EE 449 Ultrasonic Sensor

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***Abstract* - An ultrasonic sensor is an electronic device that utilizes a transmitter and receiver to measure the distance of a target object. The transmitter emits sound waves in the ultrasonic range, a range that is inaudible for humans, using a piezoelectric crystal and the receiver converts this sound wave back to an electric signal. This ultrasonic sensor emits sound waves that have a frequency of 40 kHz. The microcontroller in the ultrasonic sensor connects via USB to a personal computer and serially outputs the distance of the target object from the sensor. The sensor can measure distances up to 3.5 meters. At distances greater than 3.5 meters, the receiver will not detect any significant audio waves to trip the microcontroller. The sensor is also designed to measure distances no smaller than 0.1 meters. The design of this ultrasonic sensor also accounts for the presence of audio noise by filtering out any signals that fall outside the range of a 1 Khz bandwidth centered around the central 40 kHz frequency.**

I. INTRODUCTION

The design of this ultrasonic sensor involved the design of various subcircuits that interfaced with either the microcontroller or the transmitter-receiver pair. The microcontroller is inherently a digital device that can only read and write digital signals. Many analog circuits such as the 40 kHz oscillator and tone detector are needed for electric signal processing for both the transmitter and receiver. The breakdown of this project into various analog circuits is shown in Figure 1 below.

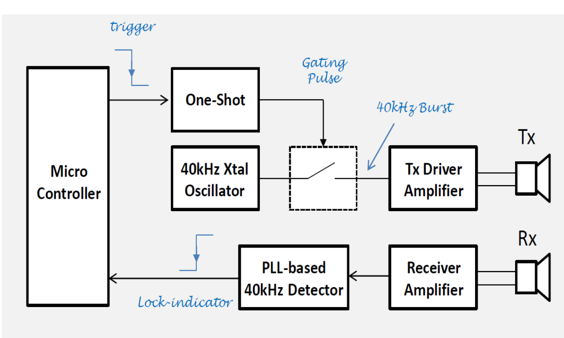

Fig. 1. Topology Breakdown of Ultrasonic Sensor.

The process of measuring distance begins when the microcontroller triggers the one-shot circuit with an active low signal. The one-shot then triggers high for 1.2 ms and activates the switch. This provides a 40 kHz burst which comes from the 40 kHz oscillator and is fed into the Tx driver amplifier. This amplifier does not amplify the voltage signal from the 40 kHz oscillator, rather it provides an extra boost of current which is needed to drive the transmitter. This current amplified signal is then converted from electrical energy into sound energy by the transmitter and emitted into free space.

If the target object is within 3.5 meters of the receiver, the audio signal will return as an electric signal. This received electric signal is typically very small and on the order of ~1 mVpp. The receiver amplifier amplifies the signal to an acceptable level for further signal processing. This amplified signal is then fed into the 40 kHz tone detector which triggers an active low output signal whenever the signal lies within a reasonable range of the desired 40 kHz. The microprocessor will read this signal and determine the amount of time between the sending of the signal to the receiving of the signal.The microprocessor then performs the necessary logic to convert this time to distance and return to the user a printed output on the serial terminal which specifies the distance of the target object.

II. TX-RX TRANSDUCER PAIR

The Tx-Rx pair can be electrically modeled as a 4th order bandpass filter. This means it will contain two center frequencies, very close to one another, and filter out all other noise signals that are outside the bandwidth of the filter. Though we don't have to design the transmitter and receiver for ourselves, we do need to know the center frequencies of the filter as well as the quality factors. The quality factor is a measure of the effectiveness of the bandpass filter. In other words, how well does the filter suppress unwanted noise that falls outside its desired bandwidth?

We obtained the parameters of this filter by pulsing an electric signal with varying frequencies through the transmitter and observing the output at the receiver. We began our sweep of frequencies with 38 kHz and incremented in steps of 0.1 Khz up to 42 kHz. The gain of the filter was taken at each step and plotted in Excel (Fig 2).

