current draw rating. This is also for safety as over drawing current from a battery can be dangerous.

The cell that the team selected is the Samsung INR18650-30Q because it sat in the middle ground of all the cells. The reason a higher capacity battery wasn't chosen is because they typically have more issues with stability. Then a 20A continuous discharge rating is greater than what the team needed so we went for a lower discharge rating and a higher capacity on the cell. The nominal voltage on a cell is 3.7-volts.

Table 14: Cell Comparison

Battery	**Capacity**	**Continuous Discharge rating**
Samsung INR18650-30Q	3000mAh	15A
Samsung INR18650-25R	2500mAh	20A
LG HG2 18650	3000mAh	20A
Panasonic NCR18650BD	3180mAh	10A
Lishen 21700	4500mAh	13.5A

4.4.6. Protection and Safety

When using lithium-ion batteries certain precautions must be made for safety reasons. A lithium-ion battery should always be taken seriously. Lithium-ion batteries have potential harmful risks from being over charged, over discharging, applied reverse voltage, and physical damage. For these reasons' protection circuity and casing are required to protect the cells from any harm. The UN and the US Department of Transportation have created testing requirements for the safe packing and transportation of lithium-ion batteries (UN DOT 38.3) [47]. This testing includes eight distinct tests that are given in the standards section.

Commercial protection modules can be purchased but they still require a little design work and assembly. We decided to take the safest approach to this aspect of the project. Because of the afore mentioned safety reasons, we have decided to leave out implementing a built-in rechargeable feature into our project. This is because protection circuitry is needed to prevent damage to the batteries. We have opted for removable cells so that we can safely recharge them in a commercial charging station. In accordance with safety we will only use the batteries in the instrument when it is being used for testing or playing, store each individual cell in an antistatic bag, and only charge them when they can be watched. If time permits after we have completed all our basic requirements for the project, we will work to include a built-in rechargeable feature so that the batteries do not have to be removed to recharge. This will aid in the ease of use for the user.

4.4.7. Voltage Regulation

Because the high voltage from the battery and pack and because components such as the MCU and sensors cannot take 11.1 volts directly from the battery pack regulators will need to be introduced in to the power system. Specifically, for the laser diodes a switching regulator will need to be introduced because of their high current draw. A switching regulator works by turning on and off to lower the output voltage. The team saw best if the MCU was powered by a linear regulator because they are more stable than a switching regulator. This doubles as a level of protection for the MCU as well. The entire power system consistent of three separate voltage regulators, one switching and two linear regulators.

4.4.7.1. Switching Regulator

Because of the laser diodes in the system at least one switching regulator will need to be used in the system. The switching regulator will have a voltage input directly from the battery pack. A single switching regulator can be used to power all parts of the system, but the team opted out of this option due to sensitivity needs of the sensors and the MCU. Most switching regulators have similar circuits that include various capacitors and an inductor to help decrease ripple in the output. The switching regulator required for the instrument should be able to handle over three amps continuous and be over 80% efficient in its application.

4.4.7.2. Switching Regulator Selection

The team considered two main switching regulators, both from Texas Instruments. Both have been in use since the early 2000's and are well documented on. This will help in the design and selection of the switching regulator to be selected. The two switching regulators the team considered are the LM2678 and the LM2576. The greatest difference between the two regulators is that the LM2678 is rated for five amps and the LM2576 is rated for three amps.

Looking into the data sheet of the LM2576 and using the charts for the estimated three-amp current draw with a twelve-volt input and a five-volt output the LM2576 is reported to have around a 77% efficiency [48]. This is considered very low efficiency for a switching regulator since most modern switching regulators achieve over 90% efficiency. Then the current rating of the LM2576 is only three-amps which is at the edge of the systems current estimation. Choosing the LM2576 means that the team will be pushing the chip to its limits and run the risk of failure.

Looking into the data sheet of the LM2678 and using the charts for the estimated three-amp current draw with a twelve-volt input and a five-volt output the LM2678 is reported to have around an 84% efficiency [49]. This is much higher than that of the LM2576 but still a low efficiency for a switching regulator. The LM2678 comes in a few different packages including an adjustable and a fixed five-volt output versions.

The team's final selection for a switching regulator was the LM2678 because it has the higher reported efficiency and the current rating is five-amps which is much higher than that of the estimated current draw for the system. This is the safer choice of the two regulators and will save power with the higher efficiency.

4.4.7.3. Linear Regulation

Linear regulators provide stable outputs but are inefficient, creating lots of heat. They are best used for low current applications or where high stability is required. Since the instrument requires highly accurate sensors as well the team will use linear regulates for them to help prevent any miss readings by the MCU from a sensor.

4.4.7.4. Linear Regulator Selection

The two linear regulators in the system are from the same family so they have the same footprints. The two linear regulators used in the system are the LM7805CV and LM7806ABV. These come in a three-pin layout, ground, voltage in, and voltage out. While linear regulators have heating an efficiency issues, they have highly stable outputs, with little noise and ripple. The reason for selecting both was because the team already had L7805CV regulators on hand from initial testing.

The five-volt regulator is used for the MCU and the alpha sensors. The MCU selected, the atmega 2560, requires a voltage supply between 4.5 volts and 5.5 volts. The team decided to move the MCU to be powered by a linear regulator to add a buffer of protection from the batteries and because the switching regulator in the system would on occasions have a voltage run away issue. Through testing the team discovered that the alpha sensors require the same power supply as that the MCU receives or the detections are not always picked up. For this reason, the team move the alpha sensors to be powered by the L7805CV as well.

The six-volt linear regulator selected was the L7806ABV. The team selected this linear voltage regulator because of the previous experience with its five-volt family member. The L7806ABV powers the op-amp in the beta sensor circuit. The reason to have the beta sensor to have a six volt supply instead of a five-volt supply is because it increases the range on the output of the beta sensors. When the op-amp in the beta sensor is supplied with six volts the max rail to rail output is about 4.7 volts, up from 4.3 if it was supplied with five volts. Since the beta sensor is highly sensitive the team selected the ABV version from CV, which the linear five-volt regulator the team used is. The ABV version has overall better characteristics, with lower swing, less noise, and more stable.

4.5. Laser Emission System

As stated previously, we intend on having visible beams of light that are able to control an output audio signal based on its reflection intensities. There are different light sources that could be used such as lamps, incandescent light bulbs, and LEDs. However, because we wish to have the appearance of a string made of light, a collimated light is desired. This can be achieved with the use of a laser. In order to have a proper array of lasers that emit at a suitable level of visibility and power, several key issues will have to be addressed.

4.5.1. Visible Wavelengths

Wavelengths can range in length from several kilometers, as is the case with radio waves, to a few molecular as seen in gamma rays. The human eye can only perceive light with wavelengths from approximately 400 nanometers to 700 nanometers [48]. This region of wavelengths is known as the visible light spectrum that houses millions of colors. Blue and violet are at and near the 400-nanometers limit while red is at the 700 nanometers. If we are to make the beams of light visible, it would be necessary to produce the beams within this region. This means that infrared and ultraviolet lasers will not be optimal to use.

4.5.2. Human Eye Response

Although the human eye can perceive light from the visible light spectrum, some wavelengths of light are more visible than others. This is due to light interacting with the retina in the eye which contains photoreceptive cells called rods and cones [49]. When light is incident upon these photoreceptive cells, a photochemical process occurs in which these cells absorb the light and produce neurological signals for the brain to interpret as sight. Since rods and cones have a certain combination of chemicals it happens to be the case that they are more sensitive to green than to red or blue. This means that for the selection of lasers, using a laser diode that can produce green, which can be between 500 nanometers and 570 nanometers, would be more receptive to the human eye than red or blue.

4.5.3. Laser Emission

In order produce a laser beam, it is important to have a basic understanding of how a laser works. A laser has three primary components: the laser pump, gain medium, and optical cavity [50]. The laser pump is an energy source that excites electrons in the gain medium to a higher state of energy than they were before. The gain medium is the material by which the electrons are excited. It provides the amplification needed of the optical power that is produced by the stimulation of electrons. The optical cavity acts as an optical feedback for the laser light by trapping it in the laser body and making the light go through the amplification process again producing more light. There are many different types of lasers that can be used such as gas, fiber, semiconductor, and dyes to name a few. Below is a comparison of some of them. A semiconductor laser uses the bandgap energy of the semiconductor to produce light when sufficiently pumped [51]. Gas lasers use a gas, usually a noble gas, to act as the gain medium. Fiber lasers work by having a fiber optic cables carry the laser beam from its emission source to its desired location. Some fibers are able to act as a gain medium to produce a specific wavelength. Dye lasers work by having a pump light be incident onto an organic dye to use as a gain medium. They are typically in a liquid solution and are used for wider range of wavelengths than most other gain mediums.

Table 15: Laser Comparisons

	Semiconductor	Gas	Fiber	Dye
Size	Very Small	Large	Small	Small
Weight	Very Light	Medium	Very Light	Light
Cost	Low	High	Medium	High
Thermal Load	Low	High	Low	Medium
Efficiency	High	Medium	High	Low
Durability	Medium	High	High	Low
Electrical Installation	Easy	Medium	Medium	Easy

Due to the cost and size, our project will implement the use of semiconductor lasers. Low-powered semiconductor lasers are usually a few dollars to acquire, as opposed to gas or dye lasers that can be in the hundreds or thousands of dollars to purchase. They are compact (typically smaller than a coin as seen in Figure 5, have a low cost, tend to emit low amounts of heat, are efficient in converting electrical input to optical output, and are easy to install. They might not be as durable as some of the other lasers but for the length of working this project, the semiconductor laser diodes will last enough time. It is worth noting that fiber lasers were consider for the project due to their reasonable cost and weight. The idea would be to use the fiber optics as the strings for the laser system to guide the user to play the beams. When the user plucks the fiber optic an interruption in the beam will occur. This interruption will act as the on/off switch for audio output and the detection would be based on how much the beam was distorted. The detection would be based off a variation of a constant laser beam to determine what note to play. In this design a laser beam could come from either the top or bottom of the frame for which a fiber optic cable would carry the beam to the other side where a photodetector would be used at the end of the fiber to detect the variations. This means that only one photodetector would be used per string. However, issues of misalignment from plucking the fiber, and the potential of shattered fiber glass if plucked too hard made us consider the free-space semiconductor laser approach as the best to implement for our laser system.

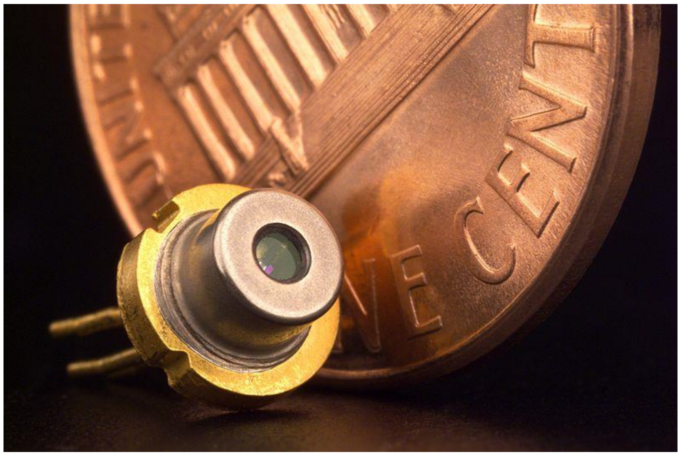


Figure 5: Semiconductor laser diode compared with a coin. Public Domain.

Certain wavelengths are easier to create than others. This mainly has to do with how the energy levels are established to get a desire wavelength. Sometimes there can be multiple energy states that make it tricky to get appropriate lasing conditions, others require multiple gain mediums to convert from one emitted wavelength to another, and some use complex optical processes to get a wavelength. It is for this reason that wavelengths which are easier to create are less expensive than those that have a more complex process to generate them. This is worth noting when looking for laser diode components.

4.5.4. Visibility of Laser Beams

Part of the project is dependent on being able to see the beam in order for the user to see whether they are playing the string and to have an audio-visual experience. The issue arises when there is so much light from the laser that it could saturate the photodetectors but if there is too little light then it might not be visible. To remedy this problem a black backdrop can be added to create a contrast of colors and make the beam more visible than before. A fog could be used to reflect some of the light off and make the beam visible. Typical though fog machines used indoors tend to cause problems with the fire alarms, often triggering them off. It would therefore be advisable to seek an alternative that is affordable, safe to use, and can last a decently period of time. It is for that reason that dry ice might not be suitable for our needs since it is not healthy to inhale and tends to melt quickly. An option worth exploring is the use of a vapor machine. They cost little to obtain, would not trigger fire alarms, are safe to inhale when using appropriate liquid solutions, and the mist can linger for a reasonable amount of time while the instrument is in operation. A combination of black backdrop and a vapor machine could help boost the visibility of the laser beam.

4.5.5. Safety

The human eye is very sensitive and can be damaged with a concentrated beam power of one microwatt [52]. Since people will be interacting with the laser beams up close, it is important to ensure that no is harmed while using the instrument. It is vital for the project to limit as much stray lights as possible in design and in practice. For the design portion, a small wall on the side where the lasers are incident on are can be implemented. This will block any stray lights from hitting someone in the eye. In practice we could have laser safety googles that attenuate the appropriate wavelength to such a degree where it would be below one microwatt and not cause harm.

4.5.6. Power Emission Limits and Tradeoffs

Throughout the course of researching for this project, it was realized that there are limits our laser diodes have and the tradeoffs with the amount of power that can be emitted. One of the limits it has is the threshold voltage. Since diode have an internal resistance, a certain amount of applied voltage is need in order to overcome this resistance. The downside to this increase in applied voltage is that the minimum amount of power the laser diode can produce also increases. This can prove to be problematic if lower power is needed than the threshold voltage will permit. Great care must also be taken when going to higher voltages since it could run the risk of overheating and burning the laser diode. Power threshold also tends to plateau after a certain amount of voltage is supplied to it [53]. This means that the maximum and minimum power values of a laser can cause problems down the road if the project needs to go beyond those limits.

As mentioned earlier, the biggest tradeoffs for the laser power output is between the photodetector and visibility. More power output would be ideal to see the laser beams, but it could saturate the photodetectors making them inefficient at sending appropriate signals to the microcontroller, as well as burning them out. If less light intensity is used, then the photodetector would be safe, but it could be difficult to perceive where the laser beams are. Using different wavelengths could prove to be useful if the photodetectors have a low response to a specific wavelength but can be seen well to the human eye.

4.5.7. Chosen Lasers

As stated, before we will be looking into semiconductor laser diodes in order to produce our laser system. Considering that certain colors are perceived more by the human eye and some colors are easier to produce than others, and are less costly, our project has decided to implement green lasers with red lasers as a back-up source. We also decided to buy the laser diode with its module since it makes electrical installation easier than the bare laser diode itself. We did this because with the module all we do is connect the voltage leads and regulate them with the electrical system as oppose to creating a separate circuit for the laser emission that might not end up being functional.

As stated before, green is the most visible color to the human eye. If we wish to make the beams as visible as possible green lasers will be our best color to use. Green is an easy color to produce because it can undergo one lasing process when creating 520 nanometer wavelength light or can undergo two simple lasing processes when using 532 nanometer wavelengths. This means that its costs are low, especially when comparing it to other colors such as yellow lasers that can price at more than $200. Ranging from around $10 to $15 each these diodes are well priced to have multiple beams in which the total laser system would be under $100. They are also easy to thermally control since they are covered by a metal heat sink and are small enough that a simple ventilation system can regulate their heat dissipation. The typically maximum rated input voltage is 5 volts which is within our voltage range from our batteries. We will be looking for an output power rating of about 5 milliwatts or less, which are available for green laser diodes, in order to maintain safety of the instrument and for the user. If we come across a laser diode that has a higher power rating, we can control the power electrical to maintain safety. It is for these reason that the green laser diode will be the primary choice for our lasers.

Figure 6: Semiconductor laser diode modules. A) Green laser. B) Red laser.

As with every project, there has to be a backup plan for when plans do not go as predicted. For our laser systems, we need to account for the possibility of the green laser diodes to not be as compatible with our overall system as presently predicted, to malfunction, or not function at all. As an alternative to the green laser diodes, red laser diodes will be considered. There are multiple reasons for this despite some disadvantages. One of which is the cost. Typically, a pack of ten low-powered 650 nanometer wavelength laser diodes cost about $2 to $6. This allows us to dramatically decrease the cost of the laser system. Although using a red laser light has less visibility to the human eye than a green laser light, it is still visible enough to be perceived. A way to mitigate the loss of visibility is to increase in the input voltage so as to increase the power and compensate for the visibility. The maximum rated input voltage is typically 5 volts which is similar to the green laser diode. As seen in Figure 6(B), the red lasers are small and will be able to easily fit in the instrument. On top of having a metal heat sink as a casting, their size also makes them easy to thermally control since a small amount of ventilation is enough to regulate their heat dissipation. For our purposes, their output is also comparable to the green laser diode since they can be rated to have a 5-milliwatt output power. It is for these reasons that despite having a lower visibility than green wavelengths, the red laser diodes can be used as an alternative to the green laser diodes. It is important to acknowledge that blue laser diodes modules were also considered as an alternative. However due to their increased cost, at an average cost of around $30 or more with some cases in the hundreds of dollars, and higher power consumption they were not selected as an alternative laser choice.

4.6. Intensity Detection

One of the main operations of the project will be its detection system. Once the laser emission system has provided the light for the user to interact with, the detection system will capture the light that is being emitted. The purpose of the detection system is to receive the optical signals from the laser system and produce an electrical output for the software to interpret what sound to allocate to which beam. The detection system will be the link between the optical side of the project and the electrical side. When it comes to detecting light, there are different methods that can be implemented to do so.

One of those methods is detecting the frequency changes of a signal. Frequency modulation involves processing information by mixing the frequencies of the carrier waveform and the center frequency. This is typically done to convert from digital to analog. To detect this modulation, the system will receive the frequency of an incoming carrier wave and interpret the difference between the carrier frequency and its center frequency. These differences in frequency reveal encoded information from the wave that can be used to reproduce a digital output. For our project, we could use a higher frequency to represent a higher note and a lower frequency to denote a lower note. However, since our input laser light will be interrupted by a hand or some other medium, the fidelity of the beam's frequency can be compromised and distort the information.

Phase detection is a technique that interprets the incoming signal based on the variations of the phase. Information can be stored by changing the phase of the wave and creating a pattern of modulation. A detection system could then sense the difference of the phases and reconstruct the information encrypted in the signal. A larger phase angle could be used as a way to determine a high note to be played and a lower phase angle could signify a low note. In this technique, high accuracy is required to detect quickly the subtle changes in phase. Similar to frequency detection, the phase could be distorted when the signal is incident to an object before reaching the detector.

Another method is doing intensity detection in which the detection system receives different intensities of light and converts it into electrical amplitudes. These amplitudes tell the software which notes to play in a range of notes. For example, a high light intensity could send a high electrical amplitude to play a high note in the range and a low light intensity could send a low electrical amplitude to play a low note. By having the user modulate the intensity of the light with their hand or using a surface, the light can undergo amplitude modulation. Due to the simplicity and feasibility to conduct this detection on a limited budget, intensity detection was determined to be the best suited detection system for our project.

4.6.1. Photodetectors

To be able to create a light intensity detection system a photodetector is essential. Photodetectors are devices that transform optical signals to electrical signals [53]. These electrical signals can be processed through electronics to provide several types of information about the environment and how the system should function with respect to that information. For our project, we will be looking into two types of functions a photodetector can perform. The first is the alpha detector that serves as a switch to turn on or off the ability for a laser beam to initiate a note. The second is the beta detector that will act as the determining factor for which pitch to play based on the intensity of the reflected light. There are a couple of factors that are involved when using photodetectors in our project such as dark current, noise, sensitivity, responsivity, saturation, response time, reflected light, and sensor housing.

4.6.2. Dark Current

When the photodiode has an absence of incident light, the carriers inside of the semiconductor are still pairing with each other in the depletion region. This causes a small electric field that drives a current known as dark current. Dark current can be seen as the intrinsic electric noise a photodetector can experience [53]. In some photodetectors, such as charged-couple devices, dark current can be the most significant contributor to noise. For other detectors, such as photodiodes, the typical dark current values are so small, in the order of a few nanoamps, that it can be negligible.

4.6.3. Noise

There are a few noise factors a photodetector can experience. One is the dark current described earlier. Another factor is the thermal noise in which the temperature of the diode can drive up the dark current from nanoamps to a few microamps. This thermal noise is often called the Johnson-Nyquist noise. Thermal noise can be mitigated by implementing appropriate cooling systems. We hope to maintain temperatures at or below 40°C in which most photodiodes would have a dark current of a few nanoamps. The biggest driver of noise however is the ambient light incident on the photodetector. Unwanted light that is picked up by the detector increases the noise threshold that the desired light needs to overcome. It can also cause unwanted electrical signals to be emitted. To remedy this issue the voltage applied to the photodetector can be increased to drown out the noise and have the desired light be the sole actor in driving the photocurrent. A housing for the photodetector can be implemented that blocks out most of the ambient light.

4.6.4. Sensitivity

When looking at photodetectors, it is important to account for its sensitivity. The sensitivity describes what wavelengths of light is the photodetector most likely to receive and operate. This is important to understand because if we want to use visible wavelengths, and we end up getting a photodetector that is sensitive to infrared or ultraviolet, then we would not have a detection since the detector is not made to sense visible wavelengths. If there is a particular visible wavelength we wish to use, for example green, then it is critical to find a detector that is highly sensitive to green wavelengths to get the maximum amount of detection. It is also useful if there is a need to use multiple wavelengths because some detectors have a broadband spectrum that can accept different wavelength in different amounts. So, if we plan to have red laser diodes as an alternative to the green lasers then a photodetector that can detect a decent amount of red would also be desirable.

4.6.5. Responsivity

The photocurrent response of a detector to an incident light is known as the responsivity. As discussed above, one of the main advantages of a photodiode compared to other photodetectors is the mostly linear responsivity they have with respect to the incident light. The more light is detected, the more photocurrent is generated. Usually photodiodes have a bandwidth of light that they can detect. At certain wavelengths they can produce higher photocurrent than other wavelengths. The amount of responsivity that a photodiode has at a particular wavelength is determined by equation 3.

$$R = \eta \frac{e}{hv}$$

Equation 3: Responsivity

Where *R* is the responsivity, *hv* is the photon energy, η is the quantum efficiency of the photodiode, and *e* is the elemental charge. This means that for some wavelengths in which the photodiode is more responsive, there is less power required to drive their illumination than for wavelengths that are less responsive. This plays a key role in determining which photodiodes are best suited to detect the emissions from the laser diodes.

4.6.5.1. Radiometry and Photometry

Throughout the course of researching which photodetectors to use, an issue of units arose. A decent number of photodetectors have responsivity shown as lux for the incident light instead of watts. Since lasers have their outputs shown as watts this presents an issue in knowing how much power a laser should have for a desired responsivity. In order to resolve this issue an understanding of the two units and conversion between them was necessary. Lasers tend to work in terms of radiometry which is a way to “describe [… the] radiant energy independently of its effects on a particular detector.” [56] This means that the measurement of the laser output does not depend on the sensitivity of a detection system but rather is the physical radiant flux. The units used to describe radiant power and irradiance (the “ratio of radiant power [over a given surface area]”) are watts and watts per meter squared respectively. On the other hand, detectors that use lux are working in terms of photometry which states that the “measurement of [… light is dependent on the] simulation of human vision.” This means that the measurements describe how light is perceived by the human eye and thus differ in the actual physical measurements of the incident light. The units for luminous flux, which is the spectral response on the human eye, and illuminance, which is the luminous flux over a surface area, are lumens and lux (lumens per meter squared) respectively.

