6.101 Final Project Proposal: A Laser Harp (v2.0)

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April 28, 2017

I. Overview

A laser harp is an electronic musical interface that replicates the functions of a harp, using laser beams as strings and analog circuitry to generate tones. We plan to construct a laser harp consisting of three main subsystems: the harp interface with the laser beam "strings," a tone synthesizer, and a class-D audio amplifier. The harp will contain six strings to play a pentatonic scale. We also plan to add a volume control interface and a damper pedal. Stretch goals include adding the capability of shifting all tones to a higher or lower octave, and adding LEDs to indicate when strings are played. Henry will be responsible for the laser harp interface, envelope generator and additional functionalities, Briana will be responsible for the synthesizer, and Mira will be responsible for the class-D amplifier.

II. Block Diagram

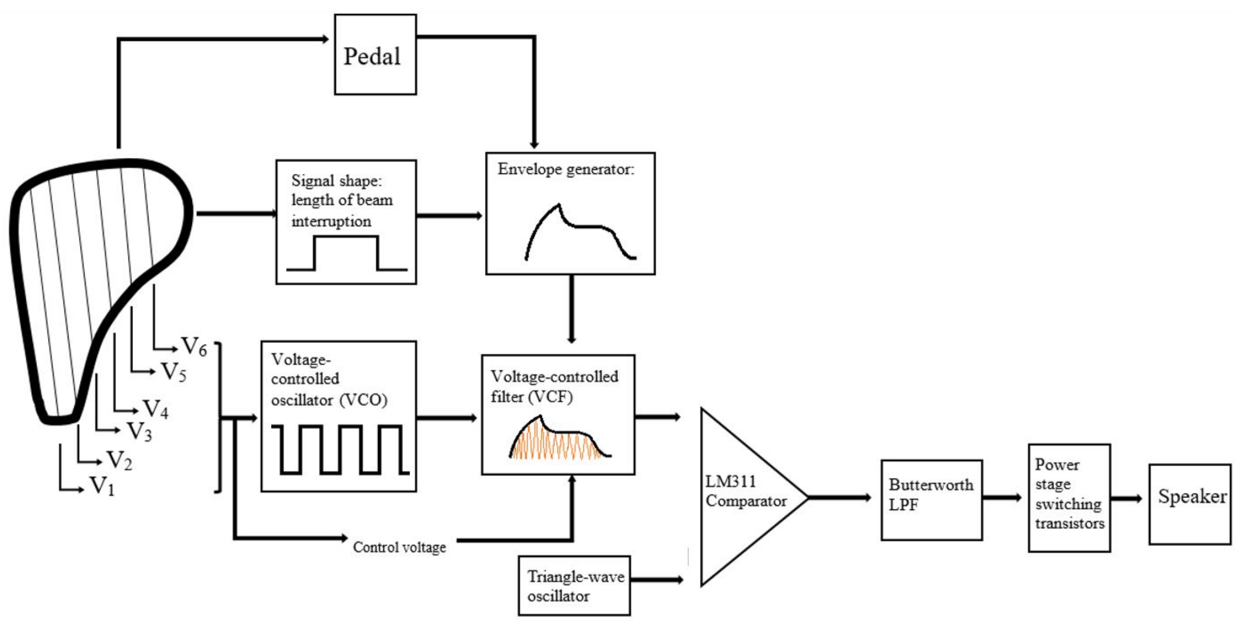

Figure 1. A simplified block diagram of the overall system.

Our entire system will be powered by a $\pm$20V power supply. Specific signal amplitudes/frequencies, power requirements for specific modules, and details of signal flow through each subsystem are explained in the sections below.

