Capacitive Touch Sensing Tone Generator

Corey Cleveland and Eric Ponce

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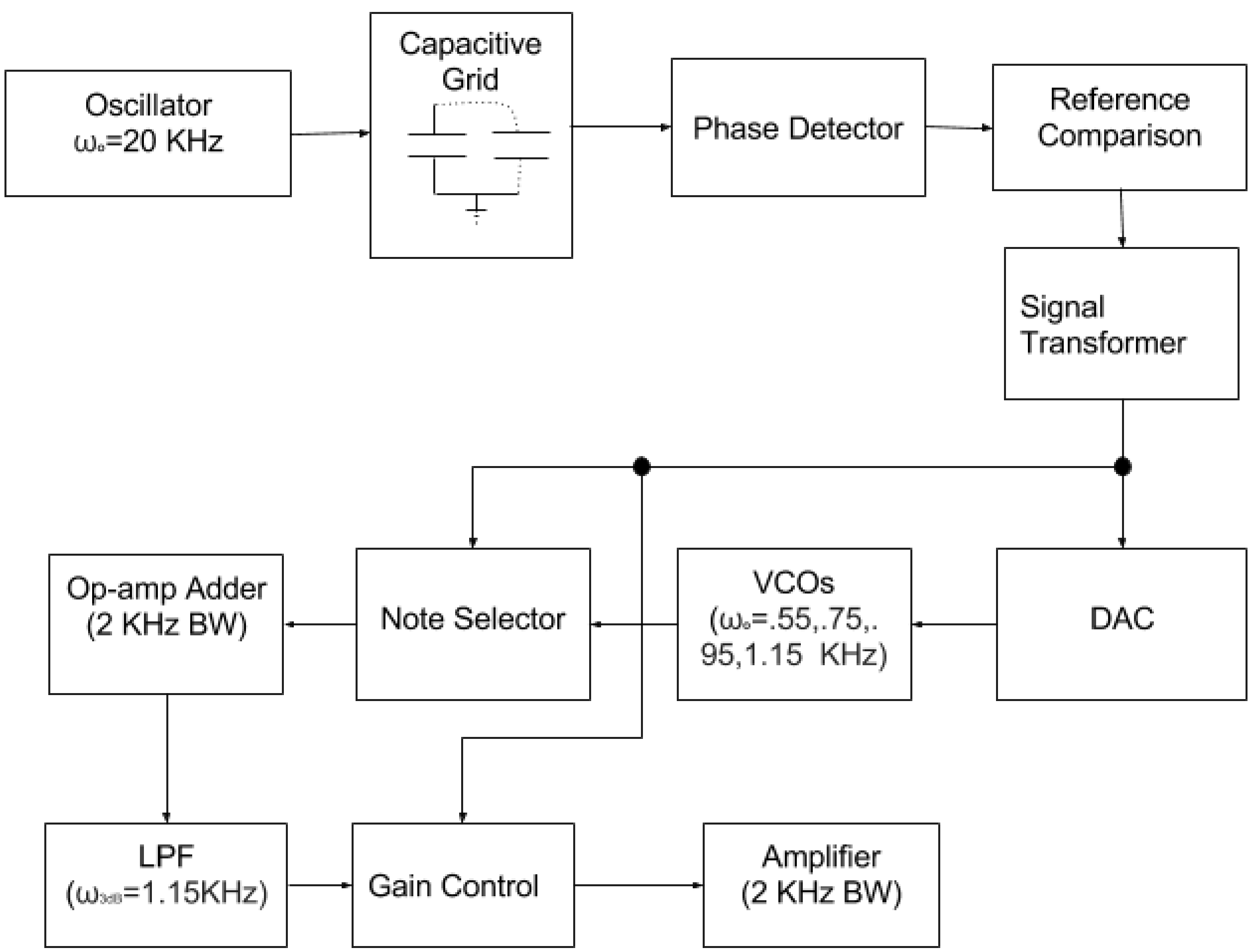
Introduction

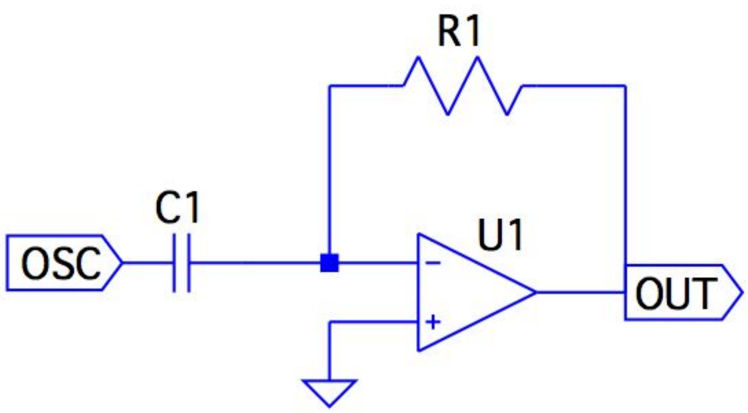
Capacitance is defined as the ability for an object to store charge. All objects have this ability, to some degree, and it turns out the human body has just enough capacitance to be detected. The project leverages this human capacitance to detect a finger press and then uses that information to generate audible tones. Generally capacitive touch is accomplished through a combination of analog circuitry and heavy digital signal processing, our approach should eliminate the second step with a minimal loss of functionality. As the user presses a given x-y point on a copper grid, a collection of voltage controlled oscillators (VCO) will generate frequencies in the audible range that will then be combined and output through a speaker. Columns will activate individual VCOs and the rows will modulate frequency around the VCO base frequency. A set of pads also activate toggle circuits that allow for volume adjustment. The output of the toggle circuits is input to the gain control. The body diagram below shows some of the major components of our proposed project.



Capacitive Sensing Overview

(Eric Ponce)

As a human finger approaches the capacitive grid, it adds capacitance to ground on the order of 30pF. The original design for capacitive sensing was to measure RC time constants of an RC circuit. This would involve carefully timed charge/discharge circuits. This design was quickly abandoned when there was difficulty controlling the timing at that scale (on the order of microseconds). This scheme was replaced with a scheme that involved a differentiator, as shown below. This scheme relied on the transfer function of the circuit being H(s) = R1*C1*s. The problem with this circuit, however, was that the capacitive increase occurring from a human press was much too small. The majority of capacitance that humans couple is to ground. So the capacitance put in parallel with the nominal pad capacitance was the series combination of the human capacitance and the capacitance between the copper-clad side of the board and ground, which is very small.

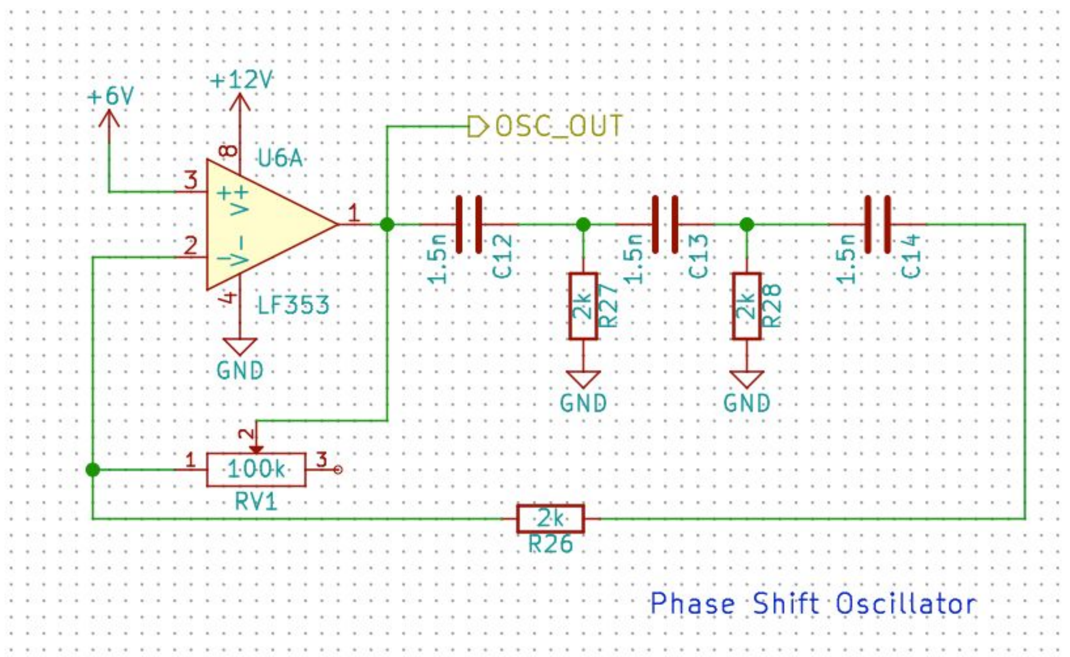


The final scheme developed was RC phase shift detection. Low pass RC filters provide attenuation in the magnitude of the input waveform but, more importantly, they also cause a phase shift in the output waveform. As the capacitance changes, the properties of the RC filter change and so the phase difference will change. The sensing circuitry detects this by using a phase detector to generate an analog DC voltage as a function of phase difference between the output and input waveforms. With this DC voltage, one is able to use a simple comparator threshold detector to generate an 'on'-'off' signal that corresponds to finger pressed. With the scheme, it was also possible to tie one end of the capacitor to ground, maximizing the amount of capacitance coupled in when a human finger touched the grid.

