ModCon Final Project: Theremin

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Abstract

The theremin, patented in 1928 by Lèon Theremin, is a musical instrument played without any contact from the musician. The theremin uses the heterodyne technique to generate an audio signal. Two oscillators, one connected to an antenna, operate at nominally the same frequency. When a hand approaches the antenna, the frequency of one oscillator shifts proportionally. The other oscillator remains at the same frequency, and by mixing the two oscillators' outputs, the signal produced is the difference between the frequencies which happens to be in the audio range. This audio signal can then be filtered, amplified, and sent to a speaker. When constructing a theremin, or any other high frequency circuit, it is important to take parasitic effects of all components into account. Also included in this document are details on the fabrication of two brass knobs.

Contents

1 Circuit Design **3**
- 1.1 Oscillators . . . 4
  - 1.1.1 Local Oscillator . . . 5
  - 1.1.2 Modulated Oscillator . . . 6
- 1.2 Differential Amplifier . . . 7
- 1.3 Filters . . . 7
- 1.4 Audio Amplifier . . . 8
- 1.5 Bypass Network . . . 10

2 Circuit Construction **10**
- 2.1 Oscillators . . . 10
- 2.2 Differential Amplifier . . . 12
- 2.3 Filters . . . 12
- 2.4 Audio Amplifier . . . 12

3 Case Design and Construction **13**
- 3.1 Front Panel . . . 13
- 3.2 Power Input . . . 14
- 3.3 Speaker Output . . . 14
- 3.4 Antenna Connection . . . 15

Appendices **15**

A Knobs **15**

List of Figures

1 Full Schematic . . . 3
2 Relaxation Oscillator . . . 5
3 Local Oscillator . . . 5
4 Local Oscillator Frequency Range . . . 6
5 Modulated Oscillator . . . 7
6 Differential Amplifier . . . 7
7 Filter Section . . . 8
8 Filter Bode Plot . . . 9
9 Audio Amplifier . . . 9
10 Bypass Network . . . 10
11 Oscillators off board . . . 11
12 Oscillators soldered to copper clad . . . 11
13 Differential amplifier . . . 12
14 Filter network . . . 12
15 Audio amplifier . . . 13
16 Renders . . . 13
17 Fully assmbled . . . 14
18 DIN-5 Connector . . . 14
19 Speaker outputs . . . 15
20 Antenna connection . . . 15
21 Knob Drawing . . . 16
22 Turning stock to diameter . . . 17
23 Sizing halfway done . . . 17
24 Turning smaller outside diameter . . . 18
25 Drilling inside diameters . . . 18
26 Knurling the outside of the knob . . . 19
27 Drilling and tapping the set screw hole . . . 19
28 Engraved, sitting near set screws . . . 20
29 Completed Knobs . . . 20

1 Circuit Design

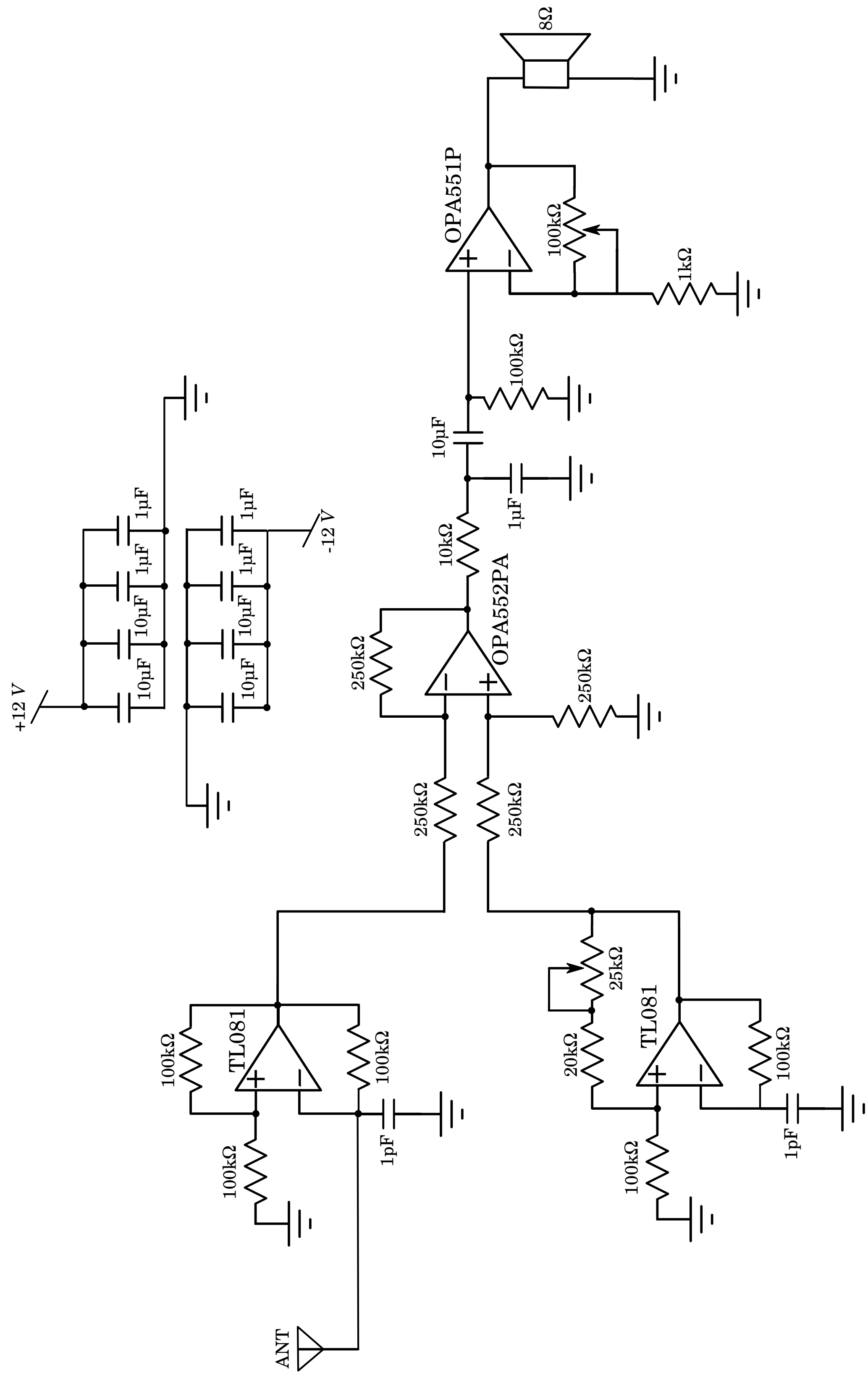


Figure 1: Full Schematic

While there are many theremin schematics available on the internet, they make compromises on various design aspects, i.e. cost, convenience, part availability, etc. I initially attempted to build one of these pre-made designs, however I quickly gave up and began to design my own with both simplicity and ease of acquiring components in mind. Figure 1 on the preceding page depicts my final circuit.

