EE1000 Project 2
Photo-Theremin

Overview

In this project, we build a simple Theremin, a musical instrument named after Leon Theremin, the Russian physicist who invented it around 1920. A Theremin generates a tone based on the position of the player's hands (which, incidentally, don't touch the instrument); one hand controls the pitch and the other controls the volume. The original Theremin detected the proximity of a player's hands using capacitance, but our Theremin will be somewhat simpler and detect the player's hands using the light or shadow they cast.

Design

The Theremin can be illustrated as shown in Figure 1. The oscillator generates a signal whose frequency depends on the amount of light striking a photoresistor. The oscillator generates a triangle wave that contains some frequencies that are unpleasant to hear, so the signal is fed through a filter that removes the higher, offensive frequencies. Finally the amplifier gives the signal enough power to drive a speaker. The gain (volume) of the amplifier is controlled by another photoresistor.
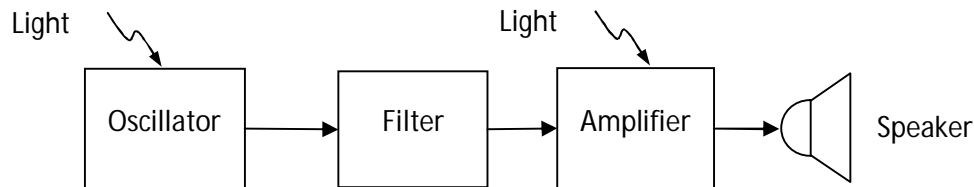

Figure 1 – Block Diagram

Oscillator

The oscillator generates a pitch based on the amount of light detected by a photoresistor. A photoresistor is a device that has high resistance in the dark and lower resistance when it is light. We will be using 200kΩ photoresistors, which means they should range from about 200kΩ (in the dark) to about 5kΩ (in a well lit room). We will also be using operational amplifiers. An operational amplifier (or op-amp) is a simple device that has two (analog) inputs and one (analog) output. The two inputs are labeled + and − (just like a comparator).
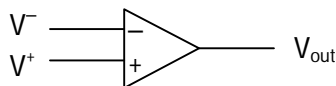

Figure 2 – Schematic Symbol for an Operational Amplifier (Op-Amp)

Based on those inputs, the op-amp drives the output voltage to

$$V_{out} = A(V^+ - V^-)$$

where A is the gain of the op-amp. Typically, the gain of an op-amp is so large we can assume it is infinite. The second assumption we make about op-amps is that no current flows in or out of the inputs. Usually op-amps are connected with *negative feedback*. This means that the output

is connected in some way to V⁻ so that if a small difference in V⁻ and V⁺ develops, the output moves to eliminate it. When op-amps are connected this way, we can make a third assumption, that is $V^- = V^+$.

Sometimes, the output of the op-amp will feed back to the V+ input. This is called *positive feedback* and it can be used to provide *hysteresis* to the op-amp circuit. (The output of a device with hysteresis depends not only upon its present inputs, but upon past inputs as well.)

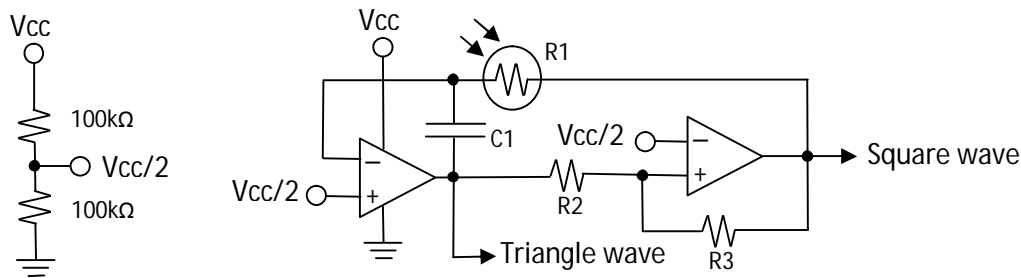We can use two op-amps to make the simple light-sensitive oscillator shown in Figure 3.

Figure 3 – Oscillator.

This oscillator generates two outputs, a square wave output and a triangle wave output. When the square wave voltage is high (≈ Vcc), the triangle wave "ramps down" until it reaches a trigger voltage that causes the square wave to toggle low (≈ 0V). The triangle wave then "ramps up" until the square wave toggles high and the cycle repeats.

To see why this works, we will look at each op-amp individually. The op-amp on the left uses negative feedback, and since no current flows in or out of the op-amp inputs, the current flowing through R1 must also flow through C1. When the square wave output is high, the op-amp must ramp its output voltage down at a rate of Vcc/(2·R1·C1) Volts per second to keep V⁻ equal to Vcc/2. (The current through a capacitor is equal to the rate its voltage changes multiplied by its capacitance). When the square wave output is low, the op-amp must ramp its output voltage up at the same rate.

The op-amp on the right uses positive feedback and has hysteresis. Once again, all the current flowing through R3 also flows through R2. If we assume, for the moment, that R3 is twice the resistance of R2, then the voltage drop across R3 is twice that of R2. When the square wave voltage is low and the triangle wave rises to ¾ Vcc, the voltage drops across R2 and R3 are ¼ Vcc and ½ Vcc respectively, which means that V⁺ is Vcc/2 exactly. When the triangle wave rises above ¾ Vcc, V⁺ rises above V⁻ and causes the output (square wave) to toggle high. A similar analysis shows that the square wave output remains high until the triangle wave falls below ¼ Vcc.