Reference Oscillator

(Eric Ponce)

The reference oscillator is used in the capacitive sensing circuit to provide a sinusoidal waveform that is input to the RC filters. This oscillator is then used in the phase detector to generate a DC voltage corresponding to phase difference. A phase shift oscillator implementation as shown below was chosen for this project. A oscillation frequency of 20KHz was chosen because it is low enough to be easily manipulated with LF353 op amps (they have a 5 Mhz gain bandwidth product), but high enough to fall outside the audible range and be easily filtered out.

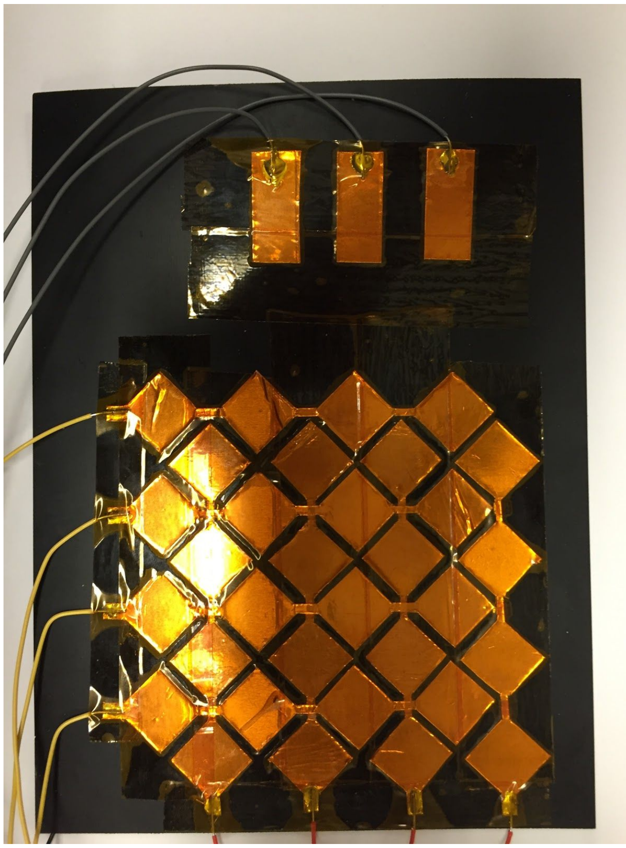


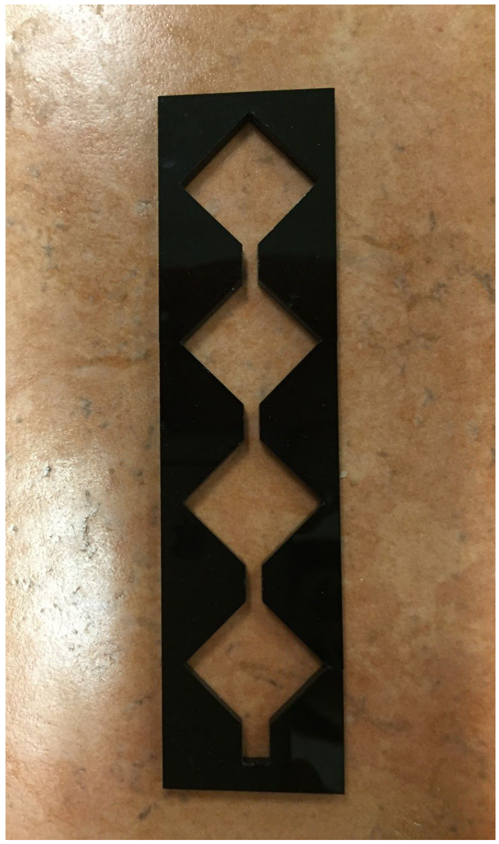
Capacitive Grid

(Eric Ponce)

The capacitive grid was constructed using a single-sided copper-clad board and copper tape. The copper tape rows and columns were cut into a cascading diamond shape, chosen to limit mutual capacitance while maximizing surface area, using a laser-cut acrylic template. Using the template allowed the rows and columns to have the same surface area, and therefore roughly the same nominal capacitance to ground. The volume pads were similarly cut using a template. To isolate the capacitive plate from the user, the grid and pads were covered in Kapton Tape, a thin, transparent, and electrically insulating material.

A capacitance meter was used to measure the various capacitances. The rows and columns measured in at 66 pF ± 4 pF and the volume pads measured in at 30 pF ± 2 pF. These capacitances were deemed reasonable for detecting a ~30 pF capacitance change from the user's finger.

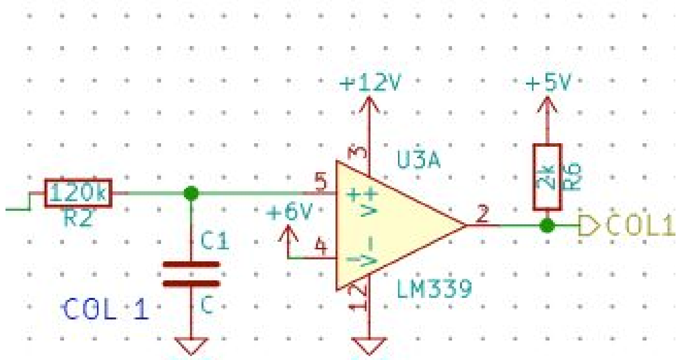




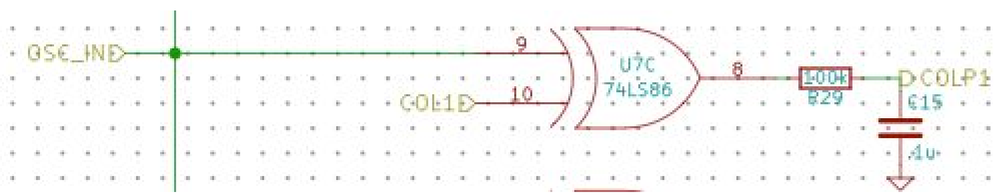
Phase Detector

(Eric Ponce)

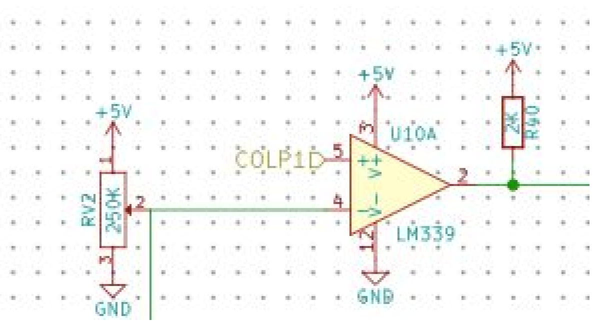
The various rows, columns, and pads are used in a RC filter. The output of the filter is an attenuated and phase shifted version of the reference oscillator. Since phase is the only necessary measurement, the input and output signals are converted to square waves using comparators with the inverting input tied to VCC/2, as shown below.