1.1 Oscillators

The heart of the theremin is its two oscillators, the local oscillator and the modulated oscillator. Both are relaxation oscillators, an example of which is shown in Figure 2 on the next page. In Figure 2, the output of an op-amp charges and discharges a capacitor, C through a resistor, $R1$. When the resistor reaches a threshold voltage set by the ratio between $R2$ and $R3$, the output of the op-amp switches to the opposite supply rail and it begins to charge in the opposite direction. This repeats at a frequency determined by the values of the circuit elements, producing a square wave on the output of the op-amp. All of the following assume the supply rails are $\pm V_s$. The threshold voltage is

$$V_{thresh} = \pm V_s \frac{R2}{R2 + R3} \tag{1}$$

and the voltage on the capacitor over time is

$$V_C(t) = V_s - V_s e^{\frac{-t}{R_1 C}} \tag{2}$$

assuming the capacitor starts at 0V and the op-amp starts on the positive supply rail. Setting these equations equal to each other and then solving for time yields half the period of the oscillator. For these calculations, the capacitor starts at its lowest voltage (i.e. the negative threshold voltage).

$$V_s \frac{R2}{R2 + R3} = V_s - \left(V_s \left(1 + \frac{R2}{R2 + R3} \right) \right) \left(e^{\frac{-t}{2R_1 C}} \right) \tag{3}$$

$$\frac{R2}{R2 + R3} = 1 - \left(e^{\frac{-t}{2R_1 C}} \right) \left(1 + \frac{R2}{R2 + R3} \right) \tag{4}$$

$$1 - \frac{R2}{R2 + R3} = e^{\frac{-t}{2R_1 C}} \left(1 + \frac{R2}{R2 + R3} \right) \tag{5}$$

$$\frac{1 - \frac{R2}{R2+R3}}{1 + \frac{R2}{R2+R3}} = e^{\frac{-t}{2R_1 C}} \tag{6}$$

$$\ln \left(\frac{1 - \frac{R2}{R2+R3}}{1 + \frac{R2}{R2+R3}} \right) = \frac{-1}{2R_1 C} t \tag{7}$$

$$t = -2R_1 C \ln \left(\frac{1 - \frac{R2}{R2+R3}}{1 + \frac{R2}{R2+R3}} \right) \tag{8}$$

$$t = 2R_1 C \ln \left(\frac{1 + \frac{R2}{R2+R3}}{1 - \frac{R2}{R2+R3}} \right) \tag{9}$$

$$f = \frac{1}{2R_1 C \ln \left(\frac{1+\frac{R2}{R2+R3}}{1-\frac{R2}{R2+R3}} \right)} \tag{10}$$

and when $R2 = R3$

$$f = \frac{1}{2R_1 C \ln 3} \tag{11}$$

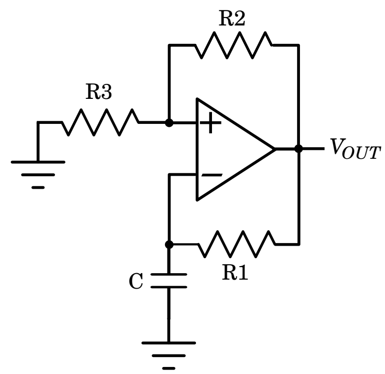


Figure 2: Relaxation Oscillator

1.1.1 Local Oscillator

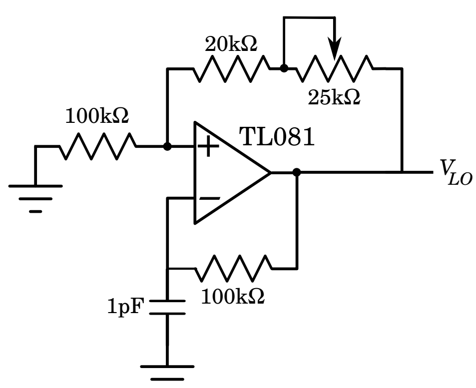


Figure 3: Local Oscillator

In the local oscillator, shown in Figure 3, the threshold voltage can be adjusted by a $25k\Omega$ potentiometer. The potentiometer's placement in the threshold voltage feedback loop isolates it from the RC circuit, which is highly sensitive to changes in capacitance (such as those that occur when a user touches or approaches the knob). Also, the potentiometer is placed as close to the output of the op-amp as possible, which allows the amplifier to compensate for the parasitic effects of the potentiometer. Unfortunately, the potentiometer's placement makes its affect on the frequency of the oscillator non-linear. In this case, naming the potentiometer variable a and including a $20k\Omega$

resistor in series with the potentiometer, Equation (10) on page 4 yields the following:

$$f = \frac{1}{2R_1 C \ln\left(\frac{1+\frac{R2}{R2+R3}}{1-\frac{R2}{R2+R3}}\right)} \tag{12}$$

$$R_1 = 100k\Omega \tag{13}$$

$$R2 = 20k\Omega + a(25k\Omega) \tag{14}$$

$$R3 = 100k\Omega \tag{15}$$

$$C = 1pF \tag{16}$$

$$f_{lo} = \frac{1}{(100k\Omega)(1pF)\ln\left(\frac{1+\frac{20k\Omega+a(25k\Omega)}{120k\Omega+a(25k\Omega)}}{1-\frac{20k\Omega+a(25k\Omega)}{120k\Omega+a(25k\Omega)}}\right)} \tag{17}$$

Plotting this oscillator's frequency response against the potentiometer parameter yields the graph shown in Figure 4.