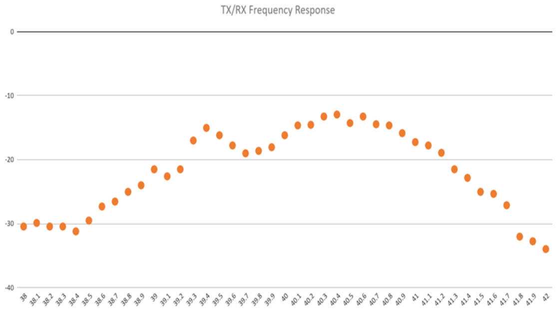

Fig. 2. Magnitude Response of Tx-Rx Bandpass Filter.

The magnitude response included an abnormal peak at 39.4 kHz. We suspect our results may have been distorted because our classmates were performing the same experiment in close proximity. This is likely to introduce unwanted noise. Otherwise, our results are consistent with the expected magnitude response of a 4th order bandpass filter. To extract the parameters of the filter, we used the Excel solver to fit this curve with the theoretical response of a 4th order bandpass filter. The result of the Excel solver is shown below as the orange trace.

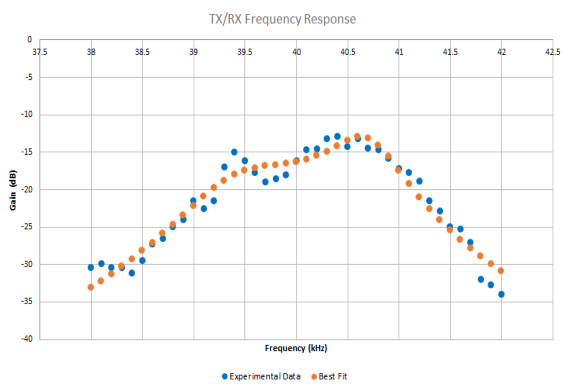

Fig. 3. Best Fit of 4th Order Bandpass Model.

The Excel solver adjusted the resonant frequencies and quality factors of the filter to obtain the best fit curve for the filter. It returned the following results:

$Q_1 = 35.14$
$Q_2 = 64.99$
$w_{o1} = 248{,}000$ rad/s
$w_{o2} = 256{,}000$ rad/s

The last procedure for the Tx-Rx pair is to obtain the step response. The duration of the step response defines the minimum duration of the signal that could be used for this application. The step response we obtained had a duration of 1.2 ms (Fig 4).

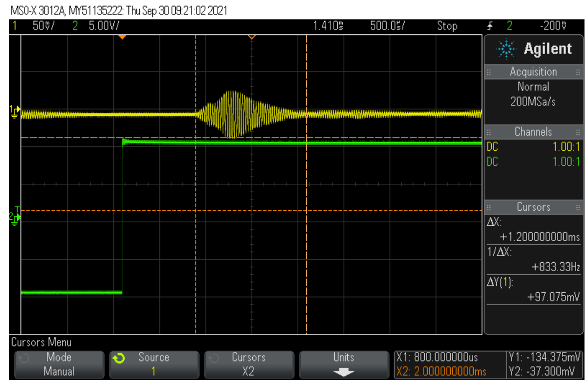

Fig. 4. Step Response of the Tx-Rx Pair.

III. TX DRIVER AMPLIFIER

The assembly of the Tx driver amplifier was fairly simple since it would only involve one IC. The gate driver IC was the appropriate IC to supply the amount of current that the transmitter demands for operation. We captured an input square wave and the corresponding output square wave of the gate driver to verify its functionality (Fig 5).

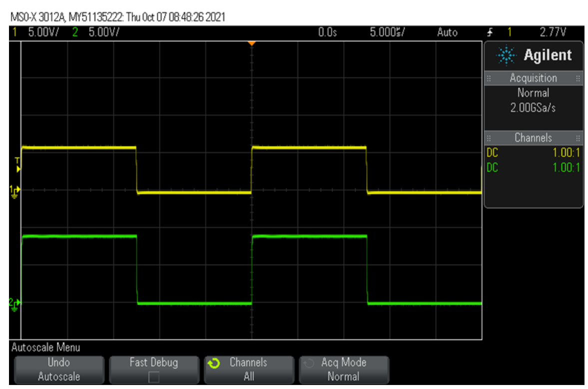

Fig. 5. Output Capture (Green Wave) of the Gate Driver IC.