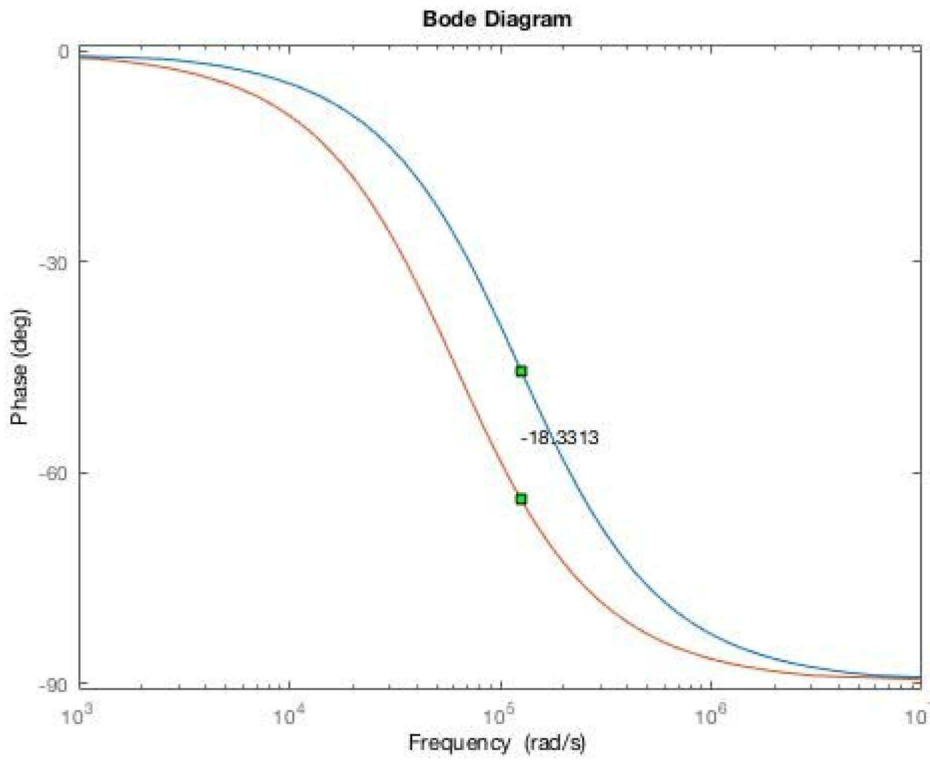
These square waves are then logically XORed to produce a square wave with a duty cycle corresponding to the phase difference between the signals. Low passing this XORed signal generates a DC voltage related to phase difference, and therefore measure capacitance. The low pass filter is a simple RC filter as the frequency for changing finger presses is much lower than the 20 KHz reference oscillator frequency.



The DC voltages are compared to threshold voltages set by potentiometers (for easy tuning) using comparators. The potentiometer is tied to the inverting input so that the output is nominally low. Because of the careful grid construction, certain pads had a close enough nominal capacitance that not every pad needed its own tuning potentiometer. The final design used a total of 5 potentiometers for 11 different capacitive pads (4 rows, 4 columns, 3 volume pads).



Resistor for the phase shifting filter (containing the capacitive pad) were chosen so that the -3dB point lied at 20 KHz. The -3 dB point of a low pass filter is also the point at which the output phase difference is -45 degrees and the slope of the phase curve is at its maximum, maximizing the phase difference between pressed and not pressed states. Shown below, is bode plot demonstrating the estimated difference in phase between a press and no press on one of the toggle button. This estimated difference was reasonably close to the actual results.



The graph shows that the phase difference between the nominal capacitance (blue) and the capacitance in the presence of a finger (orange) is 18 degrees. This phase difference produces a duty cycle difference on the output of the XOR gate of $\frac{phase}{90} * \frac{1}{2} = 0.1$ and an analog voltage difference of 500 mV after being low-passed. This can be easily detected.

The circuits shown below is replicated for every row, column, and volume pad. The LM339 comparator was chosen for its quad comparator package. The XOR gate used is a standard 74LS86 quad-xor gate IC. The output of the xor gate is low pass filtered to create a DC voltage.

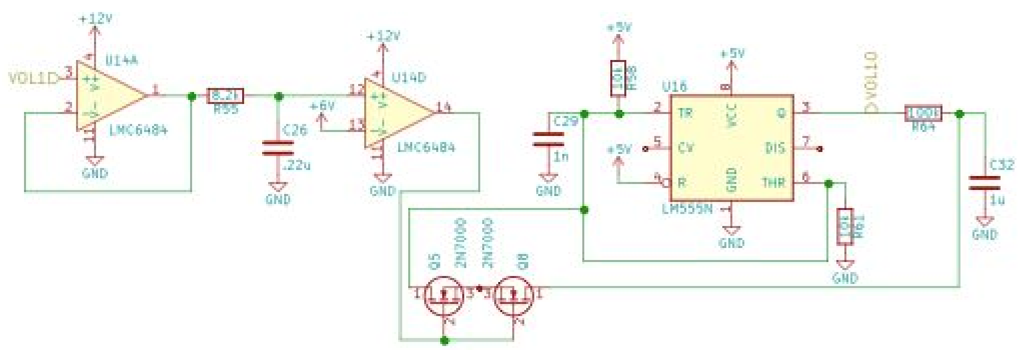
Signal Transformer

(Eric Ponce)

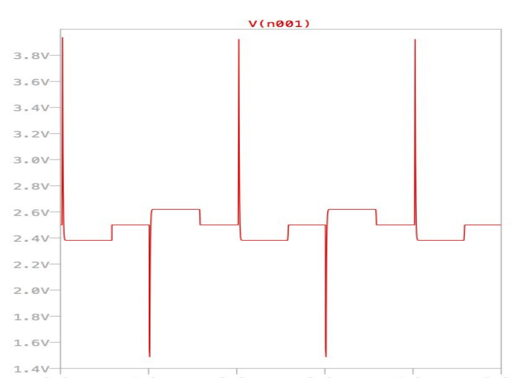
The purpose of the signal transformer module is to perform the necessary transformations on the 0-5 V ‘on’-’off’ signal from the threshold comparators so that they are compatible with the note generation half of the circuit. The column outputs must be inverted, the row outputs must be buffered, and the volume pad outputs need to pass through a toggle circuit.

The column outputs are simply passed into a 2N7000 MOSFET inverter, since 5V is higher than the MOSFETs threshold voltage. They are inverted because the note selector uses NMOS transistors for blocking the VCO outputs. The row outputs are passed through LMC6484 opamp buffers. The LMC6484 was chosen because of its quad op-amp package and because the opamps are rail to rail, allowing the use of a single-sided 5V rail. They need to be buffered because the output of the comparator is open collector and requires a pullup resistor, which would conflict with the DAC.

The toggle circuit allows the user to press and release the volume pads, rather than hold them down for different volumes. The toggle circuit takes advantage of the 555 timer's internal state flip-flops. The threshold and trigger pins are tied together and to vcc/2. Then the output, tied to a resistor and capacitor network, is tied to the threshold/trigger pins at its capacitor with a bidirectional MOSFET switch. When the input voltage rises to 12V, the bidirectional switch connects the capacitor to the pins, causing a momentary voltage spike that switches the output voltage of the 555 timer. Because of the threshold detection scheme, transitions involve 20 KHz pulsing so the input is filtered, with an RC filter, and converted to 0-12V, using an opamp as a low speed comparator, before the MOSFET switch. The toggle circuit is shown below.



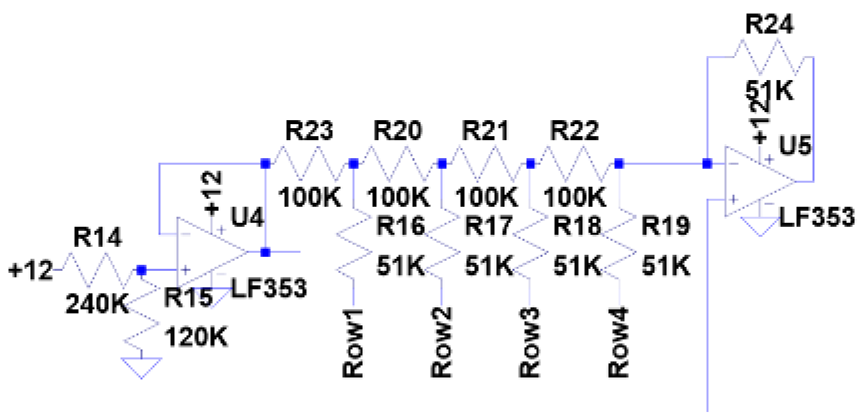
A simulated waveform of the the threshold/trigger pins is shown below. When the input goes high, the pins experience a momentary negative or positive pulse cause the output to change state.



