Barenaked Lasers

High-Level Design

EE 41430 – Fall 2012

Matt Clary
Tyler Gregory
Billy Kearns
Chris Newman

Table of Contents

1. Introduction

Musical instruments have come a long way throughout history, from early flutes to pianos to electric guitars and synthesizers. We plan on creating the musical instrument of the future—the Laser Harp. Our laser harp will utilize lasers and distance sensing technology to allow a user to play their favorite songs in a visually stunning way while emulating multiple instruments for an exciting audio experience. This project will incorporate numerous challenging aspects of electrical engineering, including microcontroller use and programming, digital signal processing, circuit design, signal control, and many more. We hope to demonstrate our mastery of these skills while producing a top of the line laser harp.

2. Problem Statement and Proposed Solution

Our aim in this project is to design and build a musical instrument that allows non-musicians without a musical background to generate in-key tones and play a diversity of songs on a versatile, easy-to-use, and cost-effective instrument. The users should be able to partake in and contribute to "jam sessions" with their more musically inclined friends without feeling left out. Although we don't have an actual real world problem to solve such as reduced energy consumption or carbon emissions, we intend to design and create a laser harp for pure entertainment. Our laser harp will be a new, futuristic musical instrument that will be easy to play, visually impressive, and able to emulate multiple instruments.

Our laser harp will be designed on the basic concept of having multiple lasers shining vertically next to each other and having the instrument generate a tone whenever the user covers up one of the lasers with his or her hand. As the user adjusts the height of his or her hand, the instrument will adjust the volume of the tone. We will use an infrared sensor placed next to the laser source to detect when the user's hand is covering the beam and how far away it is from the source. This will generate a signal that when processed through the audio processing equipment will generate the desired tone. In this way, users do not need to know the subtleties of posture and good form required to play traditional instruments such as the piano or guitar. User also do not need to know music theory, as each note is automatically played in key.

Our project design leaves much room for expansion as well. Once we can successfully construct the basic device, we will try to add additional features to the laser harp. Some of these include having the instrument play background music to play along to and using different colored lasers to indicate which notes to play for a certain song as a "teaching mode." This will facilitate the ability of the user to play along with friends and contribute musically.

3. System Requirements

Power Supply
Our laser harp will need to a power supply in order to run the lasers, IR sensors, speaker output, and associated processing and conversion circuitry. The potential IR range finders and lasers we have identified both require a 5V source. The microcontroller we plan on using requires a 3.3 V source. In order for the laser harp to be long-lasting and provided with sufficient power, we chose to use a 5V 4.4A power jack connected to a wall outlet. The 5V source will power the lasers and IR sensors. A voltage regulator can then be used to convert the 5V to 3.3V for use by the microcontroller. This avoids the lossiness inherent in voltage dividers.

Range Detection
In order to play the instrument, a mechanism needs to be used to sense when the user's hand is covering the laser. For our application, we want to be able to control volume by the height of the user's hand, so the sensing device will also need to be able to sense the distance from the laser's base and generate an output that indicates this height and can be processed by the microcontroller. Since the microcontroller we have identified has easy-to-use analog to digital conversion capabilities (as demonstrated in the project demo) we will use a detector with an analog voltage output. The distance vs. voltage output characteristics of this device will also need to be steep in the distance ranges of interest, i.e. the analog voltage output should change a lot with a small change in hand distance over the operation heights. This allows the microcontroller to distinguish hand height with a high degree of precision. Since people will generally cover the lasers from no lower than their waist to no higher than the tops of their heads, a range of 3 to 6 feet would be ideal. It will also need to output a voltage in an acceptable range to be handled by the microcontroller (3.3V) and be powered by a supply that can be provided by the 5V power source. Given these requirements, we decided to use infrared range finders with analog voltage outputs.

