Adesto

Technical Note

SmartEdge^{TM} Platform – Sensor non-idealities

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Contents

Introduction

Sensors are the fundamental elements of data acquisition driving the growth of Internet of Things (IoT). The sensor is the transducer which converts a physical quantity such as temperature or pressure into an electric quantity. This electric quantity is sometimes a voltage or current, but is often a resistance or capacitance. The incremental changes in these electric quantities need to be conditioned and processed to give a voltage signal suitable for quantization by an ADC. Additional processing such as linearization of the measurement data enhances measurement accuracy. The digitization of the sensor measurement data is the key to the control and communication intensive world of IoT.

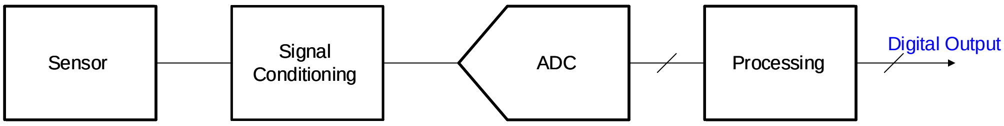

Figure 1: Sensor Front-end Signal Chain

In this technical note we look at the sensor itself and some of the non-idealities and trade-offs which influence the design of the front-end of the signal processing chain.

Sensor non-idealities and trade-offs

The ideal sensor would produce an electric signal that is directly proportional to the physical quantity that is being measured, that is it would have a linear transfer function. Ideally it would possess a sensitivity that would result in an output signal whose range would match the input range of the ADC. Its output would respond instantaneously to changes in the quantity being measured. In addition, it would give the exact same output for a given input when measurements are repeated and previous measurements would not affect successive measurements. This ideal sensor does not exist however and in designing a signal chain to capture the measurement of a physical quantity it is important to be aware of the constraints of sensors and how this impacts the requirements of the signal processing chain to be designed. Here we consider several of the innate constraints of real-world sensors.

Range

Every sensor is bounded by maximum and minimum values of the physical quantity it is designed to measure. For example, a flow meter application may require that the flow be measured accurately from a very low flow rate in the order of litres per hour up to high flow rates of thousands of litres per hour. The sensor must be capable of producing a usable electric output over the full measurement range. These minimum and maximum bounds within which the physical quantity can be measured accurately define the range of the sensor.

For a given application the required measurement range may dictate the type of sensor to be used. For example, temperature measurement in a smartphone or wearable application could use a Silicon-based IC temperature sensor with a typical range of -40^{o}C to 125^{o}C while an industrial application with temperatures of potentially up to hundreds of degrees will require a sensor with a much higher temperature range, for example an RTD (Resistance Temperature Detector) or a thermocouple.

In some cases, exceeding the specified range of a sensor may result in permanent damage to the sensor. Yet within the safe operating range of the sensor there is often a trade-off between the accuracy and the range. Figure 2 shows the characteristic curve of a typical sensor, in this case output voltage versus input measurement quantity. It is clear that as the input measurement quantity increases or decreases the output voltage becomes less linear as a function of the input and eventually saturates. In this case reducing the input range used in the application enhances the linearity of the sensor. Conversely, it more difficult to design an accurate sensing system over a larger input range.

