Chapter 1

Introduction to Systems Theory and Control Systems

1.1   Concept of a System

According to the "Web Dictionary of Cybernetics and Systems", a system is defined by various authors as:

- A set of variables selected by an observer, [Ashby, 1960]

- A set or arrangement of entities so related or connected so as to form a unity of organic whole [Iberall]

- Any definable set of components, [Maturana and Varela, 1979]

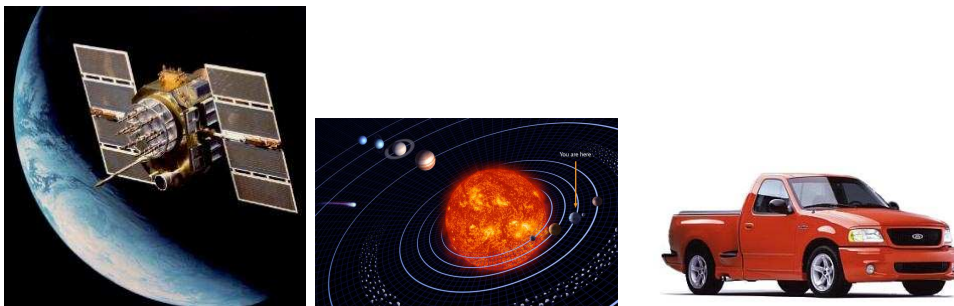A few examples are shown in Figure 1.1.

Figure 1.1: System examples: Global Positioning System, Solar System, Truck

A *dynamical system* is a system whose behavior changes over time, often in response to external stimulation or forcing, (Astrom and Murray, 2009). Examples of such systems, that occur in every branch of science, include: the weather, the stock market, street traffic, robots, chemical reactors, power systems etc.

All systems have a set of inputs, a set of outputs and a boundary that separates them from the environment (Figure 1.2). Inputs are those quantities that are acting on the system from the environment and the outputs are the results of the input acting on the system. Some of the inputs are not easily understood or cannot be controlled and are not within the capabilities of the operator to manipulate it to achieve a desired output or end result. These inputs are usually called disturbances. The boundary that separates the system from the environment can be a physical one like that of a machine or a geographical area. But in many systems, this boundary can be purely imaginary or conceptual rather than a physical
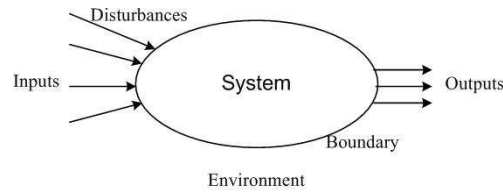
Figure 1.2: A system

one, within the definition of the system. Moreover, the same physical system may be represented using different inputs and outputs depending on the study that is being carried out, (Mohandas, 2009).

A system is represented as a rectangle (see Figure 1.3) and inputs and outputs (also called *signals*) as arrows. For a system to perform a certain task, it must be excited by a proper input signal. The system's output is also called *response* or *behavior*.
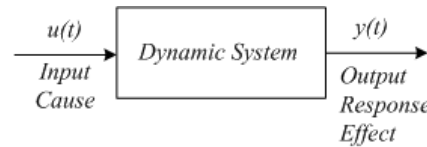

Figure 1.3: Dynamical system

Example 1. Consider the automobile shown in Figure 1.4, where the input signals may be considered: the throttle position (or the accelerator pedal) and the slope of the road (that may be considered as a disturbance). The output is the effect of applying the inputs and, in this case, is the automobile speed.

Figure 1.4: A system

Figure 1.5: Helicopter

Example 2. In case of the helicopter shown in Figure 1.5, the inputs may be considered: the power produced by the engines, the pilot control inputs using the cyclic stick, collective lever and anti-torque pedals. The wind is a disturbance input since it occurs randomly and cannot be controlled. The outputs of such a system are the actual position (coordinates x, y, z), the orientation (roll, pitch and yaw angles) and the velocity.

1.2   Short History of Systems Theory

"Systems theory is the transdisciplinary study of the abstract organization of phenomena, independent of their substance, type, or spatial or temporal scale of existence. It investigates both the principles common to all complex entities, and the (usually mathematical) models which can be used to describe them", (F.Heylighen and C.Joslyn, 1992).

Systems theory studies physical systems based on their mathematical models aiming to understand their behavior and to control it in such a way that the system behavior meets specified standards.

The general systems theory was developed by the biologist Ludwig van Bertalanffy who published "General Systems Theory" in 1931 at the University of Chicago. Further work in the field has been done

by Norbert Wiener who publishes "Cybernetics or Control and Communication in the Animal and the Machine" in 1948, and Ross Ashby ("Introduction to Cybernetics", 1955).

