Modular Analog Synthesizer

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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 32.7 Hz to 261.63 Hz within 3%[2] according to the divisions between musical notes C1 through C4.
2. The voltage-controlled oscillators 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

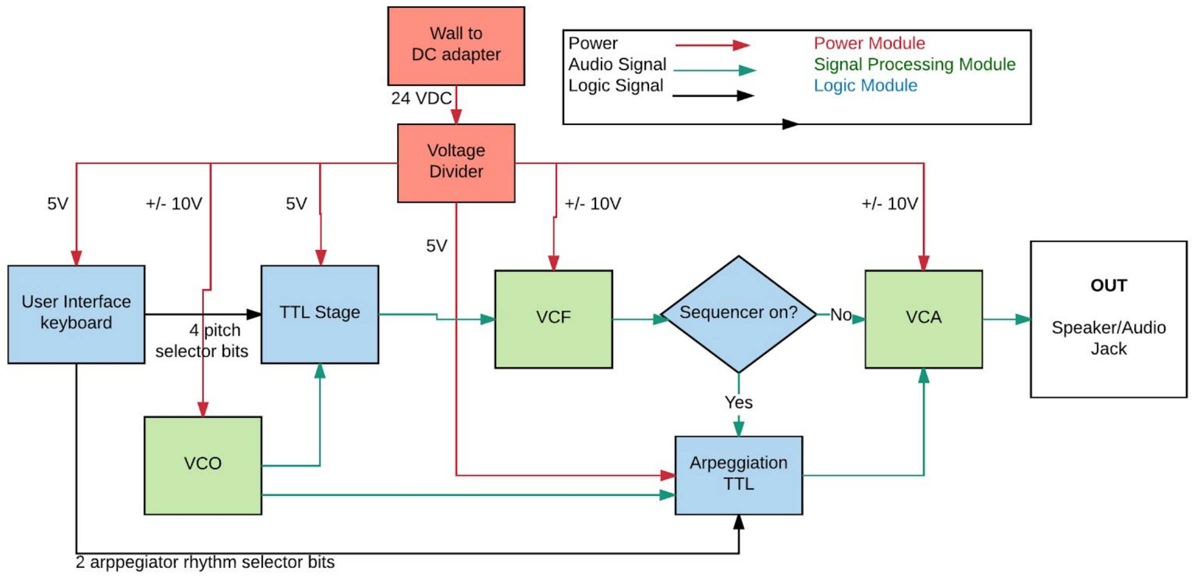

Fig. 1: Block Diagram

2.1 Physical Design

This synthesizer will have a box shape with proposed dimensions of 14" long, 8" wide and 2" deep as seen in Fig. 2. The length and width of the box are basically decided but the depth of the box may be subject to change given that we will try to slim the box down as much as possible for a sleek appearance. 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. 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. Above the row of keys, there is a one inch margin for visual separation between the control knob section and the note keys. The sketch provided below is drawn to scale and each green box from the graph paper represents one half inch. The outer appearance of the box will naturally evolve throughout our design process with things like beveled/rounded edges or 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 top row of buttons/knobs from left to right are for the four arpeggiator selection keys, arpeggiator on/off, the synthesizer on/off, octave switching knob and the volume knob. A power cord connects to the back of the box.

