Ultrasonic Sensor Qualification

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I. Introduction

I decided to build this floorplan mapping robot because of my interest in control systems and robotics. In my career I have implemented some interesting thermal control systems for ovens and processing equipment but I have not worked with a complex robotic system, namely because of the difficulty in implementing robotics for small scale assembly typically found in manufacturing catheters.

II. Background on HC-SR04 Ultrasonic Distance Sensor

For hobby robotics, a common sensor choice for noncontact distance sensing is the HC-SR04. The HC-SR04 emits eight directional 40KHz ultrasonic waves and measures the amount of time between firing the wave and receiving the last reflected signal. The distance between the sensor and the object is calculated via Equation 1 below, where D is the distance between the sensor and the object that reflected the ultrasonic waves, α is the speed of sound in the medium, and t is the measured traveled time.

$$D = \alpha \frac{t}{2} \qquad \text{Equation 1}$$

The sensor output is a digital pulse that has a pulse width equal to the travel time. This implies that to read this sensor the microcontroller must be able to measure the pulse widths in μs. The manufacturer data sheet suggests using a 60 ms measurement cycle to prevent reflected pulses from a previous cycle interfering with the distance measurement. The manufacturer specifications are listed in Table 1 below.

Table 1 Manufacturer Specifications

Working Voltage	5 VDC
Working Current	15 mA
Working Frequency	40 Hz
Maximum Range	4 m
Minimum Range	2 cm
Measuring Angle	15°
Measurement Area	.5 m^2
Input Pulse Width	10 μs

There are a few difficult to interpret specifications. The limitation on the reflection surface is given in area; it seems that from the mode of action that there is likely a minimum length and width capability but these are not defined by the manufacturer. Further, this is likely a function of distance from the object to be measured. For measuring walls, this is likely not an issue. What this does tell us is that chair legs and table legs will give this sensor a hard time. The manufacturer does not provide a resolution of the sensor. This will be an important measurement to quantify to understand the uncertainty associated with the measured distance. Another consideration from the manufacturer's datasheet is that the object to be measured should be as smooth as possible. This is likely because of potential scatter effects when the ultrasonic wave is reflected. The wavelength of the ultrasonic waves is calculated per Equation 2 below, where λ is the wavelength, f is the frequency, and α is the speed of sound. From Equation 2 we calculate a wavelength of .0086 m. As scattering phenomena often are caused by features that are a fraction of the wavelength certain rough features may lead to problems.[1] Luckily, most features inside of my apartment do not have a significant roughness on the length scale calculated above.

$$\lambda = \frac{\alpha}{f} \qquad \text{Equation 2}$$

III. Static Testing

Materials used

i. Tape Measure
ii. Arduino Uno Rev 3
iii. PC with Python3 and USB port
iv. HC-SR04 sensor unit

Procedure

i. The sensor was set up at D cm from the wall, ranging from 5 cm – 300 cm to test the full range the sensor may see in my apartment during this project. The measurement distances are shown in Table 2 below. The entire range is also within the manufacturer's specifications and spans most of the range so the results can be used to verify the specifications. The distance was defined as the front of the sensor barrel to the wall as shown in Figure 1 below.

