Pearson BTEC Level 4 Higher Nationals in Engineering (RQF)

Unit 16: Instrumentation and Control Systems

Unit Workbook 1

in a series of 4 for this unit

Learning Outcome 1

Instrumentation Systems

- Phone chargers have voltage and current control.
- Streetlights have light control.

These are small examples of control, but control can be developed into much larger systems. Heavy industry use control to monitor the condition of their equipment, we need to consider the pressure and the condition of pipework. Engineers need to make sure boilers are working effectively, producing the right amount of heat, the emissions are within government regulations.

1.1 Sensors and Transducers

1.1.1 Transducers

Transducers are the name given to components that converts variations in a physical quantity (pressure, brightness, temperature) into an electrical signal, or vice versa. They are used in data acquisition to produce the electrical signal and feed it to a microcontroller, the microcontroller will analyse the signal and decide if the system needs appropriate adjustment.

Theory Most data acquisition signals can be described as analogue, digital, or pulse. While analogue signals typically vary smoothly and continuously over time, digital signals are present at discrete points in time. In most control applications, analogue signals range continuously over a specified current or voltage range, such as $4-20$ mA DC or $0-5$ V DC. While digital signals are essentially on or off, analogue signals represent continuously variable entities such as temperatures, pressures, or flow rates. Because computer-based controllers and systems understand only discrete on/off information, conversion of analogue signals to digital representations is necessary.

Transduction is the process of changing energy from one form into another. Hence, a transducer is a device that converts physical energy into an electrical voltage or current signal for transmission. There are many different forms of analogue electrical transducers. Common transducers include load cells for measuring strain via resistance, and thermocouples and resistance temperature detectors (RTDs) for measuring temperature via voltage and resistance measurement, respectively. Transmission channels are many and varied and we will discuss these later in this workbook.

The operation of a transducer can be described by Eq.1.1, where H is the transfer function.

$$Output\ Quantity = H \cdot Input\ Quantity \qquad \text{(Eq.1.1)}$$

For the purposes of this course, all transducers convert physical quantities into electrical ones; in other words, they convert one form of energy into another. Given that the transducer is at the front end of measurement operations, its properties and performance are critical to the performance of the measurement system as a whole. Some of these properties are as follows;

- **Dynamic Response** – The change in the output y caused by a change in the input x, where x and y are functions of time t.
- **Impulse Response** – Output when presented with a brief input signal, called an impulse.
- **Frequency Response** – The quantitative measure of the output spectrum of a system or device in response to a stimulus and is used to characterize the dynamics of the system. It is a measure of magnitude and phase of the output as a function of frequency, in comparison to the input.
- **Resolution** – The smallest unit of measurement that can be indicated by the measuring system.

- **Sensitivity** – The efficiency of the conversion process. It is the smallest amount of difference in quantity that will change an instrument's reading. A measuring tape for example will have a resolution, but not sensitivity.
- **Transfer Function** – The ratio of the output quantity to the input quantity of a system
- **Stability** - A measure of how the accuracy and precision of the measurement system perform over time. In other words, it is a measure of how much the output drifts in the face of a constant input. Stability will determine the required interval between calibration of the measurement system.
- **Noise** – There are many sources of noise in electronic systems, but all electronic systems are subject to it and exhibit random fluctuations of output for no discernible input.
- **Signal to Noise Ratio (SNR)** – Simply the ratio between the wanted signal and the unwanted background noise. Obviously, it is desirable that the SNR is as high as possible.
- **Dynamic Range** – Dynamic range is a term used to describe the ratio between the smallest and largest signals that can be measured by a system. The dynamic range of a data acquisition system is defined as the ratio between the minimum and maximum amplitudes that a data acquisition system can capture.
- **Linearity** - Describes how accurate measurements are across the complete expected range of the measurements. It answers the question about how accurate the system is across the dynamic range of the system.

1.1.2 Types of Transducers

There are a large number of different types of transducers available, the idea behind most of them are to convert the physical attributes they detect into an electrical signal which is then processed by the controller.

