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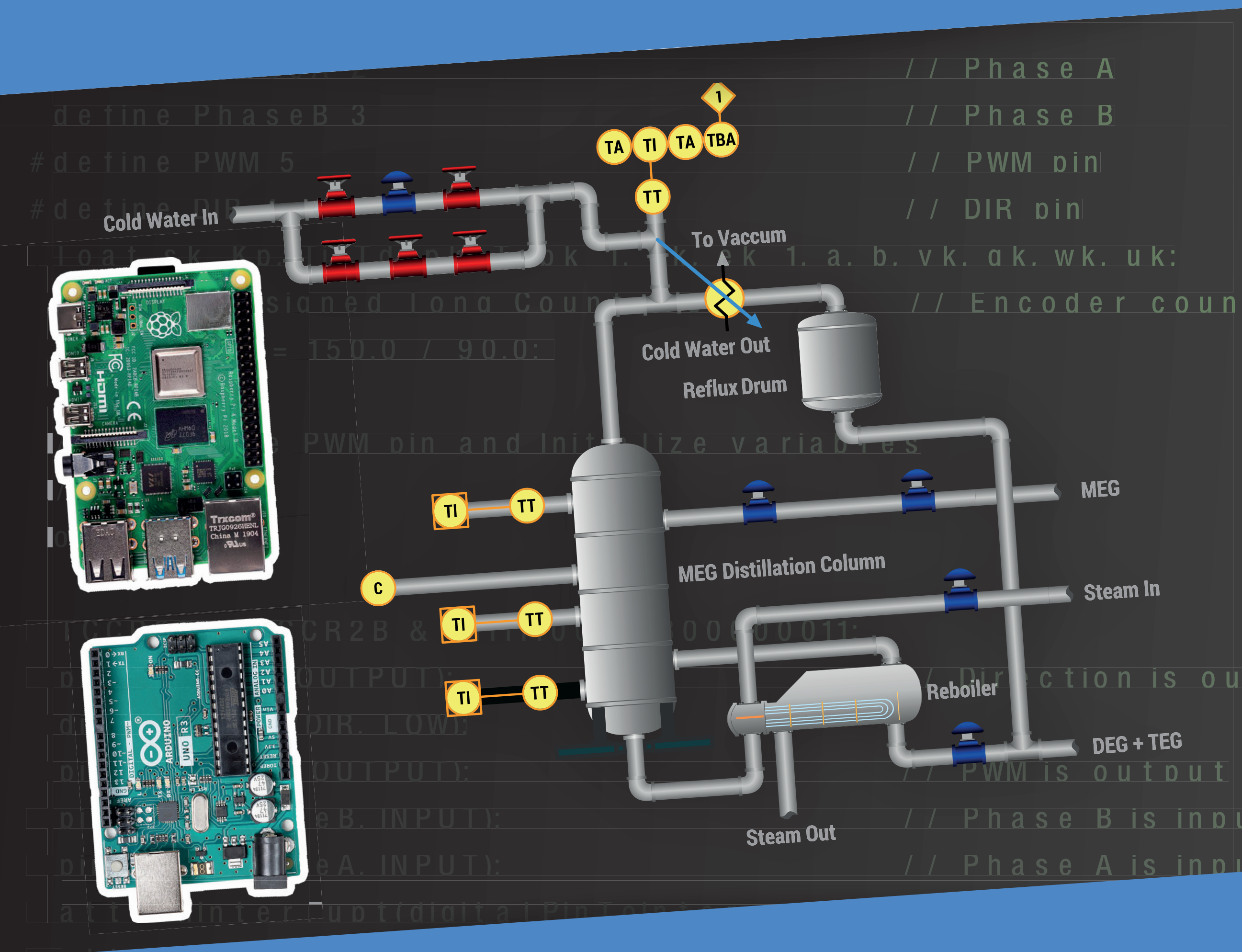
PID-based Practical Digital Control

With Raspberry Pi and Arduino Uno



Dogan Ibrahim

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Contents

Preface

Microcontrollers are highly popular integrated circuits commonly used in many domestic, commercial, and industrial electronic monitoring and control applications. It is estimated that there are more than 50 microcontrollers in every home in developed countries. Domestic equipment having embedded microcontrollers include microwave ovens, printers, keyboards, computers, tablets, washing machines, dishwashers, smart televisions, smartphones, and many more.

Arduino Uno is an open-source microcontroller development system incorporating hardware, an Integrated Development Environment (IDE), and a large number of libraries. The Arduino Uno is supported by a large community of programmers, electronic engineers, enthusiasts, and academics. There are many different designs of the basic Arduino Uno board. Although they are intended for different types of applications, they can all be programmed using the same IDE and in general, programs can be transported between different boards. This may be one of the reasons for the popularity of the Arduino family, which is also supported by countless software libraries for many peripherals that can easily be included in your programs. These libraries make programming a doddle and speed up the programming time. Using libraries also make it easier to test your programs since most of them come as fully tested and working.

