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Date: Dec, 17th/2020

Ultrasonic Rangefinder

Abstract

The goal of this project was to design and build an instrument capable of measuring the distance to an object using ultrasonic sound waves. The device was intended to have a resolution of ± 1 cm on a range of 10-99 cm. The main components of the instrument consisted of a signal generator, transmitting transducer, a receiving transducer, a timing component to measure the time of flight, a digital counting circuit, and a digital display. The rangefinder was able to meet the specified range requirements. The measurements had a standard deviation of 0.65 cm with the largest deviation for a single measurement being 2cm.

There were some notable issues with reliability for the system. It was observed that near the maximum range, the timing component would trigger improperly propagating to random values being displayed on the digital readout. This is likely attributed to the internal noise of the system coupled with a weak received signal at those instances. Overall, the instrument was successful in meeting its design criteria, however there are certainly improvements that can be made to achieve a higher signal to noise ratio and an increased reliability for the operation of the system as a whole.

Introduction

Ultrasonic range finders are commonly used in engineering applications, they typically use a sensor to emit a 40 kHz sound wave, which bounces of an object and is received by the sensor. Most ultrasonic rangefinders are coupled with microcontrollers, commonly Arduinos, in order to handle all the data acquisition and signal processing from the sensors and provide a digital readout of the distance of an object. However this project set out to take a more fundamental approach.

The goal of this project was to build the ultrasonic rangefinder using purely analog and digital circuit components, independent of any external systems such as a microprocessor or microcontroller.

Theory

An Ultrasonic rangefinder needs to provide a digital readout of the distance of an object from the measuring device using ultrasonic acoustic waves. A burst of an acoustic wave is transmitted and received by an ultrasonic piezoelectric transducer allowing the time of flight from the reflected object to be measured.

It is essential to understand the fundamental theory behind the ultrasonic transducers used in this project. A transducer essentially allows energy to be converted from one form to another. The piezoelectric transducers used in this project can receive an electronic pulse and convert it such that it can be transmitted as an acoustic sound wave. The same component can also enable the opposite function in which it receives the energy from the sound wave and converts it into an electrical signal [6].

The image below shows buzzer which is a piezoelectric transducer where a piezoelectric material is attached to a vibration plate. The dimensions of the piezoelectric material change according to the applied voltage direction which causes vibrations from the deformations. When an AC voltage of a specific frequency is applied to the piezoelectric material, the vibrations of the plate produce a sound wave.

Figure 1: The inner disk is made of a piezoelectric material and is attached to the voltage source. The outer disk is the vibrating plate which is grounded. [1]

One should also note that there's a drawback to the transducers as energy is lost during the conversion process from one form to another. Moreover, the amplitude of the soundwave on the receiving transducer is much lower than that of the transmitted signal, and this plays a major role at particularly long distances where the wave spreads out more and the amplitude further decreases. Additionally, when designing ultrasonic range systems, it is also important to account for the fact that not all of the transmitted sound wave is guaranteed to be reflected back to the second transducer.

Methods

<u>Preliminary design</u>:

The approach taken to building the ultrasonic range finder was to compartmentalize the design into smaller components as indicated in the block diagram below. Throughout the process each component was continuously tested using an Oscilloscope and Function Generator.

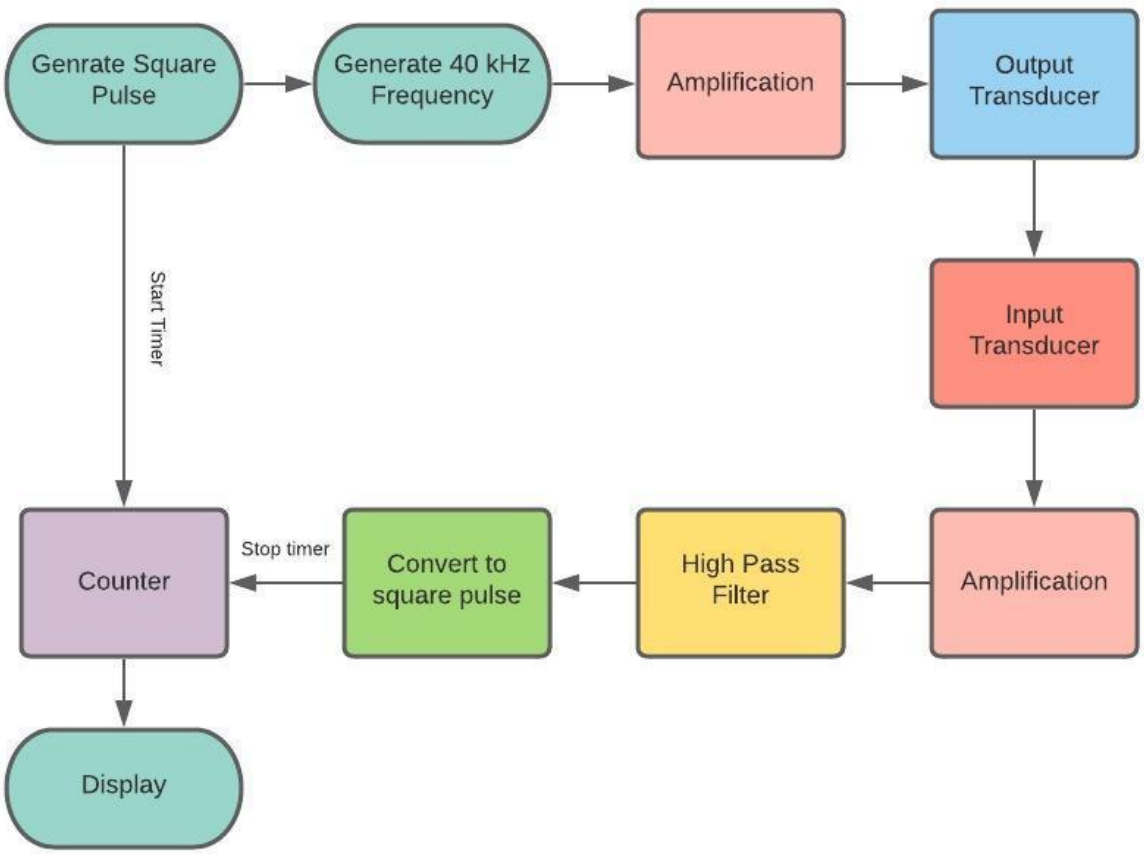

Figure 2: Block diagram of ultrasonic rangefinder.