Visible Sensor Locations
In order to play notes, the user must interfere with the infrared beam emitted by the range finders. The user must therefore be able to see the locations of the infrared beams in order to play the desired notes with precision. Infrared light is out of the visible spectrum, so our solution is to use lasers in the visible spectrum to indicate the location of the IR beam. The lasers need to be located very close to their corresponding range finders (so need to be small) and need to be strong enough to be visible in a dark room. However, they cannot be so powerful as to be potentially dangerous to the user. Thus, we chose 5V (to interface with the

5V supply) red lasers that run at 40 mA.

Converting Analog Sensor Output to Audio Signal

Once the analog signal is generated by the IR range finder, this signal must be converted into an audio signal whose frequency and amplitude (volume) are determined by the specific laser being covered and the user's hand position, respectively. The analog voltages could be read by a microcontroller. The voltages can be converted to a digital signal and stored sequentially in a register in the microcontroller. If the user's hand covers the laser, the voltage will pass a certain threshold value and the microcontroller (reading the digital information in the register) will set a flag corresponding to that channel, indicating that a note should be played. A routine that looks for this flag being set can then output a softwired digital signal that contains information on the note frequency corresponding to the laser being covered. This digital signal can then be processed by a DAC to output the desired sinusoidal audio signal. Though we are not fully sure of the device we would use to accomplish this and how this device would work, we did find several audio DACs on Digikey that claim to perform this function.

This determines note pitch based on the channel being covered. The next challenge is controlling note volume. As stated above, the analog voltage can be read by the microcontroller and converted to a digital word which is then stored in memory. This digital value can be output to yet another DAC which drives a voltage controlled amplifier (VCA). The audio signal is the input to the VCA and the gain is thus controlled by the value of the analog voltage being read. On Digikey, we found ICs that combine both the VCA and audio DAC functionalities into one package. Though we do not understand their operation, they might be useful in solving these problems.

Sound Output

In order to generate musical notes, our laser harp needs a means of converting the electrical audio signal into audio waves. This can be accomplished using speakers. The speakers need to be volume adjustable (achieved using an amplifier with a potentiometer), audible from a reasonable distance, and small enough to fit in the laser harp packaging. They also need to be operable in the possible power range of the supply and audio signal generator and operable over the frequency range of human hearing so as to produce high quality sound. For these reasons, we chose a single 20W rated 40W max 103mm x 103mm x 50mm speaker.

Computer Interface for Programming

The laser harp microcontroller will need to interface with a PC in order to be programmed to complete the particular tasks required of it. This will require the use of a serial connection to the microcontroller and pins on the board to connect to an external programmer such as the PICkit 3. This connection will allow the basic functionality of the microcontroller to be programmed and it will also allow the user to make customizable alterations later on. For example, the user could program different sounds that emulate different instruments and change the key that the laser harp is operating in.

