Preface

Subject Matter

This book is on feedback control systems covering many applications such as spacecraft orientation, positioning of mechanisms in industry, liquid level and temperature control, and engine management. The general approach taken is to commence with the simplest tentative solution to a control problem and in some cases to demonstrate and explain why this is insufficient and introduce appropriate measures to ensure that satisfactory performance is achieved, thereby giving the reader a full understanding of the features of different controllers. This approach enables the reader to apply traditional control techniques where these are sufficient but also encourages the creation of more sophisticated control systems that work better for other applications through taking advantage of modern digital implementation. For ease of understanding, the book is self-contained with very little reliance on references, much attention being paid to explanations of the underlying concepts and detailed mathematical derivations being given where necessary, showing every step. Ample use is made of diagrams to aid the conceptual explanations. The reader's interest in the subject matter is maintained by giving reasons for the inclusion of every topic and bringing the material to life by frequent reference to real applications. The numerous control system examples are backed up by simulations. The reader's understanding is reinforced by a set of problems and solutions on each chapter provided in the book website, designed to develop the reader's ability to tackle original and sometimes unusual control problems. The reader's understanding is developed further by the opportunity to experiment with any of the fully commented MATLAB®–SIMULINK® control system simulations that may be downloaded from the book website. These are also intended to help readers to develop simulations of their own control applications.

Purpose and Readership

The main benefit of reading the book is to develop the understanding and skills needed to pursue a rewarding career as a creative control engineer. The readers will include (a) undergraduates in the final year of an engineering degree, (b) master's students studying feedback control, (c) PhD students carrying out research in the control techniques covered or developing feedback control systems to support their projects and (d) research and development engineers in industry wishing to create control systems fully benefitting from the modern digital implementation media.

The numerous control system examples together with the simulations would be suitable for seeding and/or supporting final-year undergraduate or master's projects.

Content of the Chapters

Chapter 1. Introduction

After defining the notation and nomenclature used throughout the book, a review of the traditional industrial controllers is given, commencing with the simplest. This ensures some continuity between the elementary studies that will already have been undertaken by the reader and the more advanced material. Then a comprehensive treatment of the correlation between the relative pole and zero locations of the Laplace transfer function of a linear time-invariant system and its dynamic characteristics is given, quantified by the pole-to-pole and pole-to-zero dominance ratios.

Chapter 2. Plant Modelling

This chapter develops the background theory and provides the knowledge needed to generate plant models. After an introduction to the basic character of plants and their components, a subsection on physical modelling is presented. This is based on the underlying science of the various applications. Within the space limitations, the main emphasis is on mechanical systems and electric motors as actuators to cater for a large proportion of the applications. Some introductory material on thermal and fluid systems is also given. This is followed by a substantial section of identification of plant models from input and output signals in the frequency and time domains.

The appendix contains a comprehensive treatment of the kinematics of vehicle attitude control, relevant to applications such as spacecraft, aircraft and underwater vehicles. This is followed by a presentation of plant model determination from frequency response data including procedures for identifying plants with relatively close poles and/or zeros. Finally, a case study of plant modelling in the automotive industry is presented that embodies some of the techniques covered in the chapter.

Chapter 3. Plant Model Manipulation and Analysis

Further to the physical modelling and identified transfer functions developed in Chap. 2, this chapter presents means of converting these to other forms of plant model needed for the application of specific control techniques, including transfer function block diagrams and state space models, both continuous and discrete.

The theory of the z-transform is reviewed, and means of directly generating z-transfer function models including the sample/hold are derived that are directly useful for control system design. These are included in Table 3 of the Tables section preceding the index at the end of the book alongside the z-transforms usually presented elsewhere.

State representation and the associated transformations are covered. The observer canonical form, the controller canonical form and the modal form for single-input, single-output and multivariable plants are studied. Controllability and observability analyses for both continuous and discrete state space models are included.

Chapter 4. Traditional Controllers: Model Based Design

This chapter commences with the simplest feedback control systems to ensure continuity and provide some revision for readers who have only undertaken one year of undergraduate study of linear control systems. As the chapter progresses, various performance demands are introduced together with increases in the plant order. Controllers are selected through the needs of application examples. At each stage, features, either in the control structure or design methodology, are introduced that meet the specification. With this approach, the reader will fully understand the features and be able to select the simplest suitable traditional controller for a plant of first or second order and calculate its gains, based on pole assignment, to meet a given performance specification in terms of settling time, steady state error and sensitivity/robustness.

The behaviour of linear systems of the third and higher order is studied in preparation for designing control systems for second-order plants using traditional controllers containing integral terms and the more general control systems of Chap. 5. The author's settling time formulae are derived for use in conjunction with the pole assignment design of systems of arbitrary order.

Finally, connections between performance specifications in the time domain and the frequency domain are established.

