11

Sensor Selection and Integration

In the previous chapters we considered different fundamental sensing techniques (electrical, thermocouple, ultrasonic, optical, and magnetic sensing). These techniques can be employed in different ways to produce thermoelectric sensors (Dürig 2005), photoelectric sensors (Carotenuto et al. 2007), photomagnetic sensors (Giri et al. 2002), magnetoelectric sensors (Fiebig 2005; Nan et al. 2013), thermomagnetic sensors (Chen et al. 2014), thermooptic sensors (Berruti et al. 2013; Choi et al. 2008; Watts et al. 2013), elastomagnetic sensors (Jiles 1995), elastoelectric sensors (Dong et al. 2004), and thermoelastic sensors (Duwel et al. 2003, 2002; Roszhart 1990). Table 11.1 provides a brief summary of the different possibilities for input-output relationships between a measurand and the electrical quantity we wish to process by the subsequent conditioning circuit. For example, a temperature sensor can be realised using thermocouples, resistance temperature detectors (RTDs), thermistors, infrared detectors, or acoustic sensors. The decision to pick one of these technologies mainly depends on two essential criteria: the quality trade-off and the ease with which we can integrate the sensor into the rest of the system we wish to develop or monitor. In this chapter we shall discuss in some detail the sensor quality parameters and their integration aspects.

11.1 Sensor Selection

The quality of a sensor is judged by many parameters. Strictly speaking, the list of parameters required to specify a sensor can be formidably long; most of them are interdependent too. Furthermore, the significance of a particular parameter depends on the requirements of the overall system. While some of the parameters solely depend on the sensing element, some depend on the sensor as a whole (sensing and conditioning) as well as on the overall system. In this section, we shall discuss the parameters that apply to most existing sensors.

11.1.1 Accuracy

The accuracy of a sensor is a measure of the nearness of its output to the true value. The most significant challenge in measuring the accuracy of a sensor is obtaining the true value. Typically, standard references in a laboratory setting are used to determine a true value with which the sensor's output can be compared. The steps are as follows

Principles and Applications of Ubiquitous Sensing, First Edition. Waltenegus Dargie.

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Table 11.1 The selection of a sensing technology depends on the conditioning and subsequent electronic circuits

Measurand	Sensing element	Output
Magnetic	Hall effect	Voltage
	Magneto-resistive	Resistance
Temperature	Thermocouple	Voltage
	RTD	Resistance
	Thermistor	Resistance
	Infrared	Current
Humidity	Capacitive	Capacitance
	Infrared	Current
Force, weight,	Strain gauge	Resistance/voltage
Pressure, vibration	Piezo-electric	Voltage or charge
	LVDT	AC voltage
	Microphone	Voltage
	Accelerometer	Voltage
Flow	Magnetic flowmeter	Voltage
	Mass flowmeter	Resistance, voltage
	Ultrasound/Doppler	Frequency
Fluid level, volume	Ultrasound	Time delay
	Potentiometer	Resistance, voltage
	Capacitor	Capacitance
	Switch	On/off
Light	Photodiode	Current
Chemical	pH	Electrode voltage
Solution	Conductivity	Resistance/current

Figure 11.1 The accuracy of a sensor is usually determined in a lab setting by exposing the sensor to a measurand of known values (which can be measured by a standard device) and by comparing its response to reference values.

(refer also to Figure 11.1). In a controlled environment, the sensor is exposed to a measurand of known magnitude (here the term “known” refers to the use of a standard reference system to determine the value of the measurand) and the output of the sensor is observed. After a large set of measurements are taken (refer to Figure 11.2), the relationship between the input and the output is established in a probabilistic sense.

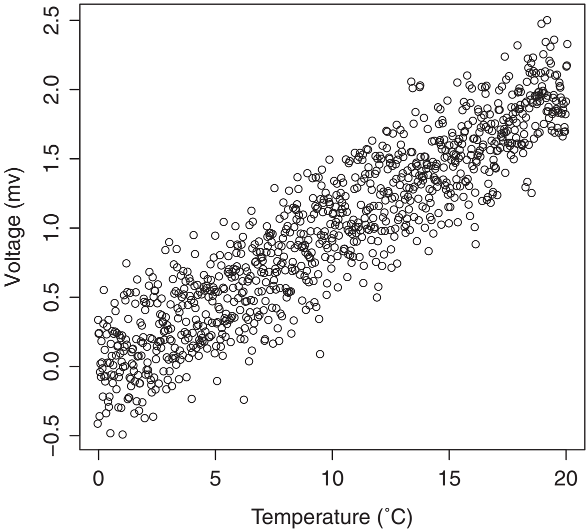


Figure 11.2 An example of the input output relationship between a measurand (temperature in °C) and the corresponding output (in mV) of a temperature sensor that can be established in a lab setting using a standard reference (by which we have measured the temperature of the measurand). This measurement can be used to establish the joint probability density function between the input temperature and the output voltage as well as the expected value between the input temperature and output voltage which will serve as the basis to establish the accuracy of the sensor.

A more detailed analysis of estimation will be given in Chapter 12. Generally, a sensor may not produce the same accuracy for all expected magnitudes of a measurand: often, the accuracy decreases towards the two extremes in the measurand's span. Furthermore, the accuracy varies when the measurand's frequency varies. Therefore, the accuracy of a sensor is calculated as the expected error (in percentage terms) of the sensor, which is obtained by taking both the magnitude and the frequency variations of the measurand into consideration.

11.1.2 Sensitivity

The sensitivity, when it refers to the sensing element, is the minimum magnitude of a measurand that can be picked up by the sensor to produce a corresponding output. Sensitivity, when it refers to the entire sensor, is not necessarily the quality of the sensing element alone but also the quality of the conditioning circuit and, most importantly, the quality of the preamplifier.

11.1.3 Zero-offset

The zero-offset of a sensor is the magnitude of the output when the measurand is zero. It can be expressed in different ways, depending on the sensor's output. For most electrical sensors, it is expressed in millivolts or milliamps. It can also be expressed as a unitless quantity, for example, as percentages of the full-scale output. Zero-offset can be corrected by proper calibration.

