Dr. Ahmed Abdolkhalig
The University of Tobruk
Department of Electrical Engineering
www.ahmed.ucoz.org

Chapter 1

Introduction

1.1 Historical review

Control theory has developed rapidly over the last 80 years. A significant and rapid development due mainly to digital computers. Indeed, recent developments in digital computers especially their increasingly low cost facilitate their use in controlling complex systems and processes.

The period 1930-1940 was important in the history of control, since remarkable theoretical and practical results, such as those of Nyquist were reported. During the following years and until about 1960, further significant research and development was reported, due mainly to Ziegler and Nichols, Bode, Wiener and Evans. All the results of the last century, and up to about 1960, constitute what has been termed *classical control*. Progress from 1960 to date has been especially impressive, from both the theoretical and the practical point of view. This last period has been characterized as that of *modern control*, the most significant results of which have been due to Astrom, Doyle, Francis, Kailath, Kalman, Zames, and many others.

The main differences between the classical and the modern control approaches are the following: classical control refers mainly to single input-single output systems. The design methods are usually graphical (e.g., root locus, Bode and Nyquist diagrams, etc.) and hence they do not require advanced mathematics. Modern control refers to complex multi-input multi-output systems. The design methods are usually analytical and require advanced mathematics. In today's technological control applications, both classical and modern design methods are used. Since classical control is relatively easier to apply than modern control, a control engineer may adopt the following general approach: simple cases, where the design specifications are not very demanding, he uses classical control techniques, while in cases where the design specifications are very demanding, he uses modern control techniques.

It should be noted that classical control techniques which have existed since 1940s predominate in the overall practice of control engineering today. Despite the impressive progress since the 1940s, practical applications of modern control techniques are limited. This is indeed a serious gap between theory and practice. To reduce this gap, techniques of modern control engineering should be designed

Dr. Ahmed Abdolkhalig
The University of Tobruk
Department of Electrical Engineering
www.ahmed.ucoz.org

with an eye toward applicability, so as to facilitate their use in practice. This course is concerned with introducing classical control theories to undergraduate students taking an introductory course in control systems.

1.2 Control system fundamentals

1.2.1 Concept of a system

Before discussing the structure of a control system it is necessary to define what is meant by a system. A system is a combination of components (appropriately connected to each other) that act together in order to perform a certain task. For a system to perform a certain task, it must be excited by a proper input signal. When one or more excitation signals are applied at one or more system inputs, the system produces one or more response signals at its outputs. Figure 1.1 shows a block diagram of a single-input, single-output system. Systems with more than one input and more than one output are called MIMO (Multi-Input Multi-Output).

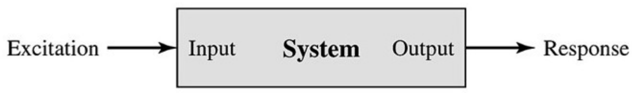

Figure 1.1: Block diagram of a simple system.

In control engineering, the way in which the system outputs respond in changes to the system inputs (i.e. the system response) is very important. The control system designer will attempt to evaluate the system response by determining a mathematical model for the system. Knowledge of the system inputs, together, with the mathematical model, will allow the system outputs to be calculated.

The system being controlled is usually referred to as *the plant*. Some inputs, the engineer will have direct control over, and can be used to control the plant outputs. These are known as *control inputs*. There are other inputs over which the engineer has no control, and these will tend to deflect the plant outputs from their desired values. These are called *disturbance inputs*.

Example 1.1 In the case of the ship shown in Figure 1.2, the rudder and engines are the control inputs, whose values can be adjusted to control certain outputs, for example heading and forward velocity. The wind, waves and current are disturbance inputs and will induce errors in the outputs (usually called *controlled variables*) of position, heading and forward velocity. In addition, the disturbances will introduce increased ship motion (roll, pitch, etc.) which again is not desirable. ■

Generally, the relationship between control input, disturbance input, plant and controlled variable is shown in Figure 1.3.

Dr. Ahmed Abdolkhalig
The University of Tobruk
Department of Electrical Engineering
www.ahmed.ucoz.org

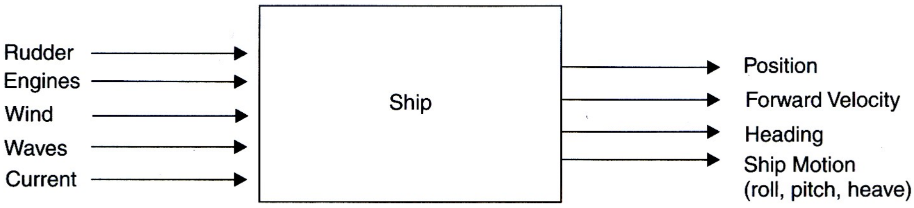

Figure 1.2: A ship as a dynamic system.

