Professor: Planck, John
EE 449 Section 05
Thursday
3:10 - 6 PM

Lux-Meter System with Ultrasonic Link

Bench Number: 3
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Objective

The objective for this laboratory class is to design and implement an electronic luxmeter system comprising of several individual circuits.

Requirements

1. Measure illuminance levels in the range of 5 foot-candles to 200 foot-candles.
2. Transmit the information using a 40kHz ultrasonic link to a remote decoder for processing and display.
3. Display the result in units of foot-candle.
4. Exhibit a relative error of 5% or less (when compared to a commercial luxmeter).
5. The operating range of the ultrasonic link will be at least 10 meters.

System Overview and Block Diagram

The system consists of two functional units – a measuring/transmitter unit and a receiver/display unit. The two units communicate using 40 KHz-carrier ultrasonic link. Both units use 9V battery power.

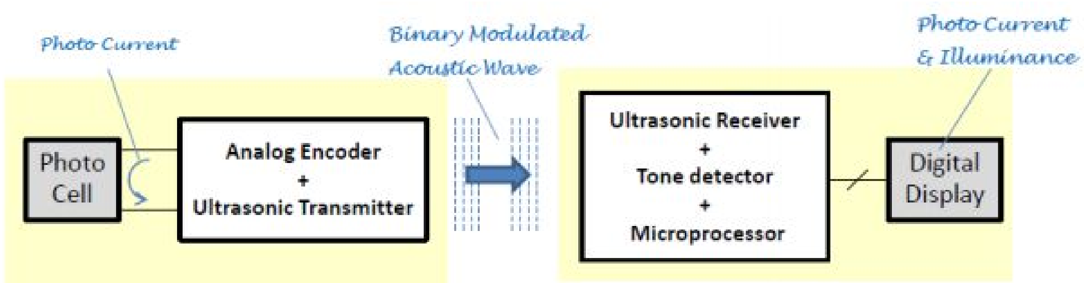

Figure 1: Block Diagram of the system, with the two functional units

The measuring/transmitter unit consists of multiple different blocks. Namely, the analog encoder, modulator, and ultrasonic transmitter. The analog encoder is responsible for taking in the current created by the photocell and producing a waveform with frequency scaled linearly to the input current. The modulator takes in the square-wave produced by the analog encoder and transmits it using binary ASK with a 40 Khz carrier signal. Binary ASK is a way to transmit a “1” or a “0” using a carrier wave. If the wave is at a fixed amplitude for a certain period of time, a ‘1’ is transmitted, otherwise a ‘0’ is sent. The last part of the measuring/transmit unit is the ultrasonic transmitter. This block consists of three major parts, a 40 Khz oscillator, a driver amplifier, and an ultrasonic transmitter. The 40 Khz oscillator is responsible for driving the driver amplifier, and the driver amplifier is responsible for providing adequate signal power to the ultrasonic transmitter.

The second functional unit of the system is the receiver/display unit. It consists of a few major components, namely, an amplifier, tone detector, and microprocessor. The amplifier is responsible for scaling up the received signal so that it can be read by the tone decode. The tone decoder takes the scaled up signal and converts it to be the like the output of the analog encoder. Lastly, the microprocessor is responsible for measuring the frequency of this signal. Because the frequency corresponds to the current of the photodiode, the magnitude of the photodiode current and therefore, the light intensity can be attained.

Subsystem design and testing

Ultrasonic devices and the Ultrasonic link

During week one of the course, our group characterized the ultrasonic devices and the ultrasonic link.

Our testing setup was to use an oscilloscope connected to the receiving end of the ultrasonic pair, and a function generator connected to the transmitting device. Using this setup, we were able to determine the peak-peak voltage values for different input frequencies into the transmitting device. Our goal was to determine the fundamental frequency as well as the upper and lower frequencies that corresponded to the 3dB cutoff point of the system. These values are summarized in the table below.

Table 1: Ultrasonic pair cutoff frequencies and peak voltage

Measurement	**Value**
Peak Voltage with frequency	680mV @ 40.03 Khz
3dB upper cutoff frequency	41.03 Khz
3dB lower cutoff frequency	38.99 Khz

Our next objective was to quantify the internal impedance of the transducer. Our testing setup was to utilize a simple voltage divider circuit. A 10.1V DC source was used as the input to the circuit, which consisted of a 150k ohm resistor and the transducer connect in series. Using an oscilloscope, we found 9.8 Volts across the resistor. This means that the remaining .3 Volts were dropped across the transducer. Using the voltage divider equation:

$$.3V = 10.1V\left(\frac{150,000}{150,000+Z}\right)$$

We were able to easily solve for the unknown Z, which we determined to be 4.9 Megohms.

High-Gain Band-Pass Amplifier

Our goal was to design a 40Khz Band-Pass Amplifier which met the following specifications:

1) Mid-band gain of 34dB +/- 1dB (when driving an 18 kΩ load)
2) Input resistance at 40kHz between 10kΩ and 100 kΩ

We started by analyzing the three potential designs posted for various ultrasonic receiving circuits. Of the three, we found the two stage op-amp design from the Renesas datasheet to be the simplest and easiest to design and implement.

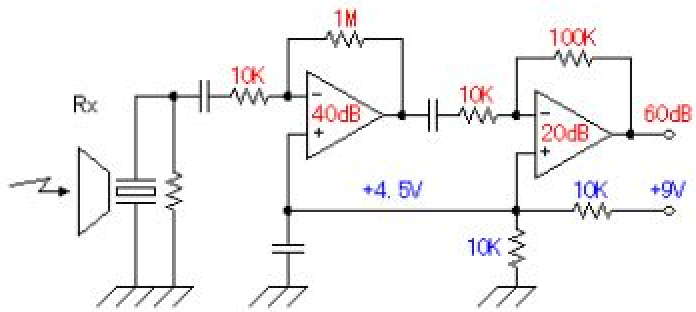

Figure 2: Renesas Signal Amplification Receiver circuit

Our next objective was to determine the resistor values necessary to give us the gain we were looking for in our circuit. According to the lab manual, a gain of 34dB, or about 50, is called for. We used the following equation for the gain of an inverting op-amp:

$V_o = -R_f/R_I(V_{in})$

Essentially, the gain is simply set by the ratio of the feedback to the input resistor of the op-amp. Because we are using two stages in our design, we set the first stage to amplify by 6.8, and the second stage to amplify by 7.5, resulting in an overall gain of 51. The resistor values we used are shown in the table below.