Each component was designed in NI Multisim and then brought together to form a complete circuit diagram for the project as indicated in the figure below. Furthermore, every component was simulated and tested using the built-in oscilloscope and function generator to verify expected functionality during this process.

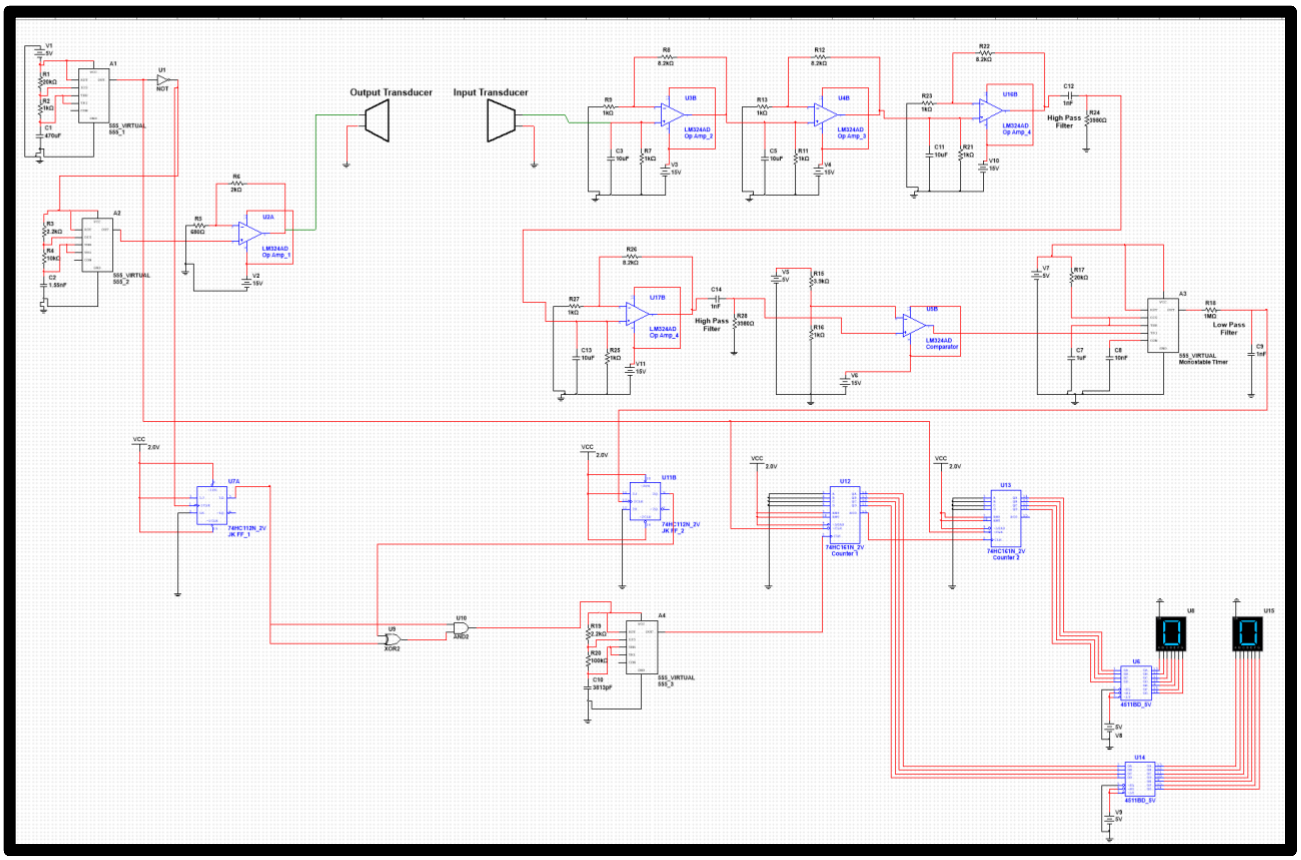

Figure 3: Complete circuit diagram of ultrasonic rangefinder.

Afterwards, based on the conceived functionality of key components of the design, a timing diagram was constructed using excel to demonstrate the electrical signals and sequence of events in the ultrasonic range finder as shown in the figure below.

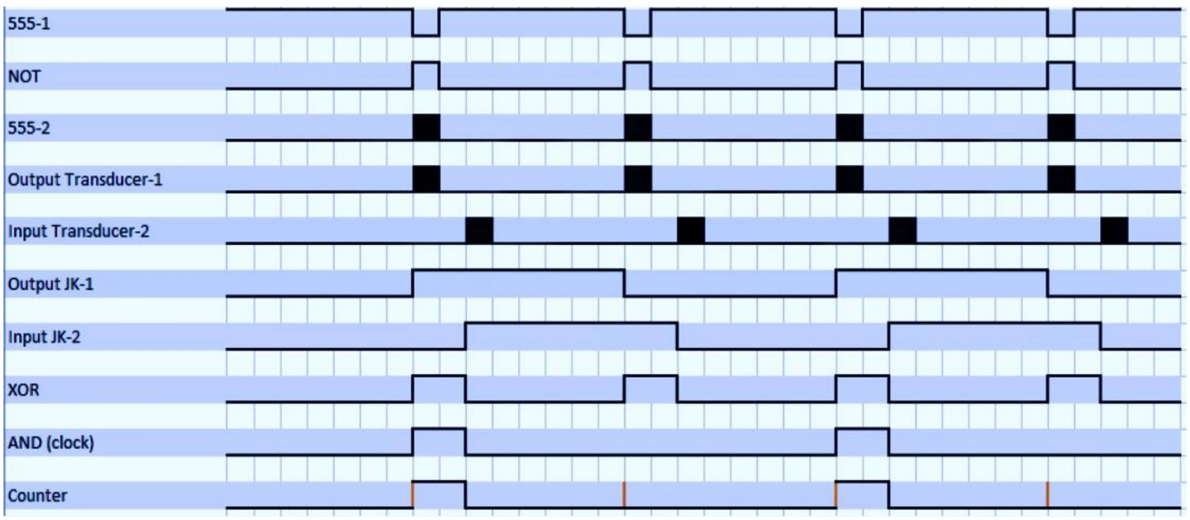

Figure 4: Timing Diagram of ultrasonic rangefinder. The black squares indicate high frequency, and the orange line indicates when the counter is reset.