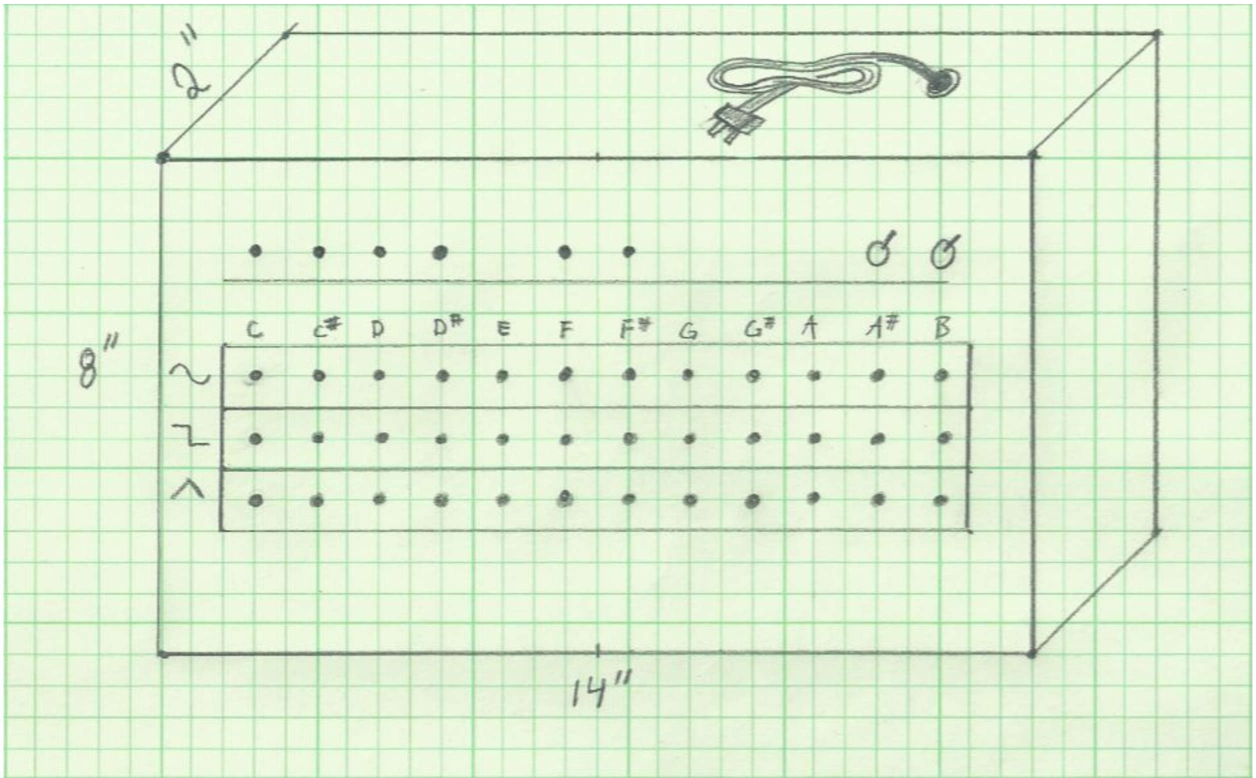

Fig. 2: Physical Design Sketch

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

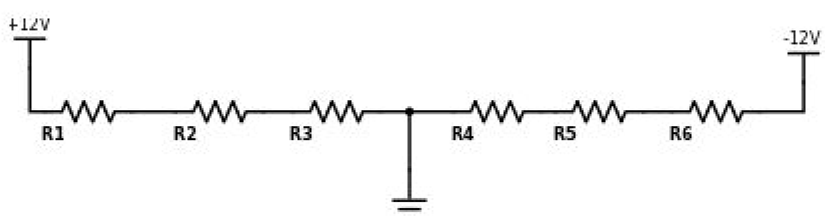

Fig. 3: Voltage Divider

The voltage divider will be responsible for distributing power to each of the other components. It will take 24 VDC from an AC/DC wall adapter and distribute appropriate voltages to each section accordingly.

Requirement	Verification
The divider must provide the correct voltage to each component as specified in the block diagram within 5%.	A. To test each module, probe its Vcc with a wire leading to a multimeter. B. Run the device through normal use (playing random notes, switching on the arpeggiator, etc) C. The device should not differ more than 5% from 5V (+/- 0.25V) for all logic modules and 10V (+/- 0.5 V) for all signal processing modules.

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 will correspond to one logic coordinate for the TTL stage to select which voltage to send through. Each switch will have its very own Schmitt trigger oscillator producing a square wave, which will then get shaped by the waveshapers and VCF later down the line.