Table 2: Resistor values for High-gain band-pass amplifier

Resistor	**Value (Ohms)**
$R1_I$	10k
$R1_f$	68k
$R2_I$	10k
$R2_f$	75k

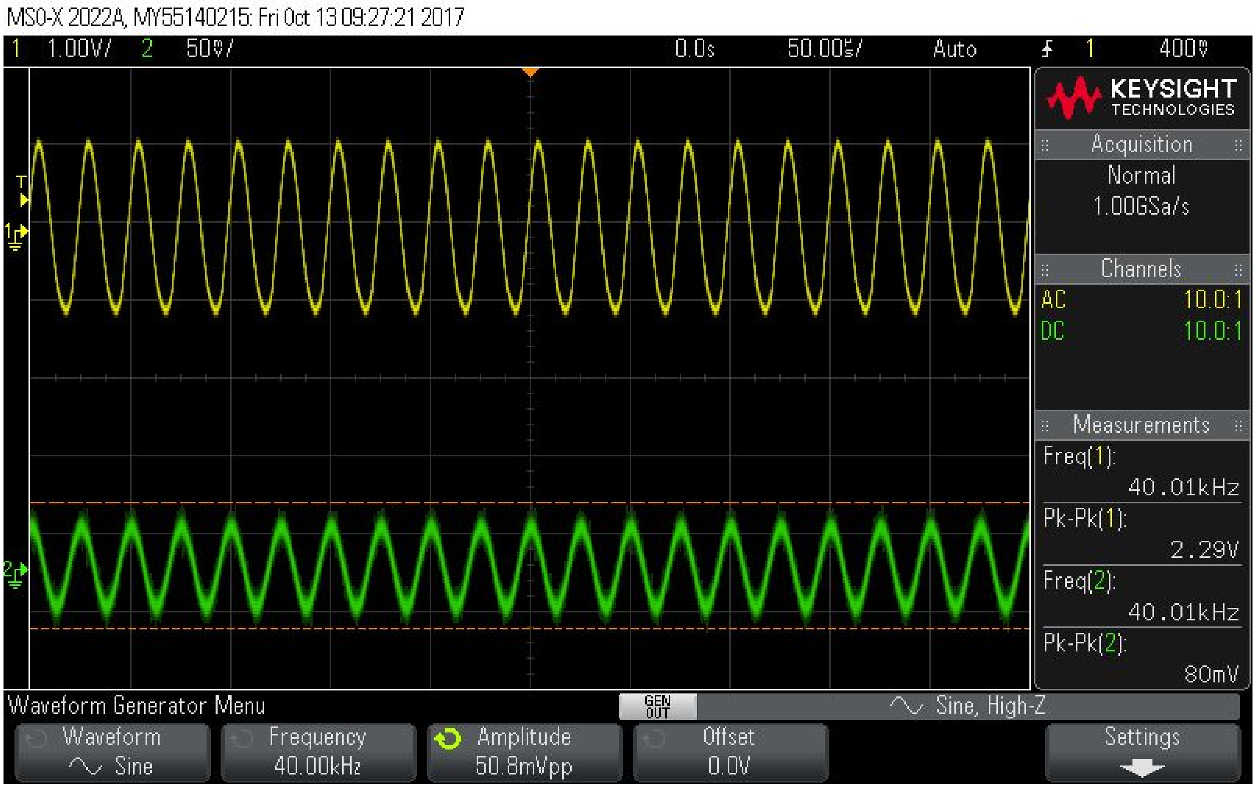

Figure 3: Gain Comparison - V1 (Yellow) is the output of the amplifier and V2 (Green) is the input to the amplifier.

Tone-Decoder

For the tone-decoder, our goal was to build a 40 Khz tone decoder and determine its capture and lock range.

We started by using the following equations provided in the NE567/SE567 data-sheet.

DESIGN FORMULAS

$$f_O \approx \frac{1}{1.1 R_1 C_1}$$

$$BW \approx 1070 \sqrt{\frac{V_I}{f_O C_2}} \text{ in \% of } f_O$$

$$V_I \leq 200mV_{RMS}$$

Where
V_I = Input voltage (V_{RMS})
C_2 = Low-pass filter capacitor (μF)

We wanted an f_O of 40 Khz as that was the frequency which yielded the peak voltage value for our ultrasonic receiver. R_1 was determined to be 10k ohms as that was what we had available. Thus, using the above equation for f_O, we found a C_1 of 2.27nF. C_2 was then determined graphically using the following graph.

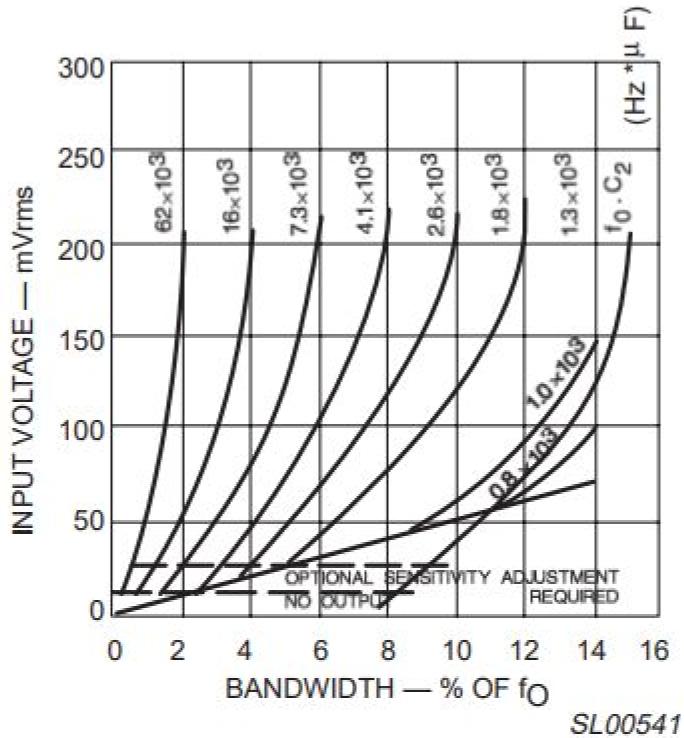

Figure 3: Bandwidth vs. input signal amplitude for Tone decoder/phase-locked loop NE567/SE567

Finally, C_3 was found by taking $2*C_2$, which was recommended by the data-sheet. All values of C are shown in the table below.