Finally, each circuit was breadboarded and brought together to form the complete functioning device. As shown in the figure below, the labels correspond to each component which will be referenced and explained further in the sections to follow.

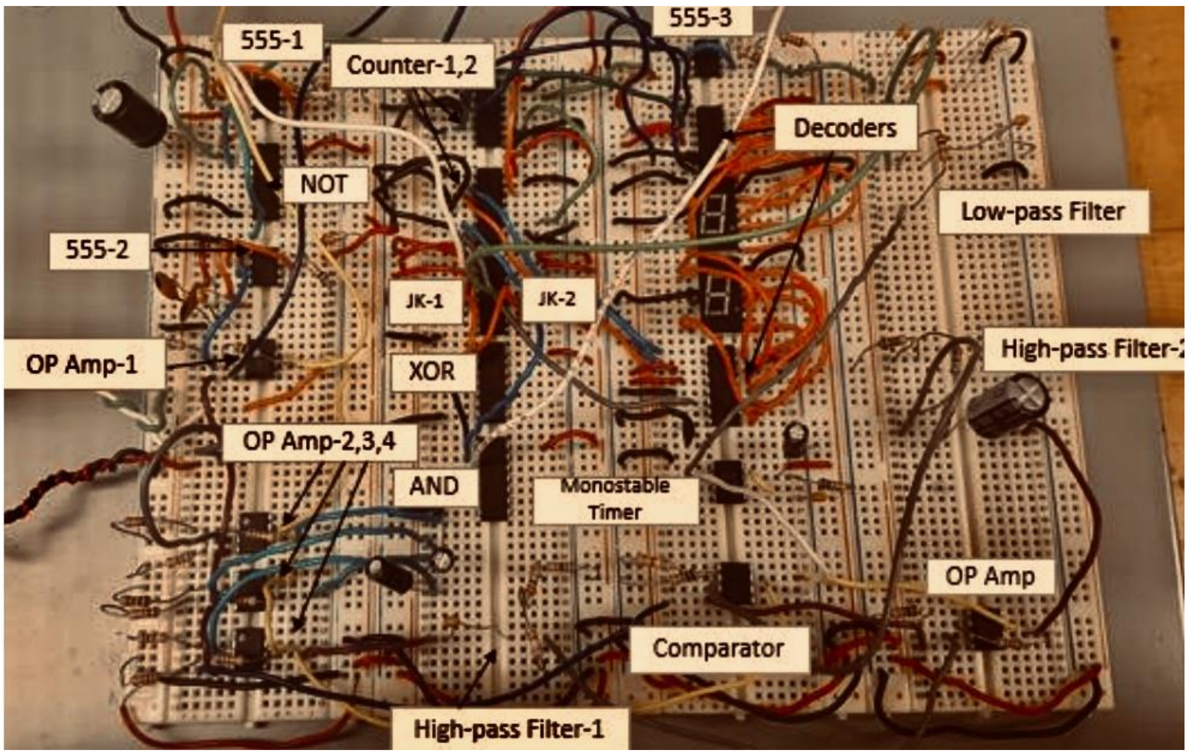

Figure 5: Labelled breadboard build of Ultrasonic Rangefinder.

Part 1: Output Signal Generation

The figure below shows the first part of the circuit design which covers the signal generation, and the amplification stage for the output transducer.