User Interface

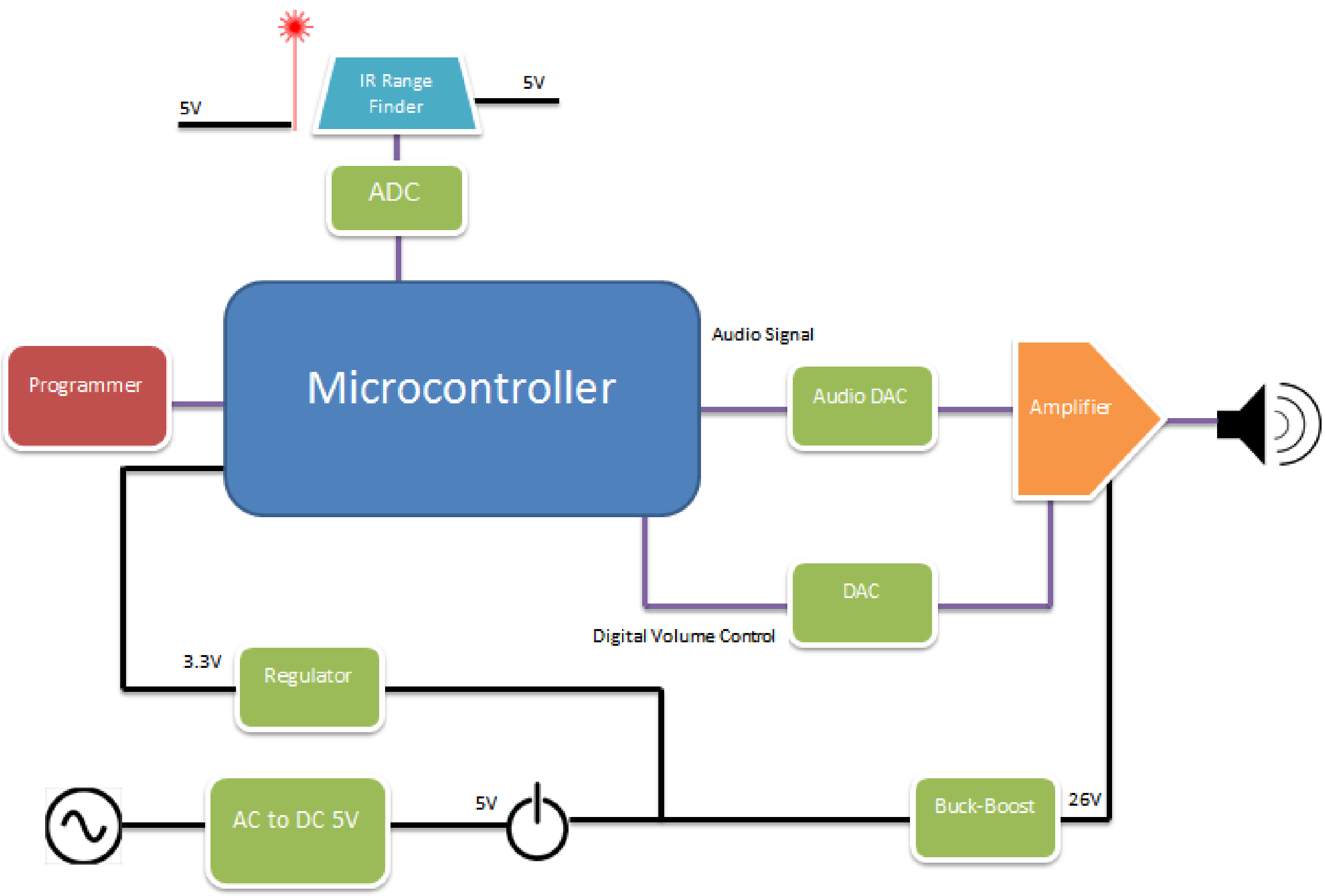
Certain properties of the laser harp need to be adjusted by the user. The user must, for example, be able to easily turn the instrument on and off, so a power switch needs to be included on the laser harp packaging in an easily visible location. It would also be useful to adjust the speaker volume mechanically by turning a knob (in addition to adjusting hand position). This allows the user to play the instrument at an overall higher or lower volume based on the situation. If he or she is outdoors playing to an audience the laser harp should be louder than if the user is in a dorm room.

Durable Packaging

The sensitive electronics of our laser harp need to be protected from environmental wear and tear, and the users need to be protected from the potentially high heat of the electronics. In order to do this and hold the entire system together, some sort of external packaging is required. It must be durable and compact but lightweight and cheap. It must also be aesthetically pleasing to look at and of a small enough size so that it can be conveniently transported. We therefore chose to use a wooden box with one side being a door made of transparent fibreglass. This allows one to see the complex circuitry inside and to access it if it needs to be fixed. This laser harp must also sit solidly on the ground without tipping or shifting during normal use. The base must therefore be low to the ground and wide enough to support itself. The lasers must also be mounted so as to point vertically up in the air. This allows the user to easily see the lasers and easily cover them to play notes.

4. System Block Diagram

4.1 Overall System:



4.2 Subsystem and Interface Requirements:

Power Supply

Converter: The power supply needs to use a wall outlet to provide power to the circuity. It therefore must be able to convert the 120V 60Hz AC to a steady DC supply for the circuit. It must also be able to provide enough current and power. The converter could provide 5V DC-the operating voltage of our sensors and lasers, but it also must provide enough power for 20 lasers (400mA) and 10 IR sensors (300mA). The converter being used also needs to be electrically isolated from the components it is driving, so a unity gain buffer amplifier could be used if that functionality is not already included in the converter package.

