Modular Analog Synthesizer

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ECE 445 Project Proposal- Fall 2017

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1 Introduction

1.1 Objective

Music is a passion for people across all demographics. From young to old, across the globe, music plays a major role in the lives of many. Music education in particular is a favorite of many schoolchildren at young ages because it is usually enjoyable and they love learning about music. One thing that most music education at young ages lacks is access for students into something called timbre. Timbre is a term that refers to the sound quality of a note. It deals with the “smoothness” or “pleasantness” of a tone. One instrument that can produce a wide variety of timbres is the analog synthesizer, which some may consider a wonder of the 20th century.

Our goal is to bring this great technology to the people who may truly appreciate its use in modern times. Aside from being a fresh take on a classic instrument, our project will serve the additional role of bringing electronic musical theory to the classroom in one easy, portable machine. We will include not only the classic musical keys and pitches, but also a way for students to experience the concept of timbre with different waveforms of sound.

1.2 Background

Musical synthesizers first became popular in the 1960’s with the popularization of modular synthesizers. This type of synthesizer employed the use of separate electronic modules like voltage-controlled oscillators (VCOs), voltage-controlled filters (VCFs), and voltage controlled amplifiers (VCAs). They were connected using patch cables to pass the signal between modules. These synthesizers were almost like a sandbox of sound, where one could synthesize any sort of tone if given the proper amount of time to configure its numerous dials, switches and modules[3]. This was usually very time consuming and tedious, which is what led to the advent of presets programmed into keyboards in the 1980s.

Something that has been scarcely available on the market is an easy way to explore timbre in relation to pitch with a keyboard setting. There is one product available (Haken Continuum) that accomplishes this, but it goes for over $5000 and takes up a considerable amount of space[1]. This is because this system in particular is very advanced in that it provides a very precise measurement on a continuous spectrum of both pitch and timbre by tracking the two-dimensional position of one’s finger as it presses down on a pad. The intricacy and precision of this device is unnecessary for our synthesizer. We will make a space-efficient, cheap, and accessible instrument intuitive enough for a child to understand, sophisticated enough to make complex tones and be fun for a musical aficionado to enjoy. This will be achieved by having three sets of keys, each with a noticeably different timbre as opposed to a system to track position of where the key is pressed. We will cut down on cost as well by eliminating most of the processing and computing that takes place in the Continuum, as they are unneeded for our application. We have selected the waveforms of sine, square, and triangle because these are three of the most popular in the industry with notable differences between them.

1.3 High-level requirements list

1. The voltage-controlled oscillator must produce frequencies ranging from 523 Hz to 987 Hz within 3%[2] according to the divisions between musical notes C5 and B5.
2. The wave shapers must produce 3 unique waveforms (square, triangle, sine).
3. The arpeggiator must produce 4 separate and unique rhythms as specified in the arpeggiation TTL section below.

2 Design

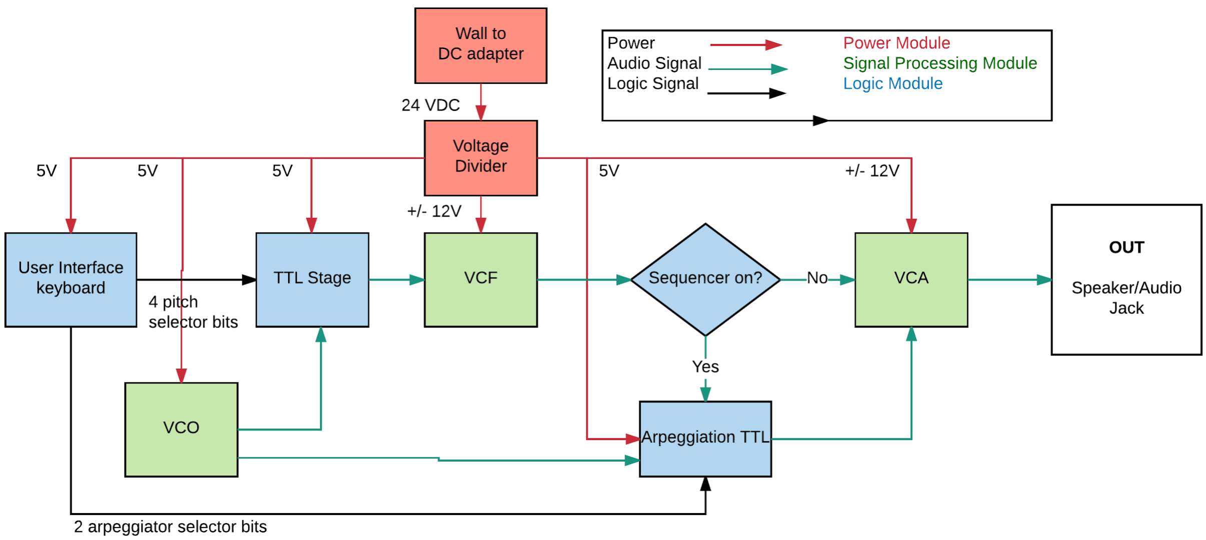

Fig. 1: Block Diagram

2.1 Physical Design

The synthesizer modules are fastened to 24' by 12" board as seen in Fig. 2. The keyboard section is mounted 4" above the base board on top of four pillars. The face of the box was designed around the keyboard and all 36 keys are placed into a grid consisting of one inch square boxes. The sharp keys are offset from the other keys 0.4" above to provide visual separation for the user. Extending this grid over the rest of the face is how we arrived at the design. The face gets a one inch margin around the edges plus an extra inch at the bottom to create space for resting your hands. To the side of the keys, there is a one inch margin for visual separation between the control knob section and the note keys. The outer appearance of the box naturally evolved with things like beveled edges and higher quality buttons. The main part is the grid of 36 buttons that make up the keyboard. There are 12 keys, representing one octave, for each waveform. There is a space below these keys to place a wrist pad if desired. The octave select switches are directly to the right of the waveform keys and the two arpeggiator select switches are underneath the column of octave select switches. Mode select is the single switch offset from the group and tempo control is underneath the keyboard located on the main base board.