IV. RECEIVER AMPLIFIER

The design of the receiver amplifier was much more complex. The primary parameter of interest for this amplifier is the gain. The gain of the amplifier had to be enough for the amplifier to output a signal high enough for the tone detector to detect at a maximum object distance of 3.5 meters. To obtain this parameter, the first step was to make a preliminary design that would have a gain of 20 dB at the frequency of operation 40 kHz (Figs. 6/7).

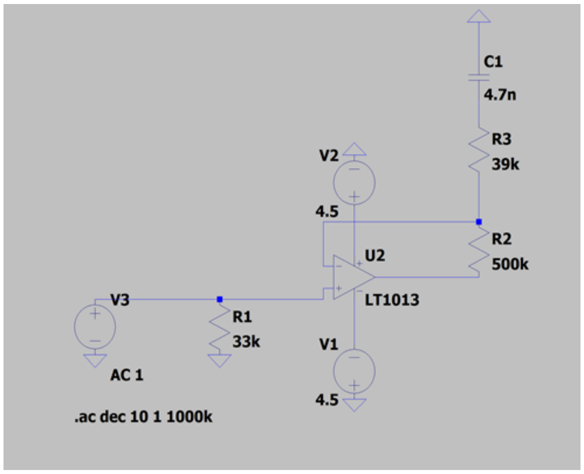

Fig. 6. Preliminary Receiver Amplifier Schematic.

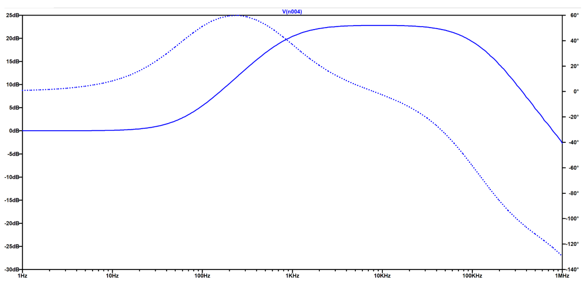

Fig. 7. Simulation of Preliminary Design with Gain of 20 dB at 40 kHz.

The minimum signal output that we need for the tone detector is 20 mVrms. Thus, this is the minimum required output at a distance of 3.5 meters. The gain of our preliminary design is not high enough to meet this requirement, however, with this preliminary design, we could do some testing to measure the signal attenuation at various distances. With this information and the help of Excel, we could theoretically predict the output magnitude at a distance of 3.5 meters and calculate the additional gain that we would need for the final amplifier design.

To obtain this data, we pulsed the transmitter with a low frequency square wave and measured the corresponding response of the receiver amplifier. We measured the rms voltage of the response while changing the distance being measured by the transmitter and receiver. The first pulse in the scope capture (Fig. 8) is due to the initial sound wave propagation from the transmitter. We are interested in measuring the rms voltage of the second pulse response.

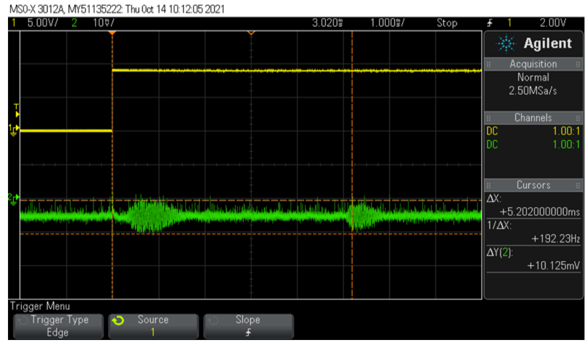

Fig. 8. Output Response of the Receiver Amplifier Due to Tx Driver Excitation.

The next step was to take this distance and rms voltage data and plot it in Excel. The output of the plot resembled a y~1/(x^2) shape which fits what we would expect according to the inverse square law. In other words, as the distance varies, we expect the signal strength to drop by the square of the distance.

