Modular Synthesizer

EGEE 485 - Electrical Engineering Design Project Laboratory

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Final Report

Abstract

A modular synthesizer is an electronic device that consists of individual modules that can be connected together by a user to create a music instrument. Modules specialize in a task such as creating a specific signal or affecting a signal in some way. For example, a sawtooth oscillator may be one module and a device to mix multiple signals together (a mixer) may be another. By connecting these devices together in various ways many sounds and musical uses may be produced.

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Description & Objective

The end goal is to create enough modules and a variety of them to provide a versatile instrument. Specifically, we wish to create a power supply for the modules, an oscillator as a sound source, an ADSR envelope as a modulation signal, and a filter. All of the modules should be voltage controlled, meaning they can be controlled by an input voltage from another module. A voltage to current exponential converter will be used to convert a controlled voltage (CV) to a controlled current. Doing this allows Operational Transconductance Amplifiers (OTA's) to be used in circuit design as a way of adjusting each module. By having each module be voltage controlled, the modules will be able to interact and control each other.

Design Specifications and Constraints

- The Power Supply will have outputs for +/- 12 Volts and ground (0 volts). It will be able to take any U.S. standard outlet for supplying the power supply through a wall wart
- Patches to modules on the user side will be done with standard 3.5mm ⅛ inch mono jacks. Stereo jacks will be used where appropriate if needed.
- One Volt per octave is the standard for the voltage to current converters. This means for each volt, the current doubles meaning, the frequency of the oscillator will double. This is a common tuning standard so that voltages correspond with musical pitches
- Case holding modules designed to EuroRack standards.

Block diagram and function description

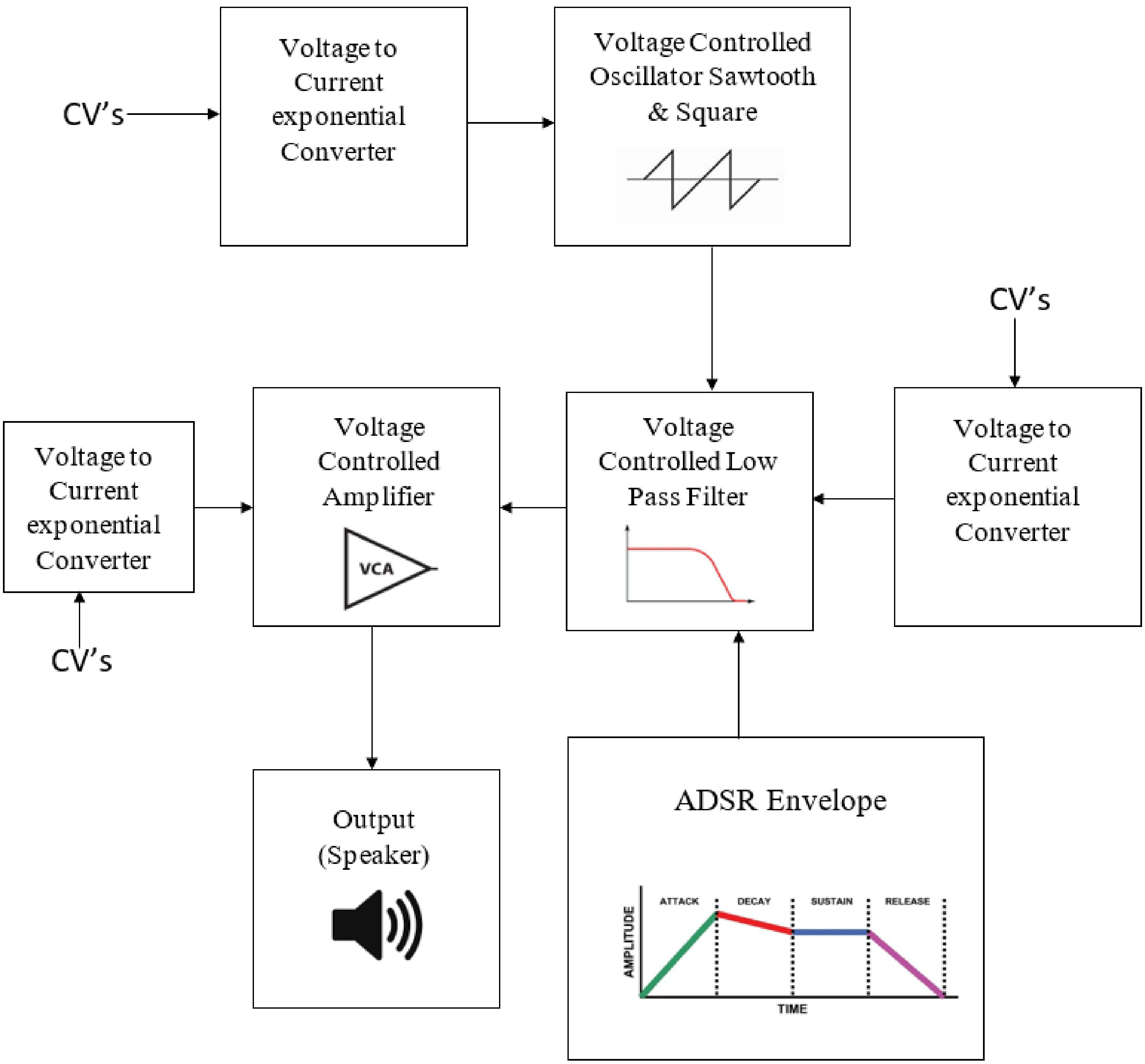


Fig. 1 - Block Diagram of Synthesizer

Description of each Block Diagram:

Voltage to Current Converter - Takes a voltage and converts it to current. There are many different types of circuits for this such as a linear or exponential version. An exponential version is being used because humans hear pitch exponentially. While circuits are said to be voltage controlled, they will really be current controlled, but the voltage to current converter allows for it to be voltage controlled.

Voltage Controlled Oscillator - The oscillator will produce a sawtooth and square wave. The amount of voltage/current inputted into them will dictate the frequency of the output. The square wave will also have a pulse width modulation (PWM) control feature that allows for different duty cycles.

Voltage Controlled Low Pass Filter - This low pass filter takes a signal in and based on another voltage/current it will determine the frequency at which the cutoff of the filter is. Filters are important because they allow for the signal to be changed and add resonance to the signal for musical purposes.

Voltage Controlled Amplifier - This is just a basic amplifier for decreasing or increasing a signal. It is important for making certain signals stronger or weaker. The amplification will be determined off a current that comes from a voltage to current converter, making it a voltage that really determines the amplification.

ADSR Envelope - The ADSR stands for attack, decay, sustain, and release. The importance of this is that it allows for a signal/voltage to be generated for the use of controlling another module. The acronym explains how it works: the attack determines how fast it rises to its peak voltage, decay is how fast it will drop in voltage to the sustain value, sustain is at what voltage it will hover at after the decay, and the release is how fast it will drop to zero volts after the sustain. This can be compared to a piano key: when the key is initially pressed the sound rises (attack), and then starts to drop (decay) after the peak. It will then hold at a certain volume while the key is being held down (sustain) and when finally the key is released, the note will finally drop to zero (release).

*Note the synthesizer is modular therefore it does not have to be connected as seen in the block diagram (Fig. 1)

Schematic Diagram and Function Description

Power Supply:

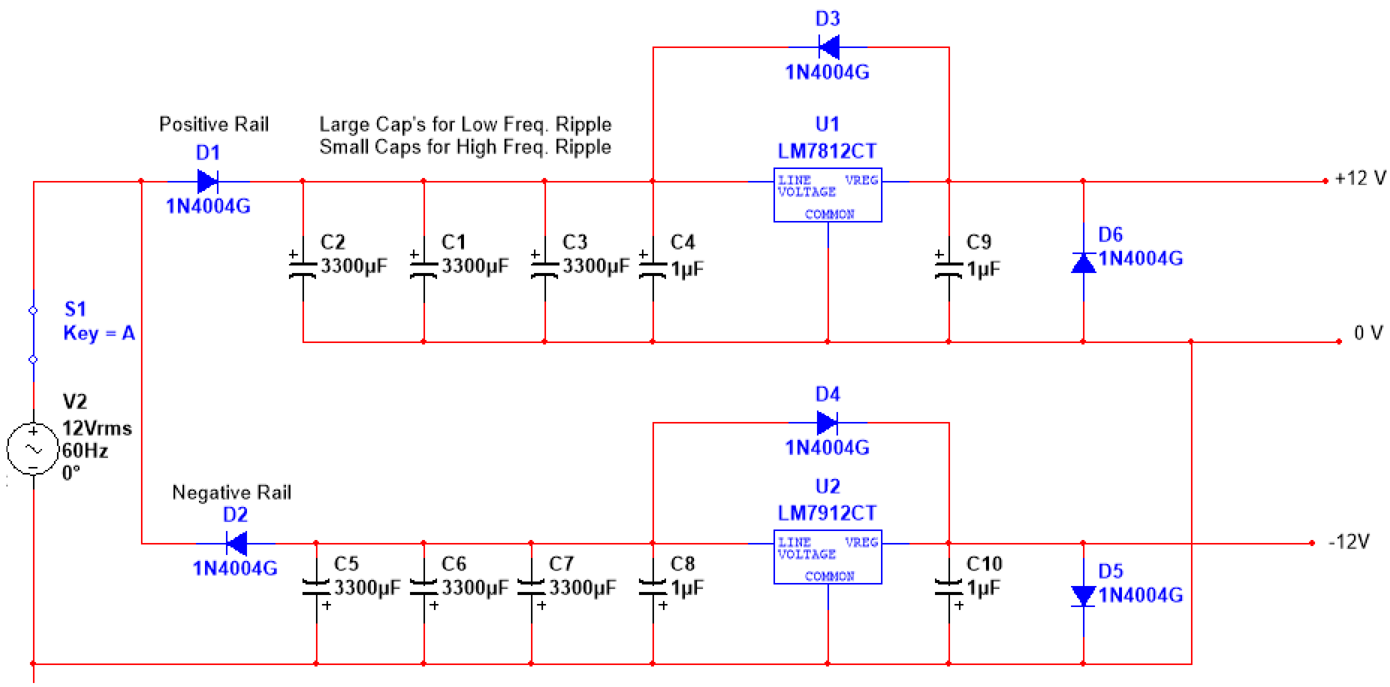


Fig. 2 - Schematic of Power Supply

This power supply connects to an outlet via a wall wart and outputs +12V, -12V, and GND. This power supply will drive all the modules.

*See appendix A for further description of power supply

Voltage to Current Converter (Source):

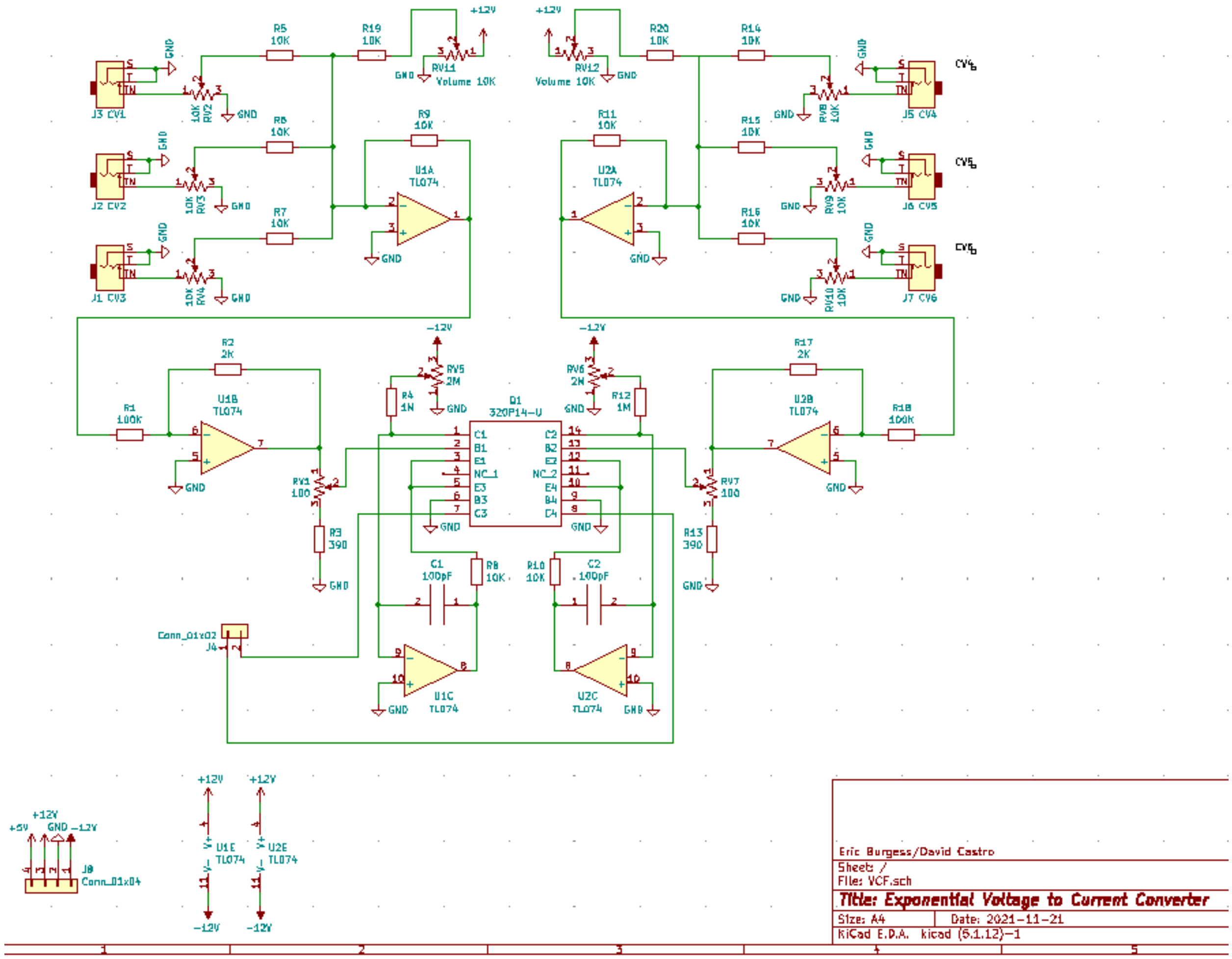


Fig. 3 - Schematic of Voltage to Current Exponential Converter (Source)

The voltage to current converter acts as a current source for the VCO and VCA. It will take in the Control Voltages and output a current based on the input voltages. Multiple voltages can be inputted through a mixing circuit. The voltage to current conversion occurs through a BJT differential pair (320P14-U). These allow for the modules to be voltage controlled. In order to maximize usage of the 320P14-U, two voltage to current converters are built on one board.

* See Appendix B for further description of the circuits operation

Voltage to Current Converter (Sink):

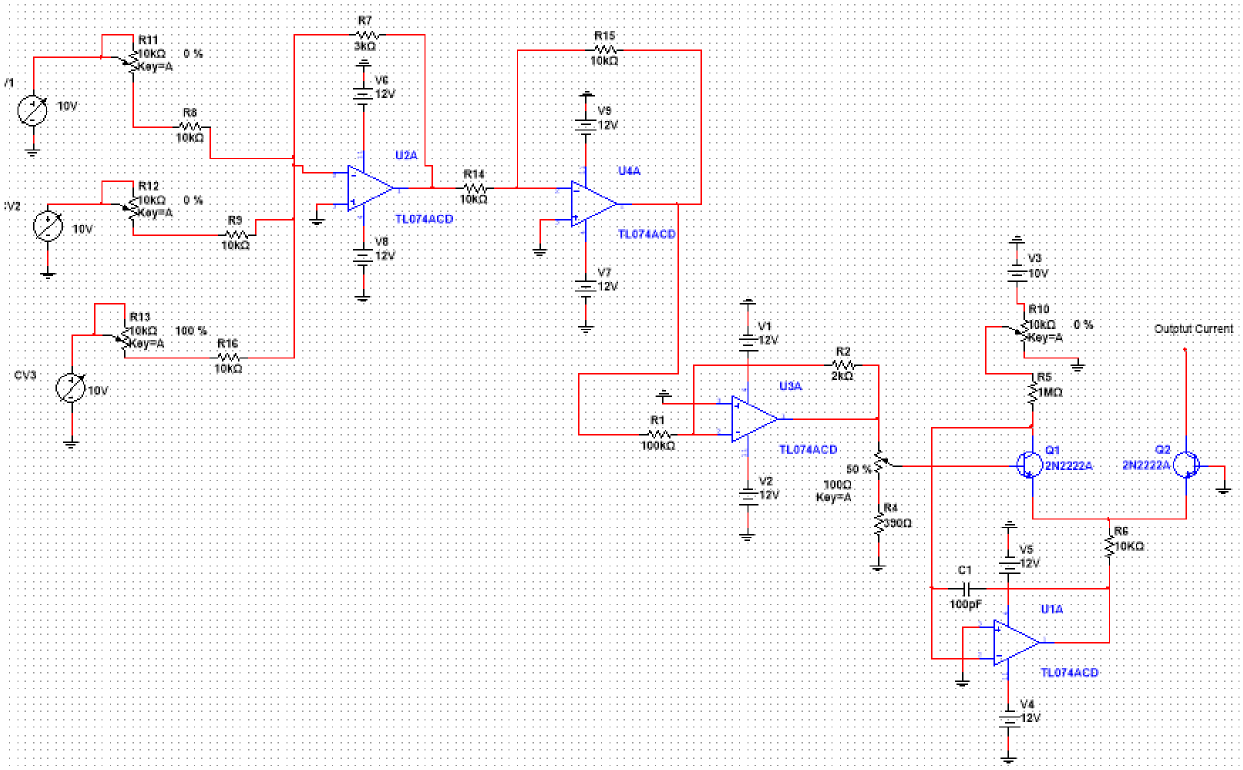


Fig. 4 - Schematic of Voltage to Current Exponential Converter (Sink)

This circuit's function is to act as a current sink. The behavior and design is very similar to the source version; there are just some slight changes as an op amp is used to invert the CV's so they are properly polarized, and that the BJT pair is an NPN. The current created here will be connected to the VCO in order to drive the oscillation. As mentioned in the source version, two of these are built to maximize IC space (300P14-U). The benefit of this allows for two oscillators to be driven as each current supplies one.

