EXPERIMENT 12

Sensors

12.1 Applications

In order to do something practical, circuits often require one or more sensors. Many types of sensors exist, and cover a broad range of physical phenomena, e.g., temperature, soil moisture, radiation, light, smoke, proximity, liquid flow, touch, acceleration, and more. Additionally, they come in a wide variety of shapes, sizes, accuracies, and power levels. In order for a sensor to really be useful, all the outputs need to be electrically processed and combined in a meaningful way to achieve an overall system goal.

12.2 Types of sensors: electrical interface

Sensors measure physical phenomena, so they are inherently analog in nature. The exact principals that a sensor works on varies widely depending on what is to be measured; however, all the sensors we are interested in affect the behavior of an electrical circuit in some predictable way.

The analog class of devices directly change an electrical property in response to their environment and require additional analog circuitry to properly convert the reading to a voltage or current. More advanced analog sensors use integrated circuits (ICs) that internally perform the processing. The digital class of sensors contain circuity that converts the analog measurements to digital representations suitable for interface with a computer or other embedded device.

Again, it is important point out that *all* sensors are analog at the core. When someone refers to a sensor as being analog or digital, they are referring to the nature of the sensor's output signal.

12.2.1 Analog class

Sensors with analog outputs require the designer to do all of the analog processing of the signal. They can be used for sensing and control with only filters, amplifiers, and comparators.

Analog sensing devices react to their environment by either outputting a voltage or current or changing the device's resistance. Some analog sensors are active and require an external power supply. This usually indicates that the device is performing additional analog signal processing within the sensor. Other devices are passive and can be measured directly.

Voltage and Current

Most active analog sensors will output a voltage proportional to the sensed value. These sensors have internal circuitry that convert the sensing element's state into a controlled output voltage. Active analog sensors can also compensate measurements in order to ensure they are accurate across a wide variety of operating conditions.

Passive analog sensors are able to use the environment to supply a small(1) amount of power to a system. The power can be measured as a current or voltage, depending on the situation and principals of operation. Both will usually need some amplification to bring the signal to a level useful for control of another device or be input into an analog to digital converter.

(1) In other words, the source acts like a voltage or current source with a large series resistance. Consider how this might lead to loading issues.

Resistance

A large set of passive sensors measure various physical quantities by altering their resistances. Temperature, force, and light are all physical phenomena that can be measured using a resistive sensor.(2) Resistive sensors do not provide their own source of energy, so they must be biased in order to measure the value.

(2) Resistive sensors tend to be the easiest to understand, but other sensor technologies can work better in other aspects like power or accuracy.

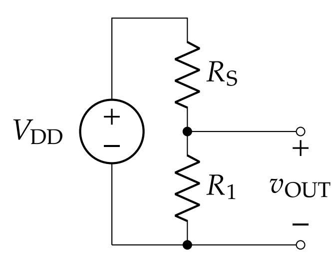

Figure 12.1: Voltage divider circuit for measuring a resistive sensor. R_S is the sensor resistance.

One of the easiest ways to measure a resistive sensor is to leverage the resistor voltage divider. A divider can be made with one known resistor and the sensor, as seen in figure 12.1.

The output of the circuit is

$$v_{OUT} = \frac{R_1}{R_1 + R_S} V_{DD}$$

If R_S is the resistive sensor and a DC voltage is applied the output will be a DC(3) voltage proportional to the sensed value through the divider equation and the sensor's relationship.

(3) Assuming, of course, that whatever is being sensed is nearly constant too!

Example 12.2.1: Thermistors

Thermistors are temperature dependent resistors. There are two types of thermistors: positive temperature coeffecient thermistors (PTCs) increase their resistance as temperature increases. They are most commonly used as resettable fuses. Negative temperature coeffecient thermistors (NTCs) decrease in resistance as temperature increases. They are usually designed to be used as inexpensive temperature sensors.