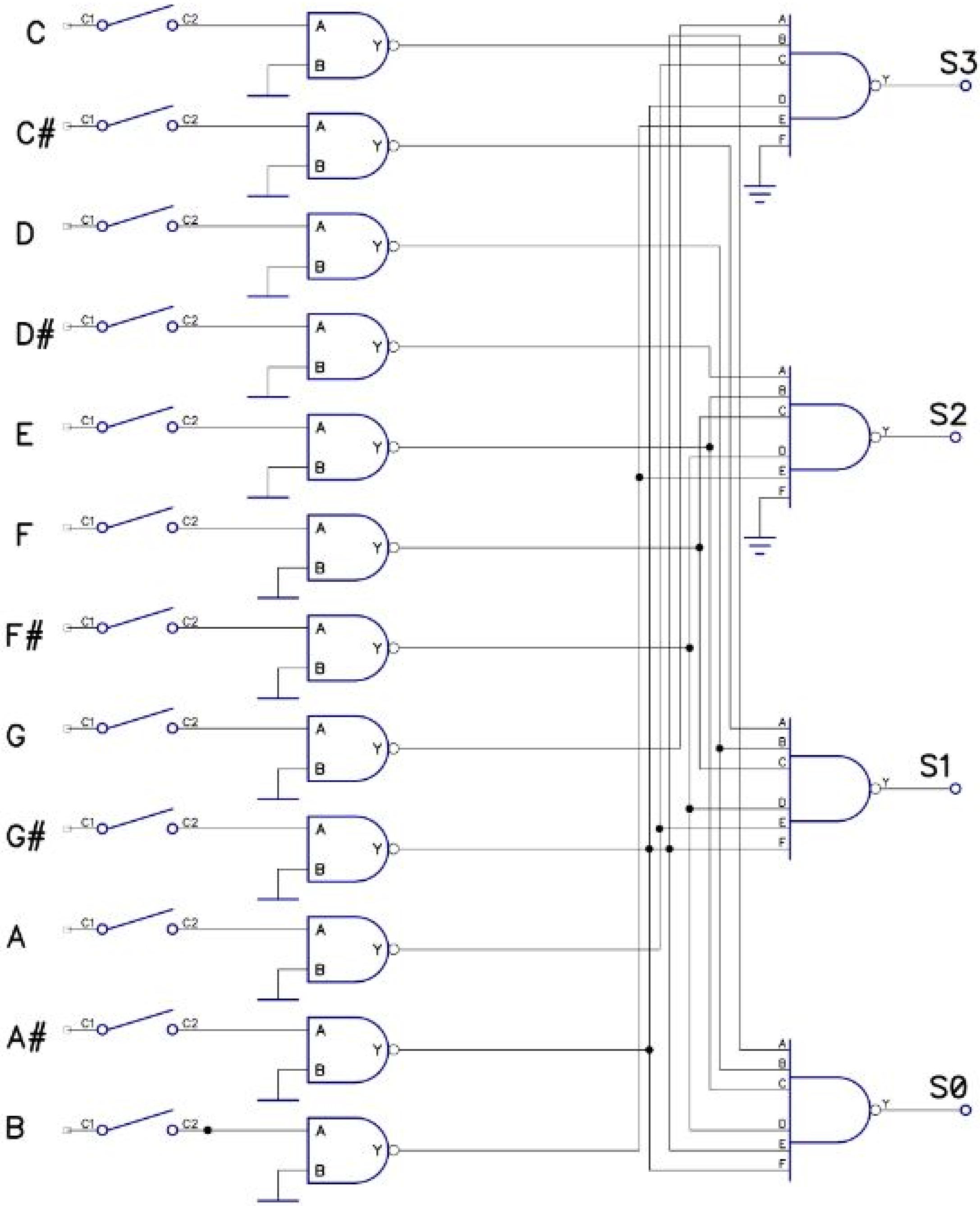

Fig. 4: Keyboard TTL

Requirements	Verification
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.	A. Start with a button pressed. B. Using an oscilloscope, probe the button being pressed and the output, respectively. C. After releasing the button, the oscilloscope will record the time elapsed between the button release and the output going to 0.

2.3.2 TTL Logic

The TTL will be responsible for relaying the correct voltage to the VCO. It will take 36 inputs and distribute them accordingly to the proper VCO. The TTL stage will also be responsible for delivering the correct waveforms to the arpeggiation function.