Digital to Analog Converter

(Corey Cleveland)

The digital to analog converter(DAC) is used to transform the high/low outputs of the rows from the signal transformer into a control voltage for the voltage controlled oscillators. Each row input can be represented as a single bit in a four bit series. The DAC is implemented using a 4-bit R-2R ladder with a negative feedback LM741 operational amplifier. An LM741 was chosen as the operational amplifier for its reliable performance in the 10 Hz range and so there would be no unused outputs. A buffered virtual ground of 4 volts was supplied as the ground so that the DAC would output a voltage between 4-9 volts since each VCO is centered at 6 volts. The R-2R ladder configuration was used to minimize the effects of resistor variation and also to allow for 16 steps from 4-9 volts in the control voltage. Since the DAC operates as an inverting amplifier the output voltage is highest at 9 volts when all of the rows are off and is at its lowest. The experimental results of the DAC show a voltage range of 3.66 to 8.5 volts with each step being approximately .31 volts incrementally.

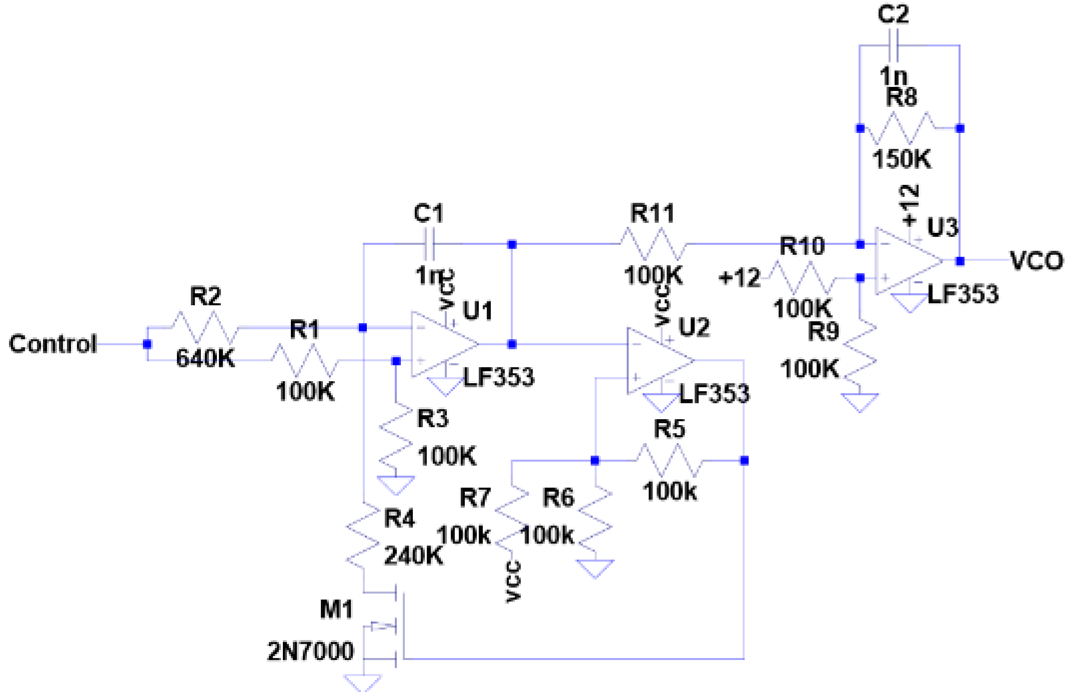


Voltage Controlled Oscillator

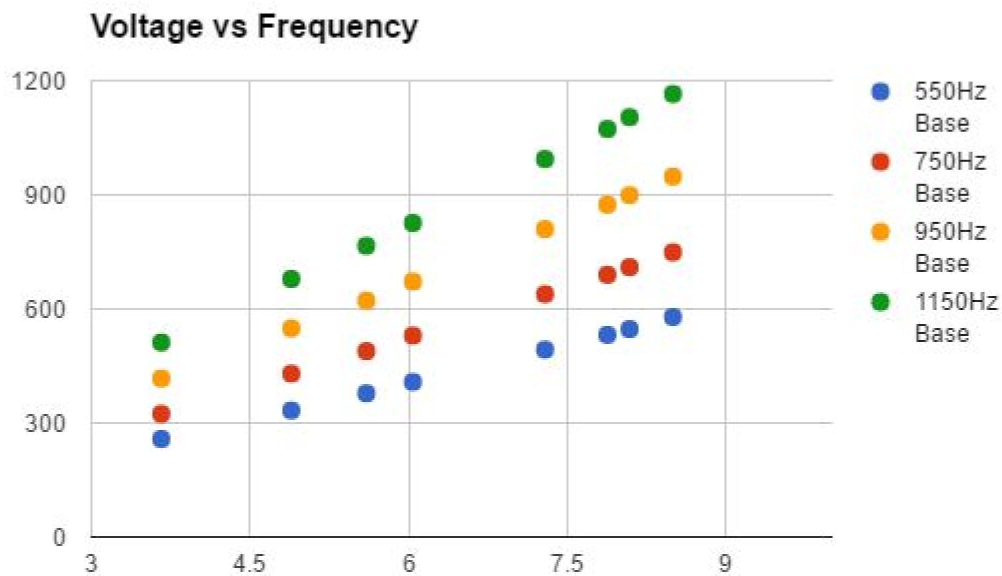
(Corey Cleveland)

The voltage controlled oscillator is the main component of the frequency generation part of the circuit. In total there are four voltage controlled oscillators whose base frequencies are 550 Hz, 750 Hz, 950 Hz and 1150 Hz and these represent the frequencies that are played when none of the modulation columns are activated. These frequencies were chosen because they are pleasant to hear and would be simpler to filter out any higher order harmonics with a first order low pass filter. Due to each the inverting nature of the control DAC these frequencies are also the highest frequency. The oscillator was also designed to be linear in frequency relative to control voltage so that evenly spaced frequencies could be achieved and the intervals between notes could remain ideally constant. Each oscillator also had a bandwidth of at least 300 Hz so that the complete frequency spectrum could be achieved between each interval.The output from the DAC is used as the control voltage for each voltage controlled oscillator. So all oscillators experience the same modulation and ensures that no duplicate frequencies can be played from the grid at the same time.

Each oscillator is implemented using two separate operational amplifiers. The first op-amp takes the control voltage as its input and creates a virtual ground at the non-inverting input. The control voltage is also connected to the inverting input through a resistor and the inverting input has a feedback loop to the output consisting of a capacitor. As the op-amp maintains the virtual ground a current is driven through the capacitor to charge it. The capacitor voltage is also the input to a schmitt trigger so that when the capacitor has charged past the threshold the trigger output goes high. The schmitt trigger output is used to turn a discharging n-channel mosfet off and on which causes the capacitor voltage to form a triangle wave. This configuration allows the capacitor voltage to remain in the linear region of its charge and discharge cycle which ensures the output is a clean triangle wave with a peak to peak voltage of 4 volts. The capacitor voltage is then passed through an active low pass filter whose -3db point is set at approximately the highest base frequency of the voltage controlled oscillator with a virtual ground of 6 volts. The -3db point was chosen to both minimize the amount of higher order harmonics that passed through while allowing each base frequency at an equal level of gain to keep each peak to peak voltage of the oscillators around the same value so there would be no volume variation based on which note was being played.



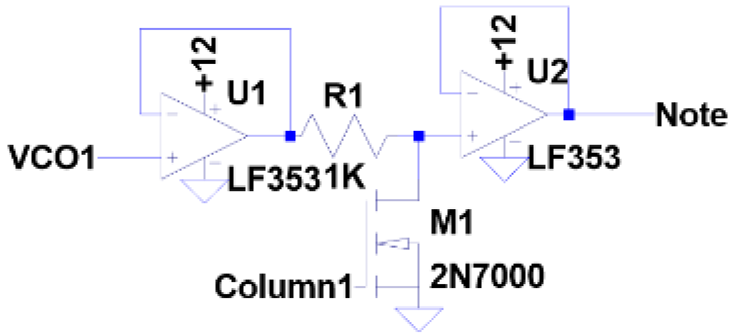
While this design for the voltage controlled oscillator does produce a linear relation between the output frequency and the control voltage the slope of the frequency changes depending on the base frequency. The change in frequency per volt increased as the base frequency was set higher. The slopes vary from 66 to 133 Hertz per Volt. This variation among the slopes meant that as the control voltage was lowered the intervals between each note also became smaller to reach a minimum of approximately 80Hz which is about half of the original interval. Instead of adjusting the control voltage for each oscillator to try and keep the intervals the same at all frequencies the variance in intervals was kept so that varying levels of dissonance could be played for each frequency allowing for different qualities when multiple tones are played. Additionally this allows for greater variation since the frequency ranges of the individual oscillators is greater than the largest interval the same note can be played from two different oscillators for different control voltages.



