Introduction to Control Systems

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1.0 Learning Outcomes

After studying this ACE-Lab learning guide, you should be able to demonstrate the Learning Outcomes listed in Table 1. On completion of the ACE-Lab learning guide, revisit Table 1 and confirm whether each Learning Outcome has been achieved.

Table 1: *Learning Outcomes from the Introduction to Control Systems Learning Guide*

ID	Learning Outcome	Achieved
1.	Identify the main components and signals within a feedback control system, including the reference, controller, actuator, process, measurement device, output and disturbance.	☐
2.	Explain the role of feedback and determine the error from the difference between the desired reference and measured output.	☐
3.	Construct and interpret a basic feedback control system using block diagram notation for a given engineering application.	☐

2.0 What is a Control System?

Control systems exist everywhere throughout the man-made and natural worlds. One example of a natural process is the regulation of human body temperature, with many other man-made systems found in everyday life. Despite their prevalence, however, control systems operate unnoticed and are

often overlooked and misunderstood by the general public. Figure 1 illustrates examples of a range of man-made engineering systems that rely on the use of feedback control. Examples of systems that require control are given for each case; however, there are many other systems that require such control.

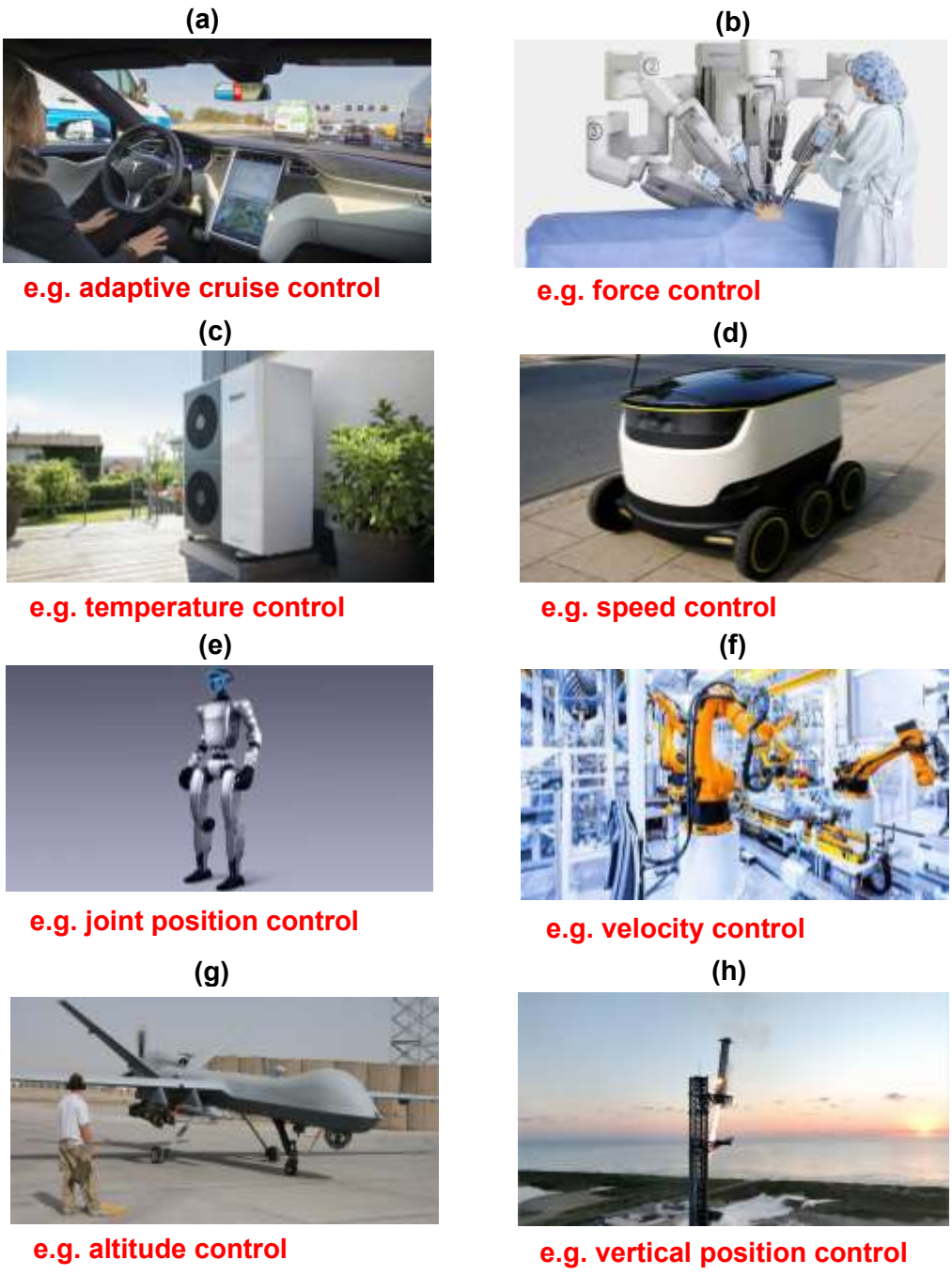


Figure 1: *Engineered Machines that Contain Control Systems: (a) Autonomous Vehicles, (b) Surgical Robots, (c) Heat Pump Units, (d) Autonomous Delivery Vehicles, (e) Humanoid Robots, (f) Industrial Robotic Arms, (g) Unmanned Aerial Vehicles and Drone, and (h) Robots for Space*

At this stage, it is important to recognise that developing a solid understanding of control engineering takes time, and this guide alone is not sufficient to understand the operation of a control system. Control engineering is a broad, multidisciplinary and technically rich discipline, and a full appreciation of its principles and applications will develop over the duration of the course.

The purpose of this guide is to introduce the core ideas and provide an entry point into the topic. As a result, questions and areas of uncertainty are expected to arise, and these will be addressed progressively as the course unfolds.

The engineered examples shown in Figure 1 contain control systems that are designed to meet pre-determined performance requirements. For example, a domestic temperature control system may be required to maintain an indoor temperature of 25°C. The physical phenomenon being controlled is referred to as the process. The way in which the process changes over time is described by its process dynamics. Depending on the application, the process may be mechanical, electrical, thermal, chemical or biological. The required behaviour must typically be achieved despite external influences, referred to as disturbances. For example, in an indoor temperature control system, opening a door or window or a change in outdoor temperature may act as a disturbance.

The examples considered so far describe what must be controlled and the factors that can influence the system. The next question is how a control system determines whether the required behaviour is being achieved. This introduces one of the most important concepts in control engineering: feedback.