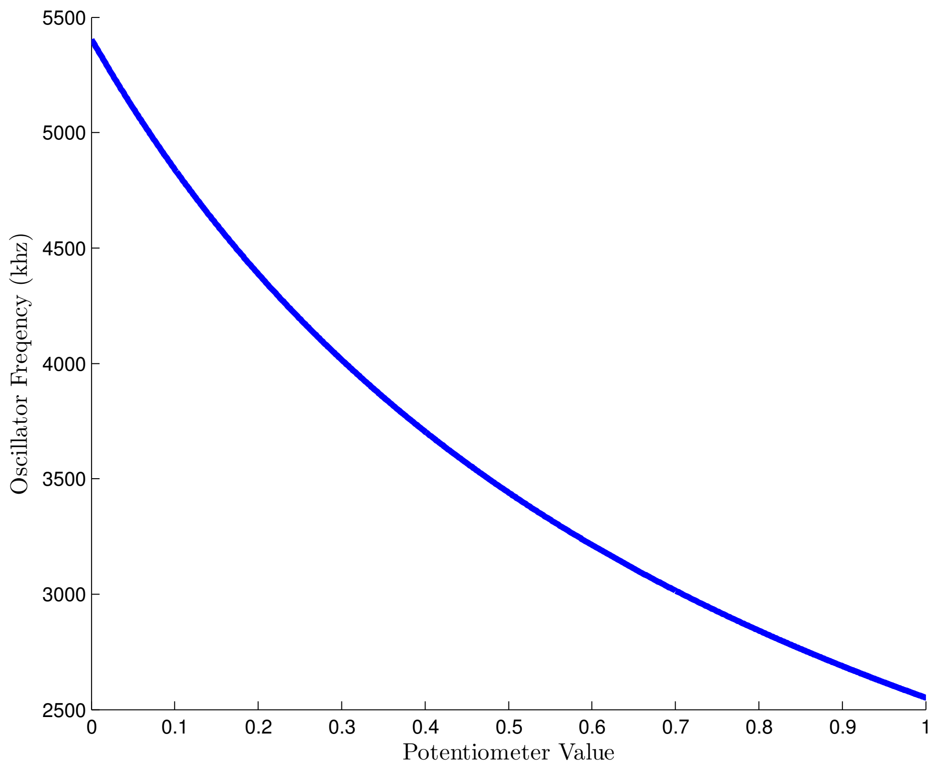


Figure 4: Local Oscillator Frequency Range

1.1.2 Modulated Oscillator

In the modulated oscillator, shown in Figure 5 on the next page, the antenna increases the capacitance in the RC network. Depending on the surroundings and other variables such as air humidity, the human hand has several hundred femptofarads (10^{-15}) of capacitance to ground. On a good day, this effect can modulate the oscillator over the majority of the human hearing range, which is commonly cited as 20Hz - 20kHz.

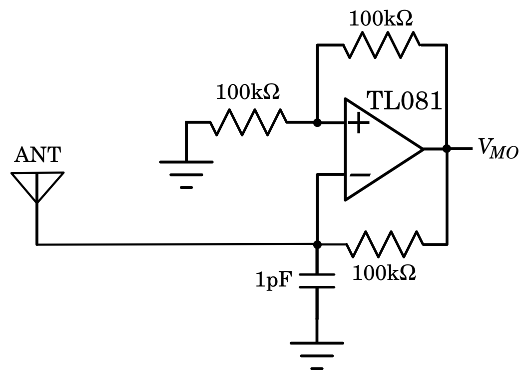


Figure 5: Modulated Oscillator

1.2 Differential Amplifier

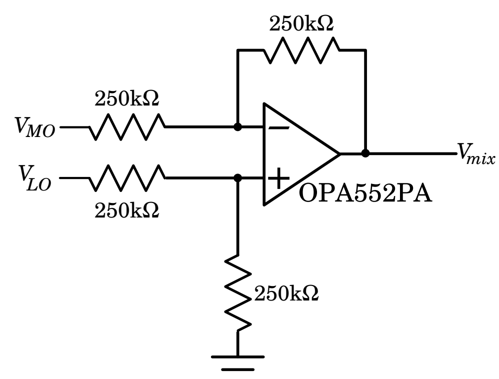


Figure 6: Differential Amplifier

To combine the frequencies of the modulated oscillator and the local oscillator, a differential amplifier (Figure 6) is used. Ideally, an integrated mixer would be used, however, these are expensive and uncommon. This differential amplifier has a number of disadvantages, namely $250k\Omega$ is the best input impedance possible, and crosstalk is increased beyond the natural amplifier crosstalk. An instrumentation amplifier would increase the input impedance at the cost of increased part cost and complexity. An OPA552PA was chosen because it is fast enough for the input signals but also has a low enough output impedance to drive a speaker directly. The output of the differential amplifier is the difference between the two input signals, which happens to be both the sum and difference of the input frequencies. The difference is in the audio frequency range, though the signal at V_{mix} must be filtered before an audio frequency waveform can be seen.

1.3 Filters

The output of the differential amplifier contains the sum of the frequencies and also the difference, along with very strong harmonics of both. The filter section, Figure 7 on the next page, is designed to remove the higher frequencies and then the DC component of the signal. The filter does not obey

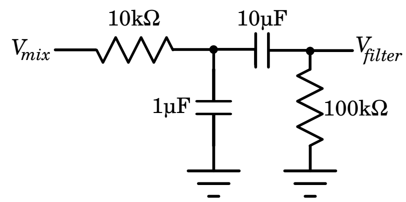


Figure 7: Filter Section

the standard filter law where the cutoff frequency is $\frac{1}{2\pi RC}$, since the $10\mu F$ capacitor and $100k\Omega$ resistor load the first resistor and capacitor. Finding the transfer function of the system yields the following:

$$\mathcal{H}(\omega) = \frac{V_{filter}}{V_{mix}} \tag{18}$$

$$V_{filter} = (V_{mix} - V_{R1})\frac{R2}{R2 + \mathcal{Z}_{C1}} \tag{19}$$

$$-V_{R1} = V_{mix}\left(\frac{\mathcal{Z}_{C1}||(\mathcal{Z}_{C2} + R2)}{R1 + \mathcal{Z}_{C1}||(\mathcal{Z}_{R}2 + R2)}\right) \tag{20}$$

$$\mathcal{H}(\omega) = \frac{V_{filter}}{V_{mix}} = \frac{R2}{R2 + \mathcal{Z}_{C1}}\left(\frac{\mathcal{Z}_{C1}||(\mathcal{Z}_{C2} + R2)}{R1 + \mathcal{Z}_{C1}||(\mathcal{Z}_{R2} + R2)}\right) \tag{21}$$

$$\mathcal{H}(\omega) = \frac{\mathcal{Z}_{C1}R2}{(\mathcal{Z}_{C1} + \mathcal{Z}_{C2}\mathcal{Z}_{C2} + R2) + \mathcal{Z}_{C1}(\mathcal{Z}_{C2} + R2)} \tag{22}$$

$$\mathcal{H}(\omega) = \frac{\mathcal{Z}_{C1}R2}{R1\mathcal{Z}_{C1} + R1 + R1R2 + \mathcal{Z}_{C1}\mathcal{Z}_{C2} + \mathcal{Z}_{C1}R2} \tag{23}$$

$$\mathcal{H}(\omega) = \frac{R2\frac{1}{j\omega C1}}{R1\frac{1}{j\omega C1} + R1\frac{1}{j\omega C2} + R1R2 + \frac{1}{j\omega C1}\frac{1}{j\omega C2} + \frac{1}{j\omega C1}R2} \tag{24}$$

$$\mathcal{H}(\omega) = \frac{R2\frac{\omega}{jC1}}{R1\frac{\omega}{jC1} + R1\frac{\omega}{jC2} + R1R2 + \frac{\omega}{jC1}\frac{\omega}{jC2} + \frac{\omega}{jC1}R2} \tag{25}$$

$$\mathcal{H}(\omega) = \frac{\omega\frac{R2}{jC1}}{R1R2 + \omega(\frac{R1}{jC1} + \frac{R1}{jC2} + \frac{R2}{jC1}) - \frac{\omega^2}{C1C2}} \tag{26}$$

$$\mathcal{H}(\omega) = \frac{\omega\frac{100k\Omega}{j1\mu F}}{10k\Omega 100k\Omega + \omega(\frac{10k\Omega}{j1\mu F} + \frac{10k\Omega}{jC2} + \frac{100k\Omega}{j1\mu F}) - \frac{\omega^2}{C1C2}} \tag{27}$$

Figure 8 on the following page is a bode plot of Equation (27).