Among the system theory developers are also: Anatol Rapoport, Kenneth Boulding, Ross Ashby, Margaret Mead, Gregory Bateson, Ralph Gerardin.

Figure 1.6: Founders of the Society for General Systems Research

The terms "systems theory" and cybernetics" have been widely used as synonyms. Some authors use the term cybernetic systems to denote a proper subset of the class of general systems, namely those systems that include feedback loops.

1.3 Systems theory and control systems engineering

Historically, engineers have developed specialized methods for analyzing the behavior of systems within their own discipline. For example, electrical engineers have developed and refined circuit analysis methods in order to determine the response of voltages and currents in electronic circuits; and mechanical engineers have developed methods of computing forces and displacements within systems assembled from mechanical components.

The generalized discipline of system dynamics has been developed over the past five decades to provide a unified method of system representation and analysis that can be applied across a broad range of technologies. System dynamics concepts are now used in the analysis and design of many types of interconnected systems including electric, mechanical, thermal and fluid systems. The general methodologies arising from this field have recently also been extended to the analysis of many other types of systems including economics, biology, ecology, the social sciences, and medicine (Jeltsema and Scherpen, 2007).

System dynamics, or systems theory is the study of the dynamics or time-varying behavior of a system and includes at least the following components (Jeltsema and Scherpen, 2007):

- Definition of the system, system boundaries, input variables, and output variables.

- Formulation of a dynamic model of the physical system, usually in the form of mathematical or graphical relationships determined analytically or experimentally.

- Determination of the dynamic behavior of the system model and the influence of system inputs on the system output variables of interest.

- Derivation of approximating models, like linearization and model reduction.

- Study of features like controllability, reachability and observability for controller design and model realizability.

- Stability analysis.

Control Systems Engineers are concerned with understanding the segments of their environment, called *systems* to provide useful economic products for society. Control Engineering must often consider the control of poorly understood systems such as chemical process systems. The current challenge to Control Systems Engineering is the modeling and the control of modern, complex, interrelated systems such as

traffic control systems, chemical processes, robotic systems and industrial automation systems. All the challenges aim to solve control problems that affect the whole of society. Control Systems Engineering is based on the foundations of feedback theory and linear systems analysis. It is an interconnection of components forming a system configuration that will provide a desired system response, (Dorf and Bishop, 1995).

1.3.1   A brief history of Automatic Control

Feedback control can be said to have originated with the float valve regulators of the Hellenic and Arab worlds. They were used by the Greeks and Arabs to control such devices as water clocks, oil lamps and wine dispensers, as well as the level of water in tanks, (Bissell, 2009).

The Greek inventor and mathematician Ctesibius (or Ktesibios) invents the first artificial automatic regulatory system, a water clock around the year 300 BC, Figure 1.7.

"In his water clocks, water flowed from a source such as a holding tank into a reservoir, then from the reservoir to the mechanisms of the clock. Ktesibios's device used a cone-shaped float to monitor the level of the water in its reservoir and adjust the rate of flow of the water accordingly to maintain a constant level of water in the reservoir, so that it neither overflowed nor was allowed to run dry. This was the first artificial truly automatic self-regulatory device that required no outside intervention between the feedback and the controls of the mechanism" (Wikipedia article on Cybernetics).
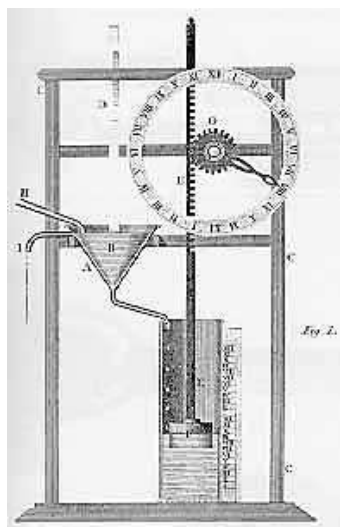

Figure 1.7: Ktesibios water clock

The first formal study of the "Theory of Control" started in the mid 1860s with a paper published by physicist J.C.Maxwell, the inventor of the theory of "Electro-Magnetism". Work on the stability of control systems appeared towards mid 1890s by mathematicians notably E.J. Routh and A.M. Lyapunov. These two mathematicians both have their names honored by the control engineering community with the naming of "Routh Stability Test" and the "Lyapunov Stability Criteria", which is found in almost all literature on control. During the 1930s, H. Nyquist from Bell Telephone Laboratories, applied frequency analysis to control systems design. Around the same time Electronic amplifiers from Bell Telephone appeared. Developed by H.W.Bode, such amplifiers were designed using the concepts of feedback control. From the 1950s onwards, control theory evolved with new mathematical techniques applied and computer technology becoming a substitute for mechanical control or human task oriented control systems.