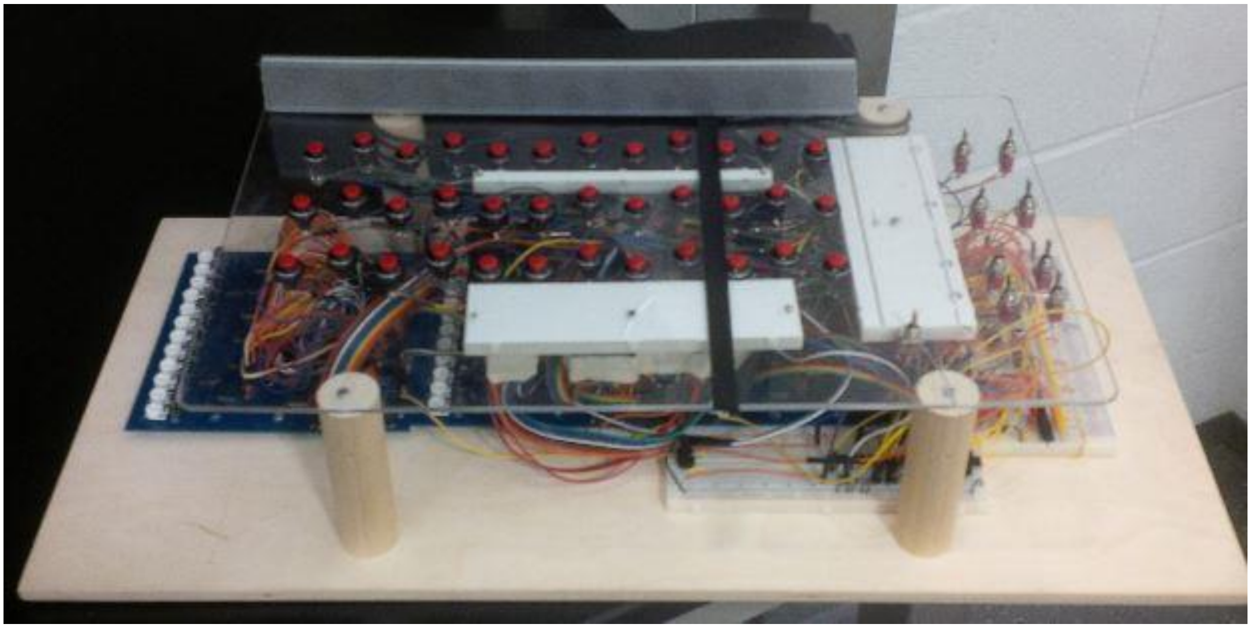

Fig. 2: Physical Design

2.2 Power delivery

2.2.1 Wall to DC adapter

The wall to DC adapter is responsible for converting the 120 VAC from the wall into 24 VDC for the synthesizer. This is store bought, so will be assumed to be in working order.

2.2.2 Voltage Divider

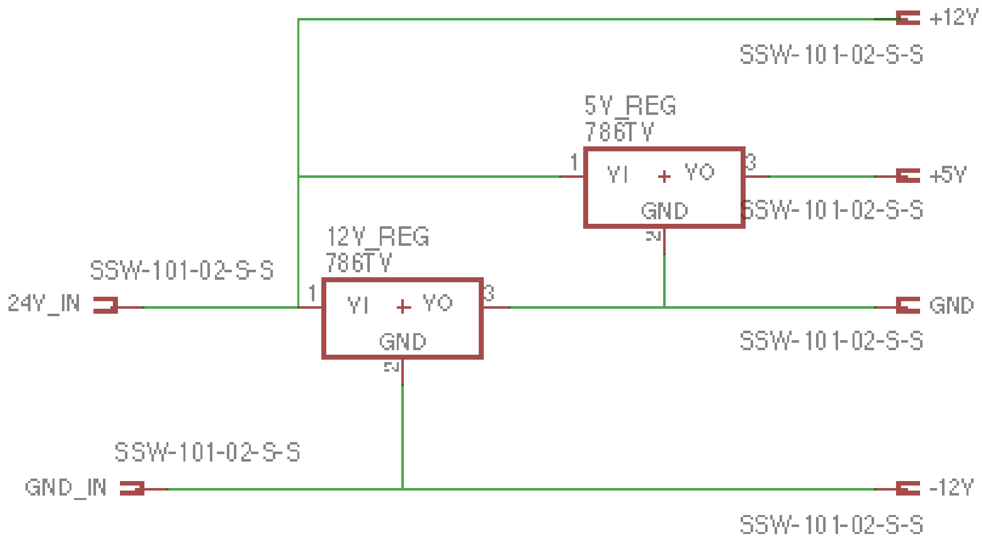

Fig. 3: Voltage Divider

The voltage divider is responsible for distributing power to each of the other components. It takes 24 VDC from an AC/DC wall adapter and distributes appropriate voltages to each section accordingly as seen in Fig 3. From the reference of the ground of the 24 V input, 24 V is +12 V for our circuit, 17 V is 5 V, 12 V is ground, and 0 V is -12 V, the latter values being from the reference of our circuit. This is achieved by using a 12 V regulator attached to a 5 V regulator.

2.3 Logic Stages

2.3.1 Keyboard Input

The keyboard input will consist of 3 rows of 12 momentary switches, the 12 notes in an octave with 3 waveforms each. Each switch is used in a 12-bit one-hot encoding scheme which gets converted to four select bits by the TTL as seen in Fig. 4. Each switch represents a unique, tunable oscillator that produces a square wave.

