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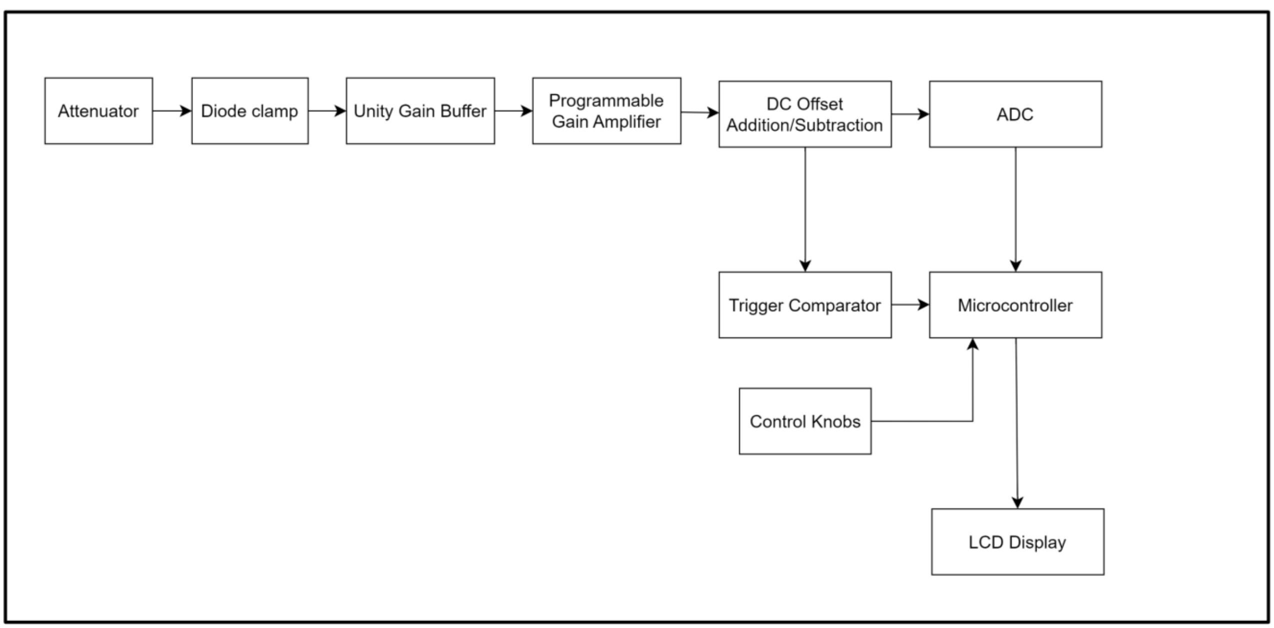
ESE 323 – Modern Circuit Board Design and Prototyping

Final Paper

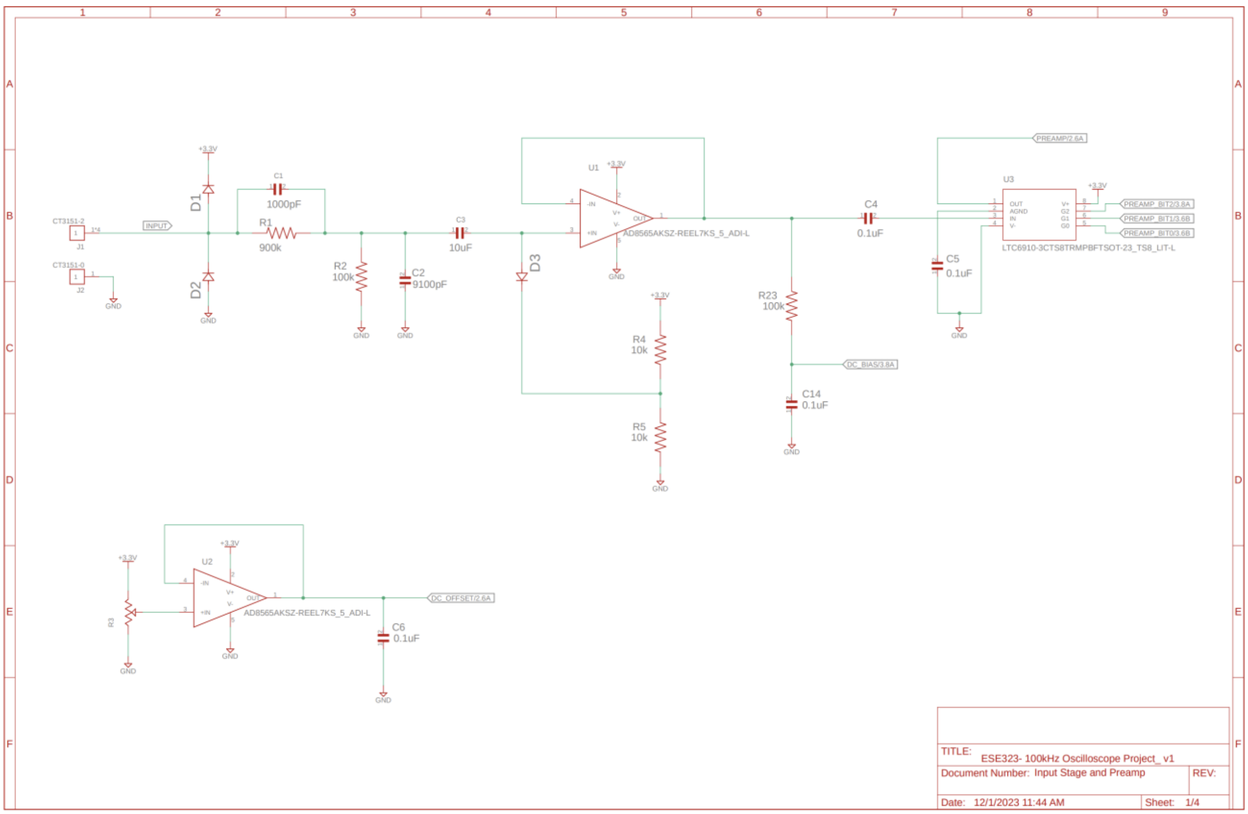
100KHz Bandwidth Oscilloscope

The goal of my project was to create a 100KHz bandwidth oscilloscope with control knobs for vertical and horizontal scaling, dc offset addition/subtraction, trigger level adjustment, and XY measurement cursors. I used Arduino IDE to write software in C++ for an ESP32 to plot the samples from the ADC on a 240x320 pixel TFT display, poll the control knobs, and perform tasks related to peripheral ICs. I designed an analog front end for signal conditioning to maximize the ADC's input range and triggering to plot a stable waveform on an LCD display module. My goal is for oscilloscope to operate on a single +3.3V power supply and be capable of receiving power from a USB connector or an AC adaptor. A block diagram of my design is shown below:



Circuit Description

Shown below is a schematic diagram of the input stage which consists of a pair of banana connectors to connect external probes, a compensated L-pad attenuator with 1MΩ input impedance, a diode clamp, and a unity gain buffer. A programmable gain amplifier is used as a preamp to adjust the resolution and range of the analog-to-digital converter.