- **Temperature Sensors** – Used to measure variations with transfer with temperature, following well-characterised transfer functions. This should be no surprise since nearly all electronic components have properties that vary with temperature. Many of these components could potentially be used as temperature transducers if their transfer functions were well behaved and insensitive to other variables. Examples include; Thermocouples, Thermistors, Resistance Temperature Detectors, and Monolithic Temperature Transducers.
- **Optical Sensors** – Used for detecting light intensity. Typically, they respond only to particular wavelengths or spectral bands. Examples include; Vacuum Tube Photo Sensors, Photoconductive Cells, Photovoltaic (Solar) Cells, Semiconductor Light Sensors, and Thermoelectric Optical Sensors.
- **Position Displacement Sensors** – Used to measure mechanical displacement or position of an object. Some require physical connection to the object, others do not. Examples include; Potentiometers, Capacitive and Inductive Sensors, Linear Voltage Differential Transformers (LVDT), Optical Encoders, and Ultrasonic Range Finders.
- **Force and Pressure Transducers** – Used for measuring force and pressure. Most pressure transducers rely on the movement of a diaphragm mounted across a pressure differential and the transducer measures minute movements in the diaphragm. Capacitive and inductive pressure sensors operate in a similar way to capacitive and inductive displacement sensors. Examples include; Strain Gauges, and Piezoelectric Transducers.
- **Magnetic Field Sensors** – Measure either varying or fixed magnetic fields.
- **Ionising Radiation Sensors** – Ionizing radiation can be particle produced by radioactive decay, such as alpha or beta rays, or high-energy electromagnetic radiation, such as gamma rays or X-rays. In many of these detectors, a radiation particle or photon collides with an active surface material which as a result

produces charged particles which are measured as an electric current. Examples include Geiger Counters, Semiconductor Radiation Detectors, and Scintillation Counters.

- **Humidity Sensors** – Relative humidity is the moisture content of the air which can cause pressure variations in the air or can cause variation in the electrical properties of materials. Examples include; Resistive Hygrometer Sensors and Capacitive Hygrometer Sensors.
- **Fluid Flow Sensors** – Many Industrial processes involve fluids and so there is a need to measure and control their flow. A wide range of transducers and techniques are commonly used to measure fluid flow rates. Examples include; Head meters, Rotational Flowmeters, and Ultrasonic Flowmeters.
- **Fibre Optic Sensors** – A new class of sensor which tend to be immune from Electro-Magnetic Interference (EMI) and measure amplitude, phase or polarization of light. The transducer is constructed so that one or more of these parameters varies with the physical quantity of interest.
- **Micro-Electro-Mechanical Systems (MEMS)** – Small electromechanical devices made using semiconductor integrated circuits.
- **Smart Sensors** – Cover a wide variety of devices which could range from a traditional transducer that simply contains its own signal conditioning circuitry to a device that can calibrate itself, acquire data, analyse it, and transmit the results over a network to a remote computer. An emerging class of smart sensors is defined by the family of IEEE 1451 standards, which are designed to simplify the task of establishing communications between transducers and networks.
- **Rotational Motion** – Tachometers are used to measure the rotational speed of the shaft, by attaching a small magnet to a shaft, another magnet is used to generate a magnetic field, which will generate a voltage pulse in the system. By counting the number of pulses, it is possible to count the revolutions for a given time frame.

1.2 Instrumentation Terminology

Purpose People make measurements for many reasons: to make sure an item will fit, to determine the correct price to pay for something, or to check that a manufactured item is within specification. In all cases, a measurement is only useful if it is suitable for the intended purpose.

Consider the following questions:

- Do you know how accurate your measurement result is?
- Is this accurate enough?
- How strongly do you trust the result?

These questions relate to the quality of a measurement. When talking about measurement quality, it is important to understand the following concepts:

1.2.1 Precision, Accuracy and Uncertainty

Theory Precision is about how close measurements are to one another. Accuracy is about how close measurements are to the 'true value'. In reality, it is not possible to know the 'true value' and so we introduce the concept of uncertainty to help quantify how wrong our value might be. The difference between accuracy and precision is illustrated in Fig.1.1 below. The idea is that firing an arrow at a target is like making a measurement. Accuracy is a qualitative term that describes how close a set of measurements are to the actual (true) value (the bullseye). Precision describes the spread of these measurements when repeated. A measurement that has high precision has good repeatability.

Fig.1.1: The difference between accuracy and precision

In practice we are not able to view the target and assess how close to the 'true value' our measurements are. What interests us is the answer to the question "How far from the target could our arrows have fallen?" We also need to ask, "How wrong could we have been?" To answer these questions, we need to look at all the factors that go into making a measurement and how each factor could have affected the final estimate of the answer. The answer to "How wrong are we likely to have been?" is known as the 'measurement uncertainty', and this is the most useful assessment of how far our estimate is likely to lie from the 'true value'. For example, we might say that the length of a particular stick is $200cm$ with an uncertainty of $\pm 1cm$.

1.2.2 Don't Confuse Mistakes with Errors!

Theory

Measurement scientists use the term 'error' to specify the difference between an estimate of quantity and its 'true value'. The word 'error' does not imply that any mistakes have been made. Where the size and effect of an error are known (e.g. from a calibration certificate) a correction can be applied to the measurement result. If the value of an error is not known, this is a source of uncertainty.

- **Uncertainty** is the quantification of the doubt about the measurement result and tells us something about its quality.
- **Error** is the difference between the measured value and the true value of the thing being measured.
- **True value** is the value that would be obtained by a theoretically perfect measurement.