Conversion between radiometry and photometry begins with understanding that both unit systems are analogous to each other. The radiant power and irradiance seen in radiometry is similar to the luminous flux and illuminance seen in photometry respectively. This means that watts and watts per meter squared are analogous to lumens and lux respectively. The conversion begins with the CIE 1931 color space standard which sought to quantitatively measure how the visible wavelengths of light were perceived by the human eye [59]. The standard highlights how different visible wavelengths are perceived to be brighter than other wavelengths because of the interactions light has with the rods and cones in the human eye. From this characterization a photopic (using just the cones of the eyes) equation can be made showing the luminous flux derived from spectral radiant power [56].

$$K_m = 683 \frac{V(\lambda_m)}{V(555.016\ nm)} \cong 683\ lm\ W^{-1}$$

Equation 4: Photopic luminous efficacy

In equation 4, "K_m is the luminous efficacy [… and] $V(\lambda_m)$ is the spectral efficiency function for photopic vision." This means that if there is a desired wavelength that is to be used, the spectral efficiency value can be looked up to find the how much luminous efficacy can be produced in radiant values. At a wavelength of about 555 nanometer the $V(\lambda_m)$ is one. A list of the spectral efficiency for the visible wavelengths is seen below.

Table 16: Photopic spectral luminous efficiency function V(λ)

λ/nm	V(λ)	λ/nm	V(λ)	λ/nm	V(λ)	λ/nm	V(λ)	λ/nm	V(λ)
360	4E-6	460	60E-3	**555**	**1.000**	650	0.107	750	120E-6
370	12E-6	470	90.98E-3	560	0.995	660	61E-3	760	60E-6
380	39E-6	480	0.13902	570	0.952	670	32E-3	770	30E-6
390	120E-6	490	0.20802	580	0.870	680	17E-3	780	15E-6
400	396E-6	500	0.323	590	0.757	690	8.21E-3	790	7E-6
410	1.21E-3	510	0.503	600	0.631	700	4.102E-3	800	4E-6
420	4E-3	520	0.710	610	0.503	710	2.091E-3	810	2E-6
430	11.6E-3	530	0.862	620	0.381	720	1.047E-3	820	1E-6
440	23E-3	540	0.954	630	0.265	730	52E-6	830	0
450	38E-3	550	0.994950	640	0.175	740	249E-6		

In order to simplify this calculation, photopic graphs have been made using the data that was gathered for this standard and presents a graphical conversion of the equation 4 and table 16 above [60].

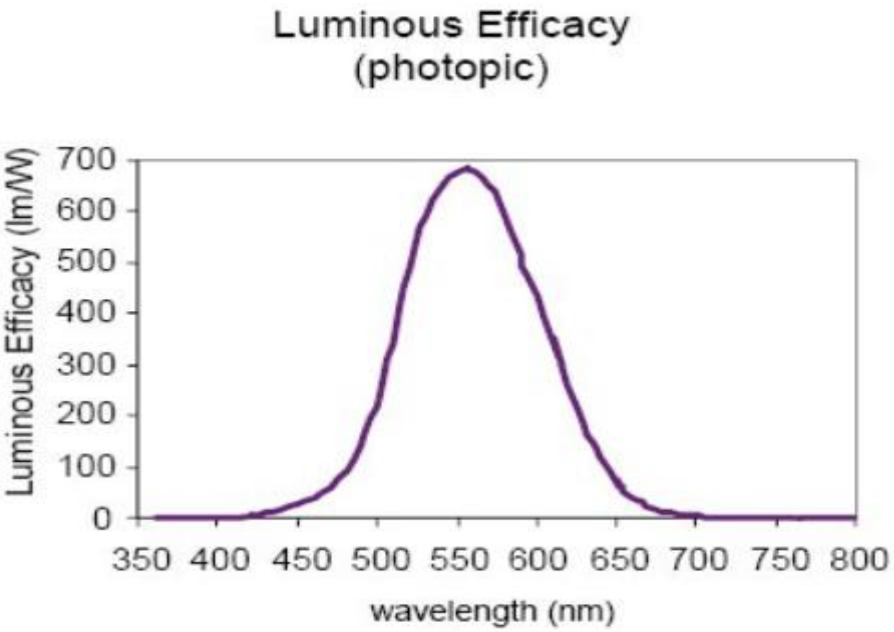


Figure 7: Photopic Curve. Courtesy of SPIE.

From figure 7 it is easy to see how much light intensity is equivalent to the power output of a laser. For example, if a 555-nanometer wavelength emits 1 watt of power then the equivalent luminous value in photometry would be approximately 683 lumens. Since photodiodes have detection areas that work with respective to lux, which is lumens per meter squared, the spot size of the laser diode will need to be accounted for in order to convert the resultant lumens to lux. This can be done by dividing the lumens with the spot size area in terms of meters squared. The reverse can also be done if one wishes to find how lux of a certain radiant power a laser beam can produce.

4.6.6. Saturation

When a photodetector receives more light than it can handle, the photodetector will not be able to distinguish between different input intensity values past its rated value [61]. It is at this point that the photodetector is said to be in saturation. On top of making the photodetector not work properly, one of the many problems with saturation is that it can cause significant damage to the device and could cause it to stop functioning all together. It is imperative to prevent saturation and avoid damaging the device. One of the ways to do so is by understanding how the responsivity of the photodetector corresponds to its saturation.

Responsivity can tell the point at which the photodetector will be saturated by the incident light. This can typically be determined from the breakdown voltage of the photodetector [62]. In order to maintain within the linear regime of light response, it is important to have the input voltage go up till approximately 60% of the breakdown voltage. At that point the responsivity starts to decrease until it plateaus in saturation. An increase in the voltage can allow for higher intensities of light to be used that would otherwise saturate the photodetector. However, if the device reaches the breakdown voltage, it will stop functioning. This is important for our project because it means we have to balance the power use of the laser diodes and how much photocurrent can be generated while not saturating the photodetector or causing the device to breakdown.

Another way to prevent saturation is by the use of an optical filter. These kinds of filters have two characteristics: the wavelength and the optical density [63]. For optical filters, the wavelength that they block is important to know in order to filter out the specific light that could cause saturation. The optical density describes how much of that light is attenuated. They are typically rating in orders of magnitude, so an optical density of 2 attenuates the light ten times more than an optical density of 1. As it relates to our project, a filter could be implemented to the photodetector to reduce how much light is incident to the device and prevent saturation. Since the top photodetector is being directly hit with the laser beam, it could have a filter installed in front of it to attenuate the beam. The bottom photodetector on the other hand could need a filter but if an interrupting hand, or another medium, absorbs some of the light then the reflected light might not be powerful enough to saturate the device and a filter might not be necessary.

4.6.7. Response Time

As with all systems, there is always a delay between processes. Usually that delay is undesired, and the less time is wasted on delays the better for the overall product. For detection systems that delay can come in the form of the response time of the photodetector. The response time is the time it takes for a photodetector to react to an incident light. The reaction is typically in the form of the generation of photocurrent or photo-voltage. It is important for our project to know how fast the response time is for photodetectors because in order to produce a seamless transition from beam interruption to an audio output, the processing has to be faster than the human perception.

Capacitance tends to affect the response time [64]. Typically, in photodetectors there is a capacitance value of the device. If the capacitance is low, then a faster response time can be achieved than with a higher capacitance. This is due to the capacitance being able to quickly release a response if it’s low than if it’s high. Usually photodetectors show graphs with one megahertz frequency dropping off in capacitance as voltage increases.

Frequency also has an effect on the response time in that the higher the frequency of the incident light, the longer the response time is than in lower frequency. This is because the device needs to work harder to overcome the higher frequency and take a longer time to do so than at lower frequencies. This relates to our project because although we are doing amplitude modulation, there is a frequency in how fast the beam is interrupted. If we were to consider the fastest human movement, eye blinking, it clocks in at about 100 to 150 milliseconds [65]. Despite it being the fastest human physiological movement, it is still slower than the response time of some photodetectors which can pick up signals in microseconds or in nanoseconds. This means that if a human hand interrupts a beam the photodiode will be able to keep up with the speed of the interruption; no matter how fast someone moves their hand.

4.6.8. Reflected Light

For the intensity detection system, the reflections of light are going to be the biggest factor in determining the notes that will be played. It is therefore important to understand how reflections work. When an incident light hits a surface, some of the light transmits through the surface and interacts with anything that is pass the surface. The rest of the light is reflected off the surface at an angle. It is important to note that the incident light has no angle when it is perpendicular to the surface (also known as the normal incidence) and a 90-degree angle when it is parallel with respect to the surface. As seen in figure 8A, when light is incident on a smooth surface, the reflected light comes out at the same angle as the incident angle at the other side of the normal incidence. When light is incident on a rough surface, as is the case in figure 8B, the light reflects in many angles. This cause the light to spread out and diffuse over an area as opposed to the smooth surface which would maintain a relatively tight output light. The effect is that the intensity of light decreases at any particular point in the emitted area.

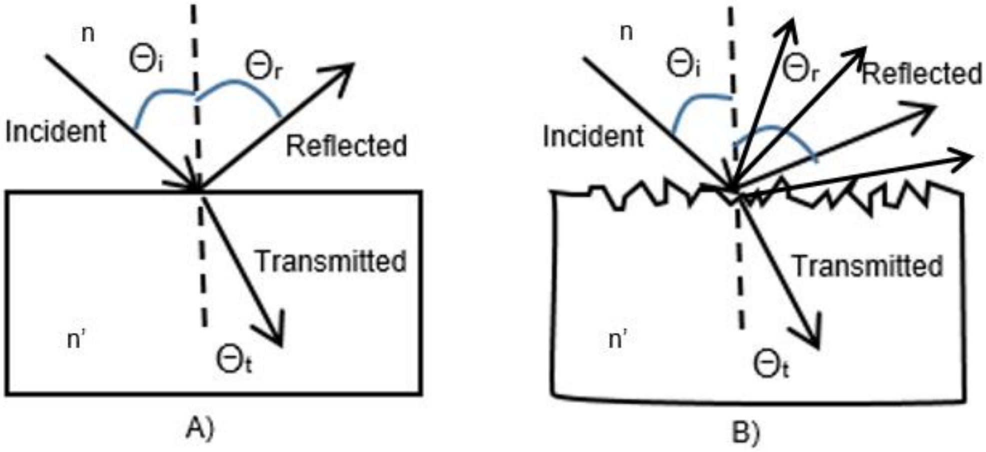


Figure 8: Reflections. A) Light off a smooth surface. B) Light off a rough surface.

On top of that if the material has a low reflectivity, then more light will transmit and be absorbed by the material and less light would be reflected. The power of the reflected light is therefore affected by the surface roughness the incident light hits and how reflective the surface is. This is important to understand because if a more collimated reflected light is need than expected, a smooth surface could be used to maintain relative beam size. If a wider beam spot size is need, perhaps to decrease an incident light's lux value (since it is lumens per surface area,) then a rough surface such as sandpaper can be used to diffuse the light. If the intensity of the reflected light needs to be maintained, then a surface with high reflectivity can be used. However, if the reflected light intensity needs to be decreased, then a less reflective surface can be used. All of these factors can allow for greater control on the lux values incident to the photodetector.

4.6.9. Sensor Housing

In order to reduce saturation of the photodetector, the housing of the photodetector can be considered. If the surface of photodetector is at the surface of the frame, then a cylindrical shell or a half spherical shell can be implemented on top of the photodetector. This limits the amount of ambient light that can come from different angles. A black inner layer can be added to absorb any ambient hitting the inner sides of the shell and prevent reflections from the sides from hitting the detector. Another way to reduce ambient light is to regress the photodetector into the frame. In this way the frame acts as an ambient light limiter in which less light can reach the photodiode and effectively reduce ambient noise. The inside of the frame that houses the photodetector can have a black inner layer to further reduce ambient light.

4.6.10. Chosen Sensors

Having considered the previous parameters for a photodetector, a selection must be made on which photodetectors to use. It is important to consider whether they can detect intensity changes, are low in power consumptions, and have small parameters as these units will be working in conjunction with the entire electrical system. Inexpensive detectors will be largely considered as well in order to maintain within budget, especially since multiple sensors will have to be implement into the instrument.

4.6.10.1. Photodetector Comparison

There are various types of photodetectors including photoresistors, charged-coupled devices (CCD), phototubes, and photodiodes among others. Below is a comparison in table 17 of some photodetector.

Table 17: Photodetector Comparison

	Photoresistor	Photodiode	Solar Cell	CCD	Quad Cell
Intensity Detection	High	High	Medium	High	Low
Dark Current	Low	Low	Medium	High	Low
Power Consumption	Low	Low	Low	High	Medium
Size	Small	Small	Large	Medium	Medium
Cost	Very Low	Low	Medium	High	High

For the purposes of this project, we will be using photoresistors and photodiodes. The biggest factor in this was their low cost and functionality of detection. We plan to have one photoresistor and one photodiode for every beam. The photoresistor will act as the alpha detector and will detect if the incident beam from the laser has been interrupted. It will send a signal to a microcontroller that the beam is being played and enable the sound for the detected light intensities. The photodiode will act as the beta detector that detects the intensity of the reflected beams and sends a signal to microcontroller to determine the note that will be emitted for certain intensities. Although the other photodetectors could have done a similar detection, it is not worth paying more for a device in which the functions can be done by a cheaper device. We were also concerned with power consumption because if we have our power supply be based off of batteries then at some point those batteries will be drained. We want to make the power life be extended as much as possible so with power consumption we are able to achieve that. We also wanted to make the photodetector as usably compact as possible so that they can fit in the instrument.

4.6.10.2. Photoresistors

Photoresistors are semiconductor resistors that change resistance when light is incident. Also known as photocells, photoresistors are passive semiconductors that do not have a PN junction. They have high resistances when in darkness that can be in the megaohms and have low resistances when fully exposed to light that can be in the hundreds of ohms. Despite having a longer response time and less sensitivity than photodiodes, they are suitable for our project because they can be used as switches to enable a beam to be played and are more affordable than photodiodes.

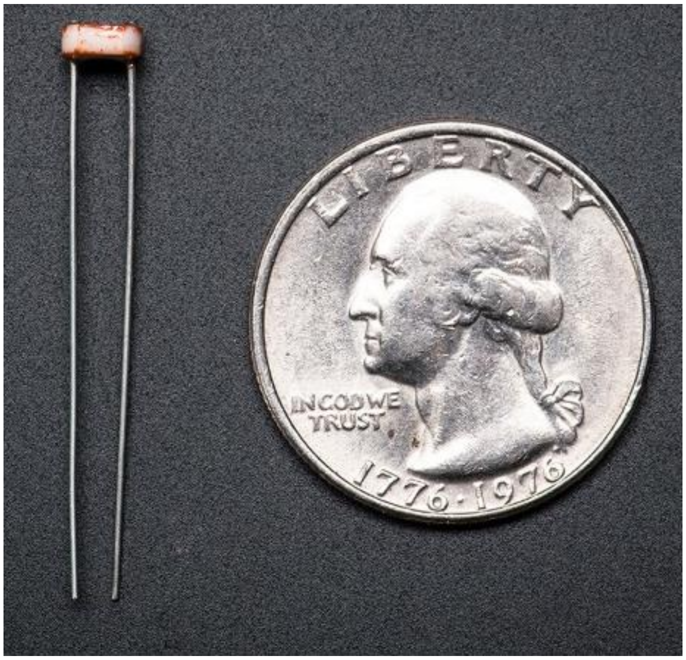


Figure 9: Photoresistor size compared to a quarter. Permission requested.

As seen in Figure 9, the size of a photoresistor is comparable to that of a coin. This means that we will be able to have enough room to have the alpha detectors and their respective housings. We plan on using photoresistors with medium to high ohm values to provide greatest amount of note range possible.

4.6.10.3. Photodiodes

Photodiodes are semiconductor photodetectors capable of receiving an optical signal and producing an electrical current or voltage output [67]. When incident light interacts with the semiconductor, a surplus of holes and electrons are formed in the depletion region. This causes an electric field to drive the surplus carriers out of the depletion region and generate photocurrent. There are several reasons for using this type of photodetector. One of the biggest factors is the mostly linear response of the incident light to the current output [68]. This linearity eases the integration of the detection system because it enables easy comparisons of the input and output of the photodetector. Other factors include fast response time, good responsivity, very low dark current, low noise, and affordable costs. All of which will be discussed in detail later in the following sections.

The main modes of operation are photoconductive or photovoltaic mode [69]. In the photoconductive mode, the PN junction has a reverse-bias where the junction is used as an optical detector. When no light is present, a small amount of current, called dark current, is able to go through the external circuit. When light is incident on the junction, the light excites extra free charge carriers. This in turn causes a dramatic increase in the reverse current. Under the photovoltaic mode the PN junction is operated in an open circuit. This means that the junction has no external voltage applied to it. Here the current is zero but across the PN junction a positive voltage is generated when light is incident. Similar to the photoconductive mode, the incoming light produces a surplus of charge carriers known as electron-hole pairs. The depletion region is then under the influence of the built-in potential that causes the electrons to go towards the N-region and the holes to go to the P-region. The result is the PN junction acting as a battery that has a positive and negative electrode seen between the P- and N-regions, respectively. With this process, the junction is able to generate a positive forward voltage to an external circuit. However, the voltage cannot increase forever as more incident light hits it. At some point the voltage will be constant and reach saturation. For the purposes of this project, we will be focusing on the photoconductive mode.

Table 18: Photodiode Types

	PN	**PIN**	**Avalanche**	**Silicon**	**InGaAs**
Sensitivity	Medium	High	Very High	High	High
Response Time	Low	Fast	Fast	Medium	Fast
Cost	Low	Very Low	Medium	Low	High
Wavelength	Visible	Visible/IR	Visible/IR	Visible	IR
Responsivity	Low	High	Very High	Medium	High

Based off of our requirements, we decided to go with the PIN photodiode. PIN photodiodes have a large number of attributes that fit in line with our project. They are better than PN photodiode because it can absorb more wavelengths, are have a faster response time, and has a higher responsivity. Although avalanche is a phenomenal in sensitivity, response time, and responsivity, they cost more than a PIN photodiode. After looking at the specification of the avalanche it was made apparent that we might not need as much of the sensitivity or responsivity it was capable of doing. This meant that it was not worth paying more for a device that we would not be using all of its functions if another cheaper device can do what we want. In GaAs has good photodetector characteristics but the cost and the fact that it is mostly used in the infrared domain meant we would not be using it in our project. Silicon is an ubiquitous material found in most visible detectors so it is probable that our photodiodes will have silicon in it. After searching for various PIN photodetectors, we decided to settle with the Vishay TEMD5510FX01 PIN photodiode as seen in Figure 10.

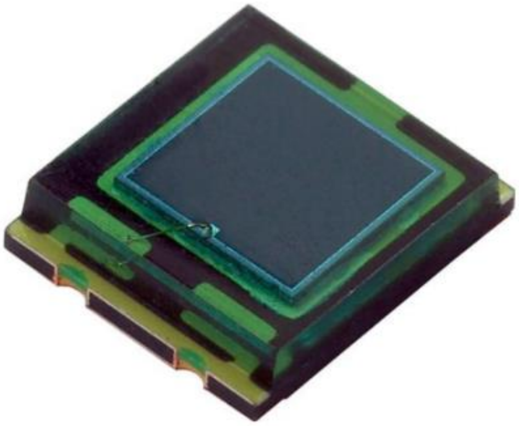


Figure 10: Vishay TEMD5510FX01 PIN photodiode. Courtesy of Vishay Intertechnology.

One of the main advantages of using this particular photodiode is that it is closely related to the human eye in regard to sensitivity [70]. This means that the photodiode is most sensitive to green light and less sensitive to other colors. There is also the added sensitivity to infrared wavelengths between 800 nanometers and 1200 nanometers which gives us extra wavelengths to use if needed. The photodiode is also similar in responsivity to the human eye. This means that if the laser beam is too bright for our eyes, it will also be too bright for the photodiode, which comes in handy when trying to get a rough estimate for saturations. The responsivity of this photodiode is given in terms of incident lux over the photocurrent generated when light is incident. According to the datasheet, the lux range is from 10 lux to 10,000 lux at a 5-volt reverse-biasing operation. As stated, before lux is the luminance of a light source over an area. With the large lux range that is provide by this photodiode we are able to have a wide tolerance of reflected light going into the photodiode and allow for greater control of the reflected light using different surfaces. With an increase in voltage biasing the lux range could widen to accept more light into the detector, which gives us an even greater range of tolerance if our sensor becomes too saturated.

The large lux range is also of particular interest to our project because it means we can have a wider range of notes for one beam since more light is permitted to go into the detector than one with smaller lux range. Under a 5-volt reverse-biasing the device can generate a photocurrent of 0.1 microamps to 100 microamps with 10 lux to 10,000 lux respectively. This allows for an adequate amount of voltage to be generated when the photocurrent passes a resistor, which determines the notes to be played. The thermal noise is very small having a dark current of 2 nanoamps to 800 nanoamps from a temperature of 25°C to 95°C respectively. Since we do not expect the temperature of the photodiode to exceed 40°C because of thermal regulation, we expect a thermal noise of no more than 8 nanoamps which is negligible. The costs of each of these photodiodes are at around $2.45 if buying them in singles or can be at about $1.16 if buying them in bulk. This greatly maintains the low cost of the prototype. One disadvantage of using this photodiode is that because the size is small, being 5 millimeters by 4.24 millimeters, soldering will be more difficult than other types of components. To mitigate this issue, multiple photodiodes can be ordered so that if we do damage one by soldering then we can have extras to use. Another solution would be to reach out to a soldering expert or company to solder it for us.

4.6.10.4. Transimpedance Amplifier Selection

Later found through testing the team discovered that we needed to use an op-amp to convert the forward current of the photodiodes to a voltage that the MCU can understand. This increased the complexity of our beta detectors to include a photodiode with an op-amp.

The team weighed the options of four different op-amps. The main criteria were for the op-amps to be a single supply two channel IC. The final selection was the LM358 because of its extremely low cost and ability to be tested on a breadboard. While it did not have the best characteristics, it did manage the job well.

Table 19: Op-Amp Comparison

Op-amp Name	**Supply Voltage (V)**	**Quiescent Current (mA/amplifier)**	**Input Voltage noise**	**Input Current noise**	**Input Impedance**
TLV2171	2.7 - 36, ±1.35 - ±18	0.525	27nV/√Hz	NG	$0.1\text{x}10^9$ Ω
TL082	±5 - ±18	1.4	18nV/√Hz	0.001pA/√Hz	100||3 MΩ||pF
LM358	3 - 32, ±1.5 - ±16	0.5	40nV/√Hz	NG	10MΩ||pF
OPA2320	1.8 - 5.5	1.45	0.8nV/√Hz	0.6fA/√Hz	NG

4.7. Microcontroller Options

The signal processing ability of this project will be based around a microcontroller, which will receive inputs from the alpha and beta detectors as well as generating an output signal that will be sent to the speaker. The input signals will be used to determine which beam has been broken and which note from that beam to play.