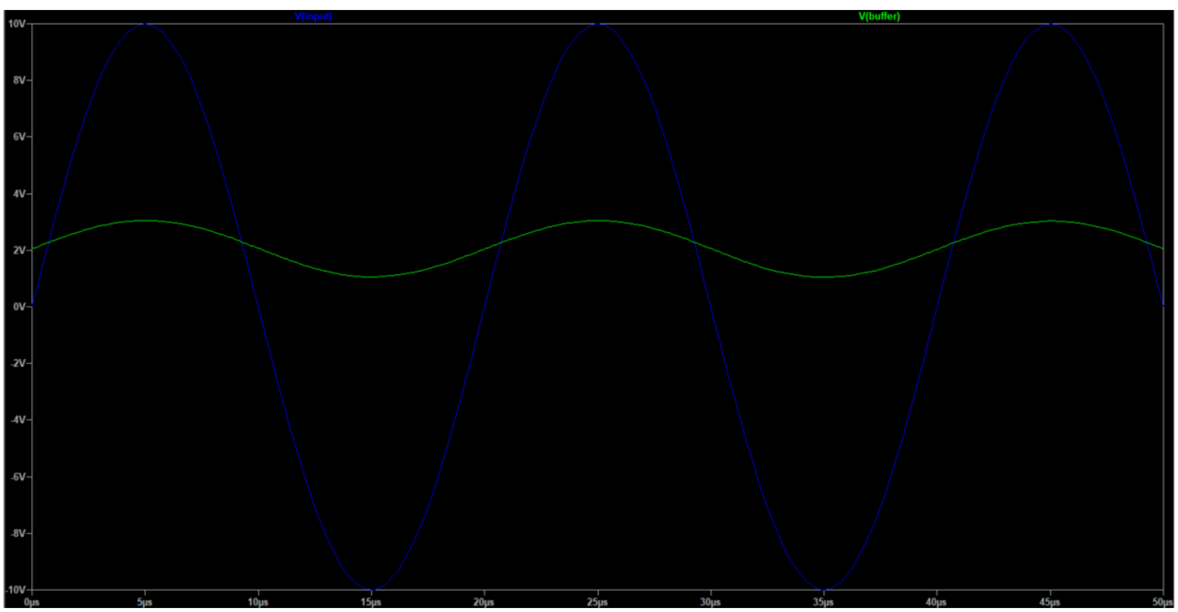


The Schottky diodes D1 and D2 are protection diodes which will forward bias and steer the flow of current into the power supply if the input voltage is above or below the power supply rails.

Capacitors C1 and C2 are connected in parallel with resistors R1 and R2 to form a 10:1 L-pad attenuator. The attenuator works in conjunction with the diode clamp to ensure that the input signal fits well within the power supply rails so that signal distortion does not occur. If the input to the unity gain buffer is outside of the range of the power-supply rails, then the signal will be clipped and there will be no way of getting it to the ADC so it can be digitized. The positive clamp is used to shift the input signal up by the mid-supply voltage. This allows for negative input voltages to be measured with a single positive power supply because it will automatically bias the input signal near the mid-supply voltage. The attenuator helps to ensure that the input signal is small compared to the clamp voltage which increases the likelihood of the input voltage level always being near the mid-supply voltage.

The trade-off of the clamp is that positive voltages above the mid-supply voltage will be shifted above +3.3V and will be clipped while negative voltages above -1.65V will be shifted to within the single-supply range. This is a good trade off to make since it allows for my oscilloscope to measure bipolar signals which are of greater interest than signals with a single polarity. The positive input range can always be increased by adding more attenuation to the input stage so there is less chance of being clipped.

The screenshot shown below is taken from an LTspice simulation of the analog front end:

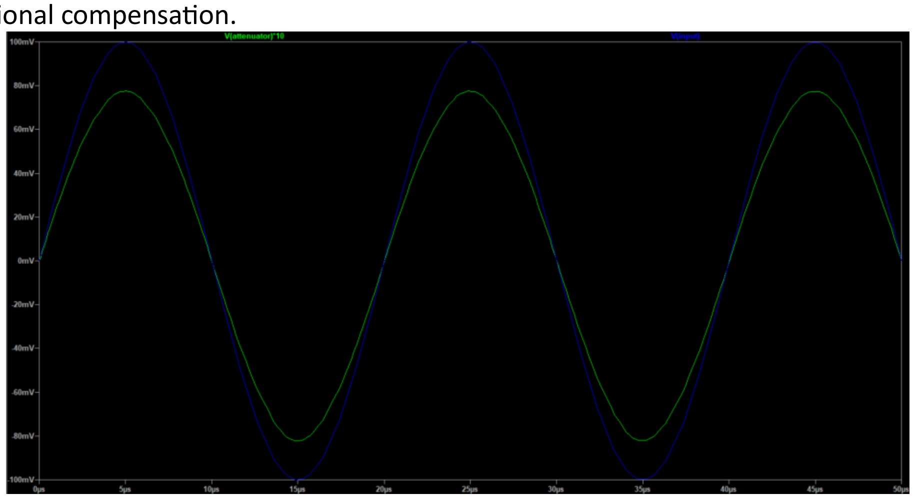


A 10V amplitude sine wave with 0 dc bias is applied at the input. The signal is attenuated and shifted up to within the supply range of the op amp buffer so that even large negative voltages can still be accommodated with a single positive power supply. Upon inspection, I forgot to account for the forward voltage across the diode when clamping so the signal is shifted above the value I would like, however, the values of resistors R4 and R5 can be adjusted to achieve a different clamp voltage.

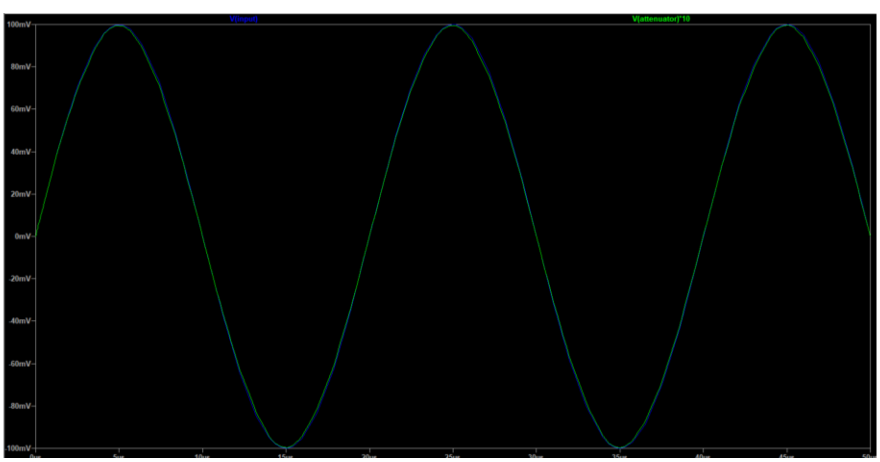
Connecting capacitors C1 and C2 in parallel with resistor R1 and R2 provides compensation for the diode clamp capacitance as well as the input capacitance of the amplifier and any stray capacitance or inductance present in the resistors or circuit board. This compensation scheme employs pole-zero cancellation to suppress undesirable frequency dependence caused by the additional reactance. If the resistor and capacitor values are chosen so that the pole and the zero are superimposed, the transfer function of the attenuator becomes independent of frequency. The component values are selected so that the following relationship is satisfied:

$$\boldsymbol{R_1 C_1 \cong R_2 C_2}$$

The screenshot shown below is taken from an LTspice simulation of the attenuator output **without** compensation. The simulation shows that the desired 10:1 attenuation factor cannot be achieved without additional compensation.



The screenshot shown below is taken from an LTspice simulation of the attenuator output **with** the appropriate compensation, the output is much closer to the desired 10:1 attenuation factor. The simulation results show that the attenuator performance is greatly improved by compensation.