Table 3: Capacitors used in tone-decoder

Capacitor	Calculated Value	Standard Value
C_1	2.27nF	2.20nF
C_2	182nF	180nF
C_3	364nF	390nF

Capture: 39.2kHz-41.8kHz
Lock: 38.6kHz-42.7kHz

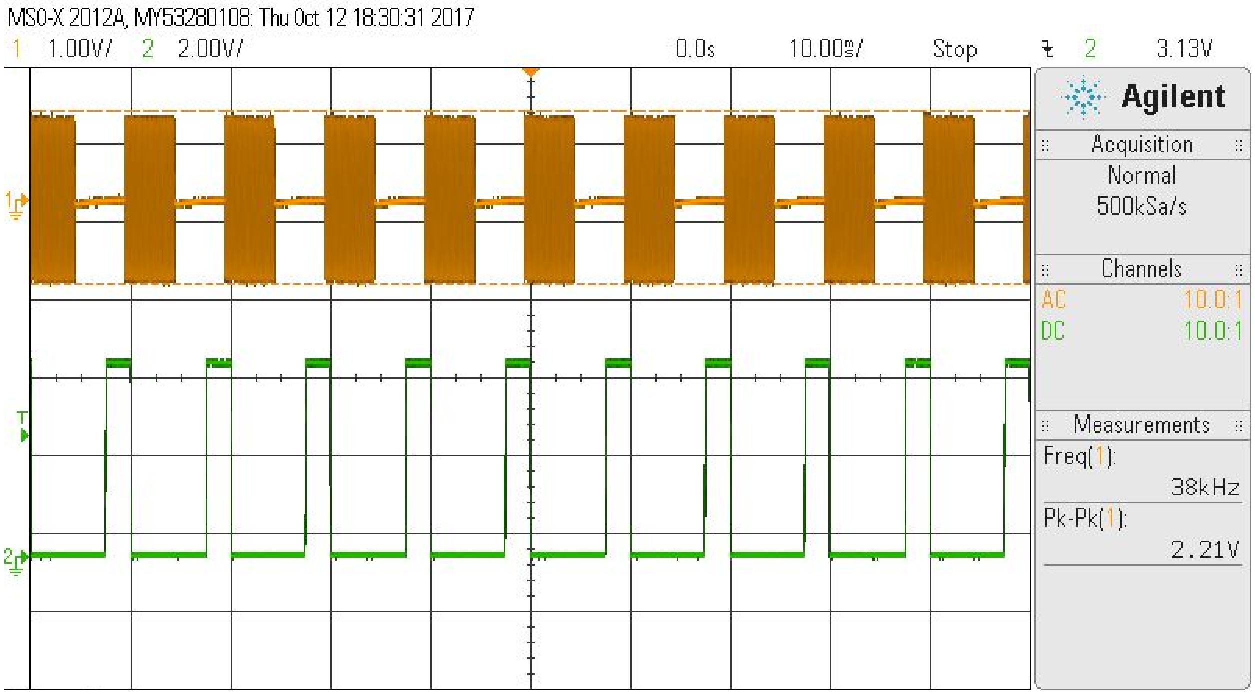

Figure 4: Successful Tone Decoding at 40kHz

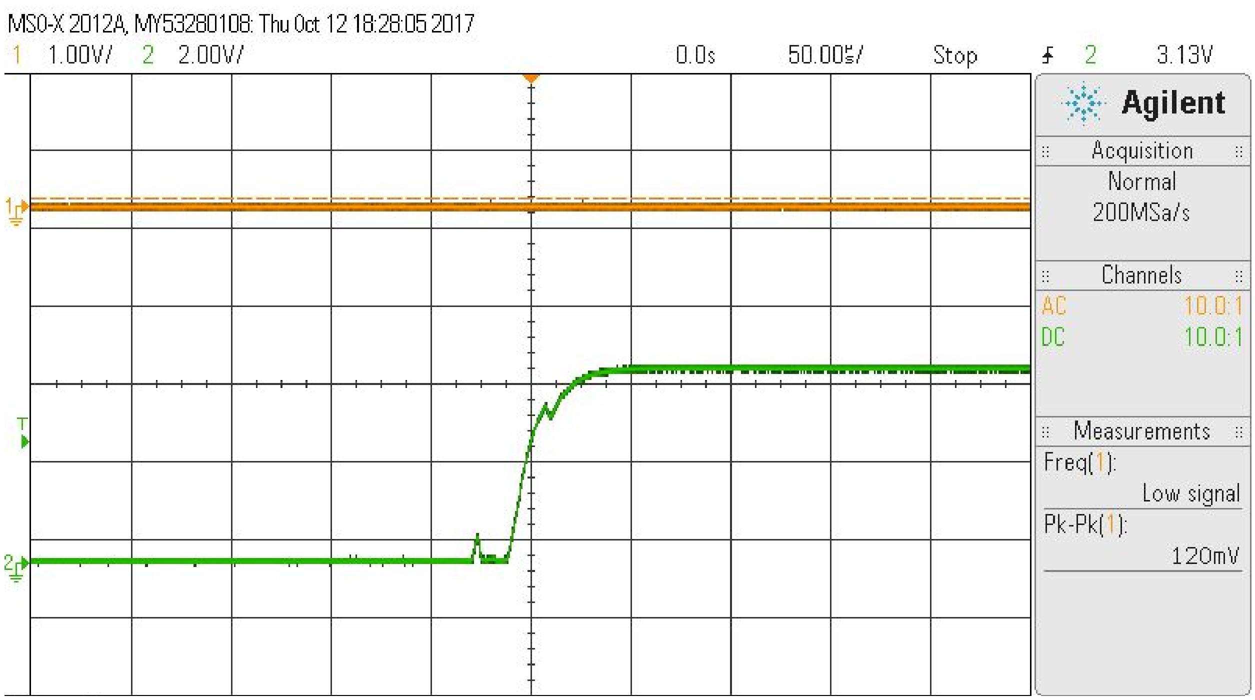

Figure 5: Rising Edge of the Output of the Tone Decoder (V2 - Green)