The appendix contains an unusual but useful adaptation of Mason's formula for direct application to linear system block diagrams to derive transfer functions and characteristic polynomials. This is followed by a pole placement procedure for cancellation of zeros introduced by traditional controllers, together with statements of its limitations. Finally, partial pole assignment is presented for linear control systems whose order exceeds the number of independently adjustable controller gains.

Chapter 5. Linear Controllers for LTI SISO Plants of Arbitrary Order: Model-Based Design

The model-based control system design approach based on pole assignment introduced in Chap. 4 is extended beyond systems of second order first by means of linear state feedback control and subsequently by means of polynomial control.

The state is assumed available for use with the linear state feedback control system designs derived in this chapter, these being rendered practicable when used with the state estimation techniques presented in Chap. 8.

The effects of closed-loop transfer function zeros are studied, and means of taking them into account or eliminating them in the control system design using dynamic pre-compensators to achieve satisfactory responses are developed.

The generic technique of polynomial control is introduced in a straightforward manner, simple means of determining suitable polynomial degrees for a given plant being devised. The solution of the Diophantine equations to calculate the polynomial coefficients for the pole assignment is expressed as a linear matrix equation suitable for computer-aided design.

The appendix contains two aids to computer-aided design. The first is Ackermann's gain formulae for the pole assignment design using any state representation for linear state feedback control, also for observers to be read in conjunction with Chap. 8. The second aid is linear characteristic polynomial interpolation for computing the adjustable parameters for the pole assignment design of any linear system whose characteristic polynomial coefficients are linear with respect to the parameters.

Chapter 6. Discrete Control of LTI SISO Plants

The general structure, timing, algorithms and flow charts of discrete controllers are first discussed. Then the correlation of the behaviour of discrete dynamical systems with the z-plane pole locations is studied, including stability analysis. The effects of transfer function zeros are also considered.

A simple procedure is presented for converting continuous controller designs for digital implementation provided the sampling period is sufficiently small. A criterion of applicability of continuous linear time-invariant system theory is developed that determines whether or not this procedure is valid.

The remainder of the chapter is devoted to a design method applicable, in theory, with unlimited sampling periods and which caters for plants of arbitrary order. This entails pole placement in the z-plane in which a specified settling time is nearly realised if it is considerably larger than the sampling period. As the demanded settling time approaches zero for a fixed sampling time, a dead beat response is approached, which has the shortest possible settling time and is therefore the best compromise.

Discrete polynomial control is presented, following the continuous version of Chap. 5. This has the same structure as the RST controller but a different design procedure. It is shown how this methodology enables computational delay allowance.

Finally, discrete polynomial control of plants containing pure time delays, aided by a Smith predictor, is addressed.

Chapter 7. Model Based Control of Nonlinear and Linear Plants

First, the focus is on the control of nonlinear plants. This commences with traditional linearisation about the operating point, which enables linear control system design provided the plant states are restricted to lie in the region of the operating point. This is followed by feedback linearising control, which removes the operating point restriction and is applicable to multivariable as well as single-input, single-output plants.

The underlying principle of feedback linearising control, which forces the closed-loop system to obey a prescribed differential equation, is extended in two directions. First, feedback linearising control is applied to linear plants, which is found to be straightforward for multivariable plants. This is further extended to the discrete domain. Second, the prescribed closed-loop differential equation is allowed to be nonlinear, catering for control strategies such as near time-optimal control. In both these cases, the title, feedback linearising control, is replaced by the more appropriate title, forced dynamic control.

Chapter 8. State Estimation

The basic full state observer for linear, time-invariant, single-input, single-output plants is first developed. The separation principle and transparency property are covered and the design procedure given. The full state observer is then extended for the estimation of external disturbances together with the plant state. The discrete version is then developed together with the design procedure. The continuous full state observer for linear time-invariant multivariable plants and its design procedure are then presented.

The remainder of the chapter is devoted to the effects of measurement noise and plant noise on the state estimate and how this may be taken into account in observer design using power spectral density and variance information. The discrete Kalman filter algorithm is then introduced and comparisons made with the discrete observer algorithm for linear time-invariant multivariable plants. A derivation of the discrete Kalman gain algorithm is given. Comparisons are made with the continuous version.

The appendix contains two approaches to nonlinear observer design restricted to plants of full relative degree. The first comprises a set of filtered output derivative estimators constituting a state estimate, practicable provided the measurement noise levels are not too high. The second affords more measurement noise filtering by using the output derivative estimates of the first approach as raw measurements for a special observer in which the nonlinear elements of the plant model are excluded from the correction loop.

Chapter 9. Switched and Saturating Control Techniques

The first technique presented is pulse modulation that enables controllers designed for continuous control variables to be utilised, highlighting applications such as power electronic drives.