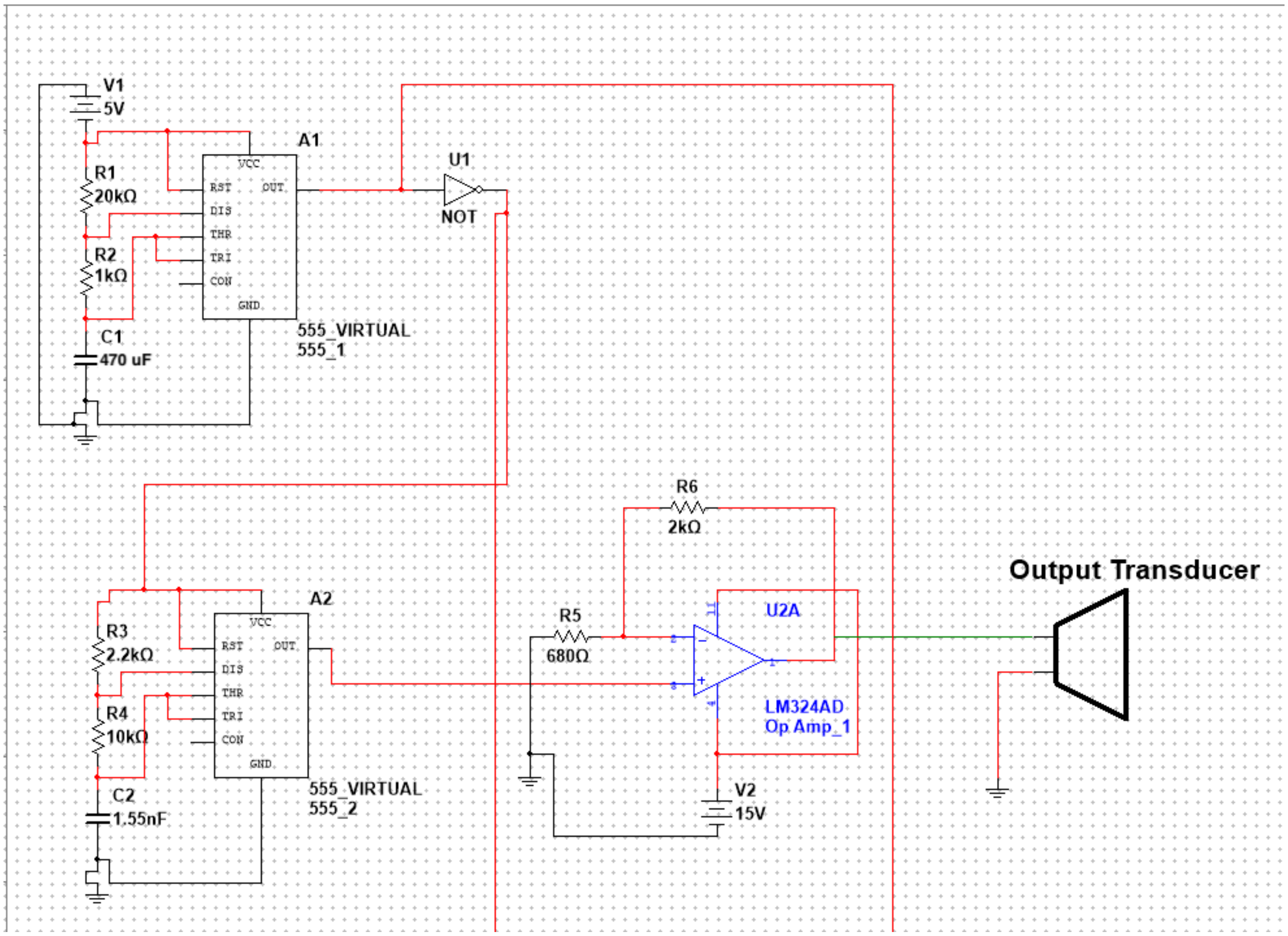

Figure 6: Part 1 of the ultrasonic rangefinder circuit. As seen, it consists of two 555 timers, an op amp and the output ultrasonic transducer.

A 555 timer is used to generate a square wave signal by alternating between high and low outputs. The duty cycle is a central aspect of this component as it controls the ratio of the period that the signal stays high with respect to how long it stays low. By selecting certain resistor and capacitor values we can modulate the duty cycle of the timer.

Since the smallest achievable duty cycle of a single 555 timer is 50%, so in order to overcome this we can simple generate a high duty cycle of 95% and use a NOT gate on the output to get short high pulses for the square wave signal generation. The circuit diagram show's that the first 555 timer has a frequency of 0.14 Hz which is done by using resistors R1=1kΩ, R2=20kΩ and a capacitor value of 470 microfarads. This frequency of 0.14Hz corresponds to a period of 7.18s meaning that a new signal will be generated every 7.18 seconds. The corresponding calculations for these results can be found in Appendix 1.

Since the transducer must receive a pulse frequency near 40kHz in order to achieve harmonic oscillation, we need to use a second 555 timer to generate a 40kHz AC signal within each pulse of the signal generated from the first 555 timer. In order to find the ideal frequency, various frequencies near 40kHz were tested by sending the signal to the output transducer and using an oscilloscope to measure the magnitude of the received pulse on the input transducer. In this fashion the ideal frequency was found to be 41kHz. Hence the resistor and capacitor values were chosen accordingly (Appendix 1).

As shown in the circuit and the timing diagram, the output from the first 555 timer after the NOT gate was connected to VCC of the second 555 timer in order to provide power and only output a high frequency pulse during the period in which the pulse from the first timer is high. The output of this 555 timer is routed to the positive input of the Op Amp that follows.

In order to improve the signal strength an additional non inverting operational amplifier was used to amplify the signal after the second 555 timer. The amplification stage would allow the 5V signal to be increased to a higher amplitude and ultimately produce stronger sound waves on the output transducer. Amplification for this stage was done by a gain of 4 using resistor values of R1=680Ω and Rf=2kΩ with a sample calculation being shown in Appendix 2. The output of this amplifier is routed to the positive input of the Output Transducer

<u>Part 2: Input Signal Processing</u>

The figure below shows the second part of the circuit design which covers the signal amplification stage and filtering after being received by the input transducers.

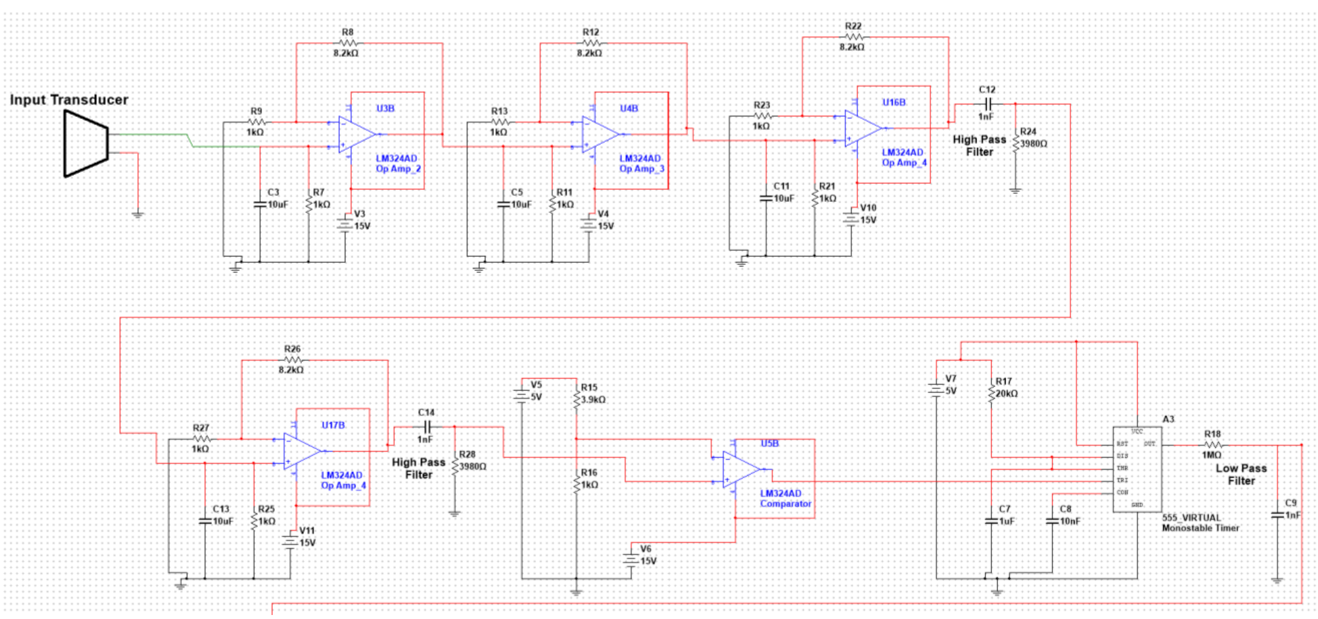

Figure 7: Part 2 of the ultrasonic rangefinder circuit. As seen, it consists of the input transducer, three Op Amps in series with a high pass filter at the end of the 3rd connecting to the fourth amplifier which is also followed by a high pass filter. This is then routed to a comparator to produce a digital signal and a 555 timer set up in Monostable mode followed by a low pass filter.