Regulator: The microcontroller requires 3.3V, so a voltage regulator could then be used to supply this 3.3V from the 5V source. The regulator needs to supply the required current to the microcontroller without significant signal noise.

Amplifier: Lastly, the audio signal amplifiers need to be powered with a higher voltage source. A buckboost circuit could be used to supply the required 10 to 26V. This would need the desired current and voltage rating to power the op amps and would also need to be stable enough to generate a steady DC signal for the power supply.

The converter we chose can output 5V at 4.4 A, so it should be able to meet our design requirements.

Serial Programmer
This system requires board connections to the microcontroller as well as pins to connect to an external programmer. The microcontroller has predefined I/O ports that are used for programming purposes. These can be wired to pins that interface with the programmer. For its ease of use and debugging capabilities, we can use the PICkit 3 serial programmer/debugger.

Lasers
The lasers we chose need a 5V DC source and have a current rating of 40mA. Initially, we will have 10 separate channels with the ability to play 10 distinct notes (allowing for a full octave plus 2, increasing the variety of songs one can play). This means we must have 10 lasers all illuminated at once. The power supply must therefore be capable of supplying 5V at 400mA in order to power the lasers. One of our potential enhancements is to include a “teaching mode” in which the laser that the user is asked to play switches off and a different color laser is switched on in its place. This requires 10 more lasers, but still only 10 will be emitting light at any single point in time.

Sensors
Each channel requires a sensor, so 10 sensors are needed for our laser harp. These sensors require 5V DC at 30mA, so our 5V power supply must be capable of providing an additional 300mA. The sensors must also be capable of outputting a signal that can be processed and used to produce the desired audio tones. Since we will be using a microcontroller with a built in ADC, the sensors we chose output an analog signal indicating the distance of an obstruction from the device. This analog voltage must be in a range usable by the microcontroller. Our sensors have a maximum output value of 3V which is within the bounds of the microcontroller supply voltage (3.3V). The sensor range is also an issue; it must be usable from roughly waist high to the user’s head. The sensors we have identified have a range of 100 to 550 cm (40 to 216 in). Though the upper bound seems much greater than what we will need, the change in voltage over change in distance falls as distance increases. The means that, at greater distances, the distance resolution decreases and it becomes harder to tell when the user moves his or her hand. For our sensor, the resolution is greatest and relatively linear between 40 and 80 in, which is our desired operating region.

Microcontroller

Our microcontroller is powered by a 3.3V supply sourced by the voltage regulator described above. It needs to be able to take in 10 analog voltages from the sensors, sample and convert the values to digital values, then store the digital words in registers. Our chosen device has 16 built in 10 bit ADCs and so accomplishes this. It also has 53 I/O ports which are more than enough to fulfill the needs of our system. The microcontroller then must output two digital signals. One must contain information on the frequency to be played and is determined by the channel being covered. When the digital distance value being stored in the register passes a certain threshold, a flag could be set which causes the microcontroller to output the corresponding digital frequency value. This value could be softwired in the code. The microcontroller must also output information about the volume of the tone to be played. When the flag is set indicating a channel is covered, the digital value of the hand's distance stored in the register could be output to a DAC which then drives a VCA. We are entirely sure how to do this but this would be an interesting future enhancement that has not been used in other laser harp models. Lastly, the microcontroller needs an operating frequency sufficient to sample each channel fast enough and output the digital signals quick enough to produce high quality audio signals that change pitch and volume at an imperceptible lag behind hand movement. The microcontroller frequency is 80MHz which is sufficiently greater than the range of human hearing and thus should be high enough for our system.