Note Selector

(Corey Cleveland)

Since the oscillators are always outputting a sine wave at their base frequency when no columns are activated, a method for turning the sine wave off and on at the speakers is needed. The circuit is designed as two buffering operational amplifiers with a resistors and mosfet to a virtual ground of 6 volts connecting them. The on and off voltages which operate from 0 to 12 volts are connected to the gate of the n-channel mosfet so that when the column is activated the gate voltage to the mosfet is 0 volts and is effectively an open circuit allowing the signal to progress. When the column is not activated the gate voltage is 12 volts which produces a gate to source voltage of 6 volts which turns on the mosfet and drains the signal into the virtual ground. The signal has to drain into the virtual ground because the signal is centered at 6 volts so that is the AC ground.

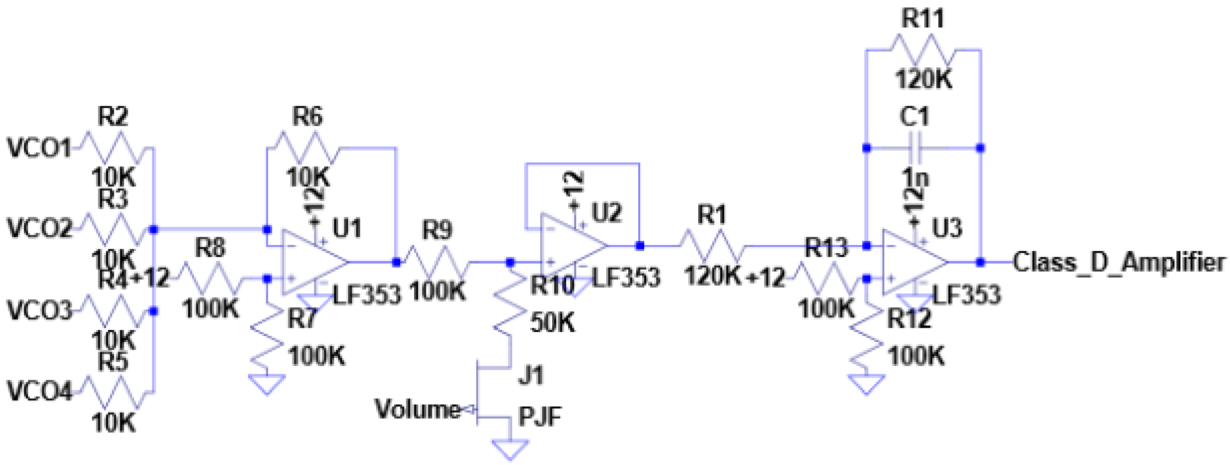


Gain Control

(Corey Cleveland)

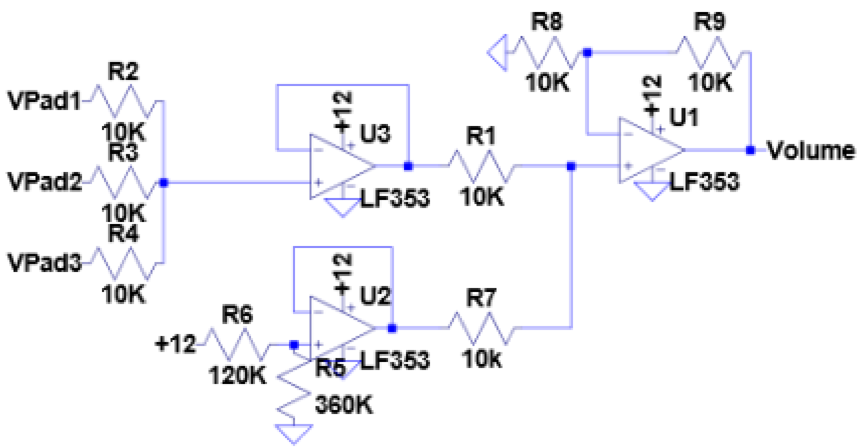
Once each individual frequency is generated they need to first be combined into a single signal so multitones can be played through the speakers. The signals are combined through an active inverting adder where each signal is given unity gain ideally. After being combined the signal is passed through a variable resistance voltage divider which lowers the signal from the 4 volts peak to peak to a range of 200 to 500 millivolts which is more appropriate as the input into a speaker amplifier. Finally before being input into the speaker amplifier the signal is low passed a final time with the -3db point of 1150Hz and then this low passed signal is the input to a class D amplifier to a speaker.

The adder circuit is implemented as an inverting adder with a feedback resistance of 10K. For unity gain each input resistance would be 10K however because of the previous low pass filters and also attenuation on the signal line the higher frequencies had a lower peak to peak voltage than the low frequency and so the adder was implemented with the lowest frequency signal having an individual gain of .8 so that each frequency had the same amplitude to better control the volume variation between notes and keep any note from overpowering the others. This was also important for the lower frequencies to be slightly lower in amplitude than the high frequencies because lower frequencies carry better over air and are naturally perceived to be at higher volumes than higher frequencies at the same amplitude by human ears. The non-inverting input of the adder was also set at a virtual ground at 6 volts. The virtual ground was chosen to be 6 volts in order to decrease the amount of DC amplification from each signal since they are all centered around 6 volts and this would reduce the chance of the op-amp railing.

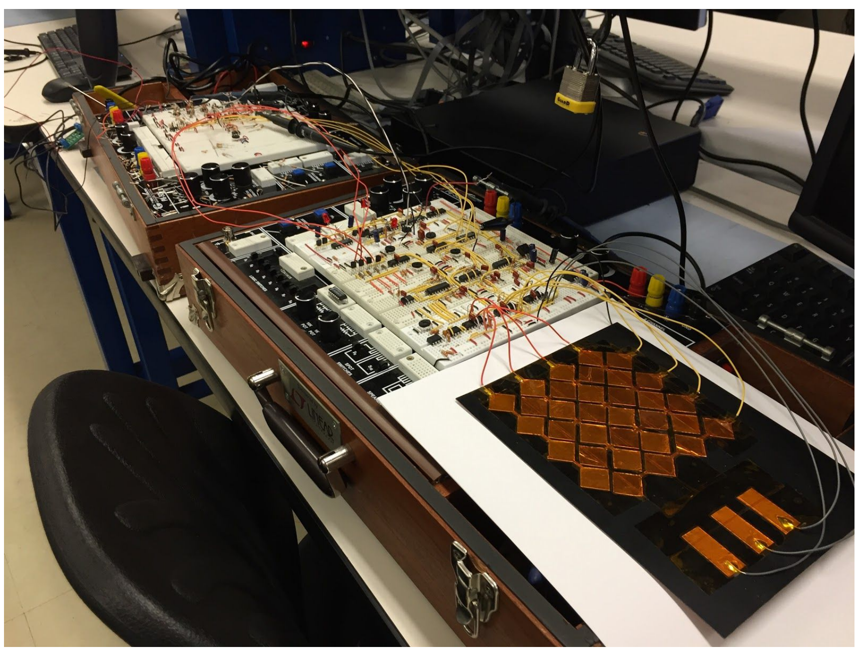


The variable resistance voltage divider was implemented as a 100K and 51K resistor in series with a 2N5462 p-channel mosfet. The gate voltage on the pfet would determine the amount of current flowing through the resistors which gives it an effective variable resistance. The values of the resistances were chosen so that the signal would be attenuated from a 4 volt signal to a 200 millivolt signal when the jfet had the smallest amount of current flowing allowed by the lowest gate voltage input. The peak to peak value of 200 was chosen so as to provide a volume level that could easily be heard and still allow for amplification without distorting the signal in the speaker. The last stage before the amplifier is a final low pass filter which is used to filter out any high frequency noise that was added to the line. The -3db point was set to be 1150Hz with a DC gain of 1 and a virtual ground of 6 volts.