1.4 Audio Amplifier

Figure 9 on the following page depicts the audio amplifier. An OPA551 was chosen due to its low-gain stability and high current output. Here, it is configured as a non-inverting amplifier which has a gain of

$$A = 1 + b\frac{100k\Omega}{1k\Omega} \tag{28}$$

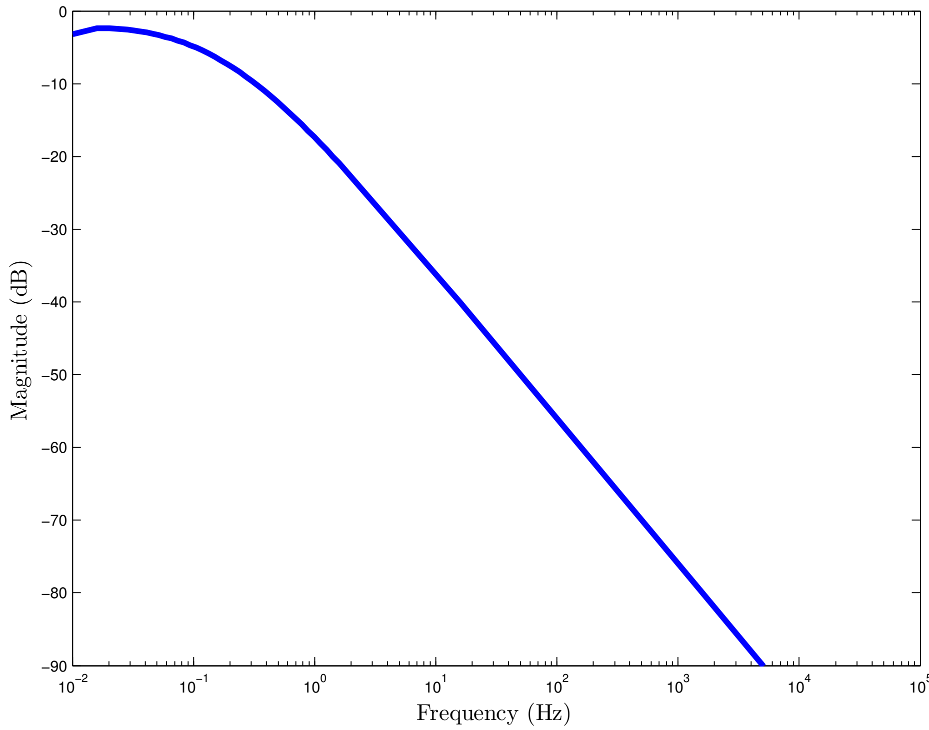


Figure 8: Filter Bode Plot

depending, of course, on the potentiometer variable b. Since the mixer outputs the signal clipped by the rails, the amplifier is primarily to counter the attenuation of the filter. Additionally, since the filter reduces the harmonics in the signal significantly, the high possible gain of the amplifier can be used like a tone control to add the harmonics back in by clipping the signal.

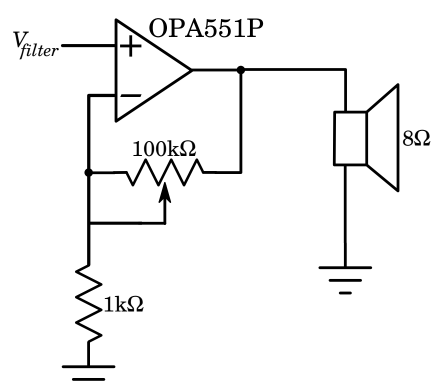


Figure 9: Audio Amplifier

1.5 Bypass Network

In a circuit where keeping the two oscillators as unlinked as possible is very important, fluctuations in the power rials can cause the oscillators to lock phase with one another. To counter this effect, the capacitors in Figure 10 are used to remove any noise in the power supply. Small, highly responsive polyester film capacitors are placed on the supply pins of the oscillators and larger ceramic capacitors are on the power amplifiers which aren't as sensitive to rail variations but could, under heavy load conditions, require more current than the supply can provide, which the capacitors will mitigate.

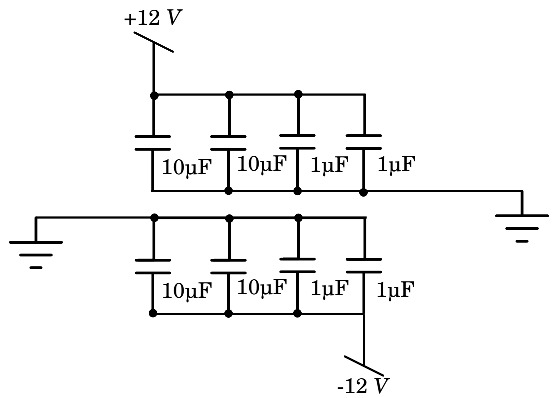


Figure 10: Bypass Network

2 Circuit Construction

In constructing this circuit, as with any high frequency circuit, it is very important to minimize parasitic effects in any way possible. All stray leads, especially in parts of the circuit not connected to the outputs of op-amps (which have the stabilizing effects of the op-amp's relatively low output impedance) have parasitic inductance and capacitance, leading to undesired (and difficult-to-predict) effects. The primary measure taken was dead-bugging the circuit. Described in a Linear Technology application note,[1] dead bugging involves bending the leads of DIP ICs so they look like dead bugs and then soldering them and associated components to a copper-clad board. The board is then grounded, significantly reducing parasitic capacitances due to the large ground plane and shortened signal paths. On a breadboard, each row can have capacitances of as much as $10pF$ between it and its neighbors–dead bugging completely removes this. Further details on the steps taken to minimize these effects are discussed below.

