APPLIED INDUSTRIAL CONTROL

An Introduction

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International Series on
SYSTEMS AND CONTROL

Volume 1

Pergamon Press

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PERGAMON PRESS

OXFORD · NEW YORK · TORONTO · SYDNEY · PARIS · FRANKFURT

U.K.	Pergamon Press Ltd., Headington Hill Hall, Oxford OX3 0BW, England
U.S.A.	Pergamon Press Inc., Maxwell House, Fairview Park, Elmsford, New York 10523, U.S.A.
CANADA	Pergamon of Canada, Suite 104, 150 Consumers Road, Willowdale, Ontario M2J 1P9, Canada
AUSTRALIA	Pergamon Press (Aust.) Pty. Ltd., P.O. Box 544, Potts Point, N.S.W. 2011, Australia
FRANCE	Pergamon Press SARL, 24 rue des Ecoles, 75240 Paris, Cedex 05, France
FEDERAL REPUBLIC OF GERMANY	Pergamon Press GmbH, 6242 Kronberg-Taunus, Hammerweg 6, Federal Republic of Germany

First edition 1980

British Library Cataloguing in Publication Data

Applied industrial control. - (International series on systems and control).
1. Process control - Electronic equipment
2. Microelectronics
I. Singh, Madan G II. Series
621.7'8 TS156.8 80-49933

ISBN 0 08 024764 4 Hardcover
ISBN 0 08 024765 2 Flexicover

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Printed and bound in Great Britain by
William Clowes (Beccles) Limited, Beccles and London

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ACKNOWLEDGEMENT

This book is the fruit of an international collaboration between the Control Systems Centre at the University of Manchester Institute of Science and Technology and the Laboratoire d'Automatique of the Ecole Nationale Superieur de Mechanique at Nantes. It brings together the diverse interests of the authors into an integrated form. We are especially grateful to Mrs. Barbara Beeby for translating some of the chapters from French into English. We are also grateful for the diligence and patience of Mrs. Elizabeth Tongue and Mrs. Vera Butterworth who so ably typed the final typescript, and to Mr. Robert Kirk for doing most of the diagrams. We are grateful to Dr. Prosper Chemouil for helping with the proof-reading. Finally, we are most grateful to Mrs. Beryl Hooley for preparing the indices and to Miss Dee Brown for her help in a general way. The errors that remain are our own.

M.G. SINGH - J.P. ELLOY - R. MEZENCEV - N. MUNRO

March 1980

PREFACE

In 1980, a quarter of the market for microprocessors is in industrial instrumentation and control. This book is devoted to the teaching of instrumentation and control in the context of the microelectronic revolution.

The book is basically divided into 8 chapters. In Chapter 1 we introduce the basic notions of control of systems. We also describe how one could build a model of a system. Chapters 2 and 3 are devoted to microprocessor hardware and software concepts with particular emphasis on real time applications. In Chapter 4 we come back to the control problem and develop the analytical and design techniques that are necessary for monovariable systems. We emphasise in particular the techniques used in industrial regulation.

In Chapter 5, multivariable systems are treated. The analysis is both in terms of the Frequency Domain techniques developed by the Manchester school as well as the optimal control approach.

Chapter 6 concentrates on industrial instrumentation. We examine the measurement of temperature, pressure, flow and level. In each case we describe the existing technology and how it is being modified as a result of the microprocessor revolution.

Chapter 7 is devoted to regulators and actuators. We describe both electronic and pneumatic regulators. We give a detailed analysis of valve calculations.

Here again, the current state of the technology is described and its evolution as a result of the introduction of microelectronic components is charted.

Thus these first seven chapters of the book provide a unified treatment of industrial control and of the increasing role that microprocessors are playing in it. The eighth and final chapter is more speculative. It treats recent advances in the control of large scale systems and shows how the new microelectronic technology will be used to control systems of increasing complexity.

The treatment in the whole book is at the level required of a final year undergraduate course or a starting graduate course in industrial control. It can be taught at a modest pace in 60 contact hours. Many worked examples are given in the book and, where applicable, exercises are also given.

This book is much more applied than a standard control text and we hope that it will provide a bridge between the theory taught in academic institutions and the pragmatic practice of industrial control.

CHAPTER 1

INTRODUCTION TO INDUSTRIAL CONTROL

1.1 INTRODUCTION

Control systems continue to play a significant role in improving the quantity and quality of manufactured products. They constitute the basic elements of automation systems and as our manufacturing activities get more and more automated, the importance of using increasingly more refined control technology becomes evident. The most important technological advance that we are currently in the process of seeing is a revolution that is taking place in the processing of information and this will have a major impact on industrial control. This revolution is based on the introduction of microprocessors.

