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The Design Process for Constructing an Ultrasonic Range Finder

ENGPHYS 3BA3 | Design Project | TA: Mohammadreza Shahzadeh | McMaster University

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Abstract

This project acted as the cumulative demonstration of all the concepts taught throughout the course in one final large device. The device to be built was an ultrasonic range-finder capable of detecting objects from 10 to 99 cm with an accuracy of ±1 cm using the knowledge taught in this course and the various ICs and complementary components available in-lab. The design was planned out with the aid of a schematic, timing diagram, and block diagram, with the first prototyping stages completed in Multisim. The final product was the constructed on a solderless breadboard with the aid of jumper wires. The desired objective was obtained in the end with mastery of the topics learned demonstrated and the sensor working to the tolerances specified. The system was validated with the use of a laptop as the object of interest for the range finder and confirming the correct readings were produced at various distances, with the sensor's complementary component values tuned as necessary. The end product was found to exceed the specifications and was able to measure with the desired accuracy between 1 cm and 175 cm. As a result, mastery of all the topics learned was demonstrated and the product was validated as working.

Introduction

The objective of this project was to put the skills to use learned throughout the duration of the course into one final culminating device demonstrating the understanding of the concepts taught. This was in the form of building an ultrasonic range finder from basic components and ICs covered in the course that would be accurate to ±1 cm to a from 10 to 99 cm. Due to the nature of the components used and the theory that was applied, the sensor constructed during the course of the project is not only an application of the knowledge, but also an extension of it as further understanding about signal processing, dealing with noise, the propagation of sound waves, and how all these components interact with each other was obtained.

Theory

Propagation of Sound Waves

To better understand the sensor that will be constructed, some theory must be discussed. Specifically, it is important to understand the premise the sensor works on. The sensor that is to be used relies on emitting ultrasonic sound waves and "listens" for their return as they reflect off solid objects in their path. Sound waves are pressure waves, disturbances in the air that cause the molecules in the path of the wave to oscillate. As such, it requires a medium to propagate and the speed of the sound wave will change based on the medium the wave is propagating through. For this sensor, the wave will be travelling through room-temperature air and so will have a speed of about 346 m/s, but can vary based on the temperature, humidity, altitude, and other factors [1]. By measuring the time of flight (TOF), the distance can be determined.

Detecting Distance with Sound

The main component of this sensor is a pair of piezoelectric transducers represented in *Figure 1*. These will produce the necessary ultrasonic waves and listen for their return, with one being the transmitter and the other being the receiver. They rely on the phenomenon of piezoelectricity which is a property of certain anisotropic materials that results in the production of an alternating electric current through the material when subject to mechanical stress and vice versa. This allows them to be used to generate mechanical oscillations at specific frequencies depending on the alternating electric current they are fed and also convert mechanical oscillations to an electric current. In this manner, they are able to both emit and detect the pressure disturbances that are sound waves and convert them into a detectable voltage. Hence, by emitting a burst of oscillations and constructing a circuit that will count at a specific rate tuned to be in alignment with the time the sound takes to propagate through twice the unit of distance (this is to take into account both the time to travel and return after reflection off an object), and then holding the count when the reflected wave is detected, the distance traveled can be determined. Assuming the sound travels at 346 m/s, this means that in order to measure in units of cm, the sensor would have to count at a clock rate of about 17.3 kHz. The calculation for this value can be found in *Appendix A*.

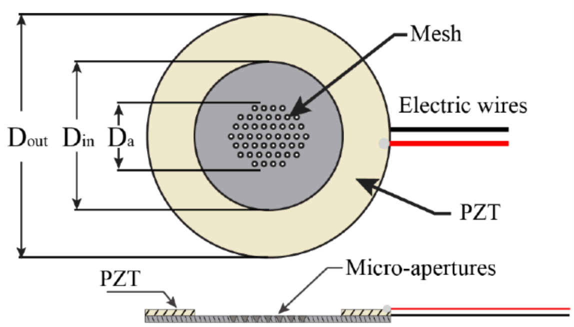

Figure 1 – Diagram of Piezoelectric Transducer [2]

Background on Integrated Circuits (ICs)

This project will also require the use of several ICs and while a deep understanding of the physics behind the semiconductors used is not necessary, the capabilities of the ICs used must be discussed at a rudimentary level. Firstly, there are two major categories of ICs that were available for use. These were Complementary Metal-Oxide Semiconductor (CMOS) ICs and Transistor-Transistor Logic (TTL) ICs. CMOS ICs are composed of Metal-Oxide-Semiconductor Field-Effect Transistors (MOSFET) while TTL ICs are made of Bipolar Junction Transistors (BJT). The main difference in these is with their construction, as BJTs are made of two junctions between two semiconductor types with a terminal on each of the three portions. MOSFETs however are made of a semiconductor acting as the main substrate and two regions of a different type embedded within the top of the other. These are separated by the main substrate with the gap being crossed by a metal-oxide layer on top. The three terminals are attached then to the metal-oxide layer, and the two embedded semiconductor regions. While there are several advantages to either construction and differences in the semiconductor properties that result in them, they are beyond the scope of this report and so the main differences that are relevant to the range-finder project are discussed at a higher level. These are that CMOS ICs as a result, have reduced power consumption and greater noise immunity while TTL ICs have faster switching speed, lower input capacitance, and less vulnerability to electrostatic discharge [3]. The most important of these for this project, would be the noise immunity as resistance to noise in the returned signal is vital to obtaining a clear reading. A slightly less important aspect would also be switching speed; however, this would only come into play at very small distances where the TOF is small enough for these differences to become much larger.

Having understood the underlying technologies behind the ICs used, some understanding of each IC and their capabilities is required. Several astable and monostable multivibrators will be used for this project as a method of keeping time and producing alternating signals at the correct frequencies. The 555 timer is of note due to its ability to be purposed as either. These ICs can produce an oscillating waveform of a desired shape and frequency using an array of complementary components to control their timing. Specific to an astable multivibrator, the wave is rather a single pulse emitted for a certain duration that is triggered on a certain input. The next major component to understand is an Op-Amp. These have numerous uses as they are capable of amplifying a given input signal to a specified gain according to the arrangement of complementary components. With an inverting and non-inverting terminal, they attempt to change their output such that the two input voltages are as close as possible with some feedback going from the output to one of the input terminals. Hence, in the default state without any feedback or complementary components, they have a gain that can be taken as extremely large, and so will clip the differential of the waveforms fed to them while amplifying it to the voltage provided by the Op-Amp's positive and negative power supplies. Tying one of the terminals to ground, the Op-Amp can then act as an amplifier of that one signal which is important for this use case. With the right components, the gain can be tuned as desired, and the waveform can be preserved in addition to performing filtering on the signal to remove noise of certain frequencies. A comparator is similar to an Op-Amp as both have two differential inputs and amplify signals. However, comparators have a much faster switching rate and so are ideal for as their name suggests, comparing two inputs and without any feedback, outputting a square wave of when one is greater than the other. In this manner, they are excellent for analog-to-digital conversion (ADC).

The next few ICs are all specific to digital operations. The first is the Set-Reset (SR) latch, this device as the name implies, will latch its output high the moment its set input goes high. The system can then be reset to a low state by toggling the reset input high. In this manner, it can act as a trigger of sorts for a given input signal. The last major components to discuss are the Binary-Coded-Decimal (BCD) counters and 7-Segment Display (7SD) driver chips. The BCD counters are composed of a network of logic gates such that they can count up and down in binary to 9, representing a single decimal place. These can be used to count at a certain clock rate and with the use of their other inputs, either stop, reverse direction, reset the count, or trigger a second counter based on the state of a carry bit representing when a full decade has been counted. The driver chips on the other hand, can take the output of the BCD counters and convert it into a high or low voltage for each of the 7 LEDs on a 7SD such that the binary output of the counters is human-readable.

Methods

Planning the Design

The construction of this sensor was done by following an iterative approach. To begin, a plan was first laid out and converted into a block diagram with a timing diagram to go along. A circuit schematic was also constructed in Multisim to confirm the design would function and to understand how the components were connected when building the device on the breadboard. Updates were made to these along the way as the physical circuit was constructed and certain components were found to not be as effective in achieving the end goal as initially thought. These prior diagrams are present in *Appendix C* for reference, however, only the most notable changes to the design over time will be discussed. During the first work period, the transmitting transducer was also fed an AC voltage from a function generator and the transmitted and received signals were viewed on the scope. These were to get an understanding of what the signals would look like and better develop a plan of action. Updates were also made in weekly progress summaries. The final schematics are presented below in *Figures 2 – 4.*