2.1 Oscillators

The oscillators were constructed to be as compact as possible. The oscillators were first free-soldered, as seen in Figure 11 on the following page. The power supply pins are soldered as close as possible to $1\mu F$ film capacitors and the feedback paths are minimized. All grounded component

[1] AN47 - High Speed Amplifier Techniques - A Designer's Companion for Wideband Circuitry - Approx 150 pages cover, among other things, high-speed prototyping techniques.

leads are on the bottom with long leads kept for maximum ground plane benefits. The output leads are solid-cored to remove skin effect that happens at high frequency. In this state, the oscillators run at approximately 200kHz $\pm$ 2kHz, within tolerance for 1% resistors and $\pm$.5pF capacitors. After building and testing the oscillators freely, they were soldered to the copper clad. For the

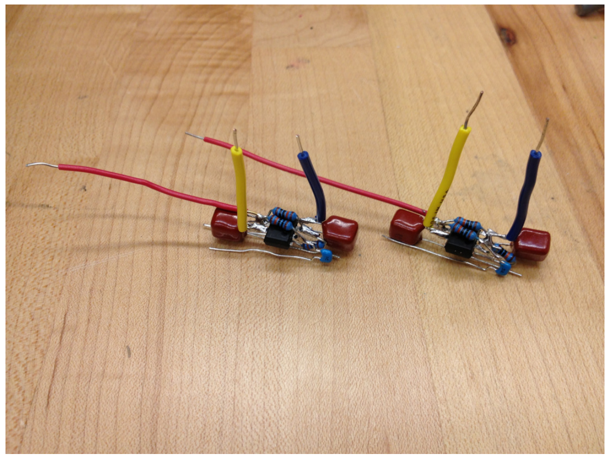


Figure 11: Oscillators off board

antenna, one of the top standoff screws was replaced with a teflon screw and the antenna standoff pinches a wire from the RC circuit between itself and a teflon washer. The oscillators were soldered on opposite sides to minimize their effects on each other. Any weak linking between two resonant systems will cause them to lock frequency and phase with each other, so the less linking there is between the oscillators the lower frequencies the theremin will output because a smaller capacitance will cause them to drift apart.

After soldering the oscillators to the board some changes were necessitated to include the pitch zero control. First, the antenna provided significant capacitance even without a nearby hand and slowed the modulated oscillator to approximately 145kHz. To counter this effect, the $100k\Omega$ resistor in the feedback loop of the local oscillator was replaced with a $20k\Omega$ resistor in series with a $25k\Omega$ potentiometer, which provides enough range to counter most environmental variations in antenna capacitance.

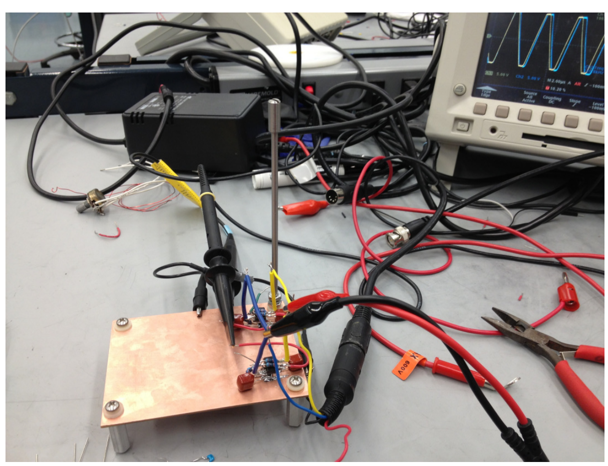


Figure 12: Oscillators soldered to copper clad

2.2 Differential Amplifier

The differential amplifier is constructed such that the inputs are never closer than when they are at the input pins. Of course, the input pins are only 0.1" away from each other, so there is a limit to the effectiveness of this strategy. Feedback paths are kept short and the supply rails are bypassed by $10\mu F$ ceramic capacitors. The differential amplifier is seen in Figure 13, with the inputs being the two red wires on the left and the output being the $10k\Omega$ resistor on the left.

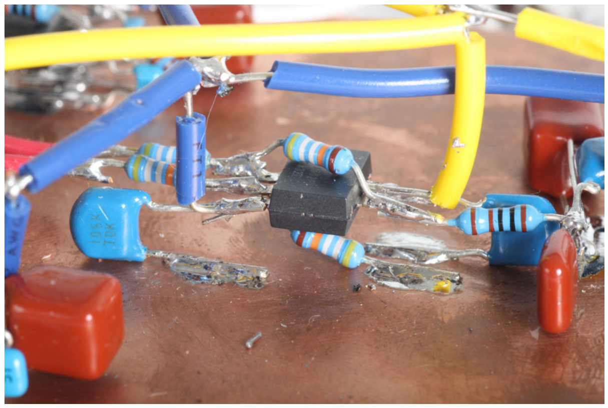


Figure 13: Differential amplifier

2.3 Filters

The filter section was designed to be modified, and modified it was. Originally, the first capacitor was $10nF$, however, a $1\mu F$ capacitor proved to be more effective and was added in parallel with the $10nF$ capacitor.

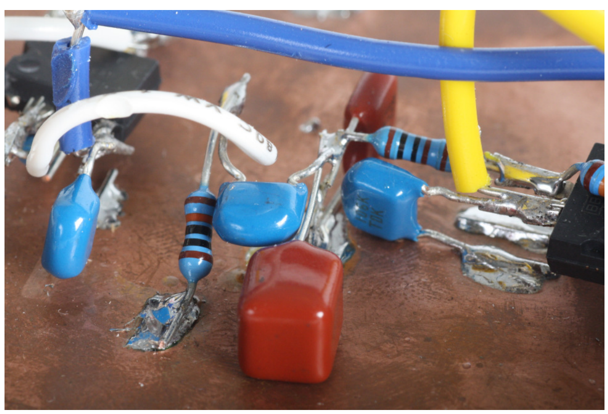


Figure 14: Filter network

2.4 Audio Amplifier

The audio amplifier is the least critical part of the system, as it is the farthest away from the oscillators both electrically and physically. It is bypassed like the differential amplifier, and designed for easy modification with changing potentiometer values. The audio amplifier is shown in Figure 15 on the following page. The white wires extending towards the camera are for the volume potentiometer, the purple wire is an (unused) thermal overload detection, and the red wire is the output.

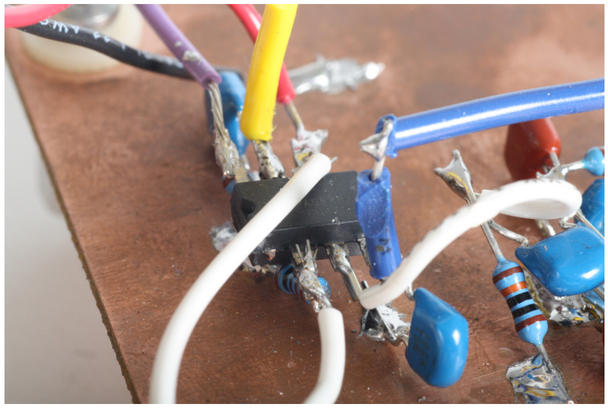


Figure 15: Audio amplifier

3 Case Design and Construction

The case is designed to be constructed from $\frac{1}{4}$" MDF, mostly because enough scrap $\frac{1}{4}$" MDF was available for a 4"×3"×7" box. All the box panels were cut on a laser cutter in the Olin machine shop. To laser cut the box, it was first necessary to made CAD files of the theremin. Figure 16a is an exploded rendering, and Figure 16b is the theremin assembled. For comparison, the fully assembled theremin is seen in Figure 17 on the next page.