Exercise 1

For each example illustrated in Figure 1, carry out additional background reading (you may use a large language model (LLM) to help build background knowledge, but do not assume everything you read is correct) and answer the following questions:

i. What is the physical phenomenon being considered, and what type of system or process is it (e.g. mechanical, electrical, thermal)?
ii. What variable(s) are being controlled, and what could be an example requirement for this control?
iii. What are the external disturbances that act on the control system?
iv. Although example control systems were given in Figure 1 (a to h), there are numerous other engineered systems that require such control. For questions (a. to c.), attempt these with a further engineered example beyond those detailed in Figure 1 (a to h).

3.0 Feedback and Error Generation

The emphasis now shifts beyond verbal description to some mathematical formulation and visual representation of control systems via the use of block diagrams.

For now, we will focus on what is being controlled and how this is achieved at a fundamental level. Specifically, attention is given to achieving the desired reference (or setpoint) of the control system, denoted by r. For example, in the indoor temperature control system discussed earlier, the reference temperature may be set to 25°C.

To achieve the reference r, it is compared with the measured output of the process denoted by y, using a measurement device. The difference between the desired reference and the measured output defines the error, denoted by e. Conceptually, this represents the difference between *what is desired* and *what is occurring*.

In the indoor temperature control example, if the measured temperature is 20°C while the reference is 25°C, the resulting error is 5°C. This relationship is expressed mathematically as:

$$e = r - y \tag{1}$$

In the feedback control configuration considered here, the control algorithm (controller) uses the error to determine the corrective control action. In other words, the controller adjusts the system input (or controller output) to drive the measured output closer to the desired reference. The control output is a signal to an actuator to adjust the input to the system.

Block Diagram Form

The components and signal information within a control system are commonly represented using block diagrams. These diagrams provide an abstract yet intuitive way to describe how signals flow and interact within a system. The key elements are:

- Blocks, which represent system components
- Arrows, which indicate the direction of signal flow and represent information flow associated with mechanical, electrical, thermal, chemical, or biological processes
- Junctions, which are used to add or subtract signals

In Figure 2, the measurement device is represented by a block (which measures the actual process output), while the reference r, measured output y, and error, e, are illustrated as signals (with the flow given by the direction of the arrows). A summing junction is used to perform the operation as defined in Equation (1).

Note that the reference can only be meaningfully compared with a measured output if both are expressed in the same physical units, for example temperature ($°C$), force (N), or position (mm).

Figure 3 presents the corresponding block diagram for the indoor temperature control system introduced earlier, illustrating how the same fundamental structure applies to a real-world example.