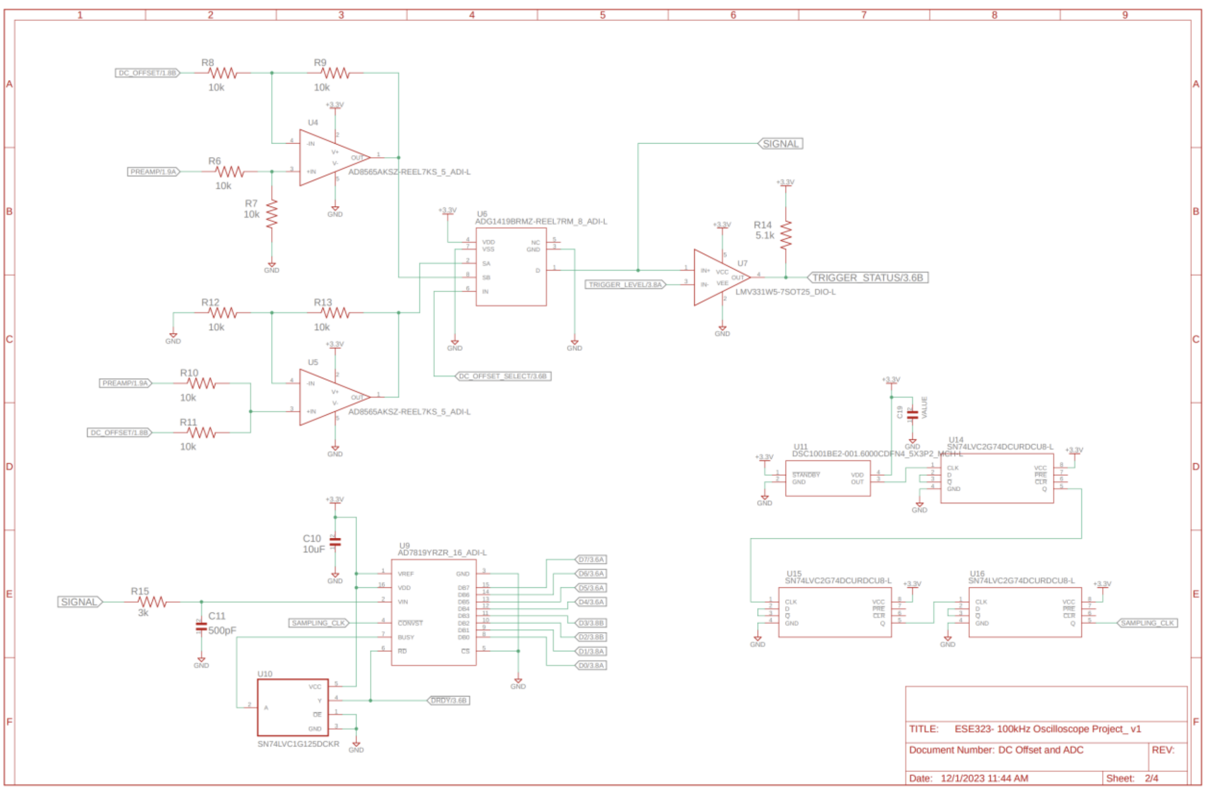


The programmable gain amplifier is used to provide variable amplification to the input signal so it can be scaled to the ADC's full range for maximum resolution. The gain of the amplifier is determined by the volts per division setting on the oscilloscope. A lower volts per division setting would correspond to a higher gain so that smaller signals can be scaled to the full range of the ADC and a higher volts per division setting would correspond to a lower gain so that larger signals can still fit within the input range of the ADC.

The LTC6910-2 is a 3-bit programmable gain amplifier with gain steps of 6dB (powers of 2). The gain of the amplifier is cascaded with the attenuator so that variable gain and attenuation can be achieved. If the gain of the amplifier is lower than the attenuation factor, then there will be a net attenuation of the input and if the gain of the amplifier is higher than the attenuation factor then there will be a net amplification of the input signal. The volts per division setting of the oscilloscope is implemented by cascading the attenuator and PGA so the dynamic range of the ADC can be adjusted for more or less effective resolution depending on the information being displayed on the screen.

The input signal is ac coupled to the amplifier so that only the ac portion of the signal is amplified. Amplifying the dc component is of little use if it is larger than a few LSBs since it will mainly just shift the input signal closer to the supply rails and introduce distortion or clipping. The signal is dc coupled to the ADC of the ESP32 by measuring the voltage across a capacitor with a large RC time constant. If the time constant of the capacitor is very large, then a low pass filter is formed to only allow dc to pass through. The dc component of the input signal can then be measured with the ESP32's ADC which is noisier and has a lower sample rate than the external ADC being used. The noise and sample rate are less important for the dc component than the ac component since it is just a vertical displacement of the ac component on the display. An averaging filter can be implemented in software to remove any noise on the dc measurement from the ESP32's ADC.

DC offset addition or subtraction is implemented through the use of summing and differential op amp configurations. The ADG1419 is a SPDT switch IC which is used to select between the outputs of the two op amps. The dc offset select signal is a digital signal which is read from a push-button and set or cleared by the microcontroller so that a dc offset can be added or subtracted from the amplified signal. The output from the switch is connected to a comparator which compares the signal to the trigger level and outputs a rising or falling edge when the signal passes through the trigger level. This edge triggers an interrupt on the microcontroller which causes the waveform to be plotted on the screen. Since the waveform is only plotted when the signal passes through the trigger level, a stable waveform can be displayed on the screen.



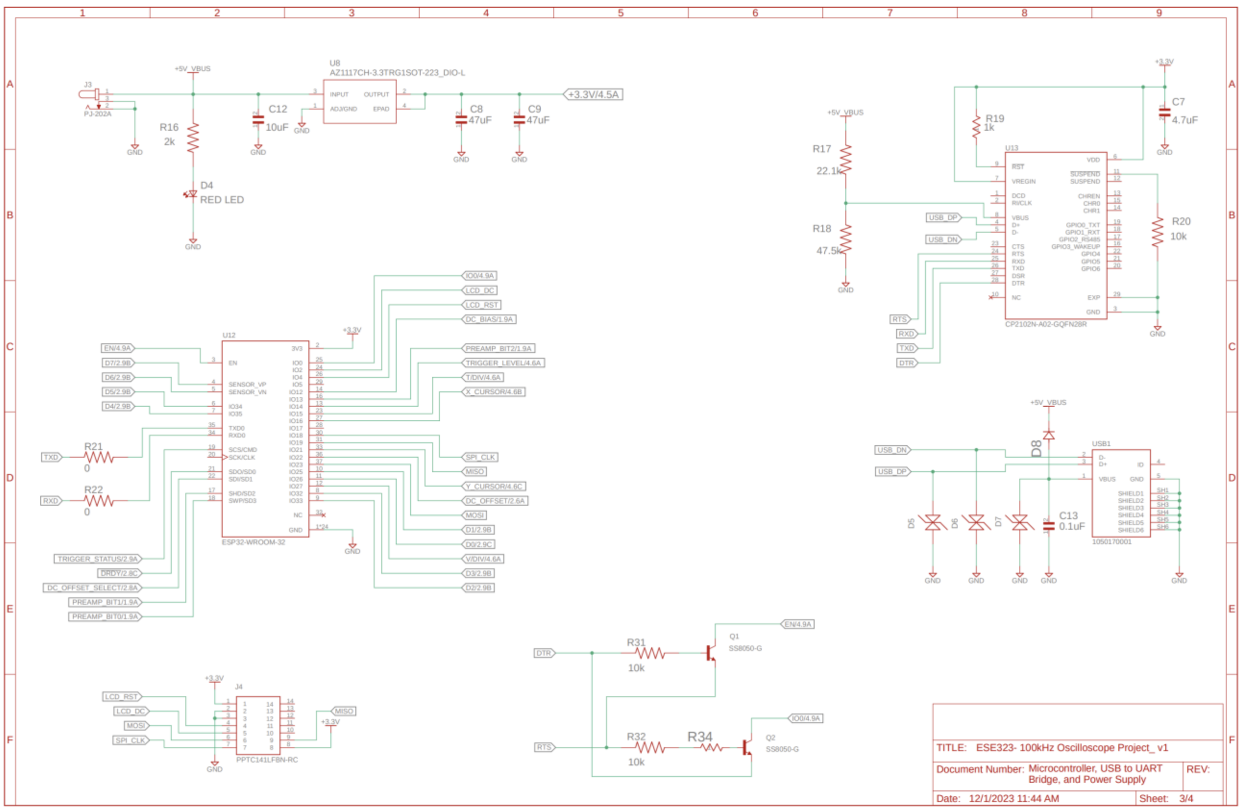
In hindsight, I now realize that the use of op amps for dc offsetting is a flaw in my design. The purpose of dc offsetting is so that signals outside of the ADC's input range can be shifted up or down to fit within the appropriate input range. Since the reference voltage of the ADC is +3.3V which is the same as the power supply voltage, using op amps for dc offsets does not do anything that cannot easily be done in software.

The op amps can only output voltages within its power supply rails which is no different from the ADC's input range, therefore, using op amps to shift the signal up or down does not provide any further resolution to the ADC since the signal is already within its input range. Furthermore, the attenuator and diode clamp at the input stage already perform the task of ensuring that the input signal is within the ADC's input range. Since the summing and differential op amps only serve to shift the signal up or down within the ADC's input range, they can be removed from the design and the same dc offsetting can be implemented in software after the signal has been digitized.