*See Appendix B for further description of the circuits operation

Voltage ControlledOscillator (VCO):

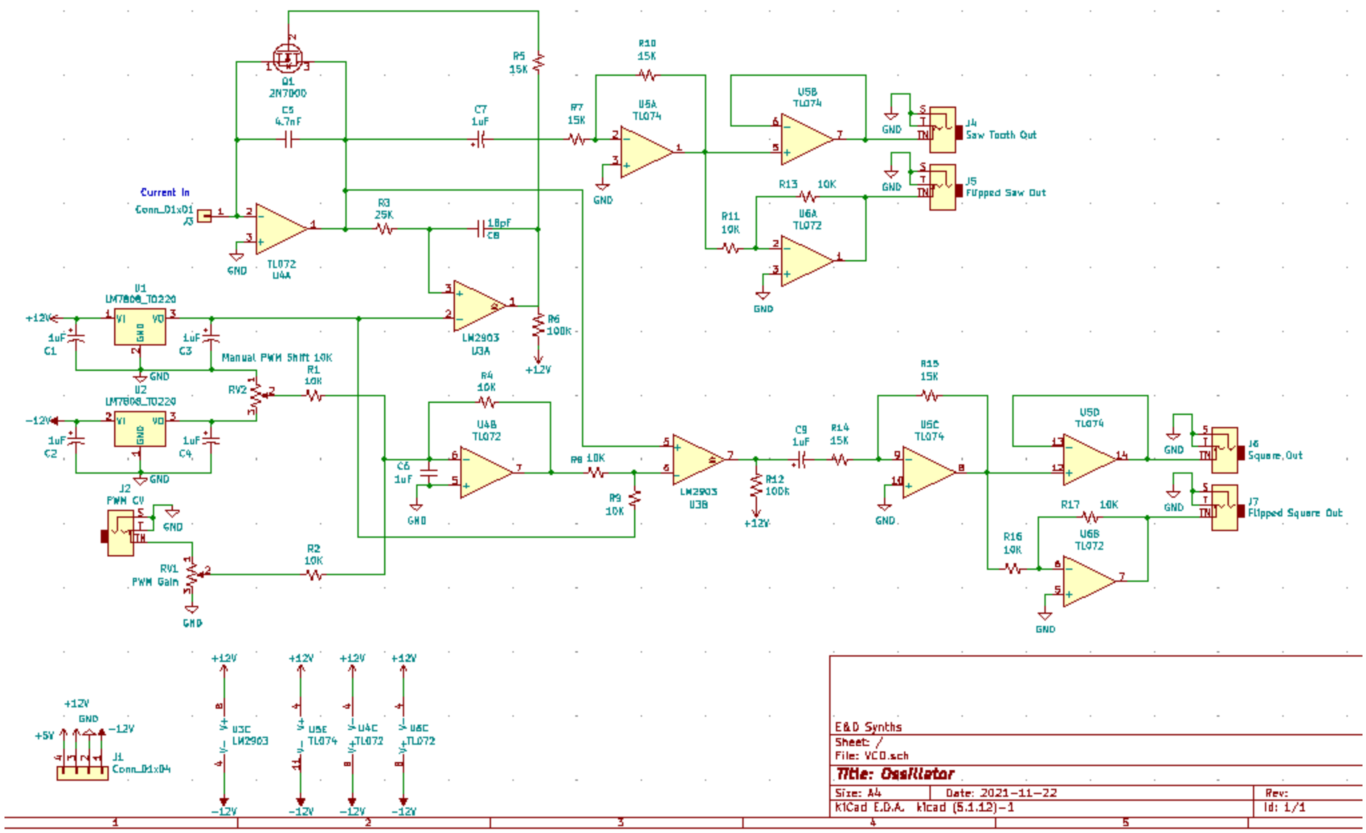


Fig. 5 - Schematic of Voltage Controlled Oscillator

The oscillator outputs a square, sawtooth, and its inverted waveforms. Because of how the sawtooth generates the square wave, a PWM function is easily added. The frequency of the waves is controlled by an input current generated from the voltage to current converter (sink). There are some high pass filters to act as a DC block at the end of each of these schematics.

*See Appendix C for further description of the VCO

Voltage Controlled Filter (VCF) - Low Pass

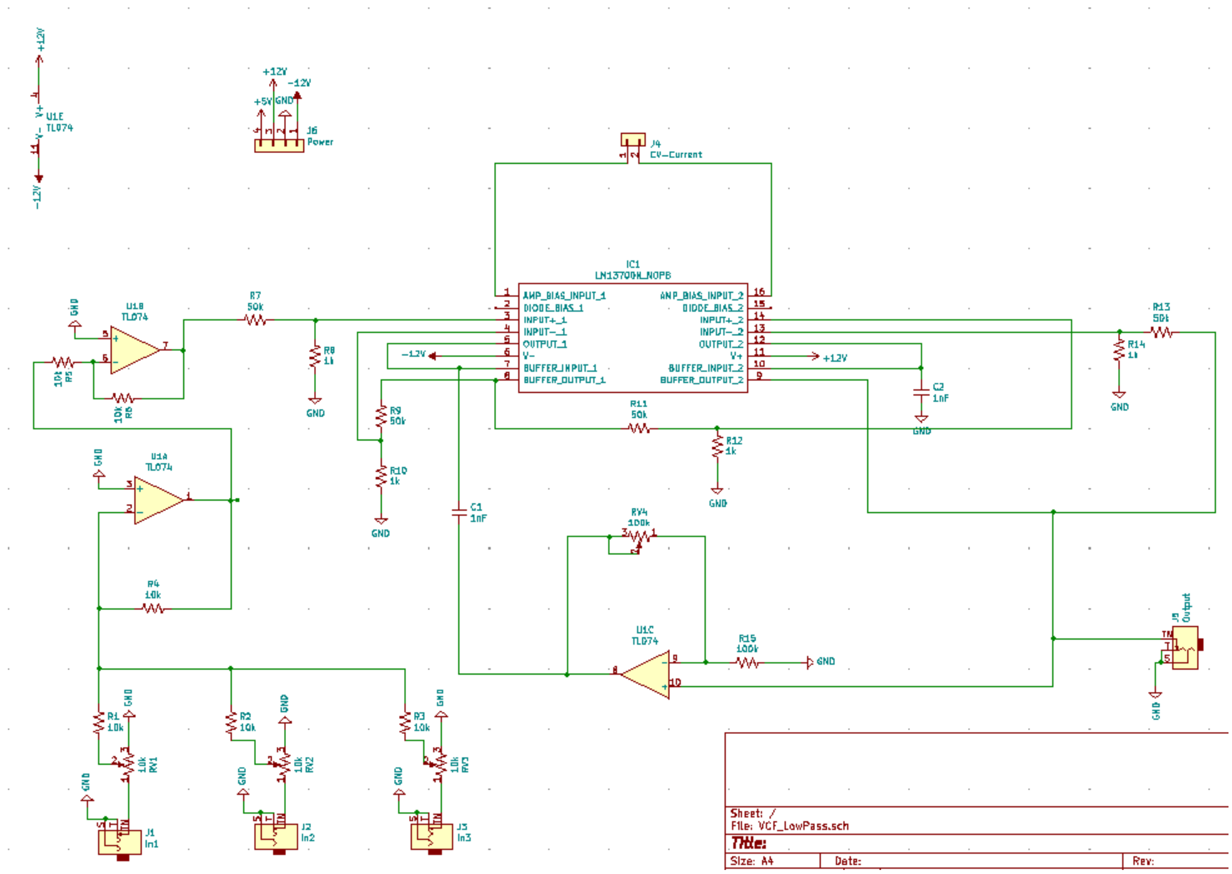


Fig. 6 - Schematic of Voltage Controlled Low Pass Filter

The Low Pass Filter features a cutoff and resonance control. The cutoff is controlled through a current input and the resonance is controlled through a potentiometer that can be turned. For the current input it is driven by the voltage to current converter (source). More current means a higher cutoff and less current means lower cutoff. An active mixing circuit is featured at the beginning of the circuit to have the ability to take in multiple signals to be filtered at once.

*Note there is an Error in the above Circuit see Appendix D

*See Appendix D for further description of the VCF

<u>Voltage Controlled Amplifier (VCA):</u>

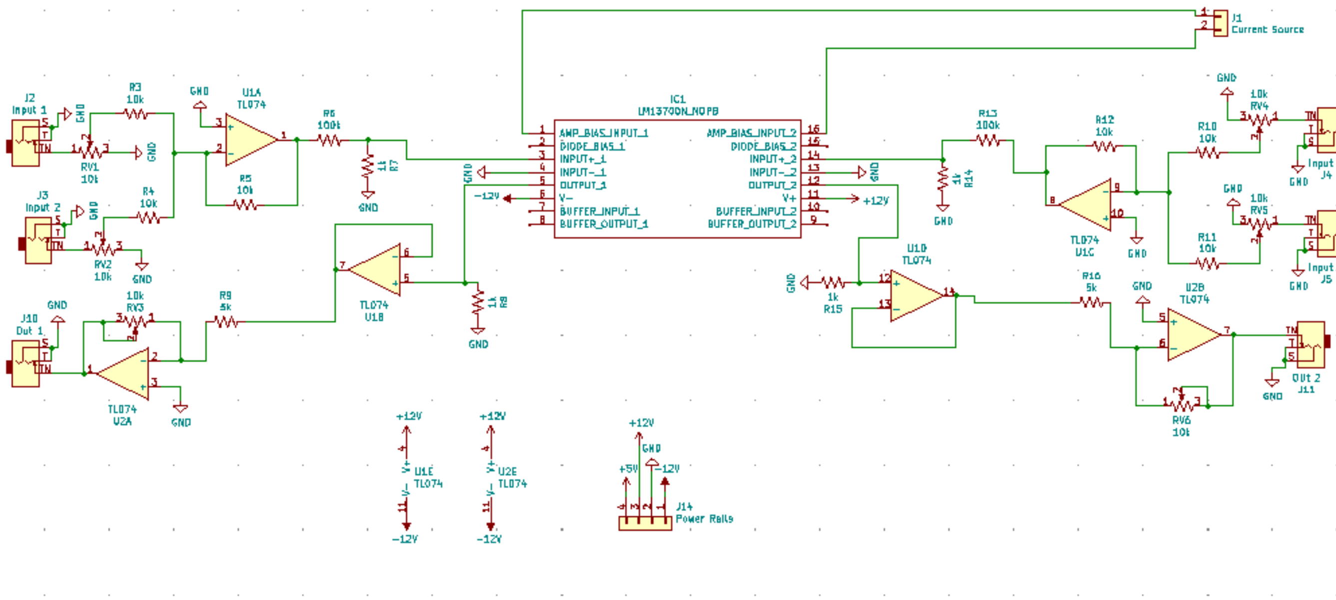


Fig. 7 - Schematic of Voltage Controlled Amplifier

The VCA schematic features two VCA's. It can accept multiple signals that will be mixed through an active mixer. From here a current drives the amplification of the VCA. The current comes from a voltage to current converter (source). It also features another potentiometer at the output for further attenuation. The attenuation has a range from 0 to 24 peak to peak Volts (-12 to +12).

*See Appendix E for further description and explanation of the VCA

<u>ADSR Envelope Generator:</u>

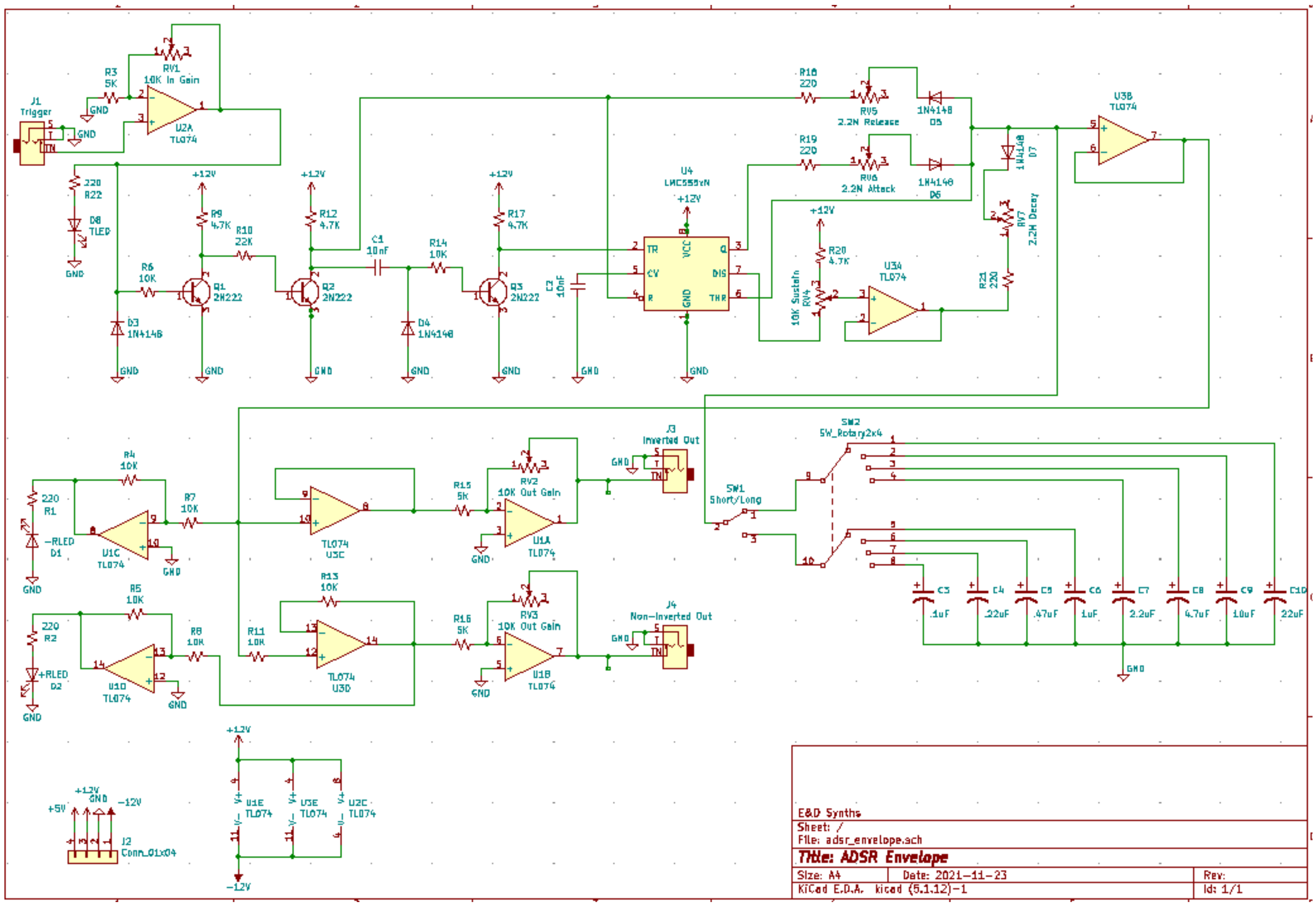


Fig.8 - Schematic of ADSR Envelope Generator

The ADSR envelope generator produces a voltage signal that can drive other modules. The circuit functions off a 555 timer. It uses a capacitor and potentiometers (time constant) to control the timing of the envelope. 8 capacitors can be selected through 2 switches. The variety of capacitors allows for slow and fast timings of the ADSR envelope. The output features the normal ADSR envelope and its inverted version.