(a) Exploded render

(b) Assembled Render

Figure 16: Renders

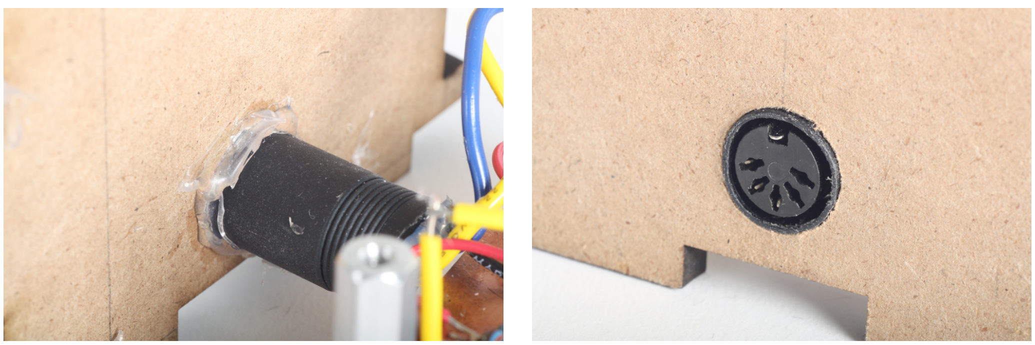
3.1 Front Panel

The front panel is designed for the two panel mount potentiometers that were available. Unfortunately, potentiometers with a $\frac{1}{4}$"-20 bushing are very hard to find with bushings longer than $\frac{1}{4}$". To solve this problem, an end mill was used to counterbore the reverse of the front panel. The text on the faceplate is engraved with the laser cutter.

Figure 17: Fully assmbled

3.2 Power Input

Due to the unavailability of a true panel-mount power input, an inline-wired female DIN-5 connector was re-purposed as a panel mount jack with the help of some hot glue, as seen in Figure 18.



(a) Inside of power jack (b) Outside of power jack

Figure 18: DIN-5 Connector

3.3 Speaker Output

The speaker outputs are on the opposite side of the theremin from the power input, and are a pair of banana jacks, spaced the standard .75” apart for compatibility with dual banana plugs, as seen in Figure 19 on the next page.

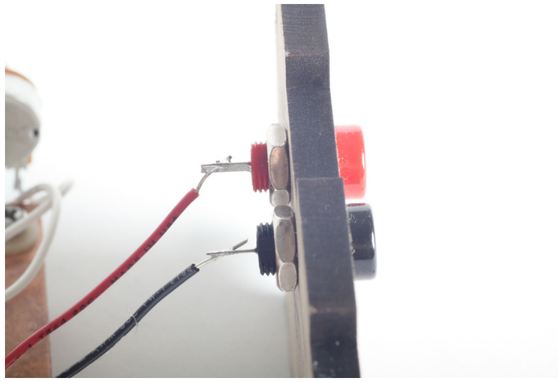


Figure 19: Speaker outputs

3.4 Antenna Connection

The antenna of the theremin is a long #8-32 screw screwed into a 1.5” standoff, which is attached to the underside of the board with a teflon screw. The wire from the RC circuit of the modulated oscillator is pinched between the standoff and a teflon washer, as shown in Figure 20. While a crimp connector would be the ”proper” way to attach the wire to a screw terminal, crimp connectors and screw terminals both induce undesired parasitic effects.

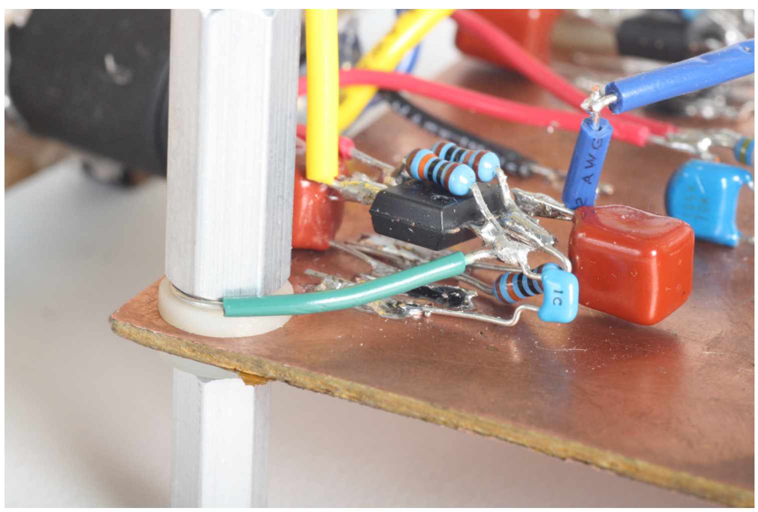


Figure 20: Antenna connection

Appendices

A Knobs

Due to the exorbitant cost of COTS (commercial off-the-shelf) aluminum knobs, which can often cost more than $5, two knobs were fabricated specifically for this project. Based on Digi-Key part number 226-2088-ND, a drawing (Figure 21 on the next page) was created to fabricate the knob on a mill and lathe. The fabrication went as follows: two small (approx. 1” long) pieces of 1” diameter

