Oscilloscope Fundamentals and Joystick Interfacing

Objectives
1) Learn the fundamentals of how all oscilloscopes (analog and digital) work:
   - Vertical amplification subsystem (Volts/Division)
   - Horizontal sweep subsystem (Seconds/Div)
   - Triggering subsystem
2) Be able to measure a waveform using the triggered mode of oscilloscope operation
3) Be able to measure two waveforms using the xy mode of oscilloscope operation
4) Be able to describe where to connect the scope’s negative/ground lead.
5) Describe how potentiometers work
6) Describe how to design a variable voltage reference
7) Build an x-y joystick controller for the oscilloscope

Prelaboratory: Read this article about potentiometers and creating a voltage reference, and skim the instructions for the lab, and answer the prelab questions.

Potentiometers

A potentiometer is a standard 2 lead resistor with a third lead attached which taps into the resistive element at a variable point; see Figure 1. The potentiometer’s control can typically be twisted from about $\theta = 0^\circ$ to $270^\circ$. At $\theta = 0^\circ$, the center tap of an 100k$\Omega$ potentiometer is taken at one extreme end of the resistor as shown in Figure 2a, leads a and b are shorted together, and both see 100k$\Omega$ of resistance with respect to lead c. As the control is twisted, lead b separates from lead a, and sees an increase in resistance with respect to lead a and a decrease in resistance with respect to lead c. When the pot’s control is twisted to the other extreme, lead b sees the full 100k$\Omega$ with respect to lead a and zero resistance (a short) with respect to lead c. This can be used to construct a variable voltage reference as shown in Figure 3.

![Figure 1: The symbol and internal construction of a potentiometer](image-url)
Prelab questions: (write out answers to each; will be graded in first 5 minutes of lab)

1. For the simple variable voltage source shown in Figure 3, what is $V_{\text{out}}$ when the potentiometer (aka “pot”) is: rotated all the way clockwise (as defined in Figure 2 and shown in Figure 1), centered, and rotated all the way counterclockwise? To analyze, replace the pot with two resistors as shown in Figure 2.

2. As you twist the pot to clockwise you decrease the top resistor from 100kΩ to 0 and increase the bottom resistor from 0 to 100kΩ so that their sum is always 100 kΩ. What value is the top resistor and the bottom resistor to make the output 2.5V? (hint: they won’t be the same).

3. As it stands, this is a poor voltage source because it changes if you place a load on it. For example, connect the output of the circuit you designed in problem 2 to a 75kΩ load (i.e. in Figure 3 connect a 75kΩ between $V_{\text{out}}$ and ground representing some load). $V_{\text{out}}$ will drop because the load forms a voltage divider with the potentiometer. What is the new $V_{\text{out}}$?

4. To fix this problem, attach an opamp buffer circuit (the same thing as an amplifier with a gain of +1) to the output of the potentiometer. Draw the entire schematic for this circuit. (You may need to refer to your EE122 notes). Now, you can load the output of the opamp with 75kΩ load, and the voltage won’t change. In fact, you can load the output of the opamp with anything, and as long as it draws less than the maximum output current of the opamp (about 15mA for a common 741 opamp), $V_{\text{out}}$ remains stable.
**Laboratory:**

**Oscilloscope fundamentals**

The oscilloscope is a device that graphically displays voltage waveforms. In this lab you will learn to use both the standard triggered mode and a less-commonly used xy mode of scope operation. Although the specific keys this lab instructs you to use are specific to the Agilent digital oscilloscope we use in the lab, the core of the material is common to all types of oscilloscopes.

Turn on the scope (the white button in the lower left corner) and reset all the weird possible configurations by waiting for it to boot and then pressing the “Default Setup” button in the upper right. The yellow line is the voltage vs. time; it is flat at zero because nothing is connected. Attach a scope probe to Channel 1 (under the “1” key). The scope probes are gray and have circuitry inside, not to be confused with the black cables that are just wires. Press the tip of the probe against your finger; you will see a small signal. Turn the horizontal knob (the knob under the Horizontal label) counterclockwise while the probe is pressed against your finger; you will see a rough 60Hz waveform that has been coupled into your body by the AC power lines in the building. You are an antenna!

**Frequency generator fundamentals**

To use the oscilloscope that measures changing electrical signals, you must first understand how to generate changing electrical signals. Last semester in EE122 when the signals did not change in time it was easy; there was just one variable called voltage, and you set it from a DC Voltage power supply. (The phrase “DC Voltage” is a misnomer since DC stands for “Direct Current” and it is not a constant current supply but a constant voltage supply; this confusing terminology became fixed a century ago.) Now in EE223 we introduce voltages that changes with time; these are functions and exist in infinite varieties. Although we could generate them by making a rat constantly rotate the amplitude knob of a DC power supply, they have a hard time doing so at audio rates (20-20,000 times per second), and tend to get tired after a few hours. Instead we rely on a function generator.