So, what is not uncertainty?

- Mistakes made by operators are NOT uncertainties – operator mistakes can be avoided by working carefully through a procedure and checking work.
- Tolerances are NOT uncertainties – tolerances are acceptance limits chosen for a process or product.
- Accuracy is NOT uncertainty – the true value of a measurement is never known.

1.2.3 Repeatability and Reproducibility

Theory

'Measure twice and cut once.' This popular proverb expresses the need to make sure we have a good measurement before committing to a potentially irreversible decision. It is a concept that you should adhere to. By repeating a measurement many times, a mean (average) value can be calculated. If the repeatability is high, the statistical uncertainty in the mean value will be low. However, if different measuring equipment is used, a different result may be obtained because of errors and offsets in the instruments.

If you take a voltage measurement three times in one minute using the same multimeter, you would expect to get a similar answer each time. Repeatability describes the agreement within sets of measurements where the same person uses the same equipment in the same way, under the same conditions. But if another person had a go at taking the same measurement on different days using different measuring equipment, a

Table.1.1: The eight different states and their relative outputs

$V_1 (V)$	$V_2 (V)$	$V_3 (V)$	State	$V_{out} (V)$
0	0	0	0	0
0	0	1	1	−0.25
0	1	0	2	−0.5
0	1	1	3	−0.75
1	0	0	4	−1.0
1	0	1	5	−1.25
1	1	0	6	−1.5
1	1	1	7	−1.75

So now, rather than just having one state (a binary on/off), the system now has eight different states developed, which can be seen in Fig.1.3.

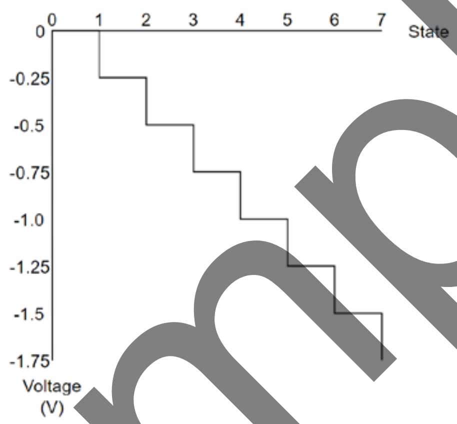

Fig.1.3: V_{out} with varying state

The current resolution of this system is three-bit (or -0.25V when considering the step size). To add more bits and increase the resolution of the system, we can add a fourth input, V_3, to the system (as many as is desired can be added). If this is to work, the relationship between the resistors must be noted, and the resistance value must be doubled again (so for a four-bit system, V_3 requires a resistance of 8R). If the fourth input is added, the step size will be reduced to $-0.125V$, with the LSB now becoming V_3. The difference that can be seen in resolution is shown in Fig.1.4.

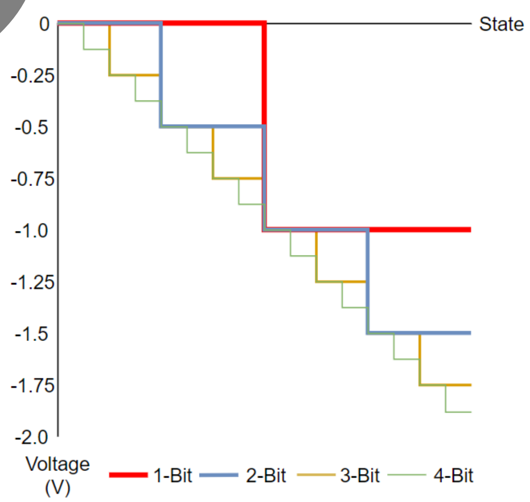

Fig.1.4: The variation in output between different resolutions

We can already see that there is a difference in the range available between different resolutions, but what effect would this have on the analogue signal it is processing.

1.3.2 ADCs

The input to an analogue to digital converter consists of a voltage that is continuously variable, such as sine waves, human speech, or camera signals. The output, however has defined states (the number of levels is almost always $2^n - 2,4,8,16,\ldots$). The simplest systems will only have two states (on/off) which is called binary.

Digital signals are well-defined and easy for electronic circuits to distinguish from the chaos of analogue signals, which will have a lot of noise (random background anomalies in the signal). A microprocessor can read analogue signals, but if a computer is going to process this information, think about a solution and talk to other systems, they must communicate in digital.

Let's look at a flash ADC, this is similar to the DAC converter, in the sense that the voltage is split into 2^n parts, which is then fed into a Priority Encoder, the priority encoder consists of a comparator at each voltage split, which translates this voltage into a binary signal to be fed into XOR gates (exclusively or, meaning an output is given when only one of the two inputs are active), which feeds into an encoder. The goal of this is to find the last comparator with a high output, starting from the bottom of the chain.