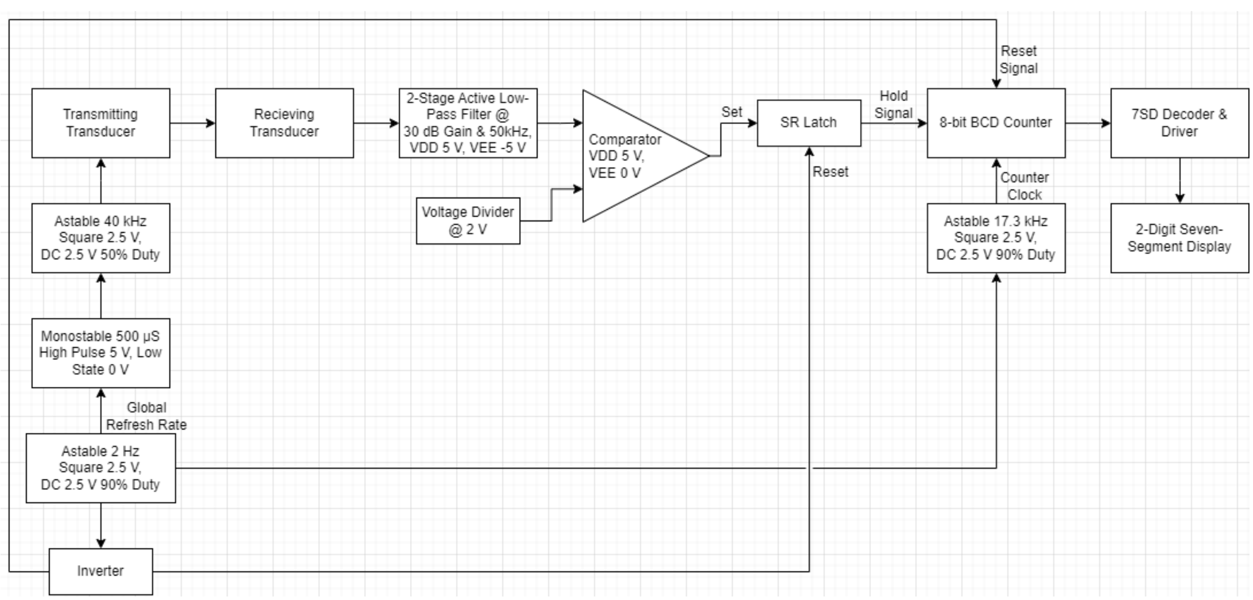

Figure 2 – Final Block Diagram for Sensor

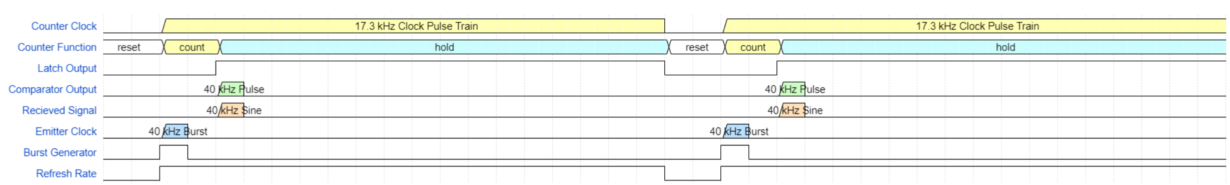

Figure 3 – Final Timing Diagram for Sensor

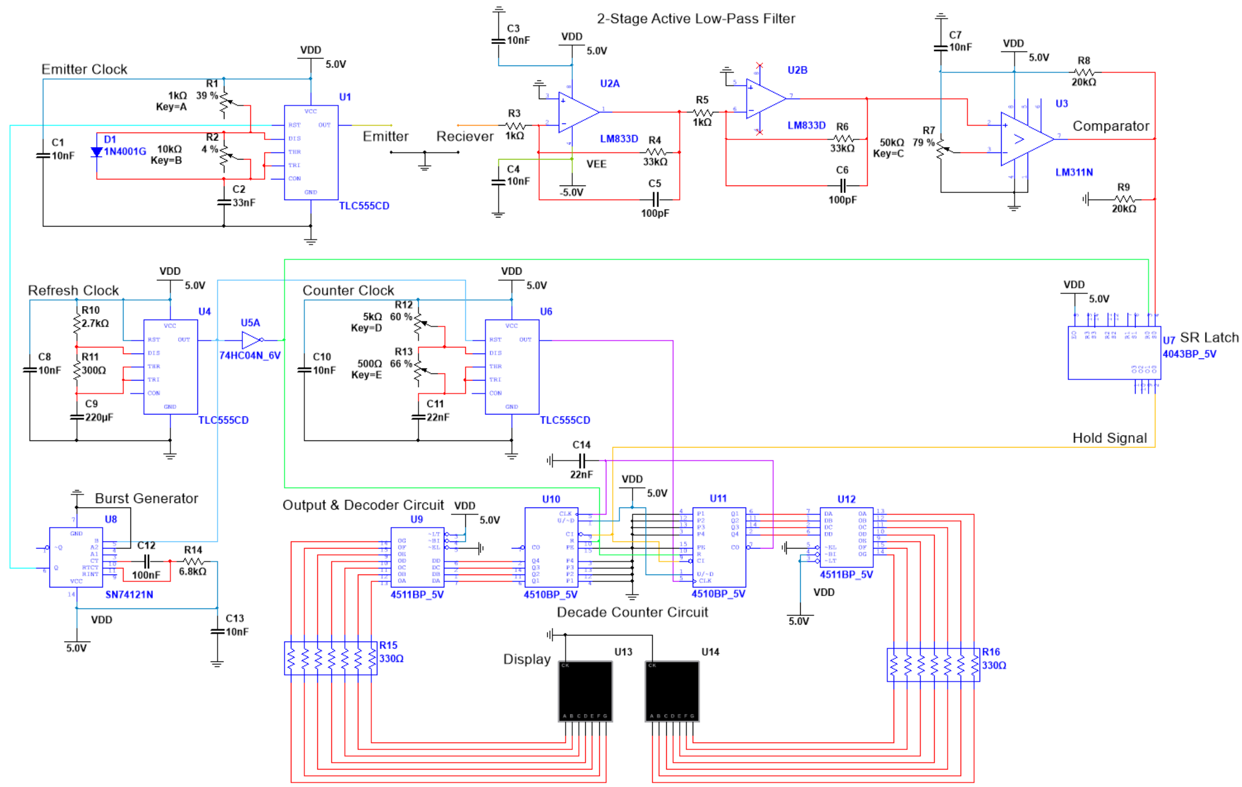

Figure 4 – Final Circuit Schematic for Sensor

Constructing the Circuit

After the initial plan was drafted and a schematic was made as a starting point, the next week was used to construct the design and identify any issues with the planned design. All work was done in a modular approach and sticking to a consistent colour scheme to make debugging easier. In addition, wires were kept as short as possible to reduce the potential of them acting as antennas and introducing noise to the system. When certain components were not working as anticipated, the wiring was first double checked, then the oscilloscope was used to confirm important signals were being produced as intended. If a flaw was found, the portion of the design would be re-thought and changed. This engineering process was used throughout and was initiated with the construction of the filter circuit for the received signal as that was deemed to be the most time-consuming aspect of the build. Initially this was configured to be a passive RC high-pass filter with the cut-off frequency set to 39 kHz as the assumption was that the most prominent noise component would be the 60 Hz mains voltage noise. However, this hypothesis would be quickly disproved after testing the assembled filter and comparator circuit. The LM311 comparator was designed as a zero-crossing detector and triggered on even the baseline noise present and it was also found that the filter did little to attenuate the baseline noise. This resulted in the SR latch holding early and the values being read incorrectly. Measuring the noise on the oscilloscope, the frequency was found to be about 90 MHz. As the signal at large distances was also quite small, this design was adapted to a 2-stage active Butterworth low-pass filter using the LM833 op-amp and the comparator reference voltage set through a voltage divider formed by a potentiometer rather than ground. This eliminated most of the false-triggering problems and would later be further tuned by changing the reference voltage to be above the baseline noise. The LM833 was chosen specifically due to its high-frequency capabilities and high slew rate so as not to alter the phase or the shape of the signal significantly.

After fixing the filter, the counter and display circuit were built and tested at a low clock frequency from the function generator. This was a fairly straightforward portion of the build with no issues occurring. The CD4511BP and CD4510BP were used to drive two 7-segment displays and act as the decade counting circuit respectively. Allowing for the system to display any number between 0 and 99. This would be the output value of the sensor in cm. The next major area tackled were the clocks. Initially three TLC555 timer ICs in the astable configuration were used for the refresh, counter, and emitter clocks respectively. However, it was found that cutting the transmission while receiving a signal improved noise reduction in the received signal and prevented false triggers. As such, the emitter clock was passed through the SN74121 monostable multivibrator IC configured to a pulse width of 500 µs which was calculated to be below the shortest TOF *(Refer to Appendix A).* This IC was used over the TLC555 in monostable configuration as it was found that the TLC555 would hold its output high even if the pulse duration configured was shorter if the trigger was held high for longer than the desired pulse. This would be problematic for the rest of the logic as the refresh clock was configured to 2 Hz and tied to the trigger pin. Moreover, this decision was made late in the development process, with the sensor already mostly functional. With better tuning of the setup, it is almost certainly possible to have gotten the desired readings at long distances without this addition, however, it was incorporated as an innovative feature and provided a slightly cleaner received signal. From here, it was a matter of performing some final tuning on all the potentiometers to get the accuracy within the desired ±1 cm as per the provided rubric and to trigger on all the required distances. For the purposes of validating the distance, a meter stick was placed to start at the point where the transducers began and a laptop was placed at the other end as the measurement object. All passive complementary component values selected have their calculations and reasoning present in *Appendix A*. The final circuit produced on the breadboard was marked with flags for each major component and shown in *Figures 5-7.*