III. Harp frame and lasers

The harp frame will be a wooden encasement that contains pairs of laser diodes sitting across from photoresistors. Each “string” in the laser harp will be represented by three laser diodes in a row. Striking all three beams in a string will correspond to a louder sound than only hitting two beams, which will likewise produce a lower sound than hitting only one beam. The volume control will be implemented with a simple inverting-feedback amplifier of the signal generated from the synthesizer (section IV), with MOSFETs turning on or off a resistor ladder to decrease or increase the gain. The amplified signal will then be fed into the class-D amplifier. The usage of focused laser diodes rather than LEDs was decided upon to obviate the possibility of stray light diffusion, so that no photoresistors in any other string are accidentally hit.

Photoresistors are variable resistors controlled by incident light on the surface of the device. When light from the laser diode hits a photoresistor, its resistance will be lowered. When the light beam is broken, the resistance will increase. Photoresistors were chosen because one can simply use photoresistors in a voltage divider relationship linked to a comparator to check if the beam was hit or not, as the variable resistance of the photoresistor will increase when the laser beam is no longer hitting the surface of the device. Utilizing a photodiode or phototransistor would require the use of a transimpedance amplifier, but a photoresistor simply deals with voltage levels. The comparator will compare to a voltage reference that can be easily changed with a potentiometer in order to account for environments with varying levels of ambient light.

The comparators will be linked to each string, and will output a specific control voltage for each string as input to the voltage-controlled oscillator, in order to generate the correct frequency for the note the string is associated with. The specific control voltage will be output with a calculated voltage divider. The comparator signal will be held high as long as the the beam is broken, so the tone is sustained until the “string” is released again.

Another two switches will be added to the harp frame to simply add or subtract 1V to the control voltage, and a linear-to-exponential circuit will transform the control voltage into the correct frequency to a lower or higher octave.

The comparator will also pass its high signal pulse (5V) to the envelope generator (EG) so it can generate the correct envelope for the tone generated.

A pedal, which is simply a switch, will cause the EG to create a longer release time in the envelope shape generated, so that the tone will last much longer. If the pedal switch is no longer pressed, the decay time will switch back to the original quick decay time.

IV. Synthesizer

Upon interrupting the beam of a given string, the control voltage corresponding to that string and the signal pulse will be sent through a linear to exponential conversion circuit. This circuit makes use of the exponential properties of current in a matched BJT pair and some set gain. The purpose of the conversion is to allow for the control voltages to be on a linear scale and thus make it easier to shift the tones into higher and lower octaves. The reason for the non-linearity is that tones increase exponentially in frequency as the pitch increases, so the input for the signal generation needs to reflect that relationship

The next module is the voltage controlled oscillator, which is responsible for generating the pitch (frequency) of mid-range tones, in the range of 260 to 2.069k Hz. The VCO is made up of an integrator, a Schmitt trigger, and a reset circuit. The integrator will utilize the on and off states of an NMOS, and the charging and discharging of a capacitor based on the value of the control voltage. The RC time constants that will be used to set the charge and discharge rate will be calculated to distinguish between control voltages in the range of 1-5V. The output of the integrator will be input to a Schmitt trigger with a set threshold voltage, which is used to reset the BJT base voltage to be low or high. This alternation will produce the frequency oscillation.

The output waveform of the voltage-controlled oscillator is then sent to a voltage-controlled filter. The control voltage used in the oscillator is the same control voltage used in the filter in order to adjust the value of a voltage controlled resistor used for a low pass and band pass filter. The VCR is composed of a back to back transimpedance operational amplifier configuration, and is used to tune the filter's RC circuits to match the filter with the appropriate frequency for incoming waveform. This stage will be designed to pass only the fundamental frequency and the first two to three harmonics.

An envelope generator will create an envelope for the frequency generated by the voltage-controlled oscillator, and a voltage multiplier will combine the two. The envelope generator will have a waveform with an attack and a decay, along with a sustain and release, that will mimic a more realistic sound, so hitting a beam will generate a tone similar to plucking a string on a harp. Hitting the pedal switch on the harp will increase the release time. A 555 timer with capacitors tied to potentiometers and the threshold/trigger pins on the chip will control how long the sustain and release will be. A figure of the waveform can be seen below.

