Systems and Control Engineering

1. Notions of Control

A Rama Kalyan and J R Vengateswaran

To control an object means to influence its behaviour so as to achieve a desired goal. To implement this influence, engineers build various devices that incorporate several mathematical techniques. The study of these devices and their interaction with the object being controlled is the subject of this article.

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Introduction

Let's begin with a simple question. When did you last use the word *control*? Perhaps, one may have to think for a while. But the paradox is that one invariably uses this almost in every walk of life but fails to take notice.

- He has no *control* over his expenditure
- The driver lost *control* and collided head on
- The law and order situation in the city is out of *control*
- Pest *control* in orchards

These are a few common phrases we come across all the time. There are many new products and services being introduced everyday that depend on control systems. Yet, they are never identified as control systems. The user of the system does not focus on the control system, but rather on the desired result. Thus, control systems are invisible.

Should we lament this apparent invisibility of control systems? Perhaps, we do as control engineers. This invisibility, however reflects the fact that control systems is a mature technology. It is the very nature of control systems, that the performance of an object or process which is controlled is improved.

The label of mature technology both exalts and haunts control

Controls discipline has played critical roles in technological advances over the last few decades.

science and engineering. There is no question that the controls discipline has played critical roles in technological advances over the last few decades. If not for modern control theory, aircraft would not be flying as far or as fast; manufactured goods, from paper to steel to gasoline to Mars Bars, would not be as readily available; Rover would still be just a dog's name; ... the list is endless. Control has been a linchpin of the modern age.

We avoid a formal definition of the word *system*. Instead, we shall rely on the popular or intuitive concept of a system that one has. That we are able to do so illustrates one of the facets of system theory which makes it so important, namely, we can find the ideas and techniques of system theory in such seemingly unrelated areas as computer design, investigation of the central nervous system, guided missiles, etc. Whenever a system is designed such that the dynamic behaviour of an initial process is intentionally altered to achieve some desired performance, then we have a control system.

An Illustration

Let us imagine we are driving an automobile. We start from a point A and our destination is B, say, 60 km away. Obviously, depending upon the time constraint, we choose to drive at a pre-calculated speed. Let us say, we need to reach our destination exactly in 60 minutes. Hence, the pre-calculated speed is 60 kmph. We would like to express this in the following sentence. 'If we drive the automobile at 60 kmph, then we reach our destination in exactly an hour'. The antecedent clause in this sentence refers to the *cause* and the consequent refers to the *effect*. This may be depicted as shown in *Figure 1*.

The cause may be physical, for example, the pressure we apply on the accelerator pedal so that the speed of the vehicle is

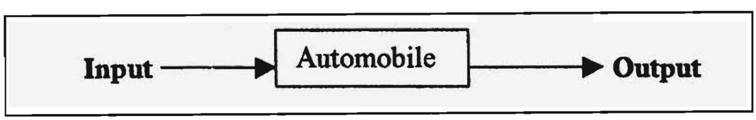

Figure 1.

VISVESVARAYA MUSEUM – INVADED BY INSECTS!

The Visvesvaraya Industrial and Technological Museum in Bangalore has been invaded by insects and arthropods – an exhibition called '*Giants from the Backyard*' has been set up in the museum. This *Science Fantasy Exhibition*, organised by the National Council of Science Museums, aims to celebrate the hidden world of Arthropoda. The National Council of Science Museums has been striving to create a scientific temper among the people of the country and popularise science through hands-on and interactive exhibition galleries, outdoor science parks, mobile science exhibition programmes and a variety of other activities directed towards the students and the general public.

Designed and developed indigenously at Science Centres in Calcutta, Bangalore, Mumbai and Delhi, '*Giants From the Backyard*' comes close on the heels of its previous, enormously successful exhibition on '*Dinosaurs*'. Giants from the backyard attempts to reveal the fascinating world of arthropods, especially the insects. Arthropoda is the largest phylum in the animal kingdom, forming almost 85% of the known species of animals. Insects themselves constitute about 80% of the arthropod species. Arthropoda and especially insects, have been dominating this planet for almost 350 million years. Much before man, they knew how to make paper, silk and sugar, recycle waste, practise agriculture, eliminate pests and so on. Familiar creatures like spiders, centipedes, millipedes and insects like ants, grasshoppers, mantids, locusts, butterflies, wasps and honeybees are displayed in this exhibition.