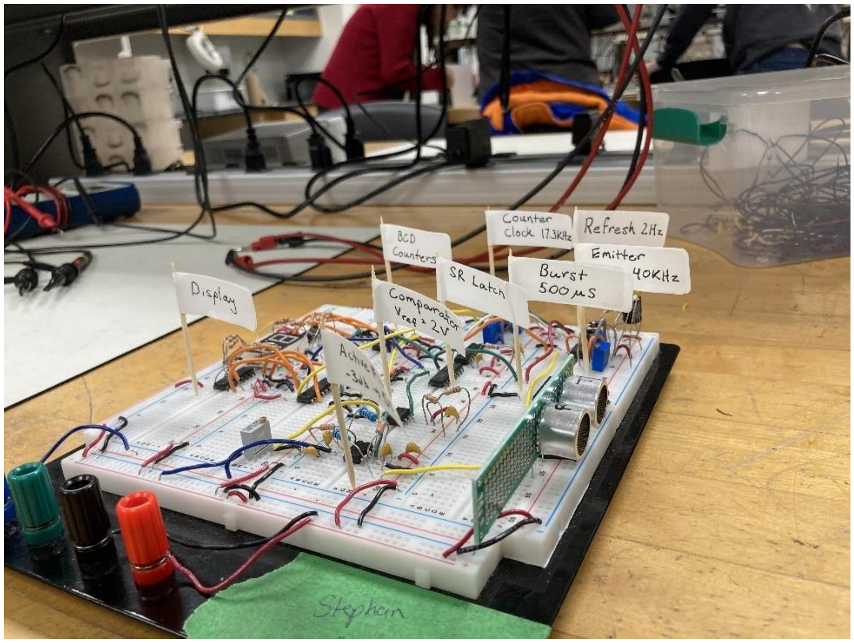

Figure 5 – Final Circuit on Breadboard from Transducer Corner

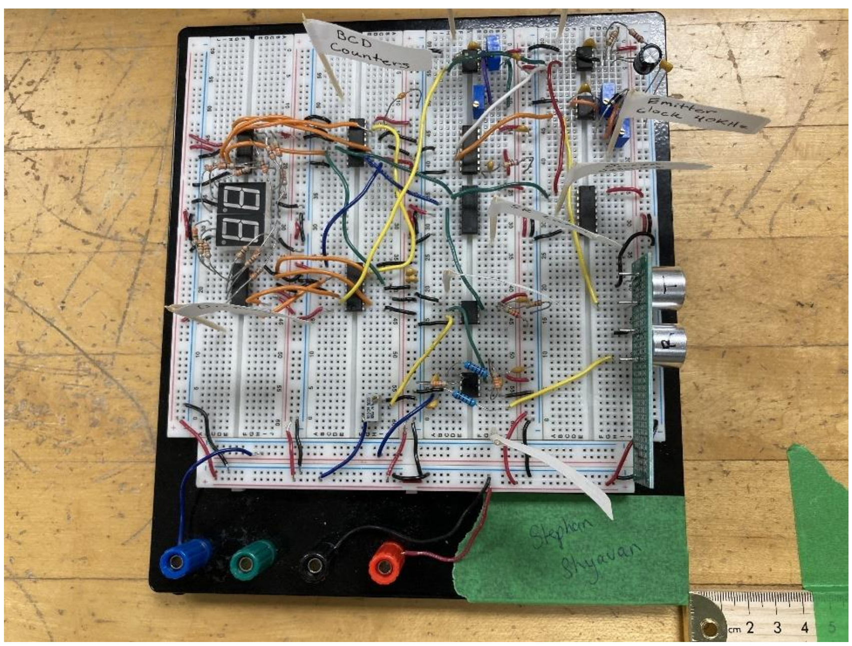

Figure 6 – Final Circuit on Breadboard from Top

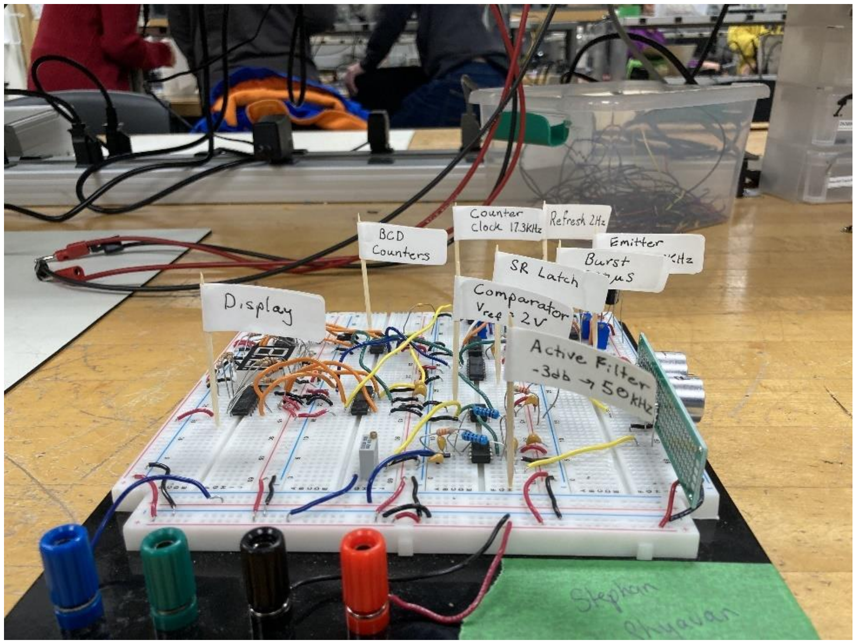

Figure 7 – Final Circuit on Breadboard from Side

Results

Using the above methods, the circuit was constructed and then validated. Uncertainty calculations are provided in *Appendix B* as per the instrument datasheets referenced in [4]–[6]. Note that the graphs made in-lab have error bars associated with the measurements by the instruments. Some oscilloscope plots are also included in *Appendix C.*

Following the methods for tuning and testing the range finder outlined above, the correct distances were confirmed to be read after tuning all the potentiometers to within the highest level of desired accuracy at all required distances. The system produced did however, provide consistently off measurements by 1 cm exactly at the very short distances, while providing perfect results as the distance became larger. Moreover, at exactly 99 cm, initially the sensor would often read either 9 or 19 cm indicating overflow to either 109 or 119 cm. After troubleshooting, it was found that a capacitor on the clock input resolved the issue. The system was also capable of reading accurate distances well beyond the requested bounds, both to a minimum of 1 cm itself and to a maximum of 175 cm. Beyond this point, the system did not trigger at all, however, as this was far beyond the scope of the intended target measurement range, this was ignored as the device was fully functional to the parameters specified. It was also found that the angle of the measurement object, with even a minute deviation of a degree or so would drastically affect the reading the system output and so the measurement object was kept as consistent as possible, handling it in such a way that there would be minimal changes to the angle. Some data was also collected on the time difference and amplitude of the received signal at set distances for further reference but was not required or used during the project as the system was already determined as working with the outlined methods. This data is presented below, with sample uncertainty calculations are provided in *Appendix A*.

Distance (cm)	TOF (µs)	Raw Received Signal Amplitude (mV)
20.0 ± 0.1	750 ± 40	28.4 ± 0.4
40.0 ± 0.1	1930 ± 40	21.6 ± 0.4
60.0 ± 0.1	3140 ± 40	18.6 ± 0.4
80.0 ± 0.1	4250 ± 40	17.8 ± 0.4
99.0 ± 0.1	5410 ± 40	6.6 ± 0.4

Table 1 – Data Collected Regarding TOF and Received Signal Amplitude at Varying Distances