For this example, we will look at a two-bit flash ADC, shown in Fig.1.5. The input voltage is compared with a reference voltage which will decrease the further down the line of comparators you go. Our input voltage, V_{in}, is (at this particular moment) 0.6V, our reference voltage, V_{ref}, is 1V. The value of each resistor is the same, all of which are 25Ω, this means that every resistor will drop the V_{ref} for a comparator by $0.25V$.

Looking at the comparator at the bottom (comparator 3), we know that $0.6 - 0.25 > 0$, so this comparator will exhibit an output (Boolean output = TRUE = 1); comparator 2 will also show an output of 1 ($0.6 - 0.5 > 0$). Comparator 1, however, now has a greater V_{ref} than V_{in} ($0.6 - 0.75 < 0$), meaning that the comparator will show now output (Boolean output = FALSE = 0). The Boolean algebra of the system means that there are four states in this system. No gates are open, or either gate 1, 2 or 3 are open). The encoder can then convert this to a digital value.

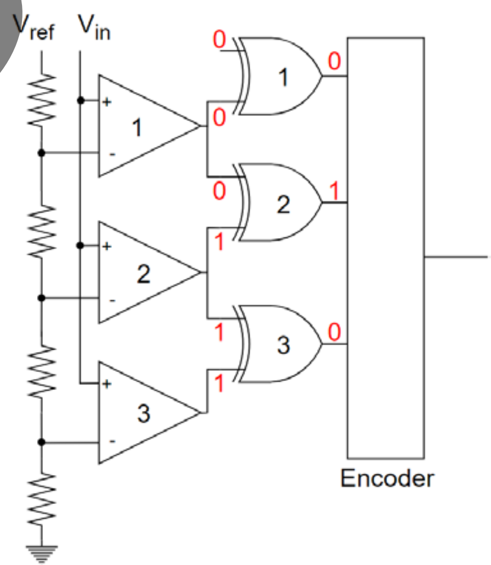

Fig.1.5: 2-bit encoder demonstrating the outputs for $V_{ref} = 1V$ and $V_{in} = 0.6V$

Table.1.2 shows the effect of changing V_{in}, including the output of the comparators and the XOR gates.

V_{in}	Comparator Output			XOR Gate Output			State
	1	2	3	1	2	3	
0.9	1	1	1	1	0	0	3
0.7	0	1	1	0	1	0	2
0.5	0	0	1	0	0	1	1
0.3	0	0	1	0	0	1	1
0.1	0	0	0	0	0	0	0

This type of ADC is very fast and will convert almost instantly, as the Boolean logic is simple and easy to encode. However, as the resolution is increased, it requires a large number of comparators (n-bit resolution requires $2^n - 1$ comparators and given that data is normally communicated in 8-bit, most systems would use 255 comparators) The large number of comparators and resistors used in such a system is also very power consuming.

There are other ADCs that exist but will require personal research, these are:

- Integrating or Dual-Slope converters
- Pipelined ADCs
- Sigma Delta converters
- Successive approximation register (SAR) converters

1.3.3 Hysteresis

Hysteresis is the lag that a system might exhibit as the difference in voltage transitions between different states. However, hysteresis is important in electronics and control; by leaving the hysteresis gap in between the different states, it can prevent accidental switching in the control when experiencing noise. Fig.1.6 shows hysteresis regarding voltage.

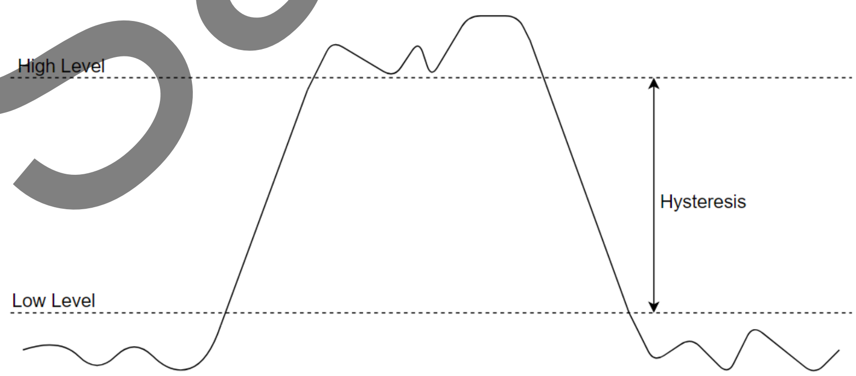

Fig.1.6: Electronic Hysteresis

1.4 Signal Range

In order to collect and condition a signal, we need to make sure our receiver and transmitter are operating on compatible ranges. The human ear can sense within a range of $20\ \text{Hz} - 20\ \text{kHz}$, but sounds exist outside