We will use an NTC thermistor as a temperature sensor. The equation for the resistance of an NTC sensor is given in equation (12.1).

$$R = R_0 e^{B\left(\frac{1}{T} - \frac{1}{T_0}\right)} \tag{12.1}$$

R_0 is the resistance at T_0. R_0 and T_0 are typically specified at room temperature, which is usually 298 or 300 Kelvin. The coefficient B is a constant reported by the datasheet. Thermistors can be purchased at many different values for R_0, but B is usually limited to a very small list.

In this example we use a thermistor from muRata's selection of NTCs [1]. The component is a 47 kΩ thermistor with a B value of 4050. The datasheet indicates that the value of R_0 is measured at $T = 25\,°\text{C} = 298\,\text{K}$. We can use equation (12.1) to find the expected relationship between temperature and resistance for this thermistor:

$$R = 47000 e^{4050\left(\frac{1}{T} - \frac{1}{298}\right)} \tag{12.2}$$

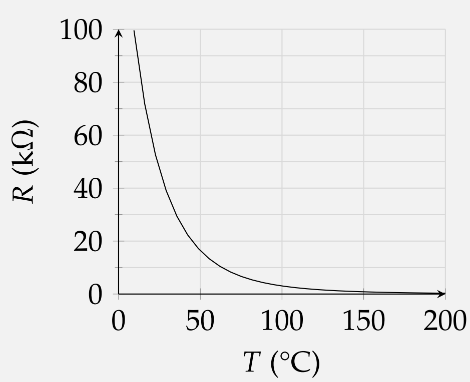

Figure 12.2: Resistance versus temperature of a 47 kΩ NTC

To use the temperature sensor in a circuit, we build a voltage divider with the temperature sensor. Using the circuit in figure 12.1 with $R_1 = 15\,\text{k}\Omega$ and $V_{DD} = 5\,\text{V}$, we can solve for temperature in terms of v_{OUT}.

$$
\begin{aligned}
v_{\mathrm{OUT}} &= \frac{15\,\mathrm{k}\Omega}{15\,\mathrm{k}\Omega + 47\,\mathrm{k}\Omega e^{4050\left(\frac{1}{T}-\frac{1}{298}\right)}} \times 5 \\
T &= \frac{1}{\frac{1}{298} + \frac{1}{4050}\ln\left[\frac{15}{47}\left(\frac{5-v_{\mathrm{OUT}}}{v_{\mathrm{OUT}}}\right)\right]}
\end{aligned} \tag{12.3}
$$

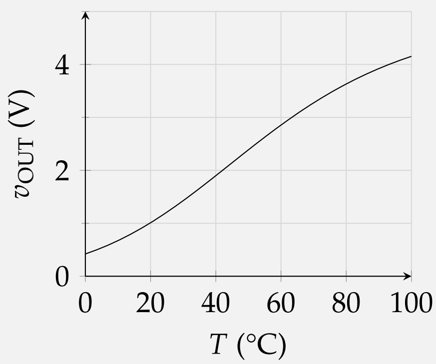

Figure 12.3: Output voltage versus Temperature

Notice that the sensor has a region that is somewhat linear. It is common to "calibrate" such system by finding the best fit line amongst measurements made in that region. If this is done, care must be taken to design the system so that the final region of operation lies only in this nearly linear part, otherwise the error can be quite large.

This circuit converted a passive resistance based sensor into an active voltage output sensor. The output of our sensor can be measured directly, passed to a comparator to determine if the sensor is above or below a temperature, or sent to an analog control circuit. Be careful to consider the output resistance of this device in relation to loading when connecting it to something else, as you may need to use an op amp to buffer the signal.

12.2.2 Digital class

Digital sensors do the hard work of sensing and amplifying sensors for us and will output a digital signal with the sensor measurement. Unfortunately, the measurements from most digital sensors necessitate the use of some sort of computer or microcontroller to process properly. Any analog sensor can also be converted to a digital sensor with the addition of an analog to digital converter.