The control voltage for the pfet was created from the three toggle voltages of the individual volume pads on the capacitive grid. Each input from the pad was either 0 or 5 volts and these were averaged and then buffered. The resistances were selected so that the output voltage due to one pad would be .5 volts and the total voltage added if all three were turned on would be 1.5 volts. The buffered output was added to a DC voltage of 9 volts through a non-inverting amplifier and then used as the gate voltage to the pfet. The values of a 9 volt base and 1.5 volt range above that were chosen because the pfet had variable resistance beginning at 9.2 volts and would then increase as the voltage increased. The resistance change was also nonlinear with voltage and so the small range of 1.5 volts was chosen so as to not allow to amplitude to be so large as to begin inducing clipping in the Class D amplifier.



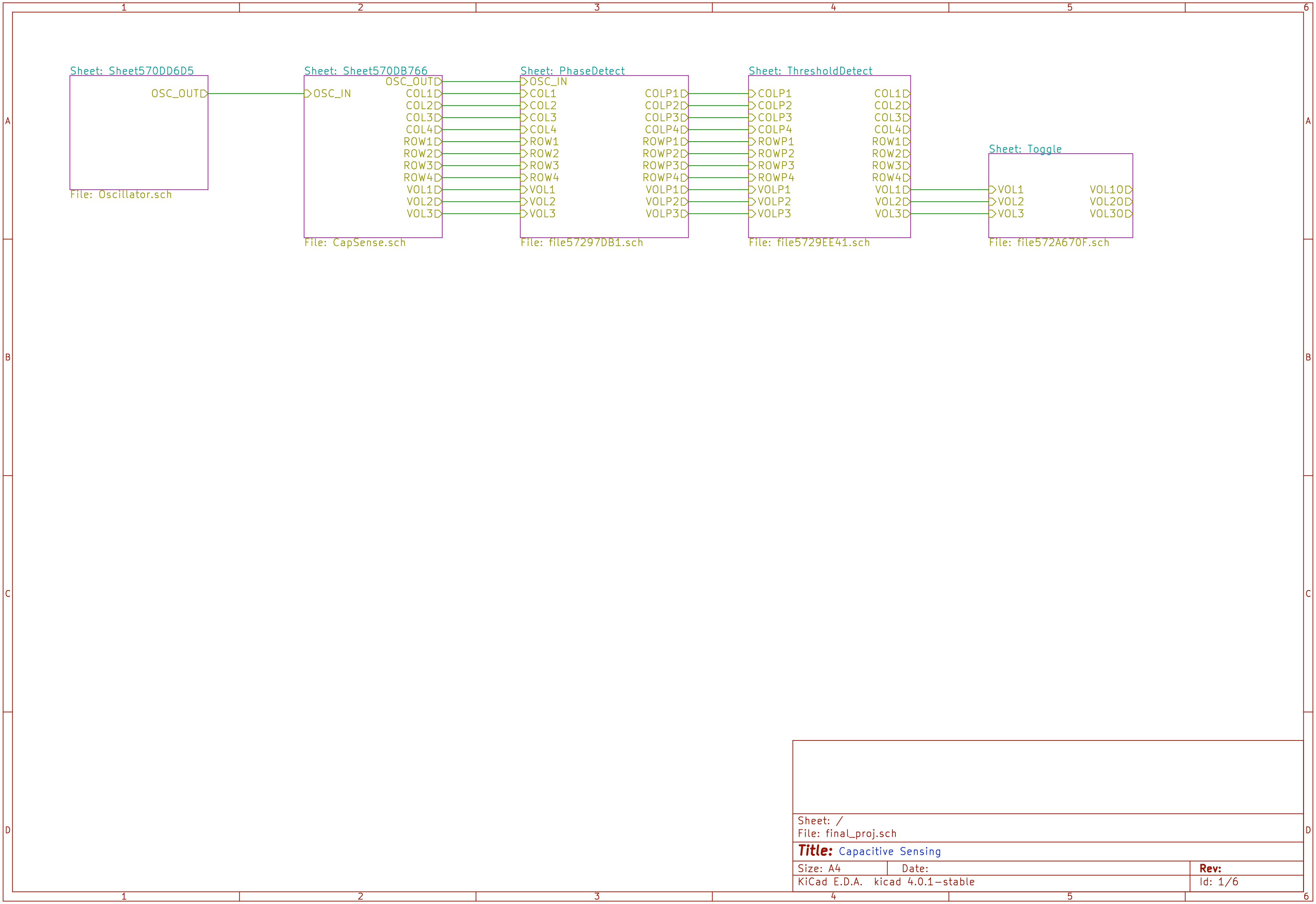
Conclusion



The final result of the project is shown above. The circuit was visibly divided between the capacitive sensing and tone generating portions and then connected together using long wires. The end result was an easy to play musical device that allowed the user to create a wide range of different tones. The capacitive sensing was surprisingly robust, rarely requiring re-tuning after an initial, careful, calibration. The tone generator had low levels of distortion and sounded very pure, except for the highest volume level, where some distortion was audible.

Although the project has been deemed a success, there are several areas of improvement that could be achieved in future designs. The capacitive grid design, although functional, could have been improved by increasing the area at the intersections and decreasing the area elsewhere. It was found that mutual capacitance between rows and columns was a small problem, but the size of the pads increased nominal capacitance, making it more difficult to detect the small changes in capacitance from the human finger. Another improvement could have been introduced in the threshold detection. With more time, it would have been useful to develop an auto calibration scheme that would allow the circuit to generate its own base level of capacitance. An idea for this would be to have some sort of integrator that can be fed back into itself during a detected press. This would make the circuit more robust to manufacturing tolerances, but would increase overall cost and complexity. On the frequency side the circuitry could have added in distortion by having a toggle switch method similar to the volume controls to switch between the capacitor voltage and the schmitt trigger output to change from a low passed triangle wave to a low passed square wave. As well the low pass filters could be made tunable and second order to lessen the impact of higher order harmonics for the low frequencies of each voltage controlled oscillator in order to get a pure sine tone out of the the speaker.

Since the capacitive touch sensing worked relatively well at the large scale, a possible application would be to scale it down to a more useful grid size and integrate all of the analog electronics into an integrated circuit chip. This would simplify capacitive touch input design and would cut down on the amount of signal processing necessary with conventional systems. Furthermore, although our system relied tying one end of the nominal capacitor to earth ground, at a smaller scale, the relative capacitances would shift so that even with less capacitive coupling from the human finger, it would still be large relative to the nominal capacitance of the grid, allowing for capacitive touch in a mobile or battery powered setting.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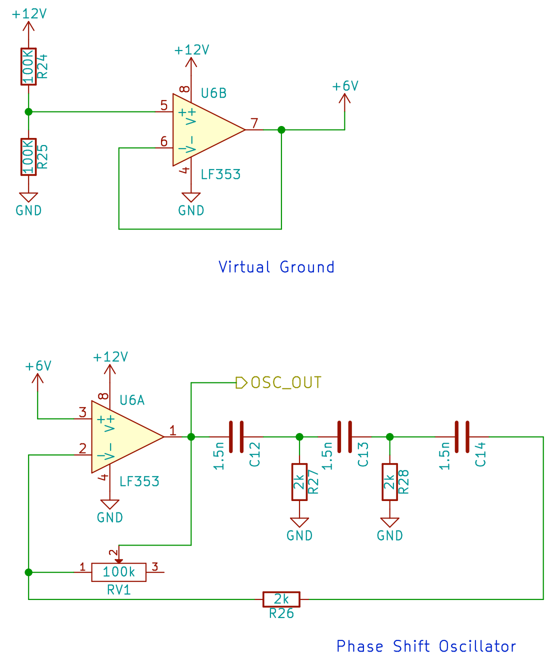