Table 2 Distances measured during experiment

Measurement	Distance from wall (cm)
1	5
2	50
3	100
4	150
5	200
6	250
7	300

[1] http://www.apl.washington.edu/programs/SAX99/IOSpapers/Richardson.pdf

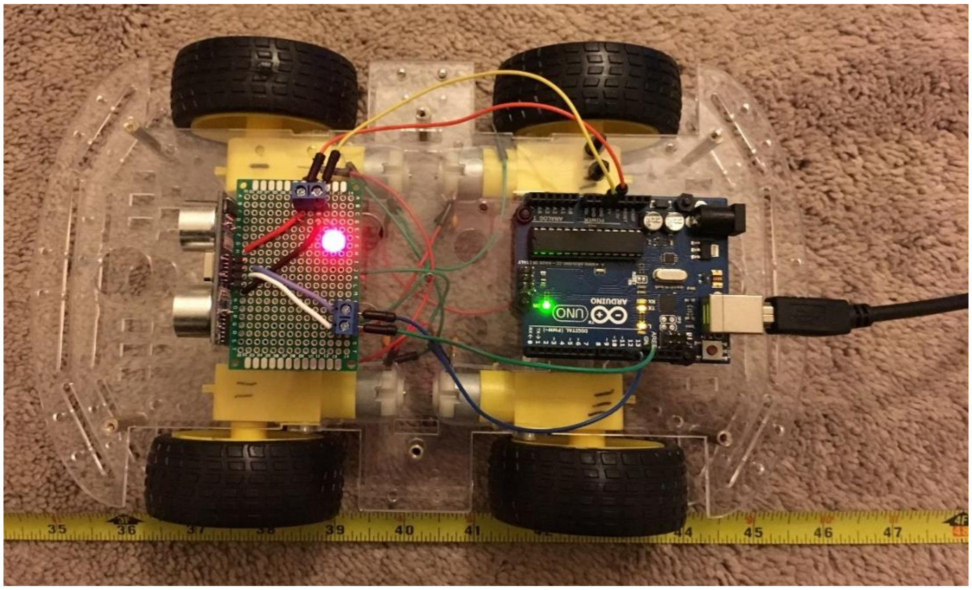

Figure 1 Experimental Setup

ii. The sensor was set so the transducer and the receiver were directly facing the wall. The experiment was performed at 50 cm increments per Table 2 below. At 100 cm, the waves were never returning to the receiver so the real life height of the setup was added with the robot buggy as shown in Figure 2 below. This height was approximately 9 cm from the ground.

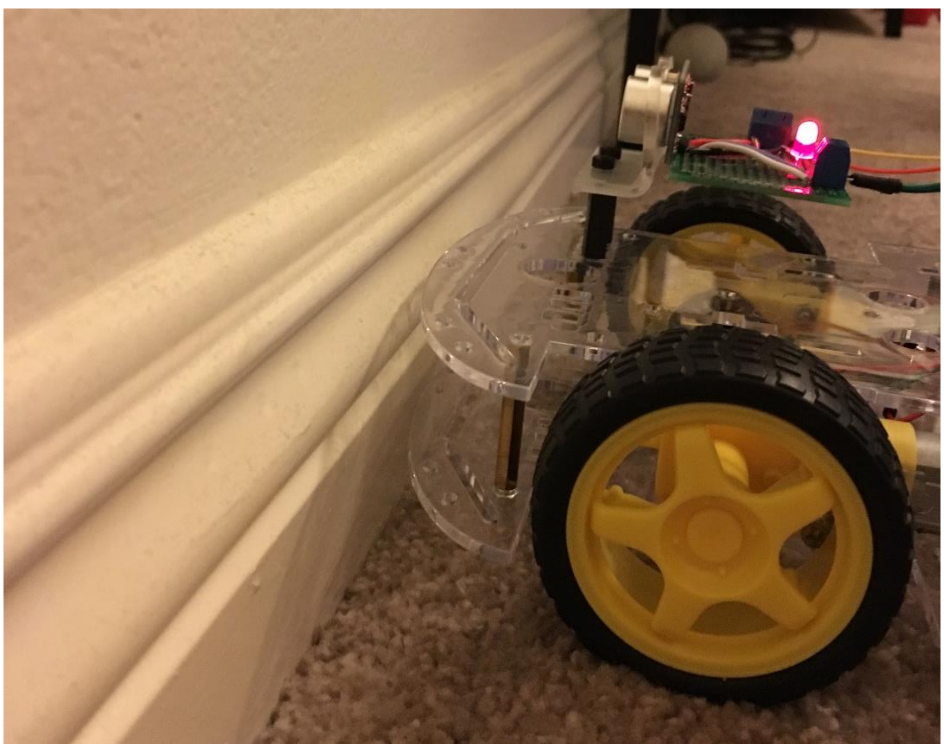

Figure 2 Sensor set mounted on robot chassis.

iii. The Arduino was set up to delay 60 ms after each measurement cycle test the reliability of the manufacturer's recommendation, calculate the distance in cm, and write the distance measured to the PC. The PC read a total of 500 measurements per location. The measurements were sorted into two buckets: reasonable measurements and errors. Outliers were sorted by taking the median and removing any measurements that were 3 standard deviations from the median. Any outliers were added to the error count. After filtering the data, each group of reasonable measurements was gauged for repeatability and accuracy.