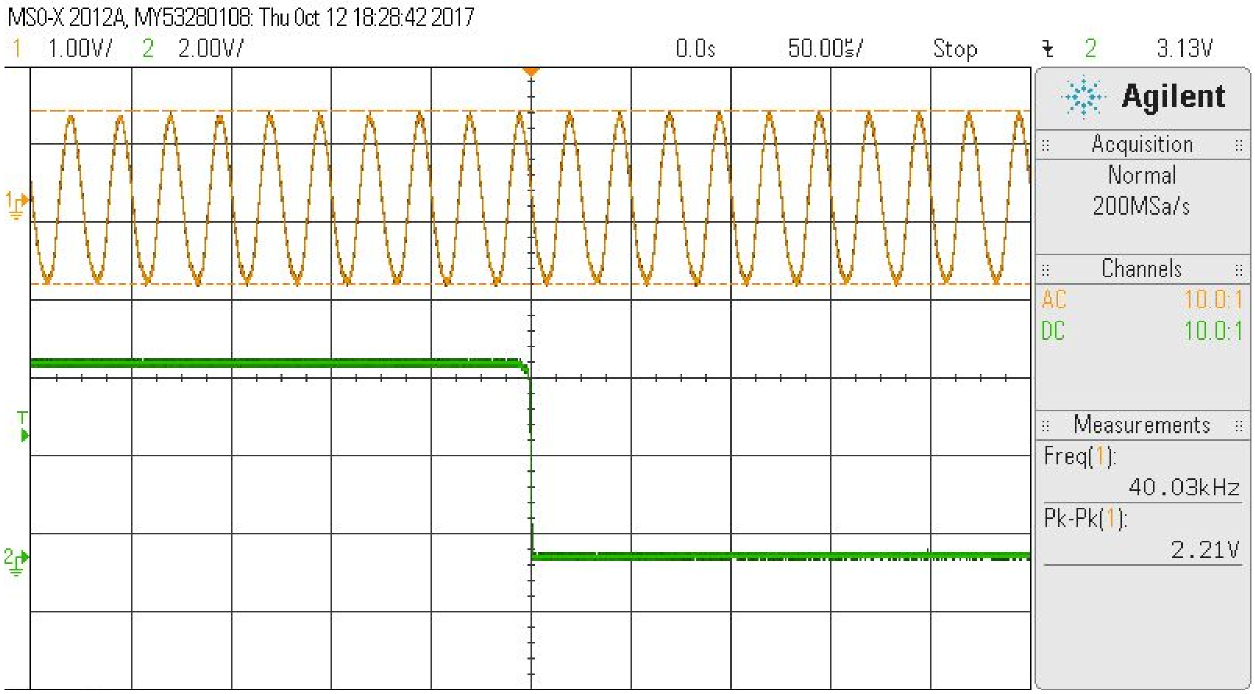

Figure 6: Falling Edge of the Output of the Tone Decoder (V2 - Green)

Linear Regulator

For the Linear Regulator, our goal was to design a system that has an input of 9V DC and an output of 5V DC. We used the LM317 voltage regulator chip provided with our lab kit. The end result was a working 9V to 5V linear regulator.

Driver-Amplifier with ON/OFF Control

Our goal was to implement a Driver-Amplifier with ON/OFF Control. The functionality of this amplifier is to increase the current drive capabilities of our ultrasonic transducer, as well as modulate the signal based on a control input. The two power levels are simply binary, ON and OFF. We decided to use an H-bridge configuration for this, as it maximizes the drive voltage for a given supply voltage. We used the hex-inverter IC, with 5 of the inverters used in our design. A BJT was used to increase the current sink capability of the Driver-amplifier when the controller input shows an off signal.

When looking at the voltage outputted by the transducer, we found it to be 18.9V.

