MAS.836 Sensor Technologies for Interactive Environments
Lab 5: Introduction to Capacitive Sensing

The purpose of this combined problem set/lab exercise is to introduce you to at least one type of capacitive sensor and familiarize you with its implementation. **There are many different ways of implementing position sensing through changes in capacitance;** this lab and problem set will focus on one of them.

Your circuit will be constructed from your lab kit, plus resistors, capacitors, and diodes from the Responsive Environments stock area. Additionally, you will need a small (a few inches square) piece of metal to use as your capacitive sensing electrode.

Your working circuit should be demonstrated to a TA on or before the due date. The report you turn in should contain the answers to the questions, a discussion of the design you chose, and schematics of the circuits you build. **Do not write your answers on this document; prepare your report neatly on separate pages.**

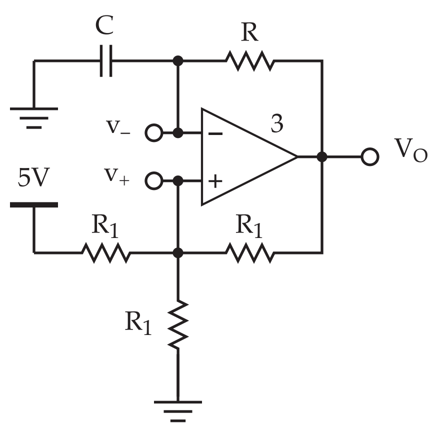
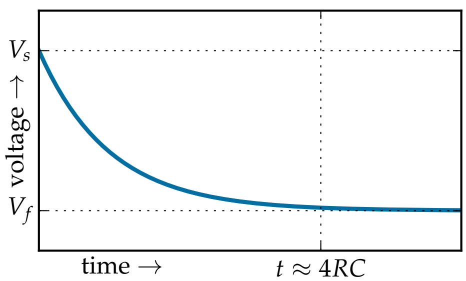


Figure 1: Relaxation oscillator schematic

1 Oscillator analysis

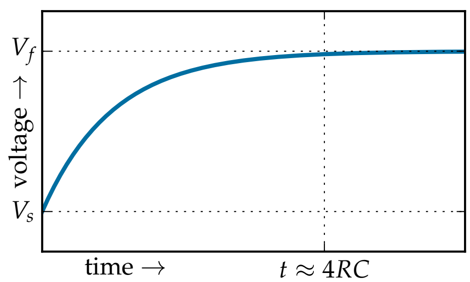
For any capacitive sensor, there must be an oscillator somewhere in the circuit. This oscillator will either be charging and discharging your sense capacitor, or creating the alternating electric field that is transmitted between electrodes. One simple oscillator design that can be built with either an op amp or an inverter is the *relaxation oscillator*, shown in figure 1.

The relaxation oscillator uses a capacitor which alternately charges and discharges to create an oscillating voltage. Since it uses a resistor with a constant voltage source to charge the capacitor (figure 4) the amount of current flowing into the capacitor changes with time. As more charge flows into the capacitor, the capacitor voltage increases. This decreases the total voltage across the charging resistor, decreasing the current flowing through it, and subsequently decreasing the rate at which the charge accumulates in the capacitor. So, the capacitor will continue to charge up, but more and more slowly as time goes on. The equations that characterize this behavior are shown in figures 2 and 3.



$$V(t) = V_f + (V_s - V_f) \cdot e^{-t/RC}$$

Figure 2: RC circuit discharging



$$V(t) = V_s + (V_f - V_s)\left(1 - e^{-t/RC}\right)$$

Figure 3: RC circuit charging

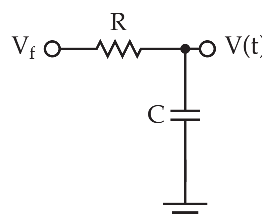


Figure 4: Series RC circuit

V_s is the starting voltage on the capacitor, V_f is the voltage on the other side of the charging resistor (the final voltage that the capacitor will attempt to reach), R is the charging resistor, and C is the capacitor value. e is the mathematical constant, with a value ≈ 2.72.

Questions

1. If the relaxation oscillator circuit in figure 1 is powered by a single 5 volt rail, what is the voltage v_+ at the non-inverting terminal of the op amp when the voltage at the output of the op amp (V_o) is 5 volts?
2. What is the voltage at v_+ when V_o is 0 volts?
3. Draw your results from (1) and (2) as horizontal lines on the plot in figure 5.
4. If the circuit is starting up after being off for a long time, there will be no charge on the capacitor. What are the values of V_o and v_+ if v_- is 0 volts?

5. Since the output voltage will not change until $v_+ = v_-$, if $R = 5\ \text{k}\Omega$, $C = 2\ \mu\text{F}$, and the capacitor starts at 0 volts, how long will it take for the output to change state?
6. Plot v_+, v_-, and V_o on figure 5 as a function of time for this starting condition.
7. What are v_+, v_-, and V_o directly after this transition occurs?
8. What is the final voltage v_f that the capacitor will charge (or discharge) to next?
9. How long will it be before v_- once again equals v_+?
10. Plot v_+, v_-, and V_o on figure 5.
11. Repeat (7) through (10) until you reach 40 ms.
12. What is the frequency of oscillation of this circuit?