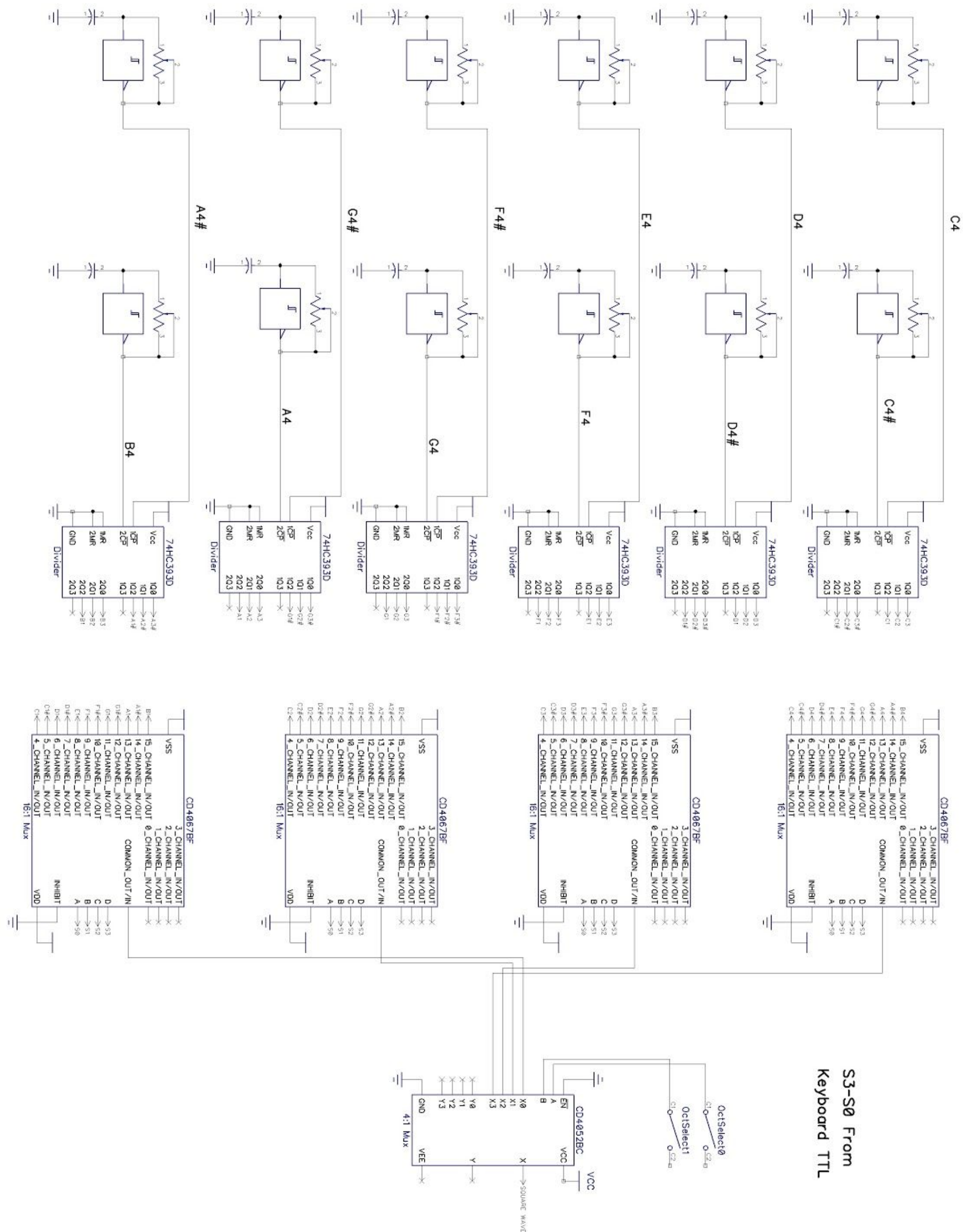
S3-S0 From Keyboard TTL
C4
D4
E4
F4#
G4#
A4#
C4#
D4#
F4
G4
A4
B4
74HC393D
Divider
CD4067BF
16:1 Mux
CD4052BC
4:1 Mux
OctSelect0
OctSelect1
VCC
SQUARE WAVE