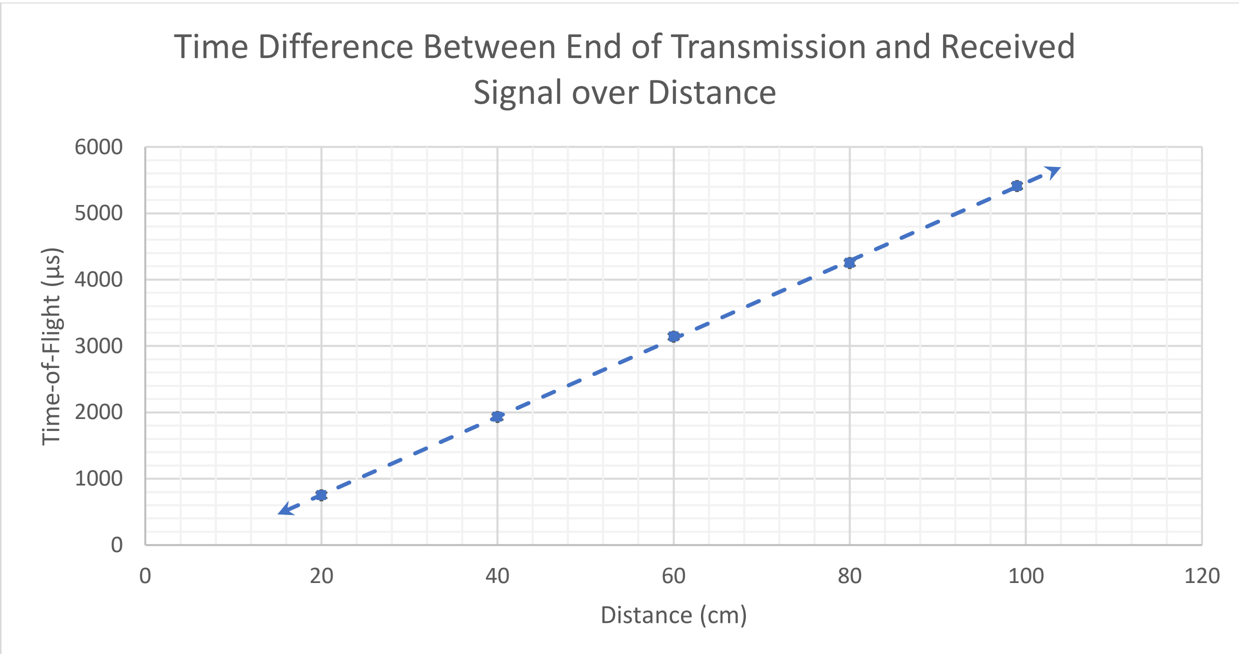

Figure 8 – Plot of TOF over Distance

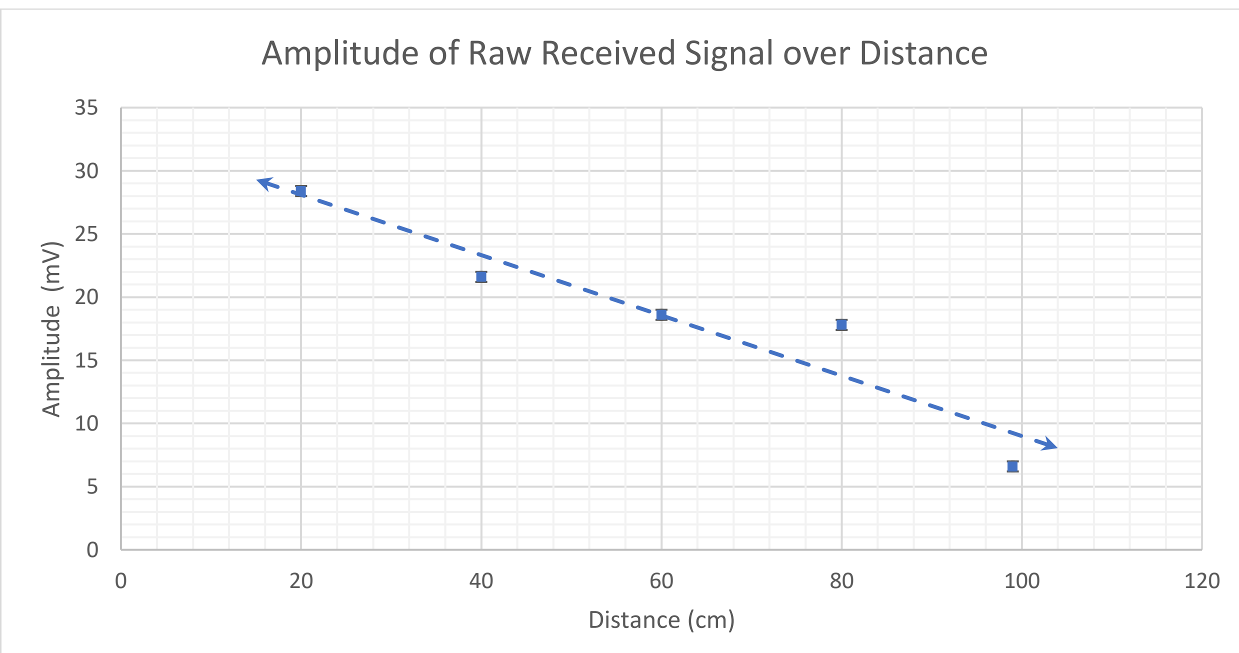

Figure 9 – Plot of Received Signal Amplitude over Distance

Discussion

Due to the nature of this experiment and as a result of most things going according to plan resulting in a working sensor meeting and exceeding all the set requirements, there is not much to be discussed. However, some variance in the results may require explanation. Firstly, the sensor's readings being slightly off albeit within the set tolerance at shorter distances must be analyzed. This is likely due to the response time of all the electronics involved. As each IC has its own switching time and other parameters, that propagation delay for the signal in combination with any discrepancies with how the angle was set on the measurement object would likely account for the variance noticed. As this issue only appeared at distances around 12 cm or lower and was within the specified tolerance, it was for the most part ignored. The next aspect to be discussed is the sensor being unable to trigger beyond 175 cm. While this was outside the scope of the requirements, edge cases such as this were tested for to see the limits of the constructed sensor's capabilities. This non-triggering issue is likely due to the noise and received signal becoming indistinguishable in amplitude at that point and both being beneath the threshold voltage set to the comparator. As a result, to better improve the performance of this sensor and enable it to work at even greater distances, it is likely that better filtering could be implemented to tune out the noise in addition to further tuning of the comparator threshold voltage. If these parameters could be fine tuned, then this sensor could be very promising for even long-range applications. The issue with reading 99 cm that were experienced early on were likely due to the clock input bouncing. Hence, adding a capacitor de-bounced the circuit and prevented the fluctuations. As the circuit is solid-state, it is not entirely certain why this portion alone tended to bounce on the one number, and so more research into that area would be required. The discrepancies observed in the distance read due to the angle of the measurement object can also be explained away as the transducers and the sound produced by them is highly directional. Any deviation in the reflection of that pressure wave would be enough to cause the wave to travel further to get back to the receiver and so result in varying measurements. Lastly, there is also a non-significant amount of variance in the received signal amplitude. At times this signal would vary between noisy and high amplitude, to low amplitude but also quite clean. The reason for this is unknown but it is likely that there was some interference from other students' projects within the lab which may have contributed to the results seen. However, this too did not affect the performance of the sensor enough to cause any problems.

Conclusion

As evidenced by the exceptional performance of the sensor, the skills learned throughout the duration of the course were applied well. Some of the results obtained did have some discrepancies, but nothing significant to cause malfunctions in the sensor operation as long as certain parameters were held consistent. Moreover, those that were present could be points for further exploration of such a circuit and adapting it to be even more resilient to noise and capable of operating at significantly larger distances. The skills learned have further applications in constructing similar projects and hence it can be said that the desired objectives were achieved.

Appendices

Appendix A – Sample Calculations

555 Timer Complementary Components

These values were all approximated using the DigiKey 555 timer calculator [7] and then adjusted by using trim potentiometers for the resistors to tune to the final values shown in *Figure 4* to produce the desired accuracy. All decoupling capacitors were set to 10 nF as per the sample schematic in the datasheet [8]. Note that final values were tweaked in the DigiKey calculator to obtain component values available in-lab.

$$T_h = 0.693(R_1 + R_2)C_1$$
$$T_l = 0.693R_2C_1$$
$$f = \frac{1.44}{(R_1 + 2R_2)C_1}$$

For Refresh Clock at 2 Hz with 90% Duty Cycle:

Set R_2 to 300 Ω for convenience.

$$0.05 = 0.693(300)C_1$$
$$C_1 = 240\ \mu F$$
$$2 = \frac{1.44}{\big(R_1 + 2(300)\big)(2.4 \times 10^{-4})}$$
$$R_1 = 2.4\ k\Omega$$

SN74121 Complementary Components

These complementary components were obtained as per the graph on page 6 of the IC datasheet [9] and did not require specific calculations. The decoupling capacitor was kept consistent with the rest of the circuit at 10 nF.

Op-Amp Complementary Components

These values were chosen using the Inverting Op-Amp Low-Pass Filter Calculator [10] using the following method. Note that once again, the values obtained from the calculator were adjusted as necessary to obtain component values available in-lab.

$$f_{cutoff} = \frac{1}{2\pi R_2 C_1}$$
$$A_V = -\frac{R_2}{R_1}$$

Set R_1 to 1 kΩ for convenience:

$$-33 = -\frac{R_2}{1000}$$
$$R_2 = 33\ k\Omega$$
$$50000 = \frac{1}{2\pi(33000)C_1}$$
$$C_1 = 96.5\ pF$$

Comparator Complementary Components

A 20 kΩ pull-up resistor was attached to the output of the comparator in order to provide a load for the device as mentioned in the datasheet [11]. The reference voltage was set by tuning the potentiometer carefully up from a point where no signal was read, to just beyond the threshold when a signal was registered, with fine tuning done by confirming the efficacy of the system along various distances.

SR Latch Complementary Components

A 20 kΩ pull-down resistor was attached to the input of the SR latch as per the datasheet [12] to improve signal integrity and prevent false triggering.

Counter Clock Frequency

$$f = \frac{v}{d}$$

Set v to 346 m/s and d as the shortest distance for resolution both ways being 2 cm:

$$f = \frac{346}{0.02}$$

$$f = 17.3\ kHz$$

Shortest Time of Flight

$$T = \frac{d}{v}$$

Set v to 346 m/s and d as the shortest distance as per minimum defined bounds both ways being 20 cm:

$$T = \frac{0.2}{346}$$

$$T = 578\ \mu s$$

Appendix B – Sample Calculations of Measurement Uncertainties

Component Uncertainties

Note that component uncertainties were not looked into apart from specific data that was gathered as the precise values were not deemed as important to the functionality of this system as long as everything was not significantly out of specification from the design. As a result, since only the potentiometers' final values were measured and are presented below, those values have their uncertainty calculation shown below. For the rest of the complementary components, values were taken to be as the same as the design without uncertainty due to the lack of influence on any of the final outcomes with the inherent digital nature of the project for the most part. Moreover, even the analog portion of the receiving circuit and clock systems do not require precise tolerance calculations.