IV. Results

Originally, the sensor was placed on the ground. This led to the sensor completely failing at only 100 cm, implying the sensor is designed to sit above the ground. The sensor was mounted to the top of the robot chassis about 9 cm above the ground, allowing for the completion of the experiment.

The results of each measurement from on top of the robot buggy are shown in Figure 3 - Figure 9 below. A statistical summary for each measurement is shown in Table 3.

The measurements made in Figure 3 were largely clustered in two categories: one at slightly less than 5.22 and 5.32. There were a small number of measurements that were not in one of these categories. From this measurement, it is difficult to determine if the resolution is .1 cm and the other measurements made were timing aberrations from the sensor and Arduino system or if the resolution is smaller and there is some other phenomenological explanation of why the data is largely bucketed between the two categories shown.

The other measurements, shown in Figure 4 - Figure 9, also show some clustering behavior. Interestingly, each band is approximately 0.4 cm apart. This seems to imply the resolution of the sensor is approximately .4 cm. Note that each band becomes relatively noisy at longer distances indicating that the pulse generating circuit on board the sensor or the pulse measuring circuit on board the Arduino become less repeatable at longer pulse widths.

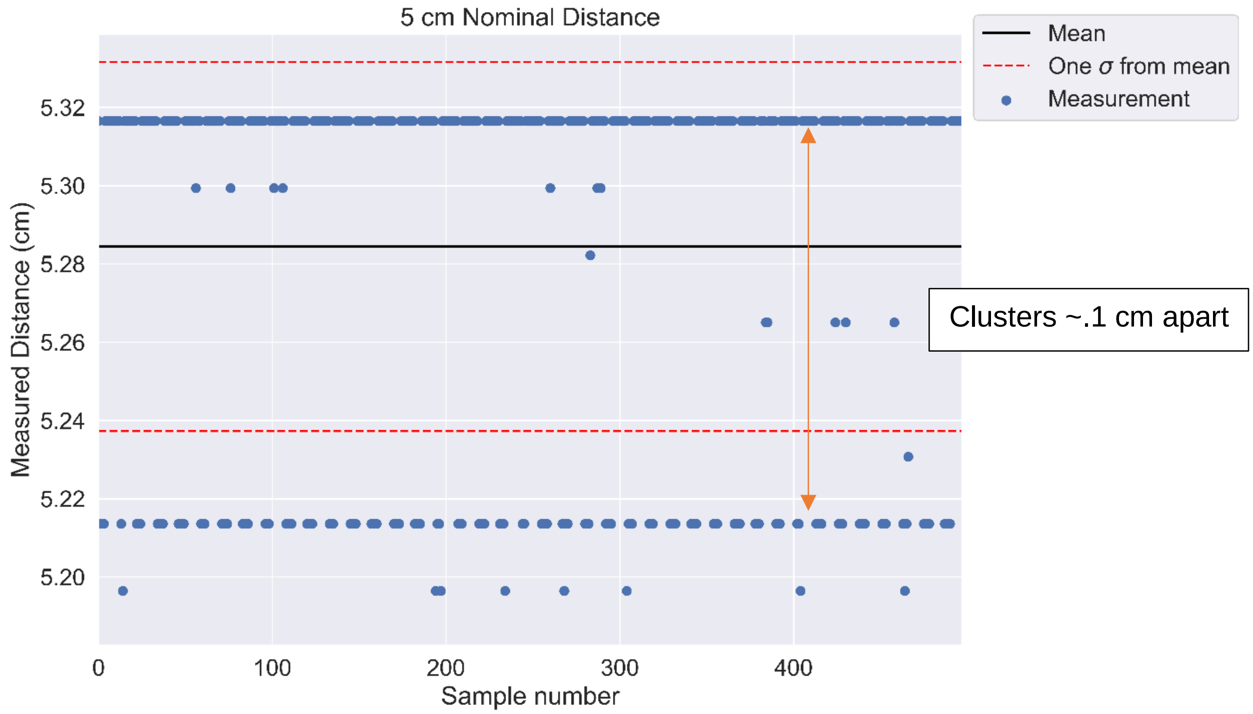

Figure 3 Measurements from 5 cm nominal. The data is largely clustered at two measurement values approximately .1 cm apart.

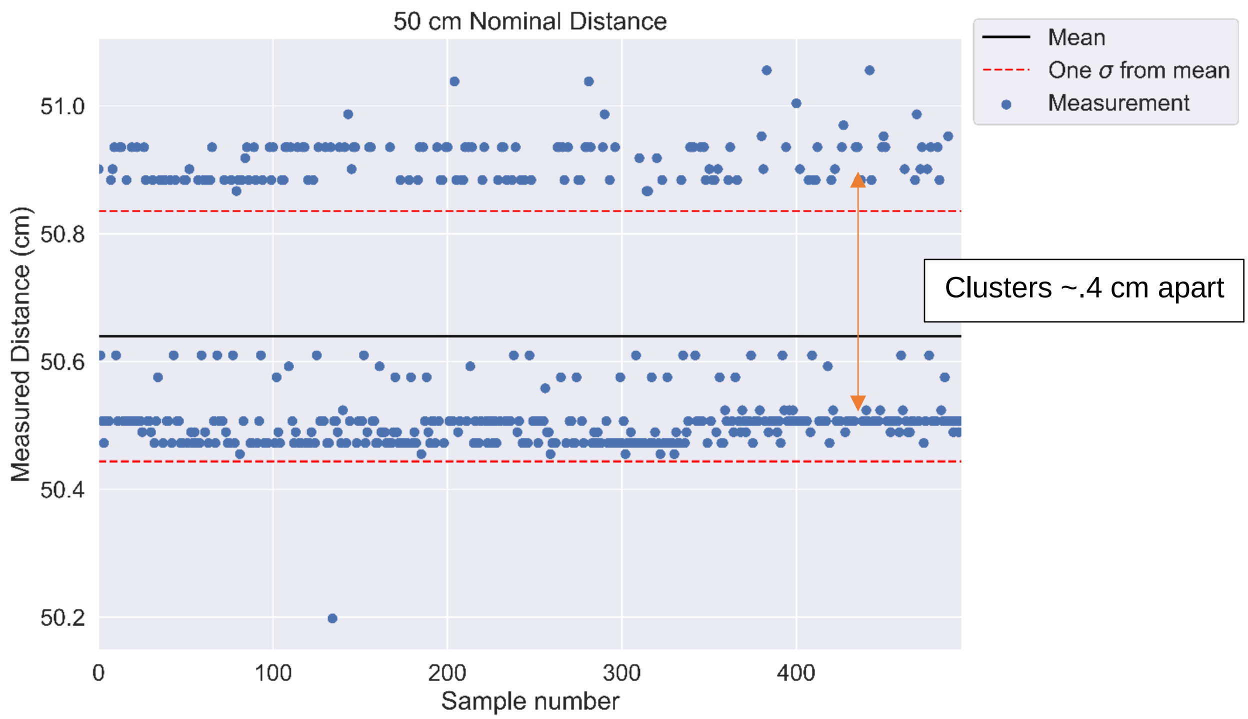

Figure 4 Measurements from 50 cm. The data is clustered approximately .4 cm apart with about .1 cm of variation within each cluster.