The microprocessor is perhaps the most significant development the electronics industry has seen for at least the last decade. The main advantages offered by microprocessing systems are lower cost, fewer components, increased reliability and versatility. Microprocessors are already taking over some of the information processing functions in industrial control and instrumentation that were previously performed by expensive hardwired logic circuits or by big central computers. The next few years will show an expansion of the use of microprocessors in all aspects of industrial instrumentation and control.

In this book, we study the use of microprocessors in industrial control and instrumentation and we examine both the current state of the technology as well as its future trends. The book has three main parts, the first being devoted to the hardware and software of microprocessors, the second to control algorithms and the third to the technology of measurement and control. In a final chapter, we examine future trends in control.

We begin the present introductory chapter by defining what constitutes a control system and the various signals that we find in control systems.

Definitions

A control system is an arrangement of physical components connected or related in such a manner so as to command, regulate or direct itself or another system. In industrial practice we usually restrict the meaning of control systems to apply to those systems whose major function is to command, regulate or direct itself or another system dynamically.

Control systems abound in man's environment. The earliest known control system appears to have been the south pointing chariot which was used in ancient China. By using a system of differential gearing, it was possible to maintain a particular heading (south in this case). Subsequently, millwrights used a control system to maintain windmills in the direction of the wind, as early as in the 18th century. The flywheel governor of James Watt was the first control which was rigorously analysed (by James Clerk Maxwell). Modern control systems arose from the development of servomotors in the second world war which were used to control the position of heavy guns. Since that time, the field has expanded extremely fast. It received a major impetus during the American space programme. Currently, control systems and control concepts are used in most areas of human endeavour.

Before considering specific examples of control systems, we define two terms: the INPUT and the OUTPUT which help in identifying or defining the control system.

The INPUT is the stimulus or excitation applied to a control system from an external energy source usually in order to produce a specified response from the control system.

The OUTPUT is the actual response obtained from the control system. It may or may not be equal to the desired response implied by the input.

In a certain sense inputs and outputs are arbitrary and it is a part of the art of the control systems engineer to choose them judiciously. The purpose of the control system usually identifies or defines the inputs and outputs. Once, the inputs and outputs are defined, it becomes possible to specify the nature of the systems components.

Control systems are classified into two general categories i.e. OPEN LOOP and CLOSED LOOP. The distinction between OPEN LOOP and CLOSED LOOP control is determined by the CONTROL ACTION which is the quantity responsible for activating the system to produce the output.

An OPEN LOOP control system is one in which the control action is independent of the output.

Example 1. The angular position of the steering wheel of a car controls the direction of the front wheels. In this case the position of the steering wheel is the input and the direction of the front wheels is the output. The control systems elements are composed of the steering mechanism.

Example 2. An automatic toaster is an open loop control system; the time required to make good toast must be estimated by the user, who is not a part of the system. Control over the quality of toast (output) is removed once the time, which is both the input and the control action, has been set.

Example 3. The velocity control of a car is an open loop control system. The depression of the accelerator pedal is the input. The velocity is the output.

Two important characteristics of such open loop control systems are:

1. Their ability to perform accurately is determined by their calibration. To CALIBRATE means to establish (or re-establish) the input-output relationship in order to obtain a desired system accuracy,

2. They are not generally troubled by problems of instability, a concept that we will discuss subsequently in some detail.

A CLOSED LOOP control system is one in which the control action is somehow dependent on the output.

In order to classify a control system as open-loop or closed-loop, the components of the system must be clearly distinguished from the components that interact with but are not a part of the system. For example, a human operator may or may not be a part of the system. In all the three examples above, we have considered the human operator not to be a part of the system. Of course, if the human operator was considered to be a part of the system, he or she closes the loop so that the system could be classified as a closed loop control system.

Examples of Closed Loop Control

1. An autopilot mechanism and the aeroplane it controls is a closed loop(feedback) control system. Its objective is to maintain a specified aeroplane heading despite atmospheric changes. It performs this task by continuously measuring the actual aeroplane heading and automatically adjusting the aeroplane controls (rudder, flaps, etc.) so as to bring the actual aeroplane heading into correspondence with the specified heading. The human pilot who presets the autopilot is not a part of the control system.