The Raspberry Pi 4 is one of the latest credit-card sized popular computers that can be used in many applications such as in audio and video media centers, as a desktop computer, in industrial controllers, robotics, games, and many domestic and commercial applications. In addition to rich set of features found in other Raspberry Pi computers, the Raspberry Pi 4 also offers Wi-Fi and Bluetooth capability which makes it highly desirable for incorporation in remote and Internet-based control and monitoring applications.

This book is about using both the Raspberry Pi 4 and the Arduino Uno in PID-based automatic control applications. The book starts with basic theory of the control systems and feedback control. Working and tested projects are given for controlling real systems using PID controllers. The open-loop step time response, tuning the PID parameters, and the closed-loop time response of the developed systems are discussed in depth together with the block diagrams, circuit diagrams, PID controller algorithms, and the full program listings for the Raspberry Pi as well as the Arduino Uno. The projects given in the book should teach the theory and applications of PID controllers. They can be modified easily as desired for other applications. The projects given for Raspberry Pi 4 should work with all other models of Raspberry Pi family.

It is expected that the readers have some programming experience with the Arduino Uno using the Arduino IDE. The same for the Raspberry Pi with the Python 3 programming language. Some basic electronic hardware experience and knowledge of basic mathematics will also be useful.

All programs discussed in the book are contained in an archive file you can download free of charge from the Elektor website. Head to: www.elektor.com/books and enter the book title in the Search box.

I hope that you enjoy reading the book and at the same time learn the theory and practical applications of the PID controllers.

Dogan Ibrahim
London, 2022

Chapter 1 • Control Systems

1.1 Open-loop and closed-loop

Control engineering covers all aspects of governing a dynamic system, also called a *plant* or a *process*. A plant can be a mechanical system, an electrical system, a thermal system, a fluid system, or a combination of such systems.

A plant can have one or more inputs and one or more outputs. The dynamic behavior of a plant is described by differential equations. Given the model (or the differential equations), inputs, and initial conditions of a plant we can easily calculate its outputs. Generally, a plant is a continuous-time system with its inputs and outputs also continuous in time. For example, an electromagnetic motor is a continuous-time plant whose input (e.g., voltage or current) and its output (e.g., speed or position) are also continuous in time.

Control engineering is based on the theories of system modelling, feedback, system response, and stability. As a result, control engineering is not limited to only one engineering discipline, but is equally applicable to mechanical, chemical, aeronautical, civil, and electrical engineering disciplines.

A plant is normally an **open-loop system** (Figure 1.1) where an actuating device is used to control the plant directly without using feedback. For example, a motor is expected to rotate when a voltage is applied across its input terminals, but we do not know by how much the motor rotates since there is no knowledge about its output. If the motor shaft is loaded and the motor slows down, there is no knowledge about this. As shown in Figure 1.1, a plant may also have external disturbances affecting its behavior, and in an open-loop system there is no way of knowing or minimizing such disturbances.

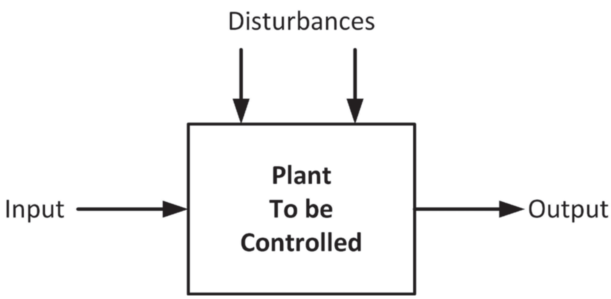

Figure 1.1: Open-loop system

In contrast to open-loop control system, in a **closed-loop** control system (Figure 1.2) the actual plant output is measured and compared with what we would like to see at the plant output. The measure of the output is called **feedback signal**. The difference between the desired output value and the actual output value is called the **error signal**. The error signal is used to force the system output to a point such that the desired output value and the actual output value are equal, i.e., the error signal is zero. One of the advantages of closed-loop control, or feedback control is the ability to compensate for disturbances and yield the correct output even in the presence of disturbances. Also, the plant output settles and remains at the desired value. For example, in a motor speed control system the speed of the motor remains the same when load is applied to the motor shaft. A **controller** (or **compensator**) is usually used to read the error signal and drive the plant in such a way that the error tends to zero.

Sensors are devices which measure the plant output. For example, a thermistor is a sensor used to measure the temperature and it can be used in a closed-loop thermal plant control. Similarly, a tachometer or an encoder can be used to measure the rotational speed of a motor and they can be used in closed-loop motor speed control applications. Notice that in electrical systems a power amplifier may be required after the DAC to drive the plant.