1.3.2   Discipline of Control Systems

Control Systems Engineering is a multi-disciplinary field. It covers areas as, Mechanical Engineering, Chemical Engineering, Electrical and Electronic Engineering, Environmental, Civil, Physics, Economics

and Finance, Artificial Intelligence and Computer Science. Control Systems Engineering is still taught in main stream Engineering and Physics courses. Within the last decade or so it has started to appear in Computer Science courses and as post-graduate papers in Real-Time Computer Control.

One of the emerging fields of Control Systems Engineering is Financial Engineering Control. This branch of engineering deals with the dynamic modeling of finance and economic systems. The majority of courses in Financial Engineering Control are still taught at post-graduate level in Mathematics, Physics and Engineering. Engineers in Financial Engineering Control use the same models and concepts as feedback and feed-forward control that are found in aircraft control systems or chemical process systems and apply them to financial and economic dynamic systems.

Computer Control Systems is one of the most complex fields in control engineering. For example, designing the control systems for a chemical process system would involve different types of engineers from the beginning. A mechanical engineer would specify and design most of the machinery parts and the electrical engineer will figure out how all these complex parts are wired together, what type of sensors and actuators to specify, and also how it all function as a whole. An actuator is a device that provides the motive power to the process, example is a dc motor. The chemical engineer will specify the time reaction of certain chemicals and the optimal temperature and pressure for operations. The software engineer will play the role of integrating all specifications by writing the software that meets the functional requirement of the other engineers. All these engineers, must communicate before and during the whole project, with each and every one understanding the language of Control Systems Engineering. Control Systems design parameters such as process rise-time, peak-time, settling-time, percentage-overshoot and so on, must be well understood by all engineers involved.

Concepts in Control Systems Engineering overlap with concepts in the branch of Physics and Electrical Engineering known as Digital Signal Processing (DSP) and Communication Systems, where analysis is done in frequency domain or time domain exactly as is done in Control Systems. There are disciplines that a DSP or a Communication Systems engineer would also use in designing embedded Real-Time Computer Control Systems.

1.4   Control engineering - terminology

As an illustrative system we choose to consider the control of an inverted pendulum, (Dutton et al., 1997). One version of this problem will be familiar, in that it requires someone to balance a broom handle vertically on the palm of his or her hand. After placing the point of the handle on the palm in approximately the required vertical position, appropriate eye-hand coordination produces the desired result. The study of such mechanisms is the theme of all control texts.

Before looking at the mechanisms, let us look at the broom handle. If its shape changed it would cease to be a broom handle. In control engineering terms the handle is the *plant* (or *process*) to be controlled. Control engineers like to use *block diagrams* to simplify the understanding of complex systems by breaking down into smaller, interconnected subsystems.
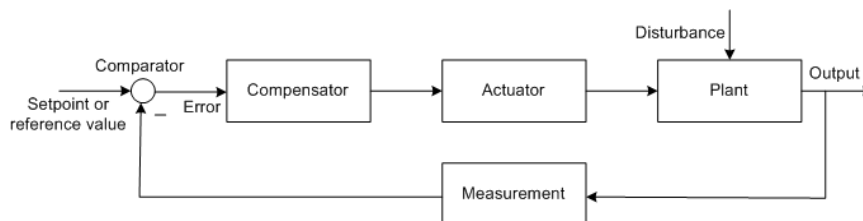

Figure 1.8: Elements in a control system

If the broom handle is the plant, then the controls are all the elements or *blocks* in Figure 1.8 which are external to the plant and which are there to ensure properly organized behavior.

Given that the objective is to keep the handle vertical, the first block to be considered is the detection, or *measurement* element, which indicates the position of the handle. The measurements are made by

eyes which send an appropriate message to the brain. There is a communication system, the neurological system which sends messages, or *signals*, from the eye to the brain. In Figure 1.8 the signals are indicated by connecting lines entering or leaving various blocks. The brain performs two main functions. It compares the measured position of the handle with the desired position (the *setpoint* or *reference value*), and it calculates the appropriate action to be taken. In the language of control, the brain performs the function of both a *comparator* and a *compensator*. Finally the signal emanating from the compensator portion of the brain activates the muscles in the arm which position the hand carrying the lower end of the handle. The arm is the *actuator*, providing both power amplification and motion.