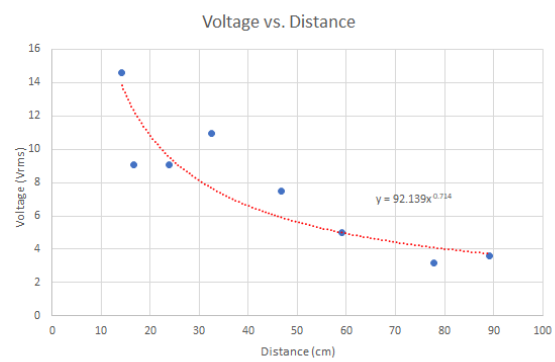

Fig. 9. Signal Strength vs. Object Distance.

Using the curve fit feature in Excel, we predicted that the signal strength at a distance of 3.5 meters would be approximately 1.4 mVrms. SInce we need this signal strength to be 20 mVrms, we need an additional gain of 20/1.4 = 14.3. Taking into consideration the gain of the preliminary design, the total gain of the final receiver amplifier had to be at least 43.1 dB.

With this gain parameter, we were now free to prepare the final design for the receiver amplifier under the constraint that it had a gain of 43.1 dB at the frequency of operation 40 kHz. Since the gain of our preliminary design worked well, we decided to design our final amplifier by cascading two of the same amplifiers. The simulation gave us a gain of ~44 dB at 40 kHz.

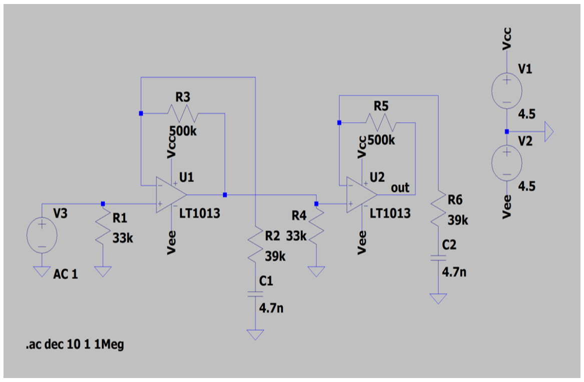

Fig. 10. Schematic of High Gain Receiver Amplifier.

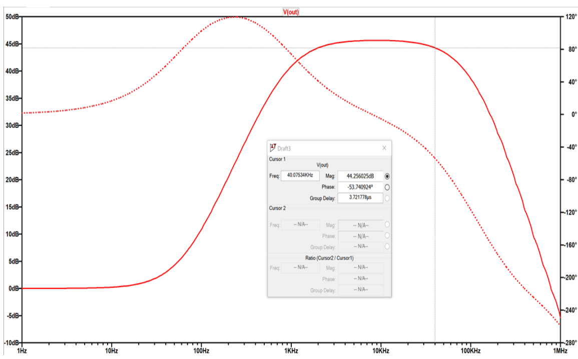
Fig. 11. Simulation Output of High Gain Receiver Amplifier.

The final step was to verify that the receiver amplifier met its original requirement. The receiver amplifier response returned the minimum required signal strength of 20 mVrms at a distance of 2 meters (Fig. 12). This did not meet the original requirement of 3.5 meters, however, the additional gain required to operate at that distance could be supplied by the 40 kHz burst that comes from the 40 kHz oscillator and one-shot circuit.

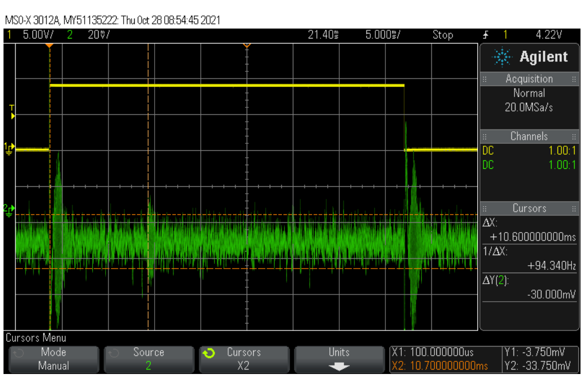

Fig. 12. High Gain Receiver Amplifier Verification.