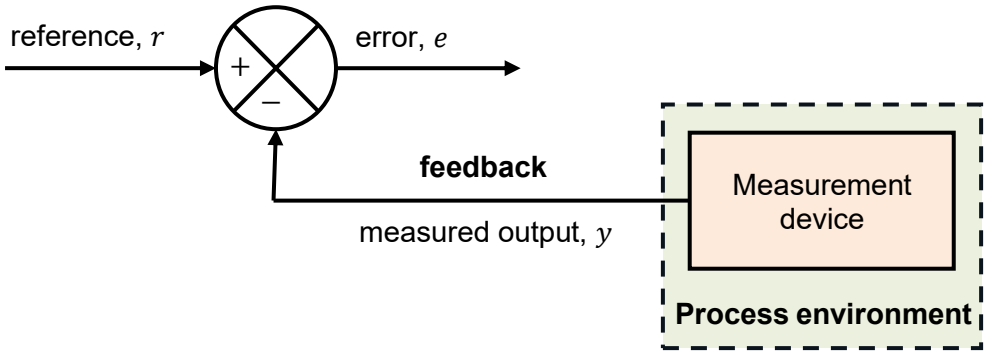


Figure 2: *Block Diagram Form for Error Generation*

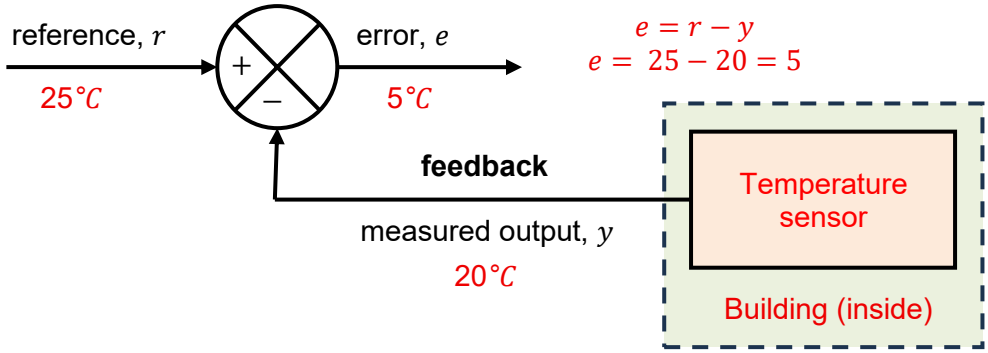


Figure 3: *Block Diagram Form for Error Generation for the Temperature Control System*

4.0 The Basic Configuration of a Control System

In Figure 4, the basic configuration of a control system is provided in block diagram form. This contains the control algorithm (controller), in the forward path with its input being the error signal. The control algorithm then generates the control output, denoted u which becomes the input signal to an actuator that then generates an adjustment to drive the system (or process) such that the measured output tends towards the desired reference value. Actuators can take many forms, e.g. electrical, mechanical, pneumatic and hydraulic. The basic function of an actuator is to adjust the input to the process.

In this guide, the process refers to the physical phenomenon being controlled. The actuator provides the physical input that influences the process, while the

measurement device (sensor) measures the resulting process output. Together, the actuator, process and measurement device form the physical system being controlled, as indicated by the dashed boundary in Figure 4.

The controller is designed to provide an input to the actuator to fundamentally drive the system/process so that its output achieves the desired reference, hence reduce the error, and to meet other key requirements. In terms of the form of the control algorithms (e.g., PID, MPC, etc) and details of actuators, these are both areas that will be expanded on in the following guides. A junction has also been used to represent a disturbance (which are unwanted external inputs), with this plus or minus depending on the effect this is having on the system.

In Figure 5, the heating element actuator has been added, along with the type of control algorithm, i.e., PID. In this example, the control output $u^*$is expressed in volts; in general, the units depend on the actuator and application. A disturbance has also been added, with this given by a negative sign due to effect of opening the door on a cold winter's day, i.e., heat is escaping the room.