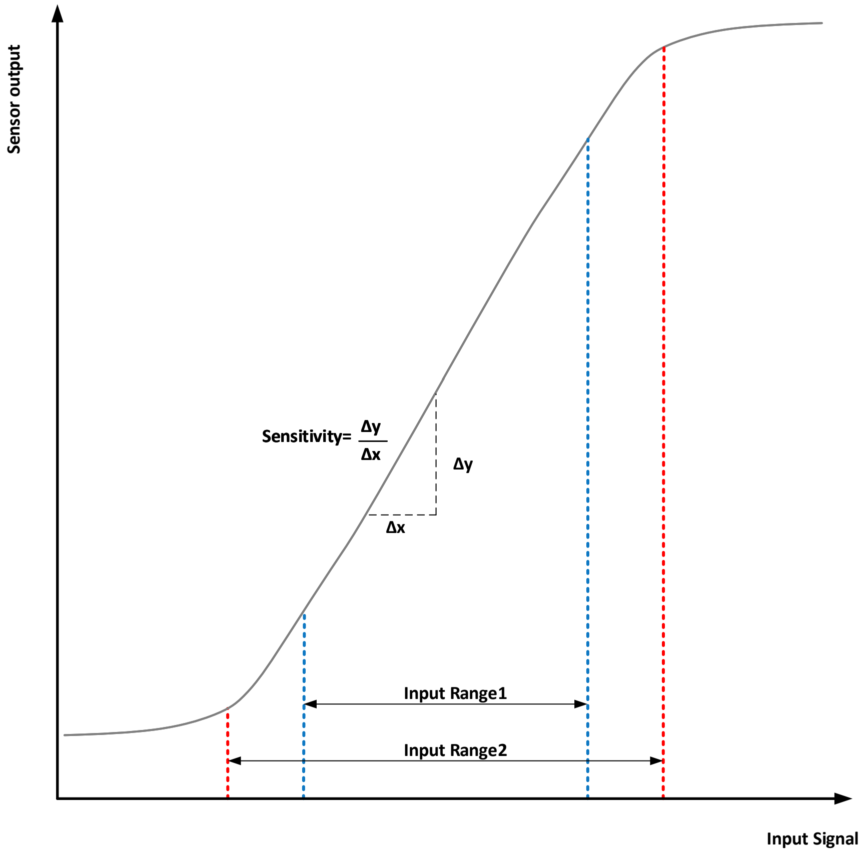

Figure 2: Input Range, Sensitivity

Resolution

Resolution is the minimum detectable change of the input physical quantity which can be detected at the output. It is fundamentally determined by the noise level in the system. This noise could be of the input signal itself or of the sensor, or the noise floor of the full signal chain to digitized output. The resolution of the measurement system can also be limited by the resolution (number of bits) of the ADC but only if the quantization noise of the ADC is the dominant noise in the signal chain.

Precision

The degree of reproducibility of a sensor's measurement defines its precision. A precise sensor would always give the same output for a given input signal. In reality the precision is affected by the random noise of the sensor and of the signal processing chain as this noise will be superimposed on the measurement. Precision is also impacted by sensor hysteresis.

Precision is often confused with accuracy – how close the measured value of the physical quantity is to the actual value. For example, if the RH is stable at 70% and a humidity sensor indicates the humidity to be 64%, 65% and 66% over three successive measurements, this is considered more precise than a sensor that gives 67%, 70% and 73%, even though the latter sensor is closer to the actual value.

Accuracy

The accuracy of a sensor is how close it is to the actual value. A more precise definition is the maximum deviation of the measured output indicated by the sensor compared to the actual value. The accuracy of a sensor depends of course on other non-idealities – resolution, precision, linearity. If the inaccuracy of a sensor can be determined by comparing its outputs with a set of reference measurements this opens the way to calibrate the sensor to improve its accuracy.

Sensitivity

The sensitivity of a sensor is defined as the change in sensor output signal for a given change in the input quantity being measured. Alternatively, it can be defined as the slope of the characteristic curve as shown in Figure1. For example, a PT100 RTD has a sensitivity of about 0.4 $\Omega/^{o}C$ at $0^{o}C$. If this change in resistance is converted to a more usable voltage signal by driving it with a constant current of 1mA, then the sensitivity of the sensor could also be defined as $0.4mV/^{o}C$.

From Fig 1 it is also clear that the sensitivity of a sensor may vary over its input range depending on the linearity of the sensor and that for input signals towards and beyond the input range sensitivity decreases and eventually saturates where there is no change in output voltage for a change in the input quantity being measured.

In general, a sensor with a low sensitivity is more difficult to incorporate in a measurement system. If the temperature sensor with a sensitivity of $0.4mV/^{o}C$ is used in an application with a temperature range of 100°C it would require a gain of 25 to map to a typical ADC input range of 1V, whereas a sensor with a lower sensitivity would require a commensurately higher gain and lower noise floor.