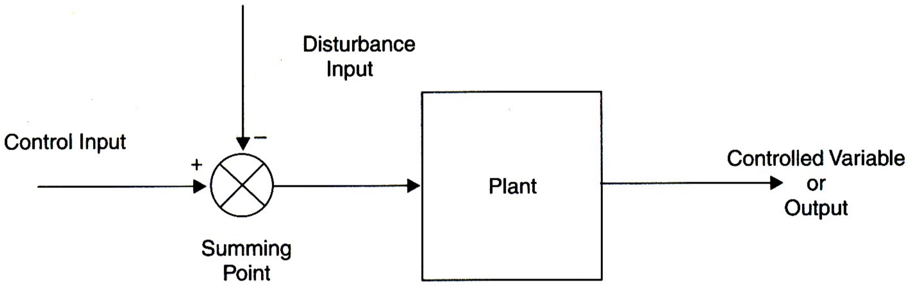

Figure 1.3: Plant inputs and outputs.

Control systems can be divided into two categories: the *open-loop* and the *closed loop* systems.

1.2.2 Open-loop systems

Figure 1.3 represent an open-loop control system. Note that the system input does not depend on the output, i.e., the input is not a function of the output. A very simple example of an open-loop system is that of the clothes washing machine. Here, the control signal is the input to the washing machine and forces the washing machine to execute the desired preassigned operations, i.e., water heating, water changing, etc. The output of the system is the quality of washing, i.e., how well the clothes have been washed. It is well known that during the operation of the washing machine, the output (i.e., whether the clothes are well washed or not) it not taken into consideration. The washing machine performs only a series of operations contained in the control input without being influenced at all by the output.

The main problem with open-loop control is that the controlled variable is sensitive to changes in disturbance inputs. So, for example if a heater is switched on in a room, and the temperature climbs to 20°C, it will remain at that value unless there is a disturbance. This could be caused by leaving a door to the room open, for example. The internal room temperature will change. For the room temperature to remain constant, a mechanism is required to vary the energy output from the heater.

Dr. Ahmed Abdolkhalig
The University of Tobruk
Department of Electrical Engineering
www.ahmed.ucoz.org

1.2.3 Closed-loop systems

A closed-loop system is a system whose input depends on the output, i.e., the input is a function of the output. For a room temperature control system, the first requirement is to detect or sense changes in room temperature. The second requirement is to control or vary the energy output from the heater, if the sensed room temperature is different from the desired room temperature. In general, a system that is designed to control the output of a plant must contain at least one sensor and controller as shown in Figure 1.4.

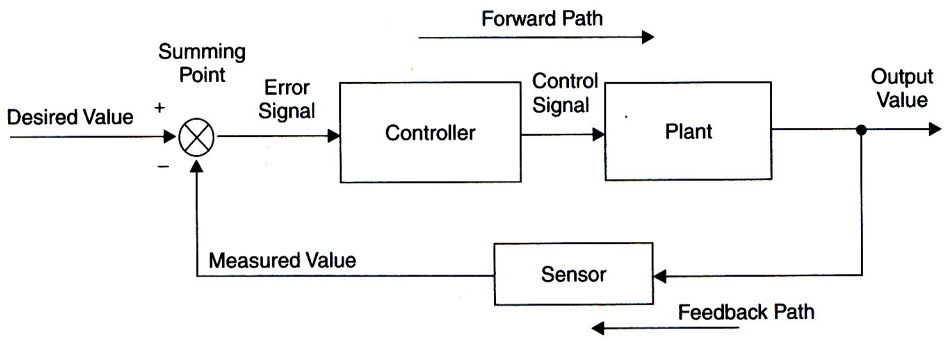

Figure 1.4: Closed-loop control system.

The controller and plant lie along the forward path, and the sensor in the feedback path. The measured value of the plant output is compared at the summing point with desired value. The difference, or error is fed to the controller which generates a control signal to drive the plant until its output equals the desired value.