11.1.4 Reproducibility

Reproducibility refers to the a sensor's ability to repeatedly yield the same output (or comparatively the same) for the same input under the same operational condition. This is an important aspect particularly for:

- magnetic sensors, because of a potential hysteresis effect (discussed below)

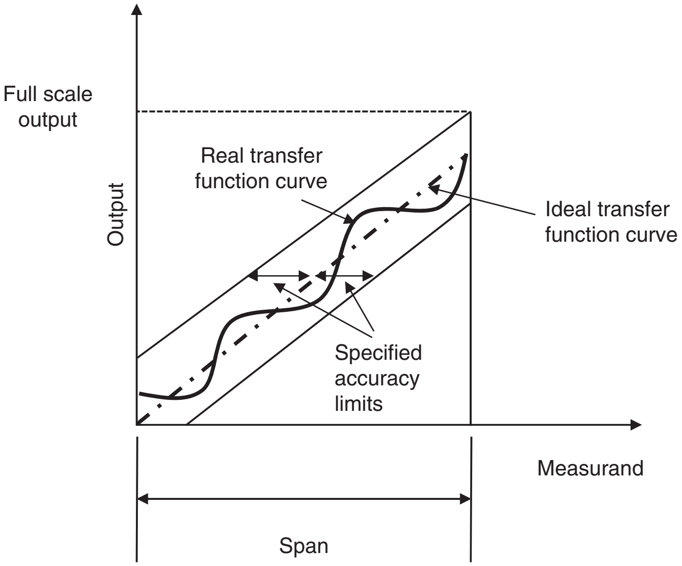


Figure 11.3 The relationship between span, full scale output, and transfer function.

- piezoelectric sensors
- strain gauges, because of the possibility of inelastic characteristics in the sensing elements.

It must be noted, however, that a highly reproducible sensor does not necessarily imply one that is highly accurate. Rather, reproducibility is a quality of consistency. It is sometimes referred to as precision.

11.1.5 Span

The difference between the highest and the lowest magnitudes of a measurand that can be detected by a sensor within an acceptable accuracy and without damaging or significantly affecting its reproducibility is called the sensing span. The span of a sensor is not merely a static value, as it is affected by the frequency response (or transfer function). Figure 11.3 summarises the relationship between span, full-scale output and ideal and real transfer functions.

11.1.6 Stability

Stability (or long-term stability) refers to the physical changes the sensor undergoes over time as a result of which there is a slow drift or shift in its operational condition. For example, some sensors adsorb biological and chemical artefacts on their surfaces in order to sense a measurand. This is, for instance, the case with chemical sensors that employ Raman spectroscopy (for example, a pH sensor). As a result of the accumulation of adsorbent, the sensor's response to the measurand gradually drifts or shifts. This drift can be observed in a shift in the operational frequency or in the expected spectrum of an output for a known input. Stability may also refer to the change in the spectrum of noise to which the sensor is sensitive. Other factors that affect the stability of a sensor are ageing, adsorption or desorption of contaminants, stress, package leaks, and gassing and chemical reactions (Clark Jr et al. 1988; Romain and Nicolas 2010; Spassov et al. 2008).

11.1.7 Resolution

Resolution refers to the minimum change in the measurand that can be detected by the sensor. The resolution of a sensor is affected by the sensing element itself as well as all the subsequent stages, including analogue-to-digital conversion (ADC). At the ADC level, the resolution is affect by the quantisation error, which in turn is affected by the number of bits allocated to digitise the analogue input. If the peak-to-peak output of the sensor is 10 mV, the resolution of a 10-bit ADC is given as:

$$\Delta_r = \frac{10}{2^{10}} = 0.009765625 = 9.8\ \mu\text{V} \tag{11.1}$$

In other words, a variation in measurand values that correspond to an output voltage of less than 9.8 μV will not be detected by the sensor as a whole system, even though the sensing element itself may be able to detect the change.

11.1.8 Selectivity

The selectivity of a sensor is a measure of its capacity to respond only to the measurand while rejecting undesired signals (noise and interference) that may in some respect have overlapping characteristics with the measurand. This is a quality of both the sensing element and the conditioning circuit. When the measurand and the interfering inputs have overlapping spectra, difference amplifiers can be used to improve the selectivity of the sensor. If the magnitude of the measurand is appreciably large, clippers and limiters can be used to suppressed the noise. If the measurand and the interfering signals occupy different spectra, analogue and digital filters can be used to separate them (to selectively amplify or suppress). However, there are also more subtle sources of noise, such as thermal, radiative, and magnetic sources, which cannot be easily suppressed or rejected. In this case, selectivity becomes a part of the structure of the sensing element. For chemical and biochemical sensors, selectivity refers to the ability of a sensor to selectively react to particular molecules or compounds while staying unresponsive to others.

11.1.9 Response Time

The duration a sensor requires to approach its true output when subjected to a step input is referred to as its response time. This parameter is typically affected by the frequency response of the sensor. An ideal sensor will have a constant (flat) speed of response within its operational band.

11.1.10 Self-heating

Self-heating is an important consideration and particularly affects electrical sensing elements. When a current (for example, a biasing current) circulates through an electrical circuit, there will be a voltage drop across the inductive, capacitive, and resistive components, as a result of which there is power dissipation in the form of heat. This phenomenon is called self-heating and it is problematic to sensing because some of the characteristics of the sensors are temperature dependent. The problem is particularly pronounced if the sensing element has a significant resistive characteristic.

11.1.11 Hysteresis

Hysteresis refers to the difficulty of a sensing element (this is specifically the characteristic of the sensing element and not of the conditioning circuits) to faithfully reproduce the same one-to-one relationship between the measurand and the sensor output in the opposite direction of operation (when the magnitude of the measurand is decreasing) as in the forward direction (when the magnitude of the measurand is increasing). A hysteresis-free sensing element faithfully reproduces the same one-to-one relationship in both directions. An instance of the effect of hysteresis on the reproducibility of a sensor is depicted in Figure 11.4. As can be seen, the sensor produces two different output curves for the same values of a measurand, depending on whether the sensor is measuring an increasing or a decreasing measurand.