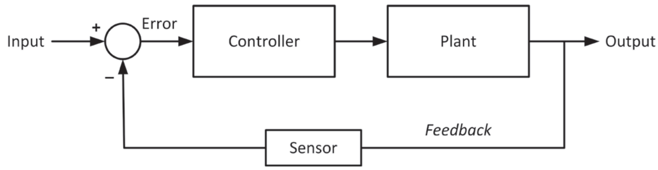

Figure 1.2: Closed-loop system

As you'll discover in a later Chapter, most sensors are analog devices giving analog voltage or current outputs. These sensors can be used directly in analog systems where the inputs, controller, plant, and the outputs are all analog variables.

1.2 Microcontroller in the loop

Nowadays, practically all control systems are microcontroller based, where a microcontroller is used as the central control device. Some sensors (e.g., temperature, pressure, humidity etc.) provide digital outputs and can be connected directly to a microcontroller. Analog sensors cannot be connected directly to a microcontroller. An analog-to-digital converter (ADC) is needed to convert the analog signal into digital form so that it can be fed to a microcontroller.

Figure 1.3 shows a digital control system where the input and the output of the sensor are assumed to be analog. An ADC is used to periodically convert the error signal into digital form and this is fed to a digital controller which is usually a microcontroller. The microcontroller implements a control algorithm (e.g., PID algorithm) and its output is converted into analog form using a digital-to-analog converter (DAC) so that it can drive the plant to set the plant output to the desired value.

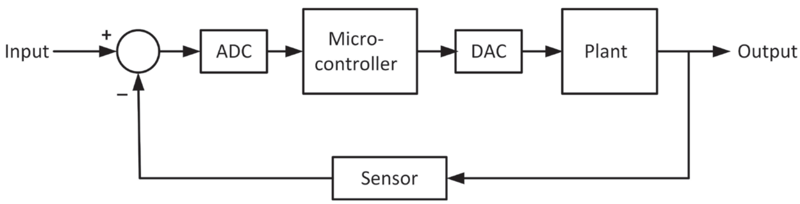

Figure 1.3: Digital control system.

Figure 1.4 shows the block diagram of a digital control system where the ADC is shown as a sampler. Most microcontrollers incorporate ADC and DAC modules and these are shown as part of the microcontroller in Figure 1.4.

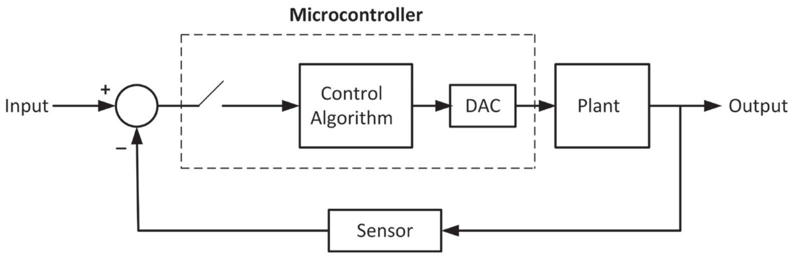

Figure 1.4: Block diagram of a digital control system.

In Figure 1.4 the input and the sensor output are analog signals. A variation of this system is shown in Figure 1.5 where the input is digital and is either hardcoded to the microcontroller software or is input using a suitable input device such as a keypad. Here, a sensor with digital output is used and is connected directly to the microcontroller.

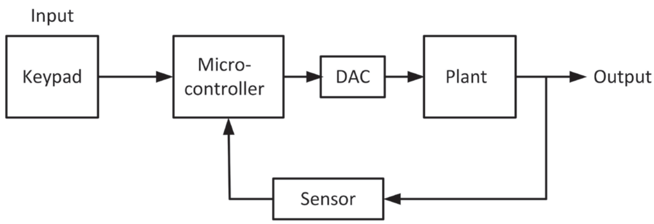

Figure 1.5: Another variation of digital control.

Figure 1.6 shows a typical analog speed control system. Here, the desired speed is set using a potentiometer. The speed of the motor is measured using a tachometer and is fed back to a difference amplifier. The output of this amplifier is the error signal which is input to an analog controller consisting of operational amplifiers. The output of the controller drives the motor through a power amplifier to achieve the desired speed.

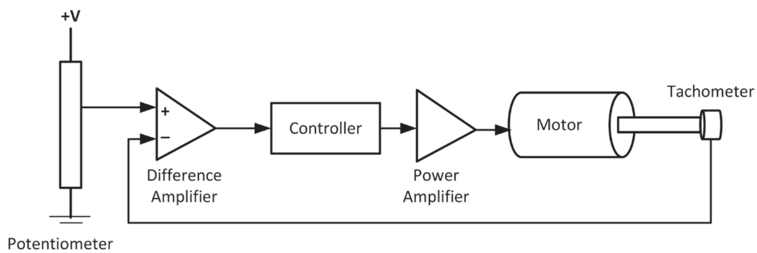

Figure 1.6: Analog speed control system.

Figure 1.7 shows the digital equivalent of Figure 1.6. Here, a digital encoder is used to measure the motor speed and this is fed to the microcontroller together with the desired speed where the speed is set using a keypad. The microcontroller implements the control algorithm and sends its output to the power amplifier in the form of a Pulse Width-Modulated (PWM) signal which in turn provides power to the motor to set the speed at the desired value.

