Ultrasonic Sensor: Planning

The experimentation setup can be seen in figure 1. An object was placed in front of the ultrasonic sensor. The sensor was used to measure the distance to the object for all permutations between distance and the angles that can be seen in the illustration.
Note that the object would always be placed perpendicular to the centred measurement line.
The object in question is a firm pencil case.

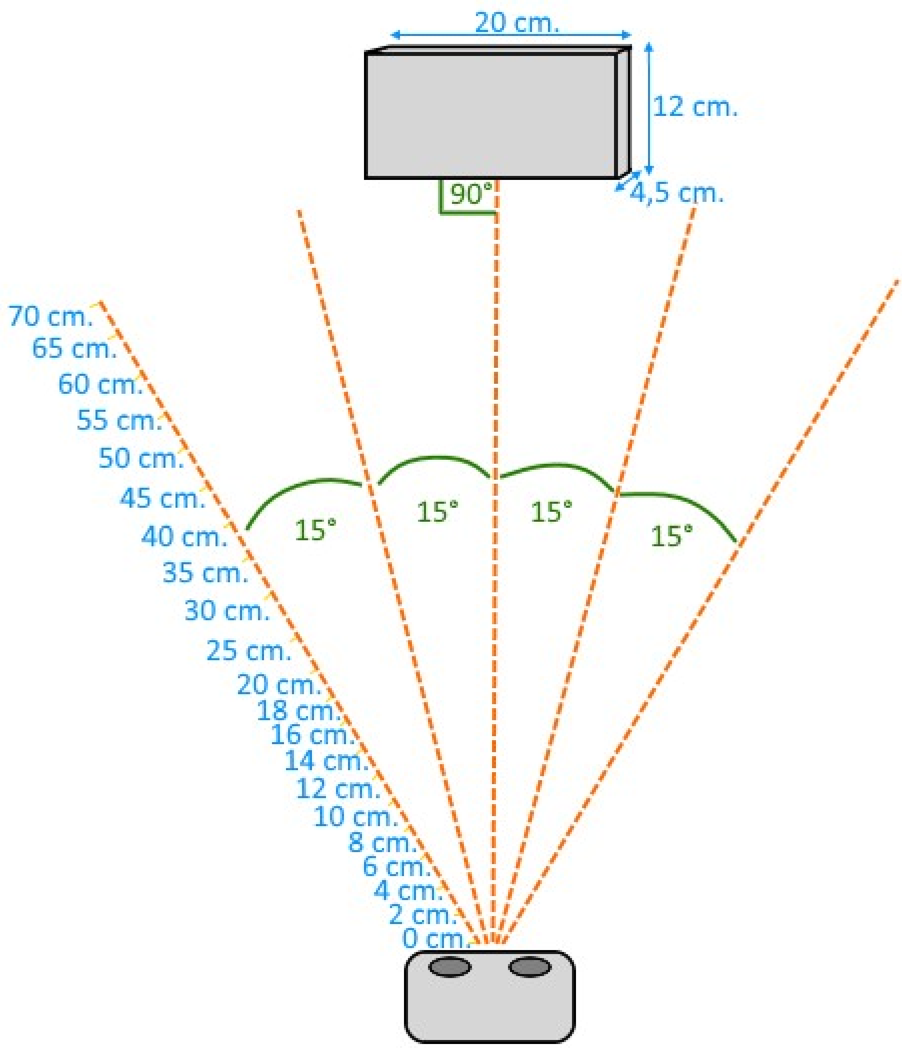

Figure 1: Testing of the ultrasonic sensor.

Ultrasonic Sensor: Hypothesis

The test is designed based upon reference [http://www.tik.ee.ethz.ch/mindstorms/sa_nxt/index.php?page=tests_us]. Similarly to their findings, our hypothesis is the following:

- The measurements of 0 and 2 cm. will likely result in a distance of 255, signifying incorrectly that there is no object within range.
- The most accurate measurements will be of the distances 4-15 cm. and 50-70 cm.
- The angled measurements will be less accurate than the centre one.
- Angled measurement accuracy will worsen more by distance than the centre one.
- Left angled measurements will be less accurate than right-angled measurements.