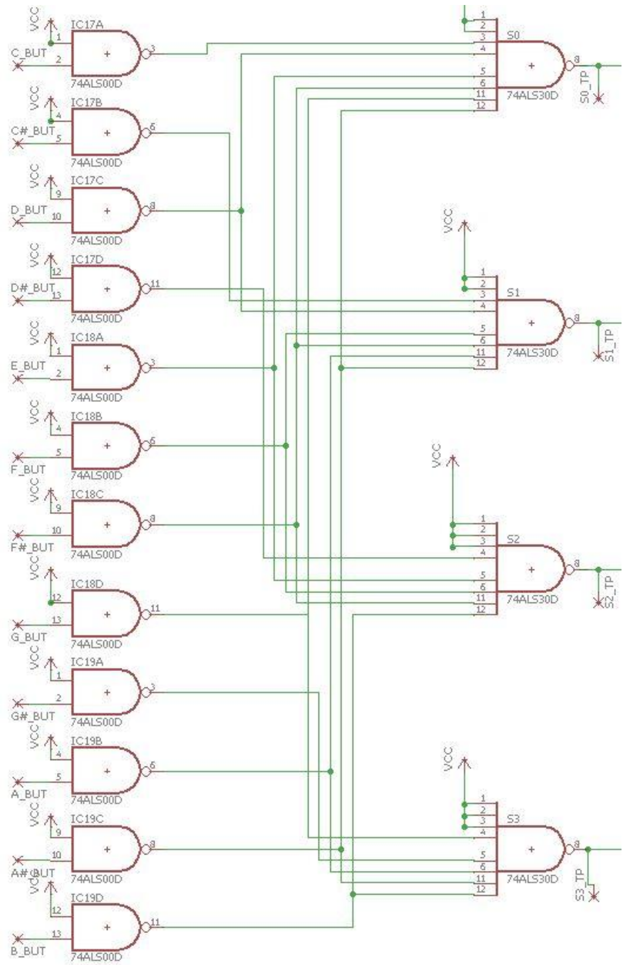

Fig. 4: Keyboard TTL

2.3.2 TTL Logic

The TTL routes the corresponding frequency, related the key pressed, to the output. It operates on an 11-bit word as seen in Fig 5 where S_3-S_0 determine the note, Oct_1-Oct_0 determine the octave (C4 through C1), and Wav_1-Wav_0 determine the wave. Mod_0 determines if the synthesizer is in keyboard or arpeggiator mode and Arp_1-Arp_0 determine the rhythm of the arpeggiator.

S_3	S_2	S_1	S_0	Oct_1	Oct_0	Wav_1	Wav_0	Mod_0	Arp_1	Arp_0

Figure 5: System Logic

The oscillator circuit drives the divider chip that provides the four octaves by dividing the input by two in a cascading fashion, as seen in Fig. 7. Each octave has a designated multiplexer, as seen in Fig. 6, and the octave present at the output is determined by the octave select bits.