4.7.1. Requirements

Our device will need to use a microcontroller (MCU) to process the signals being generated by the photodetectors in order to determine if a beam has been broken and if so, which beam is broken. It also needs to process the input from the intensity detectors from the broken beam in order to determine which note to sound. That means that the MCU will have two inputs and one output per string. One input will be a digital signal that changes between high and low depending on if a beam has been broken. The second input will be an analog signal from the intensity detectors that measure the intensity of the light reflected by the user's hand. The output will be a square wave signal at frequency of the note to be played.

Since this device will be powered using batteries in order to meet the need for portability, power consumption is a major priority when considering a potential MCU, since it will draw the most current of any individual component. In order to save power, a highly desirable feature is for the MCU to be able run in a low power mode after the input and output pins have been initialized. When no beams are being broken, no notes need to be played, so have the processor run in active mode wastes power when nothing is happening. Therefore, it is desired that the MCU be able to be in a low power mode when no beams are broken and wake up using interrupts when the value on a digital input pin changes. This ensures that the processor only runs in active mode when a note needs to be played and allows it to sleep otherwise, reducing current draw and therefore power consumption, which improves battery life.

As mentioned in the previous paragraph, the MCU will have three pins for each string. If each string covers a full octave, this means a minimum of seven strings, or 18 pins, will be needed to cover the full range of a concert harp, which has a range of six octave plus a major fifth, or 47 strings. This means that the number of I/O pins is another important consideration. The MCU also needs to be able to generate either a sine wave or a square wave output at specific frequencies. While not required, it is preferred that if the MCU can only output a square wave it has a digital-to-analog converter (DAC) connected to the output pin in order to transform the square wave into a sine wave.

As there are a discrete number of notes that can be played and the MCU needs to know which note to play depending on the signal received from the intensity detectors, the signal from the analog input needs to be converted to a digital signal before it can be processed. Due to this requirement, if an MCU is able to receive analog inputs, there needs to be an analog-to-digital converter (ADC) connected somewhere between the output from the intensity detector and the input to the MCU. The most desirable way to do this is to have an MCU with onboard ADCs connected to the analog input pins.

4.7.2. ATmega2560

The first microcontroller to be considered is the ATmega2560, which is the microcontroller used in the Arduino Mega 2560 board. This MCU was considered because one of our team members already owns an Arduino Mega 2560 board. The ATmega2560 has a total of 54 I/O, of which 16 are analog inputs, which is the most of any of the Atmel MCUs being considered and second most of all of the MCUs. Since all 16 analog pins are connected to a 16 channel ADC, all of its analog pins can be used with a string. Using all 16 analog inputs would also require 16 digital inputs and 16 digital outputs, which still leaves eight unused digital pins. Using all 16 inputs would give a range that is double that of a modern grand piano, which has a range of eight octave plus a minor third. The ATmega2560 has a total of 100 pins, which means that if all 16 analog pins are used, then there will be 42 unused pins, not including the 10-supply voltage and ground pins.

The Mega is the second most expensive MCU being considered but it is also at the top for power efficiency. In active mode running at 1 megahertz and 1.8 volts, it draws 500 microamps, which is the third best of any being considered. This improves to 0.1 microamps when running in power-down mode, which is in a tie with the ATmega238 for second best behind the MSP430G2553. Since the Mega also supports pin change interrupts the MCU can spend the time when a note isn’t being played in a low power mode to reduce current draw and wake up to play a note when a beam is broken and the voltage on that string’s digital input pin changes. When an interrupt causes the Mega to wake from a low-power mode, it has a maximum start-up time of 70 microseconds. The Mega also supports an external oscillator, which allows for something like a watch crystal to be used instead of the less accurate internal oscillator. Considering all of these features, the Mega is the most likely choice for this system.

Table 20: Summary of features for the ATmega2560 microcontroller

Feature	Value	Impact on decision
Clock speed	16 MHz at 4.5 V – 5.5 V	Average clock speed can provide sufficient processing throughput.
I/O pins	54 digital input/output and 16 analog input.	More than enough pins to cover eight full octaves, so number of strings in not limited.
ADC	16 channel, 10 bit, 76.9 KSPS	More than enough channels to cover a reasonable range.
Power Consumption	500 µA at 1.8V, 1 MHz 0.1 µA in power-down mode	Being able to run in low power mode improves battery life.
Unit price	$12.35	The second most expensive microcontroller being considered.
Additional features	Supports pin change interrupts	Allows the device to be in low power mode and only wake up to play a note, increasing battery life.

4.7.3. AT91SAM3X8E

The AT91SAM3X8E is an ARM Cortex-M3 based processor used in the Arduino Due board. This microcontroller was considered as a 32-bit ARM based alternative to the 8-bit Mega MCUs. It has a very fast clock at 84 MHz, which is the fastest of any other MCU. It also has a similar number of pins to the ATmega2560 with 54 digital and 12 analog for a total of 66 I/O pins in total. While this MCU has four fewer analog input pins than the ATmega2560, 12 is still more than sufficient for our device. The greatest number of strings that will be used is most likely going to be eight, so in that case there will be four pins that are unused. Just like with the ATmega2560, this MCU has all of its analog input pins connected to an ADC, which eliminates the need to use an external ADC before the signal reaches the pin. The AT91SAM3X8E has a total of 100 pins, which means that if all 12 analog pins and 24 digital pins are used for strings, then there will be 45 unused pins, not including the 19-voltage supply and ground pins.

In terms of power efficiency, the AT91SAM3X8E is the worst of any of the MCUs being considered. In active mode running at 3.3 V, it draws 130 mA, which is 260 times more current than the ATmega2560. In backup mode, it draws 2.5 µA, which is 25 times more than the ATmega2560.

Although it has the worst power efficiency of any MCU under consideration, it has an onboard two-channel digital-to-analog converter, which could eliminate the need for an external DAC. This is an attractive feature since the Arduino programming language contains a function to output a waveform, but it is only a digital signal. Therefore, a DAC would be needed to obtain a sine wave signal from the square wave. Despite the convenience of a DAC built into the MCU and its price being almost $2 cheaper than the ATmega2560, its excessively high current draw and lack of support for pin-change interrupts has caused it to be dropped from consideration.

Table 21: Summary of features for the AT91SAM3X8E microcontroller

Feature	Value	Impact on decision
Clock speed	84 MHz at 3.3 V	Fastest clock allows for exceptionally high processing and throughput, but at the expense of extra current draw.
I/O pins	54 digital input/output, 12 analog input, 2 analog output	Fewer analog inputs than the ATmega2560 but still more than enough.
ADC	16 channel, 12 bit, 1 MSPS	Faster sampling rate allows for a more accurate representation of analog input.
Power consumption	130 mA at 3.3 V 2.5 µA in Backup mode	Draws more current in any mode than any other MCU being considered.
Unit price	$11.54	
Additional features	2 channel, 12 bit, 1 MSPS DAC	Allows for outputting an analog signal without needing an external DAC.

4.7.4. ATmega328P

The ATmega238 is the microcontroller used in the Arduino Uno board and is a smaller relative to the ATmega2560. It has a total of 21 I/O pins, of which 13 are digital and eight can be either analog or digital, which is the second smallest of any of the MCUs under consideration. However, unlike the Atmega2560, all of the pins can be used for either input or output. This would allow for up to six strings using six analog pins and 12 digital pins. Just like the ATmega2560 and the AT91SAM3X8E, each analog input pin on the ATmega238 is connected to an ADC. The ATmega238 has a total of 28 pins, which means that a maximum of six strings can be implemented if all analog inputs are to be connected to an ADC.

This means that if six analog pins and 12 digital pins are used, there will be six unused pins, not including the four pins for supply voltage and ground pins.

ATmega238 is also the second cheapest MCU under consideration, being eight cents more expensive than the MSP430G2553. It draws the least amount of current of any other MCU in active mode at 200 µA. In power-down mode, which is the lowest power mode where external interrupts are still enabled, it draws .1 µA, which is the least amount of current and is tied with the ATmega2560 and the MSP430G2553. This allows it to run in a low-power mode to save battery life when no notes need to be played and wake up when a beam is broken, and a note needs to be played. When an interrupt causes it to wake-up from a low-power mode, it has a maximum startup time of 60 µs.

Considering all of these features, the ATmega238 will be considered as a backup option to the ATmega2560 and surpassed the MSP430G2553 due to the MSP430’s inability to easily generate an output waveform and small number of I/O pins.

Table 22: Summary of features for the ATmega238 microcontroller

Feature	Value	Impact on decision
Clock speed	Up to 20 MHz	Second fastest clock behind the AT91SAM3X8E
I/O pins	13 digital, 8 analog or digital	Second lowest pin count ahead of the MSP430G2553, but all I/O pins can be used for either input or output.
ADC	6 channel, 10 bit, 15 KSPS	Fewer channels than any other MCU being considered, limiting the number of strings. Also takes the fewest number of samples.
Power consumption	200 µA in active mode 0.75 µA in power-save mode 0.1 µA in power-down mode	Consumes half of the power of the ATmega2560 but is worse in low power modes.
Unit price	$2.28	The second cheapest of any MCU being considered.
Additional features	Supports pin change interrupts	Allows the device to be in low power mode and only wake up when a beam has been broken, causing that input pin to change value.

4.7.5. MSP430G2553

The MSP430G2553 is part of the MSP430G2X53 family of value-line microcontrollers manufactured by Texas Instruments. It is also used in the LaunchPad development board. The MSP430 line of MCUs is optimized for low power consumption and small size. It was considered because of its small size, low power consumption, and because of its familiarity since every student in the electrical and computer engineering programs has had exposure to the MSP430 family. The G2553 has the fewest number of I/O pins at 14, all of which can be configured as either input or output and only six of which are connected to an ADC. This means that a maximum of four strings can be implemented, leaving one pin unused. This is not considered to be a viable product if a maximum of only four octaves can be generated.

The MSP430G2553 is marketed for its power efficiency and has the second lowest current draw in active mode and is tied with the ATmega2560 and the ATmega238 for the lowest in low-power mode 4, which is its lowest power mode. This mode still supports external interrupts for waking up, meaning that it can wake up when the voltage on one of the input pins changes. This allows the G2553 to be in low power mode until a beam is broken and a note needs to be played. It also has the fastest wake-up time from low power mode at less than 1 µs.

Despite its low power consumption, small size, and familiarity, its low number of input pins and inability to easily generate an output waveform have caused it to be dropped from consideration.

Table 23: Summary of features for the MSP430G2553 microcontroller

Feature	Value	Impact on decision
Clock speed	Up to 16 MHz	Average clock speed allows for sufficient processing and throughput.
I/O pins	14	Fewest pin count of any MCU being considered.
ADC	8 channel, 10 bit, 200 KSPS	Enough channels for eight strings
Power consumption	230 µA at 2.2 V, 1 MHz 0.5 µA in low power mode 0 0.1 µA in low power mode 4	The second best in active mode and the best in low power modes.
Unit price	$2.20	The cheapest MCU being considered.
Additional features	Supports pin change interrupts	Allowing the device to be in low power mode and only wake up when a beam is broken increases battery life.

4.7.6. MSP430FG4618

The MSP430FG4618 is a member of the MSP430FG461X family of value line microcontrollers in the Texas Instruments MSP430 line. Like the G2553 it is optimized for low power consumption. It was considered because of its large number of I/O pins and because, like the G2553, all students in the electrical and computer engineering programs have had some exposure to the family, especially the FG4618 which is used in the embedded systems course. This MCU has 80 general purpose I/O pins, 12 of which are connected to an ADC. This means that a maximum of 12 strings can be implemented, leaving 44 pins unused. However, this is not a practical limitation since it is seen as it is considered to be neither reasonable nor an intention to implement that many strings. Using 12 analog inputs means a total of 36 I/O pins will be used, leaving 58 pins unused, not including the six supply voltage and ground pins. Leaving this many pin unused can cause excessive current draw and therefore lead to prematurely draining the batteries.

This MCU has many more features than the G2553. Along with its large number of pins, it also has a two-channel DAC which allows the MCU to output a sine wave without needing an external converter. It also supports a 160 segment LCD display like the one used on the MSP430FG4618 experimenter board. This could open up some interesting stretch goals if a display can be implemented. However, these features also come with a drawback in terms of power consumption. In active mode it has the third highest current draw at 400 µA and has the second highest in low-power mode at .22 µA, beaten only by the AT91SAM3X8E. All of the FG4618's low power modes support external interrupts, which allows the MCU to be in low power mode normally in order to save power and wake up when a beam has been broken in order to play a note. The FG4618 has a startup time of less than 6 µs when waking from low power mode.

The FG4618 has a good balance of features and power efficiency and is therefore being considered along with the ATmega238 as a backup to the ATmega2560.

Table 24: Summary of features for the MSP430FG4618 microcontroller

Feature	Value	Impact on decision
Clock speed	16 MHz	Average clock speed provides sufficient processing speed and throughput.
I/O pins	80 general purpose	More than any other MCU being considered.
ADC	12 channel, 12 bit	More than enough channels to implement a reasonable number of strings.
Power consumption	400 µA at 2.2 V, 1 MHz 1.3 µA in low power mode 0 0.22 µA in low power mode 4	Third highest in active mode and second highest in low-power mode.
Unit price	$13.59	Most expensive MCU being considered.
Additional features	2 channel, 12 bit DAC	Allows for outputting an analog signal without needing an external DAC.

4.8. Audio Signal Processing

Designing and building the laser instrument will require a sold understanding of signal processing. Signal processing will be used for reading a detection signal, analog to digital conversion, digital to analog conversion, modulation, mathematical operations and more. Most of the signal processing is to generate a desired output waveform that can serve as the audio signal to go to the speaker out. Most of the signal processing will be handled by the microcontroller and the programming. This means most of our research focuses on digital signal processing concepts. Signal processing has a high importance in our project because it has a direct relation to the final measurable output of our system. Depending on how well we design our signal processing aspects of our instrument can make the difference from having a high fidelity or a low fidelity for an output sound. Because the intensity of sound a human ear can hear depends on the frequency and the decibels of the sound wave [76], it would be best to have active filters and amplifiers in the system.

The project includes stretch goals that include audio distortion and variable output sounds. There would all happen through different means of signal processing, such as feedback and oscillations. For these stretch goals we would be looking into signal processing to more directly altering the waveforms of the signals. This kind of signal processing is closer related to analog signal processing. We have looked into using various oscillators or special modulators, both remain in the background till we move further in the project.

4.8.1. Received Electrical Signals

The system we are designing needs to be able to read both digital and analog signals. The issue faced here is that the processor that we will use can only process digital signals. This means that we will need to use an analog to digital converter (DAC) for the analog input. A simplified way to approximate an analog signal into digital signals is to use varying step functions that can approximate the analog signal at a point in time. The rate of sampling for the step function will determine how accurate the approximated digital signals are to the analog signal. The limiting factor for the sampling period in the system will be the clock speed of the processor. For most processors this should be faster than what we will need because the analog signal will be created from a user's hand movement up and down in the playing field. The speed of most processors is much faster than the speed a human can move their hand.

For the digital signal the input method should work straight forward for the processor to handle. For a user's hand intercepting a beam we will define this as a digital. For no hand in the beams path will define this as a digital 0. When the system detects a 1 then a flag will trigger the processor to pass a corresponding audio signal.

4.8.2. Signal Output

The purpose to have a good audio signal output is because it is the easiest perceived output for our system and the main purpose of the laser instrument. We have investigated different ways on how to produce audio signals at the output stage of the system. Our goal is to have a perceivable sound and to be able to hear different pitches.

4.8.2.1. Methods

There are many different ways to go about handling the signals processing aspect of the project. To name a few methods we can use saved audio files, communicate with another device such as a computer or synthesizer, or hard code a wavefunction into the program. The easiest method would be to hardcode functions into the program. This method lacks versatility because the sounds produced are fixed and limited by the processor and the code. The most versatile method would be to use another device to produce an audio signal. This would be done by using MIDI communication between the two devices. This creates a virtually unlimited amount of sounds that could be produced because the signal would no longer be produced by the laser instrument. In this method the laser instrument only serves as a medium to communicate with another device just like a keyboard for a computer.

4.8.2.2. Generation of Audio Signals

The team deemed that pre-programed functions used to generate different signals would be the best way for the project to generate the audio signals for the instrument. The easiest signals that can be produced by a microcontroller are digital pulses. These pulses are good enough be used an audio signal where the period of the pulses gives the frequency of the signal and therefore the pitch of the tone produced at the speaker. The fundamental frequency of a periodic tone indicates the first harmonic for the tone where most of the power for the tone is contained in this first harmonic. This relates to the pitch of the tone, the other harmonics in the tone are the tones timbre [77]. This aspect is a little beyond the scope of the project but presents itself as a direction to grow the project in the future. A simple method to produce different tones is to add different periodic signals. Figure 11 shows how adding signals together can create a signal at the output. The means of summing signals is easily implemented by using simple ICs that are designed to add multiple signals together, this would increase the costs of the project as more components would be needed. A reason to include an adder in the circuit is presented later when we discuss vibrato signals being generated.

A better way option for the output signal is to use an analog signal that would have higher fidelity. This is a harder process to do when using a microcontroller since it operates with digital signals. That means that a digital to analog converter would be needed. A good way to approximate an analog signal with digital signals it by pulse width modulation (PWM). PWM is where a digital square wave is pulsed at different widths or duty cycles to give a different average voltage over a period.

In a study the vibrato for a tone has been statistically found to be about +- 6% of the frequency of the tone, this is the same as +- 1 semitone [78]. A way to implement vibrato would be to have a vibrato function that would generate a small signal that could be added to the main signal that is the tone. This small signal could have a fixed frequency to a percentage of the frequency of the tone being played. This method would leave the rate of vibrato fixed which is not desirable for a musician who wants to have range or versatility in their music. This method would also require the use of an adder and other functions to be generated which would take up more of the memory.

The other way the team investigated to implement vibrato in to the instrument is directly through playing. This is the most similar to the way vibrato is implemented in all other instruments, by the musician. This can be done by a user slightly raising and lowering their hand in the beams path. The range detection circuit will produce an analog signal that can directly be passed to the output. Each string would be broken down into sections depending on the number of bits that can be used to code a signal. The value of the bits will give the height of the user’s hand which relates to the frequency of the output signal.

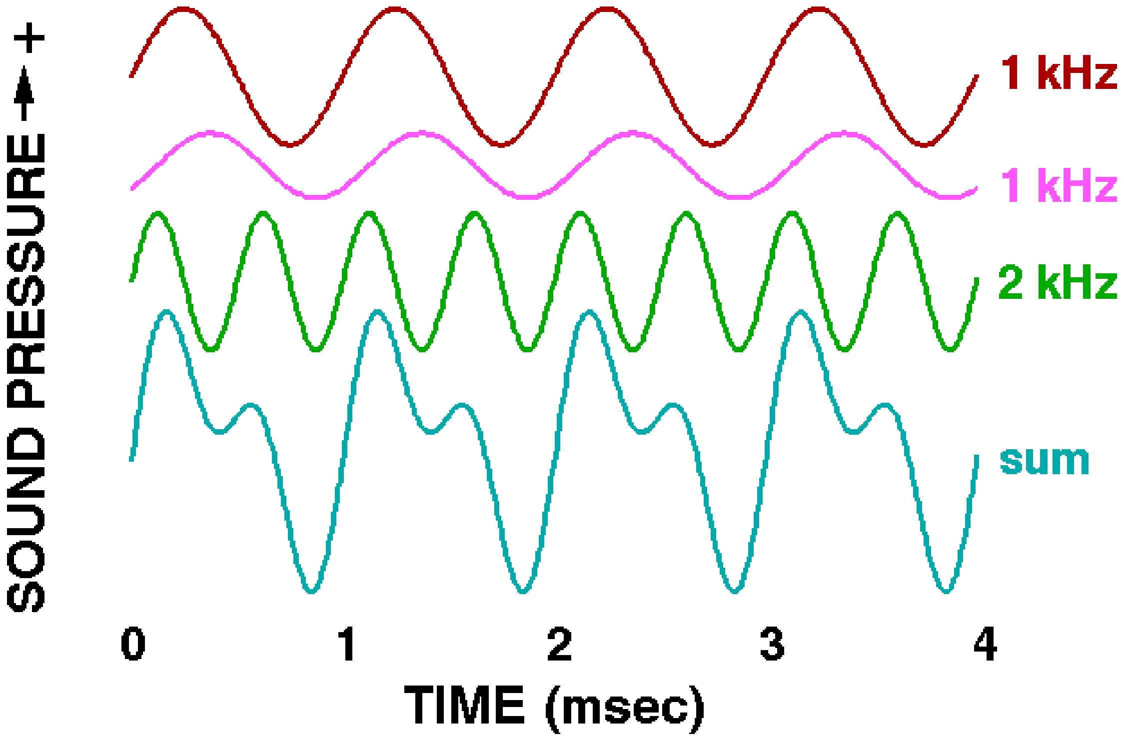


Figure 11: Summing Signals [79] {Permission pending approval}

4.8.2.3. Amplification

The purpose of the amplifier is to increase the power of the small signal audio waveform to a level that is better suited to drive the speaker with. In some systems the amplifier is also what can determine how loud the output sound is. This can be done by using an adjustable filter that impact the gain of the amplifier. We are looking into using a speaker that has a built-in amplifier to simplify our system. Once we have a working instrument able to generate a signal or an audible signal we will test for gain on the speaker. If a gain stage is still needed after testing, we plan to put in a simple amplifier before sending the signal to the speaker. We have found a simple design for a differential amplifier with a class AB output stage. This amplifier will most likely have a fixed gain in out circuit.

4.8.5. Speaker Out

The speaker's job in terms of signal processing is to transform the electrical signal produced by the microcontroller and transduce it into a sound wave. Without the speaker in our system there would be no way of detecting an output for our system. We plan to have a 3.5mm audio socket on the instrument so that most commercial speakers can work with it. Therefore, we have not selected a speaker for our project because our system should be able to work with most speaker systems that can use a 3.5mm audio cable.

4.9. Thermal Control

As with everything that incorporates electronics heat will be an issue. When the instrument uses the energy from the battery to run the electronics, heat will be dissipated from its components as there is energy loss in the operational processes and transfers of energy. If the temperature of the device increases without being regulated the instrument risks being non-operational as some components do not work under high temperatures. Other components may be able to withstand high temperatures but can suffer from a decrease in performance as more energy is required to overcome the thermal noise. In order to maintain our prototype operational at near optimal conditions, it is important to implement thermal control through the use of heat sinks, ventilation systems, and a proper placement of components.

4.9.1. Heat Sinks

A heat sink is a device that takes in excess or unwanted heat from the system [80]. They are typically made out of metal and can look similar to metal plates with fins sticking out of one side of the plate. The way they work is by having the flat side of the heat sink be in contact with the heating component. The heat would transfer from the component to the heat sink plate and then to the fins. The ambient air that passes through the fins cools the heat sink which allows the heat sink to absorb more heat from the component. The air coming out of the fins would be hotter than when it first came into the fins but if the hot air is redirected out of the system then it should not interfere with the cooling process. Other heat sinks have only the metal plate and have ambient air cool the surface of the other side to reduce the thermal load on the heat sink. In general heat sinks are an inexpensive way to thermally control the instrument and can be easily incorporated into our project.