Audio DAC

It is important to convert the audio signal from digital to analog because the speaker we are using can only read an analog signal. The DAC will receive the signal from the microprocessor, convert it to an analog signal, then pass this signal to the audio amplifier. There were many ways that we saw this possible. We could get a device specially made for this. Also, there are audio amplifiers that are variable gain that have a DAC built into them. This may be an alternative that we will look into in the future once we learn more about digital signal processing and the use of audio signals. The DAC that we found on digikey runs on 5V, which is consistent with our other devices. The DAC requires a clock signal to be sent along with the data signal. The DAC will read the input data signal following the 16th clock cycle and then convert this signal to an analog signal. Data can be read at rates up to 50 MHz, which is way faster than we would ever need it to run. Also it allows for a 16 bit input, which is high quality sound. There is also an exposed thermal pad so as to allow for heat dissipation. The benefit of using a DAC is that they are monotonic by design and allow for linearity. This means that there is less transient voltages that could alter the signal.

Audio Amplifier

We wanted to make sure to have enough power to utilize the speaker. Also, we did not want to max out the amplifier. Lack of power causes the amplifier to clip which can severely damage the speakers. We chose a 40W @ 8 Ohms amplifier to power the 20W speaker and feel this would be an appropriate combination. In order to power this amplifier, we need upwards of 26V DC. We can obtain this high voltage level using a buck-boost circuit from the original 5V power supply. The amplifier would receive a signal from the audio processor, amplify the signal to the required levels, then send teh signal to the speaker.

Speakers
The speaker that we are planning on using is rated at 20W @ 8 Ohms and has a max power of 40W. In order to drive this speaker, we need an amplifier that is rated at 40W. The speaker can play frequencies between 100Hz and 10kHz, which will hit the range of frequencies that we will utilize for the harp. The speaker connects with positive and negative wires. The speaker will be mounted to the box and will lay more or less flush with the outside. Inside the box will be the driver and connections. There is a hole in each corner which will allow us to mount the speaker easily.

4.3 Future Enhancement Requirements:

In the future, we hope improve upon our initial design. The many areas that we hope to hit are: portability, usability, reliability, and ability.

Under portability, we hope to incorporate the use of batteries so that the laser harp can be used in areas where there is no readily accessible power supply. This would include the use of rechargeable batteries as well as a circuit that was able to recharge the batteries successfully. This design would make the laser harp much heavier, so we would attempt to improve the design to make it lighter and easier to carry.

With usability, there are many features that could be added. These include: playing background music to accompany the laser harp playing, more intense lasers with a variety of colors, moving lasers to enhance the performance value, a built in smoke machine, and anything inbetween that would make the laser harp more appealing to the audience. Also under usability, we could do more to make the laser harp easier to use. A pick-up-and-play approach would help here as even the most dim witted individuals would be able to use this product. We hope to add a teaching mode where the laser harp will light up the lights in a sequential manner so as to teach the user a specific song. That can be handy for those just starting off or those that are musically retarded. The teaching mode can be done at variable speeds in order to move at the pace of the user.

Reliability is definitely an area that could be looked into more. As far as the actual components, we would do more research into what is bottlenecking the speed of the laser harp and the ability of it to play numerous notes or notes in fast succession. Power use is another concern with reliability, especially if we take portability into mind. A 26V power source would chew through the batteries so we would have to scale down the speaker as well as the amplifier and other passive components to make the entire thing more long lasting and reliable.

Lastly, future improvements to the project would add numerous abilities to it.

Like many of the above suggestions, there is much that could be added to make the laser harp more fun or increase the performance value. Adding different features, however, increases the cost as well and need to be selected with that in mind.

5. High Level Design Decisions

Subsystems:

Detecting Circuit:

The detecting circuit will use ten IR detectors to sense when each laser has been interrupted by the user's hand. These detectors output an analog voltage based on the distance of an obstruction. This analog value will be sent through an analog to digital converter to allow the microcontroller to process the signal. The microcontroller will determine the correct audio signal to output based on which laser is being interrupted and the height of the user's hand. Each IR detector requires a 5V power source.