If we continue with the assumption that R3 = 2·R2, it is clear that the triangle wave output ramps up to ¾ Vcc and down to ¼ Vcc then repeats. Since the ramp rate is Vcc/(2·R1·C1) Volts per second, it can be shown that the frequency (pitch) of this oscillator is:

$$frequency = \frac{1}{2(R1)(C1)}$$

Suppose C1 is 0.033μF, then if R1 ranges from 5kΩ to 200kΩ, the frequency ranges from about 75Hz to 3kHz, which are all within the audible range.

Choose resistors (other than R1, which is supplied) and a capacitor for your oscillator and build it. Almost any op-amp will work in this circuit, so once you have obtained an op-amp, look up the datasheet online to get its pin diagram. It is good practice to connect decoupling capacitors between the power and ground pins of all integrated circuits, including op-amps. Decoupling capacitors are usually in the range 0.01µF to 0.1µF.

Test your oscillator by connecting an oscilloscope to its triangle wave output and by varying the light to the photoresistor. You should see a triangle wave of constant amplitude whose frequency varies with the amount of light.

Filter

The oscillator output we want to use is the triangle wave, but audible triangle waves are a little raspy because they contain some high frequency components. (They sound much better than square waves, however.) Still, we would like to get rid of the higher frequencies, and to do that we need a filter.

You will learn how to design filters when you take a signals class in your Junior year. For now, it will be necessary to build the filter without completely understanding it. The filter in Figure 4 is called a Sallen-Key filter and with the resistors and capacitors shown, it starts to attenuate (reduce the amplitude of) frequencies starting at about 2kHz. The higher the frequency, the greater the attenuation.
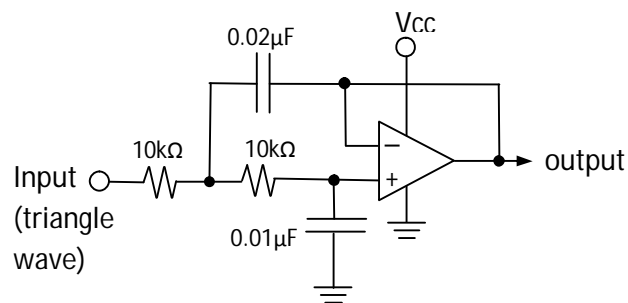

Figure 4 – Sallen-Key Filter.

Again, nearly any op-amp will work. Build your circuit and connect it to the triangle wave output of your oscillator. Test your circuit by connecting the oscilloscope to the output and varying the light to the photoresistor. You should see a triangle wave with the tops and bottoms rounded. At higher frequencies the triangle wave should morph into a sine wave.

Amplifier

Op-amp outputs are rarely able to drive a speaker directly, so it will be necessary to amplify the signal before it goes to the speaker. In this case, the gain, or the amount of amplification, should depend on the light hitting a second photoresistor (so the player of the Theremin can control the volume). The TDA7052A amplifier we used in Project 3 is a suitable amplifier, but if we were to connect it directly to the output of our filter, we would surely overdrive the speakers.

It will be necessary to reduce the signal amplitude before feeding it to the TDA7052, but by how much? Suppose the maximum speaker output must be less than 0.5 Watts. For an 8Ω speaker, the power is given by:

$$P = \frac{V^2}{R} = \frac{V^2}{8} = 0.5W$$

Solving for V we get an RMS voltage of 2V or 5.6Vpp. The TDA7052A has a gain of about 30, so its maximum peak-to-peak input voltage should be about 0.2V. Assuming the signal coming from the filter is about 5Vpp, we will need to reduce the signal by a factor of 0.2/5 = 0.04 (for maximum volume). One way to do this is to use a voltage divider. If we incorporate the photoresistor into the voltage divider, we can handle the volume control as well (Figure 5).

Build your circuit, but do not connect the speaker until you have measured the voltage on the outputs (pins 5 and 8) of the TDA7052 to verify the signal will not overdrive the speaker.
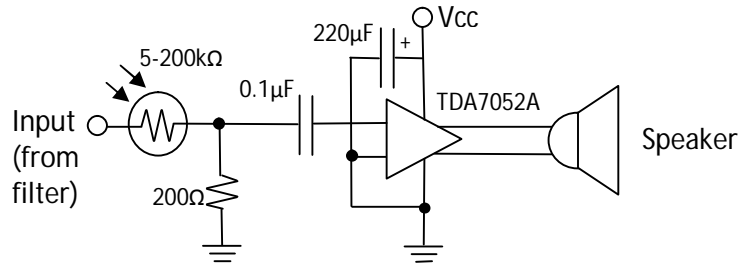

Figure 5 – Variable Gain Amplifier Circuit.

It is recommended that the photoresistors be separated by 4-5 inches at least so that pitch control and volume control do not interfere with each other. Note also that the behavior of the Theremin depends on the lighting of the room. If there are one or two overhead lights, the photoresistors will be very sensitive to the shadows that are cast. This problem can be mitigated somewhat by placing a sheet of wax paper a short distance above the photoresistors. If, on the other hand, there is a lot of ambient light, it is sometimes difficult to block enough light to get the full range of pitches and volumes, in which case it may be necessary to shroud the photoresistors in order to block out light coming in from the sides.

Finally, you may need to adjust some of the resistors to compensate for room lighting and component tolerances. Once you are finished, have some fun playing eerie music and sound effects.

Pin Diagrams