4.9.2. Ventilation

To further reduce the thermal load of the device a ventilation system can be added. The purpose of the ventilation is to actively direct air in a such a way as to create an air flow through the parts with the most heat. The air flow will cool the components and heat sinks continuously. We plan to install the ventilation using small fans (perhaps the size of a computer fan) at the ends of the frame to allow the air to flow through the system. The activation of the fans can be triggered after a moment of time has elapsed with the instrument on to conserve on power use.

4.9.3. Placement of Components

Another way to regulate the thermal load of the instrument is the placement of the components. When heating components are too close together, it makes cooling them down an issue. The reason for this is because heat can transfer more easily between components that are close together than far apart and the cluster of components can block some of the air flowing through them. By spacing them reasonably apart we can reduce the heat transfers between components which allows the cooling process for an individual component to be more efficient. The spacing also allows air to flow more efficiently than the cluster of components because more air can reach a component than before.

5. Design

Once the objectives become clear and components are selected to meet those objectives, it is then time to incorporate those parts together. The goal of design is to see the whole picture of the device and properly describe how the interactions between those components perform. It is this integration of the project that becomes the final step from taking an idea into a working device. The layout of the different processes will be expressed along with the links between those processes. In our senior design this would mean going from the user's interaction with the laser beam to the response of the photodetectors sending signals to the microcontroller that will determine the sounds allocated to the respective signal which will be sent to a speaker to finally emit an audible note. The vital components that we will be using are batteries for power supply, laser diodes, photodetectors, a microcontroller, a speaker, and a PCB. This chapter will focus on the overall hardware design, a single string prototype, the frame, power supply, the detection system, the laser emission, the signal processing, PCB design, speaker output, and software. The design we present here is for our prototype, if the instrument is to be taken further than its initial prototype stage many of its design features will be subjected to changes.

5.1. Hardware Overview

The hardware of the project focuses on how the emission of sound will be made through the interactions of the components and user. In this section there will be a block diagram on the entire process of obtaining the emission of sound, schematics of the circuit layout, and comments on other hardware that were optional to implement in the design.

5.1.1. Block Diagram

The intent of the hardware block diagram is to provide a quick and easy of understanding of how the overall system will work with its subsystems and interactions between the subsystems included. As seen in figure 12, the user starts the process of turning light into sound by interacting with the laser system. They can either use their hand or some material with a reflective surface. Once the user has interacted with the laser system by interrupting a beam, the detection system would step in. The detection of a broken beam would signal to the microcontroller that the sound for that beam is enabled and would collect different intensities of reflections caused by the user. The microprocessor reads the enabled sound signal and, based on the signals of the intensities of the reflections, would determine what note should be played for a particular amount of intensity in real-time. Each beam would be allocated with a predetermined range of notes that the microcontroller would use to determine what the intensities for each beam represent in terms of notes. Once the incoming signal from the detection system has been allocated a note, the microcontroller will then send a signal with the desired note to be played by the speaker. The speaker would take in the signal and amplify it. In doing so, when the signal converts from an electrical signal to an acoustic signal, the signal would be large enough to be audible to the human ear. From the user's interaction with the lasers to the audio output, the hardware block diagram shows this information in a simplistic fashion.

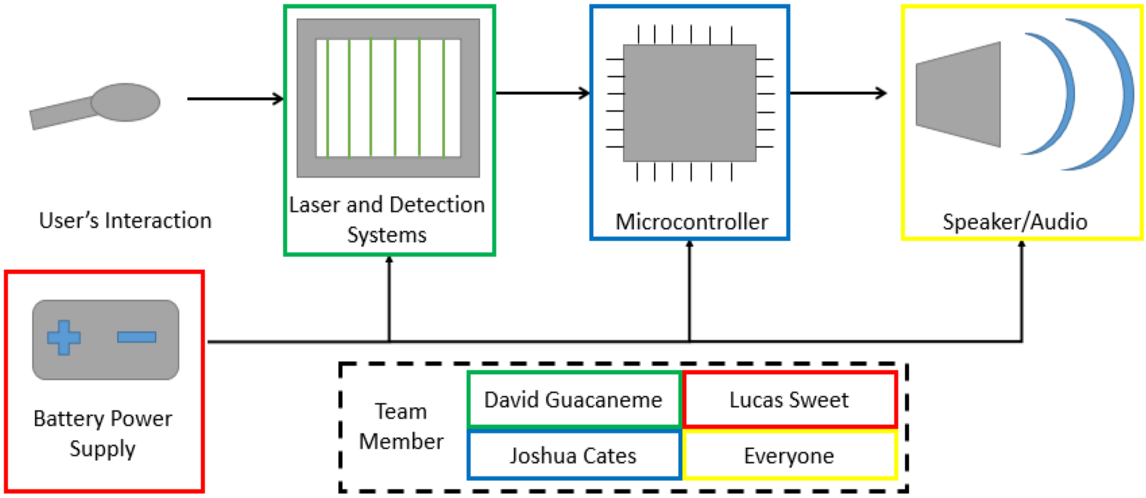


Figure 12: Hardware Block Diagram.

As it can be seen in figure 12, each team member has taken up responsibility for each section of the block diagram. The laser and detection systems are under the work of the photonics engineering team member. The skills acquired in the major suit well to understand the function and operation of the laser diodes and the photodetectors. The tasks involve include selection of components for the two systems, aligning the lasers to the detectors on the opposite side, and assuring that there is an appropriate amount of light being receiving into the detectors when the user interacts with the laser beams. The electrical engineering team was split into two areas of the project which are the power supply and the microcontroller (software). The electrical engineers are capable of powering up the systems, creating the proper circuits, and writing some embedded code. For the power supply, the task involves choosing which batteries to use, ensuring there are protections in place for voltage and current irregularities or overcharges, and making sure there is enough power supply for the entire system. As for the microcontroller, the responsibilities would be selecting an adequate microcontroller, creating a PCB, and writing the software for the system. Since our expertise in software is minimal, we will be using an open-sourced code format to help us produce a reliable code. The software block diagram will be discussed in greater detail later in the report as it includes code structure, integration with the entire system, and references some of the hardware. Both electrical engineering members will collaborate on making the entire circuitry for the instrument. For the audio output of the instrument, everyone will be involved in the production of sound to ensure fidelity is attained. Other aspects of the project not mentioned above, such as making the frame and creating a thermal regulation system, will be handled by everyone in the team and can be done by any member.

A PCB design was made and ordered at the beginnings of senior design 2. In doing so it put the project in the final stages of implementation and allowed time to troubleshoot problems that did arise. The second PCB design was able to operate properly but was missing a few parts. The second PCB was used during the midterm demo. The sections missing from the board where the reference resistor bank, regulators, and components to help with the programming of the board.

Following the midterm demo a third revision of the main PCB was made and ordered. This final revision was used during the final presentation. The third revision included additional regulators and components for programing as well as the reference resistor bank. Along with the order for the third PCB design the team ordered the boards for the beta sensors. Both boards could still use slight improvements by adding traces and adjusting hole sizes on the boards.

5.1.2. Schematic

Below in figure 13 we have provided a simplified version of our circuit's schematic. The values of the resistors in the figure are not true to our design. The schematic is purpose it serve more as a reference for the circuit's layout. We have significantly simplified our microcontroller in the schematic to only show as an 8-pin input box. The schematic is only for the detection and lasers, so it lacks the output stage for the instrument.

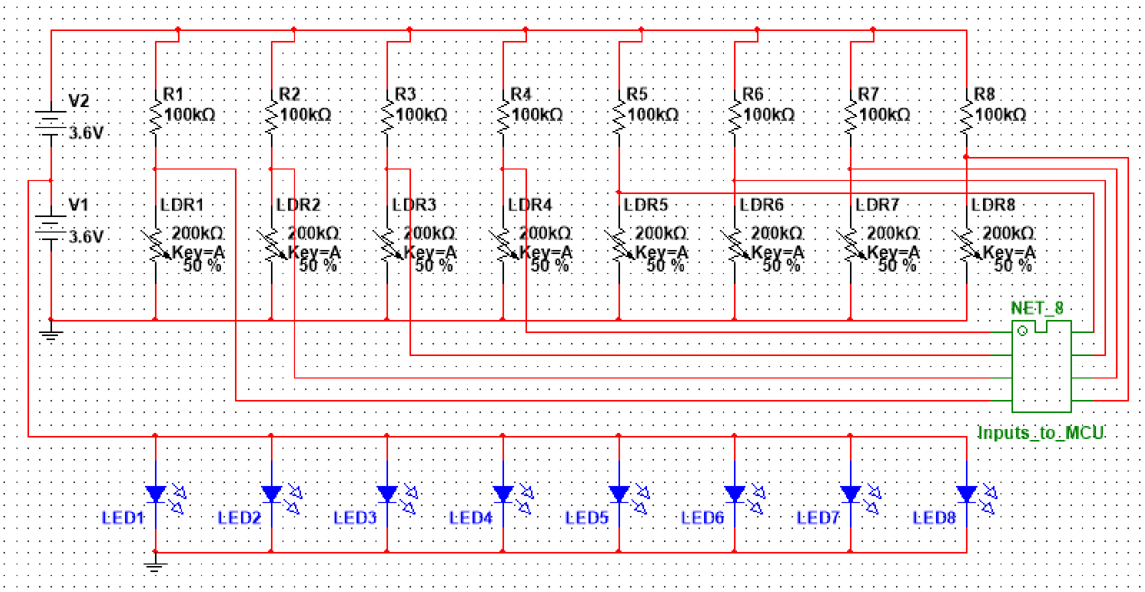


Figure 13: Simplified Schematic

5.1.3 Other

Because of tempo being an important part in playing music we have opted out of using any speed detection system for the instrument. If such a system was implemented into the instrument as a feature such as volume, then when someone is playing a fast song they will also be playing loudly. While these to two aspects sometimes go together it is not always the case. With a real string instrument, you can play them fast but soft or you can play them slow and loud. Any sort of speed detection would interfere with the tempo aspect of music.

5.2 Single String Prototype Design

The single string prototype is important for our testing. Our single string prototype is a breadboard testing with an Arduino board so that we can easily test individual parts and change the set up easily. Before any changes are made or added to the full prototype we will be testing and implementing on the single string prototype. This will help to cut down on trouble shooting and save costs by preventing damage to multiple components at a time. Once the single string prototype has been shown to work properly, it would be a matter of replicating that string into multiple strings and making minor adjustments for the emission of their specific notes and sounds.

The setup of the single string prototype is to be modular so that we can easily switch in and out different parts for testing. For this we are using a large breadboard. In the first implementation of the single string prototype we have been manually holding the laser and aiming the beam at the photodetector. Our next step from here is to include mounting equipment for the laser so they will no longer need a person to constantly hold and aim the laser. This will steady the laser's beam and keep the system stable. A photodetector will be receiving the variation of incident light and the interruption of that light. A microcontroller testing board will be implemented to serve as the medium to test the software and see how the connections between the photodetector and speaker work. Lastly, a simple speaker head will be used to serve as the audio output.

5.3. Frame

The frame will enclose all the components and set the span of the instrument. The total dimensions of the instrument shall be bounded by a 36-inch cube to maintain the portability feature but remain large enough to allow a user to comfortably wave two hands through the center of the frame. The frame will be a rectangular cube with hollow edges and an open center that serves as the playing field of the instrument. The frame needs to be lightweight, inexpensive, simple, stable on a table or a keyboard stand, and allow for ease of use for a user. We performed a few tests to determine optimal dimensions that allowed for a compact feature but still a comfortable and reasonable user experience. No weight can be determined for the instrument yet as the material of the frame has yet been selected. We set a max weight of 50 pounds. We believe from our dimensions this target can be easily reached from a variety of material types.

Our frame design also includes precautions to aid in the safe use of our instrument. Since our lasers will be shining upward this means the light from them can shine into a person's eyes from stray beams if we do not design and build the frame properly. For this reason, we plan have planned to place the lasers inside the frame below its surface facing the playing field. We will also add small cones over the lasers to block as much of the stray beams from the laser diode as possible and create a more focused beam. This will also help in the aiming in the lasers so that we can focus the light to shine more directly onto the photodetectors by only needing to adjust the cones and leaving the laser diodes alone. With the laser diodes placement inside the frame it makes it difficult to have to adjust them. Continuous or repetitive adjusting and moving of the laser diodes will create stress on the joints needed for electrical connection to where they could break. Including the cones will also aid in preventing us from having to cause such stress on these important connections. The cones will be reflective on the inside to reduce in their absorbing of light from the lasers. We are currently looking to making it so the cones can be adjusted at any time in case the aiming of the laser diodes ever changes over time.

5.3.1. Dimensions

In this section we record our chosen dimensions and how we came to the decision of the said dimensions. We have broken our instrument into two areas, the playing field and the frame. The frame encloses the playing field on four sides leave two open for a user to put their hands through.

5.3.1.1. Playing Field

Dimensions were determined by the area of the playing field where a user would interact with the instrument to play sounds by waving their hand or reflective medium through the laser beams. The playing field is treated as a two-dimensional field because the depth is limited by the relative diameter of a beam spot size from a laser diode and therefore can be excluded because of its minimal spot size. To start in the selection of dimensions we arbitrary declared to set a base of eight laser diodes to be used in the instrument. From there we realized that each laser needs to be spaced as close together but still far enough that a hand does not intercept two lasers at the same time. We selected a spacing of 2.25 inches between each laser from measuring the hand widths of each team member. This gave us a total length of 20.5 inches. Next was determining the height of the playing field, for this dimension we based it off our plan to include an intensity detection system.

This system will work by reading a voltage that depends on the resistance of the photodetector. The photodetector’s resistance changes based on the amount of intensity of light it is receiving at any particular moment in time. The intensity of the light will be determined by the height of a user's hand from a photodiode. This means that the height needs to be tall enough to give a user a practical amount of room to raise and lower their hands which will be limited by the height of the playing field. For testing we ran two tests where we shined a green and red laser into a hand that was hovering over a photodetector while measuring the instantaneous resistance on the photodetector as the hand moved up and down. For each test we had two cases for a well-lit setting and in a near completely dark setting. From the testing we determined the photodetector can detect changes in height at further ranges in the dark than in a well-lit setting. The maximum range of detection for both cases was greater than 36 inches, so both would work with the instruments selected maximum dimensions. From here we decided to investigate the user’s experience aspect of the instrument to determine the height of the playing field as this is where a user would be interacting with the instrument. We tested this out by moving our hands up and down next to a meter stick and measured what felt like a reasonable distance we wanted to move our hands up and down in. Starting with a range of 12 inches minimum and 24 inches maximum we selected that 16 inches felt to be the optimal height of the playing field while keeping the instrument compact.

5.3.1.2. Total Dimensions

Working from the dimensions selected for the playing field we worked to determine the total dimensions of the frame that would bound the instrument and house all of the components. To keep the total weight of the instrument down the frame will be hollow and be kept as small as possible while still allowing us to easily work inside of the frame. There will be three housing sections that run through the top, bottom, and left side of the instrument. The dimensions for these housing compartments will be 4 inches by 4 inches by 4 inches, these dimensions were selected because they are large enough to house the components, simplicity, and symmetry. The total dimensions for the instrument where determined from the subsequent dimensions selections to be 24 inches tall, 25 inches in length, and 4 inched deep. These dimensions are well under our definition of portable and compact that we defined as a 36-inch cube.

Table 25: Frame Dimensions

	Height	**Length**	**Depth**
Play Field	16 inches	20.5 inches	N/A
Total Frame	24 inches	25 inches	4 inches

5.3.2. Materials

The team researched into using wood, plastic, or metal for the frame of the instrument. The frame needed to be lightweight and low-cost. The frames purpose is to hold everything up and house all of the electronics, so they cannot be seen. Below in figure 14 is a first sketch design of the main frame structure. The frame is the basic shape of a square with three of the four sides to be hollow to house the electronics and reduce the weight. The material selected also had to be simple to work with. The team planned to use the laser cutter on campus so that limited the material and the dimensions that could be used for the frame. The perks of using the laser cutter where to have quick and precise cuts, this was best to aid in laser mounting and aiming.

The final frame was made from quarter inch oak wood paneling with pine blocks for joint supports, held together using wood glue and screws. The interior of the playing field was spray painted black to reduce harmful light reflections. We used hook and loop strips for the side panels to allow them to be removed so the in workings can be worked on.

5.3.3. Layout

This is our second frame design for the instrument. Our first design was three sided, top, bottom, and a single side. We thought it would be a good idea to have one side open so that a user could freely wave their hand into the instruments playing field. This would also keep the weight down for the instrument. After some more thought we took into considerations of the frame’s structural stability. To cover this concern, we closed off the side by a thin panel so that it keeps the weight and size down but keeps the frame structurally sound. For the future after the first prototype has been successfully built and tested, we plan to make the frame be more artistic and visually appealing than a box.

The second reason to include the other side is that once we are able to include the pitch intensity detection into the instrument there will need to be for a marked reference point or points for notes. This is because the intensity level of light is dependent on the hand height from base of the lasers inside the playing field. Having a single marking on one side will make it harder to line your hand up with when playing on the opposite side of the instrument. Including this side with the reference marking will make aligning your hand with it easier. This way someone can know where to put their hand inside a laser’s beam to play the main corresponding tone. This mark will be a painted bar on each side of the frame.

The exterior panels for the bottom, top, and right sides are removable so that the hardware can be easily accessed. The side panels are held to the frame using hook and loop strips. Allowing the side panels to be removable helps when needing to work on the hardware and allows the team to present the internal components during the final presentation. Currently the team plans to make grooves on the insides of the fame, so the panels can slide into these groves. The groves should be recessed into the body of the frame deep enough to where the slides can maintain a stable standing and can be easy to slide back into place. The team will take care in assuring that the groves are not so deep that they can cause structural problems to the entire instrument.

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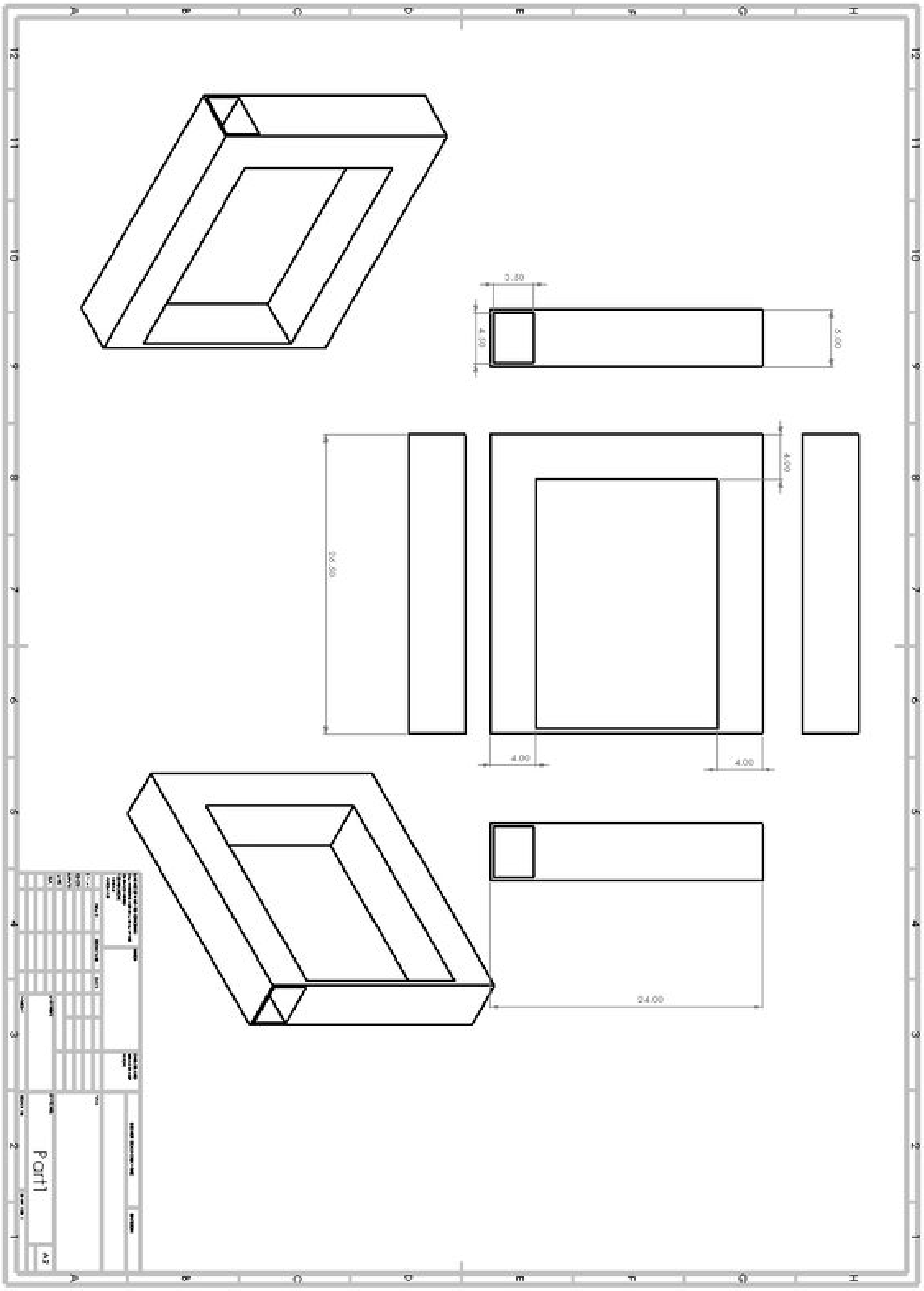

Figure 14: Initial Frame Design

5.4. Power Supply

Through the team’s design process, we have decided to use a battery source as our power supply to increase the portability of the instrument. In this section we will go over the design process and the team’s selections that relate to the instruments power supply. In our extensive research of different battery types, we have selected to use lithium-ion 18650 cells. These cells provide high energy densities, long life, are able to be recharged, and light weight. These benefits do come at a great cost of safety risks. The cells must maintain a stable state to prevent any damage or harm to the instrument and the people who use it.

5.4.1. Battery pack

Figure 15: Battery Holder

To secure the batteries to the instrument we will be using battery holders that we can manually connect the cells how we see fit. The holders can hold two cells each. The holders themselves can either be screwed or glued to the frame of the instrument. Figure 15 shows two profiles of the holders we plan to use in our instrument. The holders also have connector plates and pins that allow for simple and secure connections to the cells. The purpose for using the holders is so that we can easily put in and remove the batteries from the instrument. This allows the team to safely charge the batteries in a monitored manner using a commercial battery charger. The cell holders in the prototyped where soldered together with 12 AWG to keep the resistance of the pack low as to not act like a load for the cells.

In a future build of the instrument this design for a battery pack will be replaced by a built-in pack that could be recharged without removing the pack or the cells from the system. This design with the battery holders is for the prototype because of its ease, versatility, safety, and simplicity.