Two waveforms are the most common: square waves which alternate between one constant voltage for one time period, then switch to a second voltage for a second time period, and sinusoids which smoothly vary between a low and high voltage according to the equation $v(t) = V_{pp} \cos(2 \pi f t) + V_{offset}$. We will use sinusoids exclusively in this lab. In the equation given, the voltage between the top and bottom peaks is $V_{pp}$ ($V_{pp}$ stands for means Vpeak-to-peak), and it oscillates between those extremes centered at an average of $V_{offset}$ with a frequency of $f$, so that in 1 second there are $f$ periods (i.e. cycles) of the sinusoid and each period occurs in $1/f$ seconds. Example: you could generate a waveform that smoothly varies between 2 and 10V seventeen times per second by setting $f=17$, $V_{pp} = 4$, and $V_{offset} = 6$. What setting would you use to make a waveform that varies between -1.5V and 3.5V with a period of 100us (not 100ms)?

<table>
<thead>
<tr>
<th>$f$</th>
<th>$V_{pp}$</th>
<th>$V_{offset}$</th>
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We are lucky enough to have a function generator built into our oscilloscope, but don’t be confused: the function generator creates the signal and outputs it through the BNC cable connector in the lower left called “Gen Out”; the oscilloscope measures the signal and inputs it from the two BNC connectors on the lower right. One is an output, the other are inputs.

Make a $f = 10\text{kHz}$ sinewave that oscillates between -1.5V and of 3.5V on the frequency generator of the Agilent 2012A scope. To do this,
1) connect a standard black BNC cable with minigrabbers to the Gen Out BNC connector, and connect the grounds together (black alligator clip of the scope probe to the black clip from the frequency generator, main gray clip from the scope probe to the red clip from the frequency generator).
2) press the “Default Setup” button on the scope and then the “Factory Default” softkey (and confirm).
3) turn on the frequency generator (press the WaveGen key in the scope’s center).
4) change the Frequency, Amplitude and Offset buttons to make it output the waveform described above. You can change the values by selecting the button and twisting the knob. You are still too far zoomed out to see anything, however.
3) Twist the vertical zoom (above the “1” key) until “1V/div” in the upper-left hand corner. Press in (do not twist) the Trigger Knob that says “press for 50%”. You should see about 10 cycles displayed on the screen.

**Adjusting Basic Scope Controls**

Imagine a perfect graph of a signal exists that you want to measure. The graph measures voltage on the vertical axis and time on the horizontal axis. If the signal is fast-changing (say, 10kHz like you just measured) and exists for a long time (say, 10 minutes) the plot would be very, very long! Imagine now a small rectangular window, the scope screen, superimposed over the plot. That is what the oscilloscope displays. You need to be able to scale the idealized underlying plot to make it appear bigger or smaller so it fits correctly on your small windowed screen, and you may need to translate it up/down or left/right as well. In this section you will learn to do that.

1) Set the function generator to a 100Hz sinewave at $2V_{pp}$ with no DC offset. The scope may look screwed up (we say it has “lost the trigger lock”); you’ll fix this in a moment.
2) Increase the Horizontal zoom (the knob under the “Horizontal” label) until it is 10ms/div (read it out in the upper right corner of the display). You should now see a (possibly jittery) signal.
3) There are four things you can do to change the way the waveform is graphed in this mode: you can expand or compress it horizontally, translate it horizontally, expand or compress it vertically, or translate it vertically. Experiment with the Vertical Gain knob (the large one above the “1” button), the Vertical Offset knob (the small one below the “1” button), the Horizontal knob (the large one underneath the “Horizontal” label) and the Horizontal Offset knob (the smaller one to the right of the Horizontal knob). Write in the table below the name of the knob that adjusts the indicated action.
Turn the **Vertical Gain** knob of channel 1 clockwise and observe that you can easily saturate the scope display – do not leave it there as it can damage the scope. The waveform should always remain in the display area. Turn it counterclockwise and observe how the scope “loses its lock” on the waveform, and the waveform starts to jitter horizontally. More on this later. For now, leave the vertical gain on 1V/div. The scope has a grid pattern overlaid on it; this means each of the horizontal lines are spaced at 1Volt per division. Be able to read the voltage of the waveform using the grid division lines.

Turn the **Horizontal** knob and note how you can expand or compress the waveform. If you choose a 1 ms/div setting the 100 Hz waveform (that takes 10ms to complete one cycle) looks expanded. How far can you zoom in? If you choose a 100ms/div setting, the 100 Hz waveform looks compressed. Leave it at 5ms/div.