V. ONE-SHOT CIRCUIT

The one-shot circuit was to be designed as a monostable vibrator which triggers a pulse of duration 1.2 ms upon the active low trigger signal from the microcontroller. The 555 timer was the most intuitive IC to accomplish these design requirements. The topology of the 555 timer is one that receives an active low signal in its TRIG terminal and connects a charging capacitor in its DISCH and THRES terminal. With this topology, the output signal of the 555 timer will trigger high upon the microcontroller's signal and will remain high until the capacitor has charged to ⅔ of the supply voltage, at which point the output will trigger back low. The duration of the pulse can easily be controlled with the resistor and capacitor low-pass pair. The schematic of the one-shot below (Fig. 13) has the desired pulse duration of ~1.2 ms.

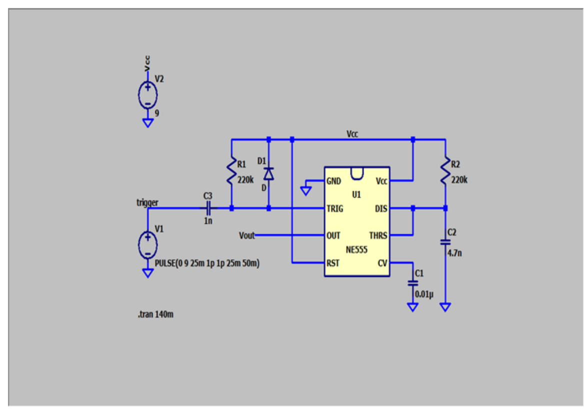
Fig. 13. One-Shot Circuit Schematic.

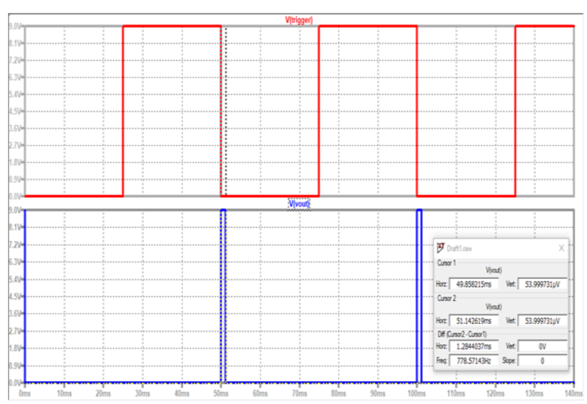
Fig. 14. One-Shot CIrcuit Simulation.

The verification of the one-shot circuit involved two screen captures. First, we had to verify that the output pulse duration upon a trigger signal was 1.2 ms (Fig 15). The final thing we had to verify was the one-shot connected to the gating circuit. When the gating circuit is triggered high, the output would be a 40 kHz wave which comes from the 40 kHz oscillator. Together with the one-shot circuit, we expected to see a 40 kHz “burst” which triggers upon an active low signal and lasts for 1.2 ms (Fig 16).

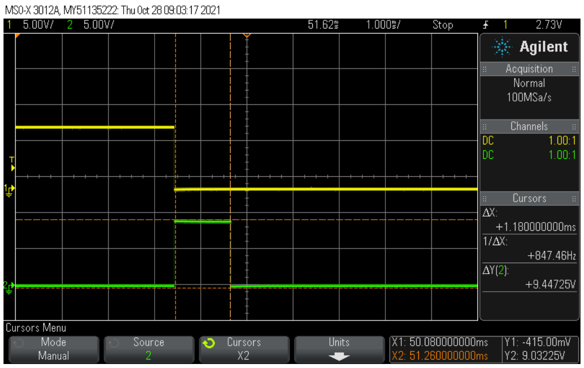

Fig. 15. Verification of One-Shot Circuit Pulse Duration.