11.1.12 Ambient Condition

All sensors require ambient conditions to function properly. This may refer to the ambient temperature, the maximum permissible exposure to external magnetic fields or radiation, surrounding vibration, and so on. In order to function properly, sensing devices such as ECGs, EEGs, SQUIDs, and many others require compete shielding from external magnetic fields and from signals produced by power lines. Similarly, the stability of most magnetic and optical sensors can be affected by thermal conditions. In general, the ambient condition of a sensor describes the surrounding or environmental conditions that should be maintained for it to function properly.

11.1.13 Overload Characteristics

The maximum amount of current or power that can be drawn from a sensor or the maximum amount of power that can be dissipated inside it without significantly affecting its operation is referred to as its overload characteristic.

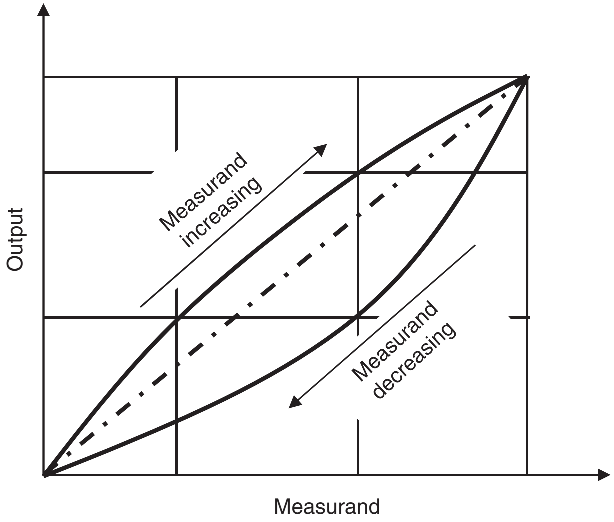


Figure 11.4 The effect of hysteresis on the reproducibility of a sensor.

11.1.14 Operating Life

The operating life of a sensor can be described in many ways, including in terms of its stability and accuracy. Generally it is the expected number of hours it can operate without its stability or accuracy deteriorating beyond a set value. In reality, the operating life of a sensor is not so easy to determine, as it depends on so many factors. For example, the operating life of a chemical sensor depends on the total amount of gas it is exposed to during its lifetime, as well as other environmental conditions, such as temperature, pressure and humidity.

11.1.15 Cost, Size, and Weight

Apart from the functional aspects of a sensor, its non-functional aspects are important too. These include cost, size, and weight. This is particularly true for those sensors that have to be seamlessly embedded into physical bodies or processes. Needless to say, non-functional aspects such as size and weight can have a direct bearing on some functional parameters, such as self-heating, span, and sensitivity. Micro-sized sensors, for example, can only allow a limited amount of power dissipation, which in turn limits their span. The same can be said of weight. Light sensors respond to surrounding heat and radiation more quickly and more accurately than heavy sensors.

11.2 Example: Temperature Sensor Selection

From the list of parameters that measure the quality of a sensor, it is clear that no single sensor can outperform all the others. Sensor selection is a trade-off. To highlight this point, we shall consider the selection of a temperature sensors as an example. A temperature sensor can be realised by using different sensing elements, as already mentioned at the beginning of this chapter. Each element has its own set of merits and demerits.

11.2.1 Resistance Temperature Detectors

An RTD is essentially a resistive sensor. As its name suggests, its resistance varies as a function of temperature. In Chapter 4 we saw that the resistance of a material is directly proportional to its resistivity and length but inversely proportional to its cross-sectional area. We can also express it in terms of the conductivity of the material, as follows (see Figure 11.5):

$$R = \frac{L}{\sigma S} \tag{11.2}$$

where S is the surface area of the material and σ is the conductivity of the resistor. However, the conductivity of the material is temperature dependent (conductivity decreases

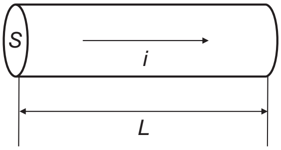


Figure 11.5 The resistance of a resistance temperature detector is temperature dependent.

as the temperature increases because temperature increases the random motion (collision) of electrons). Mathematically, the conductivity is expressed as:

$$\sigma = \frac{\sigma_0}{1 + \alpha(T - T_0)} \tag{11.3}$$

where α is the temperature coefficient of the material and T_0 and σ_0 are its reference temperature and conductivity at the reference temperature, respectively. The resistance of the material as a function of temperature can therefore be expressed as:

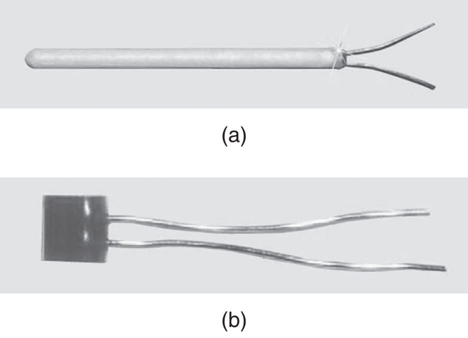
$$R(T) = \frac{L}{\sigma_0 S}[1 + \alpha(T - T_0)] \tag{11.4}$$

Among the merits of an RTD is the relative ease with which it can be fabricated. It can be produced as a wire coil (of length from a few centimetres to about 500), which can then be enclosed in a glass, ceramic, or metal housing. Alternatively, a thin-film RTD can be produced by depositing a thin layer of suitable material (such as platinum) on a thermally stable, thermally conducting, and electrically non-conducting material such as a ceramic. Figure 11.6 displays a wire coil and a thin-film temperature sensor. The RTD has a linear response over a wide range of temperatures (approximately from −250 to 700°C) and can be made small enough to have a response time of the order of a fraction of a second. It is the most stable, most accurate (±0.01 to ±0.05°C), and most reproducible temperature sensing element; it is also highly resistant to contamination and corrosion and does not require recalibration after fabrication.