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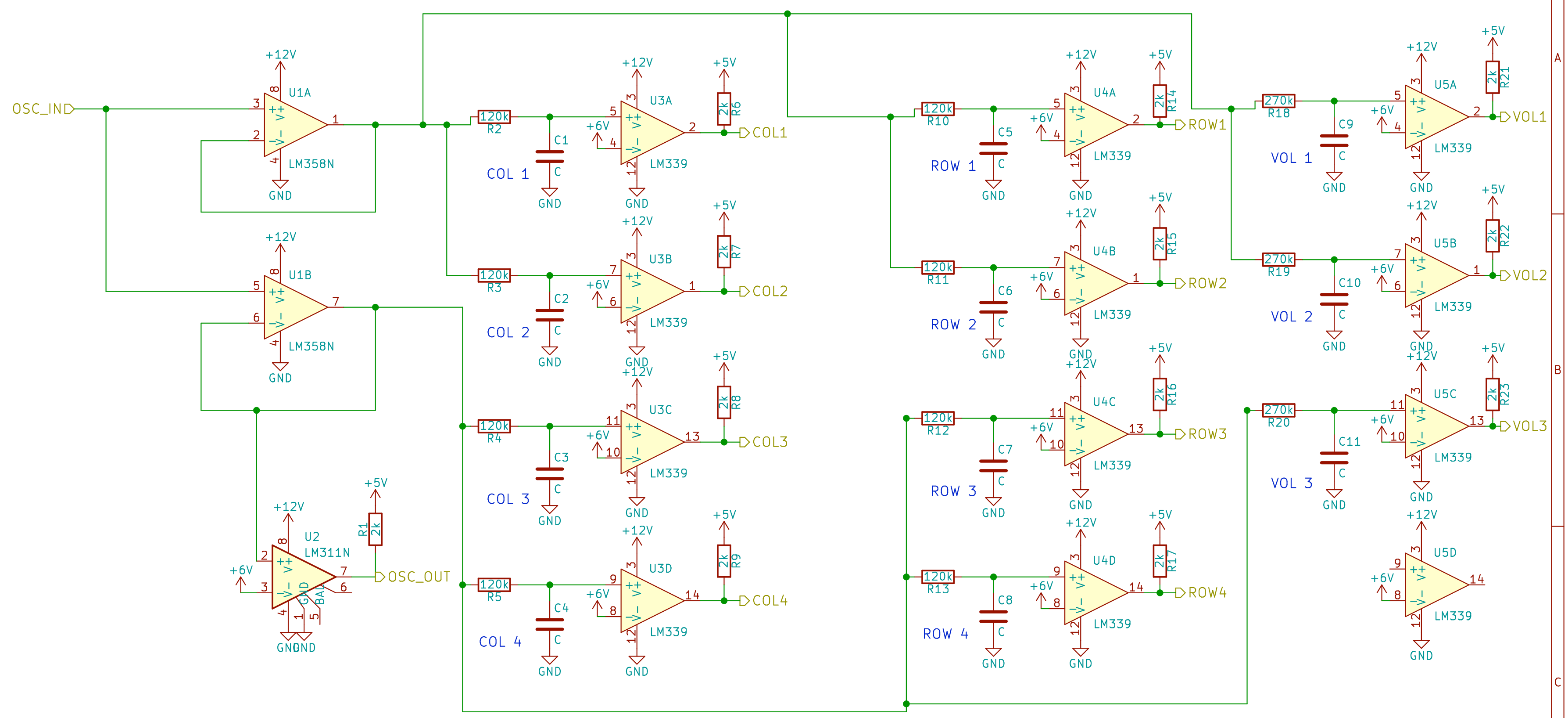

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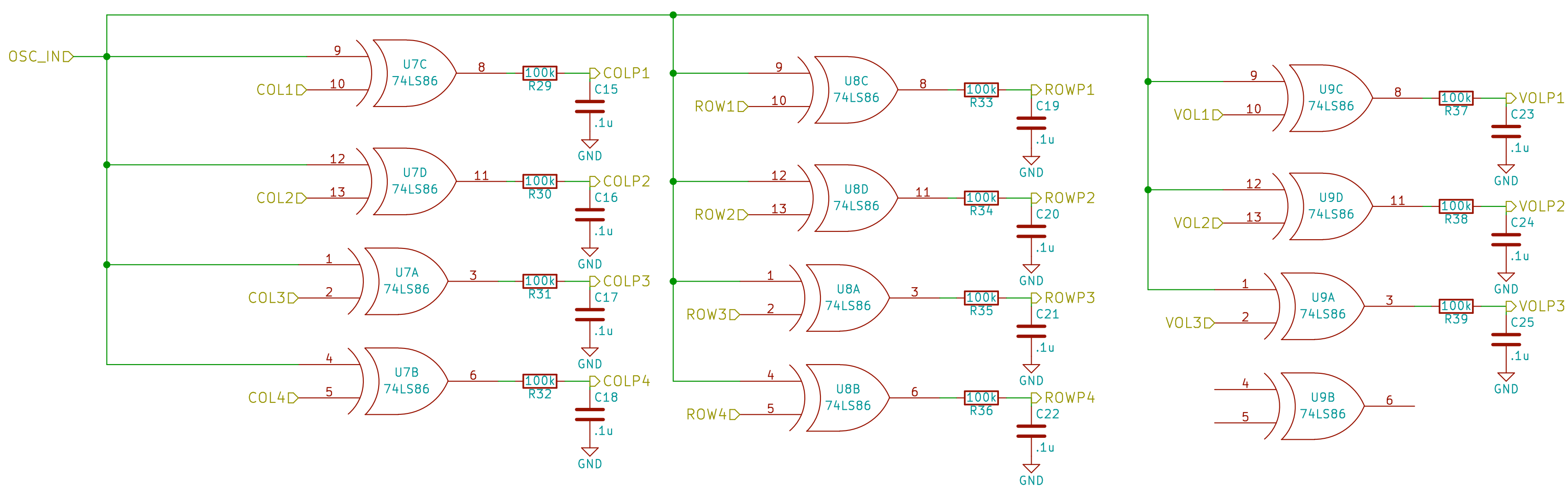

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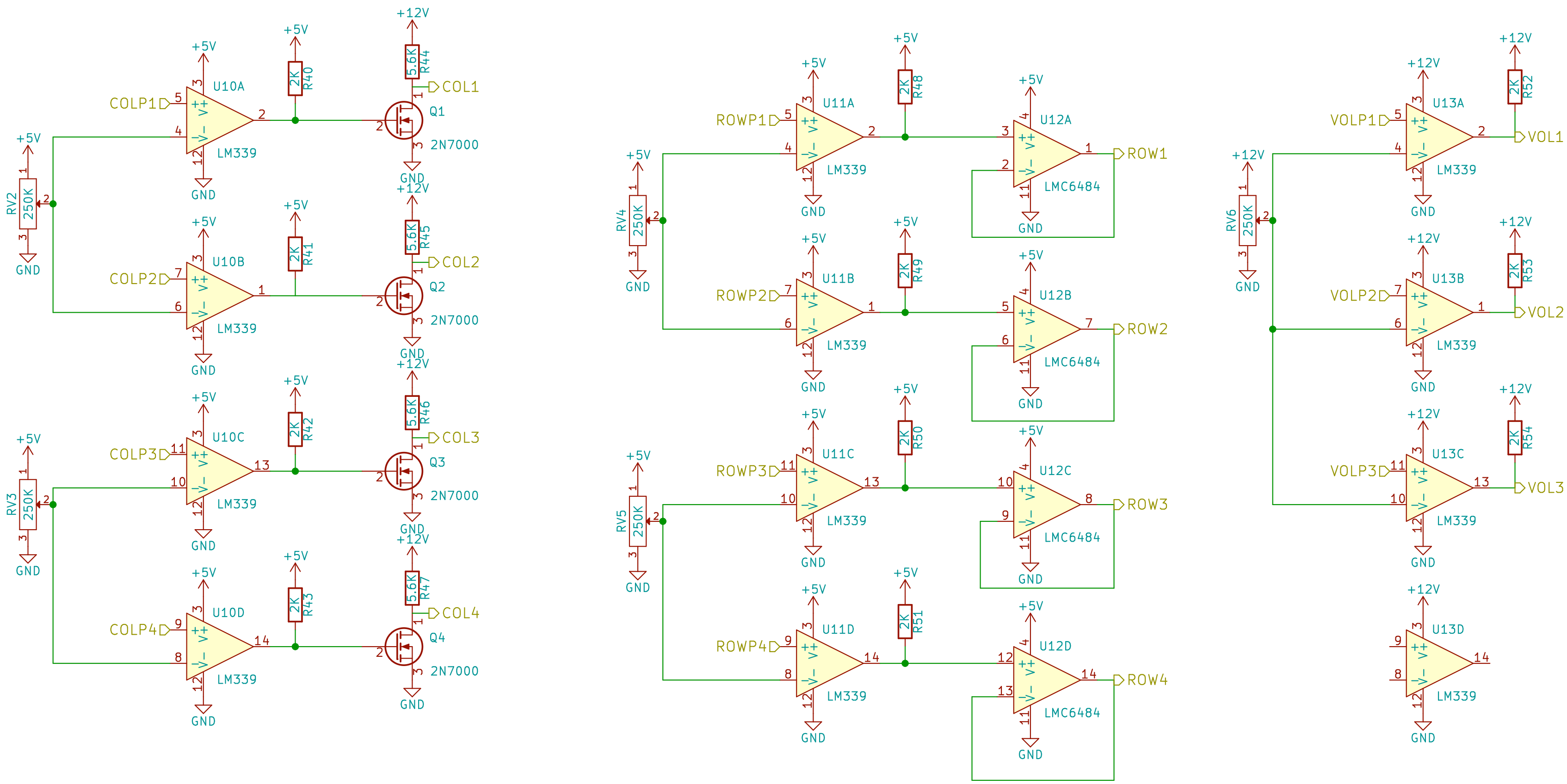