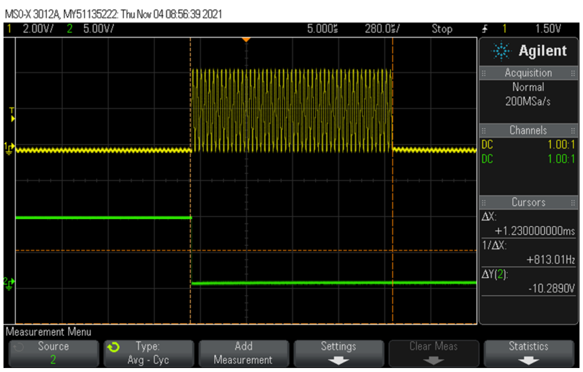

Fig. 16. Verification of One-Shot and Gating Circuit.

VI. TONE DETECTOR

The tone detector receives the amplified 40 kHz electric signal from the receiver amplifier and outputs an active low signal when this signal is present. The tone detector was designed from the PLL-based LM567C IC which allows the user to adjust the frequency of tone detection with a resistor and capacitor. In our application, we needed the tone detector to detect 40 kHz signals. The values for the resistors and capacitors in the schematic (Fig. 17). were calculated according to the information given in the LM567C datasheet. The verification of the tone detector is shown in the scope capture (Fig 18). The output signal is the yellow trace and does indeed trigger low with an input signal of 40 kHz as desired.

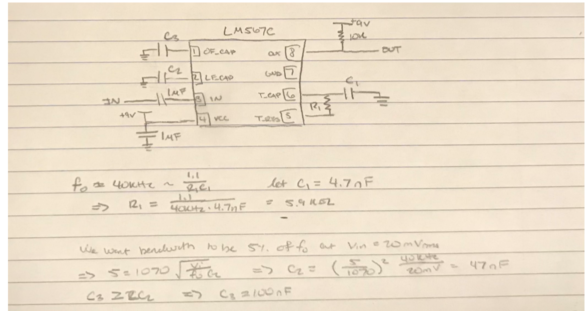

Fig. 17. Tone Detector Schematic and Calculations.

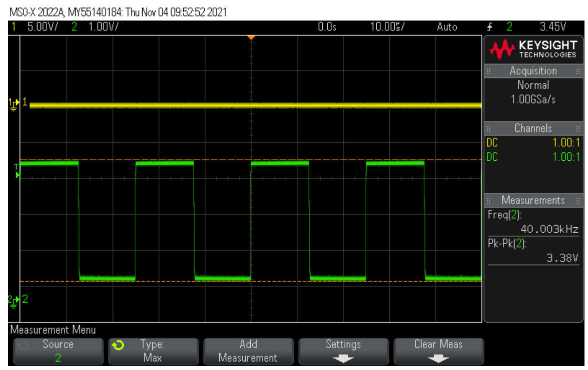

Fig. 18. Verification of the Tone Detector.

The final step for this component was to characterize the PLL in the tone detector. Our tone detector is designed to operate at a center frequency of 40 kHz, however, there is a range of input signal frequencies where the output will still trigger low. This is what we called the capture range. We also had to determine the lock range of the detector which specifies the range of frequencies where the output of the PLL will track the input frequency.

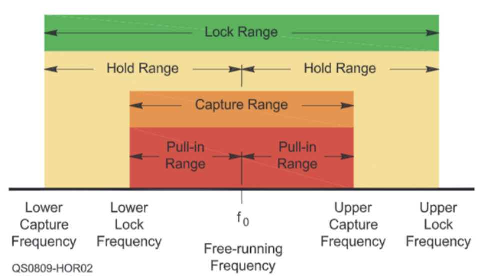

Fig. 19. PLL Characterization

	Low to High [kHz]	High to Low [kHz]
Lower Capture Frequency	38.2	38.0
Lower Lock Frequency	38.2	38.1
Free-Running Frequency	41.25	40.75
Upper Capture Frequency	43.8	43.9
Upper Lock Frequency	44	43.9

Table 1. Characterization of PLL-Based Tone Detector.