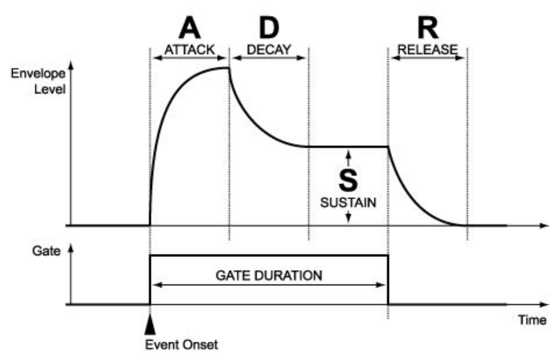

Figure 2. ADSR envelope form.

A stretch goal is to incorporate a low frequency oscillation effect, probably using a 555 timer. Including equalizing effects for the tone harmonics is another stretch goal, provided that the output of the VCF is sharp enough.

V. Amplifier

For this project, we plan on building a class-D amplifier. A class-D amp is the most efficient amplifier, having an efficiency of 85-95%. The class-D is a switching amplifier, relying on pulse-width modulation (PWM) to convert the input signal into a pulse train before amplification. The pulse train is amplified by a switching controller and output stage, after which a low-pass filter is applied to create the output - an amplified version of the original input signal.

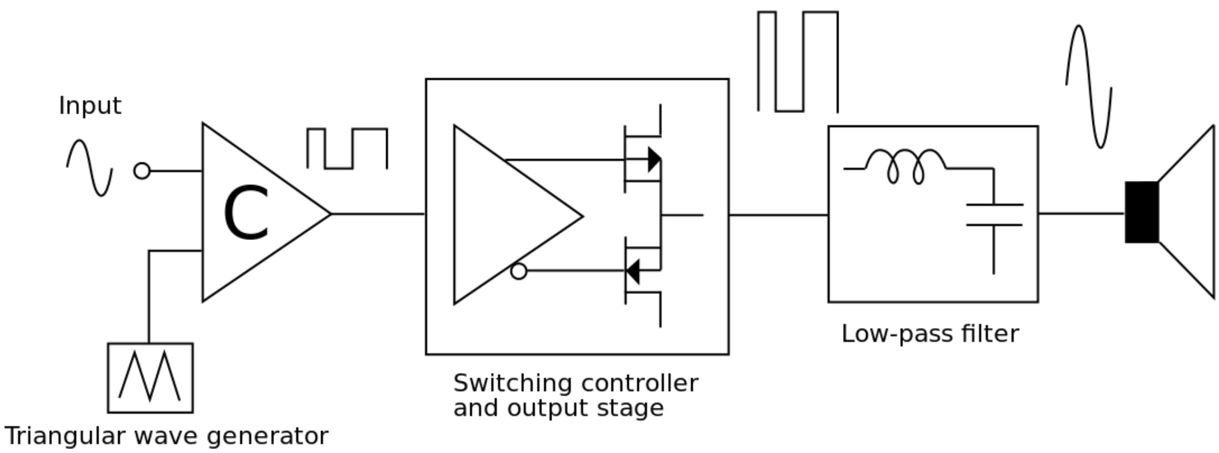

Figure 3. Simplified block diagram of a Class-D amplifier.

The input signal to the amplifier will be the output signal from the synthesizer, with an amplitude between 0 and 5 V. It will first be passed through two filters, a high pass filter with a cutoff frequency of roughly 5.9 kHz, and a low pass filter with a cutoff frequency of roughly 100 Hz (all our tones will have audio frequencies well within this band). This is done to clean up the signal so that no noise is amplified.