This exhibition explains the evolution, life cycle, locomotion, usefulness and defence mechanisms of the tiny creatures found in our backyards. The exhibition also reveals some fascinating facts about insects not known to many. This exhibition has been developed in an imaginative way to combine education and entertainment. The exhibits are enlarged to about 25–300 times the original size of the species and are animated robotic forms covering an area of about 7000 sq.ft. Along with these, the exhibition contains some interesting participatory exhibits in which the mouthparts of the insects, how they find their food, how they move and fly, their breathing mechanisms, their life cycle, their vision, their communication system, defence mechanism, usefulness and harmfulness and the distribution of arthropods, are all explained. In all the exhibition depicts 20 species of the arthropod world.

The exhibition is open to the public at the **Visvesvaraya Industrial & Technological Museum, Kasturba Road, Bangalore 560 001, from 25th of December 1998 till mid February 1999.** Apart from this exhibition, visitors can also enjoy 7 other interactive science exhibition halls in the museum premises. *Giants from the Backyard* will be a major attraction in Bangalore for about 50 days and after that it will be taken to the other NCSM Science Centres at Nagpur, Delhi and Calcutta.

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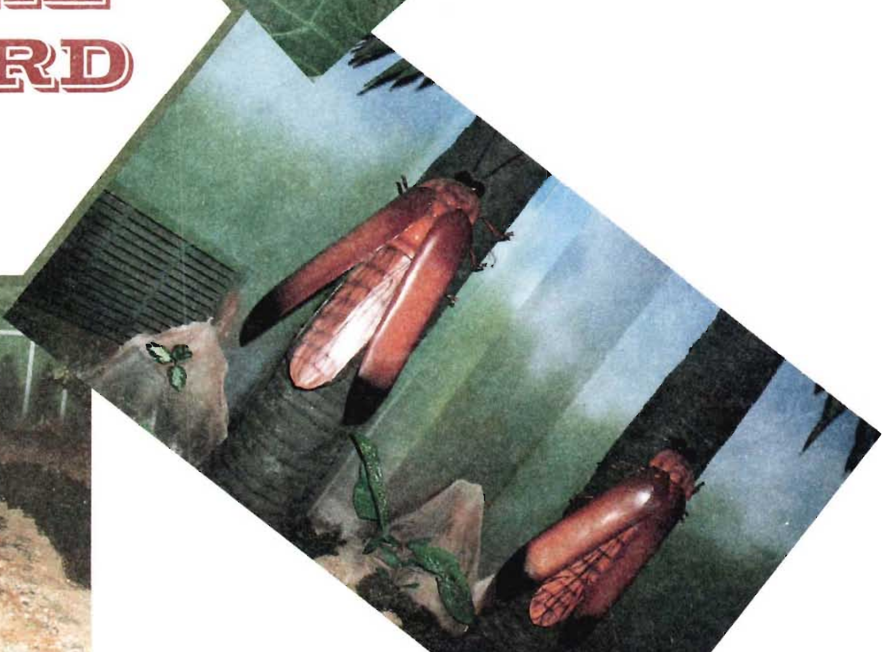

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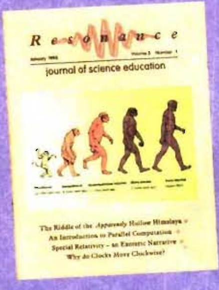

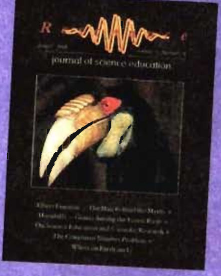

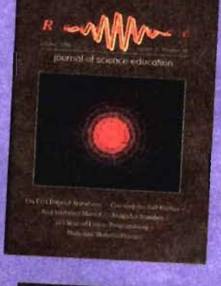

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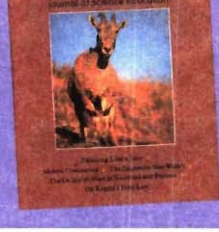