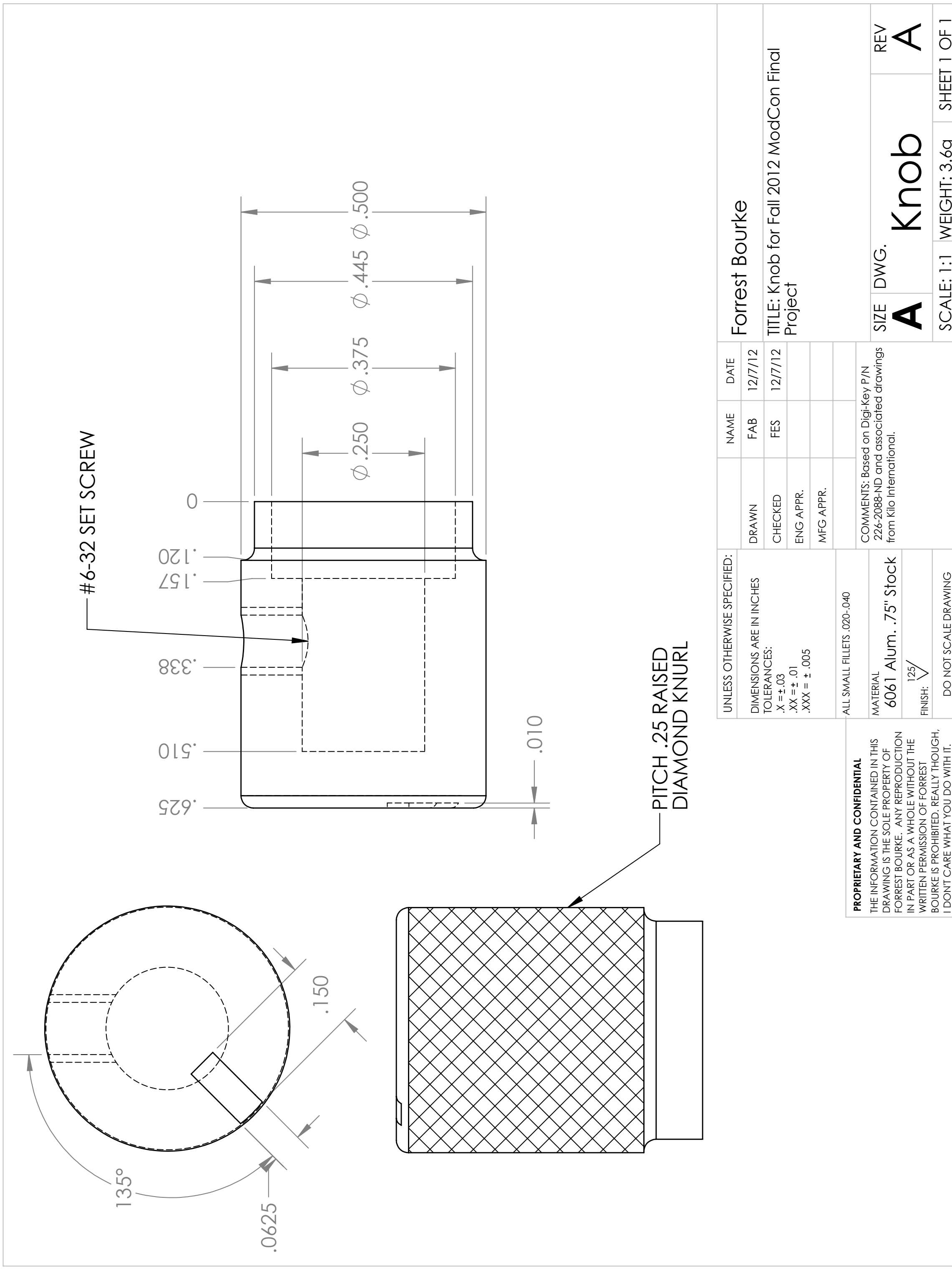


Figure 21: Knob Drawing

scrap brass stock were first turned to .500” diameter for insertion in a half-inch collet, shown in Figure 22.

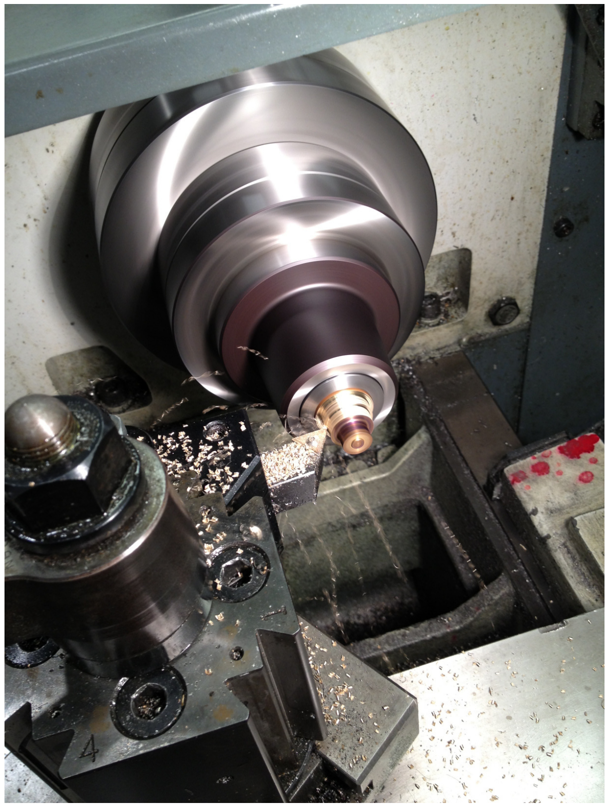


Figure 22: Turning stock to diameter

This was done in two halves: first, one half of the stock was turned to size, then the piece was reversed, placed in a collet and the rest was turned to size. This halfway point is seen in Figure 23.

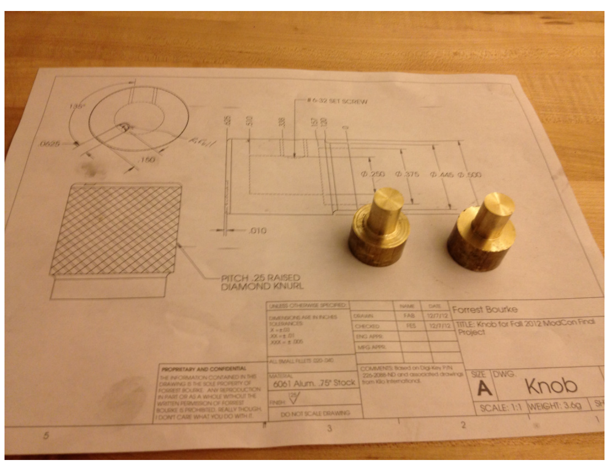


Figure 23: Sizing halfway done

After insertion in a collet, the first outside diameter was turned to size, seen in Figure 24 on the following page.

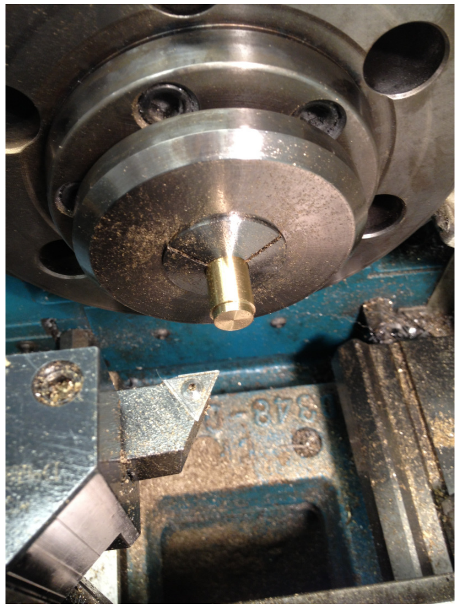


Figure 24: Turning smaller outside diameter

After sizing the outside diameter, the two inside diameters were first center drilled and then drilled to size, shown in Figure 25.