*See Appendix F for a more in-depth explanation of ADSR envelopes and the schematic

Bill of materials

VCO

Resistors (¼ watt) in Ohms	
Part	Amount
100k	2
25k	1
15k	5
10k	9

Potentiometers	
Part	Amount
10k ohms	2

OP AMPS	
Part	Amount
TL074	1
TL072	2

Comparator	
Part	Amount
LM2903	1

Transistors	
Part	Amount
2N7000 MOSFET	1

Capacitors	
Part	Amount
4.7 nF (Cermeric)	1
18pF (Ceramic)	1
1 uF (Polarized)	7

Interface Connections	
Parts	Amount
AudioJack Socket (Female)	5
4 Pin Header (Male)	1
1 Pin Header (Male)	1

Regulators	
Part	Amount
LM7808 (+8Volt)	1
LM7908 (-8Volt)	1

EXPONENTIAL CONVERTER (SINK)

Resistors (¼ watt) in Ohms	
Part	Amount
1M	2
10K	12
100K	2
2K 3300 ppm Tempco	2
390 ohm	2

3k	2

OP AMPS	
Part	Amount
TL074	2

Transistors	
Part	Amount
300P14 (SAME DIE CHIP) NPN Matched	1

Capacitors	
Part	Amount
100pF (Cermeric)	2

Interface Connections	
Parts	Amount
AudioJack Socket (Female)	6
4 Pin Header (Male)	1
2 Pin Header (Male)	1

Potentiometers	
Part	Amount
10k ohms	8
100 ohms linear	2

EXPONENTIAL CONVERTER (Source) - 2x built

Resistors (¼ watt) in Ohms	
Part	Amount
1M	4
10K	24
100K	4
2K 3300 ppm Tempco	4
390 ohm	4
3k	4

OP AMPS	
Part	Amount
TL074	4

Transistors	
Part	Amount
320P14 (SAME DIE CHIP) PNP Matched	2

Capacitors	
Part	Amount
100pF (Cermeric)	4

Interface Connections	
Parts	Amount
AudioJack Socket (Female)	12
4 Pin Header (Male)	2
2 Pin Header (Male)	2

Potentiometers	
Part	Amount
10k ohms	16
100 ohms linear	4
2M ohms	4

Low Pass VCF (2 Built)	
Resistors (¼ watt) in Ohms	
Part	Amount
10K	12
100K	2
50K	8
1K	8

Potentiometers	
Part	Amount
10k ohms	6
100k ohms	2

OP AMPS	
Part	Amount
TL074	2
LM13700N_NOPB (OTA)	2

Capacitors	
Part	Amount
1 nF	4

Interface Connections	
Parts	Amount
AudioJack Socket (Female)	8
4 Pin Header (Male)	2
1 Pin Header (Male)	2

ADSR ENVELOPE

Resistors (¼ watt) in Ohms	
Part	Amount
22K	1
4.7K	4
10K	8
220	6
5k	3

Potentiometers	
Part	Amount
10k ohms	4
2.2M ohms	3

Transistors	
Part	Amount
2N222	3

Capacitors	
Part	Amount
10nF (Ceramic)	2
.1 uF	1
.22 uF	1
.47 uF	1
1 uF	1

2.2 uF	1
4.7 uF	1
10 uF	1
22 uF	1

Diodes	
Part	Amount
1N4148 (x5)	5
Red LED	1
Blue LED	1
White LED	1

OP AMPS	
Part	Amount
TL074	3

IC's	
Part	Amount
LMC555xN (555 timer)	1

Switches	
Part	Amount
Single Pole Double Throw	1
2x4 Rotary	1

Interface Connections	
Parts	Amount

AudioJack Socket (Female)	3
4 Pin Header (Male)	1
1 Pin Header (Male)	1

POWER SUPPLY	
Voltage Regulators	
Part	Amount
LM7812	1
LM7912	1

Capacitors	
Part	Amount
3300 microF	6
1 microF Tantalum capacitor	4

Diodes	
Part	Amount
1N4004	6

Transformer	
Part	Amount
Wall Wart 120V to 12V AC RMS	1

Top Assembly

<u>Voltage to Current Converter Layout (Source):</u>

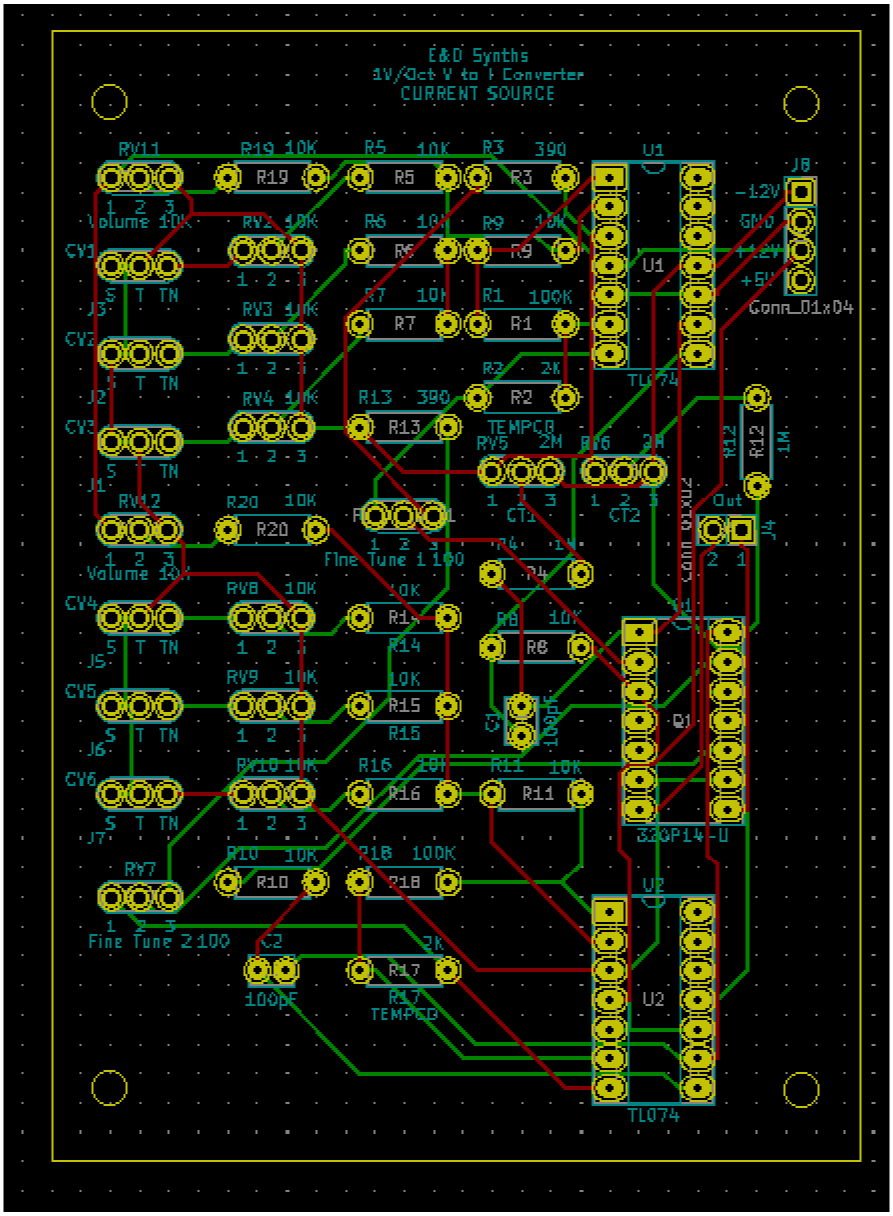


Fig. 9 - Layout of Voltage to Current Converter

Voltage Current Oscillator:

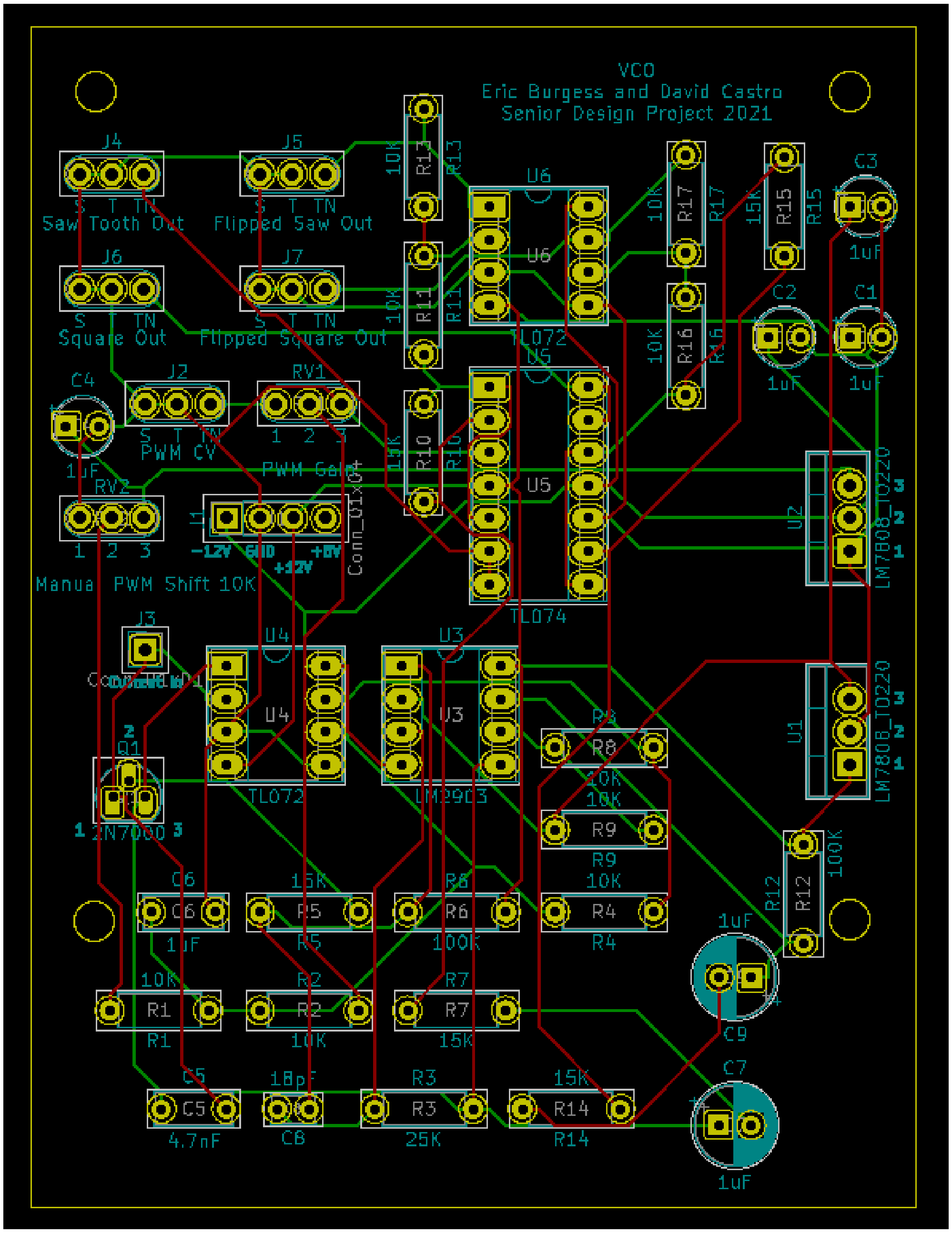


Fig. 10 - Layout of Voltage Controlled Oscillator

Voltage Controlled Filter:

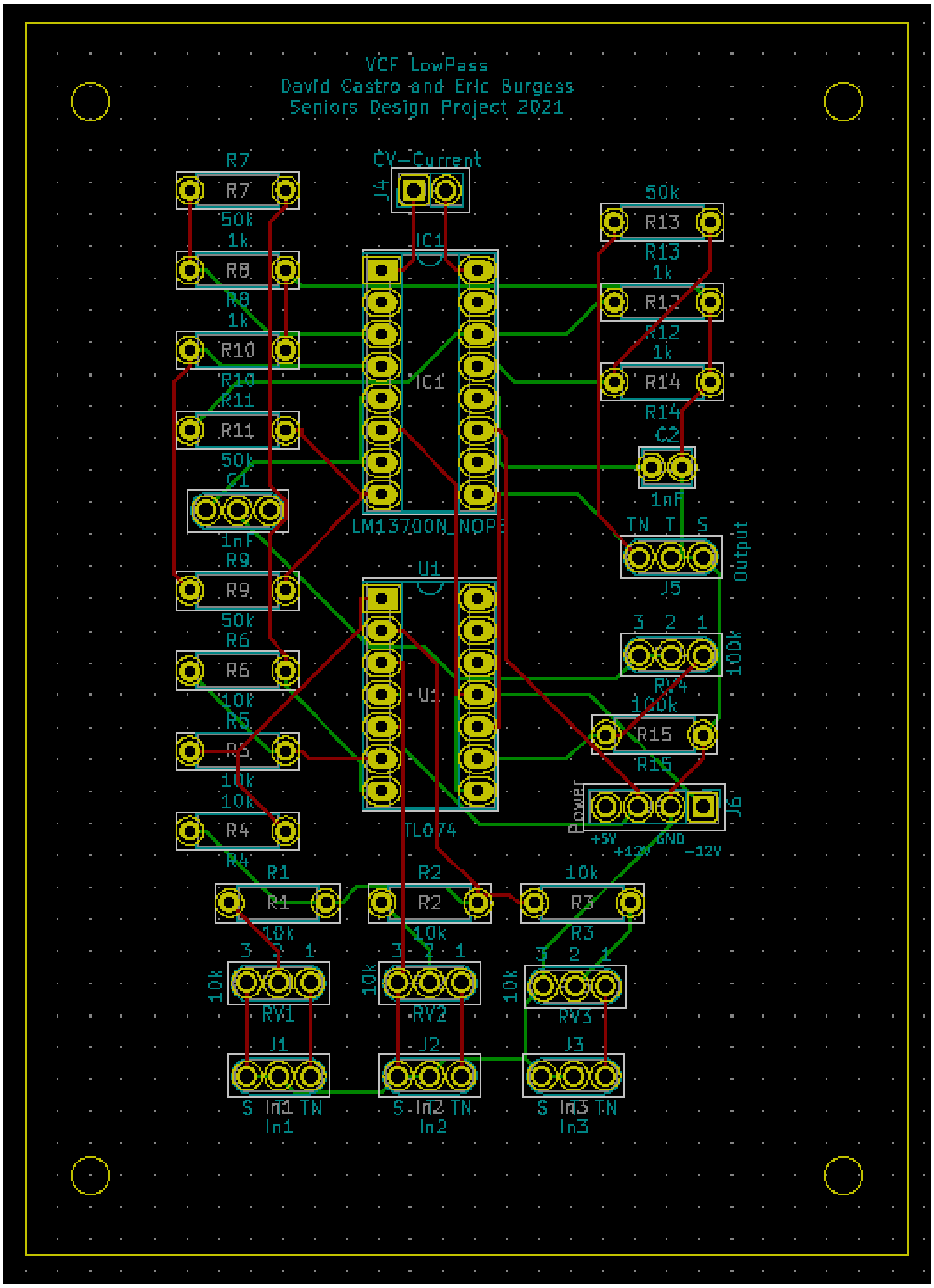


Fig. 11 - Layout of Voltage Controlled Filter

<u>Voltage Controlled Amplifier:</u>

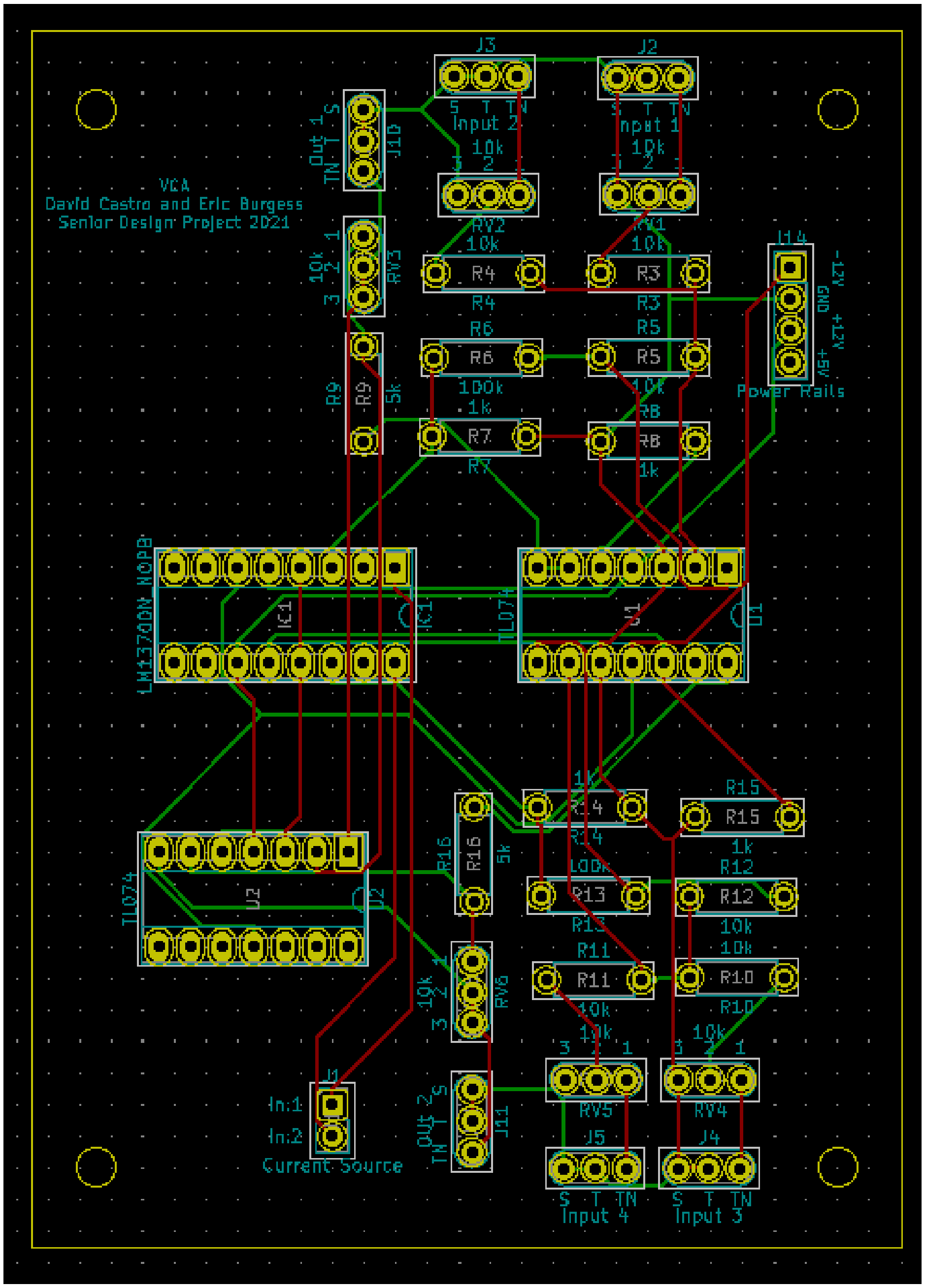


Fig. 12 - Layout of Voltage Controlled Amplifier

ADSR Envelope Generator:

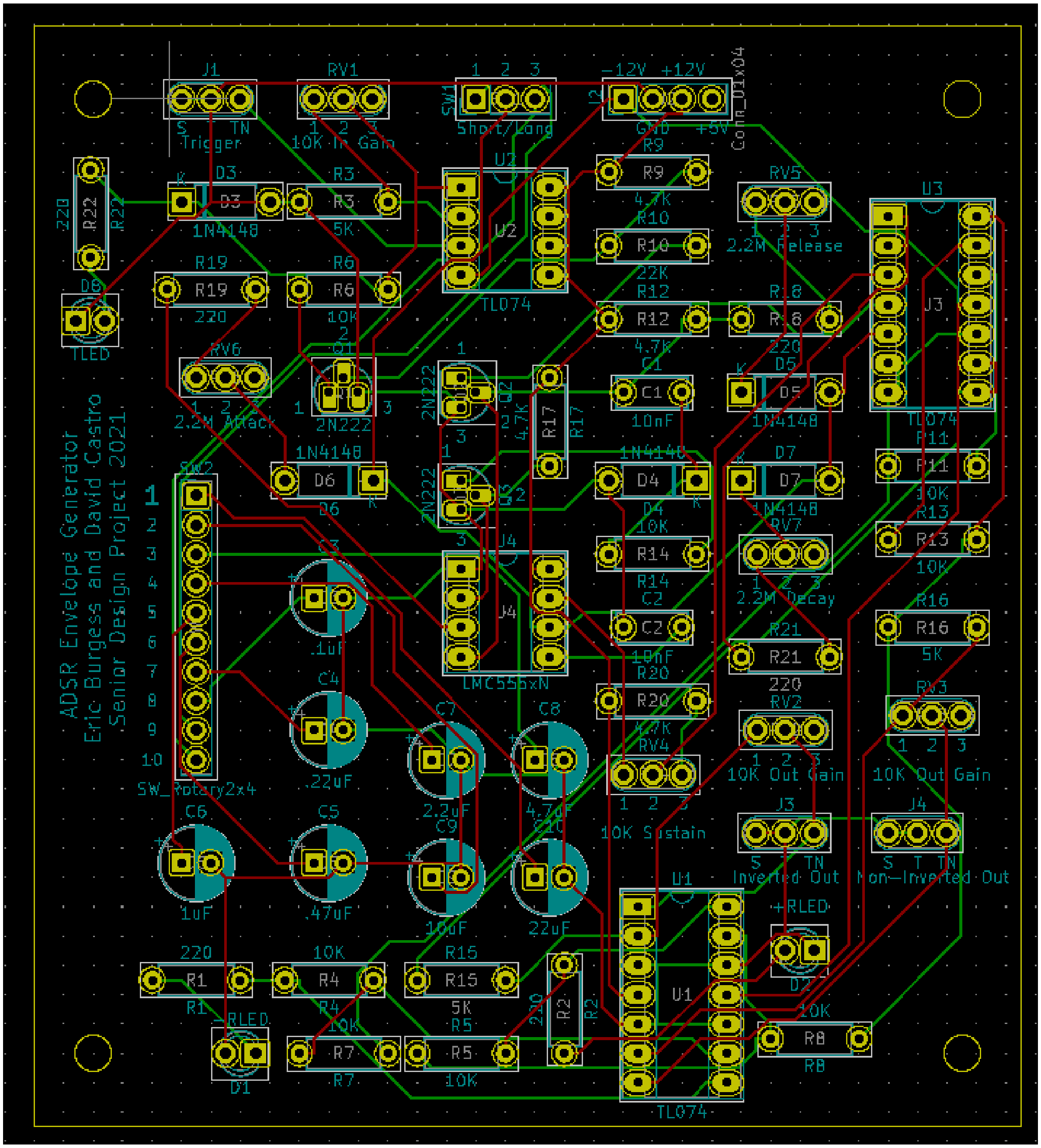


Fig. 13 - Layout of ADSR Envelope Generator

Test Set-up and Procedures

For test set-up most of the circuits were tested on a breadboard, but it was a rough draft of the circuits and only focused on the main procedure of the schematic (e.g. the circuit would not have an active mixing stage). It can be tested if the circuit functions correctly with an oscilloscope or voltmeter. The circuits are also audible so if someone had a trained ear they could also tell if the circuit behaves correctly (less accurate).

<u>VCO:</u>

The main idea/structure of the Oscillator can be tested as seen below in figure 14. The output of the oscilloscope should show a sawtooth and square wave. Increasing the input current should make the frequency of the waves go up.

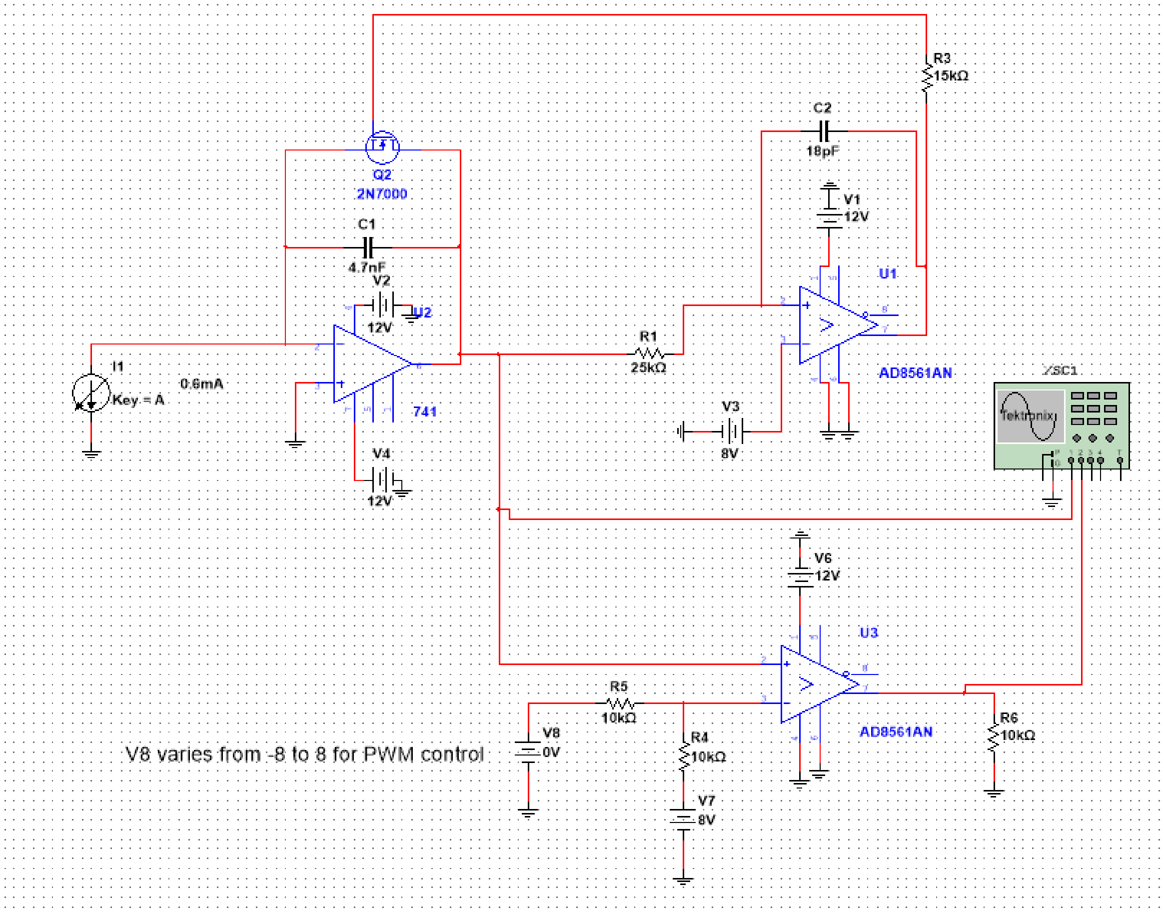


Fig. 14 - Schematic of Oscillator Testing with Oscilloscope Testing Schematic

Voltage to Current Converter:

The testing procedure is the same for the source and sink model. An ammeter (XMM1) is connected to the output and for each increase in voltage, the current should double in value. The potentiometer at the base is used to fine tune the current doubling.

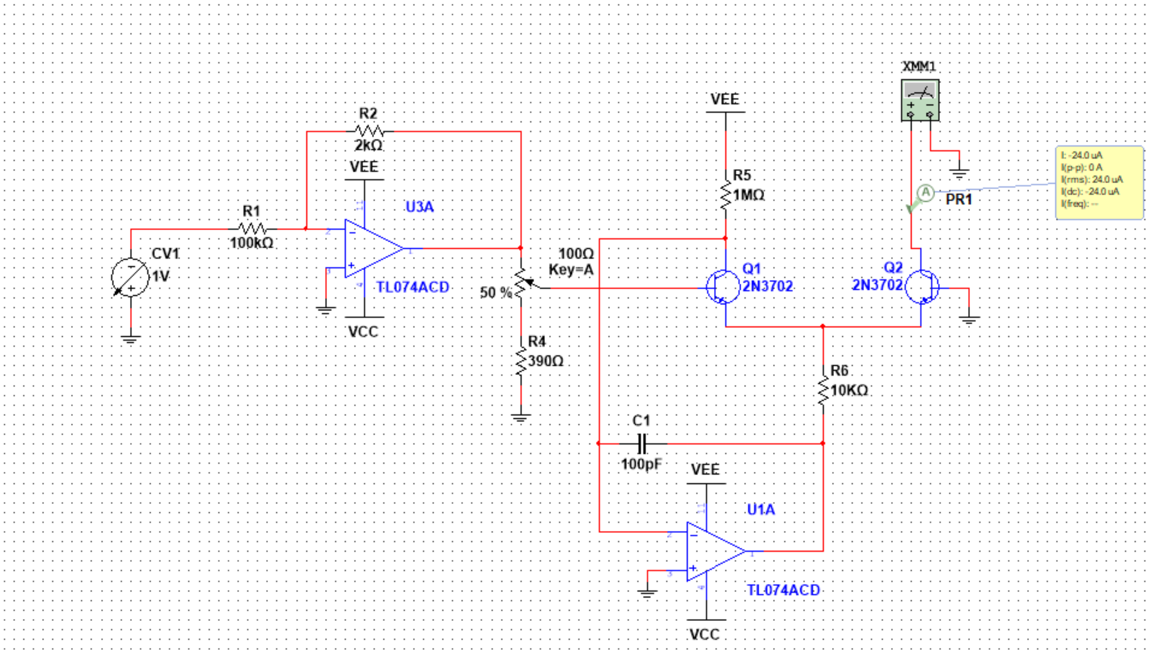


Fig. 15 - Voltage to Current Converter (Source Version) Testing Schematic

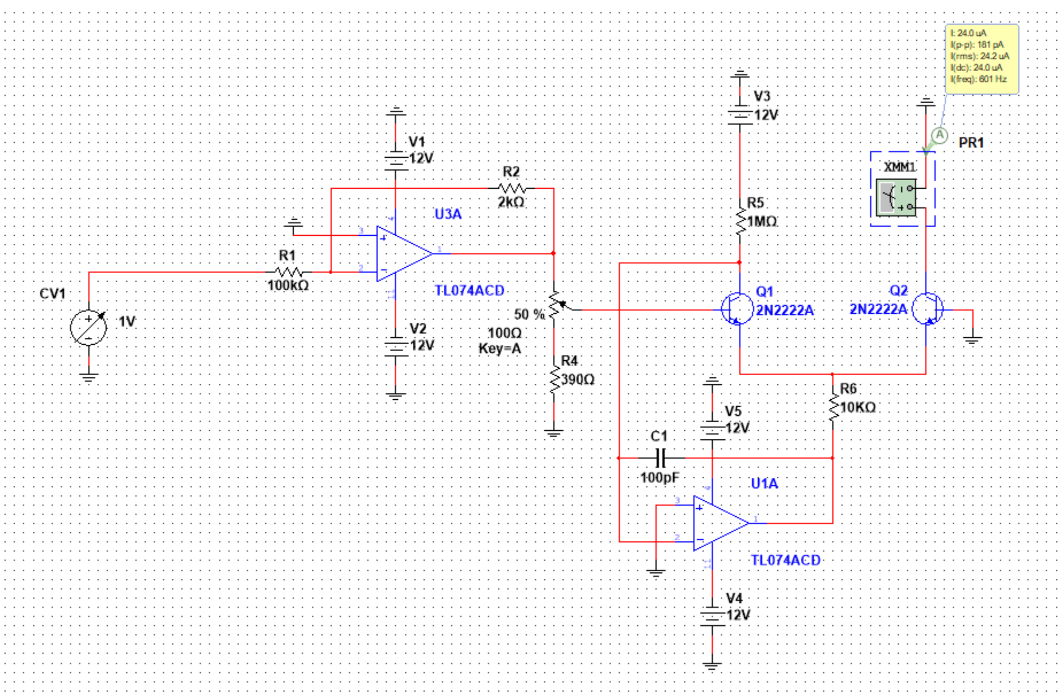


Fig. 16 - Voltage to Current Converter (Sink Version) Testing Schematic

<u>Voltage Controlled Amplifier</u>

Below shows the voltage controlled amplifier. A small signal needs to be imputed. This can either be done through a voltage divider with resistors or sending a small signal (less than 0.2 Volts). As the bias current is increased, a greater amplification of the signal should be seen. The oscilloscope compares the input signal and the output.