Fig. 5: Oscillator & Octave Select Group

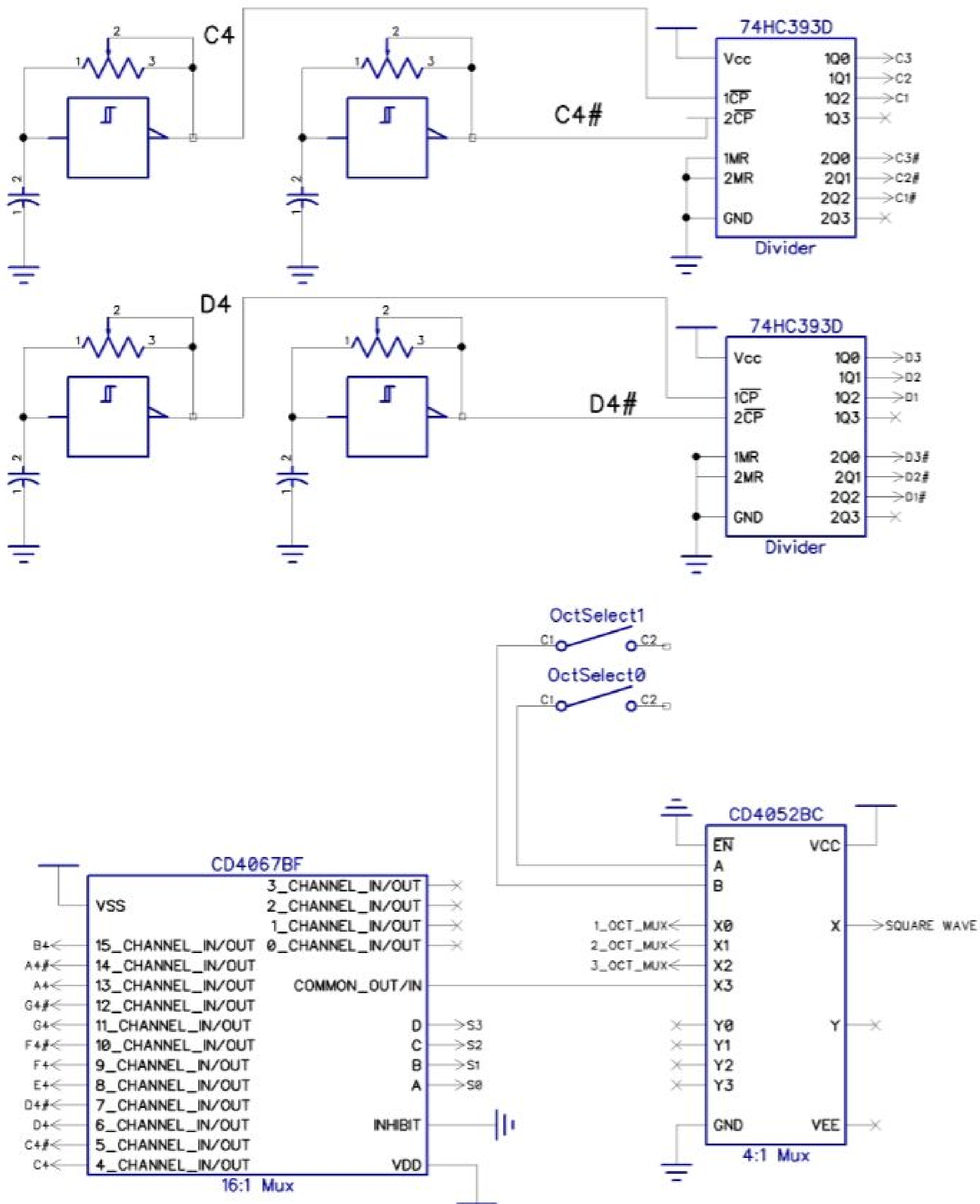

Figure 6: Oscillator & Octave Select Group Zoom

Requirement	Verification
The TTL must control the frequency route all (100% of) frequencies/waveforms in accordance with each input.	A. Press each key in the square wave row in order from left to right. B. 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. C. Repeat for triangle and sine.

2.3.3 Arpeggiation TTL

The arpeggiation TTL is responsible for deciding which notes to play at which times. There are 4 preset rhythms set to play each wave by itself at a separate time, as is seen in Fig. 5. The iterative steps are controlled by a clock signal fed into a counter, which controls with input is put in through time, cycling back to the beginning after it ends. This clock signal can be controlled via a potentiometer available to the user in the User Interface section.