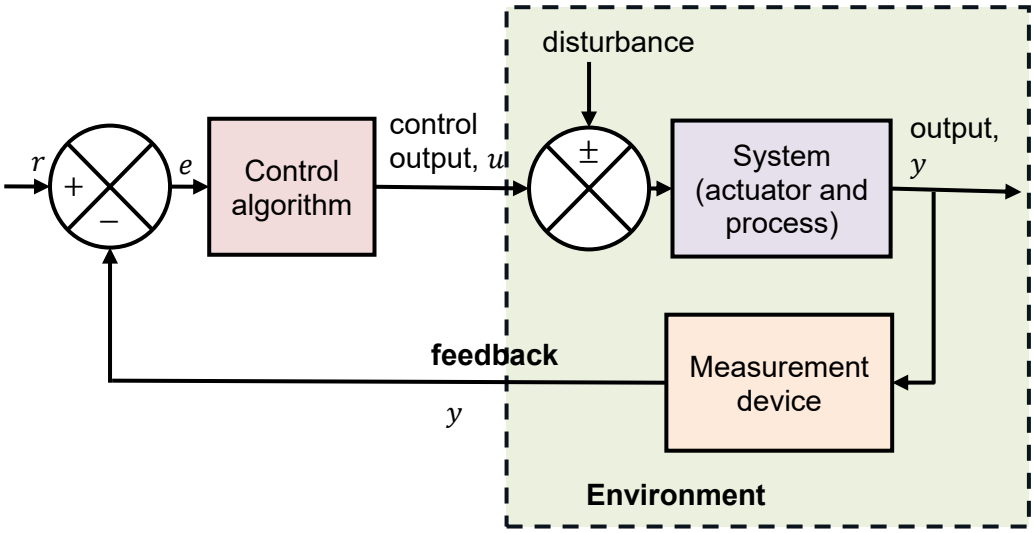


Figure 4: *Block Diagram Form for a Control System*

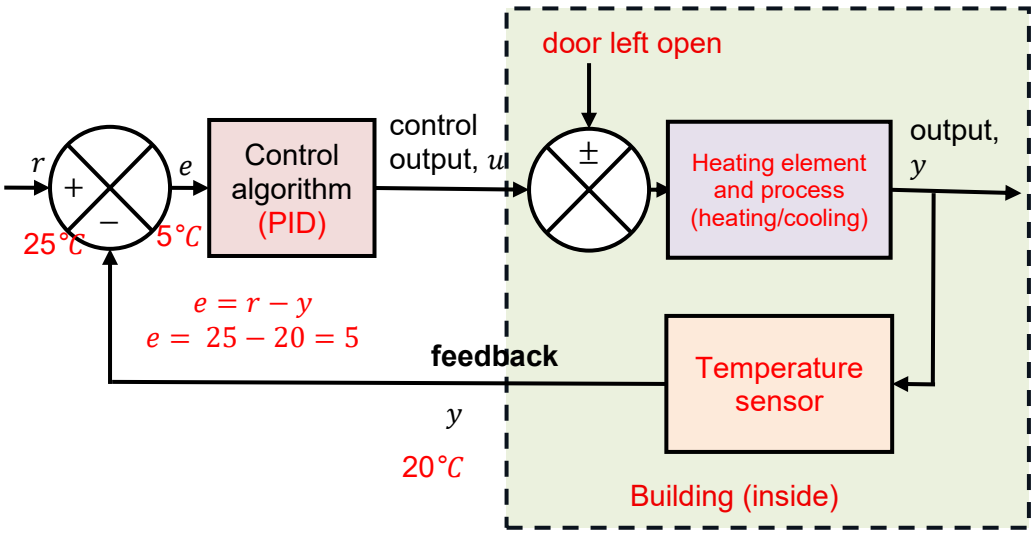


Figure 5: *Block Diagram Form for a Temperature Control System*

Exercise 2

For each example illustrated in Figure 1, carry out additional background reading and complete the following tasks:

i. Sketch and clearly label a control system, including the reference, measurement device, controller, actuator, and key signals.

ii. For the next class, prepare a single PowerPoint slide explaining one of your identified control systems. Include one block diagram and three bullet points. You will have one minute to present, so focus on clarity and key ideas.

5.0 Summary

This learning guide has introduced several new terms, and it is normal for some of these to feel unclear at this stage. Key concepts such as the process, system dynamics, reference, measured output, error, controller, actuator, and feedback will be revisited throughout the course, where their meaning and use will become clearer with practice.

The engineered systems shown in Figure 1 are inherently complex and typically contain multiple interacting control systems. In this guide, the focus has been on understanding the basic structure of a single feedback control loop, rather than capturing the full complexity of real-world systems.

These foundational ideas form the basis of control engineering and will be developed further in later guides as more advanced techniques are introduced.

Recommended Citation

If you have used this learning guide in your teaching, learning or research, please cite it using the reference below, adapting the format as required by your preferred referencing style.

> Pickering, J. E. (2026). Introduction to Control Systems. Teaching Notes: ACE-Lab Practical Exercises, Version 1.0. https://zenodo.org/records/23209659