User Interface:

The user interface subsystem of our project entails the lasers, on/off switch, speaker volume control, usb interface, and the housing box. The function of this subsystem is to enable a person to utilize the device easily and almost intuitively. The lasers will be small laser diodes (10 red, 10 green), which will show the user where to place their hand to interrupt the IR rangefinder and create a specific tone. The lasers should require either 3.3V or 5V to power them, because those are the two voltage sources we will have on the board. The on/off switch will simply be a master switch which will cut off the power coming from the wall to the board. The speaker volume control will be a knob connected to a potentiometer, which will adjust the gain of an amplifier. This will effectively change the volume of the speaker. The usb interface will be a port on the board which allows the user to connect their laptop and change the song that is currently loaded to the board. The housing box will be made of wood with a fiberglass door. This casing will be lightweight and be able to hold the elements that we will need to mount on it.

Microcontroller:

The microcontroller subsystem will need to interface with all of our external components and be able to interpret and manipulate audio signals. The microcontroller will need to be programmed via USB to perform the necessary actions for our project. As far as ports, we need a separate port for each detecting circuit, an output port to send out the audio signal, a power supply, and a serial connection for programming. All of these ports can be configured through programming the microcontroller to our group needs.

Power Supply:

The power supply subsystem will contain the electrical input, which will come from a power converter plugged into a wall outlet, and a voltage regulator, which we will use to obtain the two voltage source values that we want on our board (3.3V and 5V). The amplifier also needs a power source that is well above the sources of the board. This voltage can be obtained by utilizing a larger power supply then regulating it to the appropriate level for the board.

Audio:

In order to produce an audio signal, we will first have to program the microcontroller to send a digital signal that represents a certain sound. This digital signal then passes through a digital to analog converter and then through an amplifier where it will be amplified to the appropriate levels for the speaker. After the amplifier, the signal will reach the speaker where it will be heard. The amplifier needs to be rated according to the speaker. In our case, we are using a 20W average, 40W peak speaker so we will use an amplifier rated for 40W output. This amplifier requires a 10-26V power supply, which can be obtained using a buck-boost circuit to drive the voltage up to 26V from the 5V source.

The speaker we are planning on using is rated at 20W, which should be loud enough to produce rock show quality music. The problem with going any higher is that there is a trade off in the power supply needed for the amplifier. The last part of the audio component is the digital to analog converter. This component can be placed directly on the board next to the microcontroller. This component only needs to be rated for the output of the microcontroller, which varies based on the processor chosen.

6. Open Questions

1. We want to be able to change the volume based on how high your hand is over the IR sensor. This means that we need a digitally controlled variable gain amplifier. What would be the best way to accomplish this task?
2. Outputting an audio signal is going to be tricky. Should we use a premade integrated circuit which has numerous characteristics for audio use or should we just have the microprocessor output a digital signal? There are many ways that we can produce an audio signal but we are unsure how to realize this part of the design.
3. We have discussed what is the best way to power our device. We have currently settled on a power source which we will plug into the wall, but we are still considering batteries. We also must decide on the amount of power that we want from the source. Is it better to bring in a larger power supply and scale it down for our devices with smaller power requirements (microcontroller and lasers) or is it better to use a more reasonable voltage source and scale it up for elements that require more power (amplifier)?

7. Major Component Costs

- IR Detectors - 10 @ ~$10 each
    - GP2Y0A700K0F
- Lasers - 20 @ $12.62 each
    - 10 red and 10 green
    - VLM-650-03-LPA-ND
- Microcontroller - 1 @ $10.76
    - PIC32MX695F512H-80I/PT-ND
- Board - 1 @ ~$100
- 5V Power Supply - 1 @ $19.72
    - 102-1325-ND
- 20W Speaker - 1 @ $10.98
    - GF1004H-ND
- Amplifier - 1 @ $6.17
    - 296-22976-2-ND
- Total - $500.04

8. Conclusions

Our laser harp is the musical instrument of the future. By utilizing infrared distance sensing technology coupled with lasers and audio circuitry, we will allow users to play music easily and in a visually stunning manner. By incorporating a teaching mode, users can quickly learn some of their favorite songs. The laser harp will emulate multiple instruments and play in different keys, allowing for a great range of musical variety and flexibility.

References

-www.digikey.com