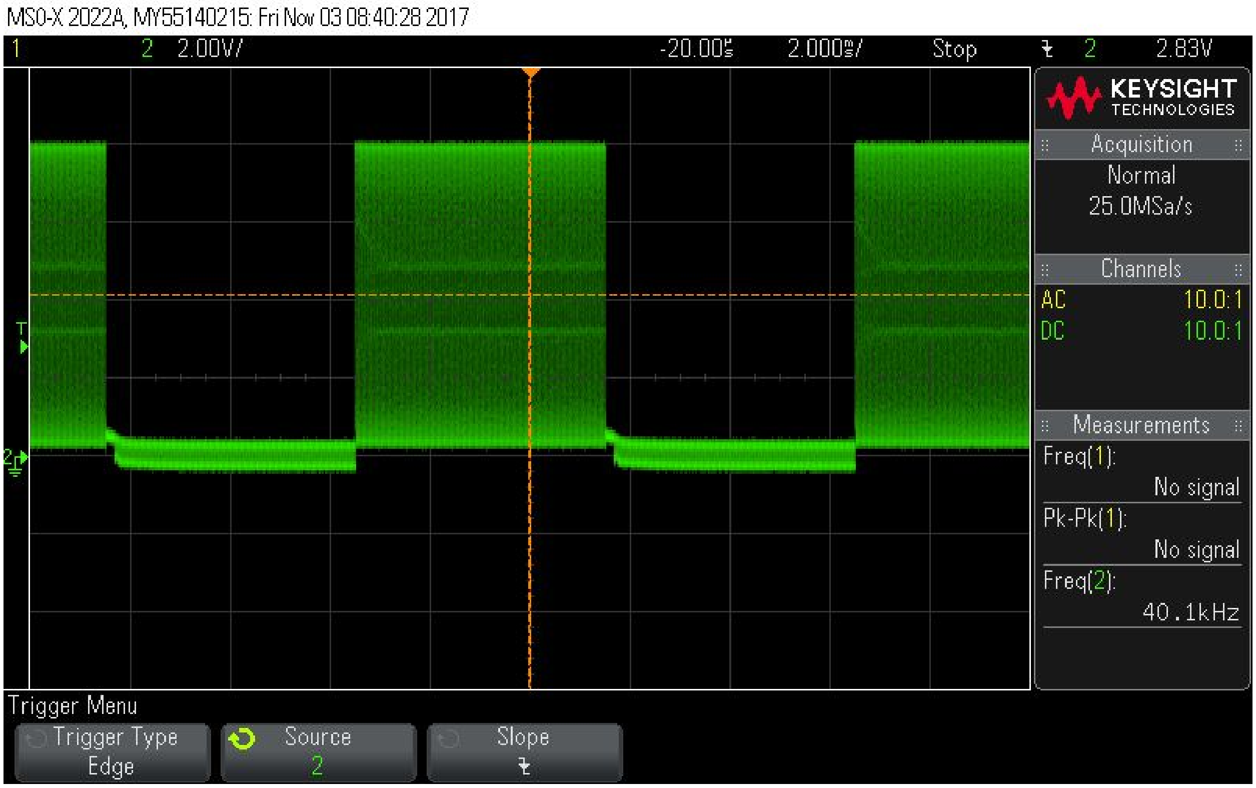

Figure 7: Driver-Amplifier with on signal of 40KHz and off signal of GND

<u>40kHz Crystal Oscillator</u>

We implemented a 40kHz +- 50Hz crystal oscillator capable of driving our driver-amplifier. We performed the necessary calculations and verified our design using Spice. The crystal we used was the ECS-31X series low frequency quartz crystal model 3X8X. According to the data sheet, it can operate at a frequency range between 20-40Khz and has a load capacitance of 12.5pF. The max drive level is 1uW. An image of the crystal oscillator signal is shown on the next page in figure 8.

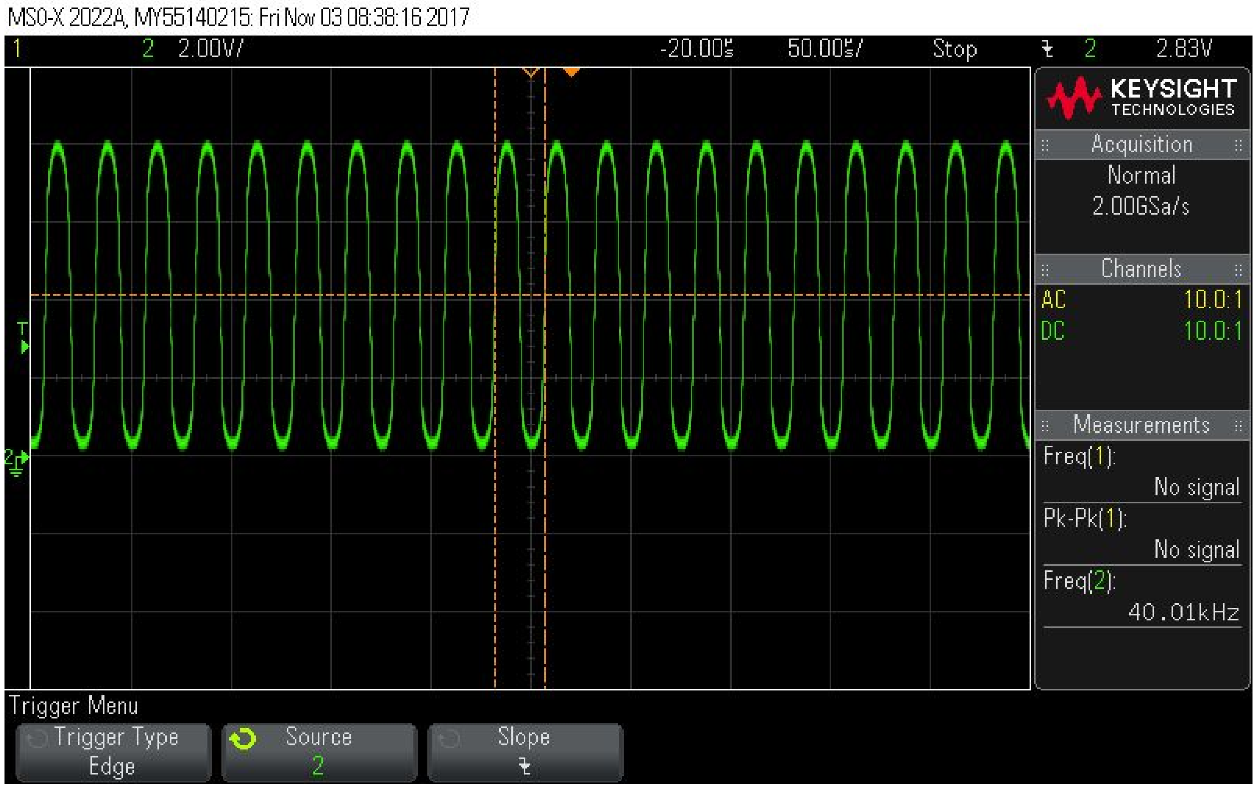

Figure 8: Image of 40.01KHz Crystal Oscillator signal

Photo Amplifier

For the photo amplifier we used a simple I-to-I current amplifier. We decided to implement this using an op-amp in a bootstrapping arrangement to prevent oscillations, high nonlinearity, and latch condition.

Current-Controlled Oscillator

Our current-controlled oscillator generated a sawtooth waveform using a 555-timer IC. The oscillation frequency is proportional to the input current as long as the discharge time is relatively small compared to the saw-tooth ramp-up time and the current drawn by the “trigger” and “threshold” pins of the timer is negligibly small compared to the input current. One problem we had with the 555 timer is that we originally had the discharge resistor value way too high. It was set to 1 Megohm and our output signal was extremely distorted. Once we changed this value to 2k, the problem was solved.

An image of the sawtooth waveform is shown below.We determined the frequency to be 23.891Hz with a peak to peak voltage of 5 Volts. As visible from the graph, there are minor oscillations in the waveform, however, we did not determine them to be big enough to cause instability or malfunction in the system.