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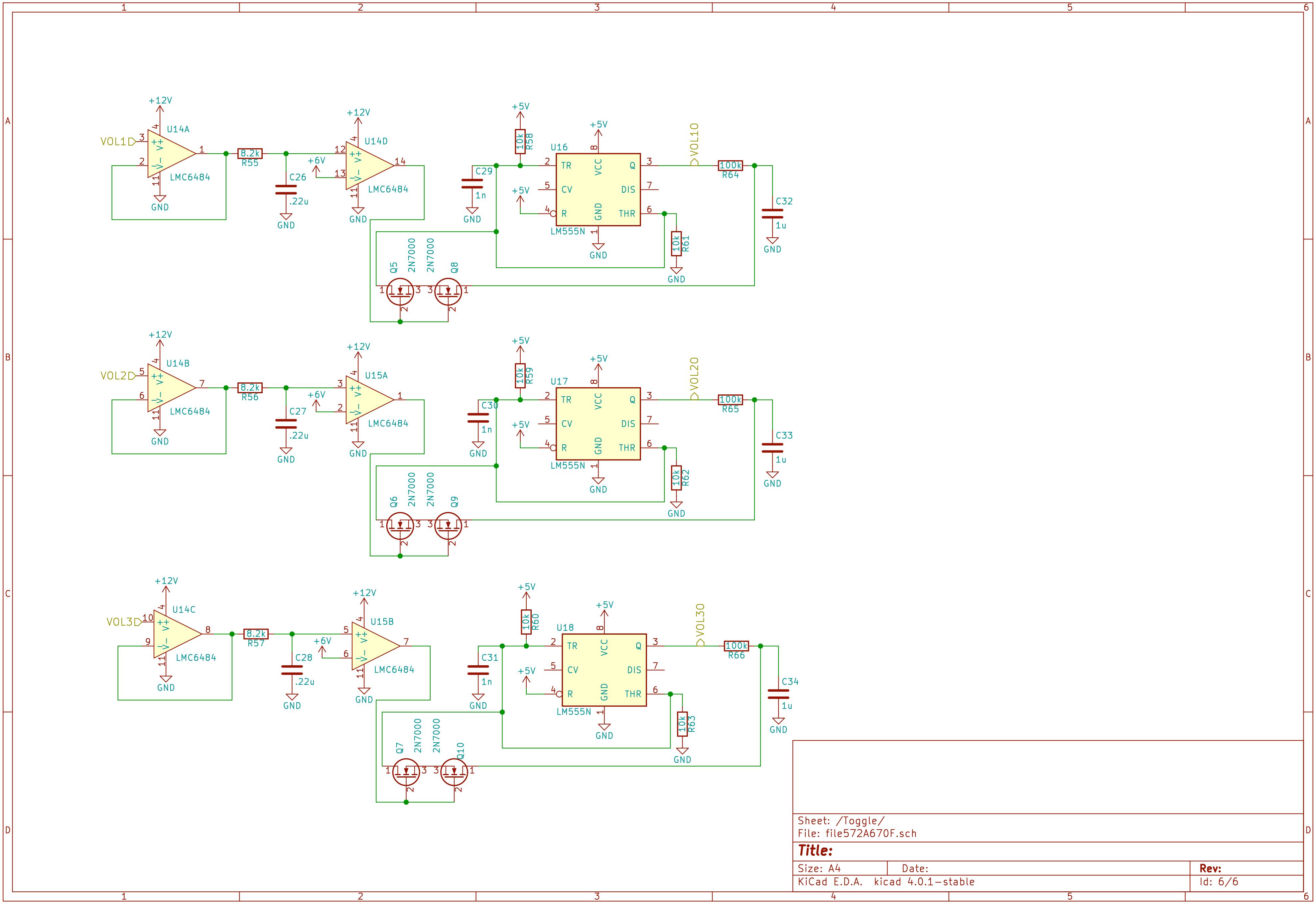

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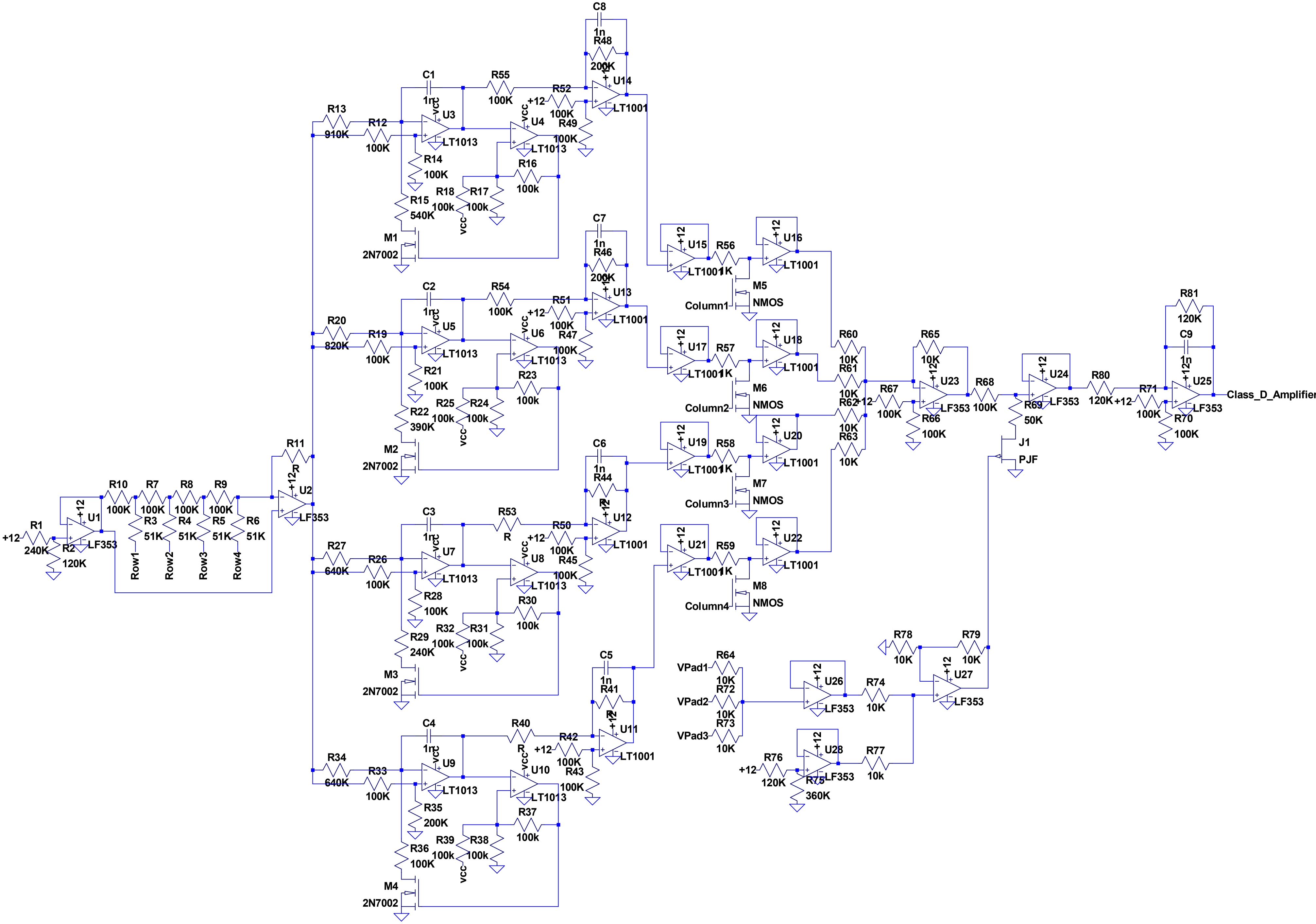

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