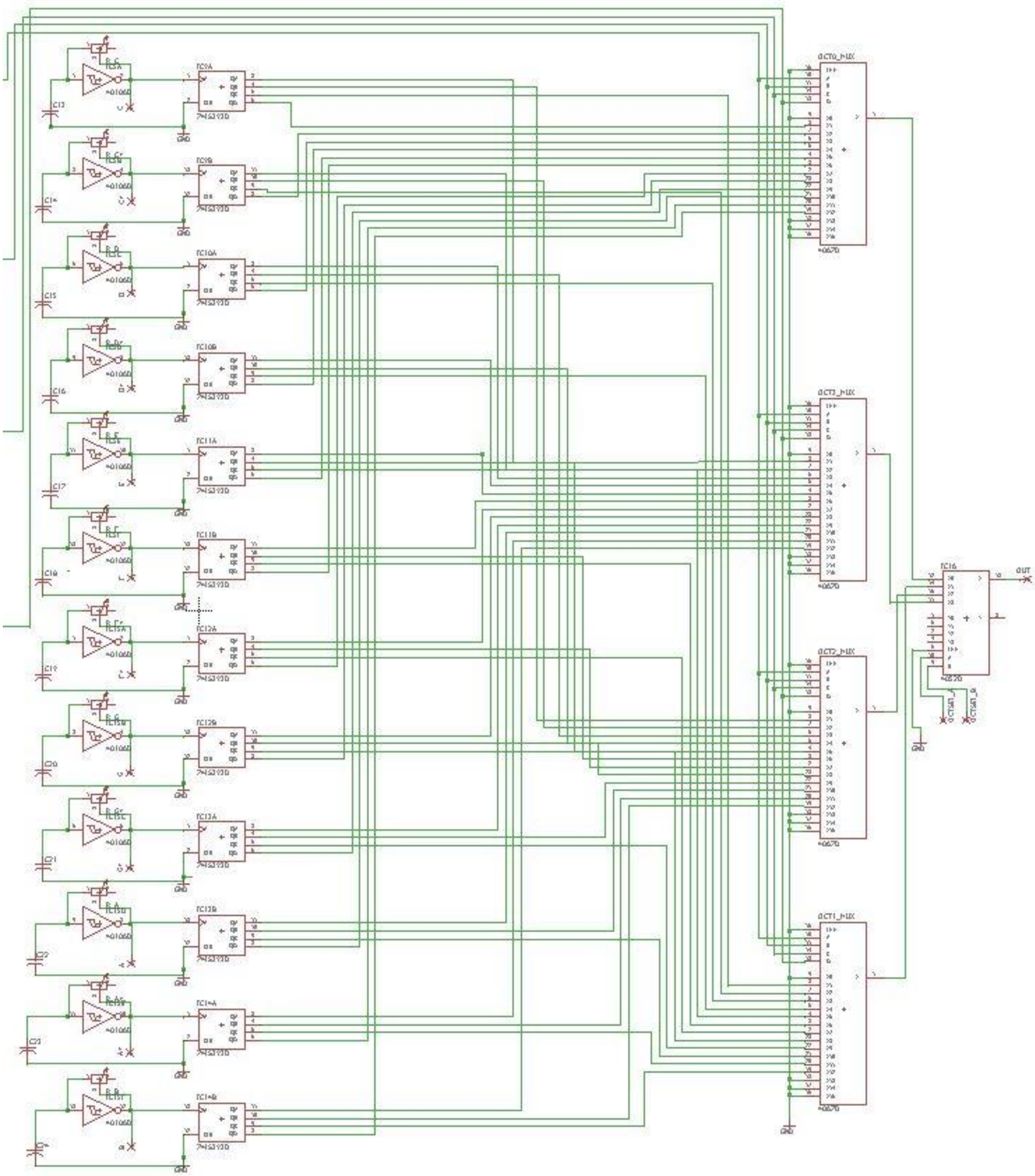

Fig. 6: Oscillator & Octave Select Group

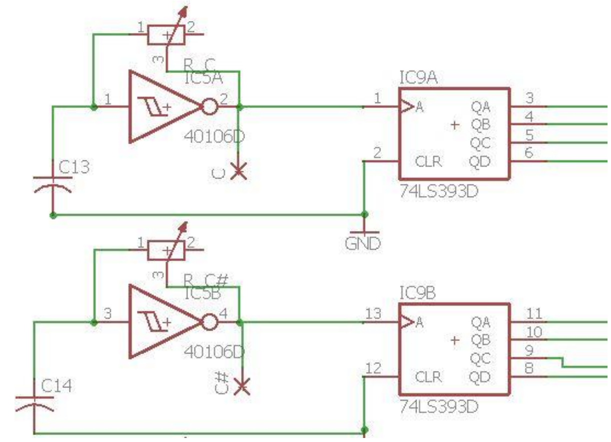

Figure 7: Oscillator & Divider Zoom

2.3.3 Arpeggiation TTL

The arpeggiation TTL determines the sequence of waveforms at the output as seen in Fig. 8. Four 8 to 1 multiplexers are controlled by a binary counter to cycle through all inputs at a tempo controlled by the user with a potentiometer The pattern of waveforms present at the inputs of each multiplexer are unique and preset. The user selects a preset pattern through the Arp_1-Arp_0 bits. The note present at the input of a multiplexer is determined by which key is pressed. Therefore, the sequence of waveforms is predetermined but the note played in that waveform is input by the user to offer fun interactivity.

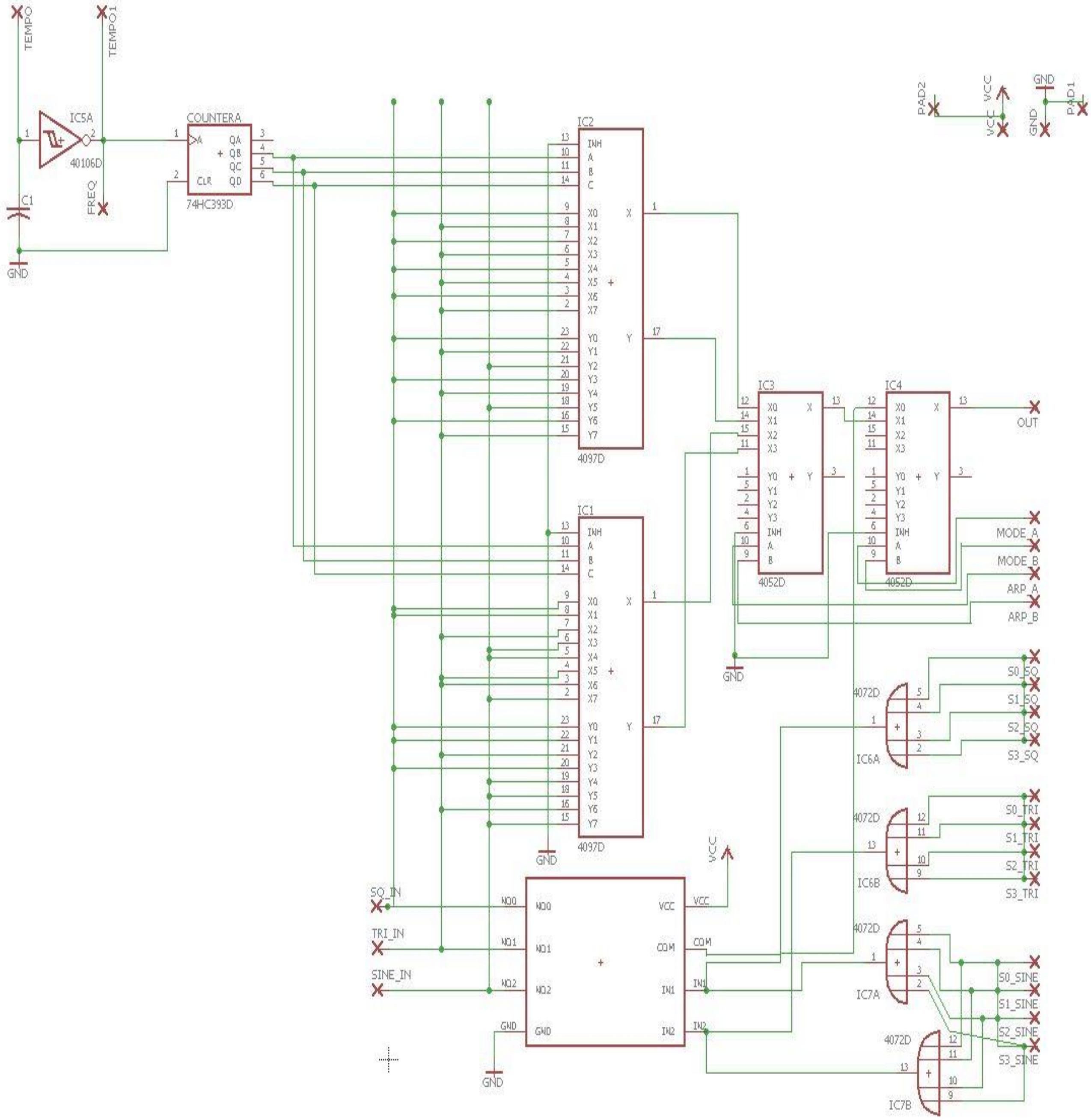

Fig. 8: Arpeggiator

The mode multiplexer has two settings controlled by Mod_0: keyboard or arpeggiator. When it is set to keyboard, only one waveform is output at a time. A high speed analog switch monitors button activity through the S_3-S_0 bits and outputs the corresponding waveform.