Pulse width modulation (PWM)

PWM changes the pulse width or duty cycle of a signal proportional to a measured value. It is unique because it can be read by a digital system as is[4] or converted to an analog signal with a low pass filter. If a PWM signal needs to be converted to an analog signal, a simple low pass filter is often sufficient. The cutoff frequency $f = \frac{1}{2\pi RC}$ should be set somewhere between the frequency of the PWM signal and the highest frequency of the phenomena being measured.

[4] The digital system only needs to measure how long the pulse is high versus the total period.

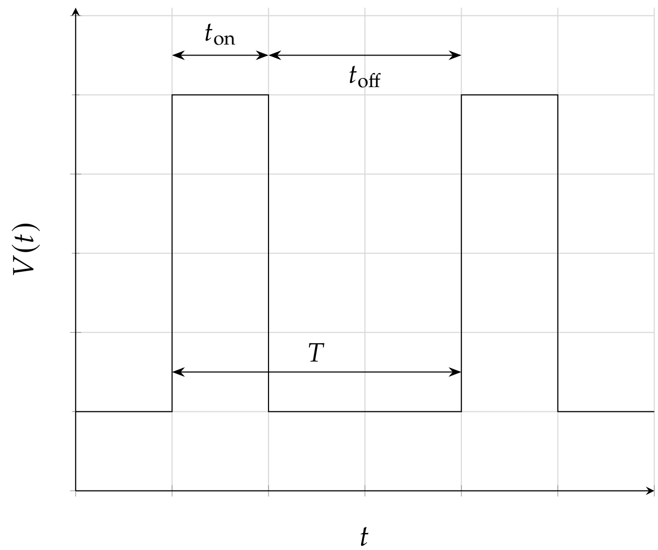

Figure 12.4: PWM signal

Example 12.2.2: Capacitive touch sensor

We will explore how a simple capacitive touch sensor can be built with PWM output. Capacitive touch allows for detecting when buttons are pushed with no mechanical movement and forms the basis for which most smartphone and computer touchscreens work. It works on the basis that humans have some capacitance to the circuit that changes depending on how close someone is to a capacitive sensor.

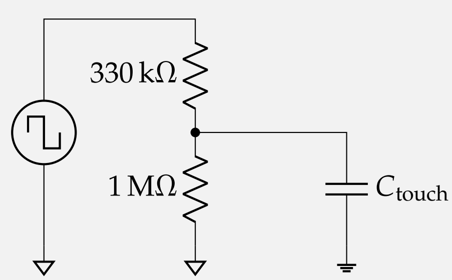

Figure 12.5: Touch sensor time constant circuit

We can measure the capacitance by finding the time constant of the simple RC circuit in figure 12.5. Note that C_{touch} is connected to a different ground than the rest of the circuit.

This is done to indicate that the user may not have a connection to your circuit ground; however, this typically is not a problem.

By measuring the voltage across the capacitor as it charges and discharges, we can determine the time constant of the system. When a user touches the sensor, the capacitance increases and the time constant will get longer. In order to convert this signal into a digital signal, we can use a comparator.

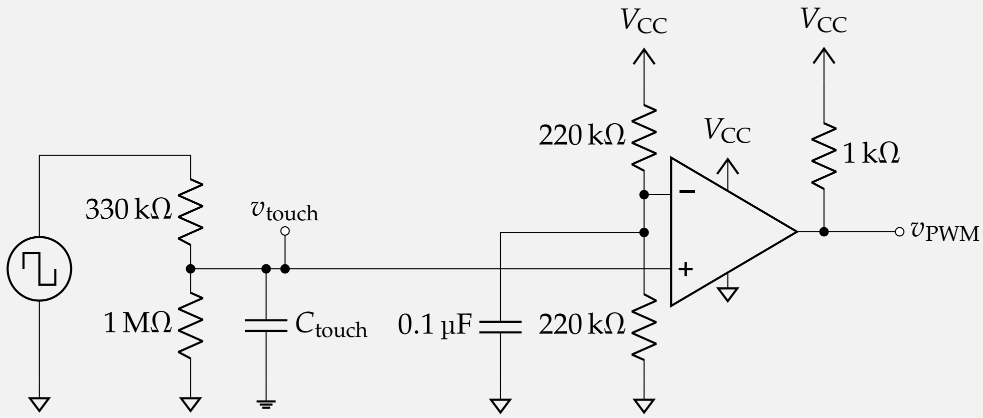

Figure 12.6: Touch sensor PWM circuit.