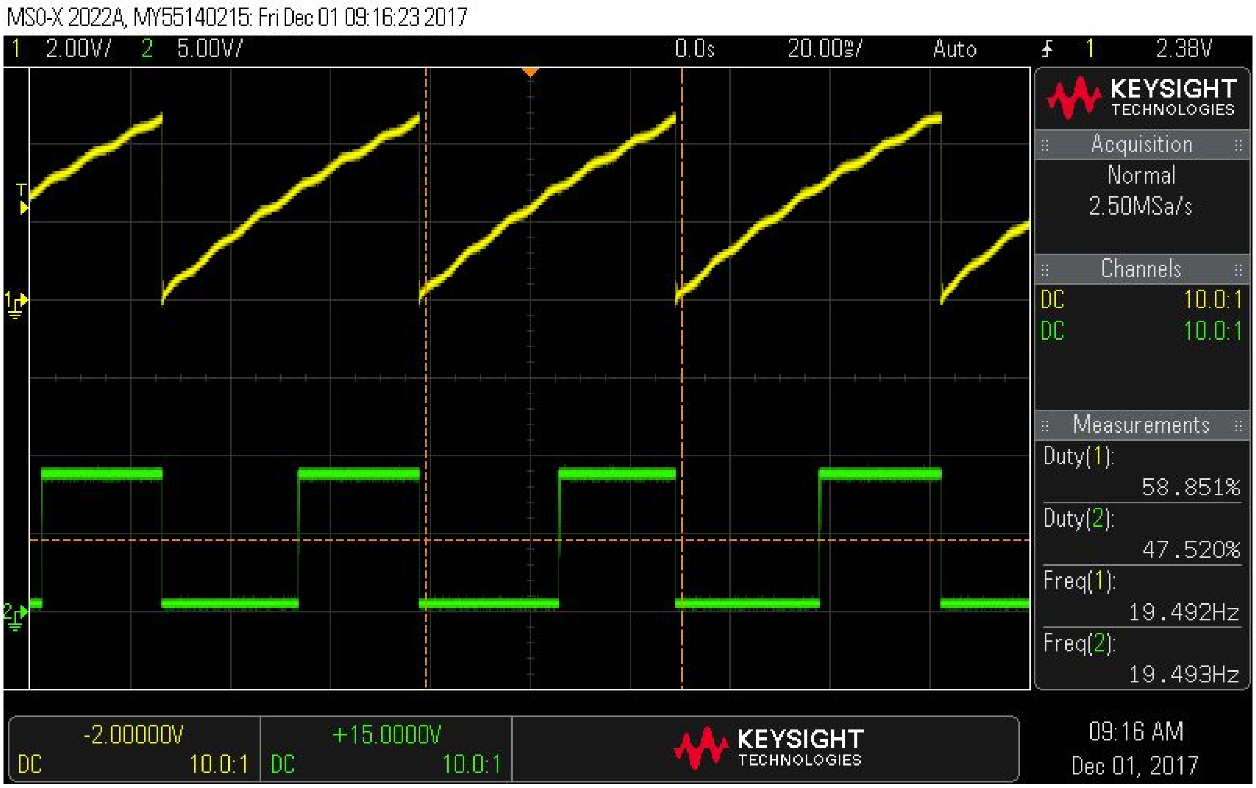

Figure 9: Sawtooth waveform(Yellow) & Output of comparator(Green)

The sawtooth waveform is fed into a comparator to transform it into a square wave. A comparator is a simple device that works by comparing two voltages. If the input voltage is higher than the reference voltage, the output is high. However, if the input voltage is lower, than the output will be low. We used a pull up resistor of 10k ohms to pull the output all the way up to 9 volts when it is high. The duty cycle can be set based on the reference voltage value. For example, if the reference voltage is at half the value of the sawtooth peak to peak voltage of 5 volts, the square wave output from the comparator will have a 50% duty cycle.

<u>Arduino</u>

An arduino coupled with an LCD panel is utilized to measure and display the frequency of the waveform, as well as the photodiode current and foot candles measured.

Source Code:

```
#include <LiquidCrystal.h>

LiquidCrystal lcd(12, 11, 5, 4, 3, 2);

long microSecs;
long freq;
long current;
long fc;
```

```
int lastBit;
int nowVal;
long secs;
long maxHz;
long minHz;
long minmax;
void setup() {
  // set up the LCD's number of columns and rows:
  lcd.begin(16, 2);
  // Print a message to the LCD.
  lcd.print("Loading... v.4");
  pinMode(A1,INPUT);
  pinMode(A5,OUTPUT);
  microSecs = micros();
  freq = 0;
  lastBit = 0;
  nowVal =0;
  maxHz=0;
  minHz=0;
  minmax=0;
  current=0;
  fc=0;
  secs = millis();
}
int x=0;
void loop() {


  if ((microSecs+20)<micros()){
      nowVal=digitalRead(A1);

      if (lastBit!=nowVal) {
        lastBit=nowVal;
        freq=freq+1;
      }
      if (freq>maxHz){
        maxHz=freq;
      }
      if (freq<minHz){
        minHz=freq;
      }
      microSecs = micros();
  }
  if (secs+1000<millis()){

    if (minmax+300000<millis())
    {
      minmax=millis();
      minHz=freq;
      maxHz=freq;

    }
    // Piecewise Conditions
```

```
    if (freq <= 150)
    {
      current = (((285.5*freq)/2)-0.8531);
      fc = ((0.37095*freq)+4.7174);
    }
    else if (freq > 150)
    {
      current = (((0510.2*freq)/2)-25);
      fc = ((0.9616*freq)-84.916);
    }
    else
    {
      current = 0;
      fc = 0;
    }
    if (current <= 100)
    {
      current = 100;
    }
    else
    {
      current = current;
    }
      lcd.clear();
      lcd.print((freq/2));
      lcd.print("hz  ");

      lcd.print(fc);
      lcd.print("ft-c");

      lcd.setCursor(0,1);
      lcd.print(current);
      lcd.print("pA");

      freq=0;
      secs=millis();

  }

}
```

System Testing

The process of overall system integration required tuning and testing of each of the subsystems in order to make sure that all of the systems achieved their desired performance. The system approached the distance specification reaching around 9.5 meters. However, the system did not meet the 5 to 200 Foot-Candle range, only achieving 5 to 90 Foot-Candles due to noise and other inefficiencies in the design. The three figures below document several important subsystems and their interactions. Figure 10 demonstrates the how the output of the comparator drives the switch system to modulate the 40kHz carrier.

