Laboratory Experiment # 2
ME 303
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Sensor Calibration

Calibrating a Capacitive Proximity Sensor using a Custom Built Calibration Apparatus

ABSTRACT

A capacitivite proximity sensor was calibrated in the range of $0\,\mathrm{mm}$ to $3.5\,\mathrm{mm}$ using a custom calibration apparatus. After determining the linear range by visual inspection (0.70 to $2.70\,\mathrm{mm}$) a quartic transfer function was fit to the data. The 90% confidence interval for the transfer function was $\pm 4.58\,\mathrm{mV}$ ($t(\alpha = 0.95,\ \nu = 38) = 1.6849$). The sensor linearity was 0.36%.

INTRODUCTION

Proximity sensors are a type of transducer that converts position information into an electrical signal (Skoog et al., 2006). Typical applications include object detection, machine axis homing, and safety interlocks (Luo, 1996). Proximity sensors are based on many different measurement technologies, but roughly divided into categories by either analog or discrete outputs. Discrete proximity sensors simply detect whether or not a target is present whereas analog proximity sensors report the distance of the target. Proximity sensors are further categorized by their physical operating principles. Common proximity sensor types include inductive, capacitive, photoelectric, and ultrasonic. Each measurement technology has trade-offs in terms of measurement range, target material requirements, and cost.

The following report will focus on the application of a capacitive proximity sensor with a particular focus on the initial setup and calibration. Capacitive proximity sensors function by measuring changes in the permittivity of air (Funaley, 1965). Permittivity is a measure of how much charge a material accumulates in response to an applied electric field.

The head of a proximity sensor consists of two metallic plates that form a capacitor. The capacitance between these plates is governed by equation 1 (Funaley, 1965). As an object moves into the field of the sensor, the permittivity, k, increases because the target material is more polarizable than air. A micro-controller on the sensor continuously measures the capacitance of the plates, and produces a linearlized output. Unlike inductive proximity sensors, capacitive proximity sensors can detect both metallic and non-metallic targets.

$$C = \frac{k\varepsilon_o A}{d} \tag{1}$$

where:
C = plate capacitance (F)
k = dialectric between plates
ε_o = permeability of free space
A = plate area (m^2)
d = plate separation (m)

Sensor calibration is the process of developing a transfer function that converts the voltage output of a sensor to a meaningful engineering unit (i.e. distance). Generally, sensors are designed such that the output is linear (Dally et al., 1993). To calibrate a sensor, an apparatus is used to set known values for the measured engineering parameter, and then the parameter is swept across the linear region while taking voltage measurements. A polynomial fit is used to characterize the sensor response.

EXPERIMENTAL METHODOLOGY

A proximity sensor (Bently Nevada 3300 XL 5/8 mm Proximitor Sensor; Part# 330180–10–00) was inserted into the calibration apparatus show in figure 1. The apparatus was calibrated by setting the micrometer to $0\,\mathrm{mm}$ and sliding the sensor forward until it just touched the steel target before tightening the sensor mounting nuts. The sensor was provided $-19.01\,\mathrm{V}$ using a lab power supply (BK Precision 9110) and read using a hand-held multimeter (Mastech). The micrometer was used to move the sensor away from the steel target, and a voltage reading was taken every $50\,\mu\mathrm{m}$ up to $3.5\,\mathrm{mm}$.

A calibration was performed by first determining the linear range of the sensor, and then applying a polynomial fit between the distance and voltage data. The polynomial fit was overlaid the original data along with a residual plot and a histogram of the residuals. The goodness of fit was determined by checking that the residuals were normally distributed and did not correlate with target position.

The sensor precision was determined by finding the mean deviation between the measured position, and the position predicted by the fitted transfer function (Equation 2). The linearity of the sensor was determined by fitting a straight line through the endpoints of the linear region, and finding the deviation from this line at the midpoint of the linear region. This was reported as percentage of the full linear voltage range of the sensor.

