Koç University
College of Engineering
Department of Electrical & Electronics Engineering

ELEC 390 - Independent Study
Week – 1: Advanced Sensor Introduction
Kaan Ataberk Yılmaz - 0069511
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1: Introduction

First week of the independent study involved an reminder of the material covered in ELEC – 390: Sensors course of the instructor as the independent study is based on the follow up ELEC – 440: Advanced Sensors course. Main topics of the week were:

- Sensitivity & Specificity
- Error Types
- Noise Types
- Signal to Noise Ratio
- Calibration
- Dynamic Range
- Operational Modes

2: Definitions

2.1: Sensitivity & Specificity

Sensitivity and specificity are mathmetically related terms that together provides the measurement of the accuracy of a test, in this case the sensor output, where sensitivity is the rate of true positives to all positive results and specificity is the rate of true negatives to all negative results. In most cases achieving a high sensitivity and specificity may prove challenging or impractical. In such cases where a decision between sensitivity and specificity has to be made, response to the sensor output is the main point of consideration. If failure to respond to the sensor output has serious consequences, such as a fire sensor, then the device should aim for higher sensitivity either by reducing the amount of false positivies or increasing the number of true positives. However, if the inverse is true where a lack of response due to a false negative has serious consequences, such as a carbon monoxide sensor, then the device should aim for higher specificity.

Calculating the Sensitivity and Specificity of a given device is rather straightforward, all that is required is the confusion matrix for the sensor with a large enough sample size [2].

Table I: An Arbitrary Confusion Matrix

	True	False
Positive	27	16
Negative	183	1280

From Table – 1 We can calculate

$$Sensitivity = \frac{True\ Positives}{All\ Positives} = \frac{27}{210} = 12.2\,\%$$

$$Specificity = \frac{True\ Negatives}{All\ Negatives} = \frac{1280}{1296} = 98.7\,\%$$

and determine that this arbitrary sensor is highly specific and should be used in conditions where the positive results require immediate attention.

2.2: Error Types

An variable that affects the sensitivity and specificity therfore the accuracy of a sensor is system error, otherwise known as bias, is the mismatch between the input and output of the sensor. The primary cause for bias is miscalibration of the sensor either by the manufacturer or by the user as the process of calibration is done by applying a bias to the sensor to correct the reported value to the actual one, depending on the sensor type calibration at regular intervals may be required as the components age.

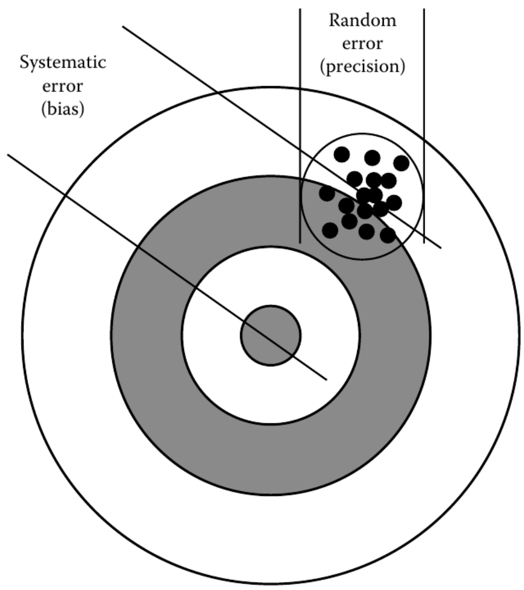

Figure I: Target Analogy for Error Types

Various other causes for systemic error exists such as invasiveness where the physical interaction of the sensor with the measured subject could effect the measurement, such as a thermometer that is changing the subjects temperature due to temperature difference between the thermometer body and the subject. Errors can also happen due to the end user of the device misreading the results, while these can be counted as systemic errors they occur on only on extreme cases. [1, p 29]

2.3: Noise Types

In the event that systemic errors are remedied completely from the system where it is fully calibrated, non-invasive and used in a proper fashion, there will still be a random amount of error present within the sensor output. This error is referred to as noise and originate from three primary sources throught the measurement system, these are, envinroment that the sensor is in, noise level of the sensor itself and the noise that occurs as the signal transmits through the connections of the device. While there are methods to combat the noise sources such as conducting measurements in isolation to prevent envinromental noise, such as a sound-proofed rooms for audio sensing or minimizing the sensor noise such as cooling infrared sensors to reduce thermal noise and finally properly designing and grounding trasmission lines. While these interventions are cheap and effective, given that sufficient data and proccessing power is available for signal processing methods prove to be a better solution to noise as it can be applied to all noise sources either individually or collectively. [1, p 30]

2.4: Signal to Noise Ratio (SNR)

As the noise that a system experiences behaves randomly, it becomes impractical to quantify noise as the sum of all noise sources on the system, therefore the the comparison between the power of the signal to the power of the noise otherwise known as Signal to Noise Ration is used when quantifying the amount of noise a system experiences, using this ratio not only allows engineers to locate and target noisier components, it also allows the analysis of systems that manipulate the signal and the noise together, such as amplifiers.