As specified by the datasheet [http://www.generationrobots.com/media/Lego-Mindstorms-NXT-Education-Kit.pdf, page 29], the sensor has an uncertainty of ±3 cm. So an additional statement for the hypothesis is:

- Measurements will at most be incorrect by 3 cm

Ultrasonic Sensor: Results

The results of the experiment are seen in figure 2. The colour of each cell represents the accuracy of the measured distance to the object compared to the actual distance, green meaning a measurement that fits the exact distance (within ±0,5 cm, as the measurements are integers), and red meaning a difference of 255 cm. The text is coloured blue whenever the results are within the uncertainty of ±3 cm. mentioned in the datasheet. Also, see figure 3 for a contour plot over the relative precision.

	Distance										
Degrees	0	2	4	6	8	10	12	14	16	18	20
-30	255	8	21	255	20	19	19	19	20	*21*	24
-15	255	6	*7*	10	14	19	17	19	20	*21*	*22*
0	255	6	*7*	*9*	*11*	14	16	*17*	*19*	*21*	*22*
15	255	7	*7*	*8*	*11*	19	*15*	*17*	20	*20*	*21*
30	255	6	*7*	10	*11*	255	*15*	18	20	*21*	*21*

Degrees	25	30	35	40	45	50	55	60	65	70
-30	29	*33*	*37*	*42*	*47*	*53*	255	255	69	255
-15	*28*	*32*	*36*	*41*	*46*	*52*	*57*	*63*	*67*	255
0	*26*	*31*	*35*	*41*	*46*	*51*	*56*	*61*	*66*	*72*
15	*25*	*30*	*35*	*39*	*45*	*51*	*56*	*61*	*67*	255
30	*25*	*30*	*35*	*41*	*46*	255	*57*	255	255	255

Relative Accuracy 0% — 100%

Figure 2: Results colored in regards to accuracy.

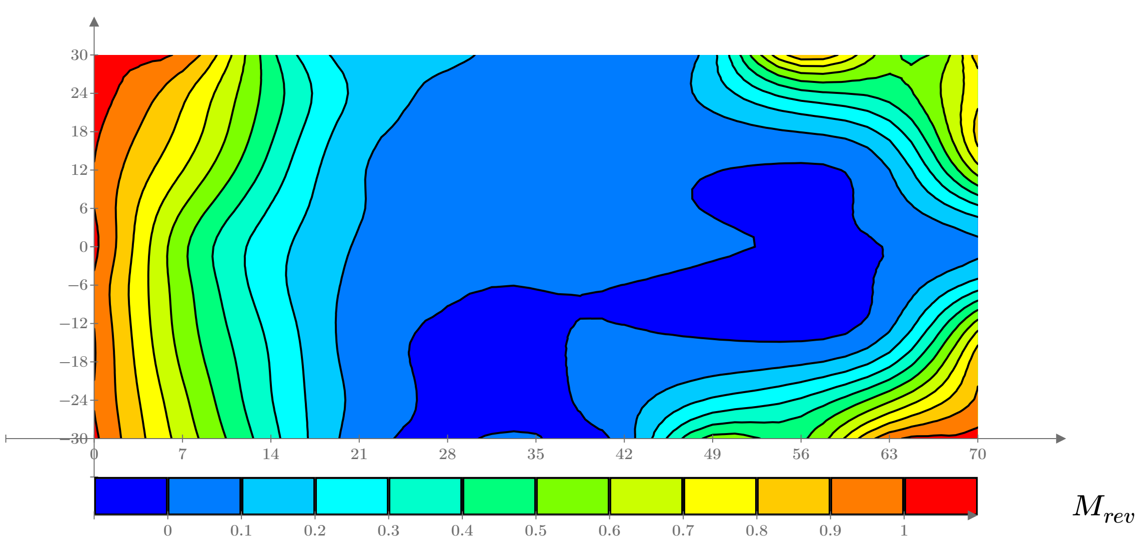

Figure 3: Contour plot with some values reversed due to program limitations. In truth the top of the y-axis is 30° left, bottom is 30° right. Red colour means a relative precision of 0%.