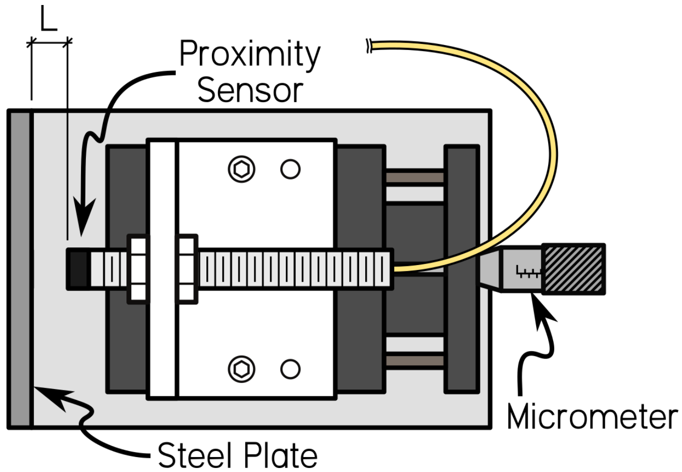

Figure 1: The sensor calibration apparatus consisted of a proximity mounted to an aluminum L–channel such that the sensor pointed at a large steel target (plate). The distance from the tip of the sensor to the steel plate, ℓ, could be precisely set by adjusting the micrometer.

$$\sigma = \frac{\sum |f(v_i) - x_i|}{n} \tag{2}$$

where:
- σ = sensor precision (mm)
- f = polynomial transfer function
- x_i = measured distance (mm)
- v_i = measured voltage (V)
- n = number of samples

RESULTS AND DISCUSSION

The proximity sensor produced a linear voltage regards with to target position (Figure 2). The sensor calibration was robust against changes in supply voltage within the specified operating range (i.e. $-18\,\mathrm{V}$ to $-20\,\mathrm{V}$). The linear range was determined by visual inspection, and a polynomial fit was applied to the data (Figure 2).

A quartic fit was chosen to calibrate the proximity sensor because it was the lowest order fit to produce normally distributed residuals that did not correlate with target position (Figure 3). The residuals grow quickly just outside of the shaded linear region for all fits (Figure 3). Chauvent's criterion (Equation 3) was used to identify outliers from the sample (Dally et al., 1993). The standard deviation over the chosen linear region was $\sigma_d = 2.72\,\mathrm{mV}$, and the critical deviation ratio was set to $DR_o = 2.498$ based on the sample size ($n = 40$). Based on calculated sample z-scores (Equation 4, Table 2), no samples meet the criteria for removal.

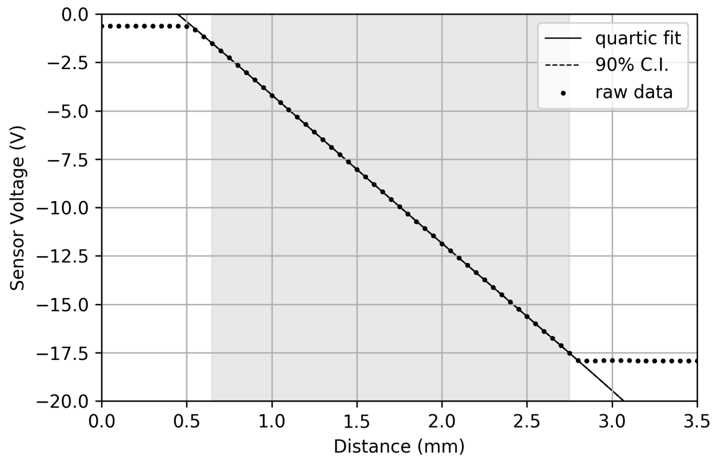

Figure 2: The relationship between sensor voltage and target position for a capacitive proximity sensor. The linear region was chosen by visual inspection to be the interval $(0.65\,\mathrm{mm}, 2.75\,\mathrm{mm})$(shaded area). A quartic fit was applied within this region ($V(x) = -0.066x^4 + 0.471x^3 - 1.139x^2 - 6.559x + 3.115$ where x is in mm and V in volts), and the $\pm 90\%$ confidence bands are shown as barely visible dashed lines.