Among its demerits are its relatively high cost, slow response time, poor sensitivity to small temperature changes (low resolution), and high sensitivity to external vibrations (due to the piezoresistive effect). Furthermore, due to the presence of a large resistive component, self-heating and, therefore, power dissipation are high. Finally, all RTDs require a small amount of operating current.

11.2.2 Thermistors

Thermistors are realised by pressing metal oxides into a semiconductor chip, bead, or wafer. Most existing thermistors have negative temperature coefficients (NTC), even though there are also some with positive temperature coefficients. For those with NTC, resistance decreases when temperature increases. Regardless of the type of temperature coefficient, thermistors typically have high temperature coefficients and high resistance.



(a)

(b)

Figure 11.6 Resistance temperature detectors. (a) a wire-wound RTD; (b) a thin-film RTD.

For an NTC thermistor, the resistance is approximated by:

$$R(T) = \alpha e^{-\beta/T} \tag{11.5}$$

where α (measured in Ω) and β (measured in Kelvin) are constants. From the equation, it can be seen that the relation between R and T is non-linear, but since β is small, the non-linearity is not significant.

Thermistors have high resolution and can be fabricated in various sizes and shapes. Due to their relatively high resistance, they permit a small amount of current to flow through them and, as a result, self-heating is comparatively small. If copper and nickel extension wires are used, temperature measurements can be stable. However, thermistors are fragile and can measure a relatively limited temperature range (from −50 to 600°C) with accuracy and stability varying along the sensing range.

11.2.3 Thermocouples

Thermocouples measure temperature directly, without requiring a biasing current or voltage. They are simple to fabricate, rugged, and inexpensive. No other sensor technology to date can match the wide sensing range that can be achieved using thermocouples (from approximately −273 to 2700°C). Moreover, they have the fastest response times and enable point temperature sensing and do not exhibit the problems associated with contact resistance (resistance arising from the interface between the sensor and the lead wires connecting the sensor with the conditioning circuit). However, they are the least stable and least reproducible. They have poor resolution and can easily be affected by ambient noise. Moreover, their accuracy is comparatively low. Unlike other temperature-sensing elements, however, thermocouples can be realised from different materials with different sensing parameters. For example, the temperatures that can be sensed by semiconductor thermocouples is typically in the range of −55 to 150°C.

11.2.4 Infrared

A heat-producing object radiates energy in the form of infrared light. A one-to-one relationship between the infrared energy and the temperature of the object can be established by setting up an infrared detector. The detector, for example, can be a photodiode or a phototransistor that generates an electrical voltage proportional to the light it absorbs. A simple infrared setup to measure temperature is displayed in Figure 11.7. This form of temperature measurement is desirable because no contact is needed between the heat-producing body and the sensor. In contrast, all the other

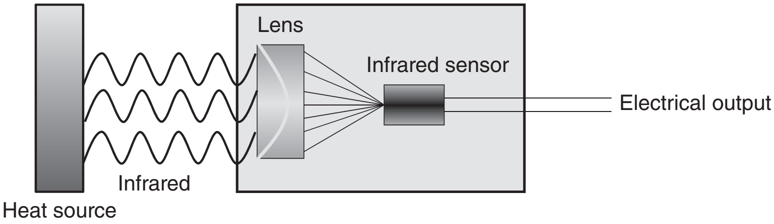


Figure 11.7 The basic set up of an infrared sensing.

temperature sensors we considered above require thermal contact to produce output. Infrared sensors have comparable response times to thermocouples and in some cases, they are even faster. They have good stability and high reproducibility, and because of the absence of direct contact with the object or process they monitor, they are not affected by corrosion or oxidation. As a result, their accuracy does not deteriorate appreciably over time. However, optical sensors in general have high set-up costs. They are more complex than the other technologies and require optoelectronic components to convert optical output to electrical output. Moreover, emissivity variations can affect their accuracy and the field of view of the lens and spot size may restrict their scope and usefulness (the spot size refers to the sensor area on which the infrared beam should focus). Likewise, their accuracy can easily be affected by dust, smoke, and background radiation.

11.3 Sensor Integration

A sensor is rarely a standalone system. Often it is a part of a more complex system, which may include advanced signal processing and actuation units. Consequently, integrating the sensor into the system is a vital step. The integration process has electrical and non-electrical aspects. One of the electrical aspects was considered in Chapter 3, namely impedance matching. Fulfilling the electrical requirements may not be very difficult, because most sensors are produced with standard interfaces, but addressing the non-electrical aspects so that the sensor functions as per its technical specification is the task of the integrator. The ease with which a sensor can be integrated into a system depends on the structure and requirements of both the sensor and the system. Two of the most important integration issues are related to optimal interface of the sensor with the process or the object it monitors and protecting the sensor from internal as well as surrounding interference. In this section, we shall consider these issues in some detail.

11.3.1 Dead Volume

All sensors should be properly interfaced with the process or object they monitor, so that what a sensor perceives is the actual change in the measurand. However, most sensors also require housing for various reasons (we shall discuss some of them shortly). This housing or shield not only minimises the exposure of the sensor to the measurand but also creates a dead volume, which can trap the measurand for some time (see Figure 11.8). The larger the dead volume, the longer the housing will hold a portion of the measurand. As a result, there will be a delay before the sensor perceives a change in the measurand. For example, for a temperature sensor, the dead volume can trap hot air, which may not represent the actual state of the process being monitored. The same can be said of magnetic or humidity sensors. Consequently, this volume has to be minimised.

