Pearson BTEC Level 4 Higher Nationals in Engineering (RQF)

Unit 16: Instrumentation and Control Systems

Unit Workbook 2

in a series of 4 for this unit

Learning Outcome 2

Process Control Systems

Engineering would not be where it is today without the appropriate control systems, they are used to design and optimise systems, while also keeping a high quality and safety. Almost every discipline in engineering needs to consider how a design is to be monitored and controlled. We can take a car as an example, the modern car is much safer, comfier and more efficient than cars from even twenty or thirty years ago.

2.1 Control Systems in a Modern Car

The component in the modern car that is the least optimised is the human driving it, hence why the largest companies are researching and developing the driverless car. Humans are prone to mistakes or can sometimes just have the smallest lapse in concentration, they can be emotional and drive in a dangerous state of mind, or some just don't have any awareness whatsoever. Some drivers may never experience a car accident, but that doesn't mean some of the safety control systems shouldn't be built in. The control system will consider all aspects of the car, the condition of the engine, fuel tank, exhaust, safety, etc.

2.1.1 Airbags

The airbag of a car is one of the most important control systems in place, it takes the momentum out of the human body to limit injury as best as it can. But the timing and the control must be very carefully designed. The URLs below shows the effect of a delay in the airbag by seven hundredths of a second ($0.07s$) and its effect on a watermelon, as well as a crash test dummy.

https://www.youtube.com/watch?v=QS6ywFGcLSk (watermelon)

https://www.youtube.com/watch?v=YAwrq9-1oQQ (crash test dummy)

From the videos shown, the watermelon was completely destroyed in the small difference in time, and the crash test dummy, if it were human, would have had severe injuries. The airbag, in conjunction with a seatbelt, showed a drop in moderate and more extreme injuries based on the Maximum Abbreviated Injury Scale (MAIS) scale used in hospitals ($MAIS \geq 2$) to describe the worst injury and the severity of the injury. Table.2.1 shows the MAIS scale in more detail.

Table.2.1: MAIS scores and an example of the injury

MAIS Score	Condition	Example
1	Minor	Sprained Ankle
2	Moderate	Closed Fracture
3	Serious	Open Fracture
4	Severe	Amputation
5	Critical	Ruptured Liver/Spleen
6	Untreatable	Heavy damage to brain or chest

So how does the airbag work? Well the cars are equipped with accelerometers that detect a change of speed (the same component used to detect if you're phone has changed from portrait to landscape), the conditions that the accelerometer must detect is the change in speed of the vehicle that clearly isn't caused by the typical acceleration or braking forces of the vehicle. Once the accelerometer has detected a significant change in speed, the airbag circuit is triggered, and a current is passed through a heating element (the same system in a toaster or a kettle). The heating element ignites a chemical explosive which will quickly produce a large amount of gas as it burns (this gas is harmless, usually Nitrogen or Argon). The gas floods into the airbag and the expanding bag blows the plastic cover off the steering wheel. To improve the unwrapping of the tightly packed bag, it is coated with a chalky substance (such as talcum powder). The driver will be moving forward from the impact and will push against the bag. As the driver moves forward into the bag, it will start to deflate from small holes in the edges, the deflation is how the momentum is slowly taken out of the driver.

2.1.2 Fuel Injection

The older generation of cars would mix the fuel and air in the intake manifold of the engine, by using a carburettor, the cross-section of which can be seen in Fig.2.1. The driver will press down on the accelerator and the throttle valve opens; as the valve opens, the suction from the intake stroke of the piston will force the fuel through the jet and mix with the air, before it is brought into the combustion chamber. This is a very simple method of control, and the most common problem is the poor mixing that this gives, which proceeds to give a poor burn and reduce the overall power produced by the engine. Incomplete combustion of the fuel also causes a variety of emission problems.