The AD7819 is an 8-bit 200ksps SAR ADC, so a simple single-pole RC anti-aliasing filter is chosen with a cutoff frequency close to the Nyquist-rate of 100kHz. A higher-order filter can be used to achieve a steeper transition from the passband to stopband, however, this would require more components and digital processing to flatten the passband response. I wanted to keep the design simple so that I could finish as soon as possible. The RC-filter serves the purpose of preventing aliasing by filtering out frequencies above the oscilloscope's bandwidth, however, it also serves as a charge-bucket to reduce the kickback settling time of the SAR ADC in between the conversion and acquisition phases by dumping charge into the internal sample and hold circuit at the start of the acquisition phase.

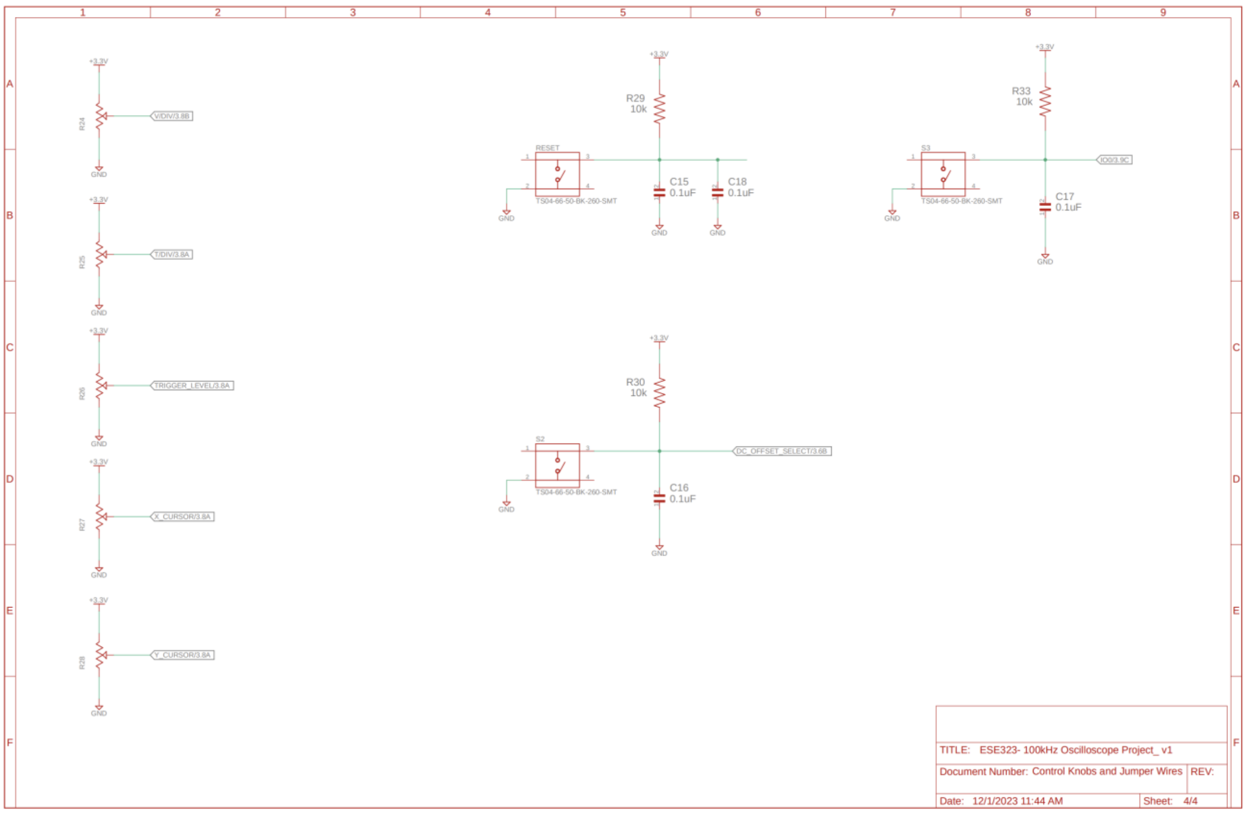
The shortest possible time per division setting is proportional to the fastest sampling period (5 microseconds) multiplied by the number of samples displayed. In order to increase the time per division setting on the display, a larger number of samples must be collected and then the sequence must be decimated in order to display a waveform corresponding to the time per division setting. The ESP32 has 320KB of memory storage so there is enough memory to store a large number of 8-bit samples. The sampling rate can be lowered to spread the samples over a longer time frame, however, this would lower the oscilloscope's bandwidth because I would have to ensure that the sampling rate was always above the Nyquist rate.

A 200KHz sampling clock for the “conversion start” pin of the ADC is generated by using a 1.6MHz oscillator and a D-flip-flop based frequency divider. Each stage divides the frequency by two, so three flip-flops are cascaded to divide the frequency by eight and convert a 1.6MHz clock into a 200KHz clock. A non-inverting buffer is used to increase the fanout of the BUSY pin as it must drive two input pins.



I have verified that I can sample all the GPIO pins connected to the ADC at a rate of 500kHz which is more than twice the 200KHz frequency of the output from the ADC, therefore, no external FIFO buffer is required to lower ADC’s output data rate. The microcontroller will poll the ADC output and store the samples in memory and then plot the waveform on an LCD display after receiving the edge-triggered interrupt from the trigger comparator.

A USB to UART bridge is used to program the microcontroller using Arduino IDE and a simple LDO regulator is used to achieve the +3.3V power supply from a USB connector or a +5V ac adaptor. A red LED lights up when the power supply is connected to indicate that the board is receiving power. The ac adaptor output and USB connector power pin are connected to the same node, however, a Schottky diode is placed at the VBUS pin of the USB connector to prevent any current from flowing into the USB host device. A 14-pin female header connector is used to mount an ILI9431 2.8” TFT LCD display on the board.



The control knobs are implemented using potentiometers. The output from the potentiometers corresponding to the volts per division, time per division, and XY cursor settings are read by the ESP32’s ADC and then software is used to map the analog values from the potentiometers onto the appropriate horizontal/vertical scaling values and cursor positions on the screen. The PGA bits are chosen so maximize resolution for a given volts per division setting and sample decimation is determined from the time per division setting. The outputs from the trigger level and dc offset potentiometers are connected to the analog front end to perform their functions. All control knob potentiometer outputs are also measured by the microcontroller ADC so it can perform tasks and display the information on the screen.

Bill of Materials

Integrated Circuits

Vendor	Vendor part number	Manufacturer	Manufacturer part number	Description	Package	Unit Cost [$]	Quantity
Digikey	505-AD8565AKSZ-REEL7CT-ND	Analog Devices Inc.	AD8565AKSZ-REEL7	Rail-to-Rail op amp	5-TSSOP	2.09	5
Digikey	LTC6910-3CTS8#TRMPBFCT-ND	Analog Devices Inc.	LTC6910-3CTS8#TRMPBF	Digitally Programmable Gain Amplifier	SOT-23-8	3.53	1
Digikey	AD7819YRZ-ND	Analog Devices Inc.	AD7819YRZ	200 ksps, 8 bit SAR ADC	16-SOIC	8.7	1
Digikey	ADG1419BRMZ-REEL7CT-ND	Analog Devices Inc.	ADG1419BRMZ-REEL7	2.4 Ohm SPDT Switch	8-MSOP	5.54	1
Digikey	AZ1117CH-3.3TRG1DICT-ND	Diodes Incorporated	AZ1117CH-3.3TRG1	Fixed 3.3V Linear Voltage Regulator	SOT-223-3	0.45	1
Digikey	LMV331W5-7DICT-ND	Diodes Incorporated	LMV331W5-7	Trigger Comparator	SOT-25	0.36	1
Digikey	296-11604-1-ND	Texas Instruments	SN74LVC1G125DCKR	Non-inverting Buffer Gate	5-TSSOP	0.33	1
Digikey	510KCAM200000BAG-ND	Skyworks Solutions Inc.	510KCAM200000BAG	200 kHz Crystal Oscillator	4-SMD, no Lead	5.3	1
Digikey	336-5890-1-ND	Silicon Labs	CP2102N-A02-GQFN28R	USB TO UART BRIDGE	28-QFN	4.66	1
Digikey	WM1399CT-ND	Molex	1050170001	CONN RCPT USB2.0 MICRO B	SMD	1.01	1
Amazon	ILI9341 240x320	Adafruit Industries LLC	2770	2.8" TFT Display - 240x320	PCB	15	1
Mouser Electronics	356-ESP32-WROOMDAN16	Espressif Systems	ESP32-WROOM-32 (16MB)	ESP32 Microcontroller	Tray	4.7	1
						Total	45.03