5.4.2. Cell Connections

Because of the plates the pins on the battery holders' connections where easily made by soldering a 12 AWG wire between them. The final battery pack was comprised in a three series two parallel arraignment. Between each series connection an interior connection was made to increase the stability of the battery pack. This arrangement in the pack gives the design to have triple the voltage and double the capacity of an individual cell. It is a good practice to make parallel connections on the 18650 cells [81] our configuration will be similar to that shown in figure 16 below, except we will be tapping the center common node to make a 3.6-volt node in the system. To further increase the run time of the instrument for any reason a third parallel line can be added. This will triple the capacity from that of a single cell. To do this a new holder will have to be made for the instrument.

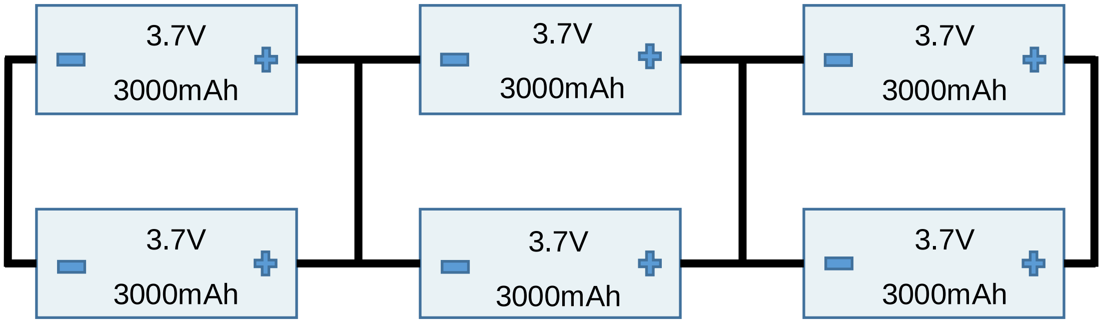

Figure 16: Cell Connections for Battery Pack

5.4.3. Stability and Protection

The final instrument had a basic level of protection included that is provided by the voltage regulators. Better protections for the system can still be added. It would be best to add protection directly to the battery pack. This new protection will need to allow the ability to charge the batteries as well.

Because to the fragility of the lithium-ion cells the circuit will need to include means of protection. Important protections to have for lithium-ion batteries are under and over voltage, reverse voltage and current, and heat. This can be done by using regulators to guard against fluctuations from the source. Shunt capacitors can be used to stabilize or buffer for any dips or spikes in voltage. There are a few IC's on the market currently that can be implemented to detect for all of these cases. The costs of these chips are on the higher which will increase the final cost.

From running the many detection circuits in parallel each will share current from the same node. Since each line has its own dependent resistance the current flowing through each line will vary. This can be problematic if one line happens to draw too much current that it can’t handle to where the components fry and then act as an open meaning the remaining lines now have to handle the excess current increasing the risk of overcurrent in a line. This will eventually lead to a cascading catastrophic failure of the system where all of the detection circuits fry because one line failed.

5.4.4.1. Voltage Regulation

The system includes two linear regulators for five and six volts and one switching regulator for five volts as well. Each selected voltage regulator has built in protection circuity that will turn off the IC’s if there is an overcurrent, reverse voltage, and excessive temperature.

At least a single voltage regulator will be needed for the microcontroller. This is because the ATmega2560 is designed to operate with a supply between 4.5 and 5 volts. Because of the need for stability the L7805CV was added to the design. The beta detectors are designed to give the op-amp a rail to rail voltage of six volts. This is why the team also later added in the L7806ABV to the system.

The laser diodes are special in the system an get their own switching regulator because they require lots of current to operate. Testing was done on the laser diodes at various voltages to record their current draws along with their dot sizes. The switching regulator needed to have a stable output to help reduce the occurrences of stray beams. The increase in stray beams would further increase the danger of the instrument. The teams final switching regulator was able to operate well over three amps and maintain a low ripple. At the higher current draw the regulator does require a heat sink.

When designing the switching regulator, the capacitors where selected to have a small ESR rating to prevent the occurrence of an output ripple. The input to the LM2678 is includes four shunt capacitors to reduce the ripple that comes into the regulator to allow the regulator to have a more stable operation. From the output of the regulator is a Schottky diode and an inductor. The inductor prevents large fluctuations in the output current and the Schottky diode keeps the voltage up while the regulator switches off and sinks current. After the inductor are output capacitors. The teams design included two output capacitors with ESR ratings below 0.1Ω. Figure 17 shows the schematic of the switching regulator. Figure 18 shows the output ripple of the switching regulator during a three-amp load test.

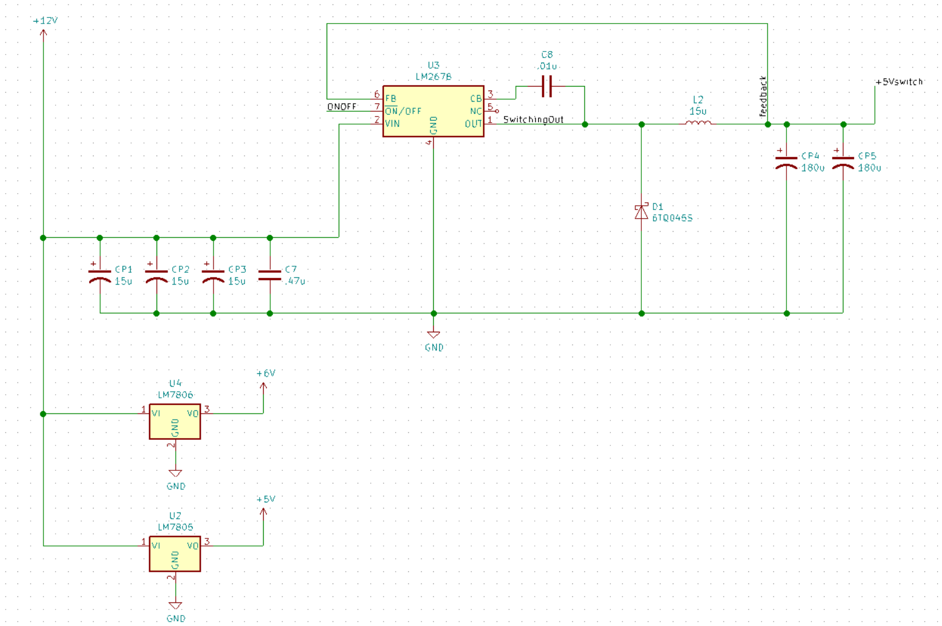

Figure 17: Switching Regulator Schematic

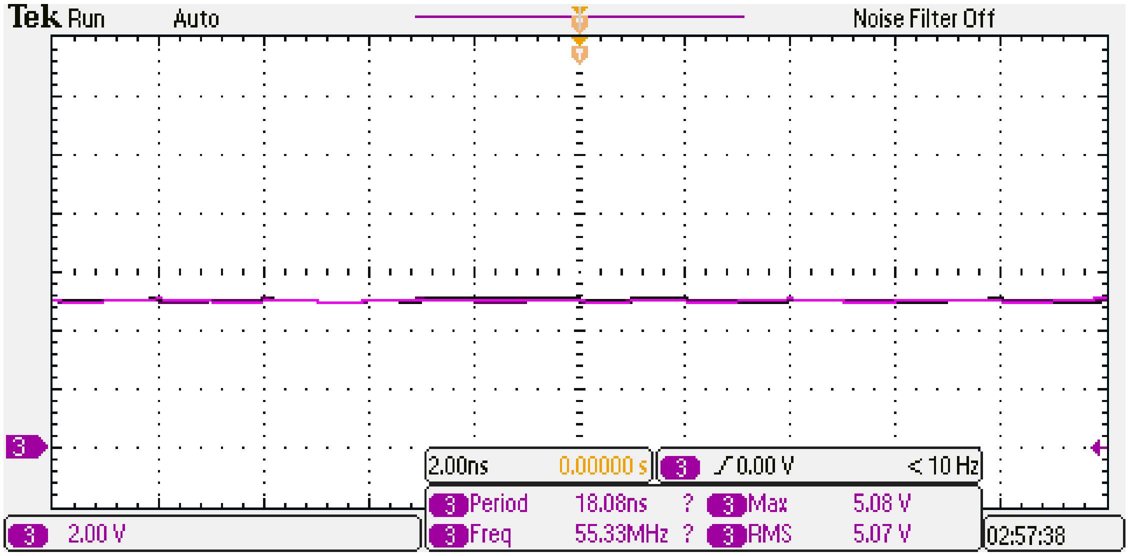

Figure 18: Switching Regulator Output

5.4.4.2. Current Regulation

A simple fix to the current issues in the system are to use current regulators on each line. The regulated current value will need to be determined from testing of the parallel detection circuits. The value should be of an optimal value so that no damage can come to the detection circuits and so that the current value can vary so that the detection is neither always triggered or never triggered. A better means of current regulation would be to have a current limiter to protect the lines from an overcurrent spike. Both depend on further testing of the circuits. From the recorded current values of the testing we can determine an optimal range to select a component. Fuses are a good means to protect a system from any kind of overcurrent but can become costly in a testing environment, so we have chosen to ignore them for the prototype.

5.5. Detection System

The detection system is the initiator and determining factor for the instrument to play notes. There will be two types of detections: alpha detection and beta detection. The purpose of alpha detection is to initiate the audio output. It would act as an on and off switch for the emission of sound from any particular beam. On top of initializing what particular range of notes should be transmitted, the alpha detection also prevents other beams from emitting sounds that should not be played. The beta detection would determine the particular notes from that a particular beam would play. This is based on the intensity of the reflections of light from a user's hand or other medium. A variation in the intensity would vary which notes should be played.

5.5.1. Alpha detection (interrupt detection)

The alpha detection is based on the interruption of the user with the laser beam. It will tell the microprocessor which beam should emit sound and play the range of notes that are assigned to the beam. In previous sections of this report, it was determined that photoresistors will act as the alpha detector to sense the interruption. As seen in figure 19B, when the beam is not interrupted, the beam will be incident on the photoresistor. The incoming light causes the resistance of the photoresistor to be low and act closely to a short in a circuit that emits a small voltage signal. This will tell the system that the beam is off, and no notes should play from this beam. When the user interrupts the beams, as is the case in figure 19C, the photoresistor is no longer receiving an optical stimulus. As a consequence of this, the resistance of the photodetector will largely increase and will cause a large voltage signal to be emitted to the microprocessor. This large voltage signal would tell the microprocessor to play any notes that are a result of the interruption of the particular beam. The processing speed of this optical switch should be fast enough, a few milliseconds, to appear seamless to the user.

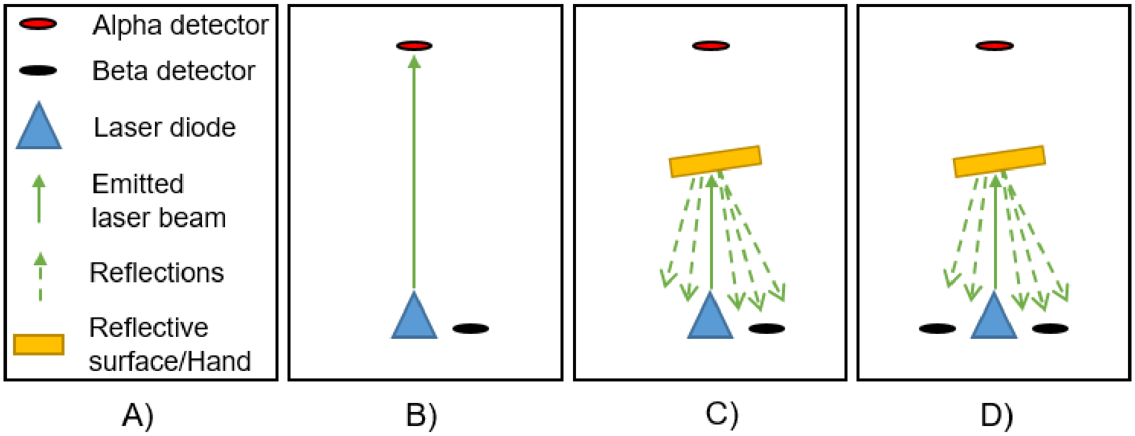

Figure 19: Alpha-Beta Detection System. A) Legend of icons. B) Emitted laser beam is on the alpha detector so the beam is off. C) Laser beam is interrupted so the beam is on. D) Optional array of beta detectors.

5.5.2. Beta detection (range/pitch detection)

The beta detection is the determinant factor in having a range of notes to be played. Earlier in the report, photodiodes were chosen to be the beta detectors. As seen in figure 19C, once a user interrupts a beam and the alpha detectors enable the sound to be emitted for a beam, the photodiodes would pick up the intensities of light reflecting off the interrupting surface. Different intensities would provide different notes from a range of predetermined notes. We could designate the beta detection to be where the higher intensities of reflections can emit a higher note and lower intensities of reflections can produce a lower note in the range.

Since intensities control what note is played, being able to control the intensities would allow the user to play the note they wish to hear. To control the intensities, we have implemented a range/pitch detection in which the user can raise and lower their hand, or reflective material, with respect to the laser beam to get varying intensities. When a user interrupts the beam far from the beta detector less reflections will be incident on the detector. When the user's interruption occurs close to the beta detector than more reflections will be collected by the detector. This can correspond to having higher notes for when the interruptions are high above the beta detector and producing lower notes when the user is close to the beta detection. The surface that the light reflects from can also determine the intensity. Previously in the report it was discussed that if the surface was smooth then a beam spot would maintain tight but if a rough surface was used then the beam spot would enlarge and be diffused. This means that a smooth surface would allow the user to get higher intensities with higher notes, and a rough surface would produce lower intensities with lower notes. The surface could be the user's hand, a retro reflector, sandpaper, a white glove, or any other material that could act as a musical pick. When these variations of intensities are detected, the photodiode will produce a variation in the output voltage signal. These changes are received by the microprocessor which emits the specific note the incoming voltage signal is assigned to in the range of notes. The transitions between notes should be seamless, a few milliamps, to the user as they are playing the instrument.

There is also the possibility of having an array of beta detectors for a beam instead of a single beta detector as is the current design. As seen in figure 19D, the array would allow greater collection of light that is reflected off the interrupting medium. Since there is reflecting angle of the interruption with respect to the incident light and a variation in the uniformity of the reflective medium, different beta detectors would receive a different amount of light from the reflections. The intensities from each beta detector for a single string would be read by the microprocessor as having different voltages. These voltages will be averaged out and the resultant value will be assigned a note. Although it is ideal to collect as much information from the reflections as possible in order to have the most accurate assignment of notes, there are concerns that implement such a method could prove to be more of a hassle than it is worth. One of the reasons for this is that because there are more beta detectors for a single beam than originally intended the implementation of extra detect can be tedious. If we are using the photodetectors described in chapter 4, then having to solder a single beta detector with a size of 5 millimeters by 4.24 millimeters requires precise soldering. An adequate location and proper installations are needed for mounting a beta detector. On top of that each beta detector would need to have the appropriate mechanism in place in order to prevent saturation from occurring. Multiply these factors across multiple beta detectors for a single beam, as well as across multiple beams, and it becomes clear how tedious the task of implementing this method can be.

Another concern about the method in figure 19D is the amount of information that the microprocessor would be receiving. Since the beta detector are giving off real-time varying information about the reflections they are collecting, they are also sending real-time varying voltage signals to the microprocessor. The microprocessor needs to be able to handle these variations of voltages from different sources and average out those values in real-time. There is concern that some of the information might not be accounted for as the microcontroller attempts to process the streams of continuous information. The processing speed can also be affected by implementing this method because there is an addition step of averaging out the voltage values it is receiving. Although the microprocessor can operate at microsecond and nanosecond speeds, it is unknown to the team how drastically the processing speed could be affected by these multiple beta detectors. In the meantime, this approach will be kept as an option and could be use if the benefit of collecting more information from the reflected light outweighs the burden of implementing it to the system.

The final design for the beta detector was an array of five parallel photodiodes that feed into a transimpedance amplifier to convert the forward current from the photodiodes into a voltage that the MCU can understand. The transimpedance amplifier also prevents any large currents to damage the MCU. Figure 20 shows a simple schematic of a transimpedance amplifier. The op-amp selected to build the transimpedance amplifier was the LM358. The cathode of the photodiodes is connected to the negative terminal of the LM358 providing a positive output of the amplifier. The array of photodiodes requires DC coupling on the anode side, which go toward ground. Originally the team was using electrolytic capacitors but when the system would turn on and off the capacitors would blow up because of the reverse voltage that occurs from the photodiodes. For this reason, the team tested replacing the capacitors with a half ohm resistor. This allowed the voltage to switch polarity without any damage occurring to the system. The small resistance value also kept the voltage on the anode side of the photodiodes to be nearly ground.

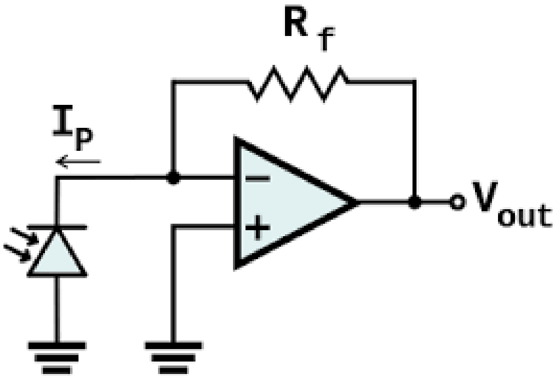

Figure 20: Basic Transimpedance Amplifier

5.6. Laser Emission System

As mentioned before in this report, our team will be using semiconductor green laser diode modules to produce the laser beams for the instrument. Most laser diode modules come with positive and negative leads that can be connected on a breadboard or on a PCB by soldering the leads to the board. Typically, an input voltage of approximately 3.0 volts to 5.0 volts and an input current of 100 milliamps to 250 milliamps would be enough to turn on the laser and maintain continuous output.

5.6.1. Alignment

One of the basic functions of the laser is to shine of the photoresistor so that when the beam is interrupted, the system can know that the beam is "on" and should play the beam's respective notes. To do so, the laser beam must be aligned to the detector. This can first be done by knowing the positions of where the detectors are going to be on the top of the frame so that the lasers on the bottom of the frame can be positioned accordingly. In order to maintain alignment of the beam on the alpha detectors, we plan to have the laser mounted through an opening on the bottom of the frame. The laser will be fitted through the opening and stick out enough to avoid the beam from being blocked while ensuring there is a minimal amount of movement. The laser will be pointed towards the alpha detector and the beam will be aligned to be incident onto the detector. This can be done by using a small piece of paper on the beam and tracking the beam’s path as it travels to the detector. If the beam is off centered, then the laser can be adjusted to ensure that the beam spot is in the middle of the detector. Once the alignment is done, the laser can be bonded to the frame and a seal can be used to close the opening in order to fix the alignment in place. This should hopefully preserve the alignment when the instrument is moved around, and while being played.

5.7. Signal Processing

Once the detectors have picked up the intensities of light, the signals from the detectors will go to the microcontroller. As mentioned before, the detection of light will produce analog signals. We will use an analog-to-digital converter module so that the microcontroller can process the information. Once the determination of a specific note is made based on the signal value, the microcontroller can send it to the analog-to-digital converter module to emit an analog signal to the speaker. This in turn would produce an analog sound that is pleasant to the human ear. There is also the option of having a very finely discrete set of digital signals that it approximates to an analog signal to the point where the human ear cannot tell the difference between digital and analog. For that option a greater level of coding and work would be involved in producing those fine discrete values, but it might be less cumbersome that attempting to produce an analog signal.

When the team connected a speaker directly to a function generator, the team was able to test out how different waveforms sound. It was proven in testing that the analog waveforms were much more pleasant than the digital waveforms. Since we found that an analog waveform produces a higher fidelity sound than a digital square wave the team plans to use pulse width modulation (PWM) to get an approximate analog signal as the output. PWM will be discussed later in this report. In a nutshell PWM allows us to control the discrete values and levels of a digital waveform. If we can use this method to control the fine separations of each discrete level then we can achieve a signal similar to an analog wave.

5.8. PCB Design

The most common method used to build all but the most basic electronic circuits today is the printed circuit board (PCB). A PCB consists of copper tracks layered between a non-conductive material called a substrate with electronic components soldered onto metal contacts on the surface of the substrate. These contacts can be connected to the copper tracks and provide electrical connections between components. Using a PCB in the design allows for a smaller package for the electronics and therefore for the whole system.

5.8.1. Design Software

There currently exist many Electronic Design Automation (EDA) programs that can be used to design the schematic and layout of a PCB. The PCB design process begins once the breadboard prototyping is completed. These programs allow for both designing the schematic for the board as well as actually laying out the components on the board and drawing the traces. Some commonly used EDAs are Eagle, Kicad, Altium, and OrCAD. For this project, Kicad will primarily be used due to it being free (libre) software and therefore having no limits on board size [82]. Other programs which offer a free-of-charge version limit the size of the board or the numbers of layers that can be used.

Once the schematic is created, the EDA needs to generate a group of files called Gerbers. These files are the standard for PCB manufacturing and will be sent to the manufacturer when the board needs to be built. These files provide a description of the board including the location of parts such as the soldering pads and the copper traces. Kicad has a utility to generate these files in RS274X format 4.6, which is the industry standard format. According to the Kicad documentation, the specific files that are expected to be generated for this project using “a double-sided circuit, silkscreen, solder mask and solder paste” are

- Front and back copper
- Front and back silkscreen markings
- Front and back solder paste
- Front and back solder mask

The front and back copper layers are the top and bottom layers of the board and are the two layers where the copper traces are created.

The top and bottom silkscreen markings are the layers that are used to write the names of the components on the board. For example, when a resistor is placed on the board and its reference names is “R1”, then the silkscreen layer is used to write this reference name on the board to denote which component is which. It is standard practice to use a silkscreen color that contrasts with the color of the board. In most cases this means using a white silkscreen.

The front and back solder paste layers are useful when using surface mount device (SMD) components. According to the Kicad documentation, these layers are “used to produce a mask to allow solder paste to be placed on the pads of surface mount components, generally before reflow soldering” [82]. These layers define the areas that should not be covered by any other layers and are occupied by SMD components.

The front and back solder mask layers are a polymer layer that is applied to the copper traces of the PCB to prevent oxidation and ensure that the solder sticks only to its own pad during reflow soldering. This helps prevent accidental short circuits between two closely spaced traces.