2.4 Signal Processing

2.4.1 VCOs

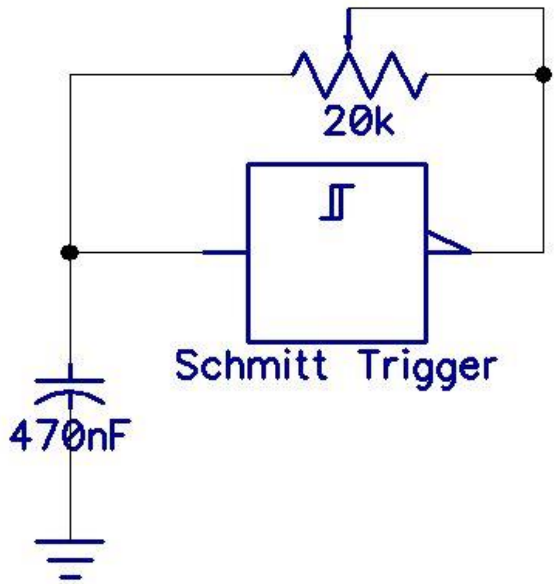

Fig. 9 : Schmitt Trigger Square Wave VCO

The VCOs are the heart of this system and each one is tuned in the 5th octave as seen in fig. 10 . This is the stage that produces the signal that will later become audible sound. It is imperative that these provide consistent outputs with minimal drift. To attain a well-shaped square wave, a Schmitt Trigger (fig. 9) was used. Error in frequency (fig. 11) was mostly within the intended range with a couple of outliers in the maximum error category.

Note	C5	C#5	D5	D#5	E5	F5	F#5	G5	G#5	A5	A#5	B5
Desired Frequency (Hz)	523	554	587	622	659	698	740	784	830	880	932	987
Measured Frequency (Hz)	517-531	540-560	561-598	605-635	642-660	676-710	710-750	773-805	802-843	853-890	935-961	960-1021
Error (absolute value)	1.14-1.5%	1.08-2.5%	1.8-4.4%	2.09-2.7%	0.1-2.5%	1.7-3.1%	1.35-1.6%	1.4-2.6%	1.5-3.3%	1.4-3.06%	0.3-3.1%	2.7-3.4%