A signal that has been received on the input transducer side has typically lost a significant amount of energy in comparison to the initially transmitted soundwave, and so it's necessary to have sufficient amplification. The maximum gain that can be produced from a single Op Amo is 10, and in this a scenario each Op Amp was setup such that they delivered a gain of 9.2. Placing three of them in series we end up with a total gain of 9.2 raised to the power of 3, resulting in a total amplification gain of approximately 778.7. Each receiving amplifier was setup using an additional 10µF capacitor and a 1kΩ resistor connected in parallel to the positive input. This was done in order to help discharge the Op Amp from charge build up propagating from the input transducer.

Since a significant level of low frequency noise was noted when testing this circuit using an oscilloscope, it was determined that it would be best to implement a filter to improve the signal noise ratio. Since the signal at this point is a pulse with a frequency of roughly 41 kHz, a cut off frequency of 40Hz was chosen and the necessary capacitor value of 1nF and resistor value of 3980Ω was used in order to achieve this (Appendix 3).

The output of this high pass filter leads to another Op Amp of identical setup to the previous 3 Op Amps in series in order to further amplify the signal. The output is then routed to a second high pass filter to further improve the signal to noise ratio.

As seen in the circuit diagram, a Op-amp comparator follows the output of the second high pass filter. A comparator is an essential component of the design as when the object is set to various distances the incoming signal amplitude changes significantly. The amplitude of a signal reflected of an object 100 cm away from the input transducer was found to be approximately 1.5V.

So an op amp voltage comparator is used to set any incoming signal above a cut-off voltage of 1V to 5V. A voltage divider with resistor values to divide the 5V to 1V was routed to the negative terminal of the comparator was used to achieve the correct functionality of the comparator for the design (Appendix 4).

A Monostable timer was then implemented to convert 41kHz signal from the comparator to a constant positive 5V pulse. A period of 1 microsecond was set for the timer using specified capacitor values of $C1=10nF$, $C2=1\mu F$, and a resistor value of $R1=20k\Omega$. The corresponding calculations to achieve these results can be found in Appendix 5.

A low pass filter was added after the monostable 555 timer in order to remove high frequency noise that had propagated from the comparator and timer. This was key in order to produce a strong low frequency signal from the monostable timer. In order to achieve this, a specified resistor and capacitor value was used to produce a cut-off frequency of 160Hz. This calculations for this follow the same equation used in Appendix 3 for the high pass filter.

Part 3: Digital Logic

The figure below shows the third part of the circuit design which covers the mechanism used to start and stop the counter of the instrument.

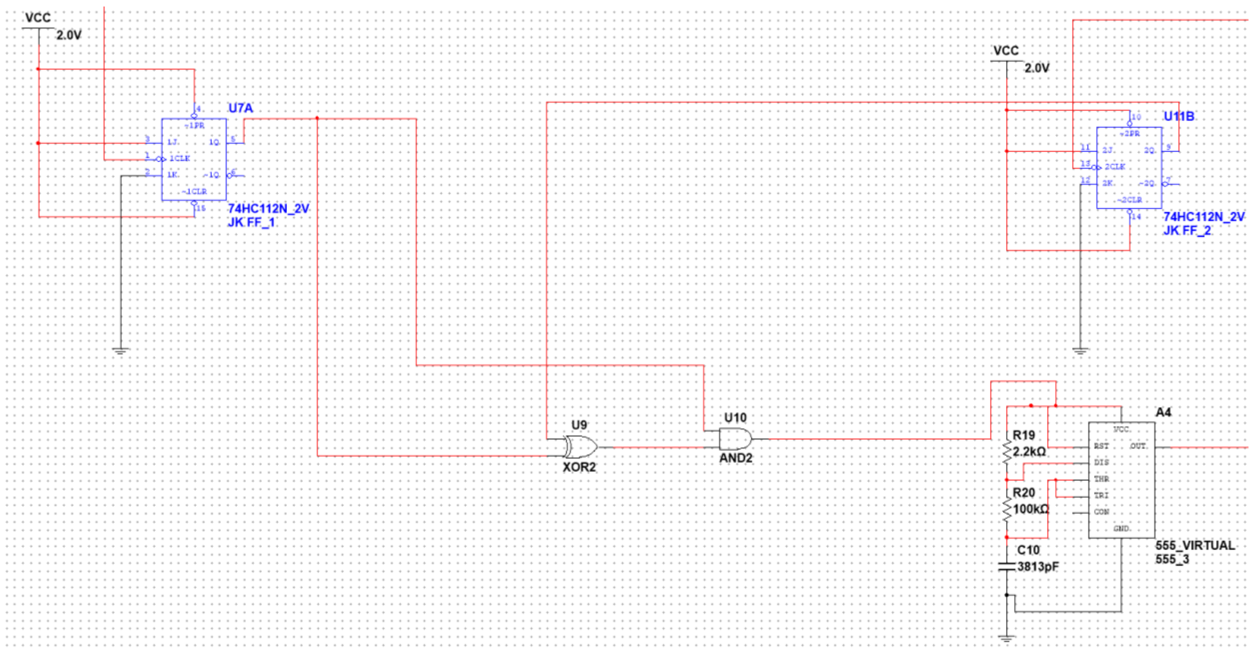

Figure 8: Part 3 of the ultrasonic rangefinder circuit. As seen, it consists of two JK flip flops which are XOR'd together, an AND gate taking the output of the first JK flip flop and the output of the XOR gate, and finally a 555 timer for the counter.

Two JK flip flop as employed in order to start and stop the counter of the device. Both flip flops are set up such that they are positive edge triggered. In both flip flops, the CLR and PR pins are routed to the voltage source, while the K pin is grounded. The first flip flop is clocked by the NOT gate that follows the first 555 timer in part 1. This allows the flip flop to trigger on the start of each outgoing pulse.

The second flip flop is then clocked by the monostable 555 timer from part 2. The output of both flip flops is routed to an XOR gate, and then an AND gate follows taking inputs from the output of the XOR gate and the output of flip flop 1. The following truth table is produced as a result:

JK_FF_1 (Tx)	JK_FF_2 (Rx)	XOR	AND
0	0	0	0
0	1	1	0
1	0	1	1
1	1	0	0

Table 1: Digital logic table of start and stop logic circuit for counter.