$$\sigma_d = \sqrt{\frac{\sum_{i=1}^{n}(\delta_i)^2}{n-1}} \tag{3}$$

where: δ_i = individual fit residual (V)
n = number of samples

$$Z = \frac{\delta_i - \bar{x}}{\sigma_d} \leq DR_o \tag{4}$$

where: δ_i = individual fit residual (V)
$\bar{x}$ = mean of the residuals (V)
σ_d = standard deviation of residuals (V)
DR_o = Chauvent's exclusion criteria

The 90% confidence interval was $\pm 4.58\,\mathrm{mV}$ using the Student's t-distribution ($\alpha = 0.95$, $\nu = n - 2 = 38$, $t(\alpha, \nu) = 1.6849$; Python Numpy v1.14.2). The confidence interval was then fit over the sample data using equation 5. The linearity over the linear region was 0.36%.

$$V = \sum_{i=0}^{4} \left[C_i x^i\right] \pm t(\alpha,\, \nu)\sigma_d \tag{5}$$

where:
C_i = i-th degree fitting coefficient
x = sample position (mm)
t = Student's t-distribution coefficient
α = confidence interval alpha level
ν = degrees of freedom
σ_d = sample standard deviation

The fitted quartic transfer function relating voltage to target position is given by equation 6.

$$\begin{aligned} V = &- 0.066x^4 + 0.471x^3 \\ &- 1.139x^2 - 6.559x + 3.115 \end{aligned} \tag{6}$$

where:
V = sensor output (V)
x = target position (mm)

From the calculations above, it is clear that the sensor is unusually precise within its linear region; however, its application is limited by the fact the linear region is only $2\,\mathrm{mm}$ wide. This makes the particular sensor a useful tool in discrete object detection, or homing applications where a precise, repeatable target position is begin determined. Before using this sensor in such an application, an engineer would want to perform further studies on measurement repeatability to ensure the calibration is the same on subsequent target distance sweeps and that the calibration of the sensor does not drift with time or dirt (e.g. oxidation on the target).

CONCLUSIONS

At target distances between $0.65\,\mathrm{mm}$ and $2.75\,\mathrm{mm}$ the proximity sensor produced a very linear plot. Outside the linear region, the sensor produced either a constant high ($-0.62\,\mathrm{V}$) or low ($-17.93\,\mathrm{V}$) voltage signal. A quartic (fourth order) equation was chosen to represent the transfer function of the sensor, because it was the lowest order equation to produce normally distributed residuals that did not correlate with sensor position (Equation 6). The 90% confidence interval ($t(\alpha = 0.95,\, \nu = 38) = 1.6849$) was $\pm 4.58\,\mathrm{mV}$.