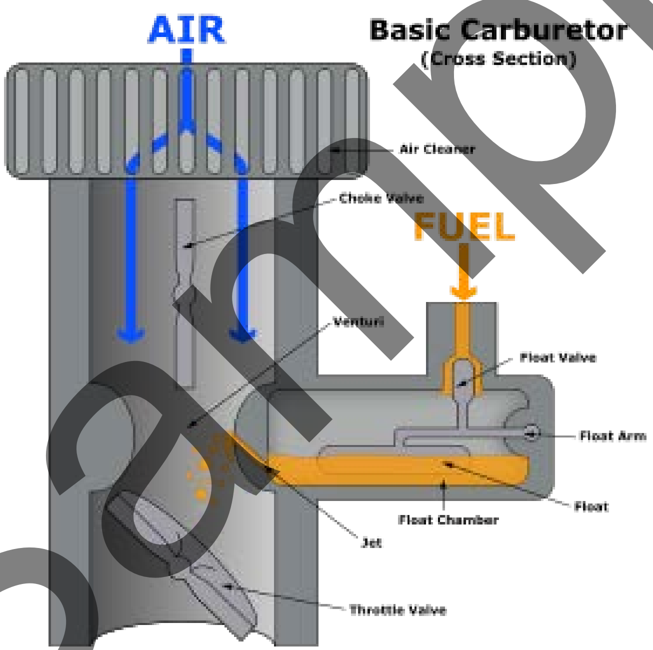

Fig.2.1: Carburettor cross section.

Fuel injection was originally designed for use in Diesel engines but has found its way into more and more petrol engines. Rather than mixing the fuel and air in the intake manifold, the fuel is squirted straight into the combustion chamber before ignition. The force from the injector provides a wider spread of fuel throughout the chamber, which allows a more complete burn of the fuel, which improves the power output, the efficiency, and the emissions of the engine. Fig.1.2 shows a diagram of the fuel injection system.

2.2 Control Systems and Key Elements

Theory

Systems can operate under an open or closed loop system, the difference between the two is what is happens to the data after the transfer functions take place. We consider all actions and processes as a function of time.

2.2.1 Open Loop

An open loop system does not use the collected data to feed back into the system and will just display the current status for manual intervention to fix any problems. The control action is not performed automatically by a processing unit within the system. Let's say we are using a cheap fan to cool something down, we press a button which give a varying fan speed, the button completes the circuit and starts the motor. We model systems with a block diagram. When drawing the block diagram for an open loop system, we have a linear path between the input and the output, with transfer function blocks in between. A block diagram for a fan can be found in Fig.2.3 below.

The main characteristics of an open loop system can be simplified to:

- desired and real values are not compared,
- no self-control or regulation,
- input is a fixed operating position for the controller,
- external disturbances do not result in a direct output change, unless manual alteration takes place.

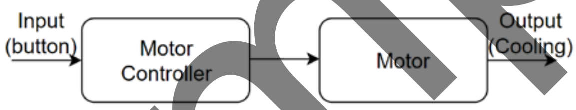

Fig.2.3: An open loop block diagram of a fan

2.2.2 Closed Loop

A closed loop system will collect data while it runs and will feedback into the system to correct to compensate for any disturbances without any external intervention. A closed loop system basically has its own element of control. Let's say our fan is now monitoring the temperature of the item we are cooling; the input is no longer the manual operator pressing the button, it is the desired temperature of the item. Fig.2.4 shows the block diagram for the closed loop fan.

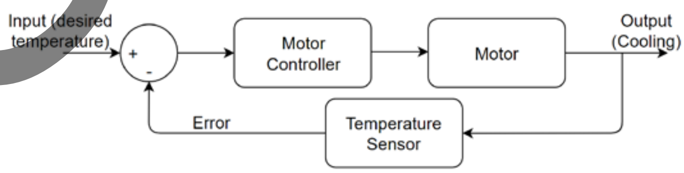

Fig.2.4: Closed loop diagram of a fan

Again, this is still a very basic system. Block diagrams can be huge pieces of work, with sensors analysing anything and everything. We can look at the block diagram for a car's power transmission in Fig.2.5, when the driver presses the pedal down to the floor as quickly as possible, the microprocessor that actually controls the throttle does not allow this, as it could damage the engine. Instead the throttle slowly opens for a more controlled and efficient acceleration.

Input – The input is typically set by the operator, this could be the flick of a switch or a button, or it could be something more finite such as a given rpm, voltage, temperature, light, or different kinds of radiation.

Controller – The controller is the part of the system that will react to the input, so in the case of the fan in Fig.2.3, we have pressed the button, and the controller is the circuitry processing the completed electrical circuit.

Process – The process is how the output is generated, they are typically a conversion or a transfer of some type of energy (engine is a conversion of the fuel's chemical energy to kinetic energy). In the case of the fan, the electrical energy of the battery or the mains is converted to the kinetic energy of the shaft, which spins the fan blades.