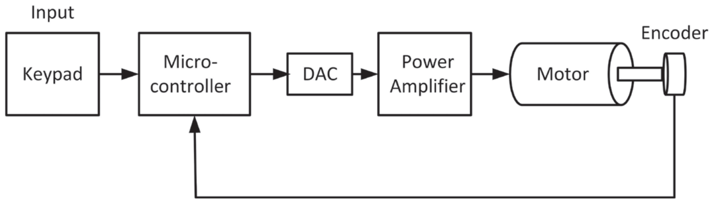

Figure 1.7: Digital speed control system.

Since a plant can be controlled using an analog approach, you might be tempted to ask why use digital control? In the 1960s, computers and microcontrollers were bulky and very expensive devices and their use as digital controllers was not justified. They were only used in large and expensive plants, such as large chemical processing sites or oil refineries. Since the introduction of microcontrollers in 1970s, the cost and size of digital controllers have dropped dramatically. As a result of this, also from the drop in the price of other digital components such as memories, interest in using digital control has soared in the past few decades.

Digital controllers have several advantages compared to analog controllers:

- Improved user interface. Digital controllers can display the system parameters and response graphically on a monitor.
- Digital controllers can be configured to be adaptive. Complex controller algorithms can easily be implemented using digital controllers.
- The cost of digital controllers are lower than the analog ones, especially if additional control loops have to be added to the system.
- It is easy to tune digital controllers. All that is required is to change pertinent parameters in software.
- Digital controllers are more dependable than the analog ones and they are not affected by environmental factors such as component aging, component tolerances, etc.
- Digital controllers can be modified easily through software. Modification of an analog controller on the other hand usually require re-wiring or the use of different or additional components.
- Almost all analog controllers have been replaced over time by digital ones.

1.3 Control system design

Control system design is an engineering process and it must be carried out systematically. The major steps to design a physical control system can be summarized by the following steps:

- Define the system input and output
- Define the variable to be controlled
- Derive a mathematical model (differential equations) of the system
- Decide whether analog or digital control is to be used
- Choose a suitable sensor
- Choose a microcontroller (if digital control is to be used)
- Choose other components such as power supply, op-amp, power amplifier etc.
- Draw a block diagram of the system
- Describe the controller to be used and develop the control algorithm
- Adjust the parameters of the chosen controller
- Simulate the overall system (if simulation tools such as MATLAB are available)
- Assemble the system and observe its behavior. If the system response is as desired, that concludes the project. If on the other hand the system does not behave as required, go back to choose a different controller or to re-adjust the controller parameters, re-simulate and re-test.

Chapter 2 • Sensors

2.1 Sensors in Computer Control

Sensors are important parts of all closed-loop systems. A sensor is a device that outputs a signal which is related to the measurement (i.e., is a function of) a physical quantity, such as temperature, humidity, speed, force, vibration, pressure, displacement, acceleration, torque, flow, light or sound. Sensors are used in closed-loop systems in the feedback loops, and they provide information about the actual output of the plant they are attached to. For example, a speed sensor gives a signal proportional to the speed of a motor and this signal is subtracted from the desired speed reference input in order to obtain the error signal. Similarly, a liquid level sensor gives a signal proportional to the level of liquid in a container. Such a sensor is used in controlling the level of a liquid in a container.

Sensors can be divided into two groups: analog or digital. Analog sensors are widely used and their outputs are analog signals (e.g., voltage or current) proportional to the physical quantity to be measured. Most environmental variables in the world are analog by nature, for example the temperature, humidity, pressure etc. An analog temperature sensor gives an analog voltage directly proportional to the measured temperature. Analog sensors can only be connected to microcontrollers using ADC converter modules.

Digital sensors are not very common and they give digital logic level outputs which can be directly connected to a computer. The advantage of using digital sensors is that they are more accurate and stable than the analog ones and they can directly be connected to a computer. Digital sensors also tend to me more expensive than their analog equivalents.

The choice of a sensor for a particular application depends on several factors such as the availability, cost, accuracy, precision, resolution, range, and linearity of the sensor. Some important sensor related parameters are described below.

Range: The range of a sensor specifies the upper and lower limits that can be measured by the sensor. For example, if the range of a temperature sensor is specified as 10 – 60 ºC then the sensor should only be used to measure temperatures within this range.

Resolution: The resolution of a sensor is specified as the largest change in measured value that will not result in a change in sensor's output. i.e., the measured value can change by the amount quoted by the resolution before this change can be detected by the sensor. In general, the smaller this amount the better the sensor is, and sensors with a wide range have less resolution. For example, a temperature sensor with a resolution of 0.01 ºC is better than a sensor with a resolution of 0.1 ºC.