Linearity

A linear sensor is one where the output is directly proportional to the input i.e. where the characteristic curve is a straight line. All sensors are non-linear to some degree and the deviation of the characteristic from the straight line introduces errors in the measurement if a linear response is assumed.

The errors introduced by sensor nonlinearity can be minimized by calibrating the sensor. Calibration requires performing one or more relatively more accurate measurements which produce a set of reference output values for known input values. Each reference output can be compared with the actual raw sensor output and the deviation from the reference output calculated and a correction applied. There are a number of calibration schemes possible, depending on the requirements of the system. Some of these are listed here in order of increasing complexity:

- Single-point calibration uses just a single reference measurement and can suffice if the range of interest to the application is at or close to the single reference measurement.

- Two-point calibration uses two reference measurements, typically close to the upper and lower limits of the measurement range.

- Linear curve fitting (linear regression) - in case of significant non-linearity multiple reference measurements are taken and the best fit straight line calculated using for example the method of least squares.

- Polynomial curve fitting - depending of the characteristic of the sensor response, a straight-line approximation may not enhance the accuracy sufficiently and a more complex polynomial curve fitting algorithm may be required.

It is clear that obtaining good accuracy from a non-linear sensor increases complexity and cost, both in terms of the reference (factory) calibration measurements and the provision of sufficient processing power and Look-up Table memory in the system.

Hysteresis

Some sensors display hysteresis, whereby the output of the sensor differs depending on whether the previous measurement was lower or higher. This memory effect is indicated by the rising and falling trajectories of the characteristic shown in Figure 3. In general, this results in an output which is too low when the input is rising and too high when the input is falling.
Hall sensors and piezoelectric sensors in particular, are prone to hysteresis. If the measurement error introduced by hysteresis is unacceptably high, one possible approach is to use curve fitting to reduce the error

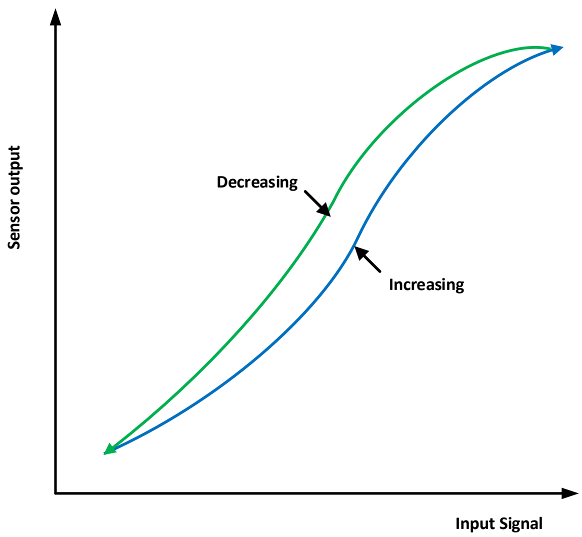

Figure 3: Hysteresis

Response time

Sensors do not react instantaneously to changes in the quantity being measured. The response time of the sensor is usually defined as the time required for the sensor output to reach a certain percentage of its final value in response to a step change of the input quantity being measured.
While the delay caused by response time is critical in applications involving safety, it is also important in the design of the full sensing chain and in the stability of closed loop control systems.
The response time of a sensor to a positive-going change at the input may be different to that for a negative-going change and these may be quoted separately.

Adesto's SmartEdge^{TM} Platform

Adesto's SmartEdge^{TM} platform incorporates all the sensor path elements from the AFE (Analog Front End) through to the calibration and signal conditioning described here into a single ASIC chip, in essence turning the non-ideal into the ideal. With more than 20 years' experience designing advanced analog and digital circuitry for hundreds of customers in every major region, Adesto's ASIC & IP division delivers a new breed of design-centric semiconductor supplier capable of optimising its designs for every customer, yet achieving cost economies not thought possible with custom chips designs until now.