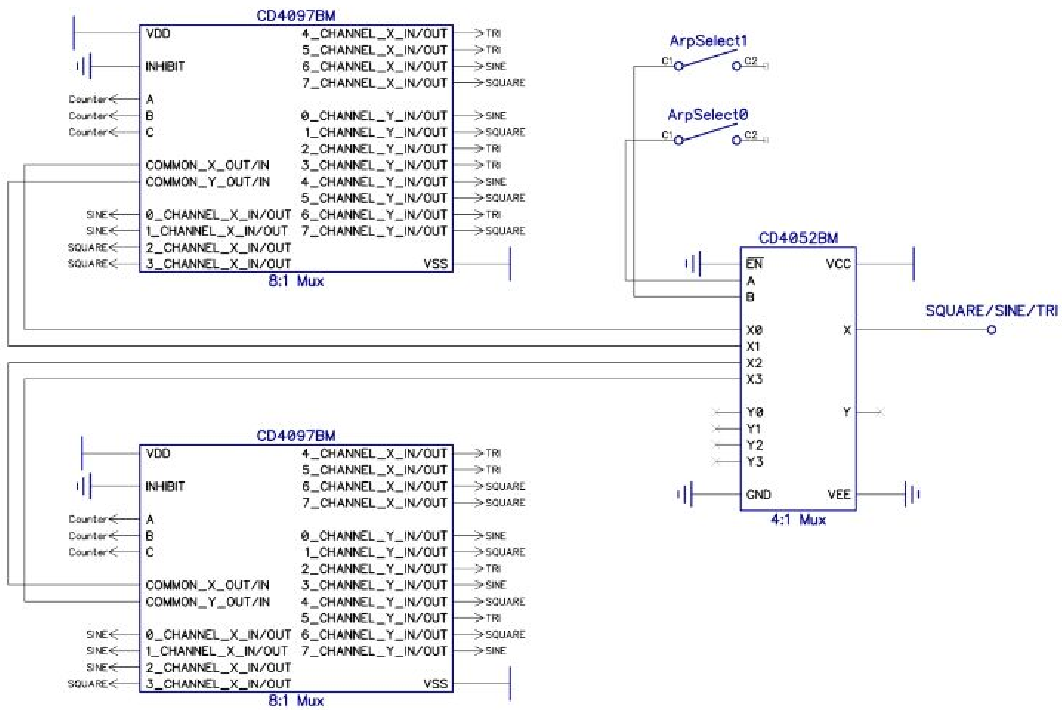

Fig. 7: Arpeggiator MUXes

Requirement	Verification
The Arpeggiation TTL must play the sequence (sine, sine, square, square, triangle, triangle, sine, 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, 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.

2.4 Signal Processing

2.4.1 VCOs

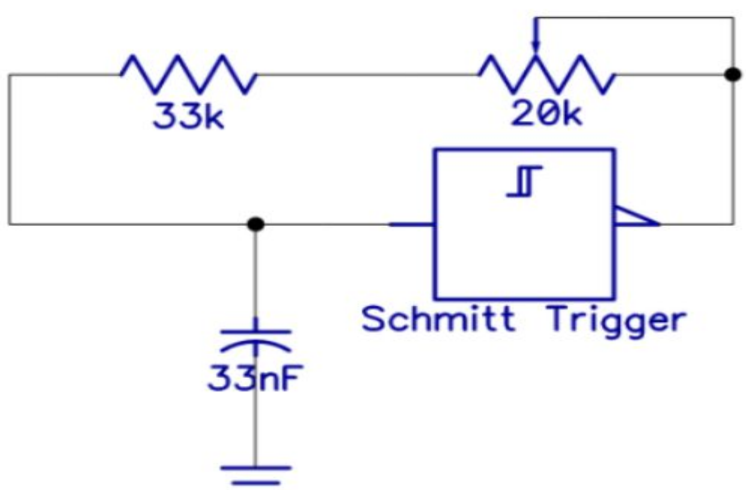

Fig. 8 : Schmitt Trigger Square Wave VCO

The VCOs are the central component, operation-wise. This is the stage that produces the signal that will later become audible sound. It is imperative that these provide consistent outputs for their corresponding voltages and waveforms. There will be one VCO for each waveform.