Sensitivity: The sensitivity of a sensor is defined as the slope of the output characteristic curve. More generally, it is the minimum input of physical parameter that will create a detectable output change. For example, a typical temperature sensor may have a sensitivity rating of 1 ºC. This means that the output voltage will not change if the temperature change is less than 1 ºC .

Accuracy: The accuracy of a sensor is the maximum difference that will exist between the actual value and the indicated value at the output of the sensor. The accuracy can be expressed either as a percentage of full scale or in absolute terms.

Repeatability: The repeatability of a sensor is the variation of output values that can be expected when the sensor measures the same physical quantity with the same conditions. For example, if the voltage across a resistor is measured at the same time several times you may get slightly different results.

Linearity: An ideal sensor is expected to have a linear transfer function. i.e., the sensor output is expected to be exactly proportional to the measured value. For example, the LM35 temperature sensor chip output is linear and is specified as 10mV/ºC. At 10 ºC the output voltage is 100 mV, at 20 ºC it is 200 mV and so on. In practice all sensors exhibit some amount of nonlinearity depending upon the manufacturing tolerances and the measurement conditions.

Offset error: The offset error of a sensor is defined as the output that will exist when it should be zero. For example, the output of a force sensor should be zero if there is no force applied to the sensor.

Dynamic response: The dynamic response of a sensor specifies the limits of the sensor characteristics when the sensor is subject to a sinusoidal frequency change. For example, the dynamic response of a microphone may be expressed in terms of the 3-dB bandwidth of its frequency response.

Response time: Sensors do not change their output states immediately when an input parameter change occurs. For example, a temperature sensor does not give new reading as soon as the temperature changes, but rather, it will take some time before the output changes. The response time can be in microseconds, milliseconds, or seconds depending upon the sensor used. Sensors with short response times, although more expensive, are preferred in most applications.

Self-heating: The internal temperatures of some sensors may increase when used continuously for long times and this is called self-heating. Self-heating is not desirable as it may cause the output of the sensor to change. For example, a temperature sensor with self-heating feature may give wrong and fluctuating outputs as the sensor is used over time.

Physical size: The physical size of a sensor can be important in some applications. Users should check the dimensions of a sensor before it is considered for use.

Operating voltage: This is also an important factor to consider before a sensor is used. The operating voltage, as well as the minimum and maximum voltages that can be applied to the sensor should be known before a sensor is used. For example, if the operating voltage is specified as +3.3 V then this value must not be exceeded.

In the remainder of this Chapter, the operation and characteristics of some popular sensors are discussed.

2.2 Temperature Sensors

Temperature is one of the fundamental physical variables in most chemical and process control applications. Accurate and reliable measurement of the temperature is important in all process control applications. The choice of a temperature sensor depends on the required accuracy, temperature range, response time, cost, and the environment where it will be used (e.g., chemical, electrical, mechanical, environmental etc.). Temperature sensors are available as either analog or digital. Both sensor types are described briefly in the following sections.

2.2.1 Analog Temperature Sensors

Some of the most commonly used analog temperature sensors are: thermocouples, resistance temperature detectors (RTDs), thermistors, and sensors in te form of chips (integrated circuits). Table 2.1 shows the basic characteristics of different types of analog temperature sensors.

Sensor	Temperature range (ºC)	Accuracy (± ºC)	Cost	Robustness
Thermocouple	−270 to +2600	1	Low	Very high
RTD	−200 to +600	0.2	Medium	High
Thermistor	−50 to +200	0.2	Low	Medium
Integrated circuit	−40 to +125	1	Low	Low

Table 2.1: Analog temperature sensors.

Thermocouples

Thermocouples (Figure 2.1) are best suited to very low and very high temperature measurements. They have the advantages that they are low-cost, very robust, and they can be used in chemical environments. The typical accuracy of a thermocouple is ±1 ºC. Thermocouple temperature sensors can be made with various conductor materials for different temperature ranges and output characteristics. Thermocouple types are identified with single letters of the alphabet. Figure 2.1 shows the temperature ranges of various thermocouples. Notice that lead color codes are used to identify thermocouples. The materials used to form thermocouples is shown in Figure 2.2. For example, one of the commonly used low-cost thermocouples is Type K which is made from chromel/alumel junction, identified with green lead color, and has temperature range of −180 ºC to +1300 ºC .

Thermocouple Type	Temperature Range (°C)				
	Short Term Use	Continuous Use	Class 1 Tolerance*	Class 2 Tolerance*	Class 3 Tolerance*
Type E	−40 to +900	0 to +800	-40 to +800	-40 to +900	-200 to +40
Type J	−180 to +800	0 to +750	-40 to +750	-40 to +750	N/A
Type K	−180 to +1300	0 to +1100	-40 to +1000	-40 to +1200	-200 to +40
Type N	−270 to +1300	0 to +1100	-40 to +1000	-40 to +1200	-200 to +40
Type R	-50 to +1700	0 to +1600	0 to +1600	0 to +1600	N/A
Type S	−50 to +1750	0 to +1600	0 to +1600	0 to +1600	N/A
Type T	−250 to +400	−185 to +300	-40 to +350	-40 to +350	-200 to +40
Type B	0 to +1820	+200 to +1700	N/A	+600 to +1700	+600 to +1700

Thermocouple Tolerances: IEC 60584-2:1982 / BS EN 60584-2:1993

*Thermocouples of this tolerance class can be used outside this range, but no tolerance is defined outside these limits.