2. Industrial Pressure Control System. Figure 1.1 shows a pressure control system. The transducer T measures the pressure "P" which is to be controlled and sends an

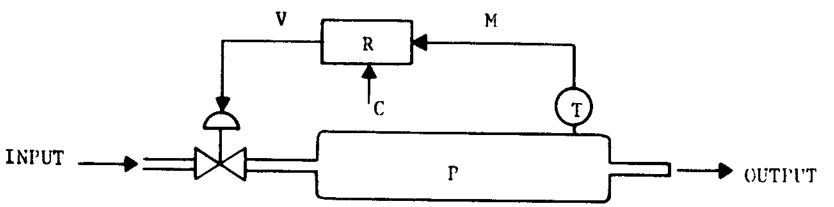

Fig. 1.1

analogue signal M (pressure or electrical) to the regulator R. This regulator compares it with its pre-set desired value C. It modifies the analogue signal V which controls the opening and closing of the valve as a function of the difference between M and C.

This leads us on to the concept of Feedback.

Feedback is that characteristic of closed loop control systems which distinguishes them from open-loop systems.

Feedback is the property of a closed-loop system which allows the output (or some other controlled variable of the system) to be compared with the input to the system (or to an input to some other internally situated component or subsystem of the overall system) so that the appropriate control action may be formed as some function of the output and input.

The concept of feedback is clearly illustrated by our two previous examples. In the case of the pressure control system, the input is the pre-set desired value C and the output is the actual pressure P as measured by the measuring instruments. The regulator R continuously compares P and C and uses the difference in order to supply a signal to control the valve which regulates the pressure.

In the case of the autopilot mechanism, the input is the specified heading which may be set on a dial of the aeroplane control panel and the output is the actual heading, as determined by the automatic measuring instruments. A comparison device continuously monitors the input and output. When the two are in correspondence, control action is not required. When a difference exists between the input and output, the comparison device delivers a control action signal to the controller, which is the autopilot mechanism. The controller provides the appropriate signals to the control surfaces in order to reduce the input-output difference. Feedback may be effected by a mechanical or electrical connection from the navigation instruments, which measure the heading, or to the comparison device.

Characteristics of Feedback

The most important features that the presence of feedback imparts to a system are the following:

1. Increased accuracy i.e. the ability to faithfully achieve the desired output values.

2. Reduced sensitivity of the ratio of output to input variations in system characteristics.

3. Reduced effects of non-linearities and distortion.

4. Increased bandwidth. The BANDWIDTH of a system is that range of frequencies (of the input) over which the system will respond satisfactorily.

5. Tendency towards oscillations and instability.

In order to design controls for most processes, it is necessary to construct a model. Next we consider models.

1.2 THE MODEL

In order to solve a systems problem, the specification or description of the system configuration and its components must be put into a form amenable to analysis, design and evaluation.

The essential feature of the response of a dynamical system to an input is that its present behaviour is influenced by its past history. We cannot, therefore, represent the behaviour of dynamical systems purely in terms of instantaneous relationships between inputs and outputs. It is necessary to introduce an additional set of variables to take into account the past history of the system. These additional variables are called the STATE VARIABLES of the system. The basic description of a dynamical system consists, therefore, of a relationship between the three sets of system variables i.e. input, output, and state variables. The state variables are functionals of the input variables and of themselves. Thus if $\{u_1(t),u_2(t)\dots u_r(t)\}$ is a set of input variables and $\{x_1(t),x_2(t),\dots x_n(t)\}$ is a set of state variables, and if we take the simplest possible functional relationship i.e. integration, the i^{th} state variable will be expressed in the form

$$x_i(t) = \int_{-\alpha}^{t} f_i\ (x_1,\dots x_n,u_1,\dots u_r,\ t)dt \quad i=1,2,\dots n \tag{1.2.1}$$

where the set of functions f_i define the nature of the dynamical systems behaviour. Equation (1.2.1) implies that the state variables satisfy the set of first order *ordinary differential equations*

$$\frac{dx_i}{dt} = f_i\ (x_1,x_2,\ldots x_n,u_1,u_2,\ldots u_r;t)\quad i=1,2,\ldots n \tag{1.2.2}$$

The model of the system is completed once we specify how a set of output variables $\{y_1(t)\ \ldots\ y_m(t)\}$ is obtained from the state and input variables. For example

$$y_j(t) = g_j(x_1,\ldots x_n,u_1,\ldots u_r;t)\quad j=1,2,\ldots m \tag{1.2.3}$$

Equations (1.2.2) and (1.2.3) define the standard state space model of a dynamical system. It is usually most convenient to represent this model using vector notation i.e.

$$\underline{\dot{x}}(t) = \underline{f}(\underline{x},\underline{u},t) \tag{1.2.4}$$

with $\underline{x} \in R^n$, $\underline{u} \in R^m$

and

$$\underline{y}(t) = \underline{g}(\underline{x},\underline{u},t) \tag{1.2.5}$$

Next we consider block diagrams and subsequently the various signals that arise in control systems analysis.