11.3.2 Self-heating

The heat produced by a sensor due to a small amount of power dissipation in its resistive elements can skew its output in the long run. To reduce the effect of self-heating, a sensor

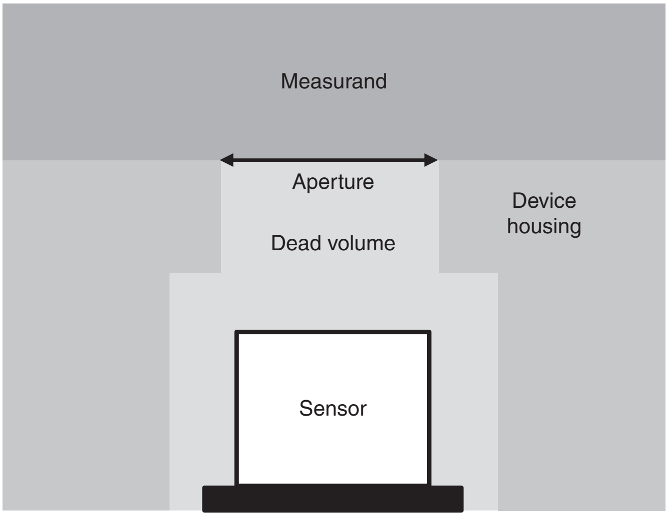


Figure 11.8 The volume created by the housing surrounding a sensor is called the dead volume. The larger the dead volume, the more probable it is the measurand will be trapped for a long time, affecting the sensitivity, accuracy, and response time of the sensor.

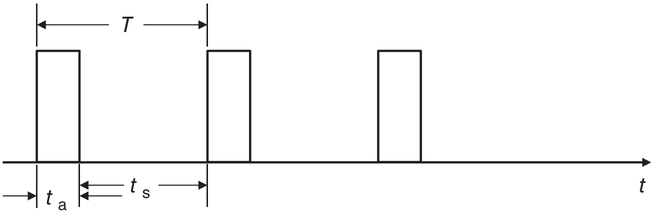


Figure 11.9 The duty cycle of a sensor describes the portion of time the sensor spends in an active state in order to reduce the effect of self-heating.

can operate in a duty cycle, so that during its sleep time, power can be withdrawn and the sensor can cool down. The concept of the duty cycle was defined in Chapter 10 and can be reused here as well:

$$D = \frac{\tau_a}{\tau_a + \tau_s} \times 100\% \tag{11.6}$$

where τ_a is the active time, τ_s is the sleep time, and $T = \tau_a + \tau_s$ is the period of a duty cycle (Figure 11.9). The duty cycle describes the portion of time the sensor spends in an active state. This time has to be very small ($D < 10\%$) for the sensor to cool down effectively. The duty cycle is also useful for reducing the power consumed by the system, particularly when it operates with exhaustible batteries.

Complementary to the duty cycle, and perhaps the most widely used approach to effectively deal with self-heating, is the use of a heat sink. In this approach, the sensor is embedded into material with a high heat conductivity (a metal) and a relatively large volume, so that when the sensor produces heat, the material absorbs the heat quickly, thereby serving as a cooling system to the sensor.

Example 11.1 Minimising the temperature generated in an RTD due to self-heating is of paramount importance for medical instrumentation because it affects the accuracy and response time of the instrument. Self-heating is the result of the biasing current flowing through the RTD, without which it is not possible to establish a relationship between the temperature of the measurand and the change in the resistance of the RTD. Figure 11.10 shows the circuit diagram of a digital RTD provided by Microchip Technology Inc. Determine the maximum power dissipation (self-heating) in the RTD for this set up.

We first begin by explaining the function of the main components. The PIC microcontroller unit (MCU) enables the sensor to be programmed and to be easily integrated with other digital systems. Since the microcontroller unit requires a digital input, the output of the RTD, which is analogue by nature, should first be changed into a digital bit stream by the ADC (MCP 3551). The ADC and the MCU are interfaced with each other by a full-duplex serial bus (SPI) which requires three lines (chip-select, master-in slave-out (MISO), and slave-in master-out (SIMO) pins). Both the microcontroller and the ADC require a DC biasing voltage, V_{DD}. Other than that, the ADC requires a reference voltage, which is the maximum magnitude of the analogue signal it should quantise. Moreover, the RTD requires a biasing voltage, which should be as small as possible to prevent the sensor from self-heating. The LDO component is a voltage regulator, which conditions the ADC reference (V_{REF}) and the RTD biasing voltages.

In order to calculate the voltage across the RTD, we should first calculate the reference voltage:

$$V_{\mathrm{REF}} = \frac{R_{\mathrm{A}} + R_{\mathrm{RTD}}}{R_{\mathrm{A}} + R_{\mathrm{B}} + R_{\mathrm{RTD}}} V_{\mathrm{LDO}} \tag{11.7}$$

Then, the voltage across the RTD is given as:

$$V_{\mathrm{RTD}} = \frac{R_{\mathrm{RTD}}}{R_{\mathrm{A}} + R_{\mathrm{RTD}}} V_{\mathrm{REF}} \tag{11.8}$$

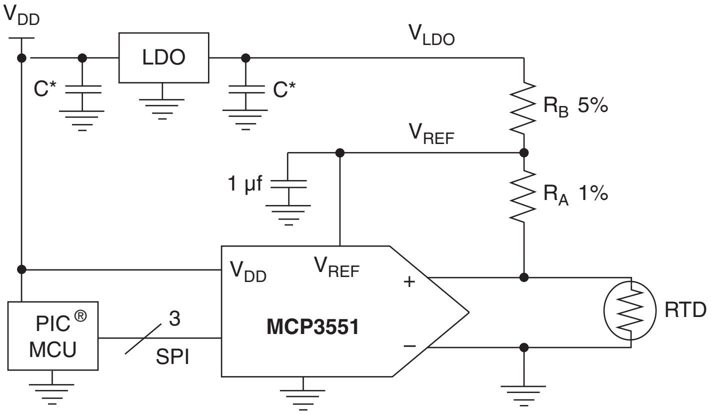


Figure 11.10 The circuit block diagram of a digital RTD. Courtesy of Microchip Technology Inc. (2013).

