Practical Control System Design

Real World Designs Implemented on Emulated Industrial Systems

Adrian Medioli • Graham Goodwin

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Preface

This book provides an introduction to control system design. It would be suitable as the basis of a first or second course in control. It has also been written as a refresher course for graduate engineers who wish to 'up-skill' in the area of practical control system design.

The book has been inspired and informed by the authors' industrial experience in control. Our goal has been to package that experience so that those reading this book and using the associated resources will acquire the tools and skills necessary to tackle real-world control engineering design problems.

The book draws upon many industrial projects conducted by the authors and associates. These projects are used as case studies throughout the book. The authors, belief is that the richest learning experience comes from testing ideas via 'hands-on' laboratory studies that closely reflect the real world. The case studies are organised in the form of virtual laboratories. Readers can explore the ideas at their own pace and to their own level of interest.

The case studies include the following:

- electromechanical servo systems
- fluid storage
- continuous steel casting
- rolling mill centre line gauge control
- rocket dynamics and control
- cross-directional control in paper machines
- audio quantisation
- wind power generation – mechanical aspects
- wind power generation – electrical aspects (including three-phase induction generator)
- boiler control.

Wherever possible, the models used in the case studies use physical dimensions and parameters from real-world systems.

The laboratories can be conducted 'on-line' without needing to access a physical laboratory. Thus, the laboratories would be well suited to remote education. Nonetheless, the laboratories have been designed so as to be as realistic as possible. Indeed sitting in front of the laboratory interface is essentially the same as sitting in an industrial control room with the following two caveats:

(i) It would be completely unrealistic for any one person to gain access to the range of physical systems studied here.
(ii) One can learn by one's mistakes on a virtual laboratory whereas, if such mistakes were ever made in practice, the consequences could be catastrophic.

For ease of use, the architectures of the various control laws have been provided. Readers can use these architectures as a starting point. In many cases, it is also possible to link the process simulations to a control law whose architecture is specified by the reader or by an instructor.[1] In either case, it is suggested that the reader begin with the given architectures to establish a starting point for further study.

The topics covered in the course include:

- modelling
- PID design
- dealing with delays
- impact of actuator limitations
- dealing with sensor limitations
- feedforward
- soft sensing
- dealing with nasty disturbances
- observers and Kalman filtering
- Bode sensitivity constraints
- dealing with periodic disturbances
- multivariable interactions
- sampled data systems
- dealing with resonant behaviour
- controlling systems which are open-loop unstable.

This book contains 30 chapters. Sixteen of these chapters provide a review of the necessary background theory, whilst the remaining 14 are devoted to testing the ideas on real-world (emulated) systems. The treatment of theoretical topics will be relatively brief since the key aim of the book is to study real-world control system design.

The authors' belief is that anybody who has understood the core concepts explained in the book will be well-equipped to tackle real-world control design problems.

Difficult choices need to be made when writing a book of this type. In particular, to present a detailed treatment of any of the topics covered in the theory sections would expand the book enormously. Hence, the driving philosophy has been to limit the presentation to the depth necessary to enable the reader to undertake the real-world designs. In other words, the goal has been to make the presentation 'as simple as possible, but not so simple as to lose important details'.