Resistors

Vendor	Vendor part number	Manufacturer	Manufacturer part number	Description	Package	Unit Cost [$]	Quantity
Digikey	RHM10KDCT-ND	Rohm Semiconductor	ESR03EZPJ103	RES SMD 10K OHM 5% 1/4W	0603	0.65	2
Digikey	RHM100KDCT-ND	Rohm Semiconductor	ESR03EZPJ104	RES SMD 100K OHM 5% 1/4W	0603	0.13	5
Mouser	13-RT1206CRE07900KLCT-ND	YAGEO	RT1206CRE07900KL	RES SMD 900K OHM 0.25% 1/4W	1206	0.638	2
Digikey	3386P-1-101TLF-ND	Bourns Inc.	356	10k OHM Trimmer Potentiometer	Through Hole	2.62	6
Digikey	311-2632-1-ND	YAGEO	RT0603DRE075K1L	RES SMD 5.1K OHM 0.5% 1/10W	0603	0.1	1
Digikey	RHM3KDCT-ND	Rohm Semiconductor	ESR03EZPJ302	RES SMD 3K OHM 5% 1/4W	0603	0.13	1
Digikey	RHM2.0KDCT-ND	Rohm Semiconductor	ESR03EZPJ202	RES SMD 2K OHM 5% 1/4W	0603	0.13	1
Digikey	RNCP0603FTD1K00CT-ND	Stackpole Electronics Inc	RNCP0603FTD1K00	RES 1K OHM 1% 1/8W	0603	0.1	1
Digikey	RNCP0603FTD22K1CT-ND	Stackpole Electronics Inc	RNCP0603FTD22K1	RES 22.1K OHM 1% 1/8W	0603	0.1	1
Digikey	738-RNCF0603DTE47K5CT-ND	Stackpole Electronics Inc	RNCF0603DTE47K5	RES SMD 47.5K OHM 0.5% 1/6W	0603	0.1	1
Digikey	RMCF0603ZT0R00CT-ND	Stackpole Electronics Inc	RMCF0603ZT0R00	RES 0 OHM JUMPER 1/10W	0603	0.1	1
Digikey	311-0.0ARCT-ND	YAGEO	RC0805JR-070RL	RES 0 OHM JUMPER 1/8W	0805	0.1	1
Digikey	CD14ZT0R00CT-ND	Stackpole Electronics Inc	CD14ZT0R00	RES 0 OHM JUMPER 1/4W	Through Hole	0.1	1
						Total	19.706

Capacitors

Vendor	Vendor part number	Manufacturer	Manufacturer part number	Description	Package	Unit Cost [$]	Quantity
Digikey	490-1641-1-ND	Murata Electronics	GRM2195C1H912JA01D	CAP CER 9100PF 50V C0G/NP0	0805	0.23	4
Digikey	490-6445-1-ND	Murata Electronics	GRM2165C2A102JA01D	CAP CER 1000PF 100V C0G/NP0	0805	0.11	5
Digikey	490-10475-1-ND	Murata Electronics	GRM188R61A106ME69D	CAP CER 10UF 10V X5R	0603	0.14	10
Digikey	490-5798-1-ND	Murata Electronics	GCJ188R71H104KA12D	CAP CER 0.1UF 50V X7R	0603	0.16	10
Digikey	490-12330-1-ND	Murata Electronics	GRT188R61H105KE13D	CAP CER 1UF 50V X5R	0603	0.18	10
Digikey	490-GRM188R60J476ME15JCT-ND	Murata Electronics	GRM188R60J476ME15J	CAP CER 47UF 6.3V X5R	0603	0.5	10
Digikey	13-CC0603JRNPO9BN501CT-ND	YAGEO	CC0603JRNPO9BN501	CAP CER 500PF 50V C0G/NPO	0603	0.11	10
Digikey	399-C0603C475K9PAC7867CT-ND	KEMET	C0603C475K9PAC7867	CAP CER 4.7UF 6.3V X5R	0603	0.16	1
						Total	12.63

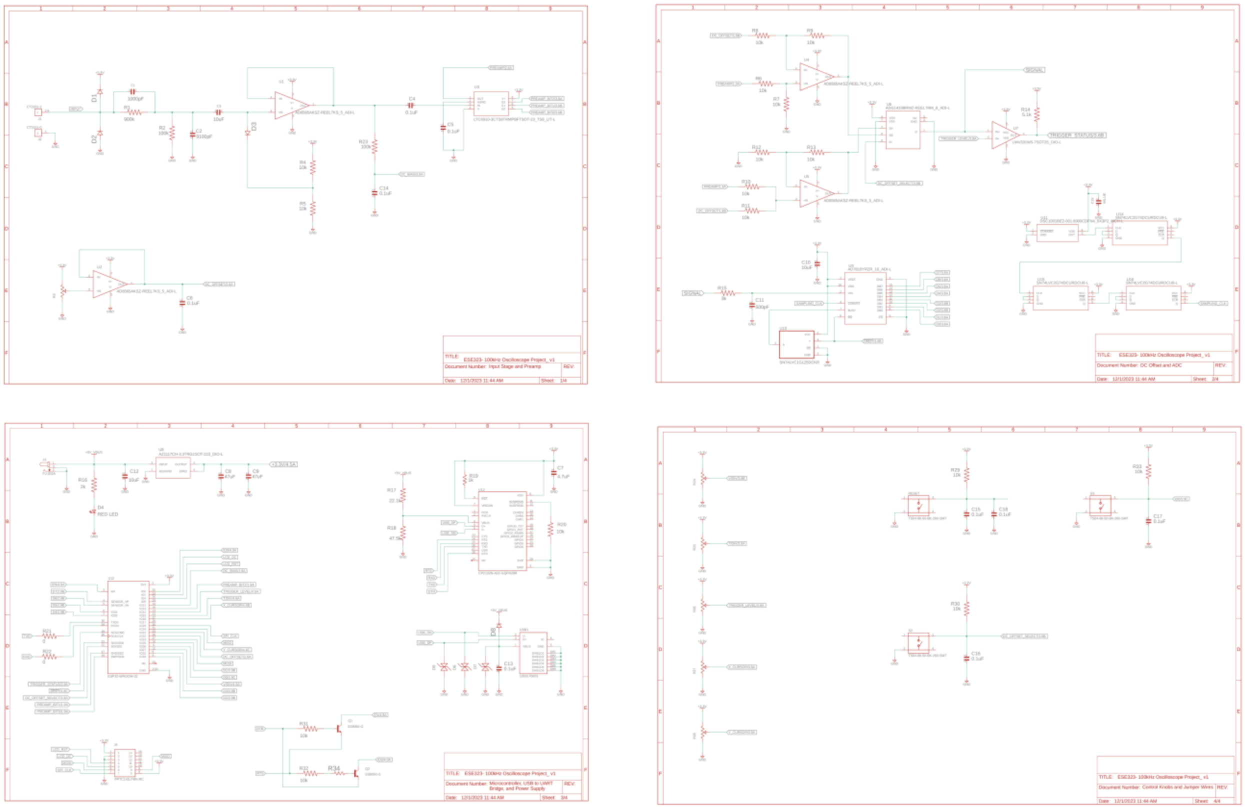
SemiConductor Devices

Vendor	Vendor part number	Manufacturer	Manufacturer part number	Description	Package	Unit Cost [$]	Quantity
Digikey	NSR05F40NXT5GOSCT-ND	onsemi	NSR05F40NXT5G	Schottky Diode	0402	0.39	4
Digikey	160-1447-1-ND	Lite-On Inc.	LTST-C191KRKT	LED RED CLEAR SMD	0603	0.25	1
Digikey	D5V0L1B2T-7DICT-ND	Diodes Incorporated	D5V0L1B2T-7	TVS DIODE 5VWM 14VC SOD523	SOD-523	0.29	1
						Total	2.1