Potentiometers for Clocks

$$I_C = \frac{15 - V_{CE}}{1000}, I_C(7.5\,V) = 6.45 \pm (0.01(6.45) + 0.02) = 6.45 \pm 0.08\,mA$$

$$\beta = \frac{6.45 \times 10^{-3}}{25 \times 10^{-6}} = 258 \pm \frac{0.08 \times 10^{-3}}{25 \times 10^{-6}} = 258 \pm 3$$

Time of Flight

Based on smallest division on 500 µs scale:

$$TOF = 1260 \pm 1\,div - 510 \pm 1\,div\,\mu s$$

$$TOF = 750 \pm 2\,div\,\mu s$$

$$TOF = 750 \pm 2\left(\frac{500}{25}\right)\,\mu s$$

$$TOF = 750 \pm 40\,\mu s$$

Received Signal Amplitude

Based on smallest division on 10 mV scale:

$$A = 28.4 \pm 1\,div\,mV$$

$$A = 28.4 \pm \frac{10}{25}\,mV$$

$$A = 28.4 \pm 0.4\,mV$$

Distance

Based on smallest division on meter stick used for measurements:

$$d = 20.0 \pm 1\,div\,cm$$

$$d = 20.0 \pm 0.1\,cm$$

Appendix C – Oscilloscope Data & Prior Schematics

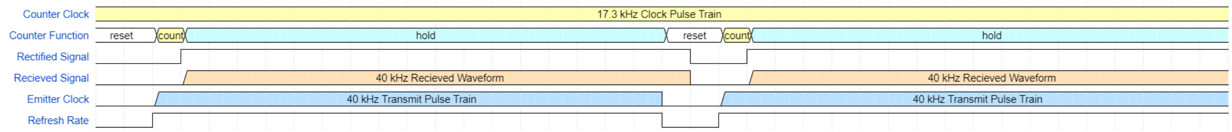

Figure 10 – Initial Timing Diagram from First Week

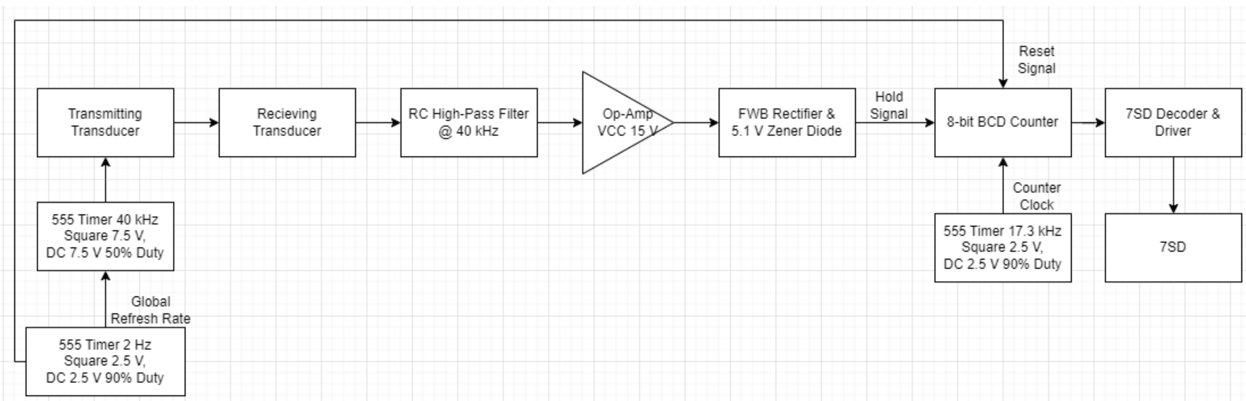

Figure 11 – Initial Block Diagram from First Week

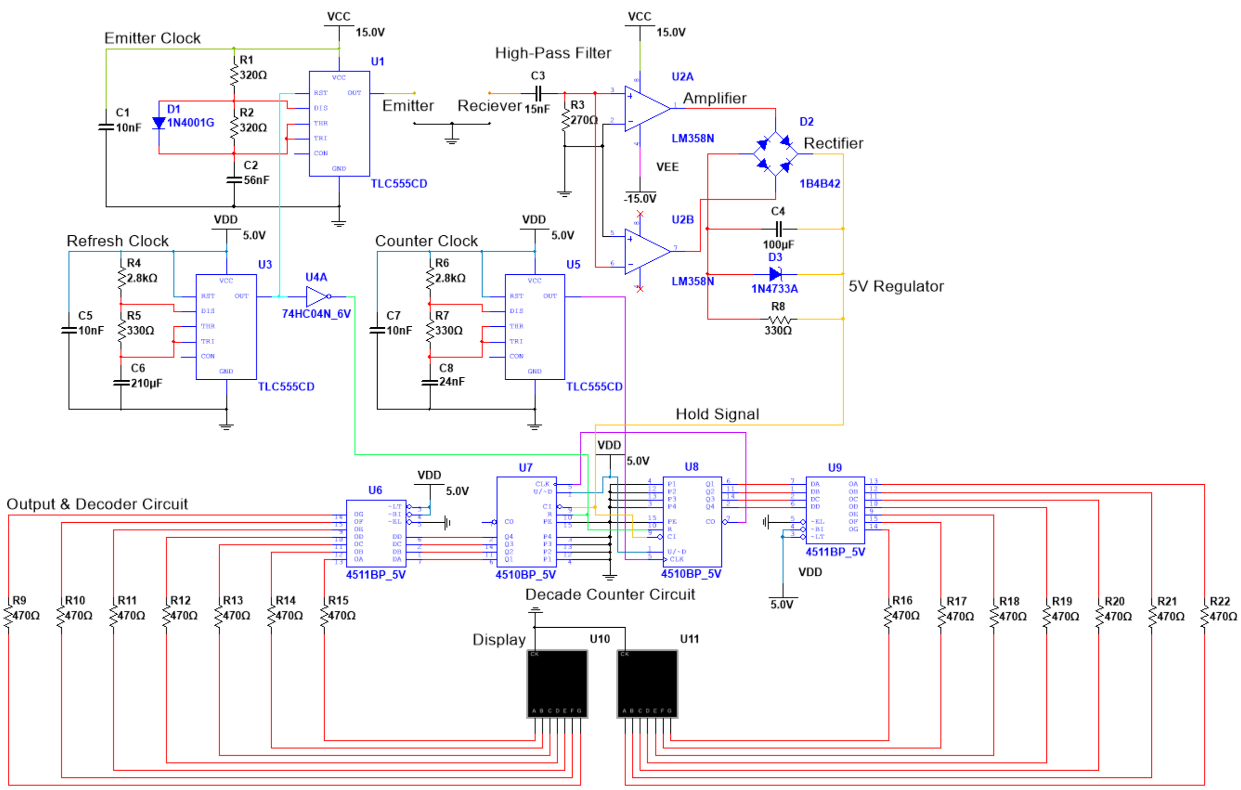

Figure 12 – Initial Circuit Schematic from First Week

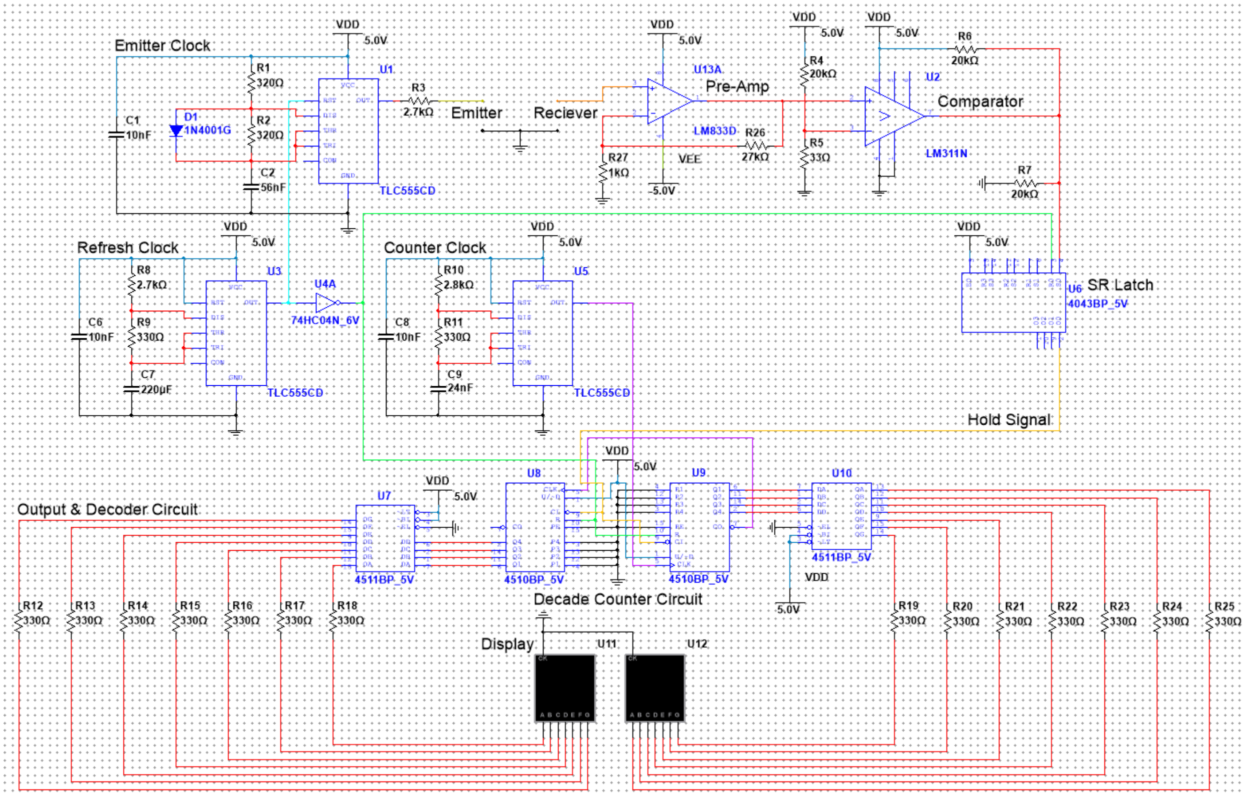

Figure 13 – In-Progress Circuit Schematic from Third Week

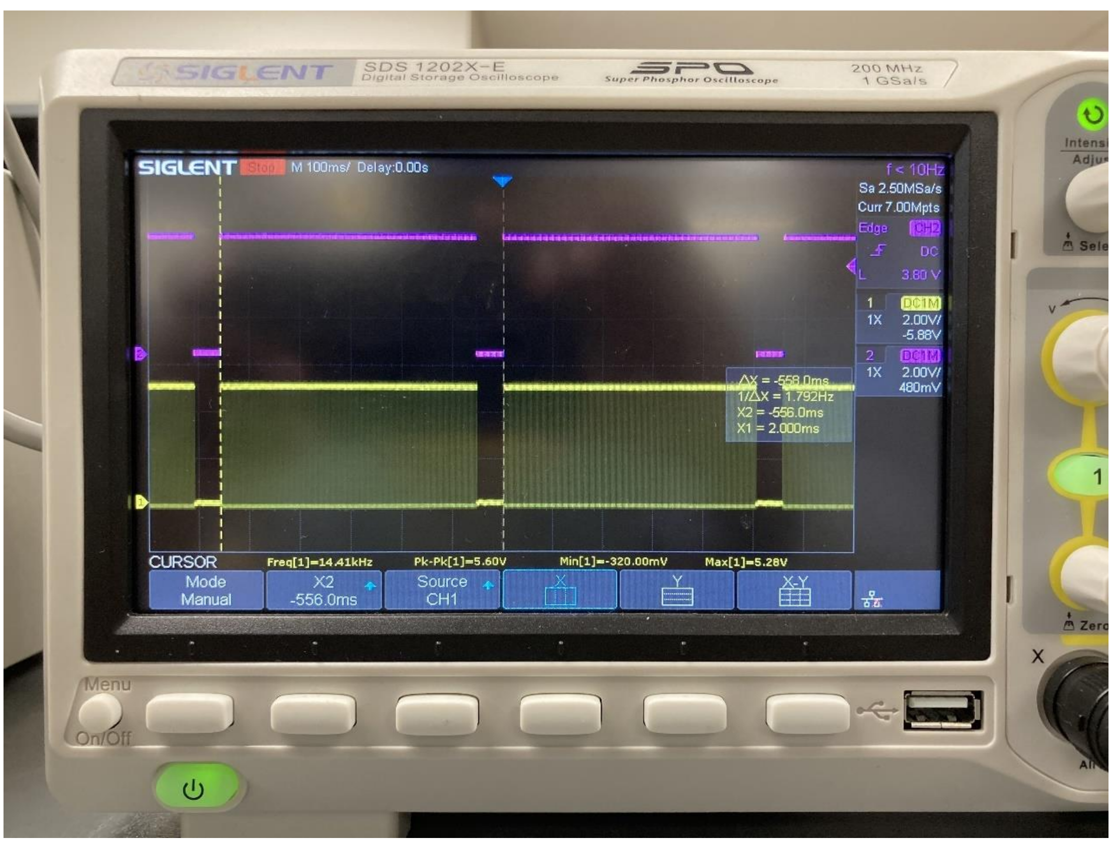

Figure 14 – Refresh Clock in Purple and Emitter Clock in Yellow

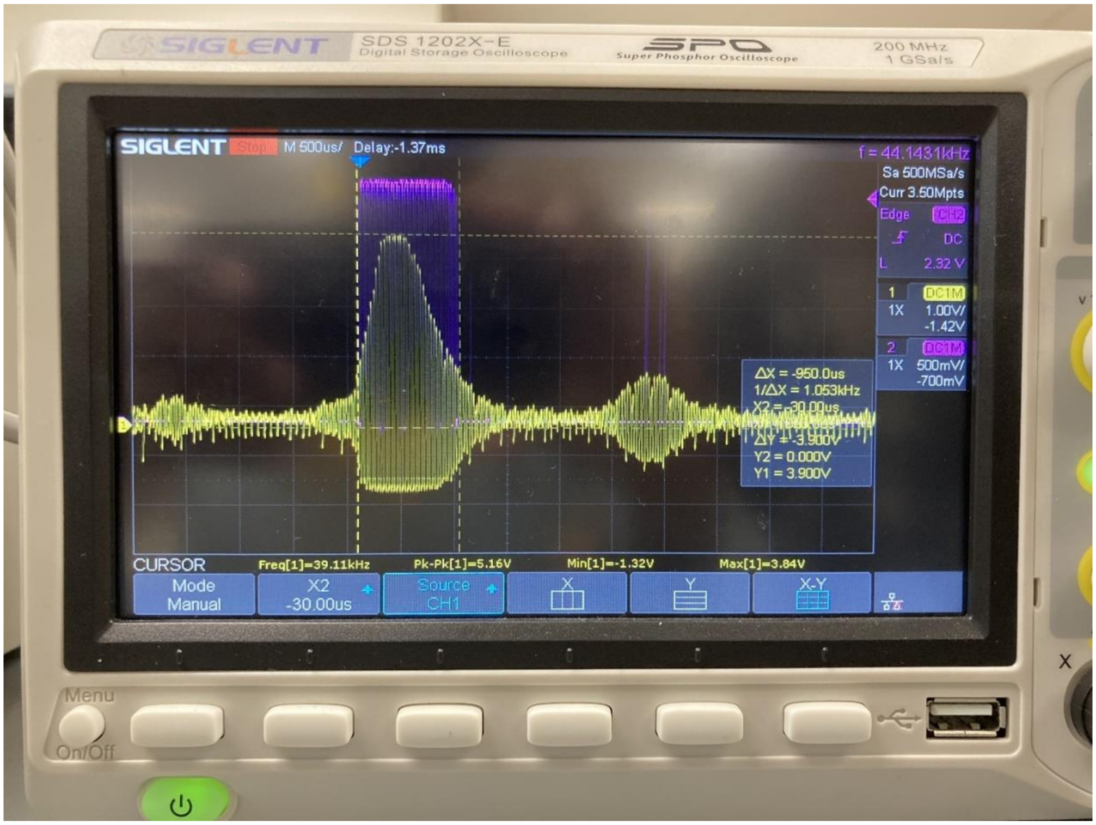

Figure 15 – Received Comparator Output in Purple and Received Op-Amp Output in Yellow at 40 cm

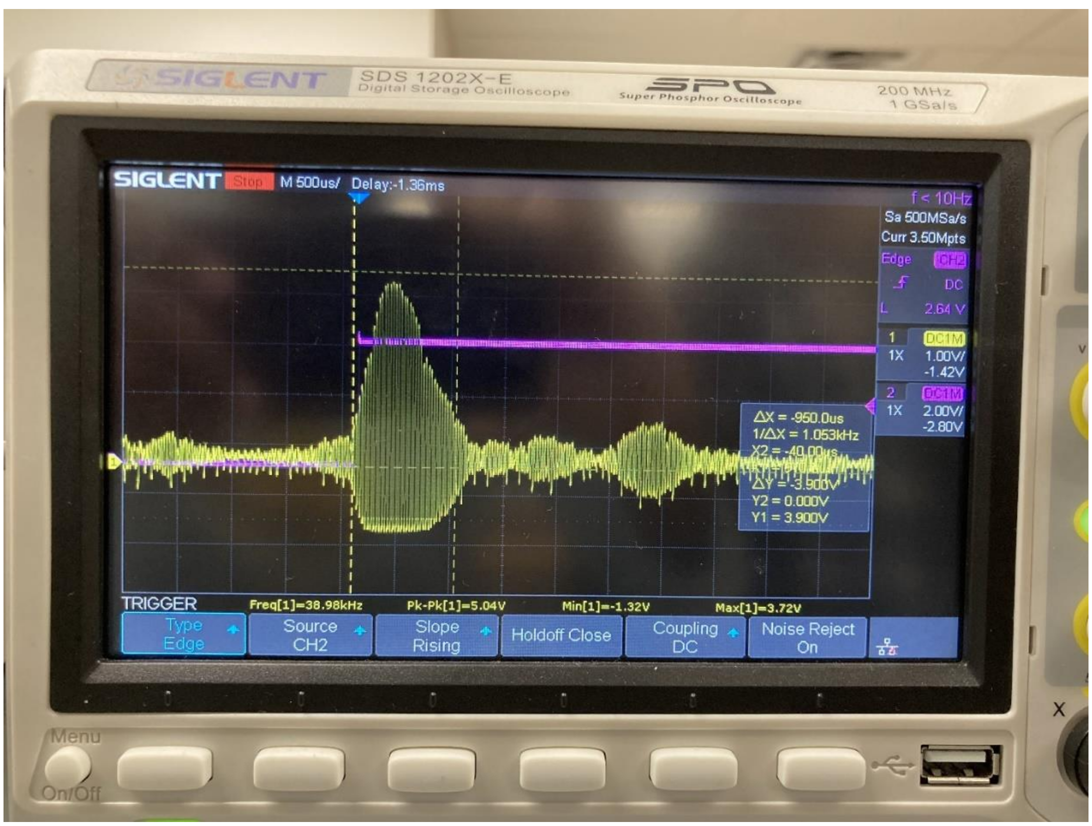

Figure 16 – SR Latch Output in Purple and Received Op-Amp Output in Yellow at 40 cm