Figure 2.1: Thermocouple types.

Thermo-couple	Material (+ / −)
Type E	Chromel / Constantan
Type J	Iron / Constantan
Type K	Chromel / Alumel
Type N	Nicrosil / Nisil
Type R & Type S	Platinum–Rhodium / Platinum
Type T	Copper / Constantan
Type B	Platinum–Rhodium / Platinum–Rhodium

Figure 2.2: Materials used in different thermocouples.

To get the temperature from a thermocouple a thermocouple amplifier is generally used. The temperature output from the thermocouple amplifier depends on the voltage of the reference junction. The voltage at the reference junction depends on the temperature difference between the reference junction and the thermal junction. Therefore, you need to know the temperature at the reference junction. The MAX6675 thermocouple amplifier module (Figure 2.3) comes with an on-board temperature sensor to measure temperature at the reference junction and also amplifies the small thermocouple voltage at the reference junction so that you can read it using a microcontroller.

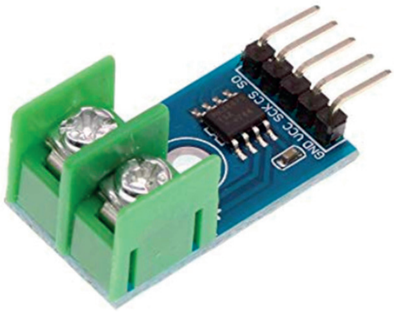

Figure 2.3: MAX6675 thermocouple amplifier module.

Thermocouples are available in various shapes and forms. Some sensors are equipped with 2-way plugs for ease of connecting to a measuring device. Figure 2.4 shows some of the commonly available thermocouples.

Figure 2.4: Some thermocouples.

RTDs

RTDs (Resistance Temperature Detector) are sensors whose resistance changes with temperature. The resistance increases as the temperature of the sensor increases. The resistance *vs* temperature relationship is well known and repeatable over time. RTDs are passive devices and they do not produce any output. Usually, the resistance of an RTD is measured by passing a small electrical current through it and then measuring the voltage across the sensor. Care should be taken not to pass large currents as self-heating of the sensor may occur. Typically, 1 mA or less current is passed through the sensor. Figure 2.5 shows some RTD sensors. RTDs have excellent accuracies over a wide temperature range and some RTDs have accuracies better than 0.001 ºC . another advantage of the RTDs is that they drift less than 0.1 ºC /year.

Figure 2.5: Some RTDs.

In order to achieve high stability and accuracy, RTD sensors must be contamination free. Below about 250 ºC the contamination is not much of a problem, but above this temperature, special manufacturing techniques are used to minimize the contamination. RTD sensors are usually manufactured in two forms: wire wound, or thin film. Wire-wound RTDs are made by winding a very fine strand of platinum wire into a coil shape around a non-conducting material until the required resistance is obtained. Thin-film RTDs are made by depositing a layer of platinum in a resistance pattern on a ceramic substrate. The most commonly used RTD standard is the IEC 751 which is based on platinum with a resistance of 100 Ω at 0 ºC.

For high accuracy it is recommended to use an RTD-to-digital converter module like the MAX31865 module (Figure 2.6). This chip is optimized for platinum RTDs. An accurate reference resistor is used to set the sensitivity for the RTD. An on-chip ADC returns the ratio of the RTD resistance to the reference resistance in digital form. Knowing the reference resistance, you can easily calculate the RTD resistance and hence the measured temperature either from temperature-resistance tables or using a library function.

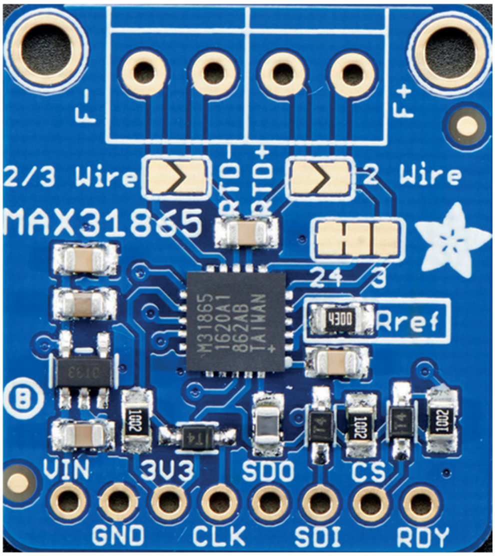

Figure 2.6: MAX31865 RTD converter module.