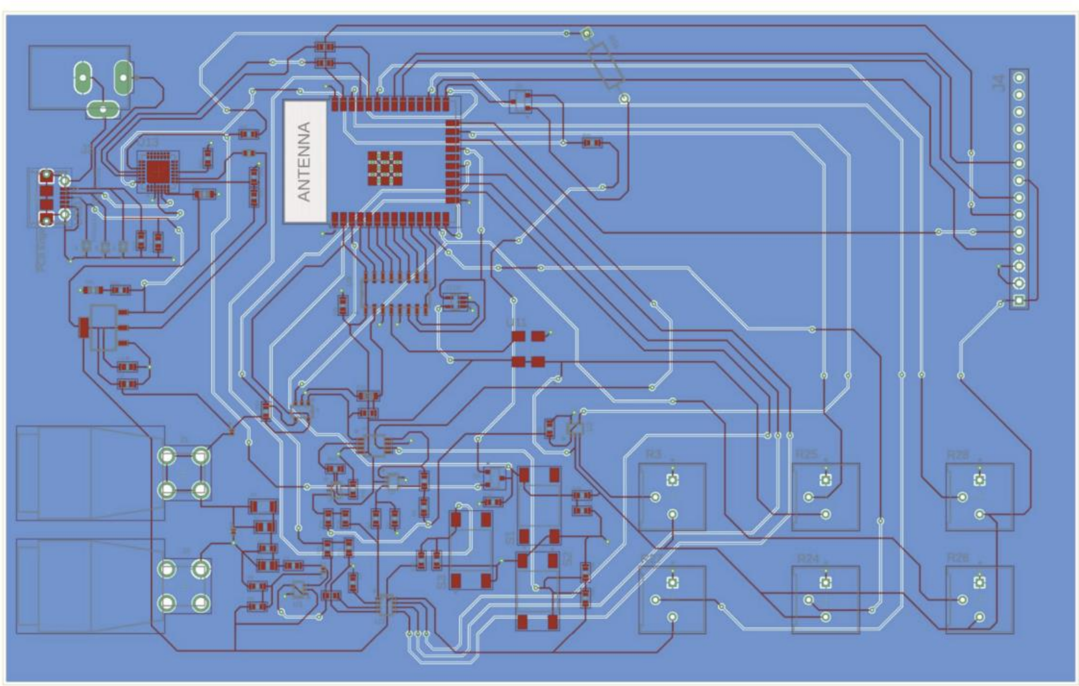
Connectors

Vendor	Vendor part number	Manufacturer	Manufacturer part number	Description	Package	Unit Cost [$]	Quantity
Digikey	S7012-ND	Sullins Connector Solutions	PPTC141LFBN-RC	CONN HDR 14POS 0.1 TIN PCB	Through Hole	0.92	1
Digikey	BKCT3151-0-ND	Cal Test Electronics	CT3151-0	CONN BANANA JACK SOLDER BLACK	Through Hole	2.45	1
Digikey	BKCT3151-2-ND	Cal Test Electronics	CT3151-2	CONN BANANA JACK SOLDER RED	Through Hole	2.45	1
Amazon	2 PCs 4mm Banana Plug Alligator Clip					10	1
Digikey	2223-TS04-66-50-BK-260-SMT-ND	CUI Devices	TS04-66-50-BK-260-SMT	actile Switch SPST-NO Top Actuated Surface Mount	4-SMD	0.18	1
						Total	15.08
						Total [$]	94.546