*Remember; the scope controls don’t change the actual signal; your function generator does that. The scope controls only change your **view** of the signal.*

### Using the Scope in Triggered Mode

Go back to our conception model: that a perfect voltage vs. time plot exists on paper, and that the scope window is a small rectangular overlay over that very long true plot. You now know how to scale the underlying true plot in size and translate it around so the scope window can examine different parts of it. But which particular small window are you observing? You could take a snapshot in time by pressing the big green Run/Stop button in the upper right, which will freeze the display. The normal “triggered” mode does something far smarter however…it takes repeated snapshots automatically. It snaps a picture, and then centers that picture on the display so that the signal is just rising past some threshold (by default 0V) in the center of the display. Look at the display now: you’ll notice that at the very center of the screen, directly under the orange triangle on top, the sine wave is rising above the 0V threshold. The scope then takes another snapshot a few milliseconds later and centers that picture in the same way. If the signal isn’t changing it will look like a still picture, even though it may be racing along at 100 cycles every second, as in our current case.

1. You need to know this because you need to understand why this sometimes fails. With the same setup as previously described (function generator at Vpp=2V, Voffset=0V, f=100Hz, and scope at 1V/division vertical gain and 5ms/division horizontal sweep speed), turn down the vertical sensitivity to 10V/division. The signal will just wiggle; it is not tall enough for the scope to be able to tell where it crosses zero, so the scope gives up and just overlays every picture it takes at a random horizontal location, giving the appearance of jitter. Turn the vertical gain back
to 1V/division. At what setting of the Vertical Gain knob does the trigger fail to lock?

2. The trigger can also fail to lock if the waveform has a DC offset. Dial in a 2V offset to the signal in the generator. Now the signal never passes through 0V so the oscilloscope never triggers. You can make the scope trigger by changing its trigger level from 0V to something else. Twist the Trigger Level knob (a new one we haven’t yet used) until the threshold rises enough into the signal that the trigger locks. For what range of voltages will the trigger lock?

   Lowest: ___________  Highest: ___________

   Remember: although you could also get it to lock by changing the $v_{offset}$ of the function generator, in practice you will be measuring some signal you have no control over so this won’t be an option. You’ll have to be able to change the trigger threshold level if the signal won’t lock.

3. **Channel Coupling**. Sometimes you’ll have a small sinusoid on a big DC offset voltage. Then if you zoom in enough to get a big enough “wiggle” on the screen to get a lock, the large offset will cause the signal to zoom right off the window. If that happens, you can put a small filter in series with your signal to remove the DC offset. It just effectively puts a capacitor in series with your input signal, changing it by removing the DC offset. Try it now:
   1. Restore the trigger level to 0V (you’ll lose your trigger lock when you do this).
   2. Press the “1” key, and then the “Coupling” menu item. Choose “AC”.
   You’ll see the signal drop down as if it had no DC offset, and the trigger will lock again. The signal in the external coax cable still has the DC offset; the scope is just removing it. Don’t keep it in this mode; the highpass filter used in the “AC Coupling” can affect signals in all sorts of odd ways; keep it in “DC” which just means the scope does not alter the incoming waveform in any way.
**Scope Ground Lead**

The scope probe has two leads; the positive lead and the ground lead. The positive lead is electrically connected to a very large resistance of about 10MΩ inside the scope. This is large enough that the scope draws very little current and therefore provides very little loading to circuits that have resistances of less than about 1MΩ. The ground lead however is electrically connected to the ground power terminal leading into the scope. This is at the exact same potential as the ground terminal that appears on your CADET II power supply or the signal generators (they are electrically connected through the wires that power both instruments). This means that while you may place the positive scope probe anywhere you desire to measure voltage, you must connect the ground lead of the scope probe to your circuit’s ground.

Connect it anywhere else (say, to the output of your complex circuit) and you have done the equivalent of shorting that terminal to ground. If you make this mistake you will have shorted the output to ground and will read exactly 0V on the scope (plus perhaps damage the circuit you are measuring if it wasn’t designed to be connected to ground). The moral of the story: **ALWAYS CONNECT THE SCOPE GROUND LEAD TO GROUND.** This is totally different than the battery-powered DMM, whose negative lead can be placed anywhere.
Numerical Measurements

1. Voltage Measurements: Set the function generator to deliver a squarewave that alternates between ±1V at 2kHz with no offset, and change the Horizontal knob on the scope so you get about 4 periods of the waveform on the display, with the Vertical Gain knob set so it mostly fills the screen without running off the top (aka saturating). Look at the middle of the scope under the Measure section and press the “Meas” softkey. Look on the bottom of the screen. Change the measurement type to Vpp (Voltage peak-to-peak) and then select the “add measurement” button. What range of Vpp voltages do you measure? Only measure to 3 significant digits.

\[ V_{pp \text{ lowest}} \quad V_{pp \text{ highest}}. \]

2. Time/Frequency Measurements: Now measure the actual frequency. By default it is shown on the right side of the screen. What is the range?