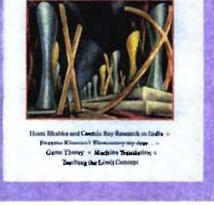

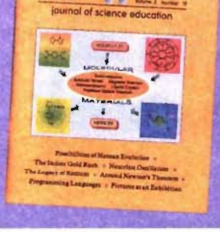

constant at 60 kmph. We also use the word *input* for convenience. Similarly, the effect may be the rate of displacement or the speed of the vehicle; or equivalently, the distance covered by the vehicle. Sometimes, we use the word *output* for the effect. Thus, we assume that if an input is applied there will be a unique response. This relationship between the input and the output is essential in defining a system.

Whenever a system is designed such that the dynamic behaviour of an initial process is intentionally altered to achieve some desired performance, then we have a control system.

Evidently, so far, we have considered an ideal case where it is assumed that there is absolutely no traffic, no speed-breakers etc. Let us now include some of these practical factors. Suppose there is some obstacle, say a railway crossing, after travelling 10 km, when we need to apply the brakes (another control!) and wait for 10 minutes. We have to increase the speed to 75 kmph so that the time lost may be 'compensated', and we reach the destination on time. What exactly is the process that we accomplished just now? We *measured* the variables – the distance and the time – and accordingly changed or modified the speed. In other words, we controlled the automobile by using the difference between the *desired* distance to be covered and the *actual* distance covered so far. This may be depicted as shown in *Figure 2*.

For obvious reasons, we call the control system in *Figure 1* an *open-loop* system and that in *Figure 2* a *closed-loop* system. In this illustration, the system we attempted to control is an automobile. In general, any system that is required to be controlled is called a *plant*. The input applied to the plant is called the *control signal* or *control law* which is provided by a compensator. In the closed-loop control system, the plant output is compared with a reference input and an error is computed. Accordingly, we also call this

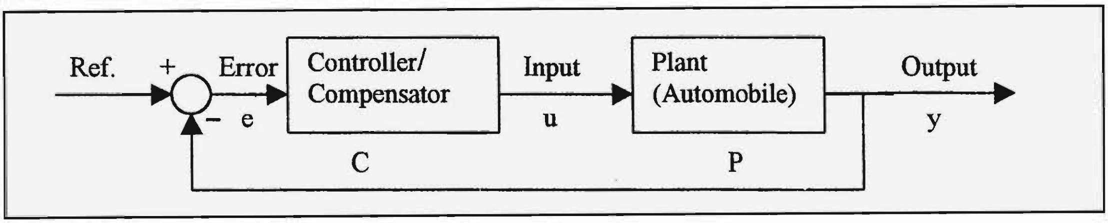

Figure 2.

system, a *negative unity feedback* control configuration. Other configurations also exist but are beyond the scope of the present article. This negative unity feedback configuration is the most used one as it is conceptually quite simple.

Success Stories of Control Systems

We often hear about new control applications in flight control, process control, manufacturing, environmental control, and many other areas. In *Box 1* and *Box 2*, we describe the application of feedback control concepts to two novel domains.

Box 1. Application of Control Systems to Multi-Storeyed Buildings

Since the collapse of the Tacoma Narrows bridge in 1940, the relevance of control engineering to the design of civil engineering structures has been noted. Protecting civil structures is of great economic and social importance. Buildings and other physical structures have traditionally relied on their strength and ability to dissipate energy to survive under severe dynamic loading. In recent years, however, world wide attention has been directed towards the use of control and automation to mitigate the effects of those dynamic loads on the structures. The basic task is to determine a control strategy that uses the measured structural responses to calculate an appropriate control signal that will enhance structural safety and serviceability. The first full-scale application was accomplished by the Kajima Corporation, Japan in 1989. The Kyobashi Seiwa building is a eleven story (33.1 m) building in Tokyo, having a total floor area of 423 sq.m. A control system was installed, consisting of two active mass damper systems (AMDs) – the primary AMD is used for transverse motion and has a mass of 4 tons, while the secondary AMD has a mass of one ton and is employed to reduce torsional motion. The role of the active (or feedback) system is to reduce building vibration under strong winds and moderate earthquake excitations and consequently to increase the comfort of occupants of the building. To date, there have been more than 20 buildings and 10 bridges that have employed feedback control strategies in full-scale implementation. A few of them are listed below:

Full Scale Structure	Location	Year	Scale of building
Sendagaya INTES	Tokyo, Japan	1992	58m, 3280 ton, 11 stories
Osaka Resort City 2000	Osaka, Japan	1992	200m, 56980 ton, 50 stories
Yokohama Landmark Tower	Yokohama Kanagawa, Japan	1993	296m, 260610 ton, 70 stories
Hiroshima Richga Royal Hotel	Hiroshima, Japan	1994	150m, 83000 ton, 35 stories
TC Tower	Kao Hsung, Taiwan	1996	85 stories
Nanjing Tower	Nanjing, China	1998	310 m

Box 2. Controlling Telescope.

The Keck astronomical telescope at Mauna Kea in Hawaii uses control innovatively. The basic objective of the telescope is to collect and focus starlight using a large concave mirror. The shape of the mirror determines the quality of the observed image. More light can be collected with a large mirror, and hence dimmer stars can be observed. The diameter of the mirror on the telescope is 10 m. To make such a large high precision mirror out of a single piece of glass would be difficult and costly. Instead, it uses a mosaic of 36 small hexagonal mirrors. These 36 segments must then be aligned so that the composite mirror has the desired shape. The control system to do this may also be depicted as a closed loop system similar to the one in *Figure 2*. In controlling the mirror's shape, it suffices to control the misalignment between adjacent mirror segments. For the mirror to have an ideal shape, the displacements should have certain ideal values that can be pre-computed; these are the components of the reference **R**. Behind each segment are three piston type actuators, applying forces at three points on the segment which adjust its orientation. The compensator **C** must be designed so that in the closed loop system, **y** is held close to **R** despite disturbing forces such as wind gusts, changes in ambient temperature, etc..

Brief History of Control Theory

When did mankind first attempt to intentionally alter the environment? Obviously, we cannot identify this specific event, but we know it has always been a human characteristic to seek to control objects with which we interact. Perhaps, the first control system was that of the Greeks and Arabs who invented water regulation devices so that they could more accurately measure time; but if we use a general definition of control systems, we suspect there are even earlier examples. Making fire is a way of controlling temperature! In what follows, we present a very brief history of automatic control. Technical details and the names of engineers/scientists are not given to sustain the flow of the narration. Motivated readers may find more details in [1]. The history of automatic control can be divided into four main periods as follows:

Early Control : Up to 1900

Most inventions and applications of this period were concerned with the basic activities of controlling temperatures, pressures, liquid levels, and the speed of rotating machinery. However, growth in the size of ships and naval guns, and introduction of new weapons such as torpedoes, resulted in the application of steam, hydraulic and pneumatic power systems to operate position control mechanisms. Further applications of control systems became apparent with the growth of knowledge of electricity and applications. For e.g. arc lamps require the gap between the electrodes to be kept constant, and generally it is necessary to keep the voltage of the electricity supplied to users constant.

The Pre-Classical Period : 1900 – 1935

The early years of the 20th century saw the rapid and widespread applications of feedback controllers for voltage, current, and frequency regulation, boiler control for steam generation, electric motor speed control, ship and aircraft steering and auto stabilization, and temperature, pressure, and flow control in the process industries. As applications multiplied, engineers became puzzled and confused; controllers that worked for one application, or for one set of conditions, were unsatisfactory when applied to different systems or different conditions; problems arose when a change in one part of the system (process, controller, measuring system, or actuator) resulted in a change in the major time constant of that part. (For a definition of the time constant please refer to the next part of this article).

The differential analyser provided a means of stimulating the behaviour of dynamical systems.

During the same period, extensive work was being done on mechanical analog computers at the Massachusetts Institute of Technology. This work resulted in the differential analyser, which provided a means of simulating the behaviour of dynamical systems and of obtaining numerical solutions to differential equations.