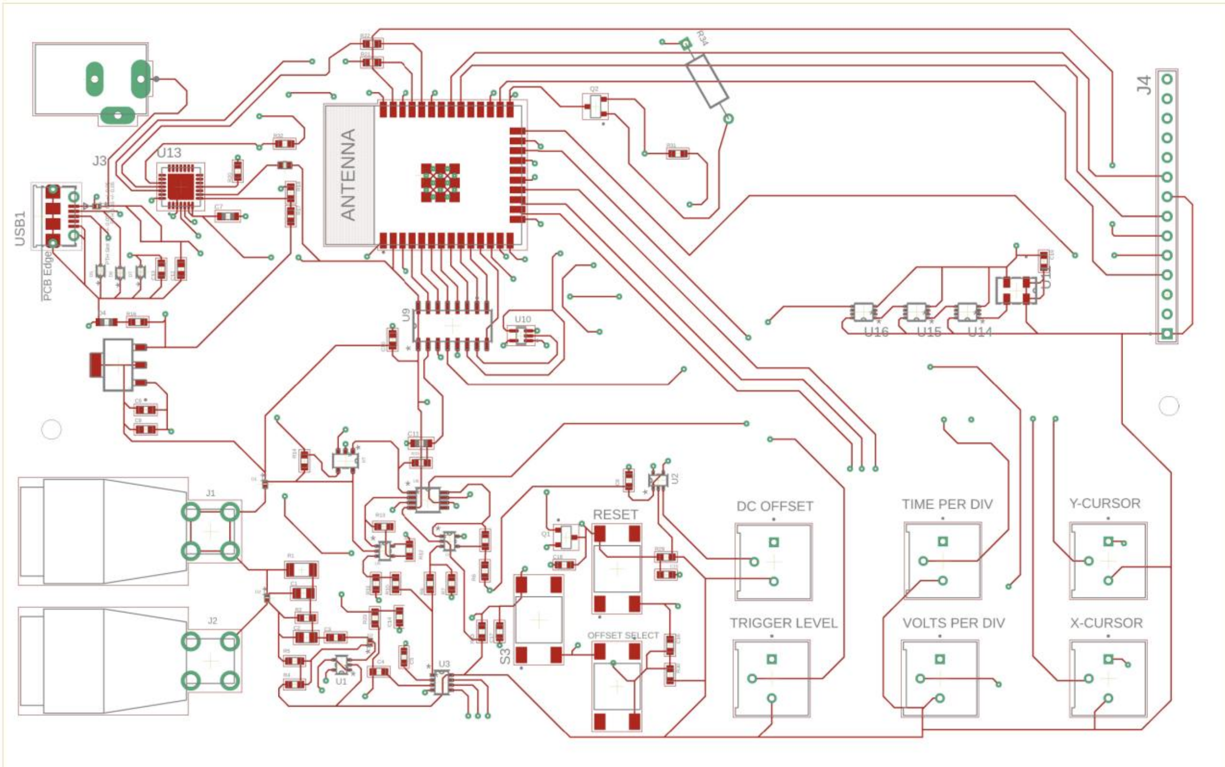
Schematic Diagram



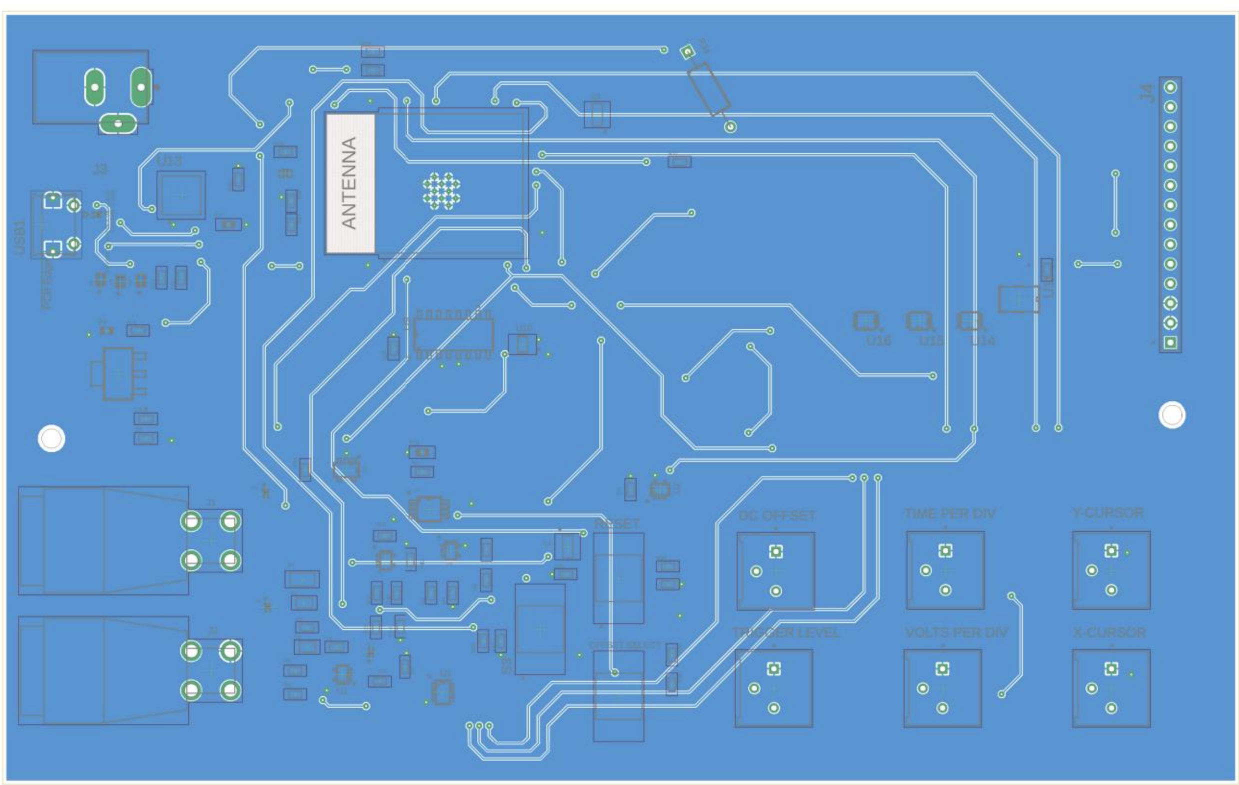
Board Layout - All Metal Layers



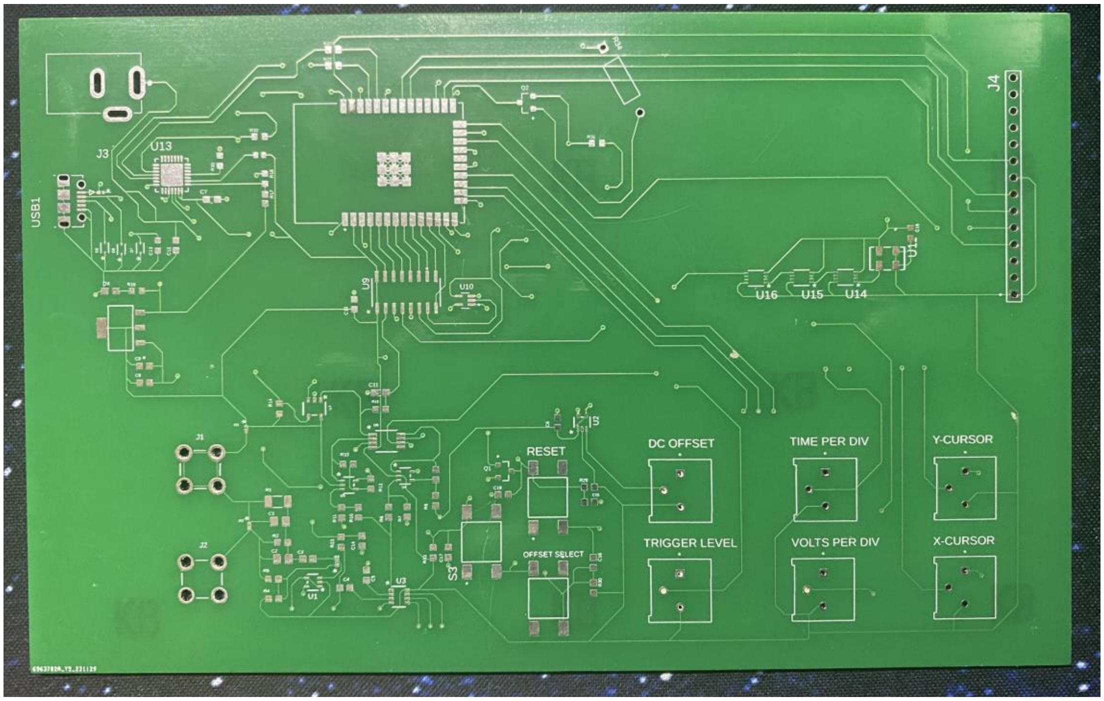
Board Layout- Top Layer



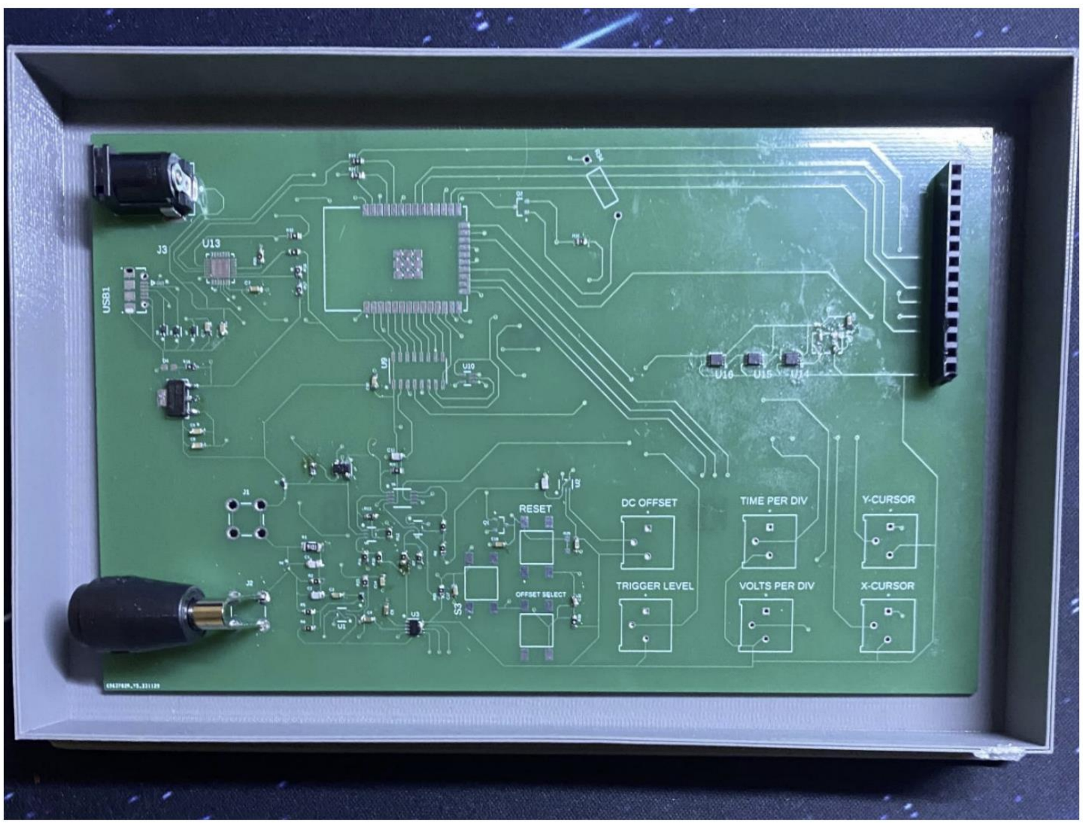
Board Layout Bottom Layer



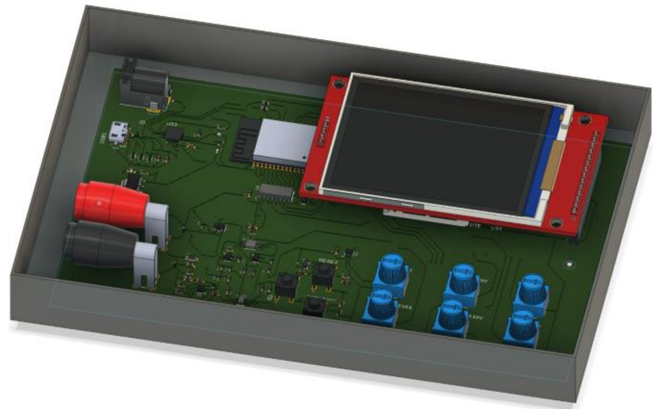
Unpopulated Board Photograph

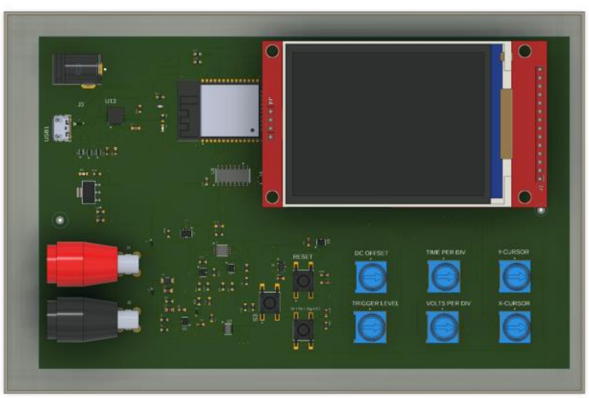


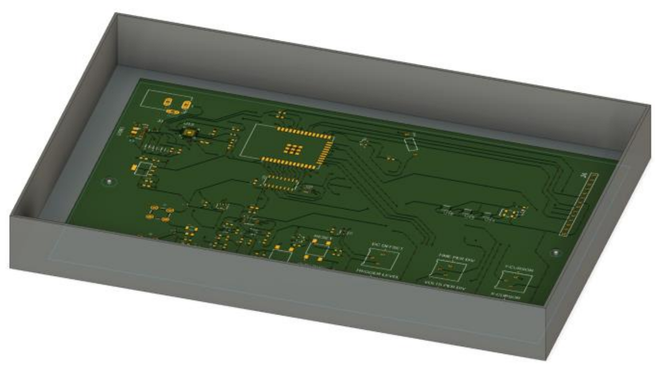
Built Board Photograph



3D enclosure

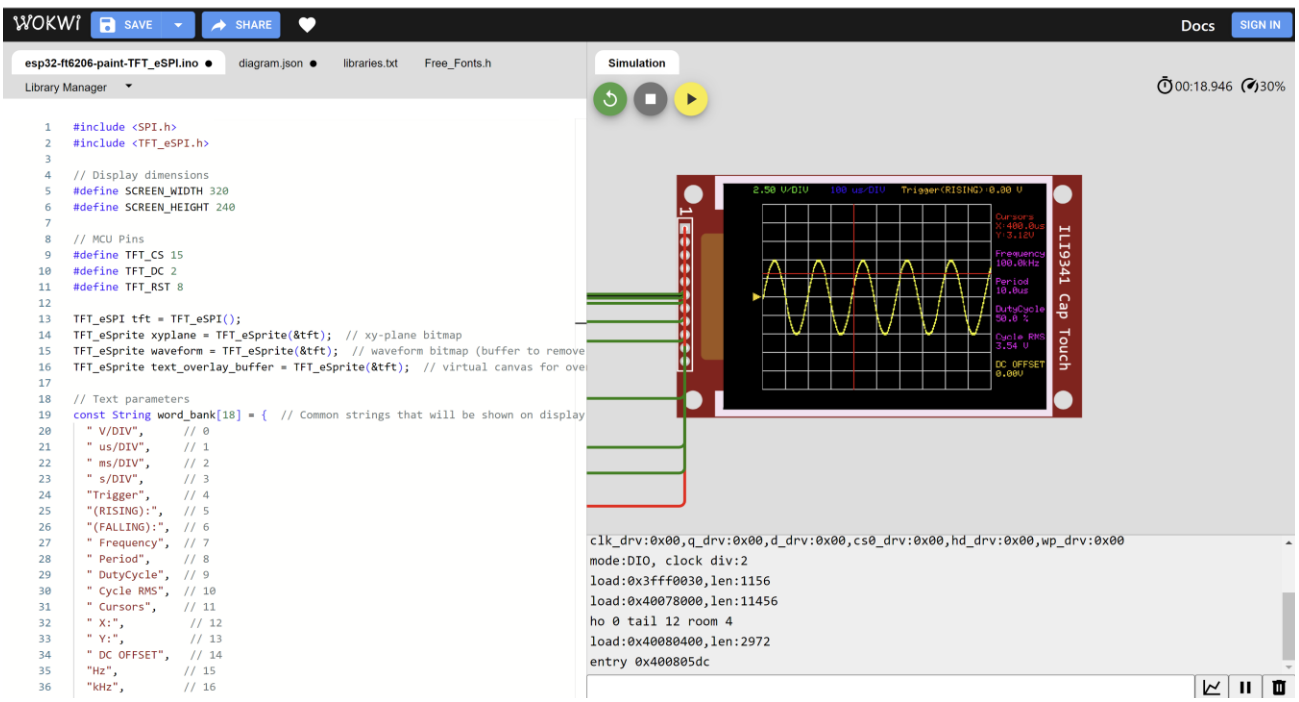






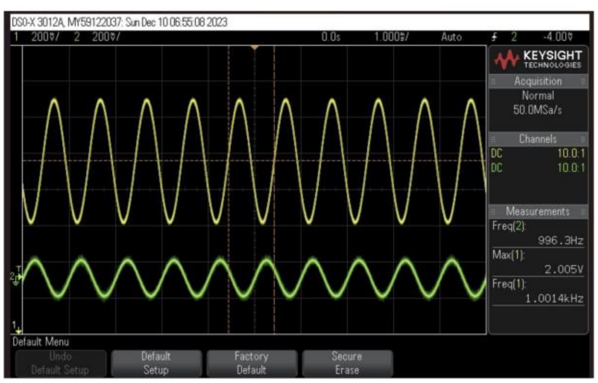
Software

This is a demonstration of the display code that I wrote for my project. I wanted to include a photo of the code running on the actual display that I bought, however, I believe that I may have left it in the lab over the weekend because I could not find it in my room. So instead, I used an online Arduino simulator called Wokwi to simulate the code and I took a screenshot of the results. The frequency , duty cycle, and period measurements are just arbitrary values that I hardcoded onto the display. I tested the XY-cursors, volts per div, and time per div functions out with my keyboard and the code worked how I wanted it to.

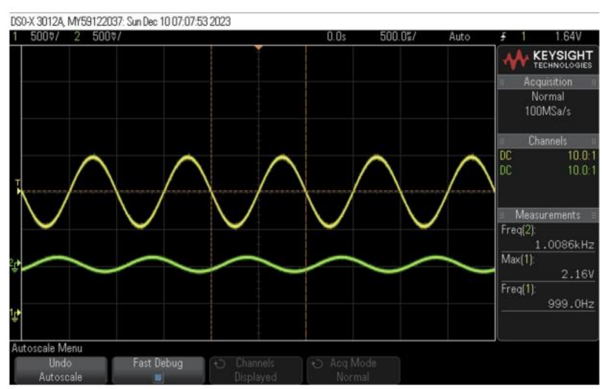


Results

My original design was too complicated to finish by the end of the semester, so I had to completely redesign it from scratch over thanksgiving break. I was able to finish the layout and schematic, unfortunately, I was not able to finish assembling my board. I lost most of my op amps and blew off some of the pads for the board that I had made the most progress on. Also, the microcontroller that I ordered from Digikey did not match the footprint that I found online so I could not solder it onto the board. I decided not to solder on some of the more expensive components so I