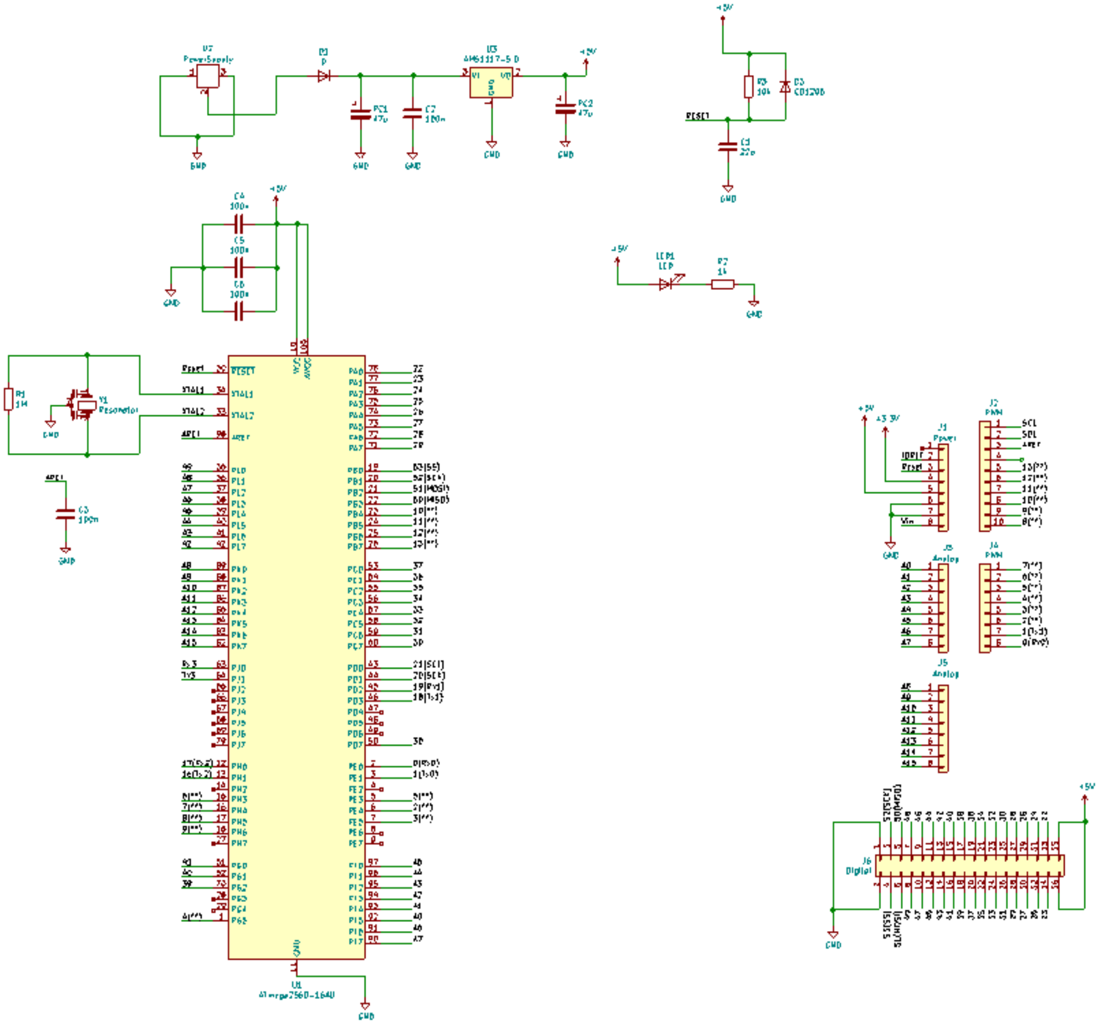

Figure 21: Schematic for the PCB

5.9. Speaker Output

At the end of the hardware is the speaker. This is the process that will produce the audio output needed to make a musical instrument. In the beginning of the project we were looking into making our own speaker. After consulting with the senior design professors, it was recommended to use a commercial speaker and connect it to our system. The reason for this is because speakers can be difficult to make correctly and it would be too much of a burden on the team to produce a speaker that could be substituted by an affordable commercial product. The amplifier and audio output would be handle by the commercial speaker. With this in mind, we plan on obtaining an audio socket soldered onto the PCB and have the ability to connect an audio jack to the system. We will be look for a socket that can accept the standard 3.5 millimeter diameter audio jack so that it is easy to connect to most speakers.

For the commercial speaker we will be looking for one that has a good amplification, capable of producing a wide range of notes, has a good volume control, and can be obtained an inexpensive price. There are a couple of options when it comes to finding an adequate speaker. One of those options include using a regular speaker used for a guitar, electric keyboard, bass guitar, etc. Since other instruments use them with great amplification, it might be suitable for our musical instrument. However, they tend to be bulky and might hinder the portability aspect of the design. Another options is to use external computer speakers that can connect easily to the audio socket of a computer. They are affordable to purchase and are portable. A downside to these speakers are that they might not provide enough amplification as the traditional instrumental speakers.

The team has also discussed using spare speaker the members have or taking apart speakers from old electronics, such as a computer. These speakers can be connected to the system externally or internally. An advantage of doing this type of approach would be that those speakers can be acquire for little to no costs, are compact enough to be installed into our frame, and could eliminate the need for an external speaker. A disadvantage in using this type of speaker is that it there might not be enough amplification and the sound fidelity could suffer from its simple design. We will continue to look and weigh other options with the different types of speakers available. In the meantime we will be using a small speaker head that will help us conduct experiments with the audio output.

5.10. Software

The microcontroller in this system will be responsible for all the signal processing and signal generation. It will receive signals from the alpha and beta detectors and will create an appropriate output based on what is received from the detectors. The alpha detectors will provide a digital signal for the state of the strings which can either be broken or not broken. The beta detectors will provide an analog signal which is used to determine the pitch of the desired note. It will be the job of the software to receive and process these inputs in order to produce the correct output signal.

5.10.1. Programming Language

Arduino microcontrollers are programmed using the Arduino language, which is a dialect of C++. Since all team members should have some experience programming with C/C++, this eliminates the need to completely learn a new programming language. Since the language is based on standard C++, it supports the standard features such as structures, classes, enumerations, etc. There are some variations in the coding language from the C/C++ but with the readily available access to information from the internet, the team can quick solve any questions that may arise from the code.

5.10.2. Integrated Development Environment

An interactive development environment is a tool that combines a text editor, compiler, and often a debugger into one package. Arduino maintains an official IDE, but others may be used as well if they support an Arduino builder to compile and export the code to the MCU. For this project, the Arduino Software 1.8.7 IDE will be used. Unlike IDEs from third parties, the Arduino IDE supports Arduino microcontrollers right out of the box, meaning that the user simply needs to install the IDE in order to begin working. The Arduino IDE also comes with fully functional example programs that could be useful during the development process.

The Arduino IDE is licensed under the GNU General Public License version 2 (GPLv2) and the GNU Lesser General Public License (LGPL). These licenses make the IDE free (libre) software and therefore mandate that the source code be made available. Releasing the IDE under a free license allows the community to create different extensions to the main program in order to improve its capabilities as well as numerous libraries that expand the MCU's functionality. The IDE also works across platforms, with releases for Windows, MacOS, and Linux. This allows the whole team to use the same IDE and therefore avoid compatibility issues that could arise from everyone using something different.

The IDE also contains a utility to burn the bootloader onto a new microcontroller. This will allow for using and programming a fresh microcontroller that is not already on a pre-manufactured board and instead will be used on a custom PCB. It also can upload the compiled code directly to the MCU through a USB cable without needing an external programmer or debugger.

The software block diagram is shown in figure 22. This diagram explains the logic gates the system will have to decide on in order to emit a sound from a detected light intensity.

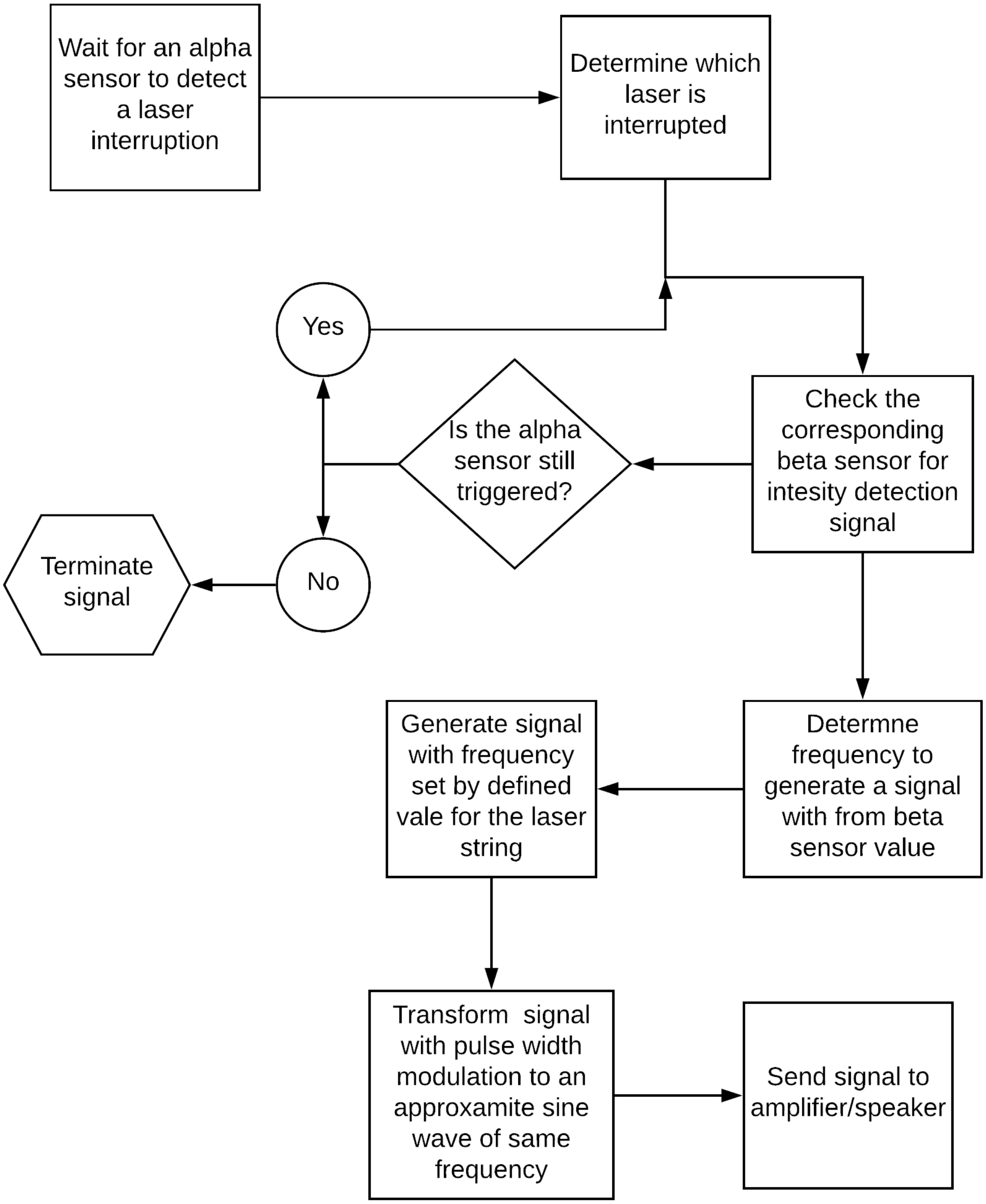

Figure 22: Software Block Diagram

6. Prototype and Testing

Since our project requires lots of repetition, we have formed a plan to develop single string prototype where we can demonstrate proof of concept and any initial tasting. The single string prototype will aid in reducing lengthy troubleshooting. Once we get the results, we want on our single string prototype we can easily replicate what we have done onto our full instrument. We have also employed a two-string testing method to see how two different notes can be played, especially a high note and a low note.

6.1. Single String Prototype Testing

To start with our single string prototype, we performed a simple voltage division circuit on a bread board. We are using the Arduino mega development board for the single string prototype because it contains the ATmega2560 microcontroller we have selected and because it provides the team with simplicity and security for programming and testing. We connected an Arduino mega development board to the common node of the resister and the photoresistor. The resistor has its other end to connect to a voltage source set to 7.2 volts to replicate our battery pack. The photoresistors other end is connected to ground. The Arduino is programmed to read the voltage at that node and then send a signal to an output pin that is can use the pulse width modulation of the board. We have connected the speaker to this pin and ground.

For testing of our breadboard circuit, we use a handheld laser pointer shine on and off of the photoresistor. Figure 23 shows our initial testing set up for our single string. We also ran testing using ambient lighting in the lab and using the shadows of a hand to trigger the system to play a sound. We also connected our output node to a multimeter so that we could see the actual value of the node as we tested our design. The development board on the Arduino is only able to output 5 volts meaning this would be the peak to peak voltage of the signal going to the speaker. The audio being passed to the speaker is at a fixed volume level.

The first issue the team ran into was the high current draw by the speaker. We had a current limit set on the power supply to help prevent damage to any components in the circuit. When the power supply would hit the current limit, it opens a circuit to drop the current being fed in our circuit. This causes the supply voltage to drop to a level lower than what is needed to set the reference voltages in our system. After increasing the current limit on the power supply the circuit operated as expected. We noticed the speaker needs about 200 milliamps to have enough power to generate an output. This should not be an issue in our final system because the speaker will be its own system whit its own power supply. Our final prototype should only pass the small signal to the speaker.

This initial testing proved to be beneficial to giving the team further insight to our project. Since we plan to use a commercial speaker with its own output amplifier, we are not too concerned about our soft output sound at the moment. One issue the team noticed when testing the circuit is that our resistor values where changing when we applied a voltage to the circuit. This is reasonable to happen on the photoresistor since it is made of semiconductor material, but we also faced this issue with our fixed resistor. Our next step in testing for our single string prototype is to vary our resistor values along with the photoresistor. We plan to design the circuit so that the fixed resistor is significantly greater than the resistance of the photoresistor in light, so the line acts similar to an open. This is to keep the currents low on the circuit while the instrument is running.

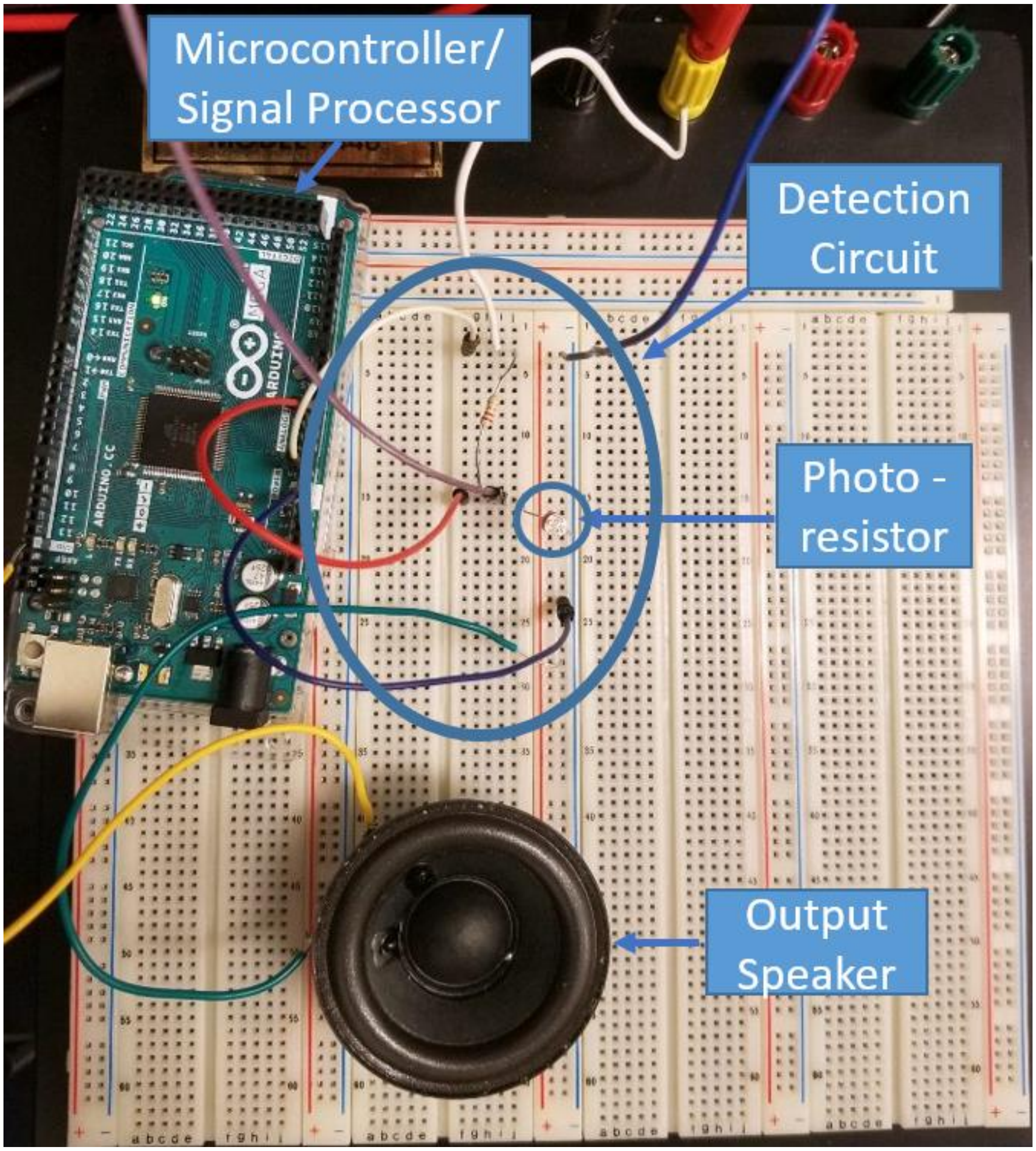

Figure 23: Single Sting Prototype Breadboard Testing

6.2. Testing Beyond the Single String Prototype

The team still needs to run testing on multiple parallel detection circuits to examine the current characteristics. From this we can determine if we will need any current regulators to limit currents on the lines. Reverse currents are also possible to occur in or system where we can add diodes to act as one-way gates.

Upon receiving our components, as is actively happening, we are testing them individually to insure they are good to their rated values. No testing has been done yet for analog detection and writing in the system. Before we are able to test for analog values in the system, we need to investigate more into the programming side of the project.

6.2.1. First Two-String Prototype Testing

To further investigate the response of sound with respective to the incident light, our team as developed a two-string prototype testing method. In this test we seek to see how different notes can be achieved by having different resistor values and incident light. We are primary interested in obtaining a high note and a low note. For our purposes, we arbitrary decided to go for a frequency of 4400 hertz as a high note and a frequency of 440 hertz as a low note. A secondary goal was to also see how we could make the laser beam visible. As seen in figure 24, this set-up is composed of a laser diode, a diffuser, two photodetectors, a microprocessor, and a speaker on a breadboard.

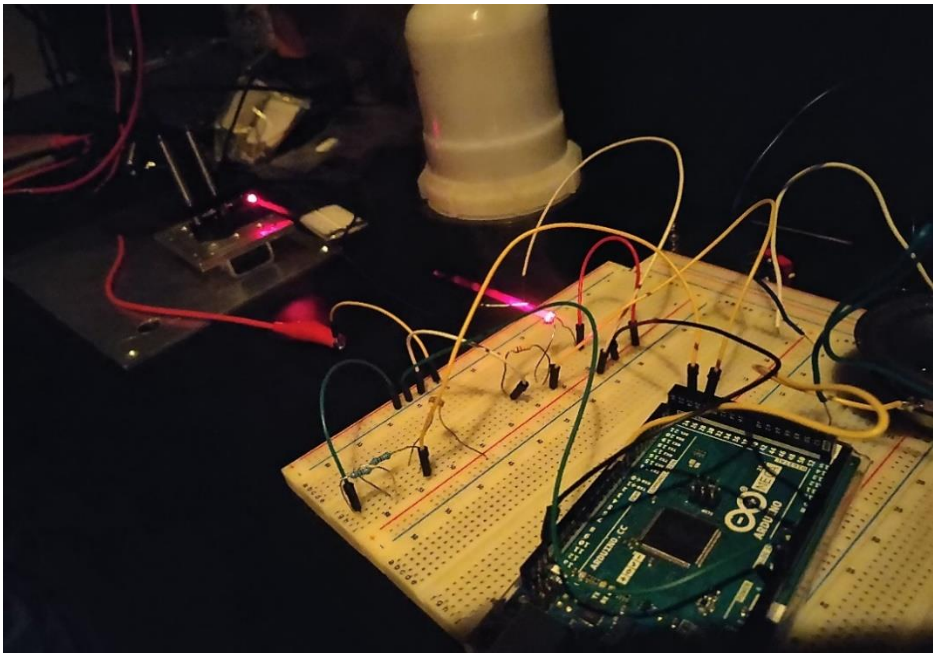

Figure 24: Two-note testing with a laser, a diffuser, two photodetectors, a microprocessor, and a speaker.

The first day of testing the two-sting prototype ran into many failures. One case we are coming across is the issue are where one note will remain on after light shines back onto the photoresistor. Another case we are having is only are able to get sound from one detector system where the audio starts out with the right not a then when removing your hand from the lasers beam the speaker plays the note that is supposed to be for the other detector circuit and the second detector circuit does not trigger any output. A third case is that second detector system will not trigger unless the first detector system has been triggered and then does not stop till the first detector system becomes triggered again and no output is produced when the first note should be playing. We believed all of these errors are in the programming of the system.

The second day of testing of the two-string prototype proved more successful than the first. From testing different kinds of loops and statements in the program the reworking of the program fixed errors in the system. The team discovered that when we test in a well-lit area the range of the detection decreases. On the first day of testing we were in a dim lit room and the range of detection we had for the single string was about half a foot while not being exactly measured. When in the well-lit room a hand had to be touching the photoresistor to trigger a sound. The laser beam was also proven to be visible if enough mist could be created from the diffuser, which can be seen in figure 25. Due to the small amount of mist the diffuser could produce, the beam was only partially visible for some of the time. This leads us to believe that if a larger diffuser were used then the entire beam could be seen for a longer period of time. Screen shots from an oscilloscope are provided below of the two notes that were being sent to the speaker. In figure 25, the high note was reproduced with the desired frequency of 4400 hertz. In figure 26, the low note was attained with a frequency of 440 hertz. The test code uses a simple function that is meant to produce a periodic square wave that can be used as an audio signal. There has been discussion about using the square waves so finely discrete that they can mimic the rich harmonics of natural sounds. We are also exploring the idea of using a sine or sinc functions to produce analog sounds.

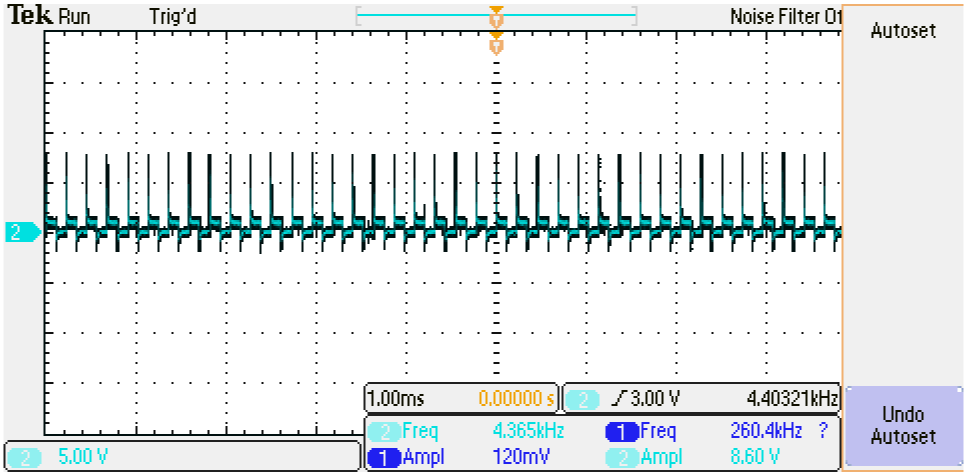

Figure 25: 4400 Hz Square wave from testing.