The Classical Period : 1935 – 1955

During the first five years of this period, advances in the understanding of control systems were made independently by three prominent groups working in the United States. A group at Bell Labs tried to find ways of extending the bandwidth of their communication systems. The second important group was mechanical engineers and physicists working in the process industries. They sought to establish a common terminology and tried to develop design methods. The third group was at the

Electrical Engineering Department at MIT. They used time-domain methods based on operator techniques and began to develop the use of block diagrams, and used the differential analyser to simulate control systems.

The advent of World War II steered control systems work on a few specific problems. The most important of these was the aiming of anti-aircraft guns. This is a complex problem that involves the detection of the position of the air-plane, calculating its future position, and the precise control of the movement of a heavy gun. Work on the 'systems' problem brought together mechanical, electrical and electronic engineers, and an outcome of this cross-fertilization of ideas was a recognition that neither the frequency response approach used by the communication engineers nor the time response approach favoured by the mechanical engineers were separately effective in designing position control systems. This led to the use of Laplace transform techniques. By the end of the war, researchers were concentrating on the nonlinear and sampled-data systems. The other major development to emerge from the fire control work during the war was the study of stochastic systems. During the same period, the teaching of control theory spread, initially through special courses run for practising engineers and graduate students and then absorption within the standard syllabus of many engineering courses.

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The Modern Control Period: Post 1955

Although the direction of some post-war work was influenced by the insights and new understandings developed during the war, the trajectory of development was largely determined by two factors : First, the problems that governments saw as important – the launching, manoeuvring, guidance and tracking of missiles and space vehicles; and second, by the advent of the digital computer. The first problem was essentially control of ballistic objects, and hence detailed physical models could be constructed in terms of differential equations, both linear and nonlinear. Further, measuring instruments and other components of great accuracy and precision could be developed and used. Engineers working in the aerospace industries, following the example set by Poincaré, turned to formulating the general differential equations in terms of a set of first-order equations, and thus began the approach now known as the *state-space* approach.

In the later part of the 1950s, Bellman began working on optimal control theory, at first using the calculus of variations but later, seeking to formulate deterministic optimization problems in a way in which they could be solved by using dynamic programming. The generalization of Hamilton's approach to geometric optics by Pontrjagin in 1956 in the form of his maximum principle, laid the foundations of optimal control theory. This and Bellman's insight into the value and usefulness of the concept of state for the formulation and solution of many control and decision problems led to extensive and deep problems of automatic control. The growing availability of the digital computer during the late 1950s made a recursive algorithmic solution possible.

By the early 1960s , the digital computer had been used on-line to collect data for optimization and supervisory control and for a limited number of applications of direct digital control. A leading advocate for the use of digital computer in the process industries was Donald P Eckman. He persuaded several companies to support research based at the Case Institute of Technology, Cleveland, Ohio. The programme was initially called *Process Automation* but it was renamed later as *Control of Complex Systems*. This was because Eckman wished to distinguish what he was doing from the popular image of automation. By the end of the decade Eckman was arguing in support of *Systems Engineering* with the idea that what industry needed was engineers with 'a broad background across conventional boundaries of the physical, engineering and mathematical sciences' and with 'an ability to approach problems analytically, to reduce physical systems to an appropriate mathematical model to which all the power of mathematical manipulation, extrapolation, and interpretation can be applied'.

Suggested Reading

[1] *IEEE Control Systems Magazine.* Special issue on the evolving history of control. Vol. 16. No. 3, 1996.

[2] *IEEE Control Systems Magazine.* Special issue on breaking through with emerging technologies. vol. 17. No. 6, 1997.

[3] Maciariello and Kirby, *Management Control Systems.* 2/e. Prentice Hall of India, 1998.

[4] M Gopal. *Control Systems: Principles and Design.* Tata McGraw Hill, 1997. (An exhaustive list of classified references may be found in this book).

[5] P R Be Langer. *Control Engineering.* Saunders College Publishing, 1995. (This book was reviewed in *The Hindu* recently).

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