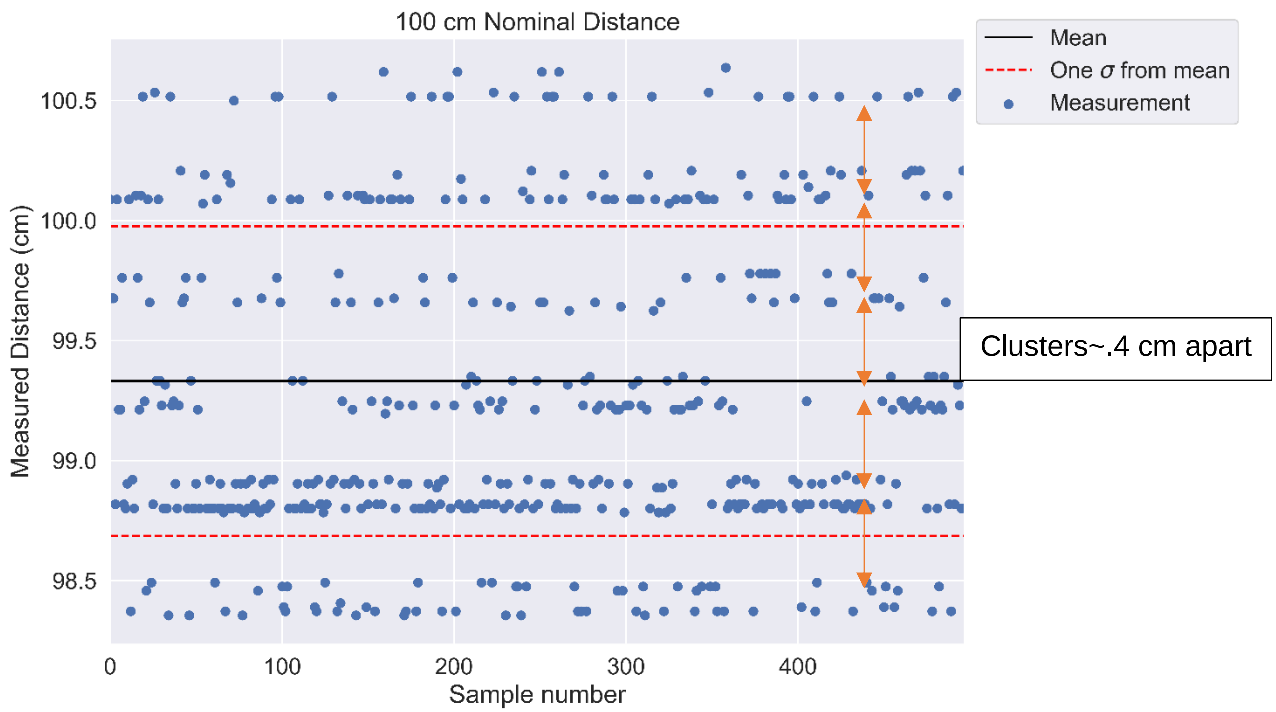

Figure 5 Measurements from 100 cm. 6 bands were measured, each .4 cm apart.