1.2.4 The control problem

We may state the control problem as follows: given a physical system or process that is to be accurately controlled and the desired system response, find a controller whose output is such that, when applied to the system, the output of the system is the desired response. Generally speaking to be able to accurately control a system, closed-loop or feedback operation is required. Typical aims of feedback are:

- disturbance rejection
- transient response shaping
- sensitivity reduction
- closed-loop stability
- tracking improvement

Solving a control problem generally involves:

- choosing sensors to measure the plant output

Dr. Ahmed Abdolkhalig
The University of Tobruk
Department of Electrical Engineering
www.ahmed.ucoz.org

- choosing actuators to drive the system
- model building
- controller design
- simulation testing
- hardware testing

1.2.5 Examples of control systems

Automobile steering control system

The driver has the task of keeping the car on track on a desired direction of travel. The driver uses the difference between the actual and desired direction of travel to generate a controlled adjustment of the steering wheel as shown in Figure 1.5.

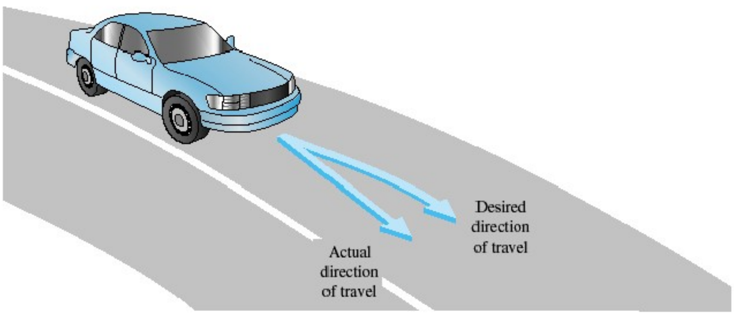

Figure 1.5: Human control of an automobile.

A simple block diagram of an auomobile steering control system is shown in Figure 1.6. The desired course is compared with a measurement of the actual course in order to generate a measure of the error, as shown in Figure 1.5. The measurement is obtained by visual feedback. In the feedback system of Figure 1.6, the driver is the controller, the actuator is the steering mechanism, the plant is the car and the sensor is the visual.

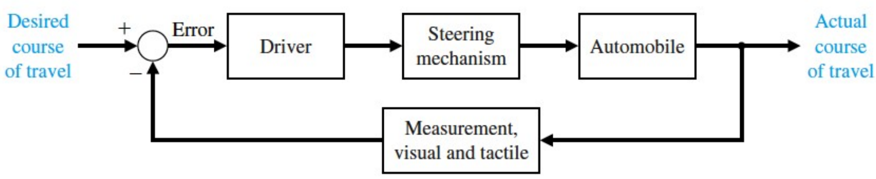

Figure 1.6: Closed-loop control system.

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The University of Tobruk
Department of Electrical Engineering
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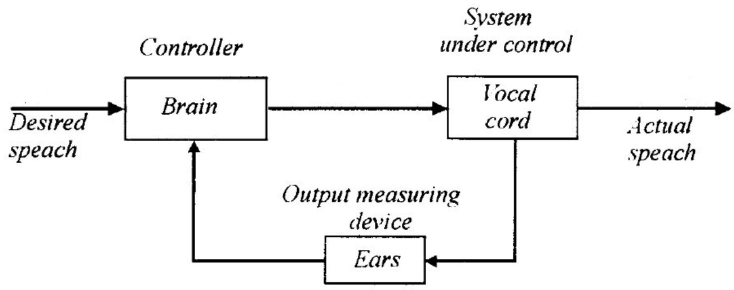

Figure 1.7: Block diagram of human speech.

HUMAN SPEECH [FIGURE 1.7]

As we all know, we use our ears not only to hear others but also to hear ourselves. Indeed, when we speak, we hear what we are saying and, if we realize that we didn't say something the way we had in mind to say it, we immediately correct it. Thus, human speech operates as a closed-loop system, where the reference input is what we have in mind to say and want to put into words, the system is the vocal cords, and its output is our voice. The output is continuously monitored by our ears, which feed back our voice to our brain, where comparison is made between ourintended (desired) speech and the actual speech that our own ears hear (measure). If the desired speech and the measured speech are the same, no correction is necessary, and we keep on talking. If, however, an error is realized, e.g., in a word or in a number, then we immediately make the correction by saying the correct word or number.