Fig. 10: Accuracy of Frequencies in VCO

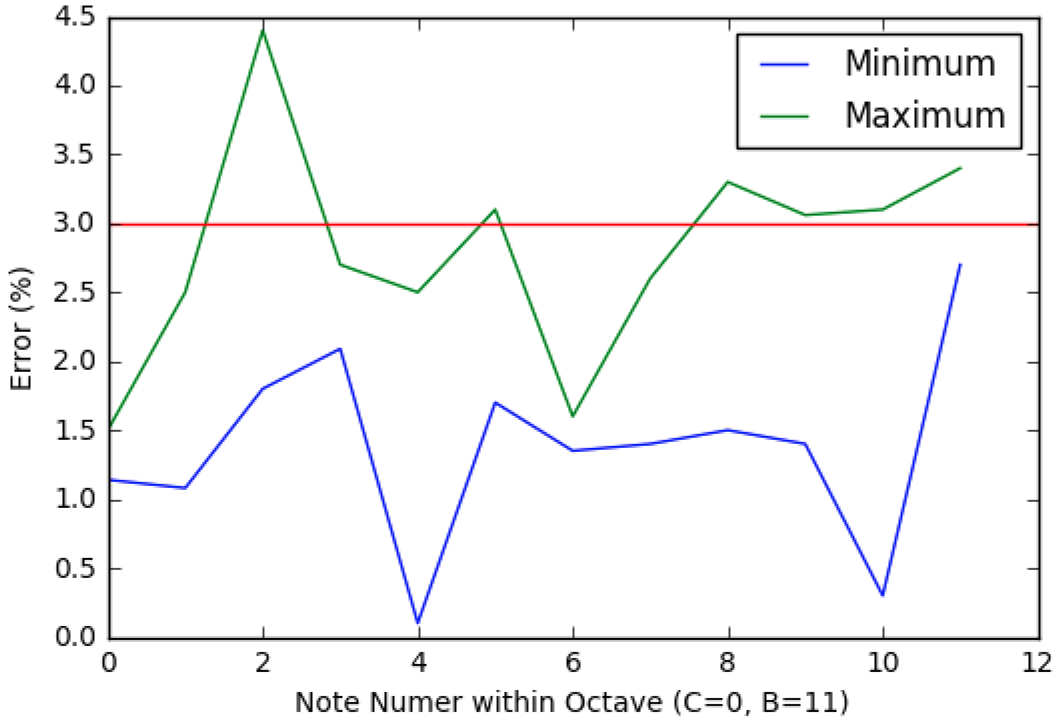

Fig. 11: Error vs Note Position within Octave

2.4.2 VCF/ Waveshapers

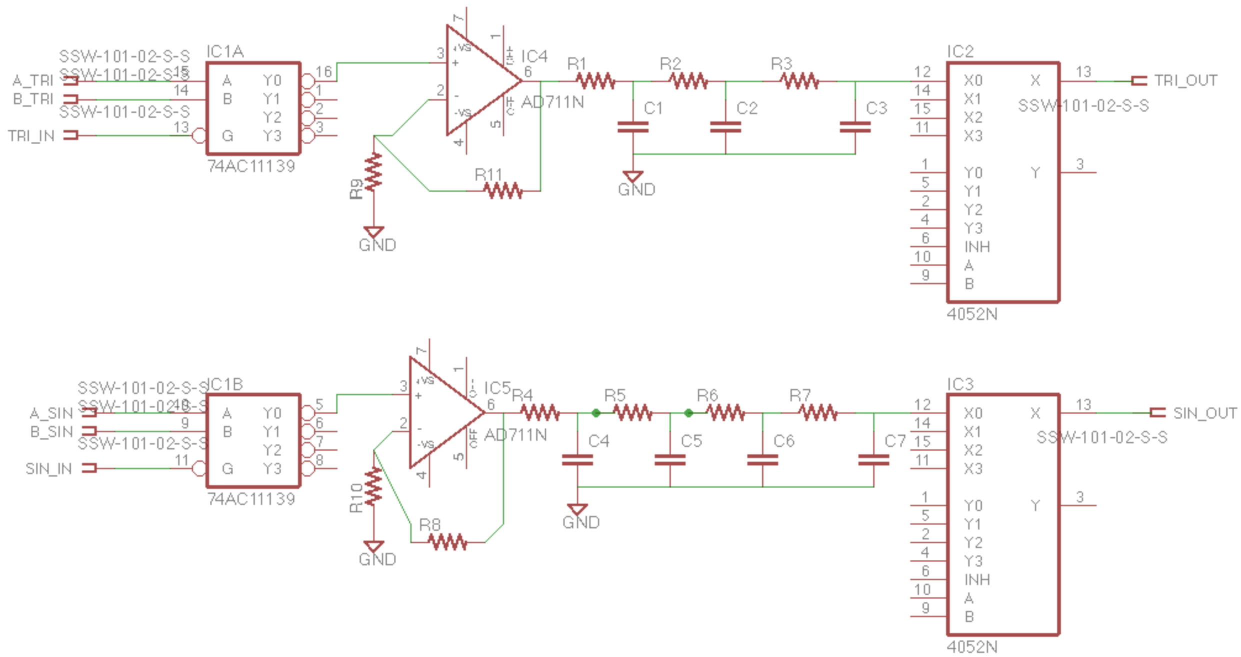

Fig. 12: Close-up of Waveshaper Circuits

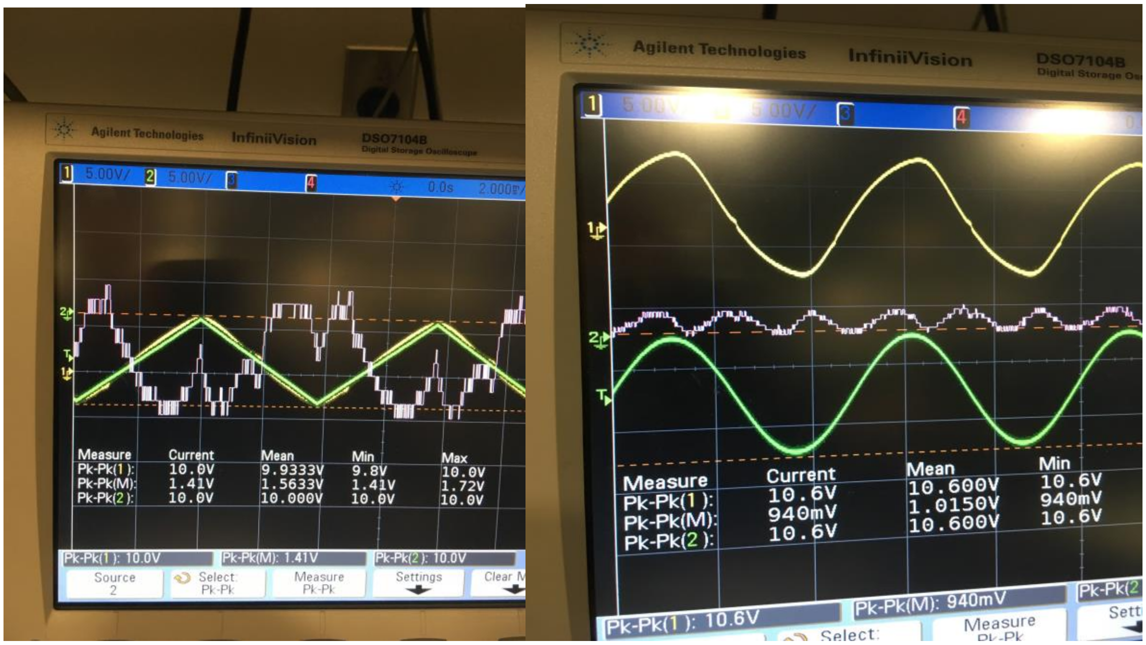

Fig 13: Waveshaper Results

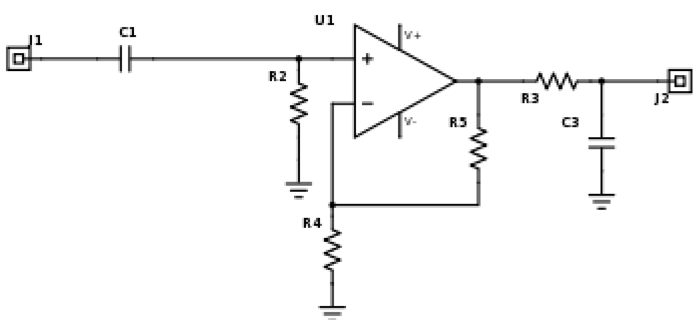

Fig. 14: Active Bandpass VCF

The waveshapers (fig.12) and VCF (fig. 14) are responsible for regulating the waves' sound quality. The VCF is an active filter that helps to eliminate noise and static from the sound before it gets amplified. It is a third-order Butterworth bandpass filter with Sallen-Key topology. The waveshapers help to make sure the sound waves are in the proper shape by filtering out upper harmonics of each octave. The waveshaper section of the circuit consists of a 1:4 analog decoder for each of the two waveforms being shaped to enter, one input for each octave. The two bits used to select the octave provided by the TTL circuit are used as the coordinates for the decoder to send the signal to its proper sequence of filters, as well as to select that same line of filters to output through the MUX. They are then amplified and passed through 3 low pass filters for a triangle wave and 4 low pass filters for a sine wave. Each low pass filter is tuned to RC values for the octave being processed. These are then fed into a 4:1 MUX for each new waveform to be output to the combiner. Seen in Fig. 13 are the results of passing a square wave through each waveshaper. The triangle shaper has an average error of about 14% while the sine waveshaper has an error of about 9%.