The nominal current flowing through the RTD is given as:

$$I_{\mathrm{RTD}} = \frac{V_{\mathrm{RTD}}}{R_{\mathrm{RTD}}} \tag{11.9}$$

The temperature produced as a result of this current (self-heating) is equivalent to the power dissipation in the RTD:

$$P_{\mathrm{heat}} = I_{\mathrm{RTD}}^2 R_{\mathrm{RTD}} = \frac{V_{\mathrm{RTD}}^2}{R_{\mathrm{RTD}}} \tag{11.10}$$

Example 11.2 One of the mechanisms to reduce the effect of self-heating is to use a heat sink to quickly absorb the heat generated by a sensor. Suppose we deposit a thin RTD sensor on an alumina (aluminium oxide, Al_2O_3) substrate, serving as a heat sink. Assuming that the RTD film can be considered as a one-dimensional conduction medium as shown in Figure 11.11, derive an expression relating the heat generated by the self-heating RTD and the temperature of the alumina substrate.

When a temperature difference between two regions exists, a temperature potential is established, in the same way an electric potential can be established as a result of a difference in electric charge concentration between two points. The tendency of this temperature potential is to generate a flow of heat from a higher temperature region to a lower temperature region. Hence, similar to current, which is the flow of electrons, the rate at which heat is transferred by conduction, q, is expressed as:

$$q = \frac{dT}{dR_{\mathrm{th}}} \tag{11.11}$$

where R_{th} is the thermal resistance between the two conduction regions. It is a function of the length (l), cross-sectional area (A), and thermal conductivity (k) of the conduction region:

$$R_{\mathrm{th}} = \frac{l}{kA} \tag{11.12}$$

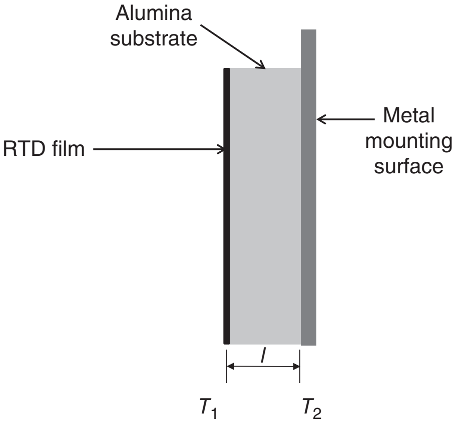


Figure 11.11 A thin film of RTD is deposited on an alumina substrate to absorb the temperature generated by the self-heating RTD. The relationship between the temperature of the two media (T_1 for the RTD substrate and T_2 for the alumina substrate) can be determined using the heat conduction equation.

where k is the thermal conductivity of the material. If the heat covers the entire surface area and transfers in one direction (along the thickness, l), then, q is proportional to the product of the temperature gradient along the conduction path:

$$q = -kA\frac{dT}{dl} \tag{11.13}$$

More generally, the time-dependent and time-independent components of the temperature gradient are related to one another by the heat conduction equation:

$$\frac{\partial u}{\partial t} - \alpha^2\left(\frac{\partial u}{\partial x} + \frac{\partial u}{\partial y} + \frac{\partial u}{\partial z}\right) = 0 \tag{11.14}$$

or in short:

$$\frac{\partial u}{\partial t} - \alpha^2\nabla^2 u = 0 \tag{11.15}$$

where $u(t, x, y, z)$ is the temperature as a spatial and temporal function, ∇ denotes the Laplace operator, and α is a positive constant representing the thermal diffusivity of the material expressed as:

$$\alpha = \frac{k}{\rho c_\mathrm{p}} \tag{11.16}$$

where ρ is the density and c_p is the specific heat capacity of the material. The solutions for the heat conduction equation determine the response time and the self-heating of the RTD structure we described by Figure 11.11. Taking into account the fact that the RTD is a very thin film and the temperature distribution can be expressed as $u(x, t)$, the solutions of the differential relations in Eq. (11.15) yield a time-independent final temperature distribution and a summation of exponentially damped orthogonal functions describing the evolution of the temperature distribution from an initial condition to a final condition:

$$u(x, t) = (T_1 - T_2)\frac{x}{l} + T_1 + \sum_{n=1}^{\infty} b_n(e^{-n^2\pi^2\alpha t/l^2})\sin\left(\frac{n\pi x}{l}\right) \tag{11.17}$$

where

$$b_n = \frac{2}{l}\int_0^1 \left(f(x) - (T_1 - T_2)\frac{x}{l} - T_1\right)\sin\left(\frac{n\pi x}{l}\right)dx \tag{11.18}$$

and $f(x)$ describes the temperature of the system at $t = 0$. When a biasing current flows through the RTD, the power dissipated in the RTD (P) generates self-heating, and this heat flows into the alumina substrate. If we combine Eqs. (11.11) and (11.13) and take into account the single-dimension assumption, the thermal conductivity between the RTD and the alumina substrate as a function of x can be expressed as:

$$q_u = -k\frac{\partial u(T)}{\partial x} \tag{11.19}$$

Furthermore, if we apply Eq. (11.19) to Eq. (11.17) as the boundary condition, we obtain the desired expression:

$$\frac{P}{A} = -\alpha\frac{(T_1 - T_2)}{l} \tag{11.20}$$

where A is the surface area of the RTD. Consequently,

$$T_1 = \frac{lP}{\alpha A} + T_2 = \frac{IV^2}{\alpha AR(T)} + T_2 \tag{11.21}$$

where P and V are the power dissipated and the voltage drop across the RTD, respectively. Remember that T_1 is the temperature of the RTD due to self-heating and T_2 is the temperature of the alumina substrate serving as a heat sink.

Example 11.3 We wish to employ a platinum RTD for monitoring the temperature of a SQUID. The RTD is deposited on an alumina substrate having a thickness of 0.254 mm and a surface area of $4.4 \times 10^{-6}\ \text{m}^2$. If a biasing current of 50 μA flows through the RTD and the temperature of the alumina substrate is kept at 0°C, what will be the self-heating of the RTD? The temperature-dependent resistance of the RTD, $R(T)$, at the specified temperature is 1000 Ω.