Ultrasonic Sensor: Discussion

- The measurements of 0 and 2 cm. will likely result in a distance of 255, signifying incorrectly that there is no object within range.
As expected, the 0 cm. measurement displays 255. Contrary to our expectations, however, the 2 cm. measurement does recognize the object being in range, though it only displays the result with an accuracy of 30%.

- The most accurate measurements will be of the distances 4-15 cm. and 50-70 cm.
See figure 4 for accuracy by distance. Contrary to the hypothesis, the range of 4-15 cm. has a low average accuracy of 61% while 50-70 cm. has 71%, both ranges being far from the most accurate. In comparison, the range of 16 to 55 cm. has an average accuracy of 91%, with no column average being any lower than 80%. Even more impressively, the range of 20-45 cm. has an average of 96% accuracy, with no column average being any lower than 90%. Neither of this fits the hypothesis, however, it can be explained by sensors deviating heavily from other sensors of the same kind.

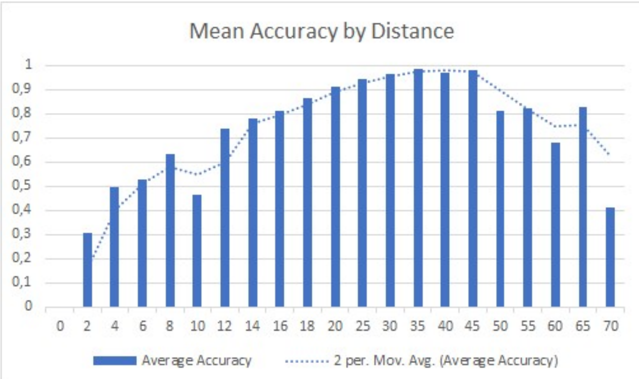

Figure 4: Graph of accuracy (as a decimal number) by distance

- The angled measurements will be less accurate than the centre one.
Figure 5 reveals that this part of the hypothesis was fully met.

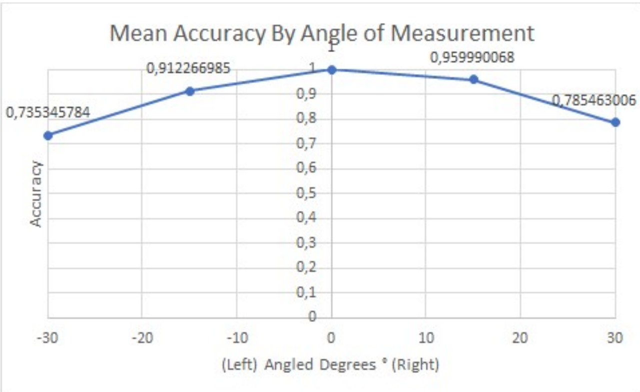

Figure 5: Graph of accuracy (as a decimal) by the angle of measurement.

- Angled measurement accuracy will worsen more by distance than the centre one.
Figure 6 shows a chart of the measurements compared to the ideal responses, which is useful for calibrating sensors, as per [https://cdn-learn.adafruit.com/downloads/pdf/calibrating-sensors.pdf, page 3]. The mapped functions are linear trendlines that have been calculated by

typing the measurements into Excel.

The ideal response is, of course, a one-to-one correspondence between the distance and the measurements. As such, the distance between each line and the optimal response function is the amount of precision error. Note that the first measurement (0 cm.) has been excluded for all trendline calculations, as we're interested in the change of error over distance, and a first invalid measurement would throw off the functions too much. The trendlines are below:

$f_{optimal}(x) := x$
$f_{l30}(x) := 2.3043\ x + 7.6486$
$f_{l15}(x) := 1.7699\ x - 10.169$
$f_c(x) := 0.9575\ x + 3.3422$
$f_{r15}(x) := 1.773\ x - 11.412$
$f_{r30}(x) := 3.142\ x - 10.002$

