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CONTROL SYSTEMS

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To the memory of my father.

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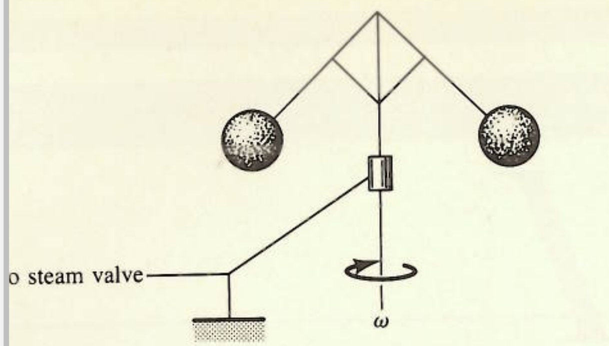
Introduction

The subject of control systems is of great inportance to all engineers. The objective is to free human beings from boring repetitive chores that can be done easily and more economically by automatic control devices. The recent developments in the large-scale integration of semiconductor devices and the resulting availability of inexpensive microprocessors has made it practical to use computers as integral parts of control systems, making them cheaper as well as more sophisticated.

Historically, the first automatic control device used in the industry was the Watt fly-ball governor, invented in 1767 by James Watt, who was also the inventor of the steam engine. The object of this device was to keep the speed of the engine nearly constant by regulating the supply of steam to the engine. A schematic diagram is shown in Fig. 1.1. The two fly balls in the governor rotate about a vertical axis at a speed proportional to the speed of the engine. Due to the centrifugal force acting on them, they tend to move out. This movement controls the supply of steam to the engine through a mechanical linkage to the steam flow valve in such a manner that the steam supply is reduced when the speed is high and increased when the speed is low.



IGURE 1.1. The Watt fly-ball governor.

t was found that by a proper design of the governor the speed pt within narrow limits of a specified value. It was also observed ried to increase the sensitivity of the governor by increasing the etween the engine shaft and the governor, it tended to "hunt" or out the desired setting. It was about 100 years later that a complete al analysis was made by James Clerk Maxwell (more well known ributions to electromagnetic field theory).

Much later it was realized that all automatic control systems worked iple of feedback. By a coincidence, about the same time the theory amplifiers had been developed by electrical engineers who had ned with transmitting telephone signals over long distances. In one may mention the Nyquist theory of stability developed about at impetus to the theory of automatic control came during World en servomechanisms were utilized for the control of anti-aircraft World War II many peacetime applications followed. Some of these opilot" for aircraft, automatic control of machine tools, automatic hemical processes, and automatic regulation of voltage at electric ts. Although originally the theory was based on frequency response e transform methods, in the 1960s the impact of the digital com- the development of time-domain theory using state variables. This lly useful as more sophisticated multivariable control systems were for more complex processes. As computers have become cheaper ompact, they have been utilized as components of more advanced tems.

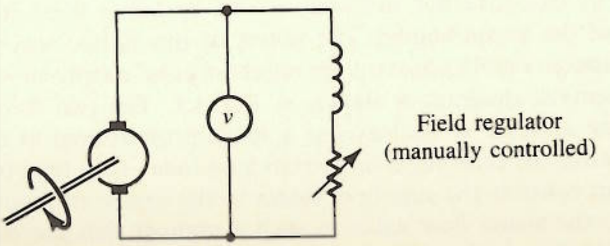


FIGURE 1.2. A voltage control system.

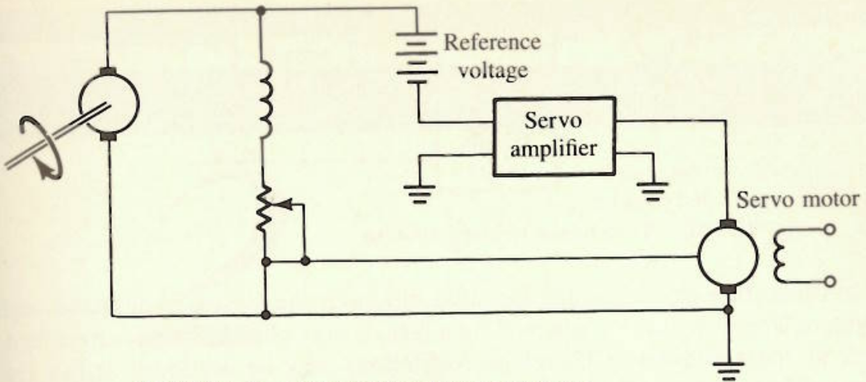


FIGURE 1.3. Automatic voltage regulator.