Figure 11.12 shows the set up of the biasing condition. The thermal diffusivity of alumina is $\alpha = 20 \times 10^{-5}\text{m}^2\ \text{s}^{-1}$. The power dissipation due to the biasing current at the specified temperature can be expressed as $P = I^2R$. With this, we have all the parameters required by Eq. (11.21) to calculate T_1:

$$T_1 = \frac{0.254 \times 10^{-3}\text{m}\ \left((50\ \mu\text{A})^2/1000\ \Omega\right)}{(1.2 \times 10^{-5}\text{m}^2\ \text{s}^{-1})\ (4.4 \times 10^{-6}\ \text{m}^2)} + 0^\circ\text{C} = 12^\circ\text{C}$$

Example 11.4 The maximum permissible junction temperature (T_{JMAX}) is one of the key factors limiting the self-heating of a device. Usually, T_{JMAX} is defined by the manufacturer and takes into consideration specific aspects such as the reliability of the die used in the manufacturing process. Suppose, for a sensor produced by Texas Instruments, the manufacturer defines the following relationship:

$$R_{\text{th}} = \frac{T_{\text{J}} - T_{\text{A}}}{P} \tag{11.22}$$

where T_{J} is the junction temperature (the junction being the interface between the device and the ambient environment), T_{A} is the ambient temperature, and P the power dissipation in the sensor producing self-heating. Show how the maximum dissipated power of a Texas Instruments synchronous step-down switcher changes when the ambient temperature changes from 25°C to 85°C. The maximum permissible temperature is 125°C and the thermal resistance is 44.5°C W^{-1}.

From Eq. (11.22), we can derive an expression for the permissible dissipated power:

$$P_{\text{MAX}} = \frac{T_{\text{JMAX}} - T_{\text{A}}}{R_{\text{th}}} \tag{11.23}$$

Substituting the given values in the above equation yields 2.25 W for an ambient temperature of 25°C and 0.9 W for 85°C.

Example 11.5 Self-heating in a sensor can be further reduced by identifying a suitable mounting surface during integration. Derive an expression for the power dissipation (self-heating) of an RTD mounted on a metallic surface, as shown in Figure 11.13.

Figure 11.12 An illustration of how self-heating generated by the RTD is absorbed by the alumina substrate in a Honeywell EL-700 platinum RTD. v_{DD} is the biasing voltage.

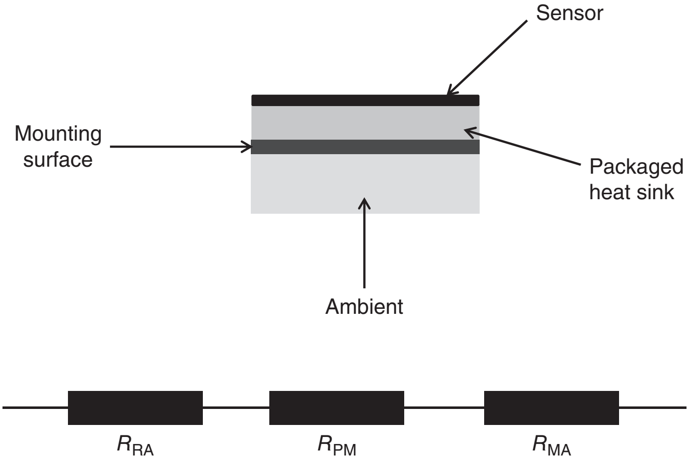


Figure 11.13 The careful choice of a mounting surface during sensor integration may reduce self-heating.

The alumina heat sink we considered above is part and parcel of the packaging process undertaken by the manufacturer and nothing can be done with it. A further improvement, however, can be achieved by using a mounting surface with good heat conduction. The overall thermal resistance of the entire assembly can be regarded as connecting three resistors in series. Subsequently, if we can apply Eq. (11.22) in Figure 11.13, we can rewrite the overall thermal resistance as follows:

$$R_{th} = R_{RA} + R_{PM} + R_{MA} \tag{11.24}$$

where R_{RA} is the junction thermal resistance between the RTD and the alumina substrate, R_{PM} is the junction thermal resistance between the sensor package and the mounting surface, and R_{MA} the junction thermal resistance between the mounting surface and the ambient temperature. Hence,

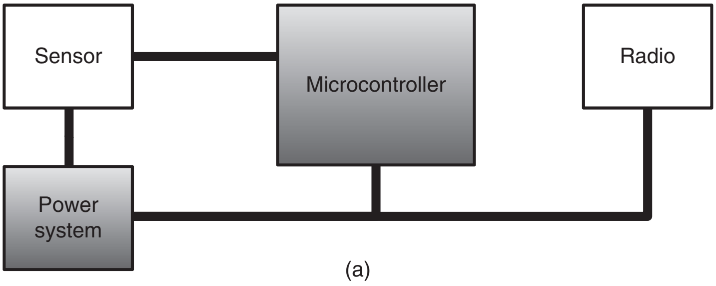
$$\frac{T_J - T_A}{P} = R_{th} = R_{RA} + R_{PM} + R_{MA} \tag{11.25}$$

From which we have:

$$P = \frac{T_J - T_A}{R_{RA} + R_{PM} + R_{MA}} \tag{11.26}$$

11.3.3 Internal Heat Sources

The relative position of a sensor with respect to other components, particularly with respect to processing units, power supply units, and on-board voltage-regulation units (power electronics) in a complex system is critical to its proper operation. The reason is that these components cause a significant amount of self-heating, which can affect the sensor's operation. Indeed, not only its placement but also the way it is connected to them is also critical because the connecting wires are heat conductors too. Figure 11.14 shows two possibilities for integrating a sensor with a microcontroller and a power supply unit. In (a), the sensor is placed very close to the two heat-generating units and it is connected to them with thick wires. This is, of course, an example of bad setup. In (b),