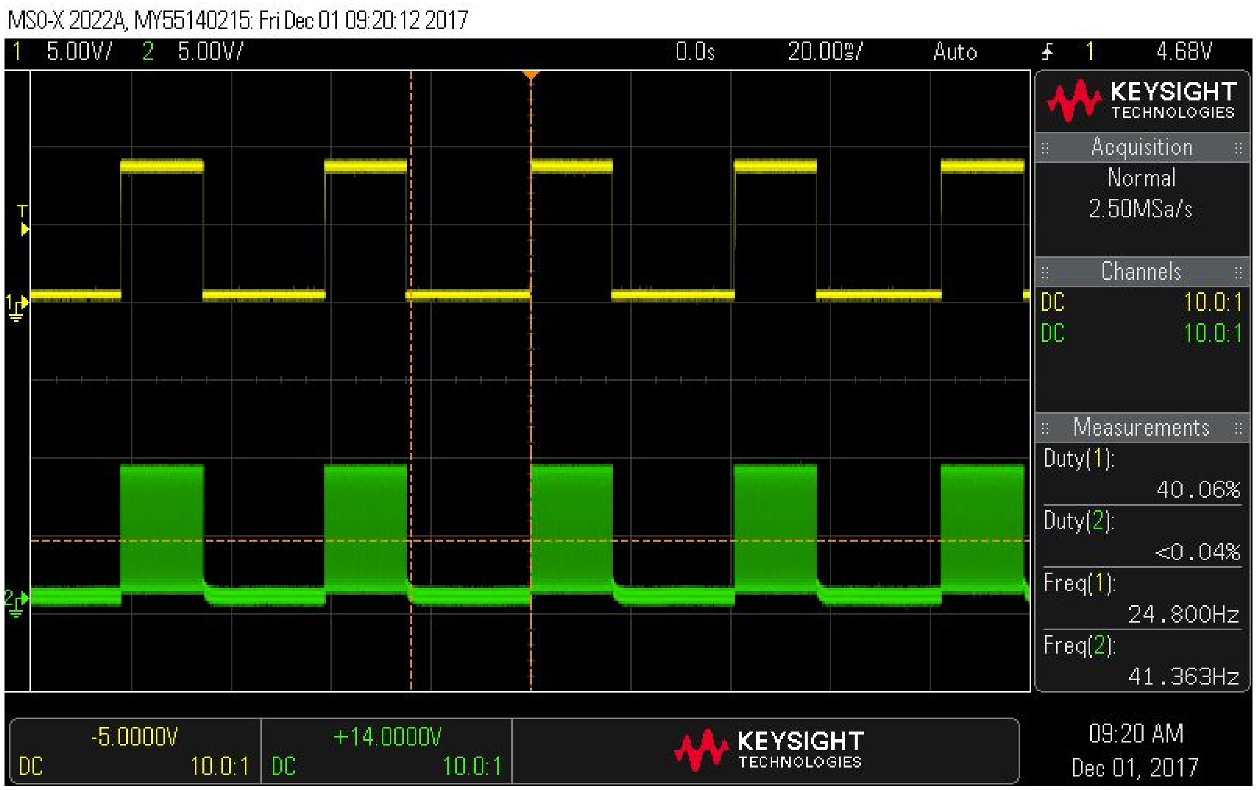

Figure 10: Output of comparator(Yellow) & Output of the switch(Green)

Figure 11 compares the square wave output by the comparator on the transmitter to the square wave output by the tone decoder. Figure 12 shows the signal at both the input to the ultrasonic transmitter and the output of the ultrasonic receiver.

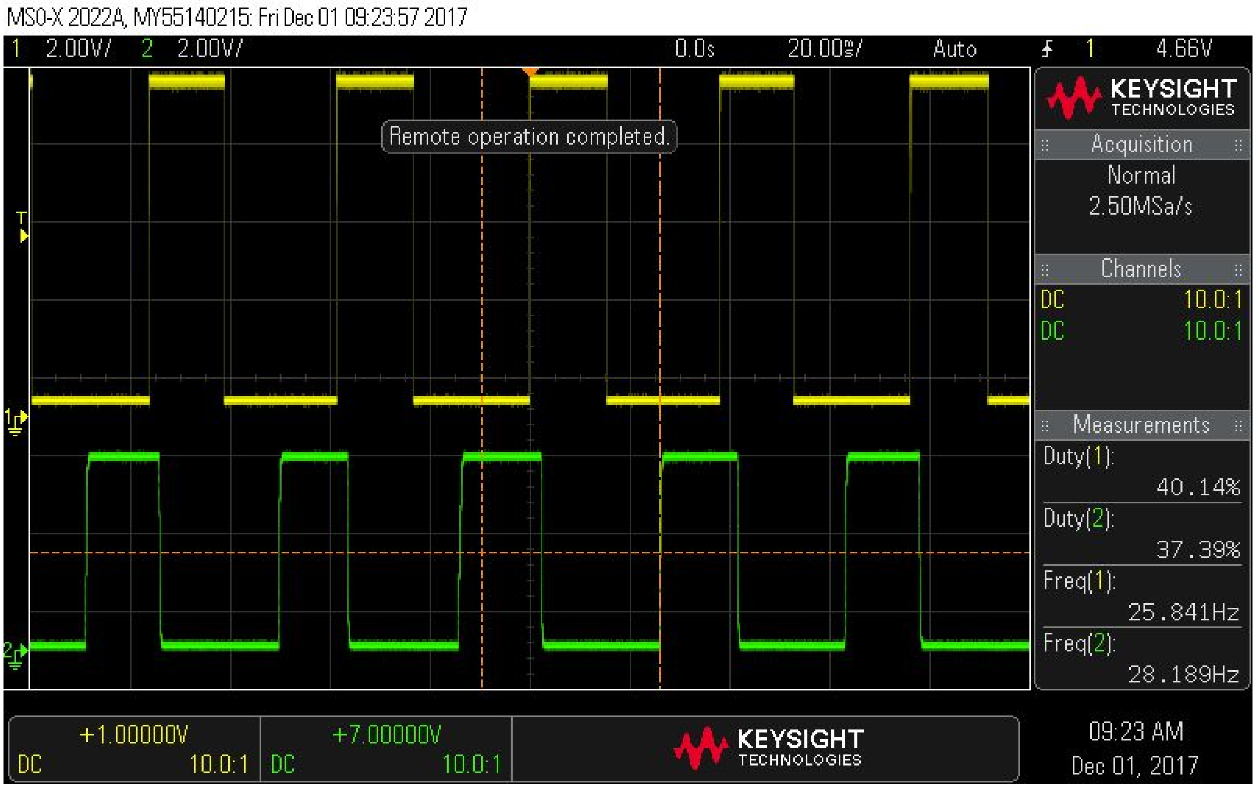

Figure 11: Square wave on transmitter side(Yellow) vs. receiver side(Green).