This setup is designed such that the AND gate will switch to a one when the pulse is outgoing and switch back to zero when the pulse is received. The AND gate also outputs power for the final 555 timer to enable counting functionality when the pulse is sent and stop when the pulse is received. This 555 timer acts as a clock for the counter with capacitance and resistor values that allow it to produce a clock frequency that corresponds to the time it takes sound to travel 1cm. Given that sound travels at 34300 cm per second, and that the pulse has to travel to and from an object, we can deduce that the timer needs to count half of that speed. This results in 17150 cm/s corresponding to 17.15kHz. The corresponding resistor values used were R1= 2.2kΩ, R2= 100kΩ, and a capacitance of C1= 3813pF. However, it is important to keep in mind that as this is a theoretically deduced value, hence the capacitance and resistance values had to be slightly modified in order to calibrate it to display the correct distance of an object during the actual breadboard build.

Part 4: Counter & Digital Display

The figure below shows the fourth and final part of the circuit design which covers the setup of two 4 bit binary counters with each routed to their own 7 segment display using a decoder.

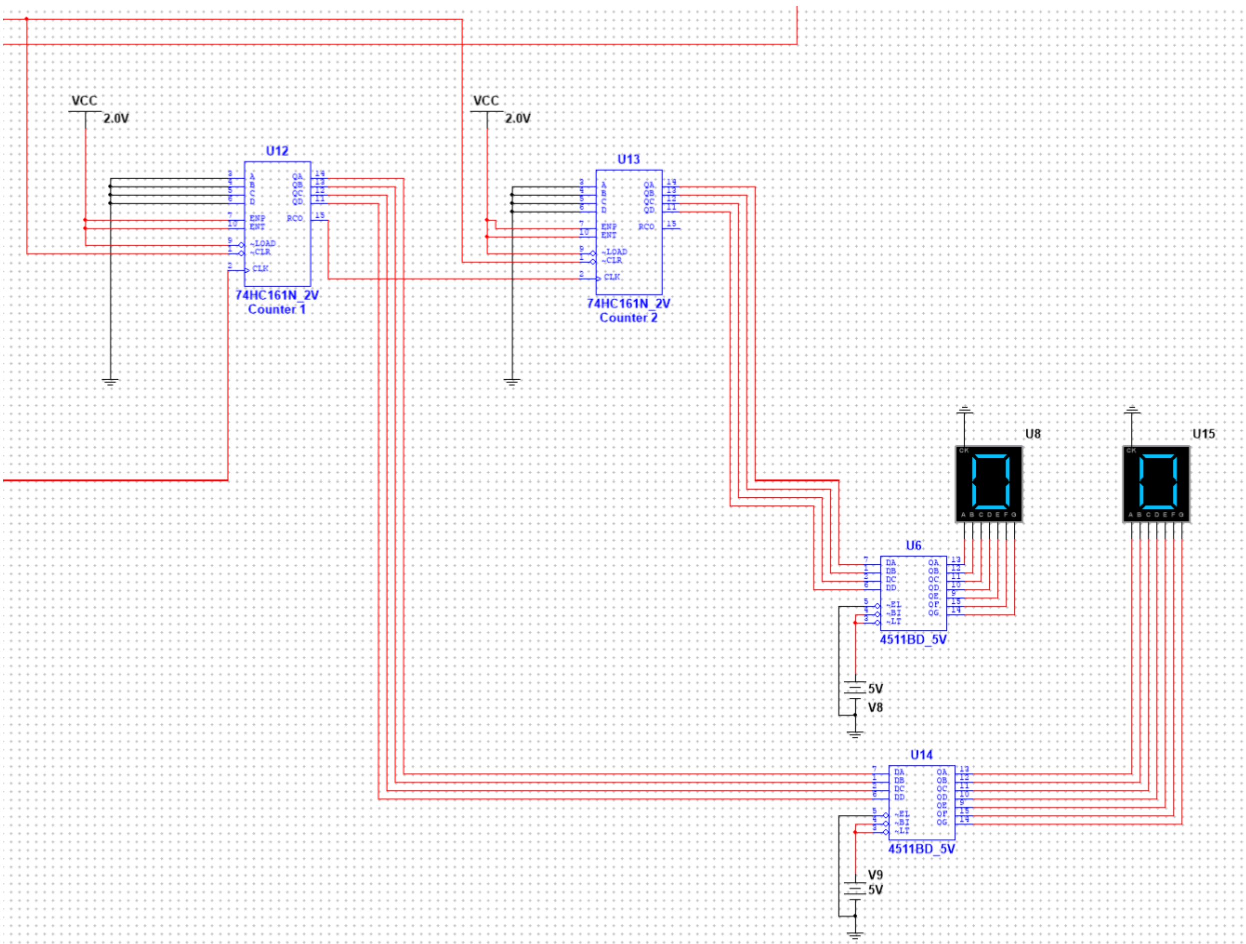

Figure 9: Part 4 of the ultrasonic rangefinder circuit. As seen, it consists of two 4 bit binary counters routed to a decoder connecting to two 7 segment displays to provide a digital readout.

In order to produce a digital readout from 0-99, it was necessary to use two 4 bit binary counter ICs. The first counter is clocked by the output of the last 555 timer from part 3. The CLR pin take input from the first 555 timer in order to reset the counter to zero every time a new pulse is transmitted. All input pins A, B, C, and D are grounded so that the counter starts at 0000. In order to enable ripple carry mode, pins ENP, ENT, and LOAD are connected to VCC. The output pins QA, QB, QC, and QD are routed to the corresponding inputs of the decoder chip whose connection to the 7-segment display is indicated in Figure 9.

The setup of the second binary counter is exactly the same as the first except it takes a clock input from the RCO pin of the first counter. This setup allows counter two to count up one every time counter 1 reaches ten, and so the counter is able to count and display values from 0 to 99.

Uncertainty Analysis

There are significant uncertainties which need to be considered in order to assess the reliability of the system and understand what improvements can be made.