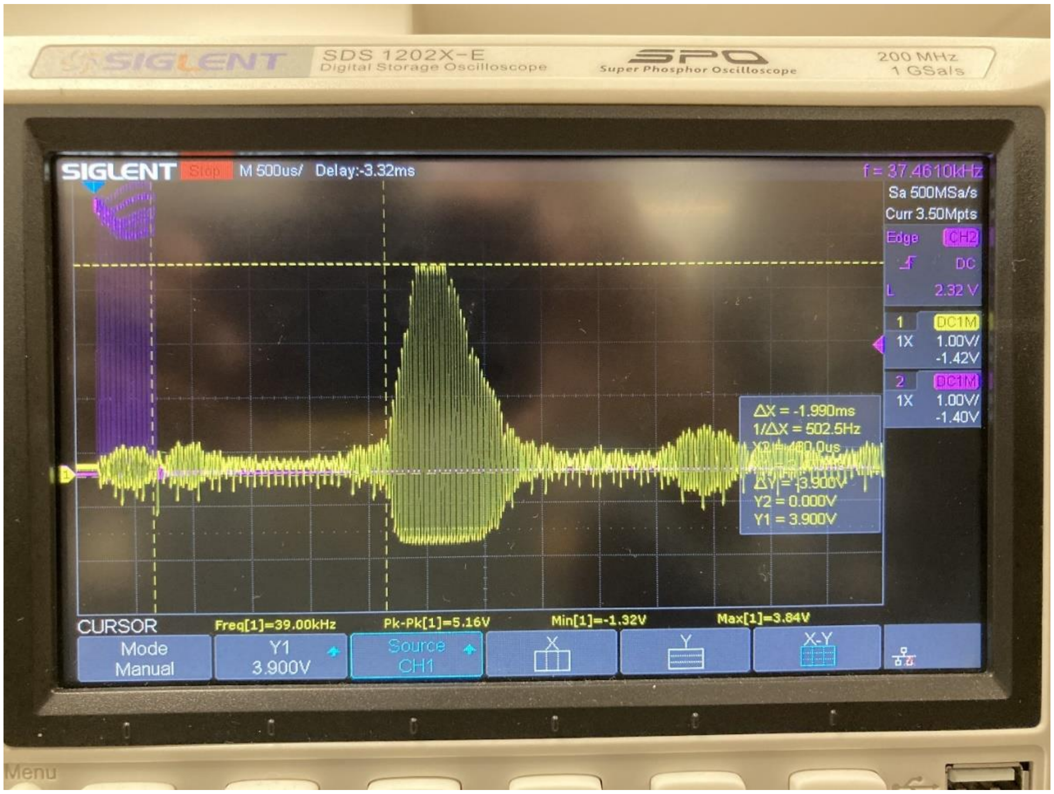

Figure 17 – Transmitted Waveform in Purple and Received Op-Amp Output in Yellow at 40 cm

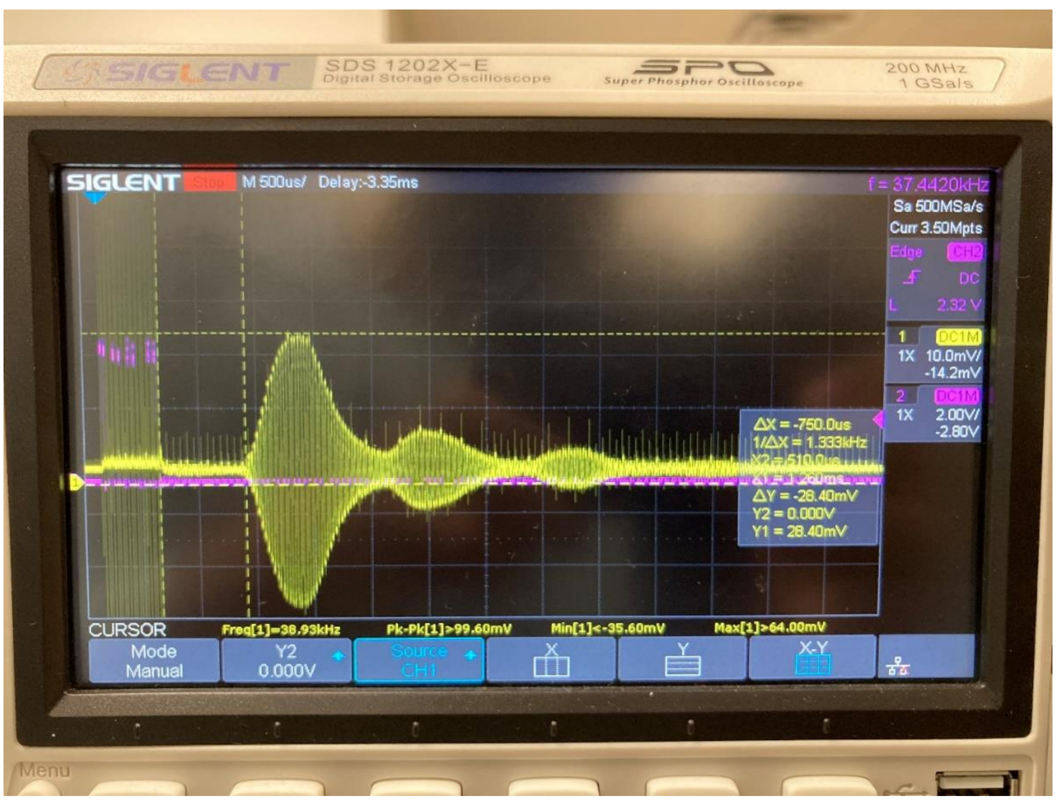

Figure 18 – Transmitted Waveform in Purple and Raw Received Waveform in Yellow at 20 cm

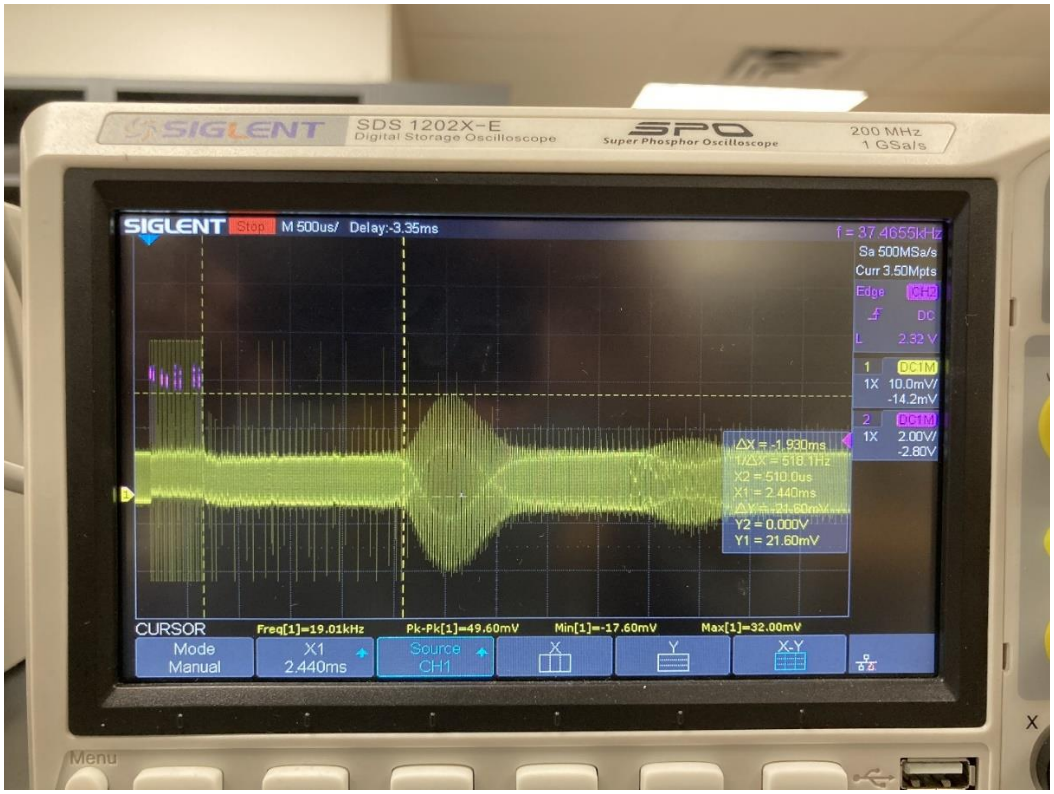

Figure 19 – Transmitted Waveform in Purple and Raw Received Waveform in Yellow at 40 cm

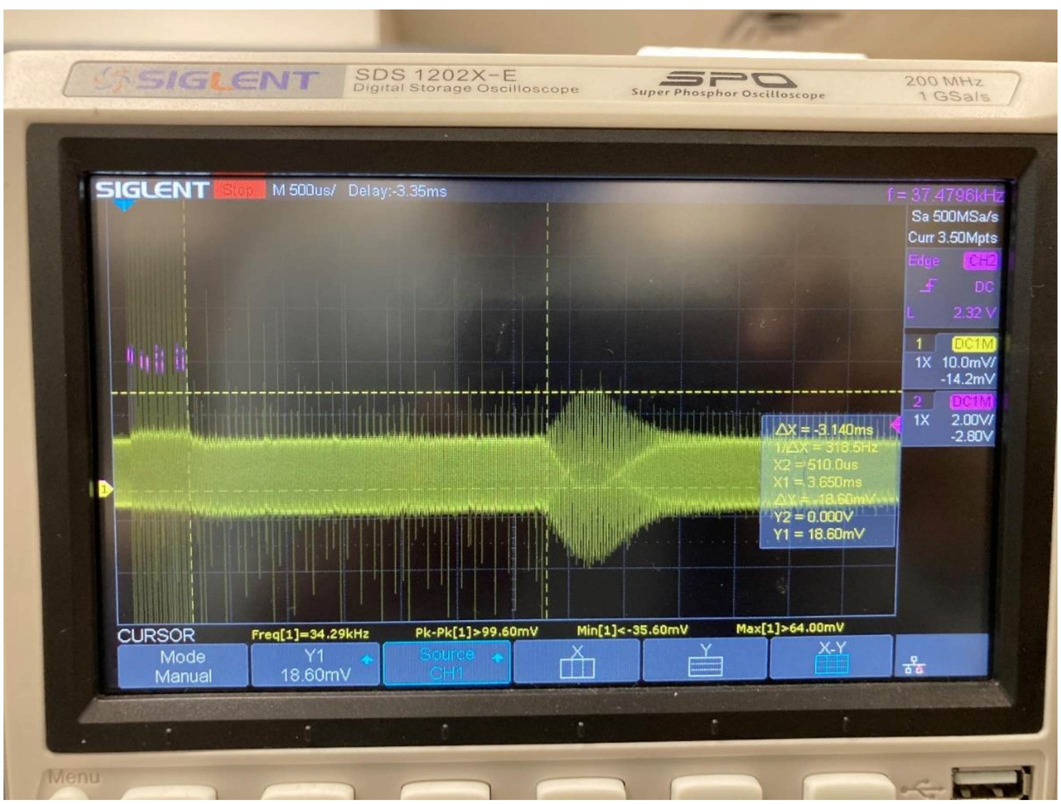

Figure 20 – Transmitted Waveform in Purple and Raw Received Waveform in Yellow at 60 cm