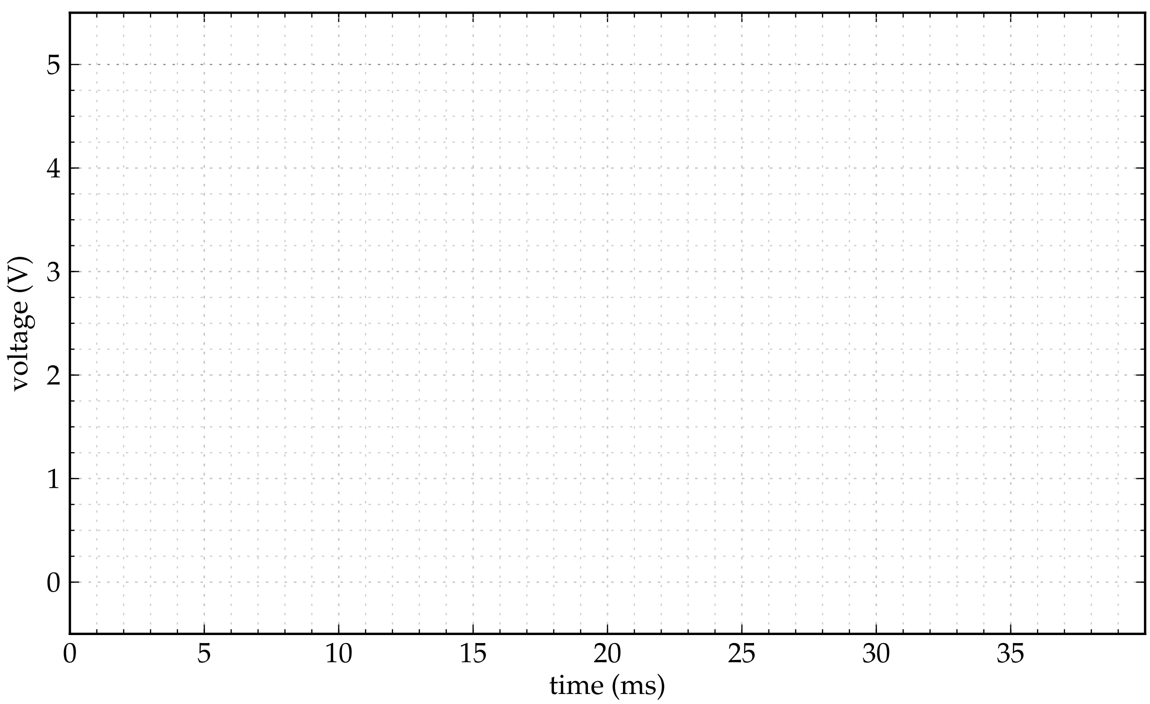


Figure 5: Relaxation oscillator plot for section 1

Please plot neatly and use different colors for each plotted line. Include a legend explaining your color code. (Labeled plots generated with MATLAB, pylab, etc. are also acceptable.)

2 Capacitive sensing amplifier construction

In this part of the assignment, you will build a capacitive sensor from the parts in your lab kit and a metal electrode. You should use an electrode that is a few (2-3) inches in each dimension. Consult with the course staff if you have difficulty locating a suitable electrode; a blank copper PCB works well. (Other metal objects can also make interesting electrodes; you might experiment with different things that you find.)

With a single electrode, you will build a loading mode capacitive sensor. In loading mode, the change of capacitance between the electrode and ground is measured as a person (or other well-grounded object) moves toward the electrode. Recall from problem set 3 that the capacitance of two parallel plates is given by $C = \epsilon \cdot A/t$, where ϵ is the permittivity of free space, A is the area of the plates, and t is the spacing between them. So, as the distance between your electrode and the sensed object increases, the capacitance will decrease.

All forms of capacitive sensor require an oscillator to drive the electrode. Using a drive frequency that is higher than most ambient electrical noise (60 Hz mains noise, for example) helps make your circuit less susceptible to this noise.

A simple oscillator design was presented in problem 1 and more can be found in books such as [1], but remember that you only have four op amps to complete your circuit.

You will drive the electrode with the oscillator and measure the changing impedance presented by your hand as you move it above the electrode. Your hand will increase the capacitance at the electrode and load down the circuit. There are many ways of measuring this added load, so choose one that gives you the best sensing range.

Finally, you should make your LED glow brighter the closer you place your hand to the electrode.

Questions

1. How close to the electrode must your hand be before the LED starts to come on?
2. How is your answer to (1) related to the dimensions of the electrode?
3. What is the largest distance you could reasonably sense with your electrode, and what might account for any discrepancies between this and your answer to (2)?

References

[1] P. Horowitz and W. Hill, *The Art of Electronics.* New York: Cambridge University Press, 1989