2.4.3 VCA

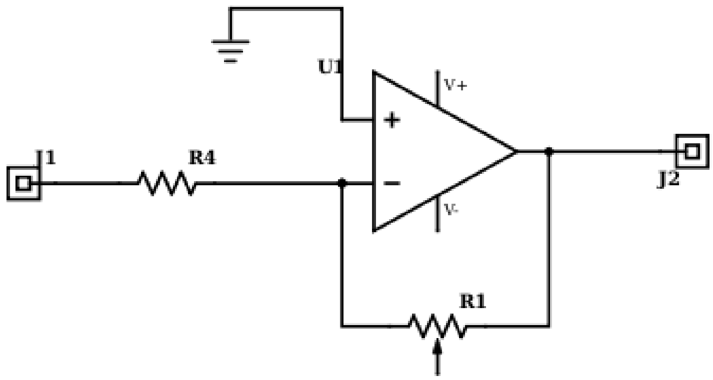

Fig. 15: Voltage Controlled Amplifier

The VCA actively amplifies the signal so that it is heard when sent through a speaker. It takes the signal into the input denoted as J1 in Fig. 15. The amplification is controlled by the resistance of a potentiometer available to the user (R1), which will be able to drive the signal anywhere from 1V P-P for headphone/external amplifier applications to 20V P-P to drive a speaker on its own thanks to the ratio of $V_{out} = V_{in}(\frac{R_1}{R_2})$.

2.5 Risk Analysis

The most significant point of failure is the TTL stage. This is where the instructions for the signals are sent. The VCO has a possibility of going wrong, but is not nearly as fragile as the TTL stage. If we cannot pass the different frequencies through our MUXes almost exactly, the wrong frequency will be produced and we will fail to achieve our intended result.

3 Calculations

Part Number	Description	ICC @ Nom Voltage (Max) (mA)	Voltage	Number needed	Power(mW)
CD40106B	Schmitt trigger	0.03	5V	7	1.05
SN74HC393	Counter/Divider	0.08	5V	20	8.0
CD4067B	16:1 MUX	0.6	5V	12	36.0

CD4097B	8:1 MUX	0.6	5V	4	12.0
CD4052B	4:1 MUX	3.0	5V	5	75.0
LM741CN	Op amps	1.7	20V	2	680.0
SN74AHC00	NAND	0.02	5V	9	0.9
CD74HC30	8-input NAND	0.02	5V	12	1.2
CD4072B	4-input OR	0.15	5V	2	0.15
TS5A3357	SP3T Analog Switch	5 Ω / 0.001	5V	1	0.005
OPA1688	Audio Op Amp	1.6	20V	1	64
LM22675	Voltage Regulator	3.4	20V	1	68
XXXXXXXXXX	XXXXXXXXXXXXX	XXXXXXX		XXXXXX XXXX	952 mW

Table 1: Power Calculations

3.1 Frequency Calculation

For this instrument, the range of 523 Hz to 987 Hz is needed. The frequency of the VCO is given by Equation 1.

$$\frac{1}{f} = RCln\left[\left(\frac{V_P}{V_N}\right)\left(\frac{V_{DD}-V_N}{V_{DD}-V_P}\right)\right] \qquad (1)$$

With this in mind, values were chosen for the oscillators and filters based on the range of frequencies we want to attain. The reason for calculating values for the 5th octave for the oscillator is that it gets immediately divided by 2, 4, 8, or 16 depending on which octave is chosen.

Oddly enough, both the low pass and high pass filters share the same equation in regard to cutoff frequency. As such, the same calculations will be carried out to properly attain a good range. For the bandpass filter, values were chosen so that frequencies of roughly 30-500 Hz will pass through. The waveshapers also use this method to be tuned to the highest frequency in each octave. Values of 10 uF and 1 uF were used for capacitors with resistors ranging from 110 Ohms to 600 Ohms in order to properly filter each octave.

3.2 Cost

Part Number	Description	Cost per part	Number needed	Total
CD40106B	Schmitt trigger	1.32	6	7.92
SN74HC393	Counter/Divider	0.82	20	16.40
CD4067B	16:1 MUX	1.29	12	15.48
CD4097B	8:1 MUX	0.84	4	3.36
CD4052B	4:1 MUX	0.51	4	2.04
LM741CN	Op amps	0.73	2	1.56
SN74AHC00	NAND	0.35	9	3.15
CD74HC30	8-input NAND	0.35	12	4.20
CD4072B	4-input OR	0.48	12	5.76
TS5A3357	SP3T Analog Switch	0.95	1	0.95
OPA1688	Audio Op Amp	1.91	1	1.91
3319P-1-203	20kΩ potentiometer	1.18	36	42.48
KTPS65-2430D	24V Power Supply	43.00	1	43.00
311050000-ND	Push Buttons	0.91	36	32.76
XXXXXXXXXX	XXXXXXXXXXXXX	XXXXXXX	XXXXXXXXXX	$180.97