Thermistors

The name **thermistor** derives from the words **thermal** and **resistor**. Thermistors are temperature sensitive passive semiconductors which exhibit a large change in electrical resistance when subjected to a small change in body temperature. Thermistors are manufactured in a variety of sizes and shapes (Figure 2.7). beads, discs, washers, wafers, and chips are the most widely used thermistor sensor types.

Figure 2.7: Different shapes of thermistors.

Thermistors are generally available in two types: Negative Temperature Coefficient (NTC) and Positive Temperature Coefficient (PTC). PTC thermistors are generally used in power circuits for inrush current protection. NTC thermistors exhibit many desirable features for temperature measurement. Their electrical resistance decreases with increasing temperature (Figure 2.8) and the resistance-temperature relationship is very nonlinear. The resistance of a thermistor is referenced to 25 ºC and for most applications the resistance at this temperature is between 100 Ω and 100 kΩ.

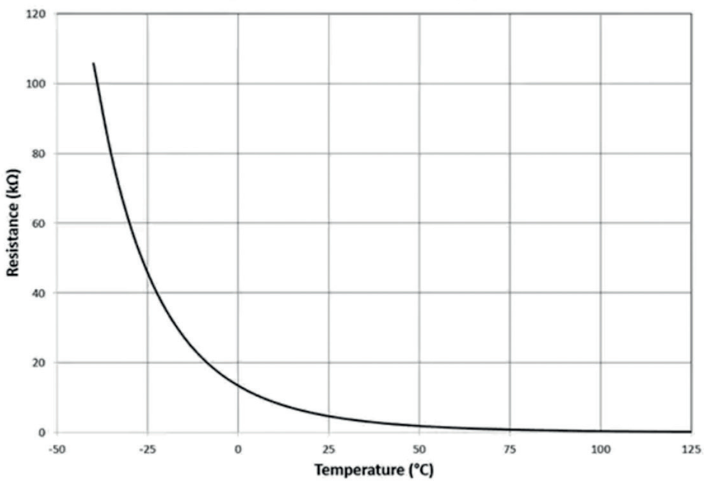

Figure 2.8: Typical thermistor R/T characteristic.

The advantages of NTC thermistors are:

Sensitivity: One of the advantages of thermistors compared to thermocouples and RTDs is their large change in resistance with temperature, typically –5% per ºC.

Small size: Thermistors have very small sizes and this makes for a very rapid response to temperature changes. This feature is very important in temperature feedback control systems where a fast response may be required.

Ruggedness: Most thermistors are rugged and can handle mechanical and thermal shock and vibration better than other types of temperature sensors.

Remote measurement: Thermistors can be used to sense the temperature of remote locations via long cables because the resistance of a long cable is insignificant compared to the relatively high resistance of a thermistor.

Low-cost: Thermistors cost less than most other types of temperature sensors.

Interchangeability: Thermistors can be manufactured with very close tolerances. As a result, it is possible to swap thermistors without having to recalibrate the measurement system.

Thermistors can suffer from self-heating problems as a result of current passing through them. When a thermistor self-heats, the resistance reading drops relative to its true value and this causes errors in the measured temperature. It is therefore important to minimize the electrical current through a thermistor.

Thermistors can be used in circuits in series with a known accurate fixed resistor. By measuring the voltage across the thermistor, you can calculate its resistance. Alternatively, constant current, bridge, or operational amplifier circuits can be designed to measure the resistance of a thermistor. After finding the resistance of a thermistor, you can calculate the temperature using tables (if available), or a library function (if available), or use the standard **Steinhart-Hart** equation given below:

$$\frac{1}{T}=\frac{1}{T_0}+\frac{1}{B}\ln\left(\frac{R}{R0}\right)$$

or

$$T=\frac{1}{1/B\,Ln\left(R/R_0\right)+1/T_0}$$

Where T_0 is the room temperature in K (298.15), B is the thermistor temperature constant, R_0 is the thermistor resistance at room temperature, and R is the measured resistance of the thermistor. An example is given below.

Example

The temperature constant of a thermistor is B = 2910. Also, its resistance at room temperature (25 ºC) is 1 kΩ. This thermistor is used in an electrical circuit to measure the temperature and it is found that the resistance of the thermistor is 800 Ω. Calculate the measured temperature.

Solution

Here, you know that B = 2910, T_0 = 298.15, R = 800 Ω, and R_0 = 1000 Ω

$$T = \frac{1}{1/2910\,Ln\left(800/1000\right) + 1/298.15} = 310.24$$ Kelvin

or T = 310.24 – 273.15 = 37.09 ºC

Integrated circuits

Integrated circuit analog sensors are semiconductor devices. they differ from other sensors in some fundamental ways:

- They have relatively small physical sizes.
- Their outputs are linear.
- The temperature range is relatively limited.
- The cost is relatively low.
- They often lack good thermal contacts with the outside world and as a result it is usually more difficult to use them other than measuring the air temperature.
- A power supply is required to operate these sensors.