1 Exceptions are the Wind Power Laboratory and the Audio Laboratory which require specific architectures.

About the Authors

Adrian Medioli, BE, PhD, OStJ, MIEEE
Adrian Medioli was born in Newcastle, Australia, and completed a B.E. (Computer) in 1992 at the University of Newcastle. He spent 10 years as a senior systems engineer working on the automation and control of steel manufacturing processes including rolling mills, galvanising lines, batch annealing, gauge control and Sendzimir mills and two years as a director of Omni Automation Pty. Ltd., a control engineering and automation startup company. In 2008, he completed a Ph.D. in Electrical Engineering at the University of Newcastle. From 2008 to 2021, he was employed as a research academic in the ARC/PRC for Complex Dynamic Systems and Control at the University of Newcastle. In 2021, he joined Whitely Corporation where he worked on the implementation of Industry Four protocols. As a professional engineer Adrian has worked on many and varied projects which resulted in extensive experience in the areas of software development, team management, control system design and implementation to steel production and manufacturing. As a researcher, he has developed and implemented new techniques in optimisation and control. Some of his achievements include a new technique for maximal controllability of unstable systems using reduced complexity Model Predictive Control (MPC); development of tools for the classification of coal loader downtime causes; ambulance fluid deployment strategy optimisation; ambulance optimal distribution and rostering to better match demand; design and testing of novel control strategies with application to the development of an artificial pancreas for better blood glucose regulation in diabetes sufferers; and re-design and development of a suite of virtual laboratories for the teaching of control system design. At present, Dr. Medioli's focus is on his research interests, including optimisation-based control strategies such as MPC stabilisation and modelling with particular emphasis on unstable systems; virtual laboratory development; and the application of control concepts and design to medical problems. He is a Member of IEEE and holds a Certificate IV in vocational training and assessment with accreditation under the Australian Quality Training Framework (AQTF).

Graham Goodwin, BSc, BE, PhD, FRS, FIEEE, Hon.FIE.Aust., FTSE, FAA
Graham Goodwin is an Emeritus Laureate Professor of Electrical Engineering at the University of Newcastle. His education includes B.Sc., B.E., and Ph.D. from the University of New South Wales. In 2010, he was awarded the IEEE Control Systems Field Award, in 2011 the ACA Wook Hyuan Kwon Education Award and in 2013 he received the Rufus T. Oldenburger Medal from the American Society of Mechanical Engineers. He was twice awarded the International Federation of Automatic Control triennial Best Engineering Text Book Prize. In 2021, he was awarded the American Control Council John Ragazzini Education Award. He is a Fellow of IEEE; an Honorary Fellow of Institute of Engineers, Australia; a Fellow of the International Federation of Automatic

Control; a Fellow of the Australian Academy of Science; a Fellow of the Australian Academy of Technology, Science and Engineering; a Member of the International Statistical Institute; a Fellow of the Royal Society, London, and a Foreign Member of the Royal Swedish Academy of Sciences. In 2021, he was recognised by the Australian Government by becoming an Officer in the General Division of the Order of Australia. He holds Honorary Doctorates from Lund Institute of Technology, Sweden, and the Technion Israel. He is the co-author of 10 previous books, four edited books, and five hundred papers. He holds 16 International Patents covering rolling mill technology, telecommunications, mine planning, and mineral exploration. His current research interests include power electronics, boiler control systems and management of type 1 diabetes.

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Adrian Medioli
Graham Goodwin

About the Companion Website

This book is accompanied by a companion website.

www.wiley.com/go/medioli/practicalcontrolsystemdesign

This website includes:

- Solutions
- Software
- Solutions to revision questions

Part I

Modelling and Analysis of Linear Systems

This part begins the journey through the fascinating world of control system design. Chapter 1 provides a brief historical overview of control. Chapter 2 explains why control is a quintessential example of an inverse problem. Chapter 3 provides an introduction to modelling of physical systems. Chapter 4 describes basic mathematical tools used to analyse linear systems. Chapter 5 contains the first virtual laboratory. A simple door-closing mechanism is used to illustrate basic principles of model building using data collected from a system. Many of the ideas covered in this part of the book would normally be presented in an introductory course on control. Hence, the development will focus on the key concepts that will be used in the real-world designs covered in the sequel.

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1

Introduction to Control System Design

1.1 Introduction

Control is the hidden yet ubiquitous technology [1]. Essentially, no piece of equipment in the modern world would operate satisfactorily without some form of feedback control. Indeed, beyond physical devices such as automobiles or aircraft, control lies at the core of many other systems, e.g. economic systems and even human psychology.

A fascinating overview of control is contained in reference [2] given in Further Reading for this chapter.