Switched state feedback control based on the switching function and the associated switching boundary is then introduced. The behaviour of second-order systems is studied using phase portraits. This is extended to saturating control with continuous control variables and the boundary layer.

Optimal open-loop control is introduced via Pontryagin's maximum principle. The special case of time-optimal control of a linear time-invariant plant is studied, and information from this is used to synthesis switched feedback time-optimal control laws for first-order plants and second-order plants with switching boundaries derived using the back tracing method. Limit cycling control is studied for first-order plants.

Switched feedback control of higher-order plants is exemplified by first deriving the time-optimal switching boundary for a triple integrator plant and applying it for spacecraft attitude control using variable geometry panels with solar radiation pressure. This is followed by posicast control of plants containing lightly damped oscillatory modes.

The appendix contains limit cycling control for switched state feedback control of second-order plants. An example is given on attitude control of a rigid body spacecraft actuated by on-off thrusters using piecewise parabolic switching boundaries with acceleration parameters adapting to a disturbance torque estimate to maintain a limit cycle of constant amplitude.

Chapter 10. Sliding Mode Control and Its Relatives

First, standard sliding mode control of single-input, single-output plants is developed from the material of Chap. 9 on switched state feedback control, first with second-order plants by study of the closed-loop phase portraits. The purpose of sliding mode control in achieving robustness is emphasised. The equivalent control is defined. Control chatter is identified. The conditions for the existence of sliding motion are derived, and the reaching of the sliding region of the switching boundary from arbitrary initial states is studied. The system behaviour with external disturbances is considered.

The introduction of nonlinear switching boundaries to prevent overshooting in second-order systems with arbitrary initial states is presented. This is followed by sub-time-optimal sliding mode control of second-order plants using a nonlinear boundary layer based on a double parabolic switching boundary tangential to a linear region passing through the origin of the phase plane.

Sliding mode control of single-input, single-output plants of arbitrary order is introduced, for which the design procedure for the linear switching boundary yielding specified closed-loop dynamics is presented.

Next, three methods of control chatter avoidance are presented. These are (1) the pseudo sliding mode controller using the boundary layer method, following from the material in Chap. 9; (2) the control smoothing integrator method entailing the augmentation of the plant with one or more pure integrators to remove the switching to a primary control variable in the controller software; and (3) higher-order sliding mode control, introducing a control structure in which not only the switching function is driven to zero in the sliding mode but also its derivatives up to a specified order.

The relatives of the sliding mode controller are presented, which stem from the pseudo sliding mode controller with the boundary layer. They comprise all the linear controllers that may be designed by robust pole placement.

The remainder of the chapter introduces multivariable sliding mode control by pairing controlled outputs with control inputs via study of the equations derived to determine the relative degrees. This is followed by discrete sliding mode control formulated for multivariable linear plants, single-input, single-output plants being included as special cases. This also constitutes a fourth method for eliminating control chatter as its control variables are piecewise constant approximations to the equivalent control in the sliding mode.

The appendix presents observer-based robust control, a technique developed by the author, which is a distant relative of sliding mode control in that it forces desired behaviour by means of judiciously applied high gains. Although requiring adjustment of controller parameters, it is capable of similar robustness to sliding mode control and, importantly, is capable of accommodating model order uncertainty while yielding a specified closed-loop dynamics with a fixed order.

Chapter 11. Motion Control

The general-purpose jointed-arm robot is first introduced together with a model that applies also to other mechanisms whose motion is to be controlled. A generalised feedback linearising control law is then given. Modelling simplifications applicable to geared mechanisms are then developed.

Dynamic lag pre-compensation is presented, including a polynomial controller with inbuilt derivative feedforward to assist in this pre-compensation.

Next, the important topic of frictional energy minimisation is introduced, which if implemented on a large scale can drastically reduce the carbon footprint. The optimal control strategy is first formulated with the aid of Pontryagin's method. This is used to derive an optimal reference input function that can be followed using a controller with a dynamic lag pre-compensator to implement optimal feedback control. The performance improvement over traditional control methods is assessed.

The appendix presents reference input function planning using cubic and quintic splines, a method enabling exact derivatives to be computed for dynamic lag pre-compensator implementation.

Recommended Reading to Support Courses

Undergraduates in their final year would benefit from reading Chaps. 1 and 2; the sections of Chap. 3 on single-input, single-output plants; Chaps. 4, 5 and 6; the sections of Chap. 7 on linearisation about the operating point and feedback linearising control of single-input, single-output plants; and the sections of Chap. 8 on observers for single-input, single-output plants. The remaining material of Chaps. 3, 7 and 8 together with Chaps. 9, 10 and 11 would be suitable for graduate students studying to master's level. All will benefit from studying the examples and working with the simulations that may be downloaded from the book website, this also providing material for establishing final-year undergraduate and master's projects.

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