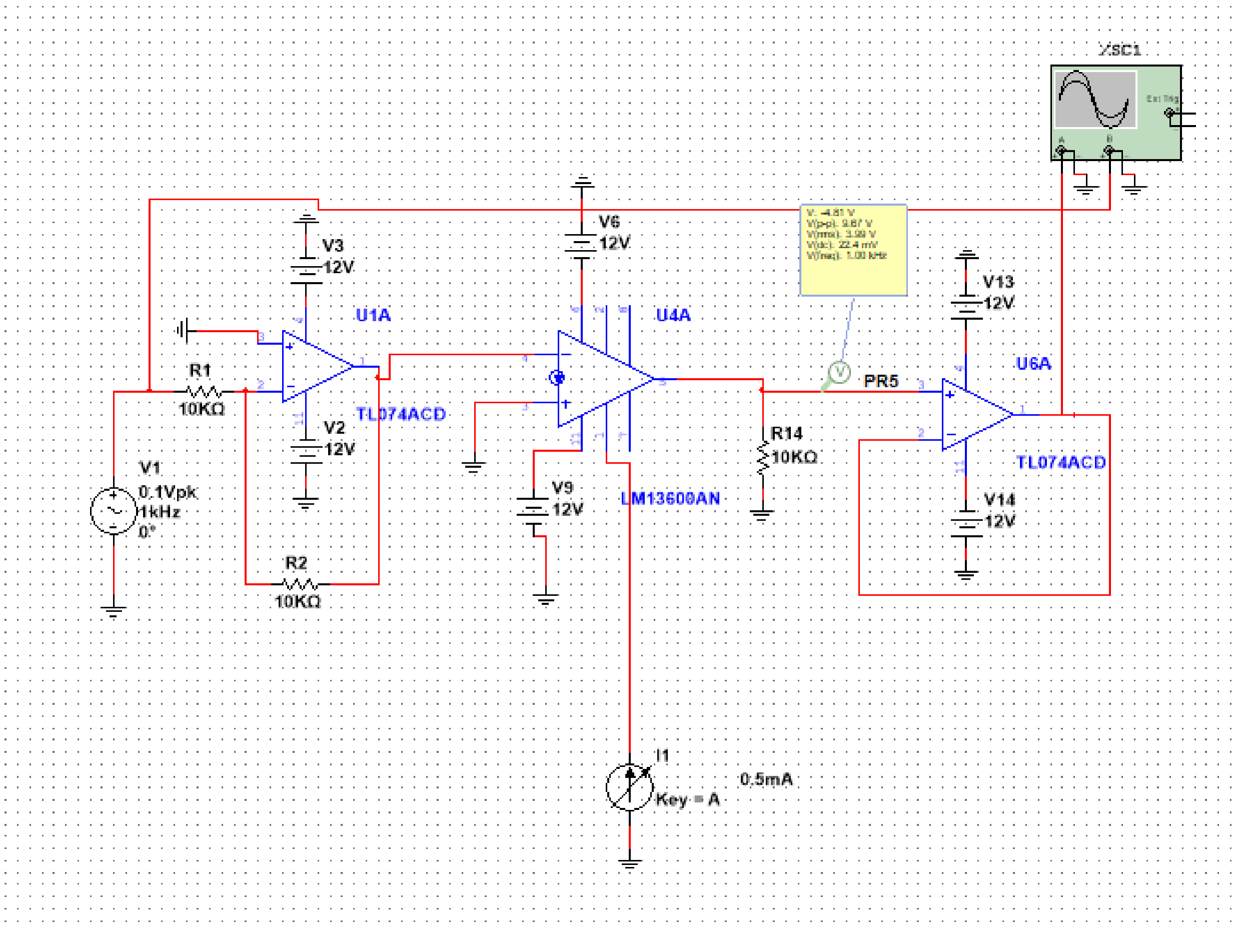


Fig. 17 - Voltage Controlled Amplifier Testing Schematic

Voltage Controlled Filter:

For the VCF, it requires an oscilloscope and an input signal. A square wave is best for testing because it is easiest to see the change in the wave in comparison to a sawtooth. By adjusting the input current, the cutoff should change (the lower the current the lower the cutoff). The potentiometer controls the resonance and should affect the square wave. By looking through the oscilloscope, the output and input can be compared to see how the filter affects it.

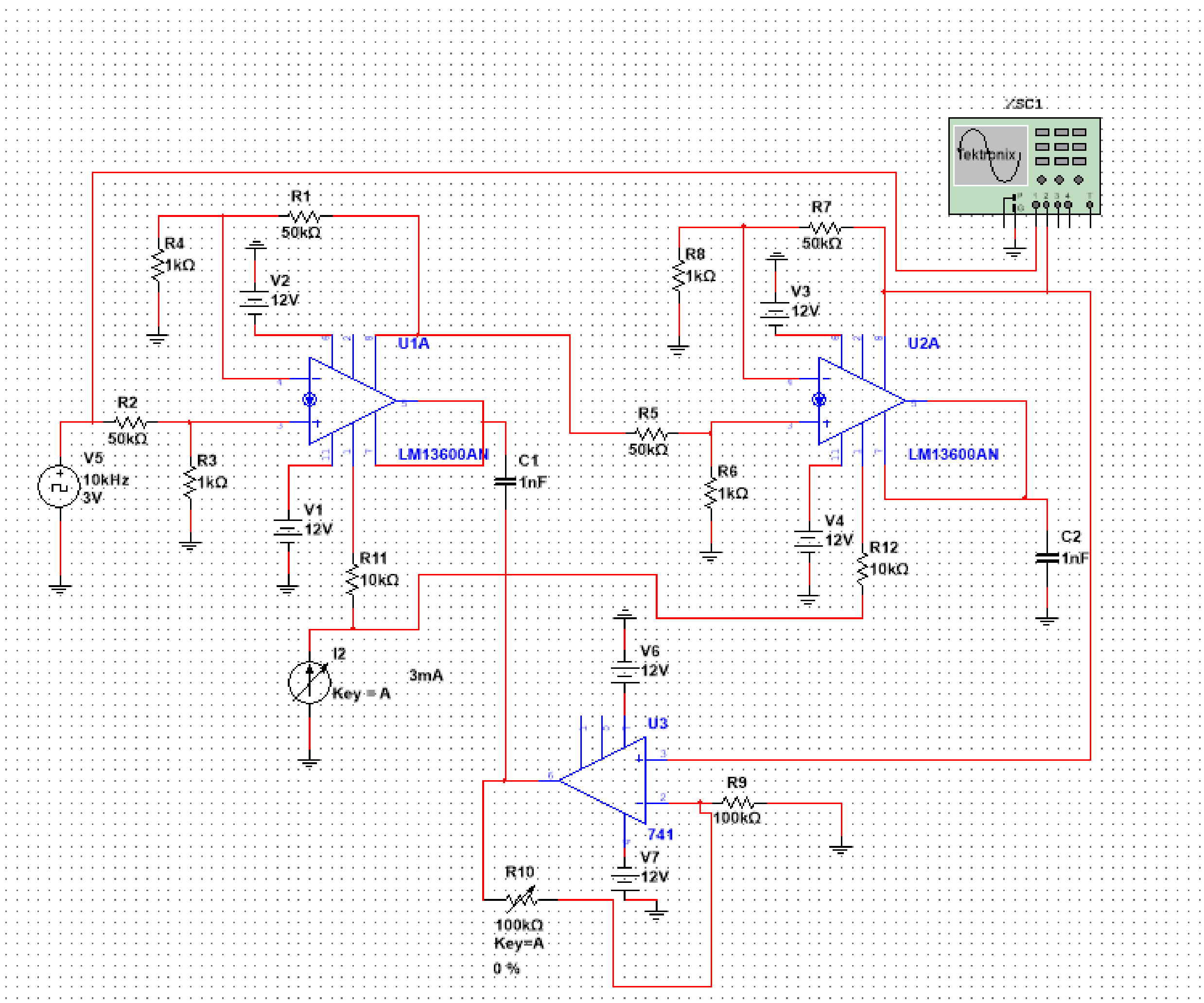


Fig. 18 - Voltage Controlled Filter Testing Schematic

ADSR Envelope Generator:

The ADSR can be tested multiple ways. It can be built and then plugged into a module such as an oscillator or amplifier and see how it affects it. Another way is to use a voltmeter or oscilloscope and see how the output comes out. This may be difficult because if the capacitor being used is small then the voltmeter and oscilloscope will have a hard time catching it. Using it with another module though allows you to hear it which can show if the device behaves correctly.

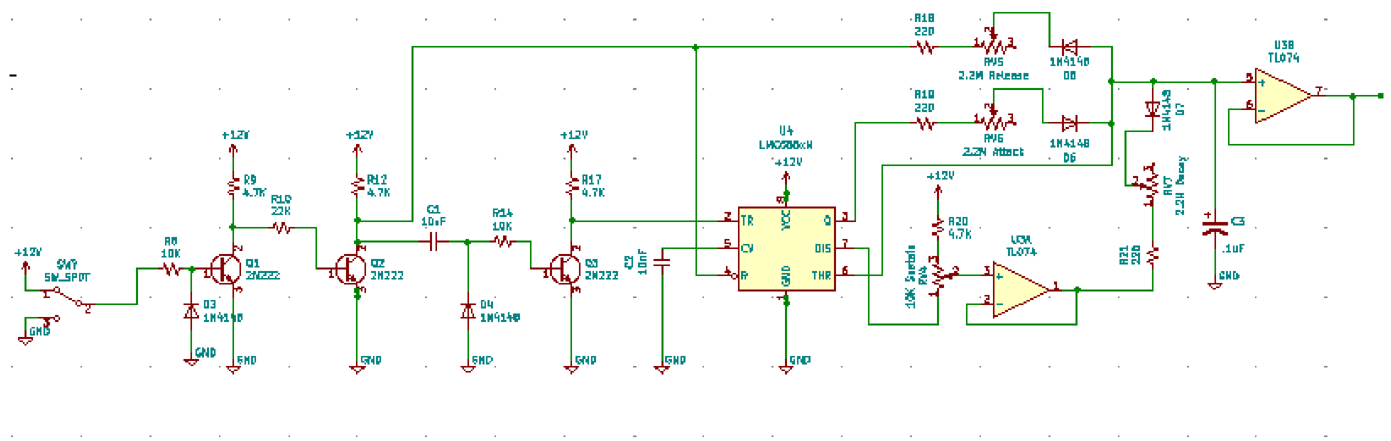


Fig. 19 - ADSR Envelope Generator Test Schematic

Results and Performance Analysis

<u>Voltage to Current Converters:</u>

Expected result from the voltage to current converters (only difference between source and sink is the direction of the current but the values should be the same):

Input Voltage (V)	Theoretical Current	Experimental Current
0 V	12 uA	12 uA
1 V	24 uA	24 uA
2 V	48 uA	48 uA
3 V	96 uA	96 uA
4 V	192 uA	192 uA
5 V	384 uA	384 uA
6 V	768 uA	768 uA

Fig. 20 - Table of Current values from Voltage to Current Converter on 1 Volt Scale

The source and sink operate really accurately because there is a 100 Ohm linear potentiometer that allows for the fine tuning. If an Ammeter is being held at the output then the desired current can be easily obtained by tuning the potentiometer.

<u>Voltage Controlled Oscillator:</u>

Expected Result from the Oscilloscope:

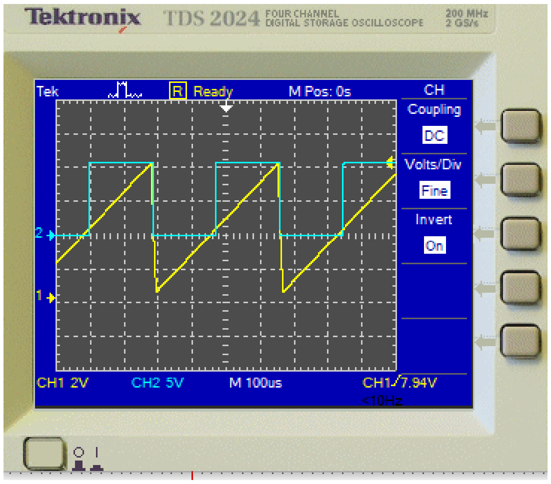


Fig. 21 - Simulation Result of Sawtooth and Square Wave output

The oscillator behaved correctly in real life. An important note on the oscillator is that since the sawtooth is generated off a time constant from the capacitor, this means there is a discharge rate for the capacitor. In figure 21 it is not noticeable since this shows a lower frequency but at higher frequencies the discharge rate will start to become noticeable. This means there will be some distortion in the higher frequencies of the sawtooth (Appendix C).

<u>Voltage Controlled Filter</u>

The low pass filter in the testing stage came out working correctly. One thing to note is that the type of OP-AMPS being used in the circuit will make quite a large difference because the output impedance can load the filter which will change how it behaves. This was noticed when not using the TL074, but instead the LM741 when connecting the oscillator to the filter.

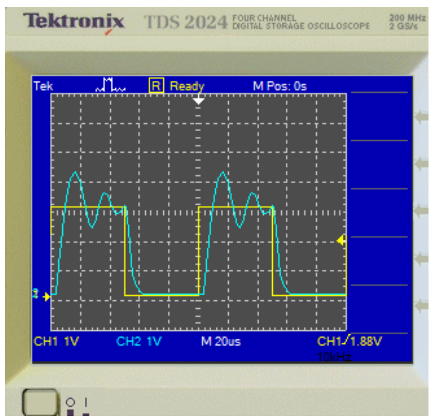


Fig. 22 - Simulation Result of Square Wave through Low Pass Filter with Some Resonance

<u>Voltage Controlled Amplifier:</u>

The VCA was tested by inputting a voltage signal and then measuring the RMS value through a voltmeter when adjusting the attenuation of the VCA. At first the device was not giving enough gain, but by switching out a resistor with another, proper full range from 0 to 24 peak to peak voltage was obtained.

<u>ADSR Envelope Generator:</u>

The way the ADSR envelope generator was tested was using it to drive the oscillator. By adjusting the potentiometers' values and capacitor of the ADSR, the oscillator would change its frequencies at different rates. This was able to show the ADSR was behaving properly as the way the frequencies would move up in pitch and then drop to a certain level and then finally go back towards its steady 0 Volt frequency showed the ADSR operated correctly. This is not the most 100% accurate way of seeing that it's behaving 100% properly, but in this case nothing was noticeably wrong that the human ear could notice.

Conclusion

There were many problems that came along the way in order to achieve the goal of this project. Some of the modules did not initially work and currently there are some things in the final product that need adjustment. The layout and schematic designs had some errors that caused the need for there to be some external wiring or modding of the PCB board. One example is that the +Vcc and -Vcc were mixed up on one IC which caused the need to do some wiring off board (Appendix C). This problem also occurred for the ADSR where the BJTS did not have the same pinout on the layout (Appendix F). Also, a few of the devices when put in the case ended up having some functionality problems. This occurs because there are many wires and no cable management which means the wires are most likely touching and creating connections when there should be none. One of the sawtooth oscillators for example is affected by the PWM adjustment of the square wave. This problem was not seen until the module was put in the case and is believed to be caused by some wires touching each other. Another problem seen when putting the module in the case is the VCF where for some reason things will stop working at certain moments or sometimes a potentiometer would affect the other VCF. These problems could be fixed with proper cable management, but overall, the modules can be seen as a success as things behave correctly for the most part. In conclusion, a modular synthesizer was achieved within our constraints, but some things need to be ironed out for it to always work properly.