TEACHING [FIGURE 1.8]

The proper procedure for teaching has the structure of a closed-loop system. Let the students be the system, the teaching material presented by the teacher the input, and the degree of understanding of this material by the students the system's output. Then, teaching can be described with the block diagram of Figure 1.8. This figure shows that the system's output, i.e., the degree of understanding by students of the material taught, is fed back to the input, i.e., to the teacher. Indeed, an experienced teacher should be able to sense (measure) if the students understood the material taught. Subsequently, the teacher will

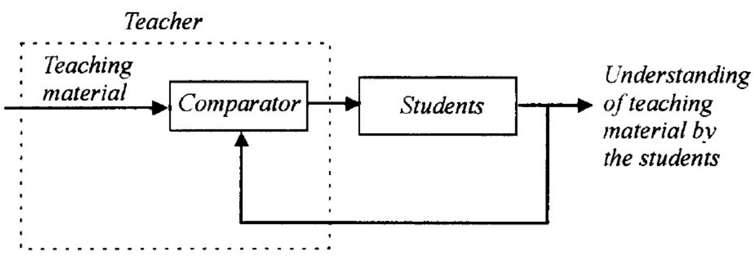

Figure 1.8: Block diagram of teaching.

Dr. Ahmed Abdolkhalig
The University of Tobruk
Department of Electrical Engineering
www.ahmed.ucoz.org

either go on teaching new material, if the students understood the material taught, or repeat the same material, if they did not. Therefore, proper teaching has indeed the structure of a closed-loop system.

Taking a shower

Imagine taking a shower from a two-knob faucet as shown in Figure 1.9. You want to set the rate of water flow and its temperature so that the shower is effective and comfortable. You can control the hot water flow and the cold water flow separately.

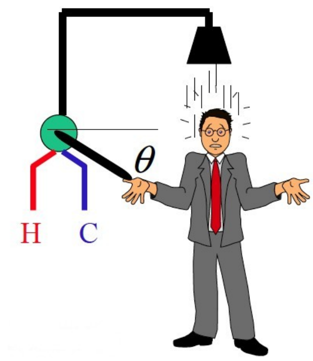

Figure 1.9: Taking a shower.

So how do you regulate your shower?

1. You test the flow and temperature
2. Decide if it is OK
3. If not OK, decide what adjustment to make
4. Adjust the knobs
5. Repeat from the first step

The system can be presnted by a block diagram as shown in Figure 1.10.

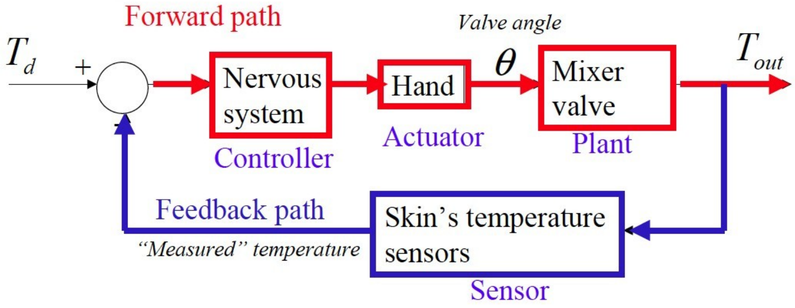

Figure 1.10: A block diagram representing taking a shower.

Dr. Ahmed Abdolkhalig
The University of Tobruk
Department of Electrical Engineering
www.ahmed.ucoz.org

1.3 A first analysis of feedback

As mentioned earlier in section 1.2.4 closed-loop or feedback control systems have many advantages. The introduction of feedback enables the engineer to control a desired output and improve accuracy. Hence, more accurate control of plant under disturbances, i.e., effective disturbance rejection. A faster response to an input signal is achieved. Systems that are inherently unstable in the open-loop form can be stabilized using feedback.

In this section the value of feedback can be demonstrated by quantitative analysis of a simple static system. Consider the open-loop static system shown in Figure 1.11. The static system G has an input u and and output y. The

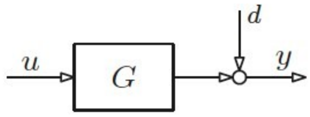

Figure 1.11: A block diagram of an open-loop system..

output is possibly disturbed by an additive disturbance d. By simple algebraic manipulations, it is simple to show that

$$y = Gu + d \tag{1.1}$$

Introducing a controller C with feedback to obtain a closed-loop system shown in Figure 1.12. The controller C has an input e and an output u. Input e is

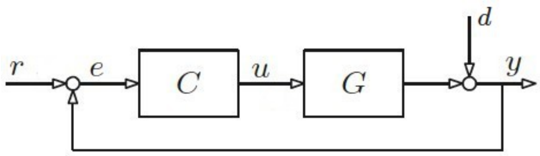

Figure 1.12: A block diagram of a closed-loop system..