VII. CRYSTAL OSCILLATOR

The 40 kHz oscillator in our ultrasonic sensor is designed as a pierce oscillator which utilizes a crystal for operation. The crystal used in our pierce oscillator is designed to mechanically vibrate at a frequency of 40 kHz. At this frequency, the crystal will act as an inductive impedance which will form the necessary parallel tank circuit. The topology of the pierce oscillator is shown in Fig. 20 and it contains the values for the resistors and capacitors that we used.

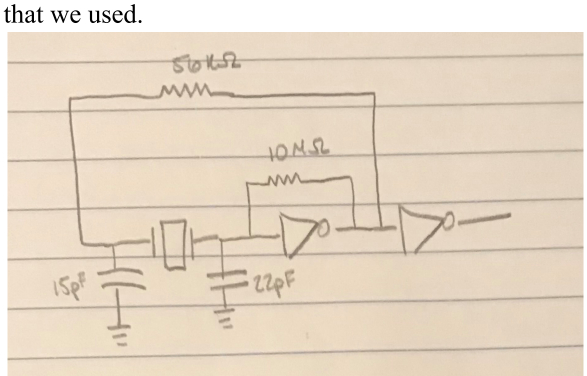

Fig. 20. Pierce Oscillator Schematic.

We first needed to verify the Barkhausen criteria for this oscillator before closing the loop with the 27k source resistor. The oscillator needs to have a gain greater than 1 and a total phase shift of 360 degrees if it is going to oscillate when the loop is closed. Our oscillator design had a gain of ~2 and a phase shift of 1.20 degrees (Fig. 21) which is sufficient to meet the Barkhausen criteria. Once the necessary criteria was met, we were free to close the loop and slowly observe the loop start to accumulate noise and amplify it into our desired 40 kHz signal (Fig. 22).

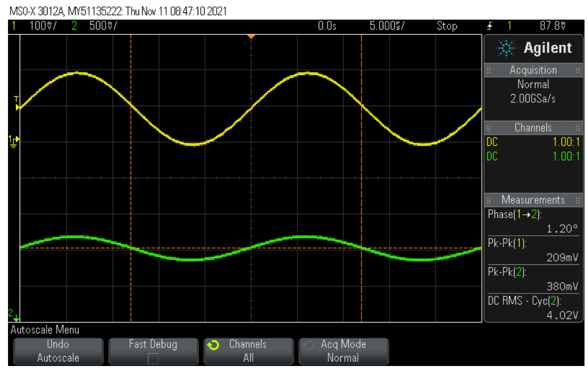

Fig. 21. Pierce Oscillator Open Loop Test.

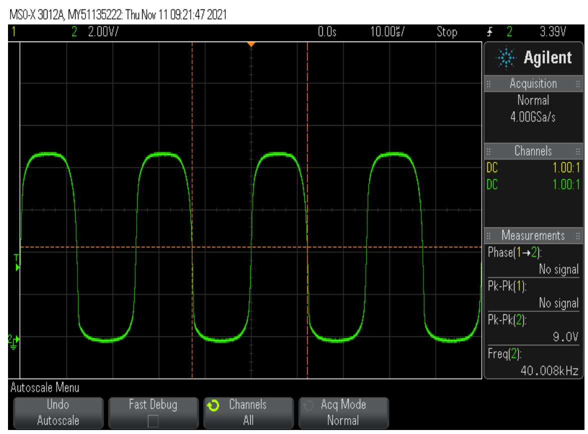

Fig. 22. Pierce Oscillator Output.

VIII. MICROCONTROLLER

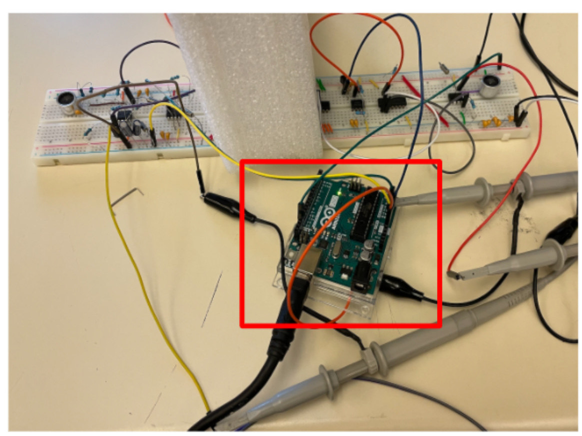

Fig. 23. Arduino Uno

We decided to go with the Arduino Uno as our microcontroller because we are already very familiar with the Arduino IDE API. Interfacing the microcontroller with the system was very simple since it only requires two connections. One analog pin triggers the one-shot circuit and is thus programmed as an output pin. The other analog pin reads the output of the PLL and is thus programmed as an input pin.