could save them for later. I am going to order a new microcontroller that fits on the pad on my board, and I am also going to get replacements for the components that I lost so I can try to assemble it next semester. I did get a chance to test the programmable gain amplifier by soldering some of the gain bit pins to +3.3V. The two images shown below are screenshots from one of the oscilloscopes in the lab. The green waveform (channel 2) is the input signal, and the yellow waveform (channel 1) is the output from the amplifier.



Gain of 4



Gain of 2

What would I do differently next time

Next time I will check the datasheets of my components to make sure that footprints from online match the actual component that I am going to buy. I am also going to make a separate board to practice soldering the packages that I buy to make sure that I do not make any mistakes while assembling my board. I also would set a strict budget to make sure that I do not overspend on parts. I am going to try and create a much more high-speed oscilloscope over the winter and spring and that can get very expensive if I do not adhere to a strict budget.

Course Feedback

I think we should have started doing CAD work a lot earlier in the semester. I think if I had learned how to do board layouts and 3D models in Fusion360 earlier, I would not have had to rush my project at the end and I would have had a better chance to finish on time and double my footprints and packages. I think we should have started learning how to do layouts and 3D models in September because the "theoretical" information like trace properties and thermal resistance is a lot easier for me to in cram in at the end of the semester than learning how to use CAD tools. That's my personal opinion, I am not sure if other people had a different experience than that.