The circuit in figure 12.6 compares the voltage across the capacitor to half of the supply voltage and outputs a 1 or 0. When the sensor is touched, it takes longer to charge, so the duty cycle of the output signal changes.

Binary

There are a number of conventions and standards for sending binary data between digital devices. The simplest method is parallel, where each bit gets its own wire. This method requires a lot of pins on a device, so it is less common. Serial interfaces are much more frequently utilized. The specific details of the standards are beyond the scope of this experiment and will likely be covered in a microcontrollers course. The basic idea is that these protocols allow for a sensor to take a binary number and send it one bit at a time over a single wire.

Miscellaneous

It is possible that some digital sensors don't implement a standard communication method. For these sensors, careful analysis of the datasheet is necessary to fully understand their function.

12.3 Prelab

Task 12.3.1: Prelab Questions

Please complete the following tasks

1. Find the datasheet for the dual differential comparator (LM393) [2] or Quad Differential Comparators (LM339) [3] (whichever one you have) and record the pinout.
2. Find the datasheet for the IS31SE5100-SALS2 and describe its general functionality.
3. Calculate the R_1 necessary for the circuit in figure 12.1 to have $v_{\mathrm{OUT}} = 2.5\,\mathrm{V}$ at 25 °C using the same thermistor used in example 12.2.1.
4. Pick a sensor that measures something interesting from `https://www.digikey.com/en/products/category/sensors- transducers/25` Open the datasheet and answer the following:
   - What does the sensor measure?
   - What is the range of the sensor?
   - Does the sensor have an analog or digital output?
   - If it is analog, what type of output is it?
   - If it is digital, what digital protocol does it use?

12.4 Tasks

Task 12.4.1: Temperature Sensor Characterization

1. *Construct* the circuit in figure 12.1 using the NTC as R_S, a 15 kΩ resistor as R_1, and a V_{DD} of 5 V.
2. *Measure* the output voltage of the sensor.
3. *Configure* the data logger in Waveforms to convert the measured voltage to temperature in Celsius or Fahrenheit. If using Scopy, configure the datalogger to record the voltage to a CSV in 0.1s increments then use Excel to calculate the temperature in Fahrenheit and Celsius.
4. *Measure* the ambient temperature. Compare the temperature sensor provided by your GTA. *Capture* a screenshot of the data logger graph in waveforms or generate a plot of temperature vs. time in Excel.
5. *Chill* the thermistor and measure the new output voltage and temperature.
6. *Pinch* the thermistor and measure the temperature of your fingers.

Task 12.4.2: Capacitance Sensor Characterization

1. Build a capacitive touch sensor on your breadboard by placing 5 medium length wires in parallel with each other. All of the wires should be electrically connected.
2. *Build* the circuit in figure 12.6 using the LM339 or LM393 comparator and $V_{CC} = 5\,\text{V}$. Note that the oscilloscope probe will act as the $1\,\text{M}\Omega$ resistor! Don't connect the capacitor yet.
3. *Apply* a 20 kHz 0 V to 5 V signal as the input.
4. *Capture* a screenshot showing v_{PWM} and v_{touch} when the sensor is not yet attached.
5. *Connect* the sensor to the circuit and *record* the duty cycle of the output.
6. *Touch* the insulation of the touch sensor wires without touching any of the exposed metal. *Record* the new duty cycle.
7. *Comment* on the relationship between the duty cycle and the amount of pressure you use when pushing the wires.