Requirement	Verification
1. Each VCO must produce a nearly perfect square wave (error within 10%).	1. Error calculation a. 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. b. 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]	2. Frequency calculation a. 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). b. The difference in frequency between the two should not exceed about 3% (2 Hz).

2.4.2 VCF/ Waveshapers

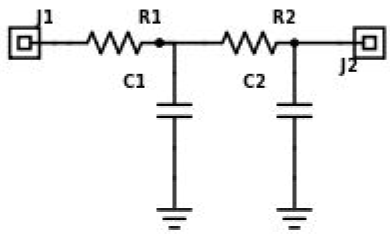

Fig. 9: Square to Triangle waveshaper

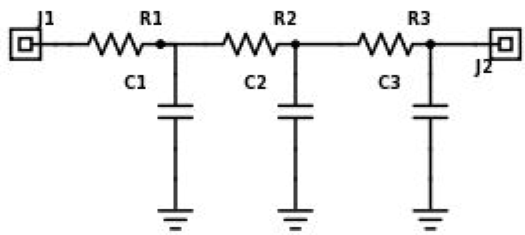

Fig. 10: Square to Sine waveshaper

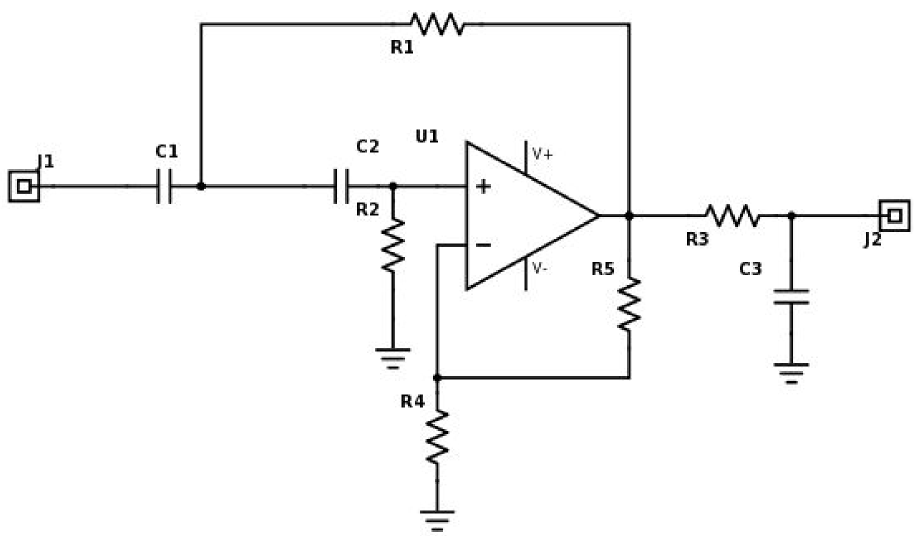

Fig. 11: Active Bandpass VCF

The waveshapers and VCF are responsible for regulating the waves' sound quality. The VCF will be an active filter that helps to eliminate noise and static from the sound before it gets amplified. It will be a third-order Butterworth bandpass filter with Sallen-Key topology. The waveshapers will help to make sure the sound waves are in the proper shape.

Requirement	Verification
1. 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.	1. A. 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). B. Display the proper waveform output from a waveform generator on channel 2 of the oscilloscope. C. 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).

2.4.3 VCA

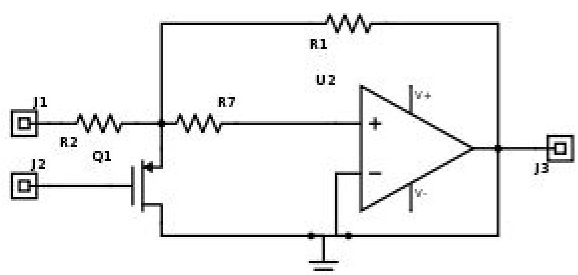

Fig. 12: Voltage Controlled Amplifier

The VCA will actively amplify the signal so that it will be able to be heard when sent through a speaker. It will take the input denoted as J2 in Fig. 10 as the voltage in control of the amplification. This voltage will be controlled by the voltage output of a potentiometer available to the user, 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.