The resulting cleaned signal will be compared against a triangle wave using a dual comparator, the LT1016 (which has a response time of 10ns, more than fast enough for the proposed switching frequency). The triangle wave will be generated using a 555 timer that is powered by a 5V supply. The switching frequency of the pulse-width modulation will be 200 kHz, as this is more than ten times the upper bound of the human hearing range, but not too high of a frequency for the MOSFETs' switching capabilities. The output of the comparator will consist of two pulse trains, in which the duty cycles are proportional to the instantaneous value of the input audio signal at any given moment. The pulse trains will be identical but exactly out of phase with each other; the phase shift should be exact, since we are using a comparator designed to provide dual (inverted) outputs.

The two pulse trains will be passed as the high and low inputs to a specialized MOSFET driver, the IR2110. This driver will be powered by a $\pm$20V supply, and produce high and low outputs with matched dead time to ensure that only one MOSFET is turned on at a time. This IC is used to avoid shoot-through and subsequent failure of the MOSFETs, but will also ensure that dead time is low enough to avoid distortion of the output, and avoid operation of the MOSFETs in linear mode (which would lower efficiency).

The high and low outputs will be passed to the gates of high and low side power MOSFETs (the N-channel IRF540N MOSFETs from Infineon), which are connected between the +20 and -20 V power rails. The output of the power stage, which is a half-bridge topology, will be identical to the input of the stage - a pulse train with the same frequency spectrum - but it will have an amplitude of 40V peak-to-peak (from -20 to +20 V).

The output low-pass filter will be a Butterworth filter (made of an inductor and a capacitor to minimize heat loss, and preserve a very flat frequency response in the passband). The cutoff frequency will be around 20 kHz, since the tones of our harp will all be less than 4 kHz (well within the audible range), and the load resistance will be 8 ohms to drive the loudspeakers in lab.

Overall, the class-D amplifier will be powered by a $\pm$20 V supply, with all other required supplies being bussed from the main power supply. It should output 100W with minimal heat loss and high efficiency. The amplifier itself has several sub-modules - the triangle wave generator, PWM, power stage, and output filter - so all of these can be tested separately. Class-D amplifiers generate a lot of RF noise because of the high frequency of the PWM signal, so this will necessitate careful wiring, lower MOSFET switching speed, decoupling capacitors, and the limiting of inductive and capacitive coupling.

VI. Task Schedule

The following timeline details our target deadlines for each step of the project:

April 26th:

- Circuit schematics and calculations finalized
- Breadboarded VCO, created wooden harp frame with lasers/phototransistors/control voltage circuitry
- Finish triangle wave generation, input filtering for amplifier; test out PWM with LM311

April 28th:

- Breadboarded volume control circuitry, envelope generator, voltage-controlled frequency generator
- Finish output LPF, PWM with LT1016 for amplifier; breadboard power stage switching transistors

April 30th:

- Finish breadboarding for laser harp and synthesizer
- Test and debug power stage switching transistors for amplifier

May 2nd:

- Integrating first two modules together, general debugging; complete the class-D amplifier

May 4th:

- Finish integrating all modules, any last debugging; finishing touches

May 9/10th:

- Final project demonstrations

VII. Parts

For the laser diodes, inexpensive 650nm 5V red laser diodes can be found online. For the photoresistors, GM5539 photoresistors were bought because of their ubiquity in the hobby market. They can simply be added to a breadboard or soldered in the future to be used on the harp frame, which will be made of wood.

The synthesizer will primarily utilize parts common to the 6.101 lab set ups. The only additional parts to be ordered are the LM13700 transimpedance amplifiers implemented in the VCO. These dual packages are priced around $1.47 per unit.

For the class-D amplifier, a specialized MOSFET driver will be needed to remove the dead-time between the higher and lower output MOSFETs. The IR2110, made by International Rectifier, will be used; this costs $2.92 per unit. We also require power MOSFETs with different specs (low gate charge for faster switching, higher V_{DS} voltage rating, low R_{DS}(on)); for this, we will be using two IRF540N N-channel MOSFETs, which cost $0.98 per unit. Lastly, we need a comparator with dual output; for this, we are using the LT1016 comparator, which costs $5.53 per unit. All parts will be through-hole devices, and the system will be breadboarded.