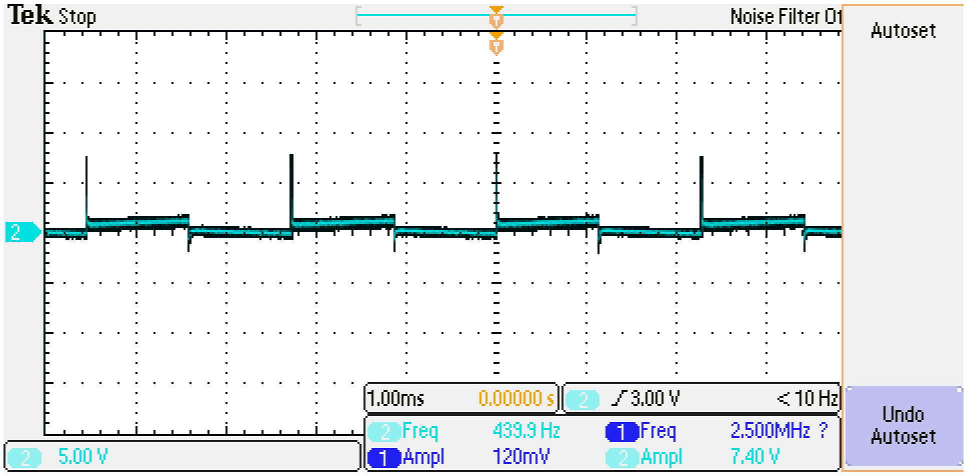

Figure 26: 440 Hz Square wave from testing.

From inspection of figures 25 and 26, it can be seen that there are initial spikes at the start of the steps. The spike for the step up to a positive voltage is much greater in magnitude than the spike from the step down to zero. The spikes are acceptable for this initial testing but to increase the fidelity of the audio removing these spikes is important. However, removing the spikes alone would not be enough to produce true fidelity as it would become necessary to increase the fidelity of the sound by also implementing a PWM into the program. We currently have been testing some programs to use PWM on the brightness of LEDs. No screen shots of PWM on the oscilloscope are given because the width of the signal changes in real time. The next step from lighting the LEDs is to use the PWM for different audio signals. The rate at which the microcontroller does the PWM will determine the pitch of the sound produced.

6.3. Expanding Prototype and Redesign Work

Moving into the second semester of senior design we will be expanding upon the number of strings that are used in the prototype. With improved results from the single string and double string experiments we can have a greater understanding of how the rest of the strings will behave and how they can be integrated together. We will also be incorporating a PCB into the instrument that would remove the need for a breadboard and make the unit more compact. At that point we will be taking into consideration on how the soldering might affect the quality of our sound and take steps to ensure there is minimal loss in the fidelity of the sound. We can have multiple parts that we can solder and use the part that came out the best. We can also reach out to a company that is specialized in soldering to do the work for us, although this might accrue additional costs. Some of the components we have may require the help of an expert because of their size or difficulty in soldering.

Testing has shown that with using the development board and a power supply set to as low as 3 volts the system is still able to operate. This is including the powering of the speaker through the development board, which is not part of the final design. The speaker is also the component that requires the most power. With further testing this may conclude that we can change our cell connection so that the battery supplies a nominal V_{cc} of 3.6 volts. This will mean that we can use the same number of cells and double the capacity of our original battery design.

6.4. Final Design

For the final design six laser beams were implemented to simulate six strings. Each string had an alpha detector and an array of five beta detectors. The number of beta detectors differs from our original concept of one beta detector per sting because it was found to be more advantageous in increasing our range detection. This is because with five beta detectors we were able to collect more light and produce a wider voltage reading from the photodiodes than with one. Having a wider voltage reading enabled us to allocate more pitches per string with an adequate amount of spacing in between each pitch transition. The beta detectors were placed underneath the surface plane with the photodiode array configured in a house-like fashion next to the lasers. The photodiodes were arranged in parallel to have their readings summed together and averaged out to a voltage value. The resultant voltage was sent to an op amp to amplify the voltage to the microcontroller and produce a wide range of pitches.

In the final version of the instrument, two PCBs were implemented. Due to the size of the system, two PCBs needed to be built. The first board contains the MCU and voltage regulation system, while the second board contains the beta detectors. In the finished system, there would be one main board and three beta boards, with one being used for two beams. The boards were designed in KiCad, which is a free (libre) program and therefore places no limit on the size of boards that can be designed, unlike the free-of-charge versions of other programs that place strict limits on the size or number of layers a board can have. Although KiCad supports up to 64 layers, only two layers were used. In the end, the main board is 130 x 64.75 mm and the beta detector is 105 x 29.75 mm. The main PCB contains the voltage regulation system that receives the 12V input voltage as well as the MCU that receives the input signals from the alpha and beta detectors and generates the note that needs to be played. After receiving the 12V input, the voltage regulation system has three parts. The first part is a 5V switching regulator that that powers the lasers. The second part is a 5V linear regulator to power the MCU. The third part is a 6V linear regulator that powers the op amps that are part of the beta detectors. An audio socket is attached at the upper right corner of the board to enable a standard 3.5mm audio jacket cord to connect the system to a speaker. A reset button has been installed at lower right portion of the board for troubleshooting purposes. Heat sinks were also incorporated for our regulator in order to dissipate the thermal load it exhibited during testing and increase efficiency of use.

The second PCB correspond to the photodiodes and laser input power. Since the photodiodes were surface mounts it was easier to designate a separate PCB for their operation and send their voltage signals to the microcontroller than to wire each individual photodiode to the main PCB. The front side of the second PCB is comprised of two groups of five beta detectors that each correspond to an individual string. The beta detectors are spaced out far enough to where two laser beams can use the same board. This was done for efficiency of cost, space, and installation. The back side of the beta detector board contains an op amp for the beta detectors. The close proximity of the op amp to the beta detectors allows a minimal loss of signals from the detectors before amplification. On this side are also the 5V connections to the lasers and the 6V connections to the op amp.

In order to test the functionality of the instrument, several testing procedures were made to ensure success in the project. One of which was the breadboard testing of the instrument. To do so a single string was constructed and tested for range detection of notes. This allowed us to troubleshoot any coding, electrical, and optics issues that arose. We were also able to test out how mist would increase the visibility of the laser beams to aid the user in playing the instrument. Once a reliable single string was achieved, two strings were made in order to test how well replicating the string would work. Issues of signal cross- overs, interruption sequences, and pitch allocation were addressed. Finally, when the frame was assembled all six laser beams were installed along with their respective alpha and beta detectors. They were tested for reliability of readings from the detectors, proper alignment, distribution of power to the beams, portability, signal cross-overs, operation over different lighting conditions, and pitch fidelity. It was found that the instrument works best under dark to dim conditions as the detectors receive less noise from the ambient light.

Using different interrupting mediums such as black tape, paper towels, Styrofoam, tissue paper, sandpaper, and a white glove enabled us to see the different responses we would be able to achieve. When using the hand only the result would usually be that most of the pitch would be achievable with the most extreme pitches not being attainable. Wearing a white glove enabled the higher pitches to be reach while the lowest note would be harder to achieve. We believe that this is due to a greater level of reflection for the glove than the bare hand. Black tape was useful in achieving the lower notes while struggling to get the higher notes. Sandpaper enabled us to test the dispersive effects of rough surfaces and how they effected the reading in our detectors. We found that although it was producing reliable notes when it was close to the lasers and detectors, the further away the rough surface was the less light we were able to detect to the point where detection was almost indistinguishable at about half-way through the playing range. The most balanced interrupting medium that we found was a white paper towel. Using it would normally enable us to attain all pitches and at a reasonable amount of spacing in between each pitch transition. With more time we would be able to create a musical pick that the user could use to reliably play all the pitches in the instrument.

7. Administration

When embarking on a project with a group that has limited funds and time, it is important to have in place a level of management that the group can adhere to in order to secure success within our constraints. In our senior design we exercised a collaborative approach to management. As opposed to the traditional way of management in which one person is the lead and everyone else follows, in the collaborative approach no one was really the lead in the project but instead everyone was a lead in their respective area of responsibility. From here the team members would convene to discuss the progress of each area and develop strategies together on tackling issues. During these meetings decisions on how to move the project forward were explored, goals were assessed and reevaluated when needed, and plans for the overall project would be decided together. Throughout the course of this project different sections of the design of the instrument were administered by the different members of the team. In figure 27, a breakdown of who is in charge of what is shown. There are also milestones shown in this report that highlight what our goals throughout senior design 1 and 2 are to keep on track with completing project. Since costs are a concern for the team, a budget was created to provide a guideline of what our expected costs should be to prevent us from overspending. Finally, in this report is a parts list with vendor, quantity, and price. This will help us find those parts again if we need to purchase more.

7.1. Division of Labor Block Diagram

In this administrative block diagram, it shows who is responsible for what in the design and implementation of the project. Figure 27 shows the division of labor of the entire process of getting a visible light input to emit an audio output. Each team member has their responsibilities within the project. Throughout the block diagram certain blocks are going to have a research designation. This means that although there is a general understanding of how the certain block functions, more information is needed to understand how to use the device or process with the overall integration of the instrument. The blocks assigned with a research and design description mean that on top of requiring more information for their use there is also a need to design how to incorporate it with the other parts. At the beginning of the project those blocks are the ones we have minimal knowledge of how to make it them functional. Blocks in white are the user’s interaction with the device. The process starts with figuring out how to power up the system and what protections are needed in order to prevent malfunctions or destruction of the instrument. For the laser diodes, research has been conducted in their power usage as well in their heat dissipation. The photodetectors have been researched and designed to be functional with the other subsystems. This includes how to turn on and off the emission of sound for a beam and how to detect the different intensities of light that reflect off an interrupting surface. The analog to digital converter involves how to take the signals of the incoming light into electrical signals that the microcontroller can process. The microcontroller block involves understanding the code and how to assign notes to the incoming electrical signals. Amplifiers require knowing how much signal is being sent to a speaker and how much to amplify it by. Vibrato involves the fine variations of sound within a note. The volume control is self-explanatory as the change in audio volume. Lastly there is need to know how to emit sound via a speaker to produce our end result.

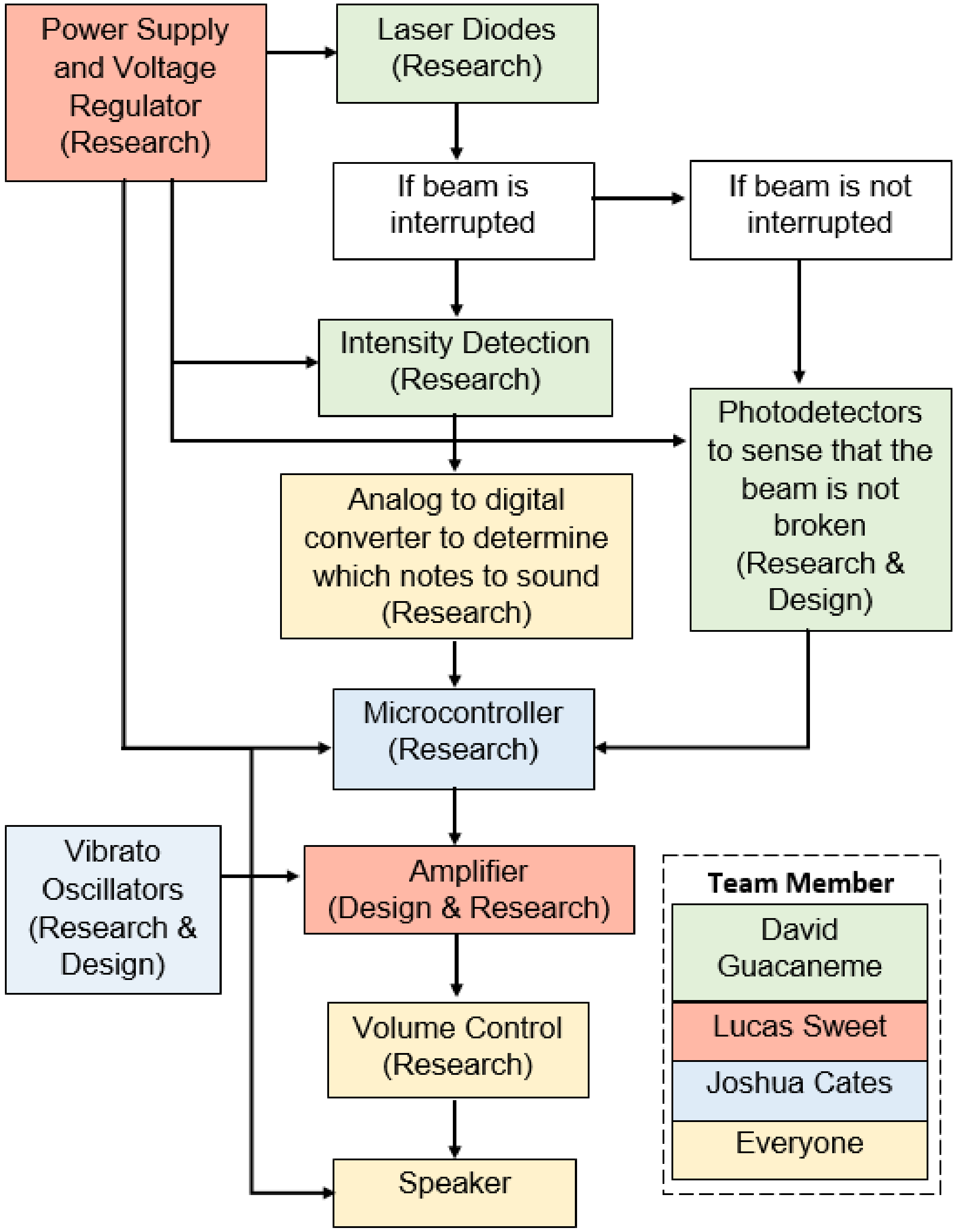

Figure 27: Administrative Block Diagram

7.2. Project Milestones

Tables 26 and 27 show the milestones for our senior design 1 and 2 semesters.

Table 26: Fall 2018 Milestones

Milestone	Approximate Completion Date
Project Idea Decision	9/14/18
Initial Theoretical Research	9/28/18
Table of Contents Organized	10/5/18
Single String Research	10/10/18
Parts and Components Research	10/17/18
Report Documentation 45 Page	10/26/18
Single Test String breadboard testing	10/27/18
Components Chosen	11/8/18
Report Documentation 75 Page	11/14/18
All Components Ordered	11/15/18
Components Checked	11/21/18
Single String Prototype Built	11/26/18
Report Documentation Full	11/26/18
Single String Prototype Demo	11/28/18
Final Report Submission	12/3/18

Table 27: Spring 2019 Milestones

Milestone	Approximate Completion Date
Initial Testing Stage – Frame	1/25/19
Initial Testing Stage – Sensors	1/25/19
Replication of Single Test String	1/30/19
Initial Testing Stage – PCB	2/1/19
Initial Testing Stage – Power System	2/1/19
Initial Testing Stage – Audio System	2/8/19
First Alpha prototype Built	2/18/19
Design Finalization	3/1/19
Second Prototype Built	3/8/19
Complete Design Testing	3/22/19
Repeat Testing	4/5/19

7.3. Budget and Costs

Our project is self-funded, so we plan to keep the project budget as low as possible. With that being said the prices below in table 28 are estimates on the higher side. Our miscellaneous is the highest individual cost because it includes any additional small cost and unseen costs that we may figure out while progressing on the project. We have a team budget of $1500 which is well over the estimated cost for the project. The team's budget is produced by equal contributions from each team member. We have set the team’s budget much higher than the estimated costs as a precaution to not be alarmed if the final costs at the end of the project is much higher than the initial estimate because we plan to allow our project to be scalable meaning that we can add more components to increase the complexity of our final product.

Table 28: Budget

Item	Price Estimate
Laser diodes	$80
Photoresistors & Photodiodes	$10
Microcontroller	$50
PCBs	$150
Speaker	$60
Packaging/Frame	$120
Batteries	$75
Miscellaneous	$200
Total	$745

7.4. Parts List and Vendors

In table 29, it shows the important components that are being used for the projected and where we obtained them from. This is made to help us keep track of our spending and know where we bought our components if we need to purchase more. All components and parts listed here may not be used in the final design. Some of the components where bought in bulk for testing purposes. They were also bought as an insurance in case our components ended up malfunctioning or damaged then we can quickly swap it out with spare parts. This allows us to avoid wasting time in ordering the parts and waiting for delivery, which can be weeks or more than a month. Although some of the components listed were made by a specific manufacturer, such as Vishay photodiodes, we found that some distributers would be able to provide the same component for a lower price. This allowed us to reduce our costs while maintain a desire quality in our components. There are also supplementary components included such as the cell charger.

As we progress through this project, components that we might not think we need could become vital to our design. In those cases, we will update this part expenditures and keep track of our budget to ensure we do not go over budget. It is worth noting that some of the testing components were given by L-3 Technology Corporation in the Advanced Laser System Technology sector. This was made possible due to one of the members having an internship there while the company was clearing out their inventory. Although the components were not expressly given as a donation, the team would still like to recognize where some of our components were obtained. Other testing components were found around the senior design lab as well as testing equipment.

Table 29: Part Expenditures

Item Name	Supplier	Price/Unit (USD)	Qty	Total Cost (USD) *	Item Name	Supplier	Price/Unit (USD)	Qty	Total Cost (USD) *
Samsung-30Q	18650 Battery Store	4.74	16	88.26	47 µF ceramic capacitor	Digi-Key	0.19	25	4.76
First Main PCB order	JLPCB	0.80	10	25.92	0.1 µF ceramic capacitor	Digi-Key	0.042	30	1.26
Second Main PCB order	JLPCB	3.37	5	41.02	Oscillator	Digi-Key	0.232	10	2.32
Third Main PCB order & Beta Sensor PCB	JLPCB	3.41 1.63	5 10	49.99	1 MΩ resistor	Digi-Key	0.12	20	2.40
L7805CV Voltage regulator	Amazon	0.40	20	7.99	500 mΩ resistor	Digi-Key	0.092	20	1.84
3.5mm mono Jack	Mouser	0.90	5	12.49	10 KΩ resistor	Digi-Key	0.19	30	5.70
VS-6TQ045S-M3 Schottky Diode	Mouser	1.19	12	14.28	Photoresistor	Amazon	0.08	30	2.23
Digital Illuminance/Light Meter	Amazon	29.99	1	29.99	AIAP-01-100K-T Inductor 10 µH	Digi-Key	0.38	10	3.80
L7806ABV Voltage regulator	Arrow	0.32	20	7.11	15 µF electrolytic capacitor	Digi-Key	0.326	20	6.52
Vishay TEMD5510FX01 PIN photodiode	Arrow	1.16	60	69.60	180µF electrolytic capacitor	Digi-Key	0.542	15	8.13
Green Laser Diodes	ebay	5.89	12	70.68	Heat sink for laser diodes	eBay	5.71	7	39.98
18650 Cell Charger	Amazon	14.99	1	14.99	Battery Holder	Amazon	1.50	6	8.99
LM358N Op-Amp	Amazon	0.16	50	7.99	12AWG Wire	Amazon	0.85	10ft	8.49
ATMEGA 2560 microcontroller	Digi-Key/ Arrow	12.06	8	96.48	Testing hardware	---	---	---	299.78
P0846NL Inductor	Mouser	2.19	10	21.90	Miscellaneous	---	---	----	134.03
LM2678T-5.0/NOPB	Mouser	5.82	12	69.84	**Proposed: $745 + $745 for reconstruction**				
CONN HEADER VERT 6POS 2.54MM	Digi-Key	0.24	5	1.20	**Total : 1159.96**				

8. Conclusion

The project has been an incredible experience for the team. Working together towards a common goal, maintaining constant communication, writing technical reports, and troubleshooting problems has helped us develop professionally. Being able to tackle such a unique project that we came up with and design it into reality has a milestone for our engineering careers.

After finishing the first semester, the team members believed that there was a reasonable amount of progress to show that the project will be feasible by the next semester. Conducting a single string prototype, as well as a two-string prototype, helped us understand what types of troubleshooting we might encounter for the rest of the beams. With these tests we were able to witness issues arise in our experiments, such as having a sound being emitted regardless of whether light is incident on the photodetector, and have addressed them in our evaluations. Important components were ordered or acquired and were used in testing before starting senior design 2. The software was able to process an input light detection into an audible sound. Finally, the speaker head that was used in testing prove that it was possible to hear an audible sound from the system.

Moving forward into senior design 2 we were looking into expanding our single string and two-string prototype into a full range of laser beams. A frame was made to house the laser diodes and photodetectors. A fixed alignment is critical to make the instrument portable because moving the device could cause misalignment of the laser beams to their respective photodetectors. This was solved using the mounting techniques describe earlier in the report. The tasks of being able to process multiple analog signals proved to be a challenge as the microcontroller needed to be able to capture all of those electrical signals in real-time and process them accordingly without mixing up the signals. A big factor to achieve for in senior design 2 was having a PCB ready as early as possible so that the product can be compact and functional by the end of the semester. We had the ability to plug in an audio jack into the system which allowed us to connect to any reasonably sized speaker. Since speakers already have a way to amplify the incoming signals, this eased our implementation of having an amplifier and a speaker at the same time with minimal loss. The lasers that were used turned out to have a higher output power than the rated power. This meant that our laser output was not eye-safe however several approaches were taken to ensure the system was as safe as possible given the conditions of the project. Apertures were implemented to increase laser safety and further protect the user. Providing eye-safe goggles to users and creating warning signs about potential eye hazards were some additional measures that were taken to ensure the safety of the user. Ultimately if this were to be developed into a real product, more time and resources would be spent to ensure the lasers are safe to use. Primarily lowering the output power and increasing the sensitivity of the photodiodes to maintain the accuracy of pitch assignation. Other safety measures would be implemented such as an emergency turn-off button, laser-on alert system, and child-locking mechanism.

If given more time and resources, we would have implemented more features to improve the project. One of which is creating a software that is capable of receiving the input light and creating a continuous gradient of pitches as the collection of light varies instead of having discrete levels of pitches. An array of different laser colors with appropriate wavelength-sensitivity beta detectors could be used for aesthetic appeal and a mist diffuser would be built into the frame to enable the user to see the beams without needing external diffusing materials. Additional safety measures as stated previously would be incorporated. Bluetooth connection to a remote speaker or electronic device (such as a phone) would be an excellent way to project the sound of the instrument without the use of cables. The ability to change the note tuning for each laser, replicate the feel of playing a real string instrument, and replicate the sound decay that naturally occurs when a string is plucked would be some of the stretch goals we see could be worked upon.

One of the biggest achievements of the project is being able to have an input light into the system and have it give an audio output. Seeing how a visible beam can produce an audible note made us believe that the project is more feasible than we ever could have imagined. It also gives us a sense of confidence that we know we are heading in the right track and it is only a matter of improving upon our results to finally obtain our laser musical instrument.

9. Appendices

The following appendices show the references, copyright permissions requested, and datasheets used for the making of the paper.