The most commonly used and the easiest way of measuring the SNR of a given device is to record the sensor output in a steady state to calculate the mean and the standard deviation of the sensor output. Since random noise exhibits a gaussian behaviour standard deviation provides a good approximation of the sensor noise. With the signal and noise powers recorded one can calculate the SNR with the formula

$$SNR = \frac{P_{SIGNAL}}{P_{NOISE}}$$

Where P_{SIGNAL} and P_{NOISE} are the average power of both the signal and the noise recorded within the same interval. However, since most sensors posess a wide dynamic range decibel is used for representation of SNR with the formula.

$$SNR_{dB} = 10 \log_{10}\left(\frac{P_{SIGNAL}}{P_{NOISE}}\right)$$

2.5: Calibration

The term Calibration refers to the relation between the physical effects that the sensor receives as its input and the output signal that it provides in turn. The calibration of a device is done by applying known set of inputs to the device and recording the output to create a calibration curve. Where the slope of the curve is the sensitivity of the sensor as shown in figure II. However, sensitivity in this context refers to the amount of change on the output signal compared to the change on the physical input to the sensor and should not be confused with the true positive rate of the sensor. [1, p 27]

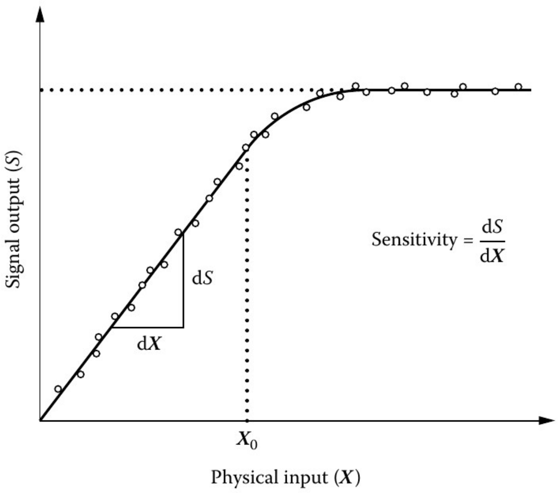

Figure II: An Arbitrary Calibration Curve

2.6: Dynamic Range

The Dynamic Range of a sensor refers to the range between the maximum and the minimum input that can be measured in a reliable and consistent fashion. Calibration and the SNR of the sensor are the 2 major factors affecting the dynamic range where a well calibrated, therefore a highly sensitive, sensor would be able to measure a wider range of inputs than a badly calibrated one. However, beyond a certain sensitivity the noise floor of the sensor or the envinroment will always be higher than the signals that can be measured resulting in narrowed dynamic range for the sensor. As seen in Figure II the sensor can reliably measure until the input reaches X_0 at which point the sensor saturates and becomes less sensitive to input changes. And the difference between X_0 and 0 denotes the dynamic range of this sensor

2.7: Operational Modes

The operational mode refers to the techniques that are utilized by the sensor to measure the properties of a given measurand. Two prominent operational modes are Null and Deflection Instrument modes, these two modes strike a balance between them that allows them to cover a wide range of cost, accuracy, speed and size limitations. [1, p 33]

2.7.1: Null Instrumentation

The null measurement method operates by nullifying the unknown effect of the measurand on the sensor by applying a known counteractive effect on it. Null instruments commonly achieve this in an iterative process to reach equilibrium using a comperator. The advantages of using a null instrument include the isolation of the measurand from the instrument itself along with the iterative process allows the instrument to reach high levels of acccuracy. However, the strengths of the null instruments also create some of its shorcomings where the iterative process takes exponentially longer to complete as the accuracy target increases and the isolation of the measurand considerably increase the size of the device compared to deflection instruments. [1, p 33]

2.7.2: Deflecion Instrumentation

The deflection method instruments posess a steady state of their own with no external effect on them, this allows the measurand to create a deflection from the steady state, the magnitude of which can create a signal output, which in turn can be conditioned to create the readout of the sensor, this allows deflection devices to be fast, cheap and compact. Although, deflection devices are less accurate compared to null devices, comperable levels of accuracy can be achieved by deflection instruments given that cost is not a limiting factor. Another major advantage of the deflection instrument is the ability to perform dynamic measurements, however, this comes with the shortcoming of loading error where due to the sensors interaction with the measurand the measured property often gets affected by the measurement creating an error. [1, p 35]

3: Datasheet Examples

3.1: NTC Thermistor Calculations

NTC thermistors often possess a non-linear temperature-resistace curve which is calculated with a polynomial formula the constants of which are defined by the properties of the sensor and presented on the datasheet by the manufacturer. With the example datasheet from Vishay BC the temperaure can be found by inputting the measured resistance to the given formula.

$$T_{(R)} = \left(A_1 + B_1 \ln\left(\frac{R}{R_{Ref}}\right) + C_1 \ln^2\left(\frac{R}{R_{Ref}}\right) + D_1 \ln^3\left(\frac{R}{R_{Ref}}\right) \right.$$

Where A, B, C, D are the component specific constants and R_{Ref} is the Thermistor resistance at 25°C, by inputting the measured resistance R of the thermistor, usually done with a voltage divider, the temperature of the sensor can be calculated.