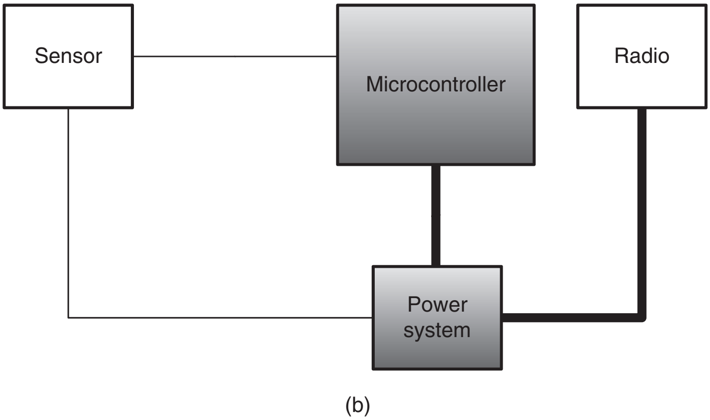


Figure 11.14 Sensor placement and wire selection are critical for protecting sensors from internal heat sources.

the sensor is placed as far away from the two heat sources as possible and thin connection wires are used. This may not be always possible, however. For example, the types of wires that can be used to connect a sensor with a processor is constrained by many factors such as the desired bit rate between the sensor and the processor, the type of duplex mechanism required, the space available, and whether or not an ADC internal to

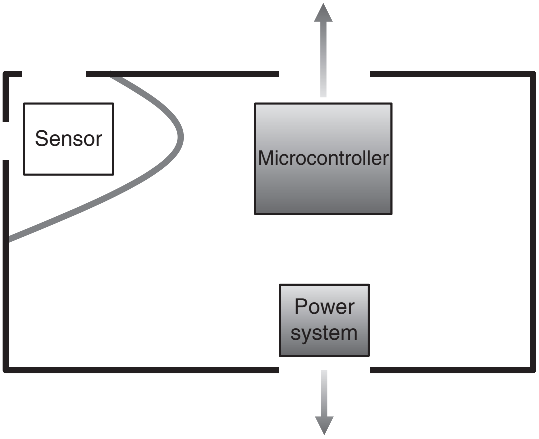


Figure 11.15 The sensor should be protected from internal heat sources to reduce the effect of thermal noise on its operation.

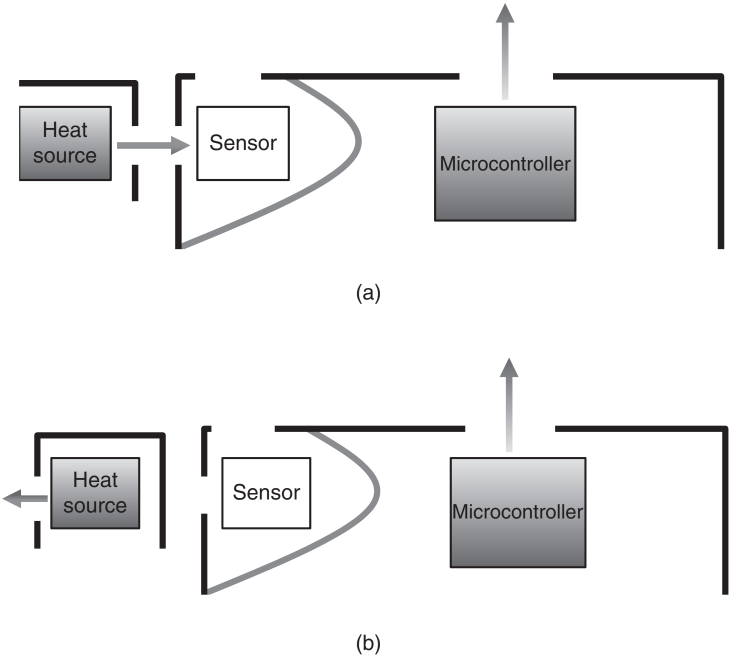


Figure 11.16 A mechanism for protecting the sensing path of a sensor from external heat sources: (a) the heat circulation path of an external heat source is not taken into account during sensor placement integration; (b) The heat circulation path of an external heat source is taken into account during sensor placement and integration.

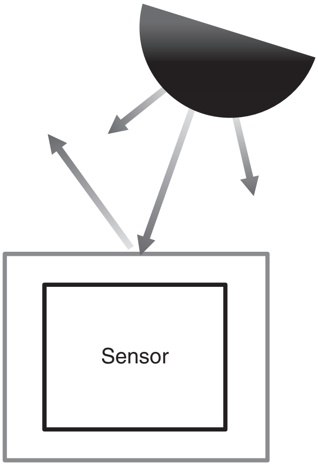


Figure 11.17 Shielding a sensor from the radiation of an external source (the sun) is as important as shielding it from internal and other external heat sources, as this can cause a wide range of interference such as heat, infrared radiation, and ultraviolet radiation.

the microcontroller is used to digitise the sensor signal. Once the placement and wiring issues are addressed, the heat produced by heat sources within the system should still be provided a proper channel to leave the system and the sensor should be shielded from the effect of this internal radiation. Figure 11.15 shows one way of providing an outlet and how a sensor can be shielded from internal infrared radiation. The extra openings at the top left-hand corner prevent the measurand from being trapped by a dead volume, and allow the sensor to make a good determination of the actual state of the measurand.

11.3.3.1 External Heat and Radiation Sources

Lastly, as the sensor or the system integrating it can also be a part of or should work with another system, the contribution of external heat and radiation sources should be taken into consideration during sensor integration. Figure 11.16 compares two scenarios. In the first, the opening through which the sensor is exposed to the measurand is the same as the heat circulation path of an external heat source producing a considerable and undesirable effect on the sensing quality of the sensor. In the second, the two paths are isolated from one another. Likewise, Figure 11.17 shows the way a sensor should be shielded from an external radiation source (in this case, the sun). Similar mechanisms should be adopted to shield a sensor from the influence of external magnetic fields, such as that of the earth.

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