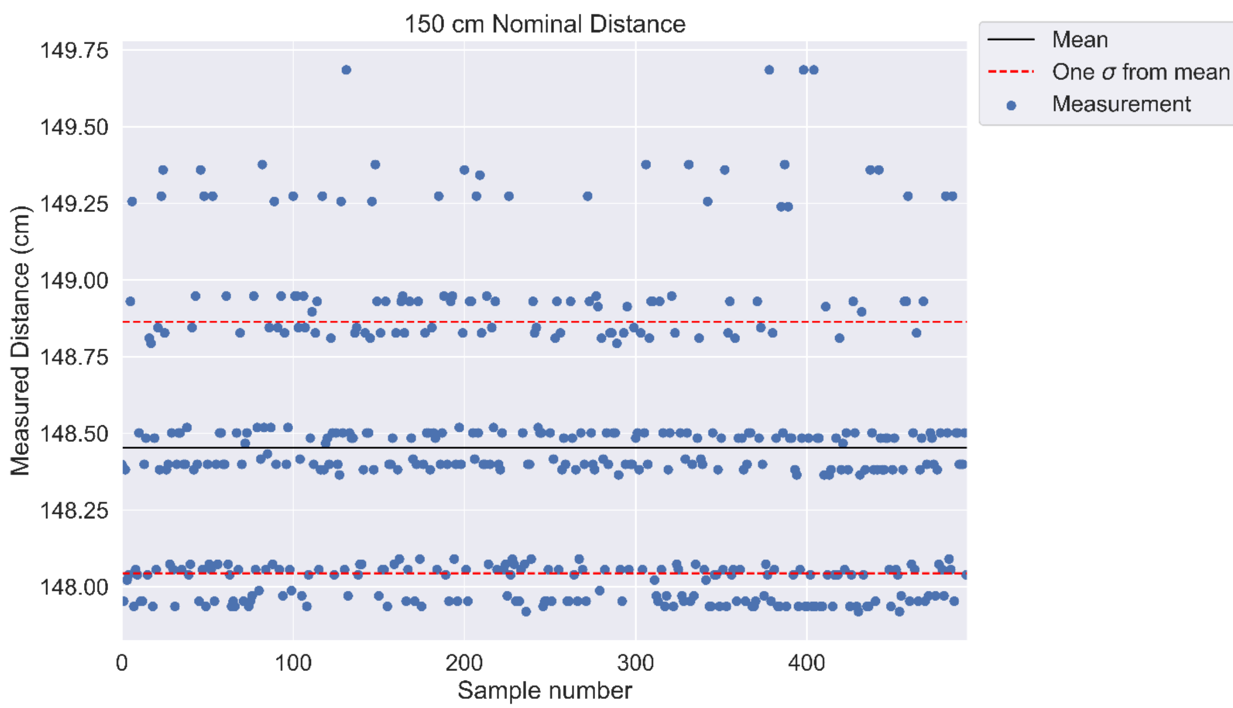

Figure 6 Measurement from 150 cm. Again, bands form at roughly .4 cm apart.