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Green laser diode module

https://www.ebay.com/p/Industrial-lab-532nm-10mw-5vdc-Green-Laser-Dot-Diode-Module/1878688616?iid=131885452111&chn=ps

Red laser diode module

https://www.ebay.com/p/10pcs-Laser-Dot-Diode-Module-Mini-650nm-5mw-5v-Head/1273735434?iid=232972748165

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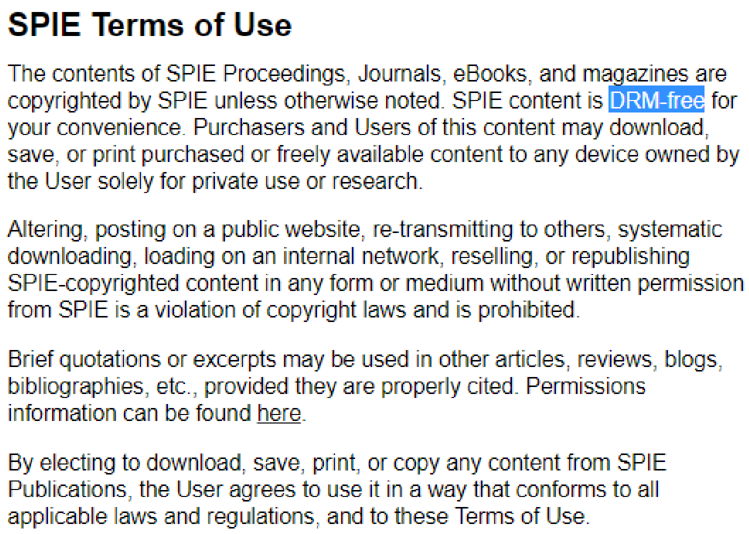

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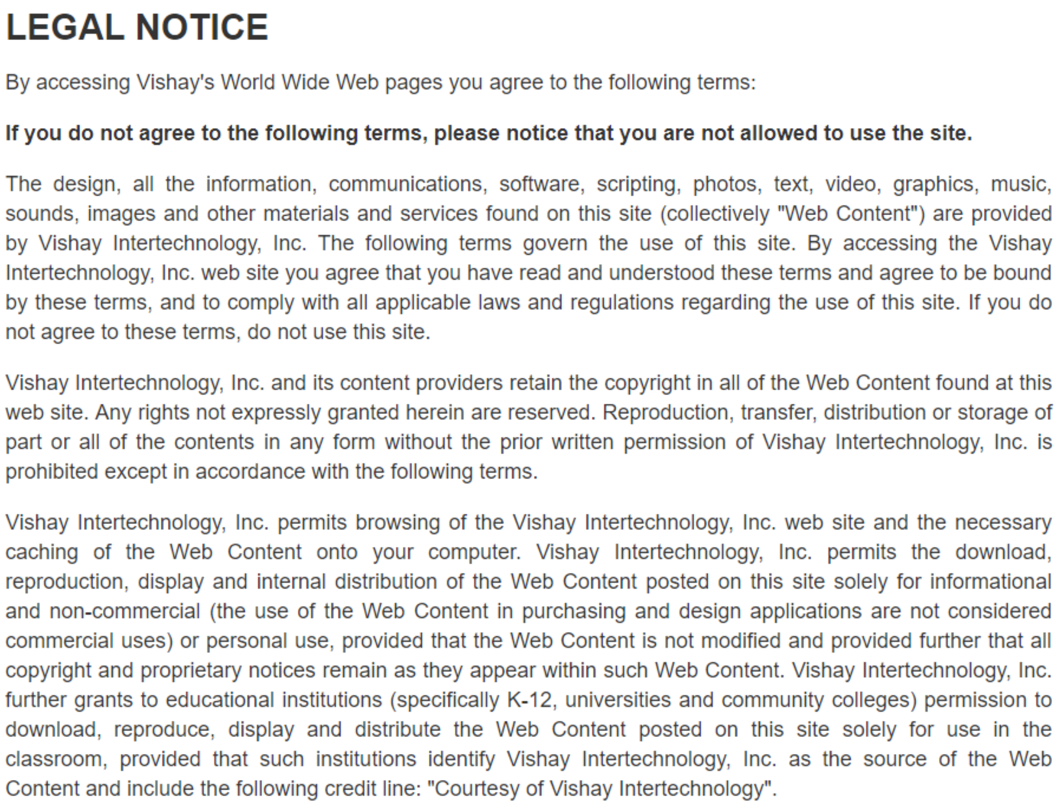

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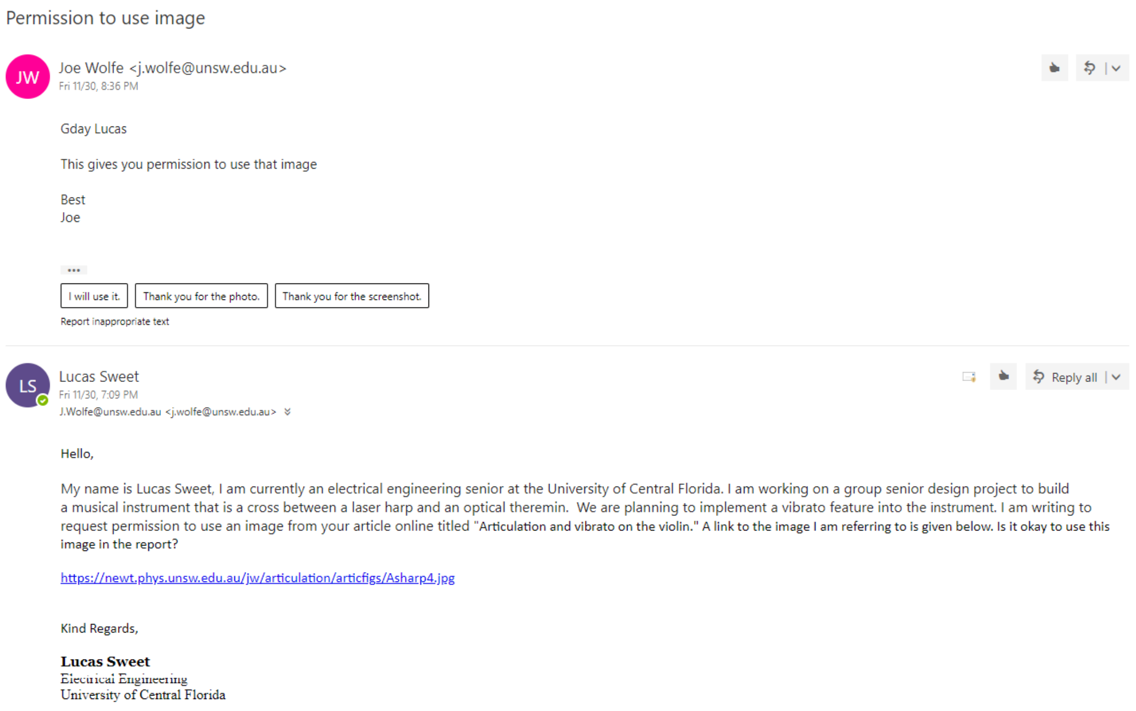


Permission to use image

Joe Wolfe <j.wolfe@unsw.edu.au>
Fri 11/30, 8:36 PM

Gday Lucas

This gives you permission to use that image

Best
Joe

Lucas Sweet
Fri 11/30, 7:09 PM
J.Wolfe@unsw.edu.au <j.wolfe@unsw.edu.au>

Hello,

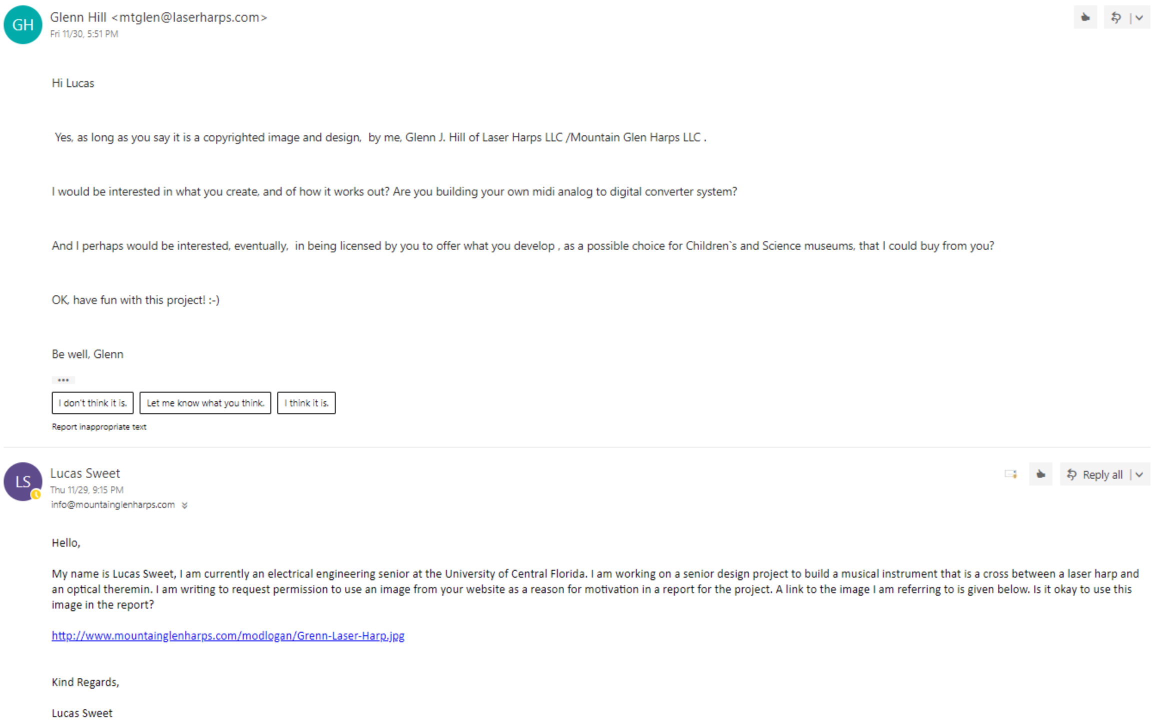
My name is Lucas Sweet, I am currently an electrical engineering senior at the University of Central Florida. I am working on a group senior design project to build a musical instrument that is a cross between a laser harp and an optical theremin. We are planning to implement a vibrato feature into the instrument. I am writing to request permission to use an image from your article online titled "Articulation and vibrato on the violin." A link to the image I am referring to is given below. Is it okay to use this image in the report?

https://newt.phys.unsw.edu.au/jw/articulation/articfigs/Asharp4.jpg

Kind Regards,

Lucas Sweet
Electrical Engineering
University of Central Florida

Permission for Figure 3: Waveform of a Vibrato sound from a Violin



Glenn Hill <mtglen@laserharps.com>
Fri 11/30, 5:51 PM

Hi Lucas

Yes, as long as you say it is a copyrighted image and design, by me, Glenn J. Hill of Laser Harps LLC /Mountain Glen Harps LLC .

I would be interested in what you create, and of how it works out? Are you building your own midi analog to digital converter system?

And I perhaps would be interested, eventually, in being licensed by you to offer what you develop , as a possible choice for Children`s and Science museums, that I could buy from you?

OK, have fun with this project! :-)

Be well, Glenn

Lucas Sweet
Thu 11/29, 9:15 PM
info@mountainglenharps.com

Hello,

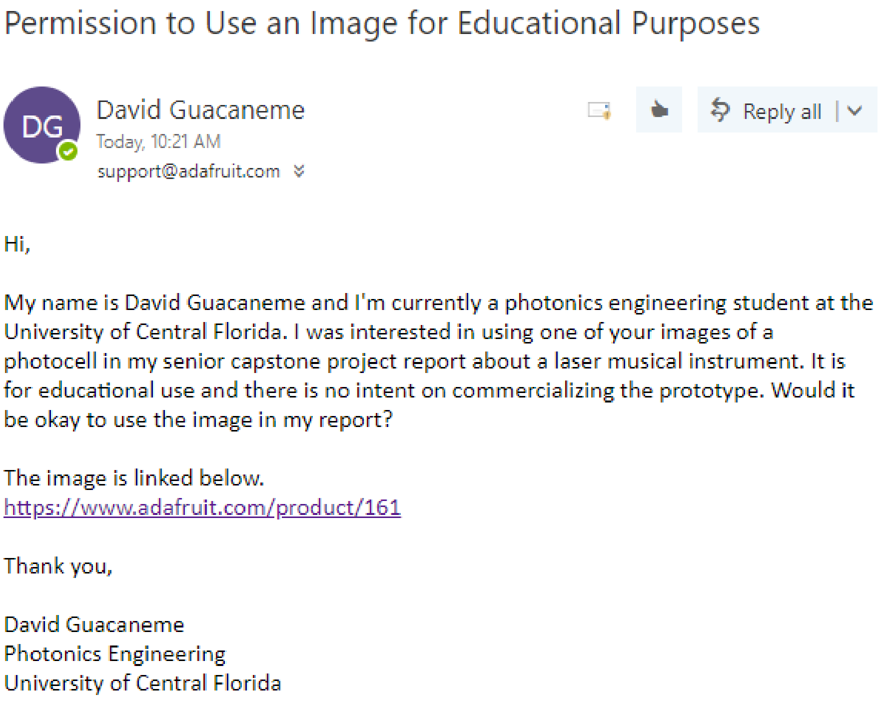
My name is Lucas Sweet, I am currently an electrical engineering senior at the University of Central Florida. I am working on a senior design project to build a musical instrument that is a cross between a laser harp and an optical theremin. I am writing to request permission to use an image from your website as a reason for motivation in a report for the project. A link to the image I am referring to is given below. Is it okay to use this image in the report?

http://www.mountainglenharps.com/modlogan/Grenn-Laser-Harp.jpg

Kind Regards,

Lucas Sweet

Permission for Figure 1: Cover Photo



Permission to Use an Image for Educational Purposes

David Guacaneme
Today, 10:21 AM
support@adafruit.com

Hi,

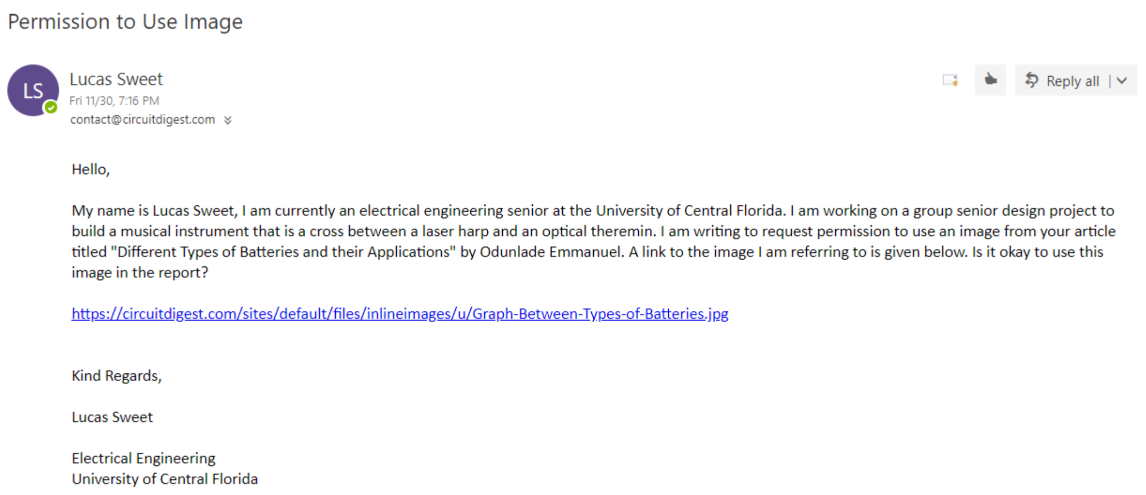
My name is David Guacaneme and I'm currently a photonics engineering student at the University of Central Florida. I was interested in using one of your images of a photocell in my senior capstone project report about a laser musical instrument. It is for educational use and there is no intent on commercializing the prototype. Would it be okay to use the image in my report?

The image is linked below.
https://www.adafruit.com/product/161

Thank you,

David Guacaneme
Photonics Engineering
University of Central Florida

Permission for Figure 10: Photocell



Permission to Use Image

Lucas Sweet
Fri 11/30, 7:16 PM
contact@circuitdigest.com

Hello,

My name is Lucas Sweet, I am currently an electrical engineering senior at the University of Central Florida. I am working on a group senior design project to build a musical instrument that is a cross between a laser harp and an optical theremin. I am writing to request permission to use an image from your article titled "Different Types of Batteries and their Applications" by Odunlade Emmanuel. A link to the image I am referring to is given below. Is it okay to use this image in the report?

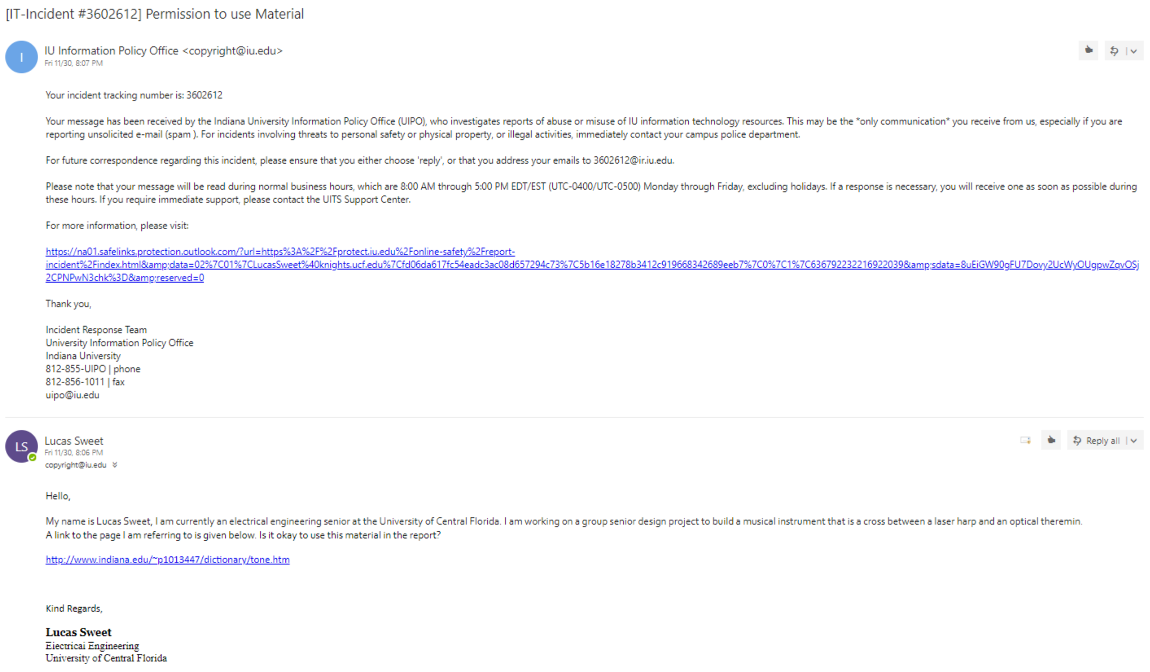
https://circuitdigest.com/sites/default/files/inlineimages/u/Graph-Between-Types-of-Batteries.jpg

Kind Regards,

Lucas Sweet

Electrical Engineering
University of Central Florida

Permission request for Figure 28: Battery density comparison



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https://na01.safelinks.protection.outlook.com/?url=https%3A%2F%2Fprotect.iu.edu%2Fonline-safety%2Freport-incident%2Findex.html&data=02%7C01%7CLucasSweet%40knights.ucf.edu%7Cfd06da617fc54eadc3ac08d657294c73%7C5b16e18278b3412c919668342689eeb7%7C0%7C1%7C636792232216922039&sdata=8uEiGW90gFU7Dovy2UcWyOUgpwZqvOSj2CPNPwN3chk%3D&reserved=0

Thank you,

Incident Response Team
University Information Policy Office
Indiana University
812-855-UIPO | phone
812-856-1011 | fax
uipo@iu.edu

Lucas Sweet
Fri 11/30, 8:06 PM
copyright@iu.edu

Hello,

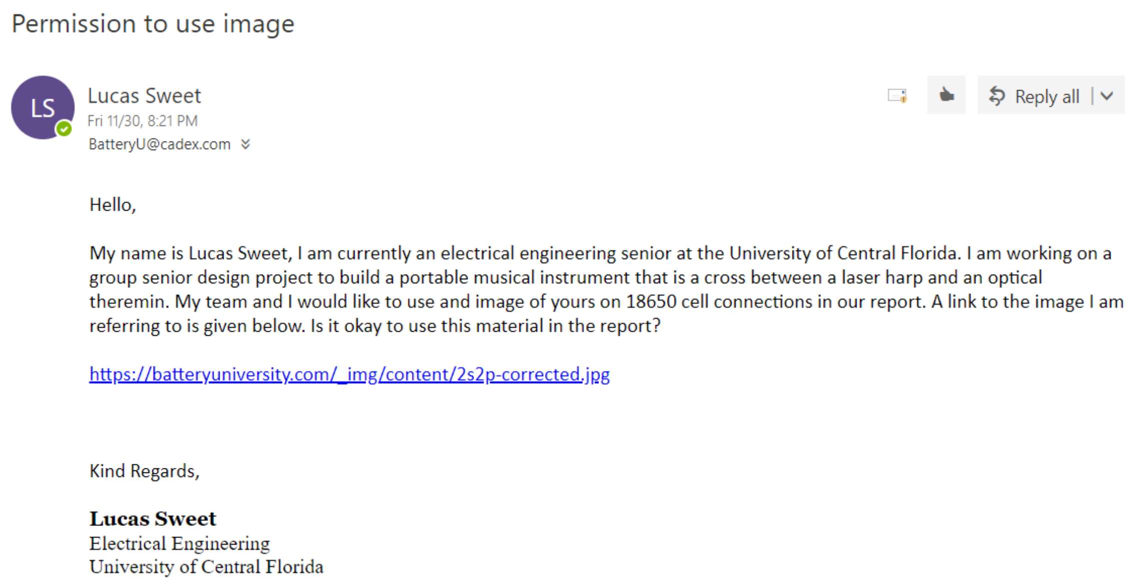
My name is Lucas Sweet, I am currently an electrical engineering senior at the University of Central Florida. I am working on a group senior design project to build a musical instrument that is a cross between a laser harp and an optical theremin.
A link to the page I am referring to is given below. Is it okay to use this material in the report?

http://www.indiana.edu/~p1013447/dictionary/tone.htm

Kind Regards,

Lucas Sweet
Electrical Engineering
University of Central Florida

Permission request for Figure 29: Summing Signals



Permission to use image

Lucas Sweet
Fri 11/30, 8:21 PM
BatteryU@cadex.com

Hello,

My name is Lucas Sweet, I am currently an electrical engineering senior at the University of Central Florida. I am working on a group senior design project to build a portable musical instrument that is a cross between a laser harp and an optical theremin. My team and I would like to use and image of yours on 18650 cell connections in our report. A link to the image I am referring to is given below. Is it okay to use this material in the report?

https://batteryuniversity.com/_img/content/2s2p-corrected.jpg

Kind Regards,

Lucas Sweet
Electrical Engineering
University of Central Florida

Permission request for Figure 30: Example of Cell Connections

9.3. Datasheets

Vishay TEMD5510FX01 PIN photodiode: http://www.vishay.com/ppg?81293