When looking at Figure 1.8, notice how information circulates around the *control system*. In this context a *control system* refers to the plant and all the associated blocks. Measurement information taken from the plant is, in turn, acted on by the comparator, compensator and actuator before being fed back into the plant. The resulting control system is called *closed-loop* system and is characterized by the *feedback* signal which carries information from the measurement device to the comparator. In contrast, an *open-loop* control system does not have such a feedback path.

1.5   Control Systems. Examples

1.5.1   Domestic oven temperature control

The temperature control of the oven in an electric cooker is an example of a closed-loop regulatory system. Here the main objective is to maintain the oven temperature at, or near, the manually adjusted setpoint temperature. A sensor within the oven measures the oven temperature. The resulting temperature signal is compared with the setpoint and a very simple compensator provides a signal which is used to switch (actuate) power to the oven's heating elements. The heating elements are switched on if the oven temperature is somewhat less than the setpoint temperature, an off is the temperature is somewhat above the setpoint. For a domestic cooker this strategy appears adequate and has, for many years been the main method of oven temperature control, (Dutton et al., 1997).

1.5.2   Domestic washing machine

A basic domestic washing machine typifies an open-loop system. Here the preset washing cycle activates various washing operations for a set period of time. It is assumed that if the set sequence of operations is followed correctly, then the clothes inserted into the machine will emerge clean and undamaged. However, because the system is essentially open-loop the manufacturers provide copious instructions to try to deal with all the variables that can occur in a typical wash, (Dutton et al., 1997).

1.5.3   Domestic central heating

For those living in a colder climate, examination of a domestic central heating reveals a number of control loops. Water heated by the boiler is continuously pumped round the house. There is invariably regulatory control on the exit temperature of the water from the boiler. If the boiler is oil, or gas fired, this temperature control system is similar to that found in the oven of an electric cooker. (Example 1)

Solid fuel boilers use a different closed-loop control strategy to regulate circulating water temperatures. A bimetallic strip, whose initial position can be set manually senses temperature changes. Deflections of this strip are used to open or close a damper (basically a flap acting as a throttle valve) altering the flow of air into the combustion chamber. The control signals are mechanical and the control action is continuous (like the handle balancing problem, but unlike the on-off control in examples 1 and 2).

Heat carried by the circulating water is dissipated by means of heat radiators. When a radiator is fitted with a thermostatically controlled valve, the heat dissipation process from that radiator is closed-loop. If the radiator has no means of detecting the room temperature, the process is open-loop, (Dutton et al., 1997).

1.5.4 Automobile steering control system

A simple block diagram of an automobile steering control system is shown in Figure 1.9. The desired
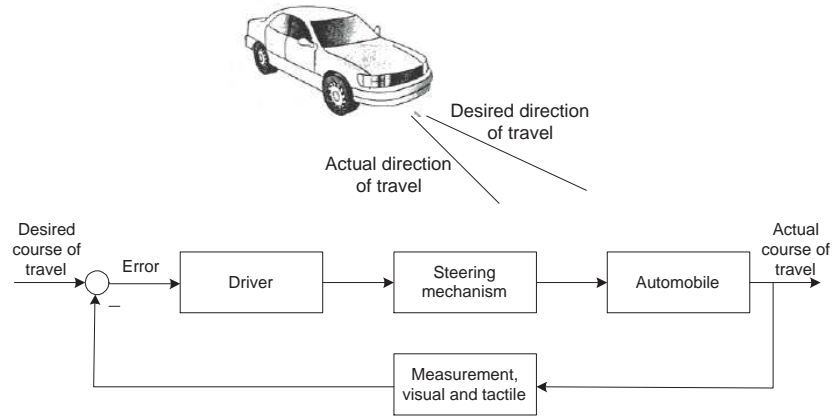

Figure 1.9: Automobile steering control system

course is compared with a measurement of the actual course in order to generate a measure of the error. This measurement is obtained by visual and tactile feedback. There is an additional feedback from the steering wheel by the hand (sensor). Control system operate in a closed-loop sequence. With an accurate sensor the measured output is equal to the actual output of the system. The difference between the desired output and actual output is equal to the error, which is then adjusted by the control device (here the driver). The output of the control device causes the actuator (steering mechanism) to modulate the process in order to reduce the error. The system is a *negative feedback* control system, because the output is subtracted from the input and the difference is used as the input signal to the compensator.

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