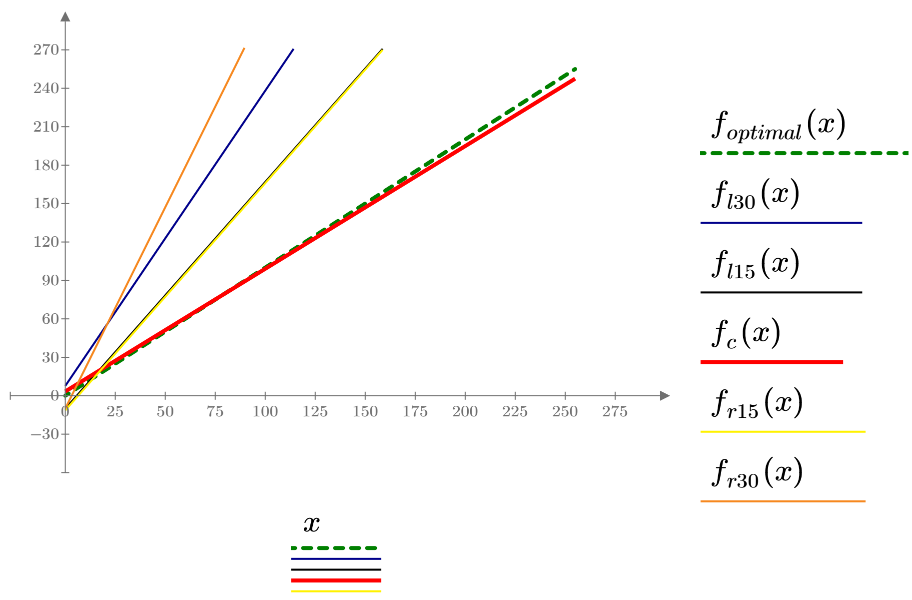

Figure 6: Chart showing the precision of the sensor, y being the measured result and x being the actual distance.

See figure 7 for the precision error by the sensor's distance from the object.

$$e_{l30}(x) := \int f_{l30}(x)\,\mathrm{d}x - \int f_{optimal}(x)\,\mathrm{d}x \rightarrow 0.65215 \cdot x^2 + 7.6486 \cdot x$$

$$e_{l15}(x) := \int f_{l15}(x)\,\mathrm{d}x - \int f_{optimal}(x)\,\mathrm{d}x \rightarrow 0.38495 \cdot x^2 - 10.169 \cdot x$$

$$e_c(x) := \int f_c(x)\,\mathrm{d}x - \int f_{optimal}(x)\,\mathrm{d}x \rightarrow 3.3422 \cdot x - 0.02125 \cdot x^2$$

$$e_{r15}(x) := \int f_{r15}(x)\,\mathrm{d}x - \int f_{optimal}(x)\,\mathrm{d}x \rightarrow 0.3865 \cdot x^2 - 11.412 \cdot x$$

$$e_{r30}(x) := \int f_{r30}(x)\,\mathrm{d}x - \int f_{optimal}(x)\,\mathrm{d}x \rightarrow 1.071 \cdot x^2 - 10.002 \cdot x$$

$$e_{r30}(x) := \int f_{r30}(x)\,\mathrm{d}x - \int f_{optimal}(x)\,\mathrm{d}x \to \text{[illegible]}$$

$$e_{optimal}(x) := \int f_{optimal}(x)\,\mathrm{d}x - \int f_{optimal}(x)\,\mathrm{d}x \to 0$$