The essence of feedback control is that one wishes to act on a system so that it performs in some desirable fashion. Often the goals are expressed as ‘set-points’ for the outputs, sometimes called ‘Process Variables’ (PVs). Action on the system is achieved by changing the inputs, sometimes called ‘Manipulated Variables’ (MVs). Examples occur in every realm. Just a few examples to think about are:

- making a small company profitable
- ensuring a national economy has a low inflation rate
- delivering electricity to a community or country
- cooling a house
- landing an aircraft
- producing a desired product in a chemical plant
- achieving a personal fitness goal
- designing an adaptive cruise controller for a car
- achieving a certain level of proficiency in a trade or discipline
- taking a drug so as to control a chronic disease.

For each of the above examples, the reader may like to think about what the PVs and MVs could be.

The tasks listed above would be easy if

(i) one knew the exact impact that changing the MVs have on the PVs (i.e. one has an exact model), and
(ii) there were no external disturbances.

Alas, in practice, neither of the above requirements is met. Thus, the art of control system design is to build a ‘control’ system that achieves the desired goals, as closely as possible, in the face of uncertainty in both the model and external disturbances.

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1.2 A Brief History of Control

Control underpins the operation of almost every piece of modern equipment, including automobiles, aircraft, chemical plants, national economies and medical devices. It is thus not surprising that people have been thinking about control for hundreds of years. Indeed, Ref.[3] describes a feedback mechanism aimed at regulating the accuracy of a water clock. This device was developed several thousand years ago.

A very well-known application of feedback control was the regulation of the speed of steam engines in the eighteenth-century CE. This was the work of Watt and colleagues and was an enabling technology in the industrial revolution. These speed governors worked amazingly well but were known to sometimes exhibit oscillatory behaviour. James Clarke Maxwell, who is famous for his work on electromagnetic theory, provided a theoretical description in (1868) for this in terms of the properties of ordinary differential equations in the time domain [4].

An important early practical discovery was the use of 'integral action' to achieve zero steady-state error. This was introduced in 1790 in a governor designed by the Perrier brothers [2].

Turning to the process industries, control is an essential technology in all chemical processes. Indeed, modern chemical plants are 'littered' with controllers. The most common controller is a device known as a PID controller. The letters PID stand for Proportional, Integral and Derivative feedback. Though simple, such controllers are incredibly robust and achieve remarkable performance in many cases.

Another remarkable area where control is essential is in powered flight. Indeed, the Wright Brothers, aircraft critically depended on the pilot adjusting the wing surfaces to maintain stability of flight [5].

Moving to an entirely different area, feedback control is a key enabling technology in the telephone. The telephone was invented by Alexander Graham Bell in 1876. However, as the number of repeaters was increased internally generated noise and distortion became intolerable. A major breakthrough was made by Harold Black at Bell Laboratories in 1927 with the development of the negative-feedback amplifier [6]. The essential idea was to use feedback around a high-gain amplifier to reduce the impact of noise on the output signal. In these feedback amplifiers, instability was again sometimes observed (appearing as a 'whistle'). A remarkable engineer, Harry Nyquist, studied the problem of stability at Bell Laboratories [7]. He moved away from the time domain and instead studied how sinusoidal signals propagated around a feedback loop. This was the initial step in using frequency domain analysis of feedback systems.

The frequency domain insights were a huge breakthrough. This was built upon by many people. For example, major contributions were made by Bode in 1940. He recognised that complex variable theory could be used to give deep insights into the frequency domain analysis of feedback systems [8]. In a truly remarkable result, he proved that the integral of log sensitivity with respect to frequency was constant. (Actually zero for an open-loop stable system.) This meant that the action of feedback was simply to shift the impact of disturbances around in the frequency domain. In particular, reducing sensitivity to disturbances at low frequencies would necessarily be accompanied by an increase in sensitivity to disturbances at higher frequencies. This idea underpins many systems used in audio quantisation, industrial electronics and process control.

The above body of work, which emphasises frequency domain concepts, is often classified as part of the 'Classical Control' era. This circle of ideas dominated until the 1960s when a step back to time domain ideas was made. A major contribution was the work of Pontryagin, Boltyanskii, Gamkrelidze and Mishechenko (1962) in the USSR on 'optimal' control [9]. A related stream