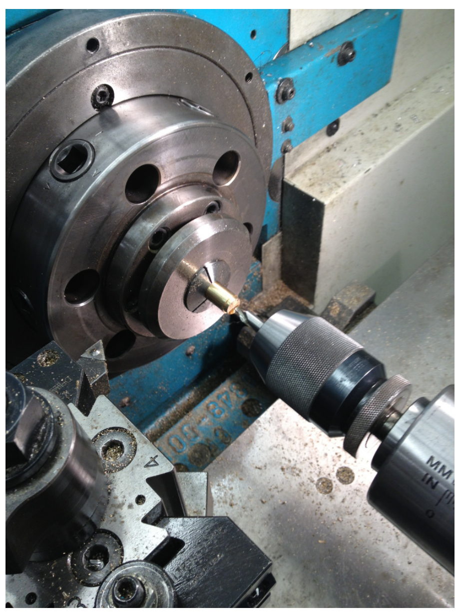


Figure 25: Drilling inside diameters

The sides of the knobs were knurled (Figure 26 on the following page) and the front of the knob was filleted with a file.

Figure 26: Knurling the outside of the knob

After filleting the front, the knob was cut off with a parting tool and re-inserted in the other direction so the opposite side could be filleted with a file. Once all work was completed on the lathe, the knobs were placed in a vise for the milling operations. The first mill operation was to drill and tap a hole (Figure 27) for a #6-32 set screw in the side of the knob.

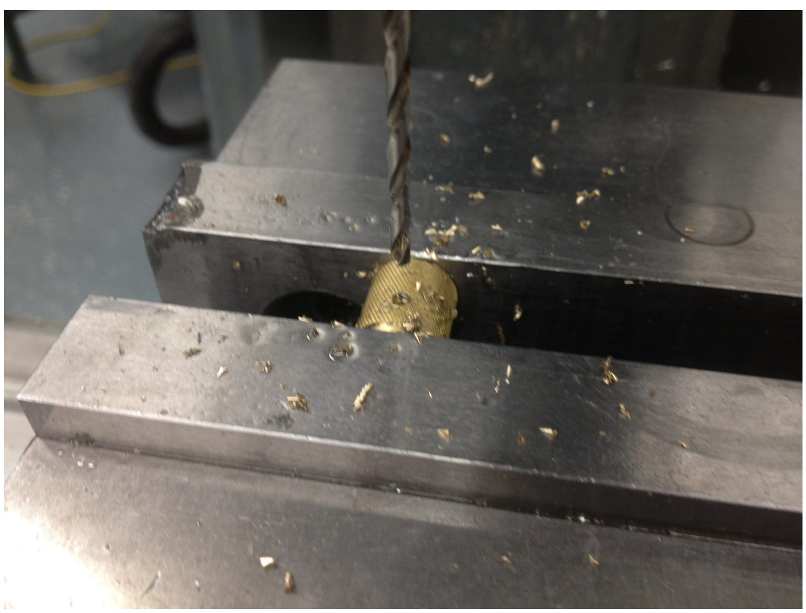


Figure 27: Drilling and tapping the set screw hole

After the hole for the set screw was drilled and tapped, the knob was re-oriented so the top faced the quill of the mill. To make the indicator line, a small, broken high-speed steel twist drill was ground flat on one side and relieved on the other side. This drill-turned-engraver was spun at around 2000 RPM and drug along the surface of the knob, producing a fine line, seen in Figure 28.

Note that with each step the drawing becomes increasingly stained with cutting fluid.

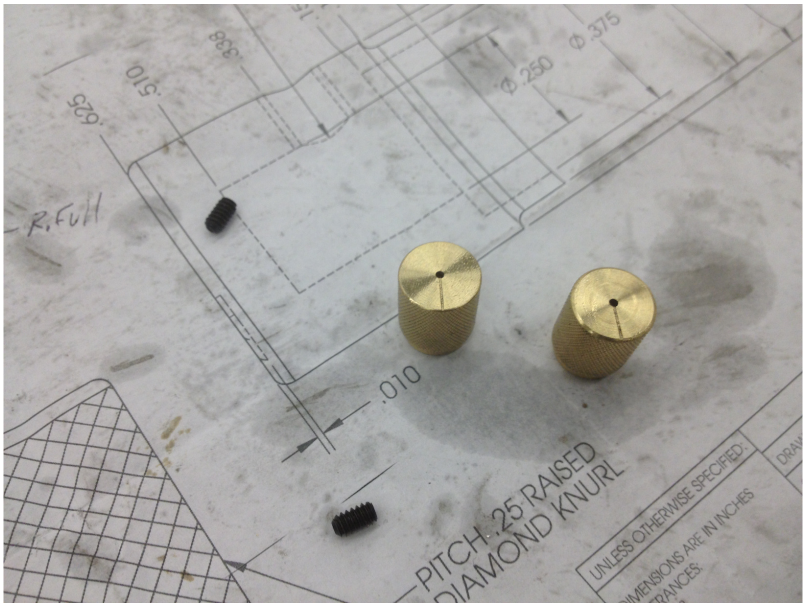
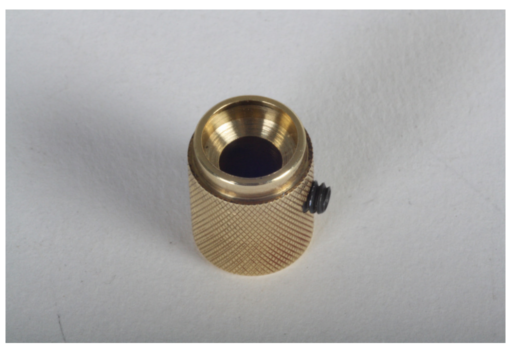
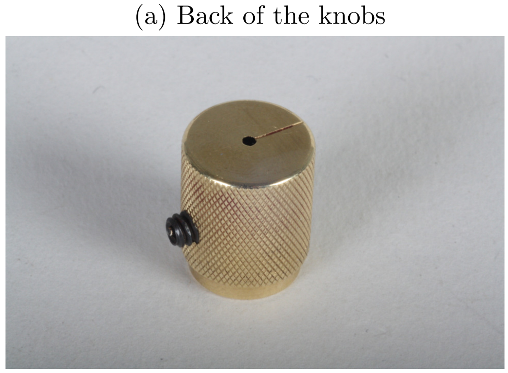


Figure 28: Engraved, sitting near set screws

The finished knobs are shown in Figures 29a and 29b.



(a) Back of the knobs



(b) Front of the knobs

Figure 29: Completed Knobs