ACKNOWLEDGEMENTS

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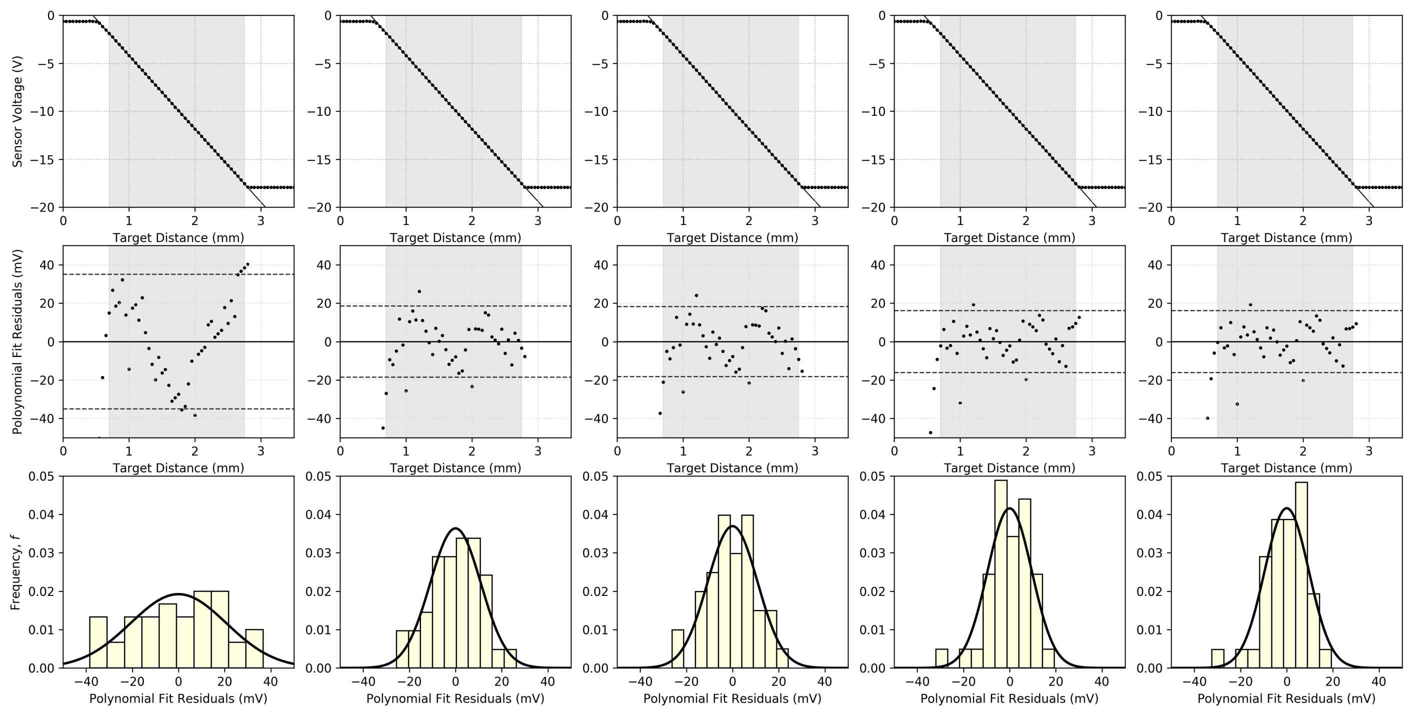

Figure 3: Polynomial fits of increasing order of proximity sensor voltage and target position data (top, left to right, linear to quintic). Residual plots for each fit (middle) and normalized histograms of residuals (bottom) with fitted Gaussian normal probability curves (black line). Shaded region represents the chosen linear region ($0.65\,\mathrm{mm}$ to $2.75\,\mathrm{mm}$). Dashed linear indicate 90% C.I. for each polynomial fit on residual plots. The quartic fit (4th to right) was the lowest order fit to produce uncorrelated, normally distributed residuals.

REFERENCES

Dally, J. W., Riley, W. F., and McConnel, K. G. (1993). *Instrumentation for Engineering Measurements*. John Wiley and Sons, New York, NY, 2th edition.

Funaley, S. L. (1965). Capacitive proximity sensor.

Luo, R. C. (1996). Sensor technology and microsensor issues for mechatronics. *ASME Transactions on Mechatronics*, 1(1):39–49.

Skoog, D. A., Holler, F. J., and Crouch, S. R. (2006). *Principles of Instrumental Analysis sixth edition*. Brooks Cole, 6th edition.

APPENDIX A
RAW SENSOR DATA

The following is a listing of the raw data collected during the experiment. Again, a digital, `*.csv` can be found on `www.github.com/mmolter/ME303`.