Block Diagrams

Block diagrams are shorthand graphical representations of either the schematic diagram of a physical system or the set of mathematical equations characterising its parts.

The simplest form of the block diagram is a single block with one input and one output

Fig. 1.2

The interior of the rectangle representing the block usually contains a description or the name of the element or the symbol for the mathematical operation to be performed on the input to yield the output. The arrows represent the direction of unilateral information flow or signal flow.

Figure 1.3 shows the block diagram of a feedback control system. In Fig. 1.3 it must be emphasised that the arrows of the control loop, connecting one block to another, represent the direction of flow of control energy or information and not the main source of energy of the system.

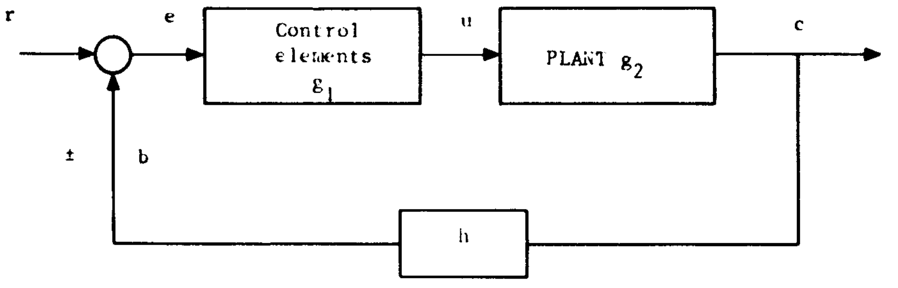

Fig. 1.3

Definitions. The PLANT g_2, also called the control system, is the body, process or machine, of which a particularl quantity, or condition is to be controlled.

The control elements g_1, also called the controller, are the components required to generate the appropriate control signal as applied to the plant.

The feedback elements h are the components required to establish the functional relationships between the primary feedback signal b and the controlled output.

The reference input r (or set point) is an external signal applied to a feedback control system in order to command a specified action of the plant.

The controlled output c is that quantity or condition of the plant which is controlled.

The primary feedback signal b is a signal which is a function of the controlled output c, and which is algebraically summed with the reference input r to obtain the actuating signal e.

The actuating signal e also called the error or control action is the algebraic sum consisting of reference input r minus (or plus) the primary feedback b.

The manipulated variable u (control signal) is that quantity or condition which the control elements g_1 apply to the plant g_2.

A disturbance p is an undesired input signal which affects the value of the controlled output c. It may enter the plant by summation with r or via an intermediate point.

The forward path is the transmission path from the actuating signal e to the controlled output c.

The feedback path is the transmission path from the controlled output c to the primary feedback signal b.

A transducer is a device which converts one energy form into another.

Negative feedback means that the summing point is a subtractor:

$$e = r-b$$

Positive feedback means that the summing point is an adder

$$e = r+b$$

The time response of a system or element is the output, as a function of time, following the application of a prescribed input under specified operating conditions.

Next we consider Laplace transforms and transfer function models since these will serve as important tools in our analysis.

1.3 THE LAPLACE TRANSFORM

1 - Definition: Let f(t) be a real function of a real variable t defined for t>o. Then

$$L\left[f(t)\right] \equiv F(p) \equiv \lim_{\substack{T \to \infty \\ \varepsilon \to o}} \int_{\varepsilon}^{T} f(t)\, e^{-pt}\, dt$$

$$= \int_{o^+}^{\infty} f(t)\, e^{-pt}\, dt \ , \quad o < \varepsilon < T$$

is called the Laplace Transform of f (t). p is a complex variable defined by:

$$p = \sigma + j\omega$$

Table of useful Laplace Transforms

F(p)	f(t)	F(p)	f(t)
$1/p$	1	$p/p^2+\omega^2$	$\text{Cos}\,\omega t$
$1/p^2$	t	$\omega/p^2+\omega^2$	$\sin\omega t$
$1/p^n$	$t^{n-1}/(n-1)$	$(p+a)/(p+a)^2+\omega^2$	$e^{-at}\cos\omega t$
$\frac{1}{p+a}$	e^{-at}	$\omega/(p+a)^2+\omega^2$	$e^{-at}\sin\omega t$
$\frac{1}{(p+a)^2}$	$t\,e^{-at}$		

These results are generally obtained using integration by parts.

Fundamental Properties

If $L\left[f(t)\right] = F(p)$; $L\left[g(t)\right] = G(p)$