The code for the microcontroller is fairly straightforward. The arduino measures the distance by triggering the one-shot pin and measuring the time delay before the PLL triggers low. This process is programmed to run 100 times and the results are stored in an array for further processing. To protect against false detections, the program ignores any PLL trigger that is shorter than 2.5 ms or longer than 36 ms (which translates to 20 ft).

Once all the samples are collected, the program will calculate the average, standard deviation, median, maximum and minimum values of this data set which is in time units. The program will then convert these time values to distance in feet using the speed of sound and print these values to the serial terminal.

IX. SYSTEM INTEGRATION

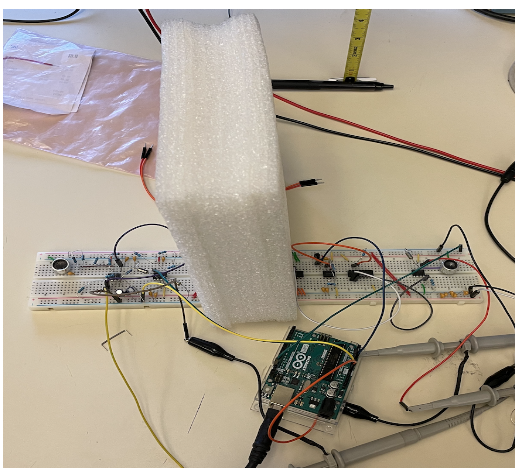

Fig. 24. Complete Rangefinder

When we initially started system testing, the PLL was falsely triggering due to noise from the power supply and mechanical vibrations. To eliminate undesired noise causing premature triggering on the PLL, we bypassed the supply rails on the RX amplifier and power supply with parallel capacitors to eliminate 40kHz leakage from the TX breadboard. In addition, we mechanically isolated the RX and TX breadboards with a piece of foam to dampen any vibrations caused by the TX transducer.

We performed a short range and long range test to test the performance of our system. For the short-range test, we placed a cardboard box 15 inches from the sensor. The average distance was calculated to be 13.92 inches which is approximately 1 inch off the expected value. For the long-range test, we measured the distance to a nearby wall. The system was able to obtain accurate results up to a distance of 90 inches ~ 2.3 meters. The system returned a result of 87.79 inches at a distance of 90 inches.

X. CONCLUSION

This project gave us great exposure to the engineering design process and the intricacies that are involved when designing seemingly simple electronic devices that we use on an everyday basis. To create a simple ultrasonic sensor that is available on the market for ~$5, we had to dip into every aspect of our electronics knowledge to design this simple product.

An important lesson that we learned is to verify the functionality of each component before integrating them in the system. When first designing the receiver amplifier, we wasted a good hour in the lab because we had assumed our LTspice simulation was enough to verify that our receiver amplifier would work. We integrated the amplifier into the system without verifying that it worked by itself.

Another example of this occurred when we were designing the tone decoder. The datasheet had the schematic that we were supposed to use as well as the values for the resistors and capacitors. We constructed the circuit without giving much thought and it did not work. After a good hour of troubleshooting, we found that the VCO terminal was drawing too much current and we therefore needed to increase the resistance. We had assumed that the datasheet schematic would automatically give us a working circuit.

For future classes, perhaps the structure of the project and the class could be slightly altered to allow for more competition between lab groups. For example, instead of specifying that the ultrasonic sensor must be able to detect distances at at least 3.5 meters, you give the highest grade to the lab group that was able to design for the furthest distance. This could incentivise students to go above and beyond in the design process and use their own creativity to beat their competition.