x (mm)	v (V)	x (mm)	v (V)	x (mm)	v (V)	x (mm)	v (V)
0.00	-0.62	1.00	-4.21	2.00	-11.87	3.00	-17.91
0.05	-0.62	1.05	-4.56	2.05	-12.22	3.05	-17.91
0.10	-0.62	1.10	-4.94	2.10	-12.60	3.10	-17.91
0.15	-0.62	1.15	-5.33	2.15	-12.98	3.15	-17.92
0.20	-0.62	1.20	-5.70	2.20	-13.35	3.20	-17.92
0.25	-0.62	1.25	-6.10	2.25	-13.73	3.25	-17.92
0.30	-0.62	1.30	-6.49	2.30	-14.12	3.30	-17.93
0.35	-0.62	1.35	-6.88	2.35	-14.50	3.35	-17.93
0.40	-0.61	1.40	-7.27	2.40	-14.88	3.40	-17.93
0.45	-0.62	1.45	-7.64	2.45	-15.25	3.45	-17.93
0.50	-0.65	1.50	-8.03	2.50	-15.64	3.50	-17.93
0.55	-0.81	1.55	-8.41	2.55	-16.01		
0.60	-1.16	1.60	-8.80	2.60	-16.40		
0.65	-1.52	1.65	-9.19	2.65	-16.76		
0.70	-1.89	1.70	-9.57	2.70	-17.14		
0.75	-2.26	1.75	-9.95	2.75	-17.52		
0.80	-2.65	1.80	-10.34	2.80	-17.90		
0.85	-3.03	1.85	-10.72	2.85	-17.93		
0.90	-3.40	1.90	-11.09	2.90	-17.92		
0.95	-3.80	1.95	-11.46	2.95	-17.91		

Table 1: Complete listing of raw sensor calibration data. Complete dataset available in digital form on `www.github.com/mmolter/ME303`

APPENDIX B
CALCULATIONS AND CODE

All calculations and plots were perfomed in Python. A Jupyter Notebook explaining the analysis, along with an electronic copy of this report, can be found on `www.github.com/mmolter/ME303` within three days of submission.

Position (mm)	Voltage (V)	f(x) (V)	δ_i (V)	Z-score
0.70	-1.89	-1.889	0.001	-0.121
0.75	-2.26	-2.267	0.007	0.847
0.80	-2.65	-2.647	0.003	0.071
0.85	-3.03	-3.028	0.002	0.242
0.90	-3.40	-3.411	0.011	1.358
0.95	-3.80	-3.794	0.006	-0.363
1.00	-4.21	-4.178	0.032	-0.308
1.05	-4.56	-4.563	0.003	-0.022
1.10	-4.94	-4.948	0.008	0.149
1.15	-5.33	-5.333	0.003	-0.627
1.20	-5.70	-5.719	0.019	0.490
1.25	-6.10	-6.105	0.005	-1.232
1.30	-6.49	-6.491	0.001	-1.331
1.35	-6.88	-6.876	0.004	-0.556
1.40	-7.27	-7.262	0.008	0.220
1.45	-7.64	-7.647	0.007	-0.897
1.50	-8.03	-8.031	0.001	-0.121
1.55	-8.41	-8.416	0.006	-0.292
1.60	-8.80	-8.800	0.000	0.484
1.65	-9.19	-9.183	0.007	1.259
1.70	-9.57	-9.566	0.004	1.088
1.75	-9.95	-9.948	0.002	0.918
1.80	-10.34	-10.329	0.011	1.693
1.85	-10.72	-10.710	0.010	1.523
1.90	-11.09	-11.091	0.001	0.406
1.95	-11.46	-11.471	0.011	-0.710
2.00	-11.87	-11.850	0.020	1.957
2.05	-12.22	-12.229	0.009	-1.051
2.10	-12.60	-12.608	0.008	-1.222
2.15	-12.98	-12.986	0.006	-1.392
2.20	-13.35	-13.364	0.014	-0.829
2.25	-13.73	-13.741	0.011	-0.659
2.30	-14.12	-14.119	0.001	-1.434
2.35	-14.50	-14.496	0.004	-1.264
2.40	-14.88	-14.874	0.006	-1.093
2.45	-15.25	-15.251	0.001	0.023
2.50	-15.64	-15.629	0.011	-0.752
2.55	-16.01	-16.008	0.002	0.364
2.60	-16.40	-16.387	0.013	-0.411
2.65	-16.76	-16.767	0.007	1.651
2.70	-17.14	-17.148	0.008	1.822

Table 2: Polynomial fit over the determined linear region according to equation 6. No data points within the linear region could be removed using Chauvent's criterion for two dimensional data.