created by comparing output y of the system G with the reference signal r: $e = r - y$. Note here that the reference signal r represents the desired response of the system, i.e., in other words one would like the output y to track the reference signal r. The controller output u, is given by

$$u = Ce$$

Hence, the output y is

$$y = GCe + d \tag{1.2}$$

The tracking error signal e, is given by

$$e = r - (GCe + d)$$

$$\Longrightarrow \; e = \frac{1}{1 + GC}(r - d) \tag{1.3}$$

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The University of Tobruk
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Next, substitute (1.3) in (1.2) to obtain

$$y = GC\left(\frac{1}{1+GC}(r-d)\right) + d$$
$$\Longrightarrow\ y = \frac{GC}{1+GC}r + \frac{1}{1+GC}d \tag{1.4}$$

1.3.1 Effect of feedback on tracking and disturbance

The output of an open-loop system with no control was seen in (1.1) to be

$$y = Gu + d$$

On the other hand, with feedback control the output was given in (1.4) as

$$y = \frac{GC}{1+GC}r + \frac{1}{1+GC}d$$

Without control the map from the disturbance d to the ouput y is simply 1. Any disturbance d will be seen directly (without reduction) on the output y. With control, the map from disturbance d to output y is

$$\frac{1}{1+GC}$$

therefore any disturbance d will be seen with a factor on the output y. Hopefully, the $\left(\frac{1}{1+GC}\right)$ factor can reduce the disturbance. It can be seen that if $C \gg 1$ (large or high loop gain), then

$$\frac{1}{1+GC} \approx 0$$

which implies that the effect of the disturbance d is eliminated. Similarly, the map from reference r to output y is

$$\frac{GC}{1+GC}$$

and if $C \gg 1$ it can be seen that

$$\frac{GC}{1+GC} \approx 1$$

which implies that $y = r$, i.e., the output is tracking the reference closely. In conclusion: *Good tracking and disturbance rejection both require high loop gain.*

1.3.2 Effect of feedback on sensitivity

Generally, any control system will contain parameters that change with temperature, pressure, humidity, time, and so on. However, we prefer that the control system characteristics not vary as these parameters vary. Of course, the system characteristics are a function of the system parameters, but in some cases the sensitivity of system characteristics to parameter variations can be reduced.

Dr. Ahmed Abdolkhalig
The University of Tobruk
Department of Electrical Engineering
www.ahmed.ucoz.org

Consider the closed-loop system in Figure 1.12, with $d = 0$ (i.e., disturbances are neglected), from (1.4) we obtain

$$y = Hr$$

where

$$H = \frac{GC}{1 + GC} \tag{1.5}$$

Clearly H is the map from reference r to output y, (it is usually referred to as the overall system gain). The sensitivity of the system gain H to changes in C for example is defined as a measure of the percentage change in H to a percentage change in C. One such definition is

$$S = \frac{\partial H/H}{\partial C/C} = \frac{\partial H}{\partial C}\frac{C}{H}$$

where ∂H is the variation in H caused by ∂C, the variation in C. We will now find the sensitivity of H with respect to C

$$\begin{aligned} S &= \frac{\partial H}{\partial C}\frac{C}{H} \\ &= \frac{G(1+GC) - GCG}{(1+GC)^2}\frac{C}{GC}(1+GC) \\ &= \frac{1}{1+GC} \end{aligned} \tag{1.6}$$

For this sensitivity to be small, we require that $C \gg 1$. In conclusion: *Sensitivity reduction requires high loop gain.*

1.3.3 Effect of feedback on stability

In a nonrigorous manner, *a system is said to be unstable if its output is out of control*. To investigate the effect of feedback on stability, we can refer to the expression in (1.5). If $GC = -1$, the output of the system is infinite for any finite input, and the system is said to be unstable. therefore, we may state that feedback can cause a system that is originally stable to become unstable.

1.3.4 The cost of feedback

Almost all the benefits of feedback can be achieved, provided that the loop gain is sufficiently high. Unfortunately, for most plants, high loop gain tends to drive the system into instability. Don't forget $u = Ce$ so if $C \gg 1$, the control signal u will be large and this gets amplified in the feedback loop over and over causing instability. Other disadvantages of closed-loop systems but not limited to:

- require the use of sensors which increase the system costs
- more complex design, harder to build
- power costs (due to high gains) are high

It is essential in the design of controllers to trade-off between high gain, disturbance rejection, tracking and stability. For good design trade-off knowledge on dynamic behavior of the system is essential. In conclusion: **In most cases the advantages of feedback far outweigh the cost and feedback is utilized**.