Task 12.4.3: Capacitive touch board soldering

1. *Solder* the components to the provided capacitive touch board.
   a) First, solder all of the surface mount components on the bottom.
   b) Next, solder the through hole resistor and diode.
   c) Third, solder all of the LEDs.
   d) Fourth, solder the SIP resistor.
   e) Last, solder the headers.
2. *Verify* that everything is soldered correctly with your instructor.
3. *Set* a 150 mA current limit on the power supply.
4. *Apply* 3.3 V to the power supply input on the board.
5. *Verify* that the capacitive touch sensor works.
6. In your report, describe the process used to solder the board. Make sure to include all safety considerations for soldering including a discussion of the chemical safety of the solder and flux used. Your discussion should include potential concerns for the technician while soldering and the end user while using the product.

Task 12.4.4: Extra Credit: Infrared Object Detector

This entire task is extra credit.

A phototransistor is a device that changes the current flowing through it based on the amount of light that it measures. Phototransistors can be fabricated to only respond to certain wavelengths of light. For example, the infrared phototransistor (PT204-6B) [4] measures infrared light at a wavelength of 940 nm.
We will build a system that detects an object by measuring reflected infrared light and outputs a binary signal that indicates if an object is too close.

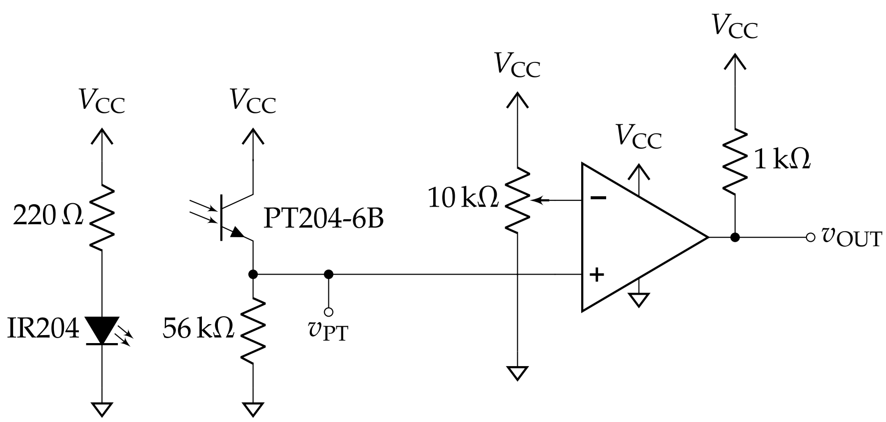

Figure 12.7: Active infrared proximity sensor

1. *Build* the circuit in figure 12.7 using the LM339 or LM393 comparator. Install the phototransistor and infrared LED next to each other on the breadboard and have them point in the same direction.
2. *Set* $V_{CC} = 5\,\text{V}$ and measure v_{PT}.
3. Hold your hand or a sheet of paper over the infrared LED and phototransistor. *Describe* the relationship between v_{PT} and the proximity of the object to the sensor.
4. *Record* the voltage of v_{PT} when your object is about 5 cm away.
5. *Adjust* the potentiometer to output this voltage to the negative comparator input.
6. *Record* the value of v_{OUT} when the object is farther than 5 cm and when the object is closer than 5 cm.
7. *Capture* an oscilloscope screenshot or data logger window showing both v_{PT} and v_{OUT} as an object crosses the object detection threshold.

12.5 References

[1] *NTC thermistors*, muRata, Aug. 2018. [Online]. Available: https://www.murata.com/~/media/webrenewal/support/library/catalog/products/thermistor/ntc/r44e.ashx.

[2] *LMx93, LM2903 dual differential comparators*, LM393, SLCS005Y, Texas Instruments, Jun. 2015. [Online]. Available: http://www.ti.com/lit/ds/symlink/lm393.pdf.

[3] *LM339, LM239, LM139, LM2901 quad differential comparators*, LM339, SLCS006U, Texas Instruments Inc., Nov. 2018. [Online]. Available: http://www.ti.com/lit/ds/symlink/lm2901.pdf.

[4] *3mm phototransistor t-1*, PT204-6B, DPT-0000293 Rev. 2, Everlight, Jun. 2013. [Online]. Available: http://www.everlight.com/file/ProductFile/PT204- 6B.pdf.