Table 2: Cost of Parts Calculations

Factoring average engineering pay, in labor, this would cost

2*$35/hr*10hrs/week*10 weeks *2.5 = $17,500

Total cost = $17,588.20

4 Schedule

Date (week of)	Robert	Joshua
10/9	Research filter topologies and configurations	Power calculations
10/16	Breadboard the signal processing sections	Order parts and breadboard TTL if possible
10/23	Design Signal Processing PCB in Eagle	Design TTL PCB Submit PCB order
10/30	Progress Report/breadboard signal processing	Progress report/breadboard TTL
11/6	Test breadboarding/start soldering	Test breadboarding/start soldering
11/13	Finish soldering/construct final product	Finish soldering/construct final product
11/20	*Thanksgiving*	*Thanksgiving*
11/27	Test product/mock demo	Test product/mock demo
12/4	Demo/mock presentation	Demo/mock presentation
12/11	Presentation / Final Paper	Presentation / Final Paper

5 Ethics and Safety

The only relevant safety concern for our project is the danger presented by the use of electricity. It is supplied by 120 VAC from the wall and then converted to 24 VDC inside the closed box. Our team has years of experience working with these voltages and in fabricating electrical circuits. We will follow all the normal safety guidelines such as the one-hand method. However, the only danger presented to the end user will be plugging in the power cord to the wall outlet. In accordance with IEEE Code of Ethics Section 7, this synthesizer box will be designed so the end user will not be exposed to any hot wires[4]. The danger exists inside the synthesizer box and it is designed to remain closed for the end user. Certain ethical concerns have been raised about preloaded melodies and so we have eliminated this by designing a unique method for arpeggiation where the user chooses the sequence of notes from the keyboard.

Appendix A

Requirement	Verification
The divider must provide the correct voltage to each component as specified in the block diagram within 5%.	To test each module, probe its Vcc with a wire leading to a multimeter. Run the device through normal use (playing random notes, switching on the arpeggiator, etc) The device should not differ more than 5% from 5V (+/- 0.25V) for all logic modules and +/-12V (+/- 0.6 V) for all signal processing modules.
The keyboard logic must encode the 100% correct binary number when a key is pressed.	Verify the correct MUX channel is activated when the corresponding key is pressed. This can be done by displaying the S3-S0 bits on LEDs and checking them against a reference list for each note.
Signal must go to zero within 120 ns when switch is released.	Start with a button pressed. Using an oscilloscope, probe the button being pressed and the output, respectively. After releasing the button, the oscilloscope will record the time elapsed between the button release and the output going to 0.
The TTL must control the frequency route all (100% of) frequencies/waveforms in accordance with each input.	Press each key in the square wave row in order from left to right. Frequency should increase with each key pressed (can verify by listening). This shows that the proper oscillator is routed to each key pressed. If frequency decreases as one proceeds rightward, something is wrong. Repeat for triangle and sine.
The Arpeggiation TTL must play the sequence (sine, sine, square, square, triangle, triangle, sine,	Using an oscilloscope and a slowed down tempo (minimum tempo noted on UI knob labels), the

square).	output should be fed into an oscilloscope so that one can observe the shapes in real time.
The Arpeggiation TTL must play the sequence (sine, square, triangle, triangle, sine, square, triangle, square).	Using an oscilloscope and a slowed down tempo (minimum tempo noted on UI knob labels), the output should be fed into an oscilloscope so that one can observe the shapes in real time.
The Arpeggiation TTL must play the sequence (sine, sine, sine, square, triangle, triangle, square, square).	Using an oscilloscope and a slowed down tempo (minimum tempo noted on UI knob labels), the output should be fed into an oscilloscope so that one can observe the shapes in real time.
The Arpeggiation TTL must play the sequence (sine, square, triangle, sine, square, triangle, square, sine).	Using an oscilloscope and a slowed down tempo (minimum tempo noted on UI knob labels), the output should be fed into an oscilloscope so that one can observe the shapes in real time.
The Arpeggiation TTL must supply tempos Largo (1 Hz), Moderato (2 Hz), and Presto (3 Hz) to within 10% accuracy.	The aforementioned tempos will be labeled around the circumference of a potentiometer. Using an oscilloscope, one can track the clock signal using a probe to observe its frequency of oscillation.
Each VCO must produce a nearly perfect square wave (error within 10%).	Probe the output of the VCO playing an arbitrary note with channel 1 of an oscilloscope. Into channel 2, put a square wave generated by the bench with the same frequency and amplitude. Using the math function of the oscilloscope, perform a subtraction operation to find the voltage difference between the two waves in time. This difference should not exceed 10% of the maximum amplitude of each wave.
Each VCO must produce its correct frequency within +/- 3% [2]	Probe the output of the VCO playing C2 with channel 1 of an oscilloscope. Into channel 2, put a square wave generated by the bench with the ideal frequency (65.41 Hz). The difference in frequency between the two should not exceed about 3% (2 Hz).
The waveshapers must regulate the shapes of the waves coming out of the VCO to within 10% of the ideal. They are responsible for taking a square wave and making it into a triangle and sine wave.	Probe the outputs of the waveshaper for sine and triangle waves, respectively, and display them on channel 1 of an oscilloscope (only analyzing one waveform at a time). Display the proper waveform output from a waveform generator on channel 2 of the oscilloscope. Use the math function to calculate the voltage difference vs time. The difference should be within 10% (same methodology for testing VCOs,

	but now for the other two waveforms).
The VCA will amplify the signal to have voltage amplitude between 1 and 20 V P-P +/- 5%	Turn voltage control knob to lowest setting and play any note. Probe the output voltage with a wire leading to a multimeter. This should read within the margin of 1 V P-P. Now, turn the voltage control knob to the highest setting. Repeat the previous process, but instead it will be at 20 V P-P +/-5%.

References

[1]http://www.hakenaudio.com/Continuum/hakenaudiopricia.html

[2]Olson, Harry F. (1967). *Music, Physics and Engineering*. Dover Publications. pp. 248–251. ISBN 0-486-21769-8.

[3]http://www.vintagesynth.com/sites/default/files/2017-05/moog_voyager_xl_lg.jpg

[4]http://www.ieee.org/about/corporate/governance/p7-8.html