There also exists an output error in NTC thermistors where deviations from the expected resistence of the sensor occur as a function of the ambient temperature, this error can be estimated with the formula provided by the manufacturer

$$Z = \left[\left(1 + \frac{X}{100}\right) \times \left(1 + \frac{Y}{100}\right) - 1 \right] \times 100$$

and

$$\Delta T = \frac{Z}{TCR}$$

Where X, Y and TCR are the manufacturer provided tolerance specifications for the reference resistance, B value and temperature coefficients respectively. With these two formulas the sensor output can be converted to a temperature value with a uncertainty margin.

3.2: Dynamic Range & Sensitivity Relation

BMI270 or similar devices with a built-in Analog to Digital Converter (ADC) with selectable ranges are a great example to help understand the relation between dynamic range and sensitivity. While ADCs will be explored in greater detail in the future, for our purposes ADCs help process analog signals by assigning equally spaced binary reference points to represent the magnitude of a signal. The more reference points can be placed in a linear scale, the more sensitive the ADC output becomes as each bit represents less change in the sensor measurement. The built-in ADC of the BMI270 has a 16-Bit resolution meaning it has $2^{16} = 65536$ available points to place along the analog output range of the sensor. The measurement range of the sensor can also be configured to the selection of $\pm 2g, \pm 4g, \pm 8g, \pm 16g$.

At $\pm 2g$ setting, the sensor has the dynamic range of

$$\left(+2g \cdot 9.81\, m/s^2\right) - \left(-2g \cdot 9.81\, m/s^2\right) = 39.24\, m/s^2$$

At this range the 16-Bit ADC can measure down to

$$39.42\, m/s^2\; 65536\, Bits = 6 \times 10^{-4}\, m/s^2/bits$$

At $\pm 16g$ setting, the sensor has the dynamic range of

$$\left(+16g \cdot 9.81\, m/s^2\right) - \left(-16g \cdot 9.81\, m/s^2\right) = 313.92\, m/s^2$$

At this range the 16-Bit ADC can measure down to.

$$313.92\, m/s^2\; 65536\, Bits = 4.7 \times 10^{-3}\, m/s^2/bits$$

as can be seen with the ADC being the limiting factor the sensitivity of the device diminishes as the dynamic range increases.

3.3: Calibrating Pressure Sensors

Pressure sensors are rather sensitive to the external stress sources to the point where the manufacturers often recommend recalibrating the sensors after mounting due to the stress induced from soldering or the adhesives used. Along with periodic recalibrations throught the sensors lifetime due to aging and environmental exposure. Fortunately however, pressure sensors are often linear, therefore, these errors can be fixed with a simple offset value without affecting the dynamic range of the sensor.

To recalibrate the sensor first we need to know its output, the transfer function of which can be found in the sensor datasheet.

$$P_{Mes} = \frac{(Output_{max} - Output_{min}) * (P_{max} - P_{min})}{Output_{max} - Output_{min}} + P_{min}$$

where:
Output = Pressure reading from the sensor.
Outputmin = Ideal output at minimum pressure.
Outputmax = Ideal output at maximum pressure.
Pmin = Minimum operating pressure.
Pmax = Maximum operating pressure.
Pmes = Measured pressure

Which can be retrieved from the sensor datasheet

With the transfer function we can subject the sensor to a known pressure and compare it with the sensor output to get the offset.

$$Offset = Measured\ Pressure - Applied\ Pressure$$

Which can be applied to any future measurements

$$Corrected\ Output = Measured\ Output + Offset$$

4: Conclusion

First week of the independent study focused on the common properties of sensors that are used to measure the quality of devices such as the SNR, error rate and dynamic range, these metrics are crucial for engineers when designing sensing systems to choose the correct sensor packages for the desired levels of accuracy, these concepts will prove useful in the following weeks where when discussing sensors that use different methods for measuring the same property.

References

[1] J.G. Webster ed., The Measurement, Instrumentation and Sensors Handbook, CRC Press, 1999, ISBN: 084932145X

[2] Tharwat, A. (2021), "Classification assessment methods", Applied Computing and Informatics, Vol. 17 No. 1, pp. 168-192. https://doi.org/10.1016/j.aci.2018.08.003