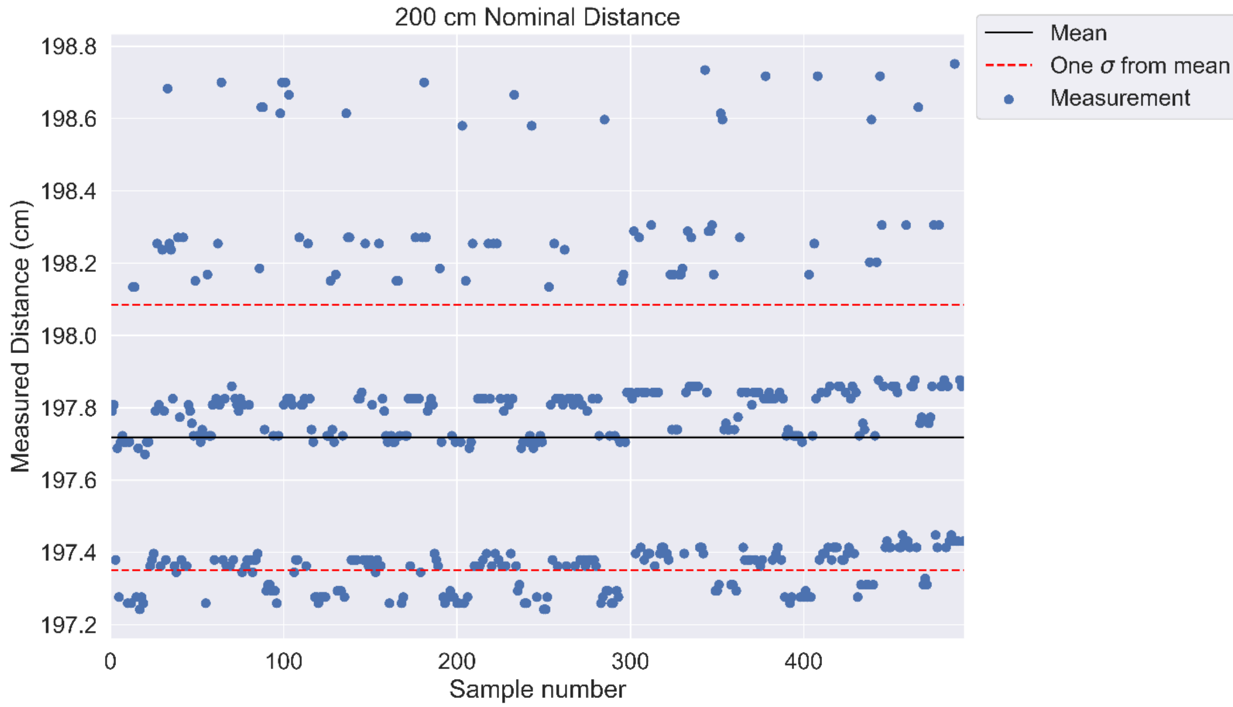

Figure 7 Measurement from 200 cm with bands forming at .4 cm.

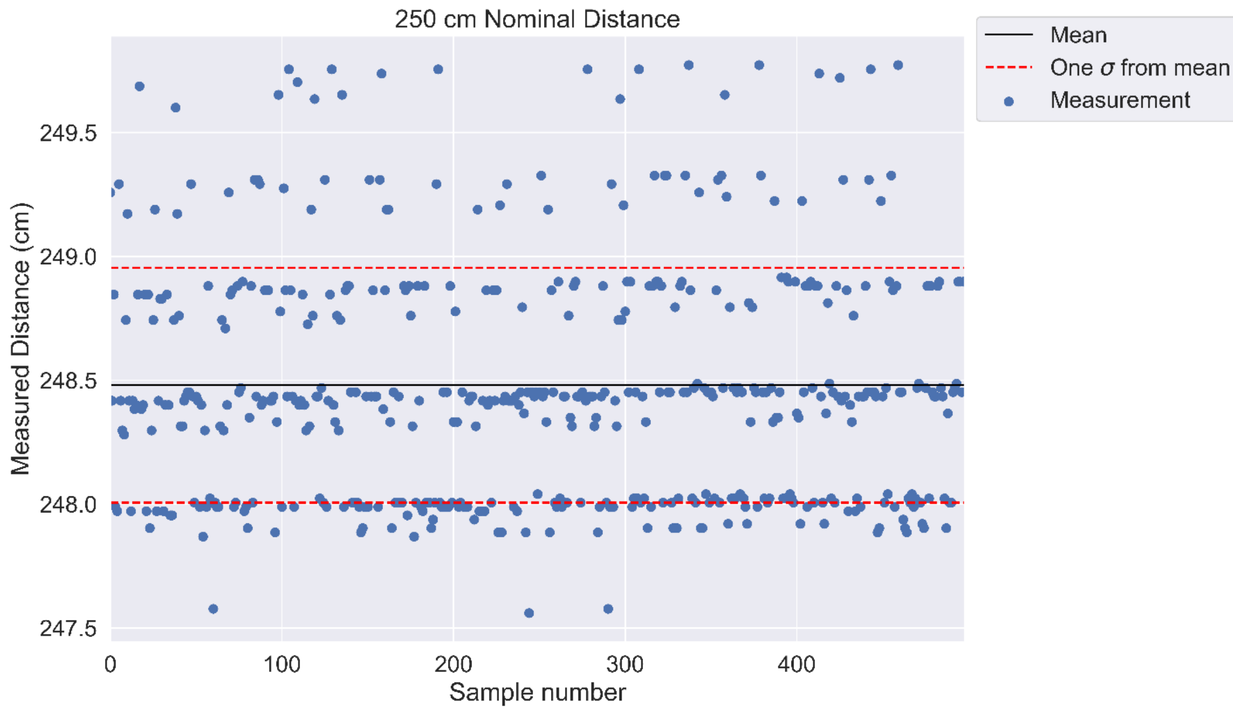

Figure 8 Measurement from 250 cm with bands forming at .4 cm.