The first most notable source of uncertainty in the system is due to propagation delay. Propagation delay refers to the response time of digital components in a circuit as there's a time delay involved as a digital signal goes from high to low throughout the system [5]. In this design the timer starts when the sound wave is triggered by the first 555 timer, and once the signal is received, the pulse must travel through a series of components in the digital domain. Even though the response time of digital chips is very fast, there is always a slight time delay in signal propagation. This delay is constant for the system regardless of the distance measured, and is usually defers several orders of magnitude from the time scale of the system so it's very hard to mitigate. Even though this uncertainty source may play a negligible role in its influence of the system's reliability, it is still a fundamental concept to keep in mind when working with digital electronics and should always be considered.

Temperature is also a factor that can affect the speed of sound which would mean that improper calibration to the environment could skew the measure values of the device. Let's consider the case where the ambient temperature changes from 18°C to 25°C.

Calculating the frequency required for the last 555 timer detailed in part 3:

The approximate speed of sound with respect to temperature can be calculated using the following formula [2]:

$$Speed\ of\ Sound\ (m/s) \approx 331.5 + 0.6 * T(°C)$$

Therefore at 18°C the speed of sound is approximately 342.3 m/s.

Calculating the necessary frequency we get:

$$\frac{342.3(m/s) * 100}{2} = 17115(cm/s) \ = \ 17.115kHz$$

Now at 25°C the speed of sound is approximately 333 m/s.

Calculating the necessary frequency we get:

$$\frac{333(m/s) * 100}{2} = 16650(cm/s) \ = \ 16.65kHz$$

The difference between these two value is found to be:

$$Diffrence = 17.115kHz - 16.65kHz = 0.465kHz$$

Now calculating the relative error with respect to the original temperature of 18°C we get:

$$Percent\ Error = \frac{0.465kHz}{17.115kHz} \approx 2.72\%$$

Therefore a variation of 2.72% would be observed for the required frequency of the 555 timer as a result of the temperature change for the system. Therefore, if the ultrasonic rangefinder is calibrated in a room with a specific temperature, it will have to be recalibrated if there are any temperature changes in order to mitigate the uncertainty in measurements.

Another source of uncertainty is due to the tolerance values of resistors used in the devices. For instance, consider the 10% tolerance value for resistors with a silver band [3]. This uncertainty factor is very important to consider in cases where large resistances are used. In the case of the monostable 555 timer detailed in part 2, an R1 value of 20kΩ is used with a tolerance of 10%. The uncertainty of this component would be 2kΩ meaning that the actual resistance of the component can range from 18kΩ to 22kΩ.

This will inevitably translate to variations on frequency for 555 timers, and also impact the expected gain values of the OP Amps. A solution to this would be to use potentiometers adjusted to the exact measured resistance for higher accuracy instead of set resistor components.

Results

After the final breadboard build, the ultrasonic range finder was tested with a textbook as the object at various distances within the devices measurement range. Each measurement was taken twice in order to assess the stability of each reading. The actual distance was also measured using measuring tape with an uncertainty of ±0.05cm. The results are shown in the table below.

Actual Distance (cm) ±0.05cm	Measured Distance (cm)	Absolute error |Actual-Measured| (cm)
5	4	1
5	5	0
10	10	0
10	10	0
20	21	1
20	24	4
30	30	0
30	31	1
40	41	1

40	43	3
50	52	2
50	50	0
60	63	3
60	16	44
70	73	3
70	02	68
80	84	4
80	82	2
90	90	0
90	06	84
99	19	80
99	98	1

Table 2: Tabulated values for the actual distance of the object and the measured distance using the ultrasonic rangefinder. The absolute error for each measurement is also included on the left column.

Based on the absolute error we can determine the standard deviation of the measurements as follows:

$$\sigma = \frac{Sum\ of\ errors}{Number\ of\ points}$$

In order to get a true assessment, extreme outliers from the measured values are not considered as they can change with multiple measurements at the same point, and is mostly attributed to incorrect triggering of the instrument.

$$\sigma = \frac{1+1+4+1+1+3+2+3+3+4+2+1}{18}$$

$$\sigma \cong 1.44$$

So the standard deviation of the resulting measure values is 1.44 cm

The tabulated values are plotted in the graph below.