Time Table

<u>Week 1 and 2</u>
Block Diagram on a lower level and determine circuits of a suitable type for the modules.
<u>Week 3 and 4</u>
Power supply design and Voltage to Current Exponential Converter
<u>Week 5,6 and 7</u>
Oscillator design, build power supply and test Voltage to Current Exponential Converter
<u>Week 8 and 9</u>
Design Filter and test oscillator
<u>Week 10</u>
Test Filter, build case to hold modules, and solder power supply onto a permanent board
<u>Week 11-12</u>
Choose design of ADSR envelope generator and test it
<u>Week 13</u>
Finalize Circuits and do layout for soldering (Voltage to current converter)
<u>Week 14</u>
Switch from doing by hand soldering of layouts to PCB design in KiCad and also doing cover panels in KiCad
<u>Week 15</u>
Solder on parts onto PCB designs and mount final modules into case
<u>Week 16</u>
Finish up soldering of PCBs/debug and Showcase

References

Power Supply

http://musicfromouterspace.com/analogsynth_new/WALLWARTSUPPLY/WALLWARTSUPPLY.php
https://www.youtube.com/watch?v=pQKN30Mzi2g

Synthesizer Modules

Textbook resources:

Musical Applications of Microprocessors (Hal Chamberlin) - chapter 6

Websites of Synthesizer Designs and Explanations::

https://www.schmitzbits.de/expo_tutorial/index.html

- ADSR design https://www.schmitzbits.de/adsr.html

http://ijfritz.byethost4.com/sy_over.htm

Georgia Tech Professor: - Aaron Lanterman Lectures:

VCA - https://www.youtube.com/watch?v=96j2tNKFCPI&t=202s
VCO - https://www.youtube.com/watch?v=qF4G4QfC9dM&t=699s
Exponential Voltage to Current - https://www.youtube.com/watch?v=ZWJhApUmfEU
Playlist of Lectures:
https://www.youtube.com/playlist?list=PLOunECWxELQS5bMdWo9VhmZtsCjhjYNcV

Musical Instrument Digital Interface

Youtuber - Benny Bones: https://github.com/BennyBones/midi2cv

Appendix

Appendix A: Power Supply

Description of Schematic:

This power supply features +12Volt, -12Volt, and ground. It is fed by a wall wart that steps it down from 120Vrms to 12Vrms. Diodes are placed in the circuit to make sure current flows a certain direction to obtain the proper polarity. Capacitors provide stability for the voltage regulators for when the load changes. The diodes that hang in parallel with the voltage regulators act as safety nets in case there is a short. The power supply also includes the ability to output +5V but this is currently not being used in any of the circuits therefore was not included in the schematic.

Appendix B: Information Regarding the Voltage to Current Converter

Description of Schematic (Source Version):

In order to maximize usage, this circuit consists of two voltage to current converters because the IC (320P14-U) consists of two differential PNP BJTS. Three control voltages can be fed into each voltage to current converter.They will be mixed through an active mixing circuit. A Vcc (+12V) also feeds into a voltage divider (potentiometer) at the mixing circuit so that a CV is not needed to adjust the VCA, and VCF. Potentiometers are used in the mixing circuit to make CV's stronger/weaker than others. From here a voltage to current conversion is done by using a BJT differential pair (320P14-U) that has an op-amp at the emitters. The op-amp at the emitter acts as a current source for the current needed for the voltage to current conversion. In order to account for any heat or temperature drifts, a tempco resistor is used (R2 & R17). The output current is then taken from the emitter of Q2 in the BJT differential pair.

Dealing with temperature drifts so 1 Volt/Octave is stable:

A tempco resistor is used to help with temperature deviations that would arise as the circuit operates for longer periods of time. This is necessary because temperature drifts could cause the current to not double for each volt. This could be noticeable to a trained ear (musician) when they do not hear an octave for each volt, but it is slightly out of tune. Another thing done to help with temperature drifts is using matched transistors in the BJT differential pair. The THAT300 and THAT320 IC chip provides two matched BJTs.

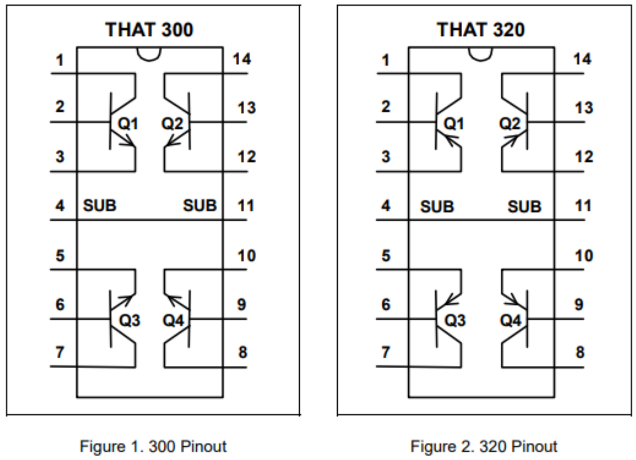


Fig. 23 - THAT300 & THAT320 IC Schematic

Why this design for the voltage to current converter?

There are many designs for a voltage to current converter. The importance of this design is that it is an exponential voltage to current converter. Humans do hear pitch (harmonic frequencies) linearly, but exponentially. A synthesizer in this case is meant for audio/musical purposes. This means it is important that it functions properly for the user and feels natural.

The voltage to current converters connect to which modules?

The oscillator uses the current sink version, while the VCF and VCA use a current source version. While the VCA can use a current sink version, this would require adjustment in feeding the signal into the opposite terminal.

Appendix C: Voltage Controlled Oscillator

Description of Schematic:

This circuit consists of a sawtooth and square wave. The square wave is generated from the sawtooth. In order to generate a sawtooth an OP-AMP integrator circuit (U4A) is used. The way this works is integrating a constant will cause a slope. This will produce the ramp of the sawtooth. Next the capacitor in the integrator (C5) needs to be discharged. This is done with the MOSFET acting as a switch. What controls the MOSFET is a comparator that has a reference voltage from a 8 Volt regulator. When the capacitor reaches 8 Volts, the Comparator will turn on the Mosfet and discharge the capacitor. There is some feedback in the Comparator to create some hysteresis to allow for the capacitor to discharge fully. A square wave is created by taking the sawtooth and using a comparator. The PWM can be controlled by comparing the sawtooth to a different voltage for the square wave. The comparison voltage can be controlled by a potentiometer setup to variate between +8V and -8V or feeding a CV that can be mixed with this potentiometer voltage. The sawtooth and square wave outputs are then fed into a high pass filter set at cutoff of around 10Hz to remove any DC voltage but keep the audible frequencies.

Irregularities/Distortion in the Sawtooth:

The sawtooth ramp charges up through a capacitor and discharges through the MOSFET. The mosfet will have some resistance, meaning there is a discharge rate for the capacitor. At lower frequencies the sawtooth looks nearly perfect because the ramp is much slower than the discharge rate therefore it looks like the capacitor discharges instantly, forming an instant drop. At higher frequencies though, the ramp catches up to the discharge, showing how the sawtooth is not ideal. This can cause problems because the waveform is moving more towards a triangle wave, and this will cause the square wave to no longer act properly as it requires a sawtooth.

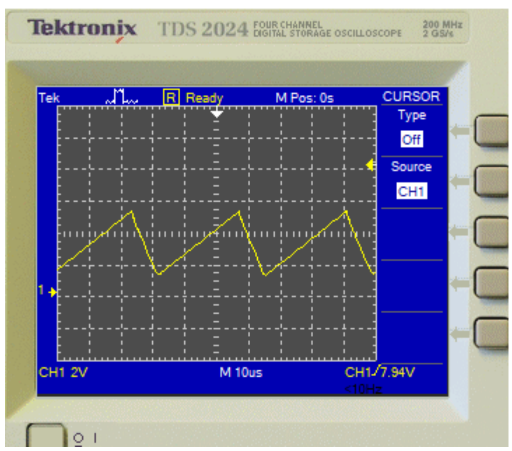


Fig. 24 - Showcasing the distortion/error occurring at higher frequencies

PWM Operation of Square Wave:

A 0 to +8 Voltage sawtooth is generated. This is fed into a comparator which has a reference value that it compares too. This reference value allows for the PWM value to be chosen as a positive voltage will only be generated when the sawtooth wave is greater than the reference voltage. A reference voltage of 0 Volts will produce a PWM of 50% while it goes towards 0% from 0 to -8 Volts. A duty cycle of 50% to 100% will be generated from a reference voltage of 0 to +8 Volts. This is the purpose of having a +8Volt regulator and a -8Volt regulator as it allows the user to go from 0 to 100% duty cycle of the PWM.

Errors in the Layout of the PCB:

This circuit contains a significant error where the +Vcc and -Vcc for a chip are flipped. This means the negative power supply goes to +Vcc and the positive power supply goes to -Vcc. This can be fixed by modding the board so that the IC's float above the PCB and are hand wired and not directly go through the holes of the PCB.

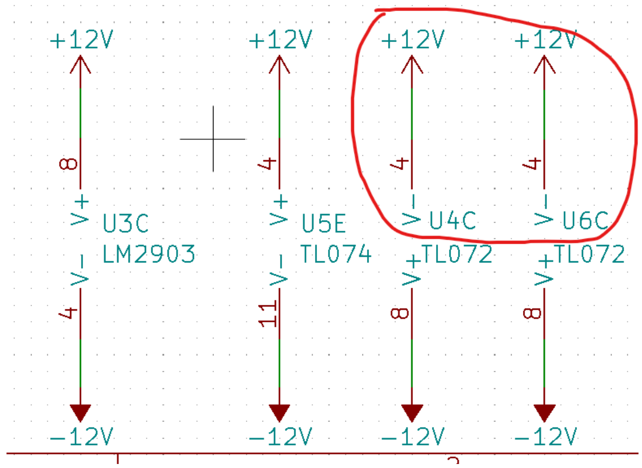


Fig. 25 - Error in PCB design of VCO

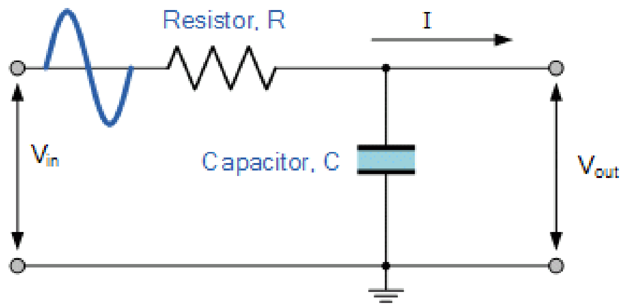
Appendix D: Voltage Controlled Filter

Description of Schematic:

This is a second order low pass filter. The design is of the Sallen Key topology. There are three inputs so that multiple signals can be mixed and then fed into the filter. In order to make this current controlled (Voltages converted to Currents) operational transconductance amplifiers (OTA's) are used. This is what IC1 is - two OTA's. In a sallen key filter there are resistors that control the cutoff of the filter. By switching the resistors with the OTA's, cutoff can be controlled now with the OTA's through a bias current. There are resistors between the inputs of each OTA that act as voltage signal dividers. This is meant to keep the signal small because the OTA's only operate correctly under small signal conditions (less than 0.2V). Resonance can be controlled through a potentiometer that is in the feedback of the filter. There is a mistake in this schematic that had to be changed in the final design. This circuit should be controlled by the same current that is divided by two resistors of the same value and then fed into each OTA. Basically J4 (two pin header) should be a single pin header that takes in one current and is then divided equally through two resistors of the same value.

How an Operation Transconductance Amplifier (OTA) is used:

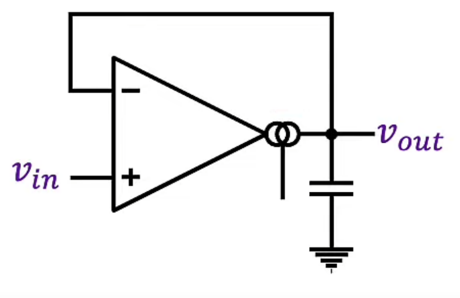
Using a Basic low pass RC filter seen below:



$$f_c = \frac{1}{2\pi RC}$$

Fig. 26 - Basic Low Pass RC filter

The resistor can be replaced with an OTA to form:



$$f_c = \frac{g_m}{2\pi C} = \frac{19.2 i_{abc}}{2\pi C}$$

Fig. 27 - OTA replacing resistor in RC filter

By inputting a bias current (i_{abc}) the cutoff can be changed. This applies for higher order filters and other topologies.

Errors in the Layout of the PCB:

The VCF had an error in the KiCad design that revolved around bias current coming from the voltage to current converter. The design is supposed to have one current fed into it for controlling both OTA's. Looking at the image below it shows a single VCF but two current inputs. What is supposed to occur is one current being inputted, but being split equally through two resistors.

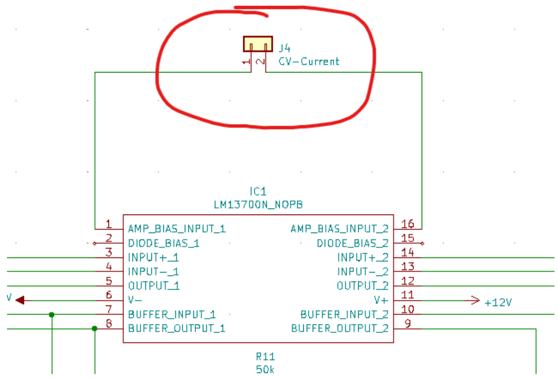


Fig. 28 - Error in Design of VCF

The fix for this was not too difficult. Two same value resistors were connected to each header and have their other ends tied together and the current fed into it. This would split the current equally and have the circuit operate properly.

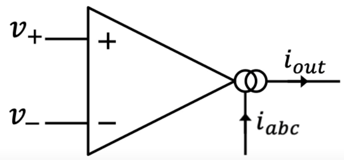
Appendix E: Voltage Controlled Amplifier

Description of Schematic:

This circuit consists of two VCA's. The left is one VCA and the right is a second VCA. Each VCA accepts two input signals that will be mixed and then fed into an OTA. There are voltage dividers before each OTA two step down the incoming signal and make sure it operates within the proper conditions of the OTA. From here the gain of the signal will be controlled by an incoming bias current from J1 (two pin header). There are two currents, each controls one of the amplifiers. A current is then outputted by the OTA. Since we want a voltage signal, a resistor is placed at the output of the OTA to generate the input signal attenuated. The output signal can have a max range of 24 volts (-12V to +12V). There is an output amplifier with an op-amp and potentiometer for any further attenuation wanted from the user.

Function of the Operational Transconductance Amplifier (OTA):

The operation of the OTA can be seen below in the figure. It acts very similar to a regular OP-AMP but uses a bias current to control its amplification. While a current is outputted, a resistor can be placed at the output to create a voltage.



$$i_{out} = g_m(v_+ - v_-)$$

$$= \frac{i_{abc}}{2V_T}(v_+ - v_-)$$

$$= (19.2/V)\, i_{abc}(v_+ - v_-)$$

Fig. 29 - OTA and basic operation equations

Important notes about using an OTA is that an OTA usually can only handle around a max of 2mA for its bias current, and it requires small signal inputs at its input terminals in order to act properly. This is important since it will affect the design if resistances are not placed to shrink the signal.

Appendix F: ADSR Envelope Generator

ADSR Envelope Understanding:

The purpose of an ADSR envelope generator is to generate voltages/signals that can control the modules. The modules are voltage controlled therefore having a device that can produce voltages allow for capabilities that cannot be as easily obtained. The attack stands for how fast the signal rises to its peak. The decay is how long it takes to reach the sustain voltage. Sustain is the voltage the signal will be held at until there is no longer a trigger being held. Release is the final decay of the signal to 0 volts. This image below can be compared to a piano key where the key being pressed is the trigger which will cause the signal to rise and then decay, and while the key is being held there will be amplitude the sound is held at until the key is finally released where the sound will approach zero.

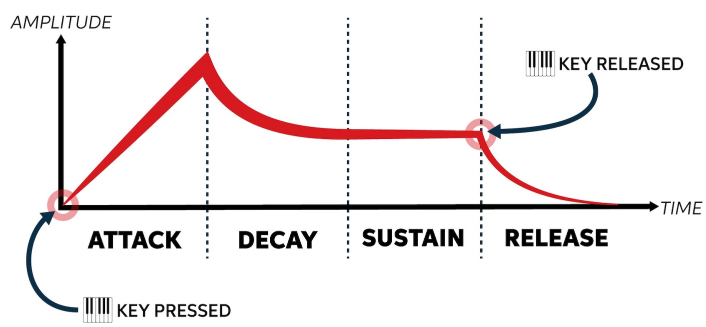


Fig. 30 - ADSR Envelope Graph

Description of Schematic:

The ADSR uses a 555 timer and time constants with resistors/potentiometers and capacitors to create the attack, delay, sustain, and release of an ADSR envelope. RC time constants with a variable resistor (potentiometer) can control how fast a voltage signal charges up (attack), how fast it discharges (delay), and then with an OP-AMP and potentiometer the voltage can be held (sustain) and finally the 555 timer is setup so that when there is no longer an input the voltage signal completely goes to zero (release). The first stage of transistors going into the 555 timer acts as an impulse generator for the 555 timer to trigger it. There is a gain stage ahead of the 555 timer to make sure if a voltage signal is inputted, it is large enough to trigger the BJT's. The huge line of capacitors allow for a range of selections for the user. If the user wants a really slow time constant that can't be achieved with the potentiometer, a higher value capacitor can be selected through the switch. If the user wants a much faster time constant then a small capacitor can be selected. The output stages incorporate the normal ADSR signal and an inverted ADSR signal. There are LED's for the user to see if an output is coming out and an input is coming in.