Analog integrated circuit temperature sensor can be voltage output or current output. In this section you will look at the characteristics of some commonly used sensors.

LM35DZ

This is a popular 3-pin temperature sensor (Figure 2.9) chip whose output voltage is linear, given by 10 mV/ ºC . For example, at 10 ºC the output voltage is 100 mV, at 20 ºC it is 200 mV and so on. this sensor has the range 0 ºC to +100 ºC (the CZ version of this sensor has a wider temperature range like –20 ºC to +120 ºC). The accuracy of this sensor is ±1.5 ºC and the operating voltage is 4 to 30 V.

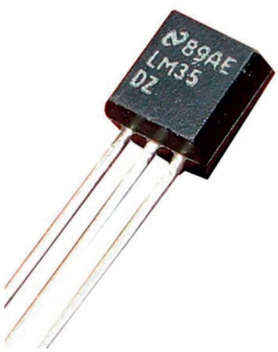

Figure 2.9: The LM35DZ temperature sensor.

The LM34 is similar to the LM35DZ but it measures in degrees Fahrenheit. The LM134, AD590, and AD592 are current-output temperature sensors where the output current is directly proportional to the measured temperature. For example, the output of AD590 (Figure 2.10) is given as 1 μA/K.

Figure 2.10: AD590 temperature sensor.

TMP36
This is another popular analog integrated circuit temperature sensor chip. The size and configuration of the sensor is same as in Figure 2.9. The output of TMP36 is linear with the measured temperature given by: V_o – 500 /10, where V_o is the sensor output voltage in millivolts.

2.2 Digital Temperature Sensors
These sensors produce digital outputs and therefore they can be directly connected to microcontrollers. The outputs are non-standard and the measured temperature can be extracted in software by using a suitable algorithm. Table 2.2 gives a list of some popular digital output temperature sensors.

Sensor	Output	Maximum error	Temperature range
LM75	I2C	±3 ºC	−55 ºC to +125 ºC
TMP03	PWM	±4 ºC	−25 ºC to +100 ºC
DS18B20	1-Wire	±0.5 ºC	−55 ºC to +125 ºC
AD7814	SPI	±2 ºC	−55 ºC to +125 ºC
MAX6575	1-Wire	±0.8 ºC	−40 ºC to +125 ºC
DHT11	Serial 1 wire	±2 ºC	0 ºC to +50 ºC
DHT22	Serial 1 Wire	±0.5 ºC	−40 ºC to +80 ºC

Table 2.2: Some digital-output temperature sensors.

DHT11 and DHT22 (Figure 2.11) are highly popular 3-terminal digital output sensors. Both devices can measure temperature as well as relative humidity. Arduino and Raspberry Pi libraries are available for both sensors for reading the temperature and humidity data easily.

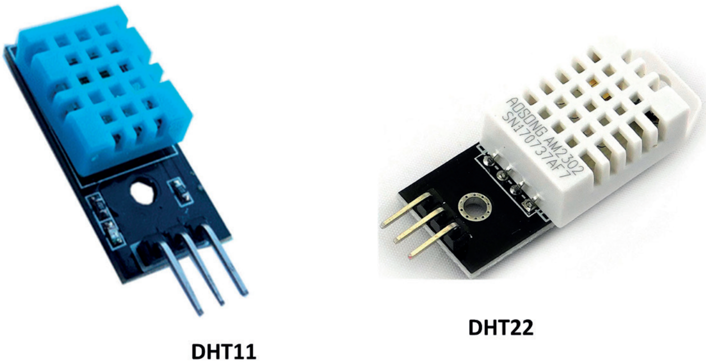

Figure 2.11: The DHT11 and DHT22 sensors.

2.3 Position Sensors

Position sensors are used to measure the position of moving objects. These sensors are basically of two types: sensors to measure linear movement, and sensors to measure angular movement.

The simplest position sensor is a potentiometer. Potentiometers are available in linear and rotary forms. In a typical application, a fixed voltage is applied across the potentiometer and the voltage across the potentiometer arm is measured. This voltage is proportional to the position of the arm, and hence by measuring the voltage you know the position of the arm. Figure 2.12 shows a linear potentiometer. If the applied voltage is V_i , the voltage across the arm is given by:

$$V_a = k\, V_i\, y$$

where y is the position of the arm from the beginning of the potentiometer, and *k* is a constant.

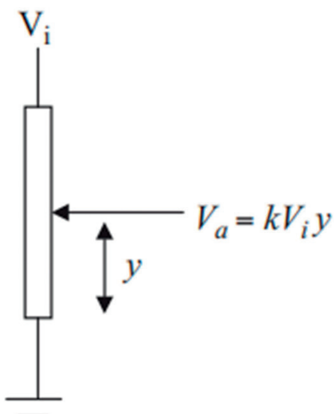

Figure 2.12: Linear potentiometer.