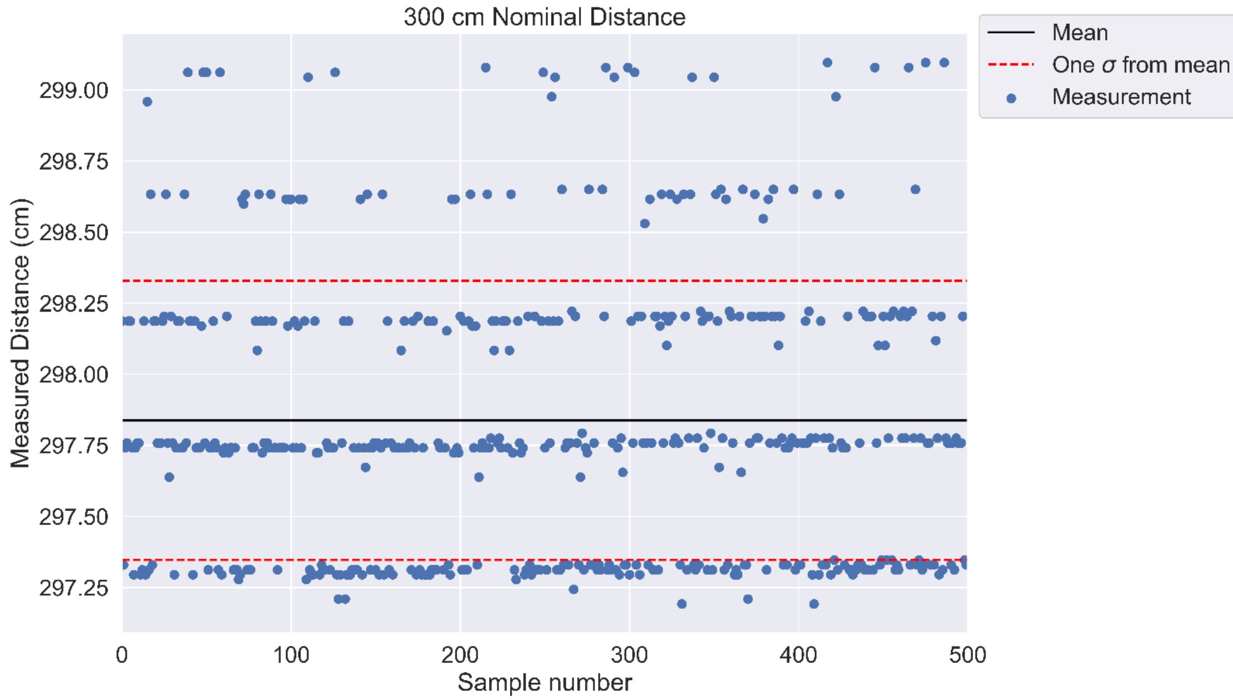

Figure 9 Measurement from 300 cm with bands forming at .4 cm.

Table 3 Summary statistics of each measurement range. Note that D is the distance and σ is the standard deviation.

D (cm)	Success rate	Mean (cm)	σ (cm)	Range (cm)	Min (cm)	Max (cm)
5	99.4%	5.28	0.05	.12	5.20	5.31
50	99%	50.63	.20	.86	50.20	51.06
100	99.4%	99.33	.65	2.28	98.36	100.64
150	98.8%	148.45	.41	1.77	147.92	149.69
200	98.6%	197.72	.37	1.51	197.24	198.75
250	99.6%	248.48	.47	2.21	247.56	249.77
300	100%	297.84	.49	1.90	297.19	299.10

V. Conclusion

The HC-SR04 is a cost-effective sensor that is suitable for sensing the distance to walls. For proper operation, the sensor must be mounted high enough off the ground to prevent the ultrasound from being reflected away from the receiver. The accuracy of the sensor is approximately within 1% but with poor repeatability. Any measurement to be used in mapping should be repeated and averaged.