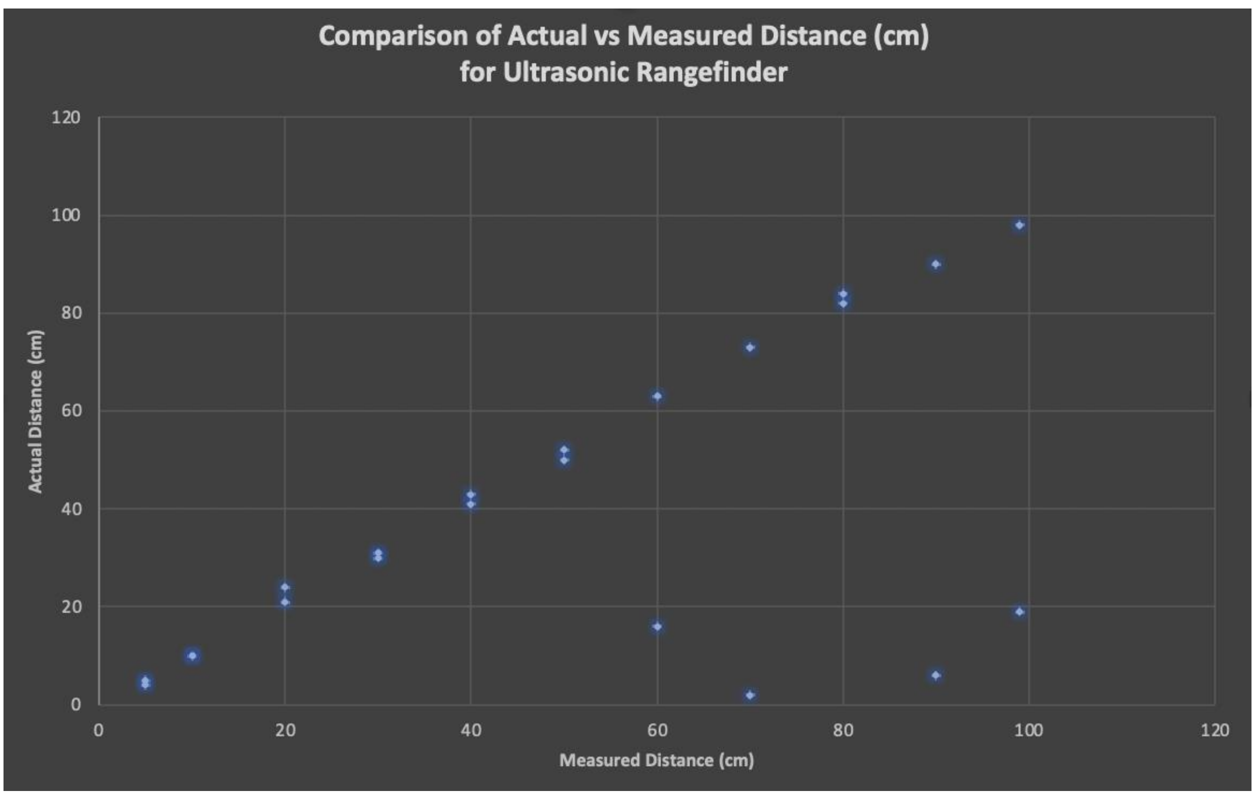

Figure 10: This figure shows a comparison of the actual distance vs the measured distance with the device that was recorded twice.

From the figure above we can see that there are major deviations from the actual measurement as the distance gets closer to the maximum range of the instrument. Ideally there would be a linear correlation without any outliers as the measured distance would equal the actual distance of the object from the instrument.

Discussion

From the results above we now know that the standard deviation for a sample of 18 measurements is approximately 1.44cm with a max deviation of 4cm at 20cm and 80cm. Overall, the performance of the device was significantly impacted by noise. At approximately every 4th consecutive measurement, the system would trigger improperly and display a random value that deviated severely from the actual distance as seen in the results above. Additionally, the performance of the device also varies with different materials of objects. In comparison to a textbook, a baking sheet was tested as the object and it produced more reliable measurements. This can be attributed to the absorption of the material. Additionally, it was observed that the most precise measurements are recorded with objects of uniform surface and that are completely perpendicular to the incoming acoustic waves from the output transducer. This makes sense as it is very likely that the waves could be reflected at various angles and result in a lower proportion of the initial signal reaching the transducer if the object is angled or non-uniform. Moreover, based on the results it would seem that the instrument's optimal range for precise measurements is within the 5-50cm range. Outside of this range there was a significant amount of deviations noted as shown in figure 10. However, more measurements are needed to be taken in order to further examine the devices performance.

Although the instrument was relatively functional, there are definitely some improvements that could be made in the design of the system to improve its reliability as a rangefinder. One of the major hurdles of the design was providing sufficient signal amplification. Although multiple amplifiers were used on the receiving end, there was only one amplifier used in the transmitting end. Adding more amplification stages in part 1 would most definitely mitigate the issue with signal strength. By further amplifying the signal before it reaches the first transducer, we'd be increasing the signal amplitude without also increasing the noise as there's no noise in the signal prior to the output transducer. One downside to this would be the fact that increasing the gain too much for a strong signal in this stage could damage the transducer and other components in the circuit. It was only possible to achieve a high gain after the signal was received since it was a weak signal.

In part 2 of the circuit design an Op Amp based voltage comparator was used and this design choice could be improved by using a dedicated comparator IC such as the LM339 as they are less sensitive to noise [4]. Another improvement could be to improve the signal to noise ration by using a higher quality transducer as there is a constant noise factor associated with the transducers used for this project.

Conclusion

All in all, ultrasonic rangefinder met design goal as the results show that it was functional and capable of achieving relatively precise measurements within the range of 0 to 99cm. With the exception of outliers resulting from improper triggering, the measurements held a standard deviation of 1.44 cm, holding extremely high accuracy within the 5 to 50cm range. The major challenge of this design was figuring out how to amplify the signal strength while maintaining a high signal to noise ratio. Despite the fact that multiple amplification stages and filtering stages were implemented, noise still played a major factor in impacting the overall performance of the instrument. Moving forward, the goal will be to eliminate noise triggering issues by employing more complex filters, including further amplification at the pre-transducer stage, using a dedicated IC as a comparator, and using higher quality transducers to improve signal strength.

References

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Appendix

This section details the calculations used for determining key components in the design of the Ultrasonic Rangefinder.

1. <u>555 timer calculations:</u>

The duty cycle of the timer is defined as follows:

$$Duty\ Cycle = \frac{R1 + R2}{R1 + (2 * R2)}$$

In order to achieve a high duty cycle the following resistor values are used:

R1=20kΩ and R2= 1kΩ

Therefore the duty cycle is 0.95.

The frequency of the timer is defined as follows:

$$Frequency = \frac{1.44}{\left(R1 + (2 * R2)\right) * C}$$

In order to achieve a period of that is long enough for the whole measurement process to complete within each cycle, a capacitor value of 470 microfarads is used.

This gives a frequency of 0.139 Hz.

The period is defined as follows:

$$Period = \frac{1}{Frequency}$$

Hence the period of each clock cycle for the timer is 0.7 seconds

2. <u>Non-Inverting Op Amp calculations:</u>

   The gain of a non-inverting amplifier is defined as follows:

$$A = \frac{V_o}{V_i} = 1 + \frac{R_F}{R_1}$$

   Given that Rf is the resistor providing negative feedback and R1 is the resistor that is grounded, we are able to achieve a gain of roughly 3.94 using R1=680Ω and Rf=2kΩ.

3. <u>High Pass Filter calculations:</u>

   The cut-off frequency is defined as follows:

$$F = \frac{1}{2\pi * R * C}$$

   In order to achieve a 40kHz frequency for the ultrasonic transducer, we can choose a capacitance such as 1nF and solve for the resistance which is found to be approximately 3980Ω.

4. <u>Comparator calculations:</u>

   The threshold voltage used in the voltage divider to divide the 5V source to around 1V is determined using the following formula:

$$V_{ref} = V_s \frac{R2}{R1 + R2}$$

   Given that Vs=5V, we can use resistor values of R1 = 3.9kΩ and R2=1kΩ to achieve a threshold of approximately 1.02V.

5. Monostable Timer calculations:

The duration of the output pulse of the monostable timer is determined using the following equation:

$$t = 1.1 * R * C1$$

Given that a resistance value of R=1kΩ and a capacitor value of 1 microfarad is used, we are able to achieve a duration of 0.0011 seconds which is very close to the desired period of 1ms.