\[ f_{\text{lowest}} \quad f_{\text{highest}}. \]

3. Custom measurements: Measure the risetime of the squarewave, defined as the time to rise from 10% to 90% of the waveform. Ideally this should be 0. Press the “Type:” button on the bottom of the screen and select “Rise Time” using the button, and then “Add Measurement”. Record this value below.

\[ \text{risetime} \]

It’s not very precise, is it? That’s because it can’t do much better than you can from looking at the scope trace, and the trace makes it look like it rises pretty much instantaneously. To be able to see it more accurately, zoom all the way in using the Horizontal knob until you see the non-vertical slope of the rising edge. Notice that the risetime measurement is now precise. What is it?

\[ \text{risetime} \]

If you zoom out a bit so you see the area just after the trace rises, you may be lucky enough to notice a tiny ripple in the waveform after it rises. You are now zoomed in so far that you are seeing nanosecond artifacts (that is, characteristics of the waveform that last only a billionth of a second!). These ripples are caused by relativistic effects, and you could measure the speed of light in the cables by dividing twice the cable length by the time period of the ripples. (You’d find confined to the cables that it travels roughly half the speed of light in a vacuum).

Turn the Wave Gen button off; you are done with the signal generator for this lab.
X-Y Mode and Joystick Control

The last scope mode is called XY mode. In all previous modes, one of the axes represented voltage and other time. In XY mode, time is not swept or measured; instead Channel 1 represents the x position of the cursor and Channel 2 represents the y position of the cursor. (Do you see that the previous modes really were all x-y modes with a repeating ramp waveform used for the x input, and the voltage to be measured connected to the y input?) The xy mode is not commonly used, but the need occasionally arises. In this section we will build a joystick that controls the cursor position using a set of gimbaled potentiometers.

1. Ask for a dual potentiometer joystick from the instructor. Examine how it works. These are fairly delicate. Keep one hand on the joystick body when you rotate the control stick after you place them in the protoboard.

2. Build the circuit shown below using the potentiometers:

![Circuit Diagram]

Note that each of the two axes $V_x$ and $V_y$ can be powered by the Cadet II power supplies as shown below for $V_x$:

![Power Supply Diagram]

3. Reset the scope by pressing the “Default Setup” key. Hook $V_x$ and $V_y$ into the scope channels 1 and 2. Place the scope in xy mode (Press the “Horiz” button, then from the screen menu choose the Time Mode as “xy”) and adjust the scaling (the Vertical Gain for channel 1 and 2) to 2V/division so that the joystick allows you to move the cursor over most of the display screen.

Get checked off by the instructor.
Discussion Questions

For this laboratory, no procedure is required, since that is provided in this lengthy lab packet itself. Instead, turn in this lab packet with the fill-in-the-blanks completed. Go back and examine the learning objectives. We concentrated primarily on objectives 1 and 2 since these are the most complex, but all 7 objectives are important to understand.

1. A friend is tempted to check her house current by plugging in her scope into an electrical plug. One side of a two prong outlet is called “neutral” and is set to the same ground potential as the scope’s ground lead; the other is “hot” and is the one that oscillates at ±120Vrms relative to ground (we will explain in detail what Vrms is later in the course; for now it is one of several ways to describe the amplitude of an AC voltage).
   a. If she hooks the scope’s ground lead to the electrical outlet’s neutral wire and the scope’s probe to the outlet’s hot wire, what should she see?
   b. How about if she reverses the leads?

2. The most common type of potentiometer has a linear taper, which means the resistance between lead b with respect to leads a and c in Figure 1 changes in a linear manner with \( \theta \) (the angular position of the control). Given a 100k\( \Omega \) linear taper potentiometer connected to +5V and –5V as shown to the right, graph the relationship of \( V_{\text{out}} \) with respect to \( \theta \) (i.e. graph \( V_{\text{out}} \) as the potentiometer is rotated). A neatly-labeled hand-drawn sketch is fine.

3. An ideal voltage source has zero internal resistance. The general rule for a good voltage source is that its internal resistance should be no more than about 1/10 of the resistance of whatever load it powers. To understand why this is true, consider what would happen if a 6V voltage source that had an internal resistance of 1k\( \Omega \) (think of an ideal 6V source in series with a 1k\( \Omega \) resistor) was intended to power a load of 500\( \Omega \). The internal resistance of the source would appear in series with the load resistance forming a voltage divider and only 6V * (500 / (500 + 1000)) = 2V would appear across the load!
   a. What is the Thevenin equivalent of the above circuit as seen by \( V_{\text{out}} \) when it is rotated fully clockwise?
   b. When the potentiometer is centered? (Hint: it is not 100k\( \Omega \) or 50k\( \Omega \) for either case. Instead, draw the equivalent circuit replacing the potentiometer with two resistors as shown in the prelab circuit of Figure 2).