Let us consider some simple examples of control systems. Figure 1.2 shows the scheme for controlling the voltage at an electric power station in the 1940s. A human operator was required to watch a voltmeter connected to the busbars and adjust the field rheostat in order to keep the voltage close to the specified value. A scheme for automatic voltage regulation is shown in Fig. 1.3 and shows that it works by comparing the actual value of the voltage with the desired value. The difference or "error" is applied to a servomotor, after suitable amplification. This servomotor drives a shaft coupled to the field rheostat to alter the resistance in the field winding in such a manner that the error is reduced. Hence, it may be said that "feedback" is utilized to obtain automatic control. As a matter of fact, all automatic control systems use feedback and can be represented by the block diagram shown in Fig. 1.4. It can be seen that the controlled output is fed back and compared with the reference input. The difference, called the "error," is then utilized to drive the system in such a manner that the output approaches the desired value (i.e., the reference input).

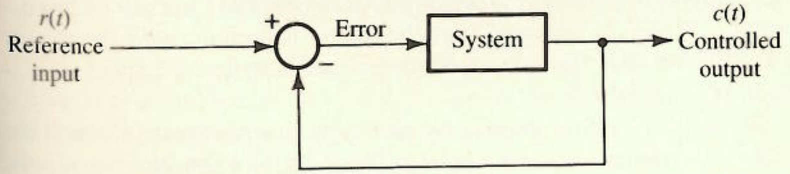
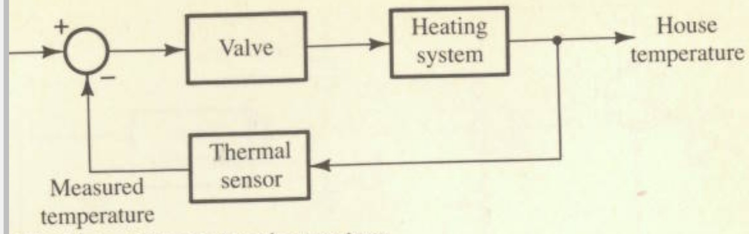


FIGURE 1.4. Block diagram of automatic control system.

Another example is the home heating system. A thermostat senses the temperature and if it is lower than a set value, the furnace is turned on. The furnace is turned off when the temperature exceeds another set value. The block diagram is shown in Fig. 1.5. Although it is similar to Figs. 1.3 and 1.4, it may be noted that this is an on/off-type control system, whereas the voltage regulator is a continuous-type system.

It was noticed at the very outset that if one tried to improve the accuracy of a control system by increasing the loop gain, it led to instability,



GURE 1.5. A home heating system.

t is caused by the fact that although the system is designed with back, due to inherent time lags, it may change into positive feede frequency. Therefore, oscillations may be produced at this fre: gain is increased sufficiently. The Nyquist criterion of stability, r feedback amplifiers, provides a good understanding of this. We ee how one can increase the sensitivity (or accuracy) without bility.

he components used for control systems are usually of a wide example, these may be electromechanical, electronic, thermal, r pneumatic. In order to analyze the response of the various we replace them by their mathematical models. Although the e output of these devices are generally related through nonlinear quations, it is customary to obtain simplified linear models about g points because such models are easier to analyze. Transfer functe-variable models are most commonly employed.

n our development of control theory, we shall generally be carrying ysis and design in terms of the mathematical models. Although this ay sometimes appear abstract, one must appreciate that these esent real systems. To a certain extent this abstraction is necesesloping a unified theory of automatic control systems despite the of components. One important aspect is the problem of obtaining al models for different types of physical systems. This will be discuster 2. It will be assumed that the reader is familiar with the theory ransforms. For the sake of completeness, a review of Laplace transen in Appendix A.

We shall close this chapter by mentioning some areas in which the ontrol systems has been applied. These include robotics, automatic arge-scale power systems, numerical control of machine tools, autorcraft, prosthetic devices for handicapped persons, and the steering ocean liners. An important consequence of the development of conhas been the increased use of automation in the industry with a view ng productivity. The concept of modeling developed by control as been applied to many diverse areas, including biomedical systems, mical systems, and ecological systems. With the rapid advances in microelectronics and the exciting possibility of using inexpensive as parts of control systems, it can truly be said that the applicaare limited only by human imagination.

2

Mathematical Models of Physical Systems

2.1 INTRODUCTION

A crucial problem in engineering design and analysis is the determination of a mathematical model of a given physical system. This model must relate in a quantitative manner the various variables in the system. A model may be defined as "a representation of the essential aspects of a system which presents knowledge of that system in a usable manner." To be useful, a model must not be so complicated that it cannot be understood and thereby be unsuitable for analysis; at the same time it must not be oversimplified and trivial to the extent that predictions of the behavior of the system based on this model are grossly inadequate.

The systems that we shall be concerned with are dynamic in nature, and their behavior will be described in the form of differential equations. Although these will normally be nonlinear, it is customary to linearize them about an operating point to obtain linear differential equations. This is done in order that the analysis can be carried out conveniently. It should, however, be borne