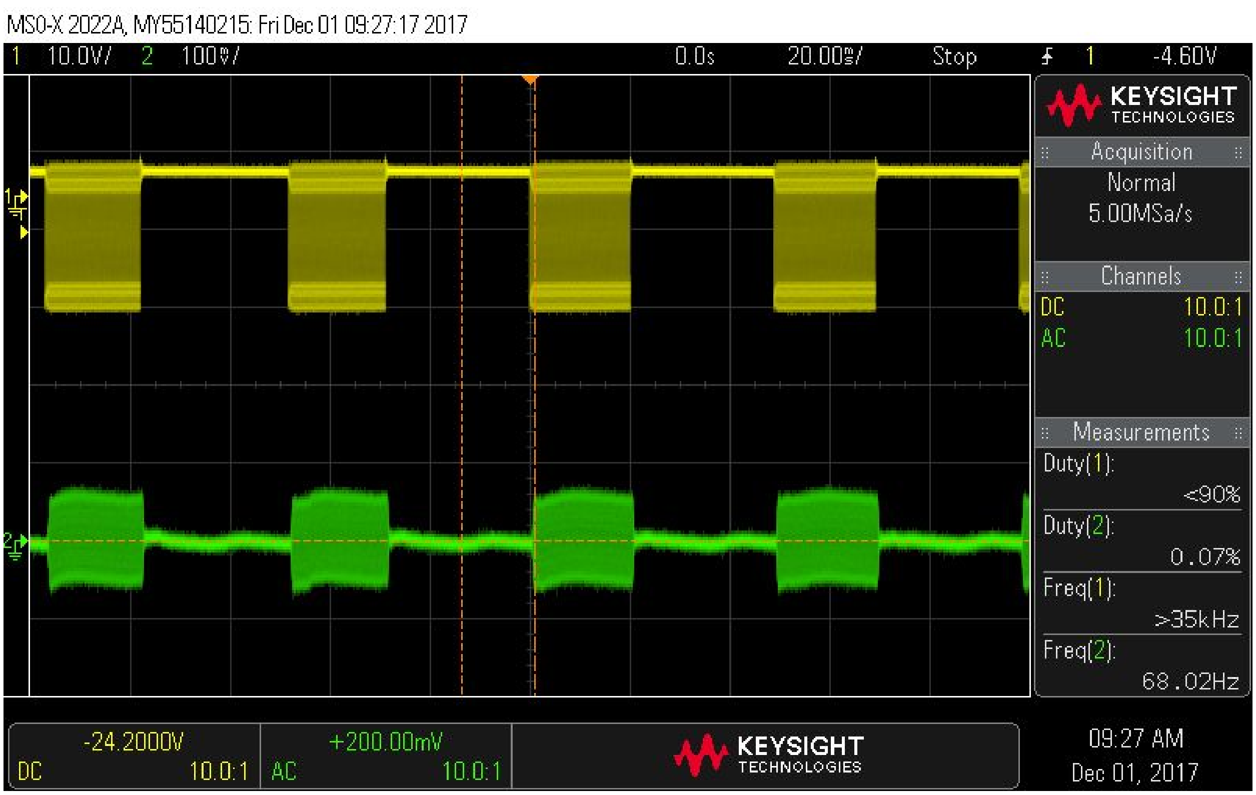

Figure 12: Transmitter wave(Yellow) vs receiver wave(Green)

Bill of Materials

Table 4: Transmitter Bill of Materials

Item	Quantity	Reference	Part
1	1	BT2	9V
2	2	C11,C12	.18u
3	2	C13,C14	22p
4	1	C15	1.2p
5	5	C18,C22,C23,C24,C25	10p
6	1	C19	10n
7	1	C20	1n
8	1	C21	15p
9	1	D1	PHOTODIODE
10	1	LS1	Ultrasonic Transmitter
11	1	Q1	2N3906
12	1	R12	470k
13	1	R13	6.2Meg
14	1	R14	300k
15	1	R15	5.6k
16	1	R16	33k
17	2	R17,R18	9.1k
18	2	R19,R20	1k
19	1	R21	1.5k
20	1	R22	750
21	1	U4	CD4069UB
22	1	U5	CD4066B
23	1	U6	LMC662
24	1	U7	ICM7555
25	1	U8	NCP431
26	1	U9	LM393
27	1	Y1	40kHz, 12.5pF

Table 5: Receiver Bill of Materials

Item	Quantity	Reference	Part
1	1	BT1	9V
2	2	C2,C4	0.1uF
3	1	C3	10nF
4	1	C5	0.18uF
5	1	C6	0.38uF
6	1	C7	2.2nF
7	1	C8	1u
8	3	C9,C16,C17	100n
9	1	C10	1nF
10	1	MK1	Ultrasonic Receiver
11	1	R1	100k
12	5	R2,R3,R5,R6,R8	10k
13	1	R4	57k
14	1	R7	12k
15	1	R9	270
16	1	R10	820
17	1	R11	120k
18	1	U1	LM358
19	1	U2	LM567
20	1	U3	LM317/CYL
21	1	U4	Arduino Uno
22	1	U5	16x2 LCD

Course Conclusions and Feedback

This course provided us with a hands on experience building a product to certain specifications, just as we would be doing in industry. Building each component block by block and interfacing them together allowed us to gain valuable experience combining various electronic components together. In addition, the team aspect of this project gave us essential team skills which will surely be of use in industry. For example, in some situations we found that the best way to work was together, where each of our ideas and knowledge could compliment. Whereas in other situations, the best approach was to divide up the work and adopt a more autonomous dynamic. One other thing we learned was that tweaking and troubleshooting take up the most amount of time. Therefore, it is imperative to allow ample time for these procedures, especially when deadlines are looming. Overall, the class was very interesting, and we enjoyed the process of creating a complex system from basic components.