Requirement	Verification
The VCA will amplify the signal to have voltage amplitude between 1 and 20 V P-P +/- 5%	A. 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. B. 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%.

2.5 Risk Analysis

The most significant point of failure is definitely in 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 voltages 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	6	0.9
CD4017B	Counter/Divider	0.03	5V	20	3.0
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	4	60.0
LM555CN	555 Timer	0.05	5V	1	0.25
LM741CN	Op amps	1.7	20V	2	680.0
SN74AHC00	NAND	0.02	5V	6	0.6

XXXXXXXXXX	XXXXXXXXXXXXX	XXXXXXX		XXXXXX XXXX	792.75 mW

Table 1: Power Calculations

3.1 Frequency Calculation

For this instrument, the range of 32.7 Hz to 261.63 Hz is needed. The frequency of the VCO is given by Equation 1.

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

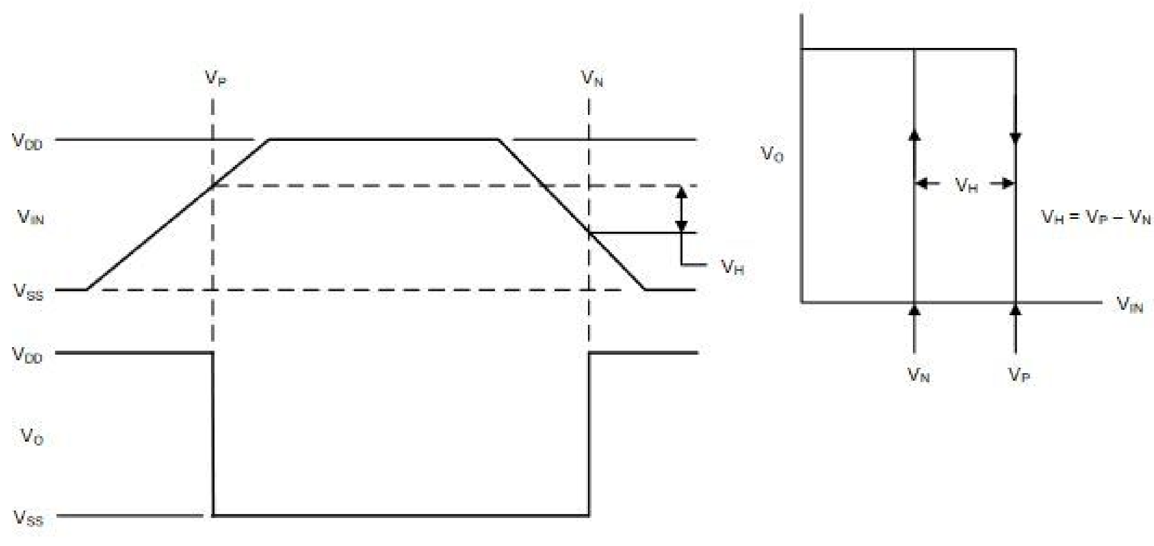

Figure 13. Hysteresis Definition, Characteristics

With this in mind, an ideal value for capacitors and resistors would be somewhere on the order of 80 nanoFarads and 7 kΩ, which together yield 284 Hz, very close to the upper frequencies we want to attain. The reason for calculating more for the upper frequencies than the lower ones is because the highest octave gets divided as part of the octave select circuit, so the lower octaves will be taken care of.

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 will be chosen so that frequencies of roughly 30-300 Hz will pass through. The waveshaper will also use about the same resistor and capacitor values so that all frequencies below 284 Hz will be able to pass through.

3.2 Cost

Part Number	Description	Cost per part	Number needed	Total
CD40106B	Schmitt trigger	1.32	6	7.92
CD4017B	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
LM555CN	555 Timer	0.52	1	0.52
LM741CN	Op amps	0.73	2	1.56
3296W-1-203	20kΩ potentiometer	1.18	36	42.48
XXXXXXXXXX	XXXXXXXXXXXXX	XXXXXXX	XXXXXXXXXX	$88.20

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 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.

[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

http://www.electronics-tutorials.ws/filter/filter_8.html