Function of the switches for selecting Capacitors:

The capacitor and the potentiometers determine the charge and discharge rate of the signal being generated. Having a wide range of capacitors allows for a greater usage as the user will not be as limited.

Errors in the Layout of the PCB:

There is an error in the PCB design of the schematic. The error is not too big, but was difficult to find initially. The footprint of the BJT's in the schematic do not match the pin layout of the actual transistor in real life. This requires making sure the pins are connected properly because the footprint does not match the transistor in real life. See the figures below for comparison

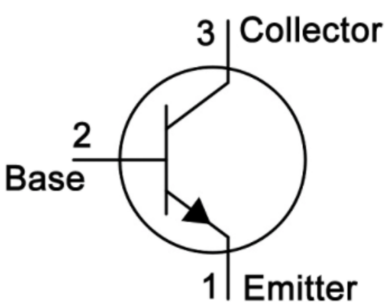


Fig. 31 - Real life Pinout

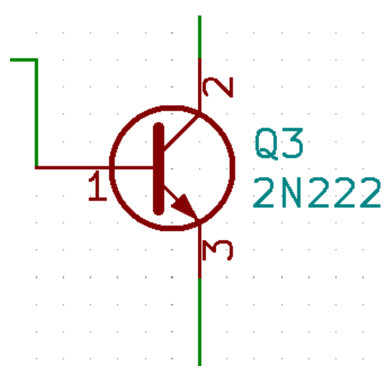


Fig. 32 - Schematic Pinout

Appendix G: MIDI Instrument

What is a MIDI Instrument?

MIDI stands for Musical Instrument Digital Interface. This device allows for a digital signal (pulses) to be converted to analog voltage signals through a digital to analog converter (DAC) which can then be fed into any module. The importance of this device is that it allows for a digital interface to send control voltages to the modules in the synthesizer. A computer has a lot of tools for controlling a synthesizer and a MIDI instrument makes full use of it.

Design and Resources:

This is the only device we did not design because of time constraints. The current MIDI instrument is a modified version of *Elkayem's midi2cv* design done by a youtuber named "Benny Bones." In references, the github repository that provides the gerber files and code to run the MIDI is provided.

Appendix H: Cover Panels

Design of Panels:

The design of the panels were initially planned to be done by hand on aluminum sheet metal. Due to seeing other synthesizer creators use PCB materials and design tools to create the panels, the decision to switch to this method was made. Each of the panels were carefully done in KiCad. Precise measurements were made of jacks for audio cables and the potentiometers. Even with these measurements, some of the drill holes were a bit small and needed to be expanded upon arrival.

Example of Measurements Made:

Holes had to be placed in correct positions so the potentiometers did not interfere with each other on the back side of the panel.

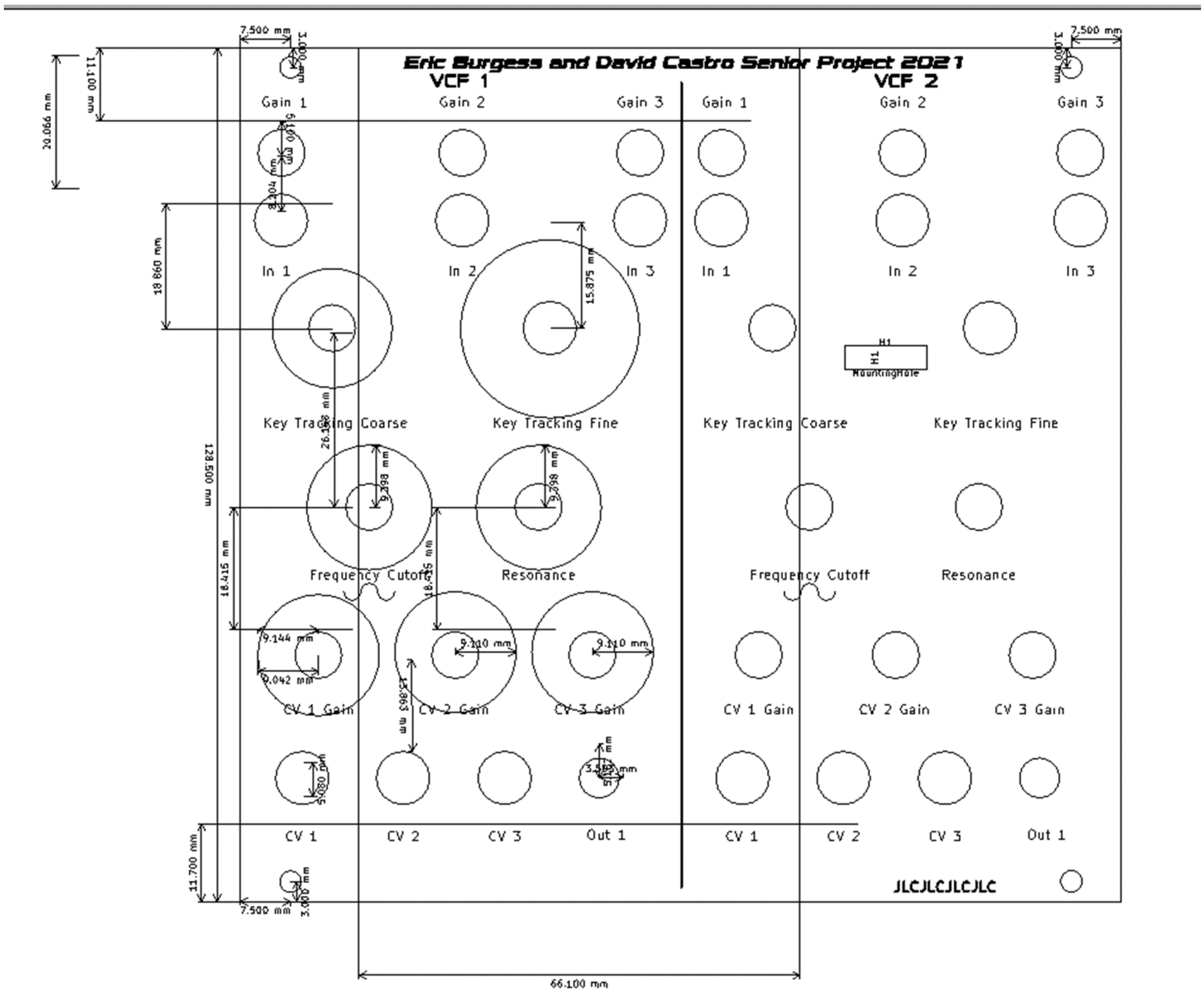


Fig. 33 - VCO cover panel with measurements

Panel Designs:

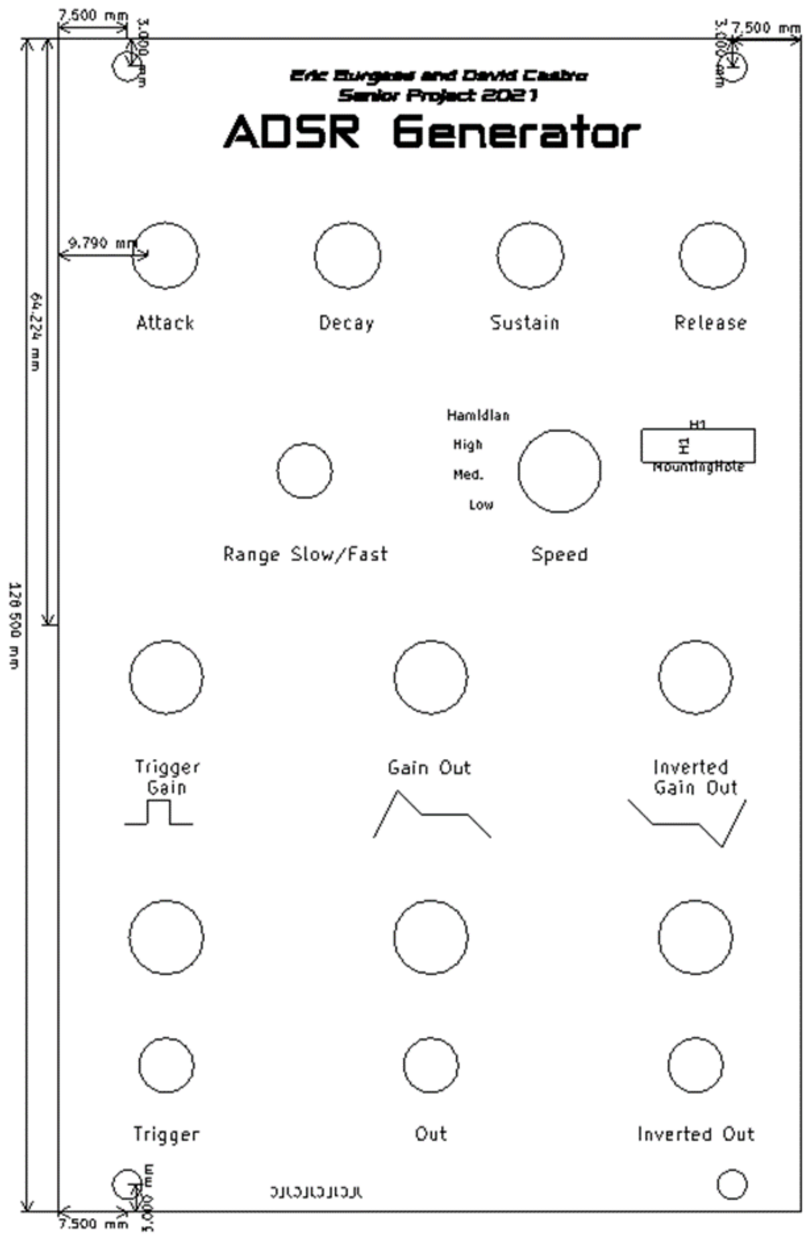


Fig. 34 - ADSR Front Panel

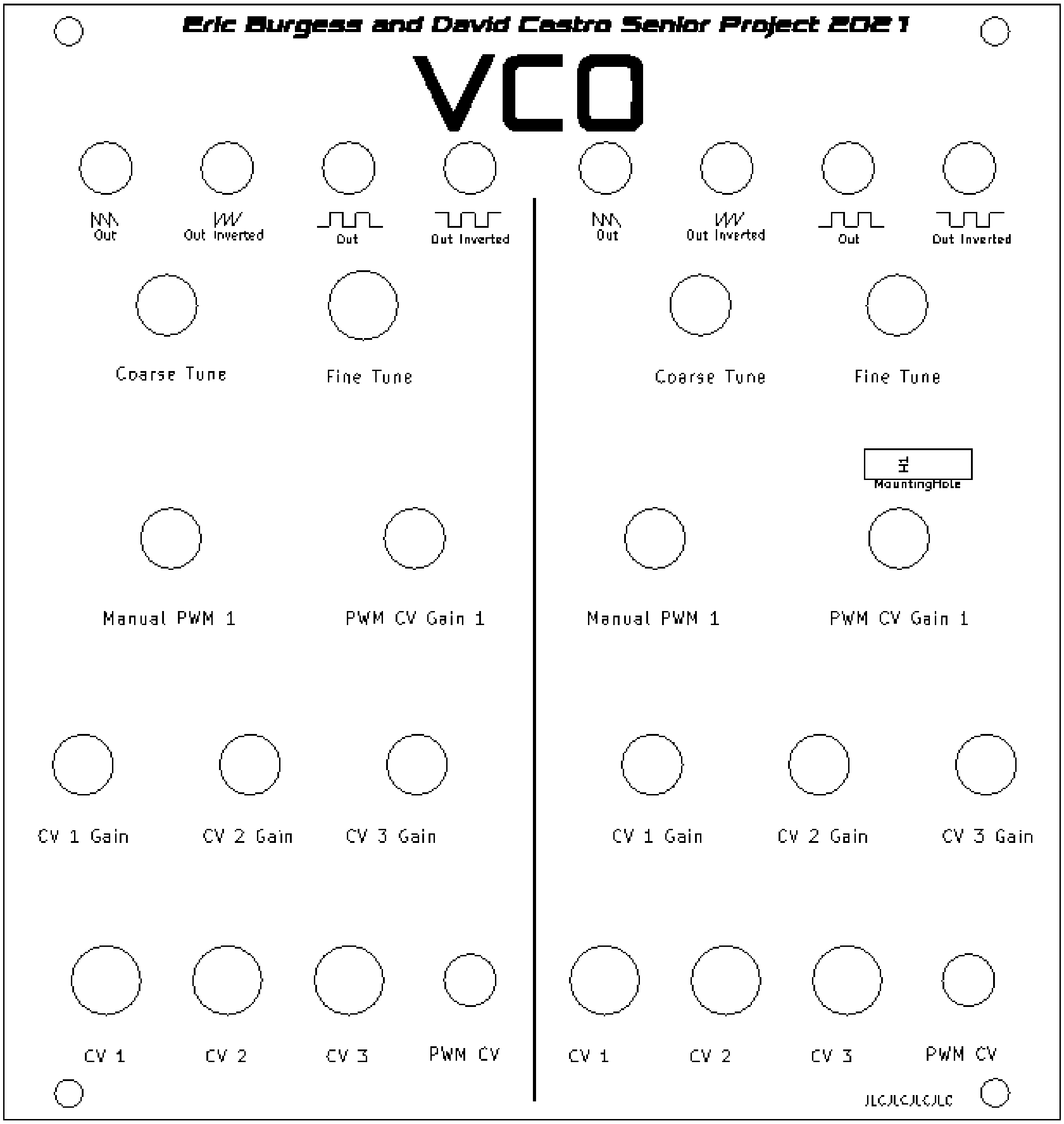


Fig. 35 - VCO Front Panel

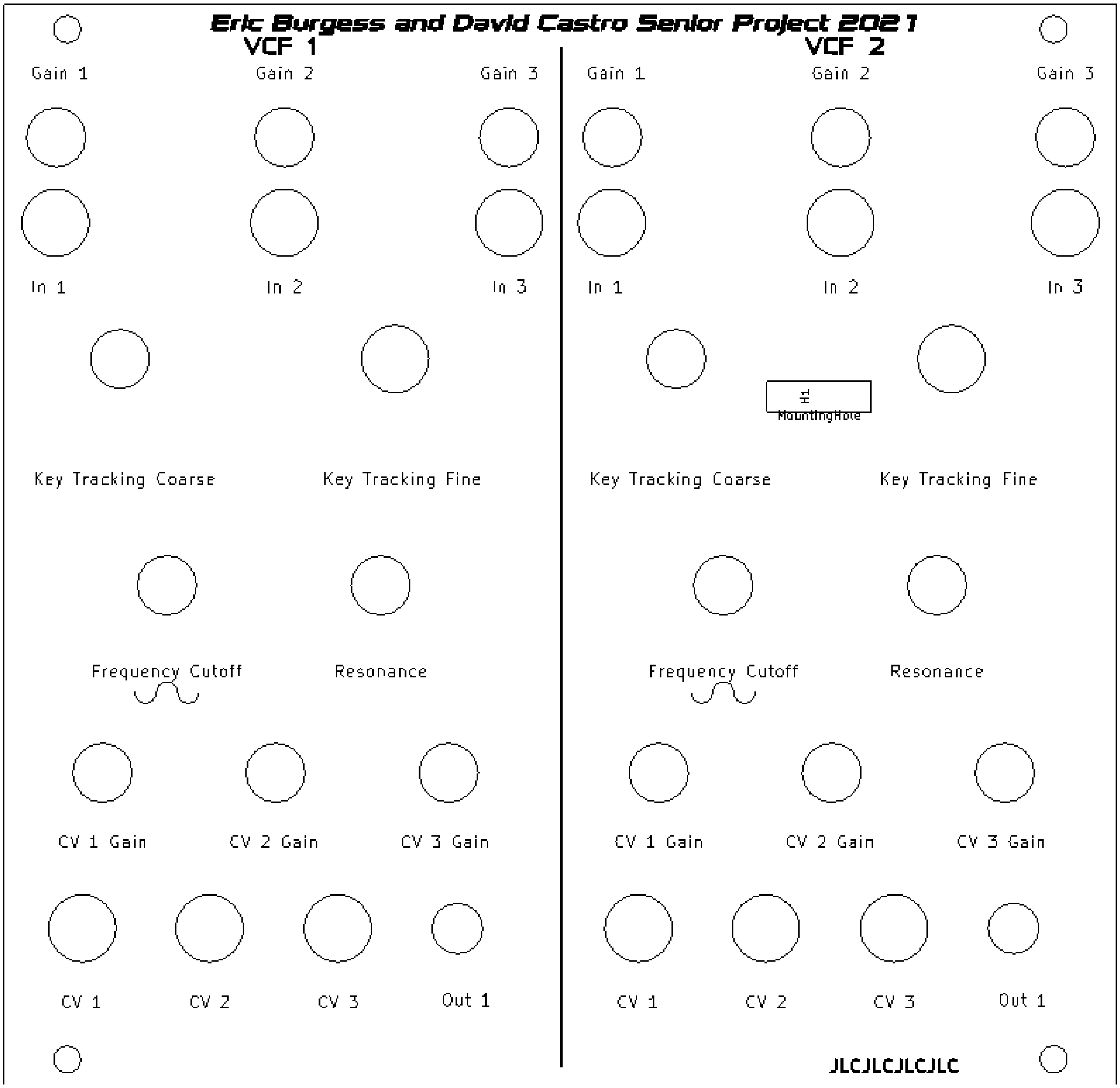


Fig. 36 - VCF Front Panel

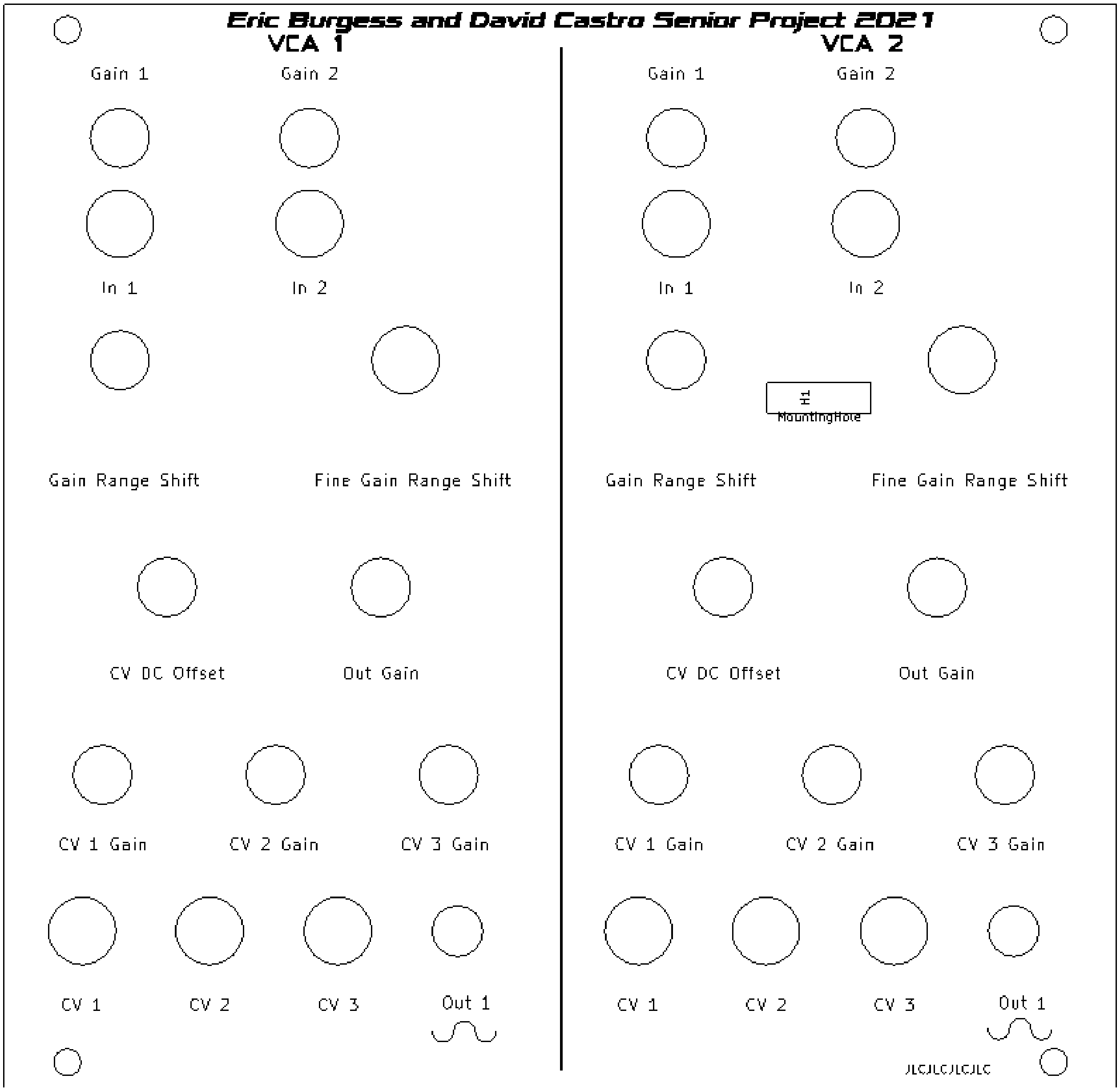


Fig. 37 - VCA Front Panel

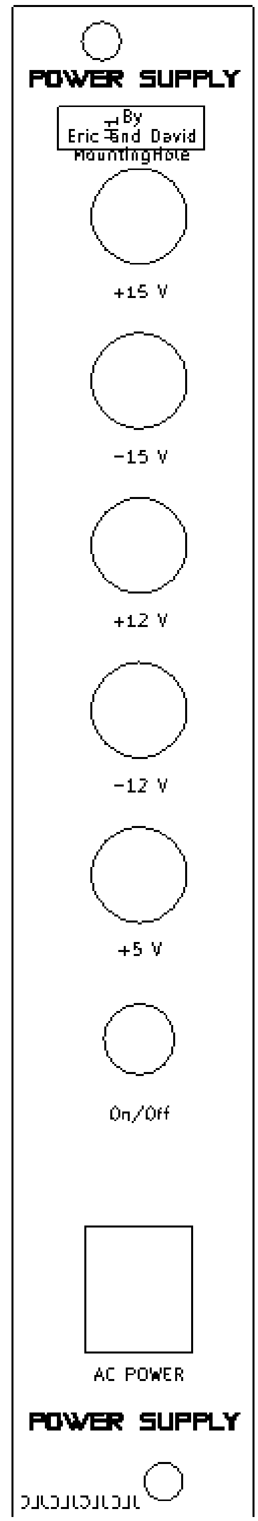


Fig. 38 - Power Supply Panel

Appendix I:Final Product

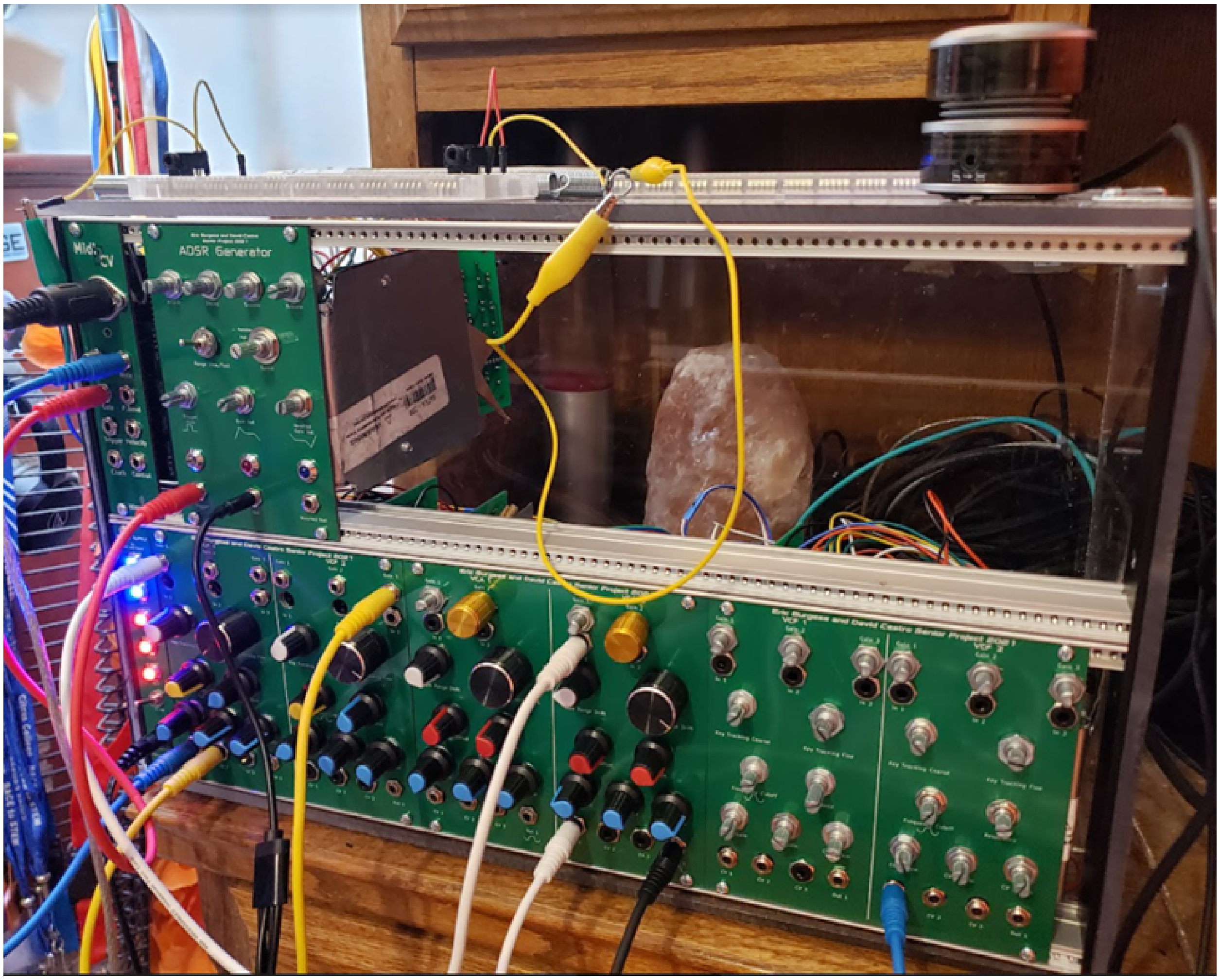


Fig. 39 - Completed Modular Synthesizer

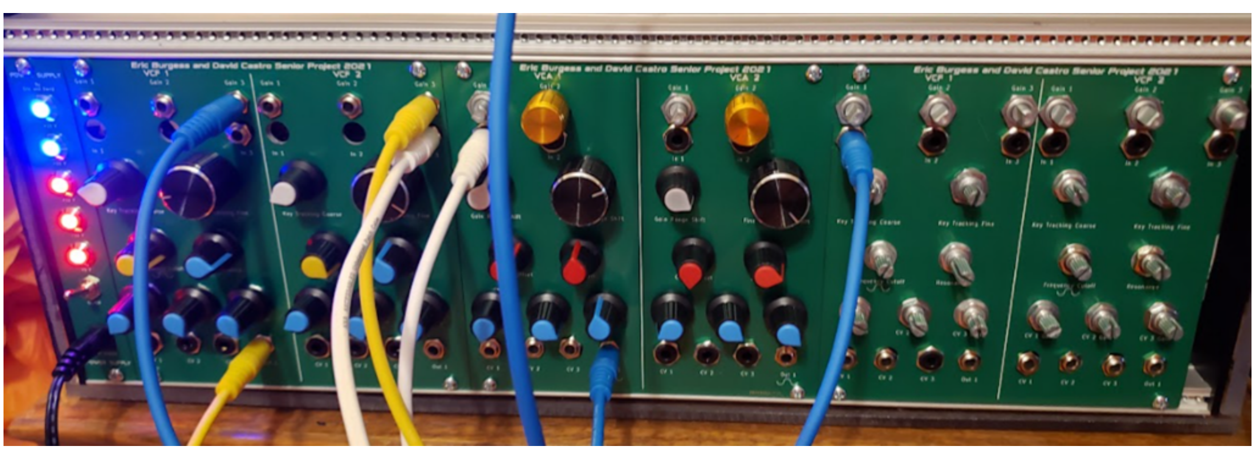


Fig. 40 - Bottom Portion of Modular Synthesizer

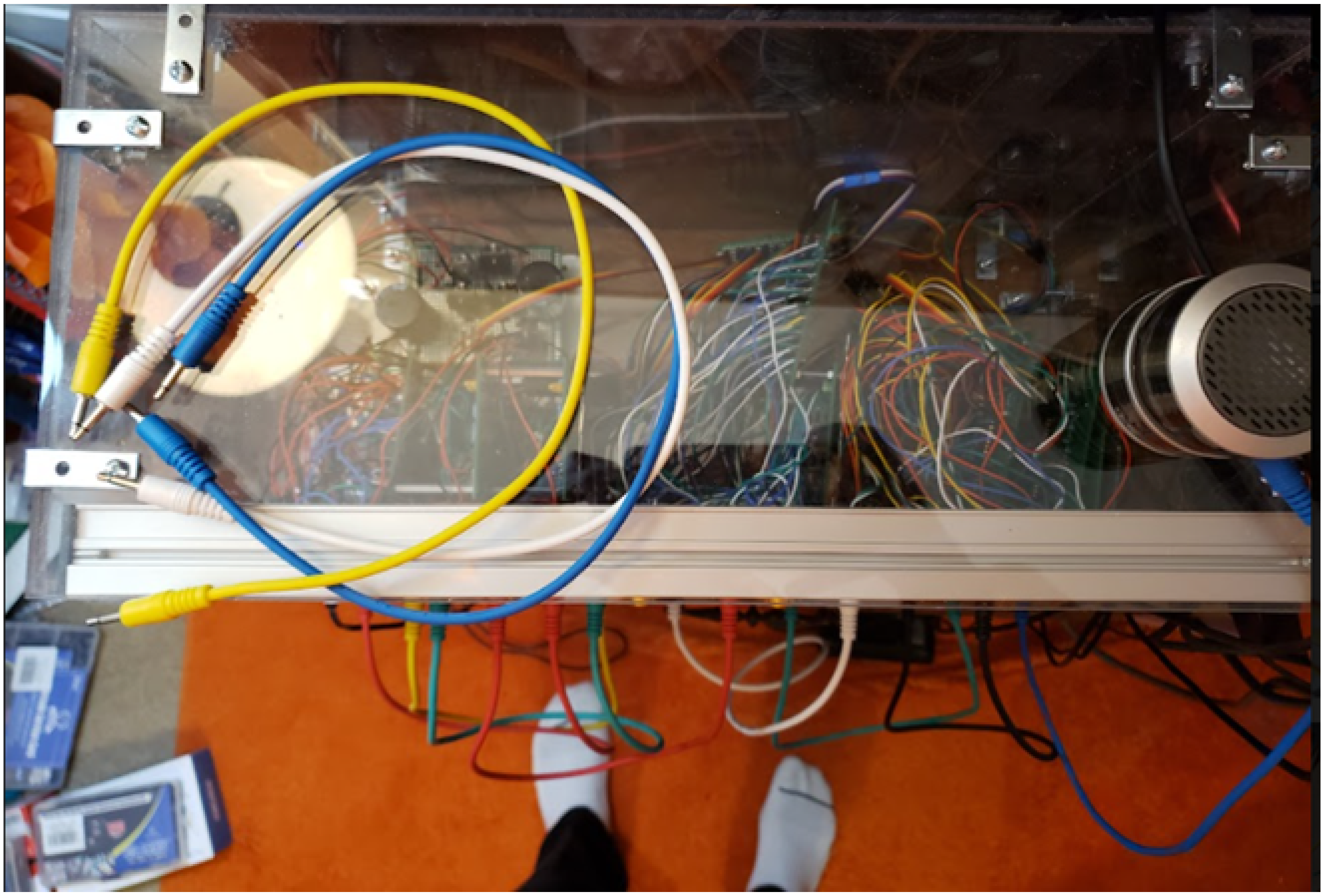


Fig. 41 - Inside Cable Management of the Synthesizer

The modular synthesizer overall was a success. The only problem was the VCF and the sawtooth output for one of the VCO's. Cable management was <u>not</u> done within the synthesizer for each module, and when putting the modules within the case it caused some weird behaviors. It is believed this is causing the problems for the VCF and VCO, since some of the wires are touching and creating connections when there should be none. This can be easily fixed by pulling out the modules and rewiring them in a clean manner.