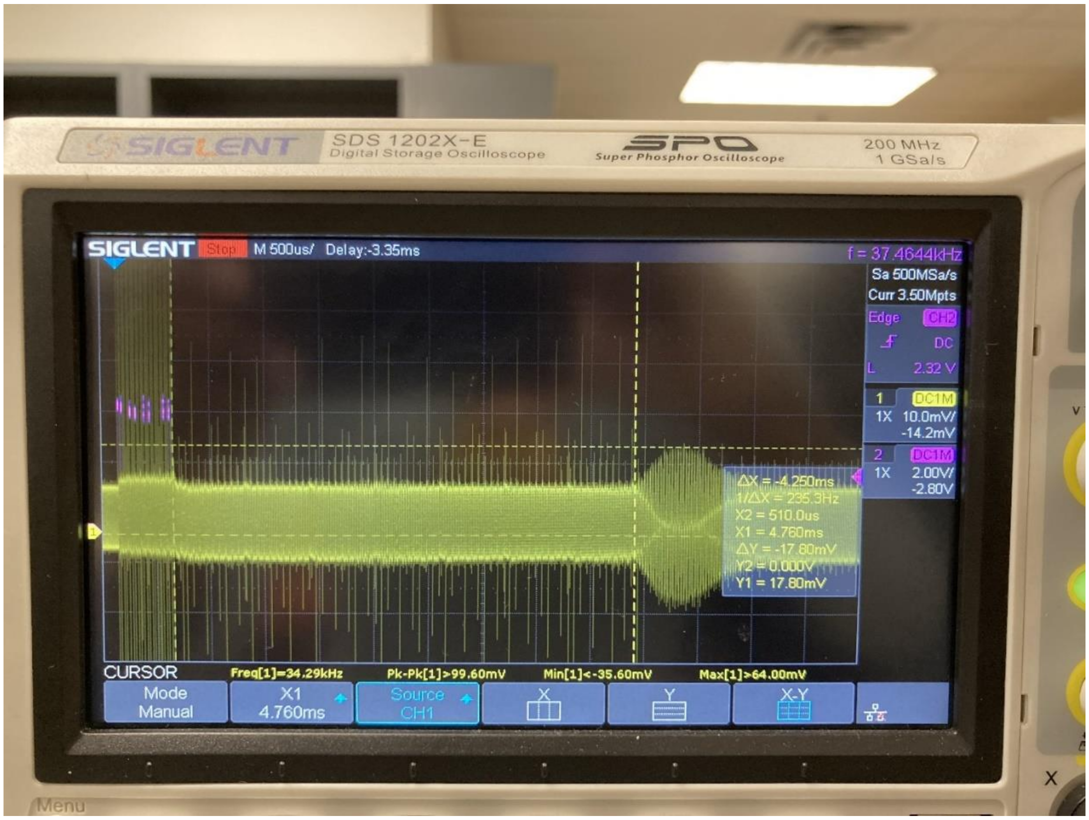

Figure 21 – Transmitted Waveform in Purple and Raw Received Waveform in Yellow at 80 cm

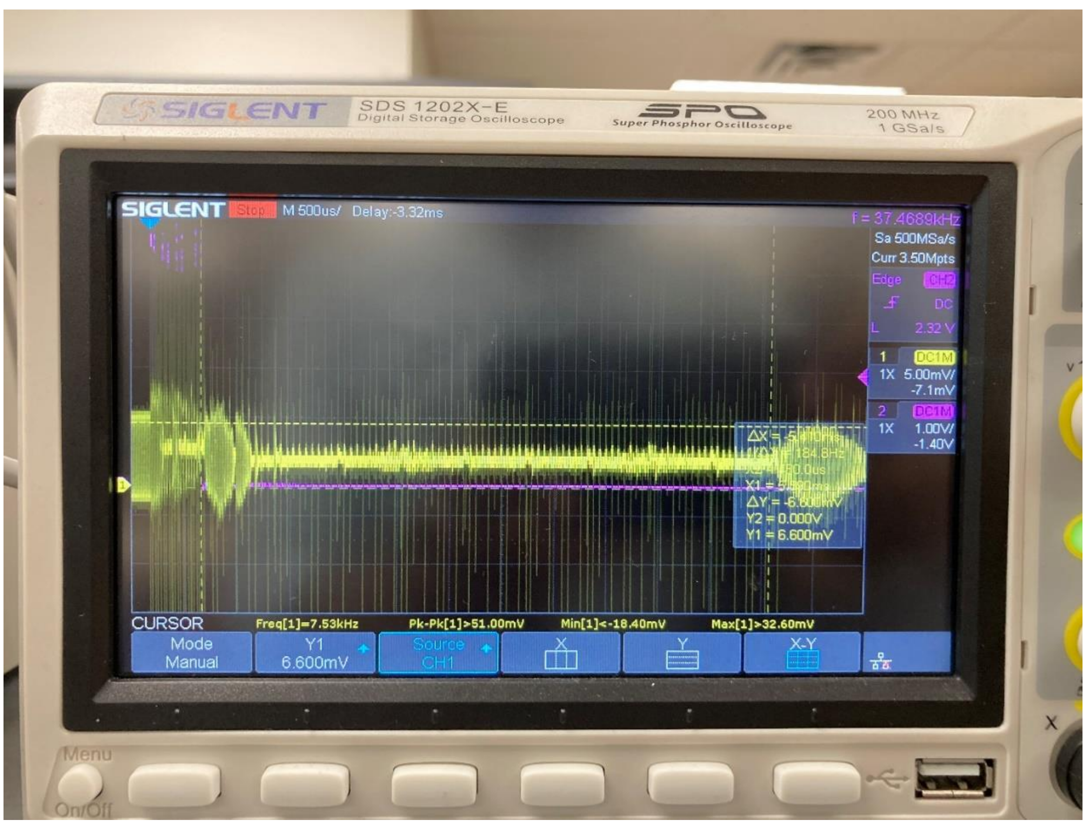

Figure 22 – Transmitted Waveform in Purple and Raw Received Waveform in Yellow at 99 cm

References

[1] "Nondestructive Evaluation Physics : Sound." Accessed: Dec. 16, 2023. [Online]. Available: https://www.nde-ed.org/Physics/Sound/tempandspeed.xhtml

[2] E. Guerra-Bravo, H. J. Lee, A. Baltazar, and K. J. Loh, "Vibration Analysis of a Piezoelectric Ultrasonic Atomizer to Control Atomization Rate," *Applied Sciences 2021, Vol. 11, Page 8350*, vol. 11, no. 18, p. 8350, Sep. 2021, doi: 10.3390/APP11188350.

[3] "Difference Between TTL and CMOS ICs and How to Choose Between Them." Accessed: Dec. 16, 2023. [Online]. Available: https://components101.com/articles/ttl-vs-cmos-ics-and-how-to-choose-between-them

[4] "SDS1000X-E Digital Oscilloscope," 2021.

[5] "Ranging Auto/Manual Auto/Manual Auto/Manual Manual Manual Auto/Manual Manual Manual".

[6] "Handheld Digital Multimeters Test Bench ® Series Data Sheet", Accessed: Oct. 22, 2023. [Online]. Available: www.bkprecision.com

[7] "555 Timer Calculator | DigiKey Electronics." Accessed: Dec. 16, 2023. [Online]. Available: https://www.digikey.ca/en/resources/conversion-calculators/conversion-calculator-555-timer

[8] "TLC555 LinCMOS™ Technology Timer Simplified Schematic," 2023, Accessed: Dec. 16, 2023. [Online]. Available: www.ti.com

[9] "SDLS042A-MAY 1983-REVISED MAY 2005".

[10] "Low Pass Filter Calculator." Accessed: Dec. 16, 2023. [Online]. Available: https://www.learningaboutelectronics.com/Articles/Low-pass-filter-calculator.php#answer3

[11] "LM111, LM211, LM311 LM111, LM211, LM311 Differential Comparators," 2016, Accessed: Dec. 16, 2023. [Online]. Available: www.ti.com

[12] "CD4043B data sheet, product information and support | TI.com." Accessed: Dec. 16, 2023. [Online]. Available: https://www.ti.com/product/CD4043B