Output – The output will be the change from the end of the processes. We normally just include the desired output in the block diagram, but we can by all means include any waste products. The fan will have a small amount of wasted heat from the motor and the circuitry, and the engine will have a large amount of heat loss from the combustion process.

Feedback – The feedback is the sensors that are monitoring the system, when we look at the closed loop we need the feedback to figure out whether the current system operation is acceptable. With the fan, it is important that the temperature of the item being cooled is known. So, we use a temperature sensor of some nature to give us the feedback needed. This then moves onto the summing point. **(Note: not all feedback loops require a sensor, as is shown in Fig.1.6 below)**

Summing Point – A summing point is a way to merge the two or more signals. Fig.2.6. shows the different types of summing points that are used in block diagrams, the summer and comparator.

Fig.2.6: A two input summer (left) and two input comparator (right).

A summer is used to monitor something that requires a counter, such as a timer. Summers are used in all sophisticated electronic devices. Batteries carry a finite amount of charge, the rate of depletion is depended on the amount of current demanded, activating ancillary equipment such as Wi-Fi and mobile data require more current, which drops the charge quicker. Battery charge is monitored by coulomb counting, or energy counting. Fig.2.7 shows a block diagram for a coulomb counter being used as a charge monitor. The summer can be considered as a discrete integral device.

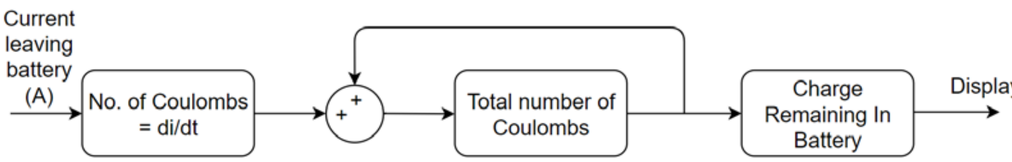

Fig.2.7: A block diagram for a charge monitor using coulomb counting.

2.4 Proportional, Integral and Derivative Controller

The proportional, integral and derivative (PID) controller is a control loop feedback mechanism to ensure that the system is operating as intended. The PID is used to calculate the deviation to determine a correction factor and pass onto the process systems. PID controllers are used to remove the need for constant adjustments by the operator. The system can use previous, current and predicted error data to determine the size of the adjustment that would be appropriate. This is a continuous process so that any changes are automatically accounted for.

There are three types of PID controller, which are discussed in more detail in workbook 3. But this workbook will just describe the typical "Parallel" PID controller. The control output of the PID, $u(t)$, is adjusted in order to minimise the error value $e(t)$ (essentially the deviation) over time, demonstrated by Eq.2.1, where K_p, K_i and K_d are the coefficients of the proportional, integral and derivative terms, respectively.

$$u(t) = K_p e(t) + K_i \int_0^t e(t)dt + K_d \frac{de(t)}{dt} \qquad \text{(Eq.2.1)}$$

The coefficients essentially apply a weighting to each term and are then fine-tuned to achieve the most desirable correction characteristics. We class PIDs as either two-term or three-term controllers. Two term control signifies that the system will only use two of the three systems that are available to the PID, referred to as just PI or PD control, depending on which parameters are used.

2.4.1 PI

PI control uses just the Proportional and the Integral systems of the controller, which monitors the integral of the distance between the current value and the set point. This control is good at tracking small errors, but large errors will cause some overshooting. The function of a PI controller will remove the derivative and become Eq.2.2.

$$u(t) = K_p e(t) + K_i \int_0^t e(t)dt \qquad \text{(Eq.2.2)}$$

2.4.2 PD

PD control uses the Proportional and Derivative systems. This monitors the deviation and the rate at which the process variable is approaching the set point. This is much more effective at tracking large distances between in deviation, but not tracking smaller changes. The equation involved for a PD controller is shown by Eq.2.3.

$$u(t) = K_p e(t) + K_d \frac{de(t)}{dt} \qquad \text{(Eq.2.3)}$$

2.4.3 PID

Three term control uses the entirety of the PID (using Eq.2.1) to create a more accurate, but much more complicated response changes in the system that has the best of both systems when it comes to tracking small and large changes in error.