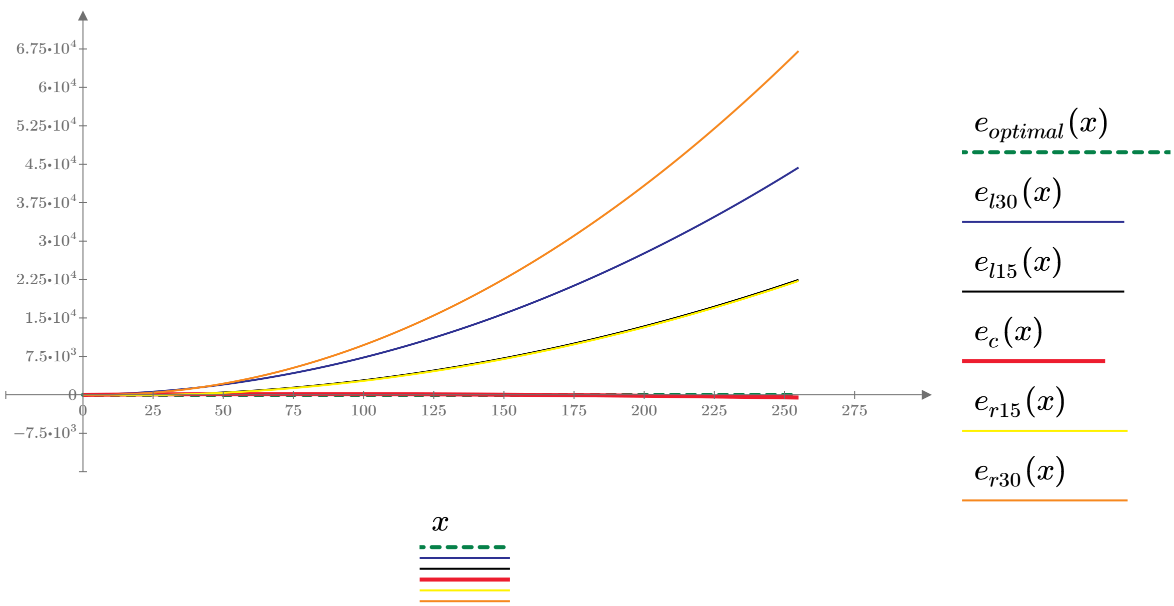

Figure 7: Chart showing sensor imprecision over distance.

The chart reveals that the centre function clearly is the least imprecise, followed by both 15° functions, followed by both 30° functions. All of this fits the hypothesis perfectly.

- Left angled measurements will be less accurate than right-angled measurements.
According to the source that the experiment was based on, the right eye of the ultrasonic sensor should be more accurate than the left one. Figure 5 shows this to be true for our measurements. However, figure 7 does not reflect this with regards to both the 30° and 15° measurements.

For the 30° measurements, the results are the opposite of the expected, while for 15° the differences between the two are negligible. As there is little consistency in these two results, we speculate this to be a result of the early, inconsistent blind spots throwing off the trendlines. To really figure out whether this result should be considered valid or not, we would need a much larger amount of measurements, covering the area much more tightly, as this would make the result less affected by any single blind spot. As a side note, however, our sensor appears to have fewer complete blind spots than the one used in the source, but it still is somewhat inconsistent.

- Measurements will at most be incorrect by 3 cm.
Figure 8 shows that this hypothesis is incorrect, and so is the claim from the datasheet. There is a non-negligible amount of measurements, even if one would discount the blind spots, which are imprecise.

By comparing figure 8 to figure 4, it can be seen that the two curves fit well except for the 4, 6 and 8 cm measurements being within the error margin. This, however, makes sense because the close measurements will show a higher accuracy deviance for smaller differences. This means that while we can measure close objects within the error margin, the results may not be very precise.

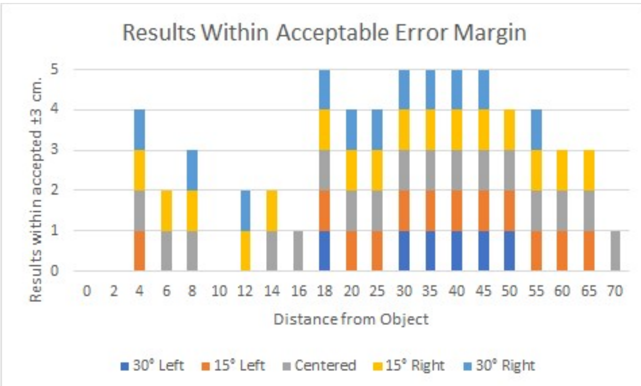

Figure 8: Chart showing whether results are within the error margin or not. Every 1 point on the y-axis is a TRUE value.

Ultrasonic Sensor: Conclusion

The ultrasonic sensor has inaccuracies that differ significantly from the sensor in the source, and the claims in the datasheet.

However this is not problematic per se, as many of these inaccuracies can be planned around, specifically because there are only very few complete blind spots in the measurements. To filter out the invalid measurements that do turn up, we could use the median of any series of measurements as the real result.

Beyond that, we can adjust the inaccurate sensor results of the early few centimetres to increase the precision.

If we intend to use the sensor for angled measurements, however, we should consider turning the sensor with a motor so it always faces the target head-on. The reason for this being that our angled measurement results appear too inconsistent to calibrate the sensor for.