

Preface

Methods for the analysis and design of nonlinear control systems are growing rapidly. These developments are motivated by extensive applications, in particular, to such areas as mechatronic systems, robotics, and aircraft flight control systems. A number of new ideas, results, and approaches has appeared in this area during the past few decades.

This text was developed as a systematic explanation of one such new approach to control system design, which can provide effective control of nonlinear systems on the assumption of uncertainty. The approach is based on an application of a dynamical control law with the highest derivative of the output signal in the feedback loop. A distinctive feature of the control systems thus designed is that two-time-scale motions are forced in the closed-loop system. Stability conditions imposed on the fast and slow modes, and a sufficiently large mode separation rate, can ensure that the full-order closed-loop system achieves desired properties: the output transient performances are as desired, and they are insensitive to parameter variations and external disturbances.

A general design methodology for control systems with the highest derivative in feedback for continuous-time single-input single-output (SISO) or multi-input multi-output (MIMO) systems, as well as their discrete-time counterparts, is presented in this book. The method of singular perturbation is used to analyze the closed-loop system properties throughout.

The material is structured into thirteen chapters, the contents of which could be outlined as follows.

Chapter 1: Regularly and singularly perturbed systems. The main purpose of this chapter is a short explanation of some preliminary mathematical results concerning the properties and analysis of perturbed differential equations. The results constitute a background for an approximate analysis

and design of nonlinear control systems under uncertainty.

Chapter 2: Design goal and reference model. The problem statement of output regulation for nonlinear time-varying control systems and the basic step response parameters are discussed. The model of the desired output behavior in the form of a desired differential equation is introduced; its parameters are selected based on the required output step response parameters (overshoot, settling time). Particularities of the reference model construction, in order to obtain the required system type, are also discussed.

Chapter 3: Methods of control system design under uncertainty. In this chapter a short overview of robust control synthesis techniques on the assumption of uncertainty is given. Main attention is devoted to discussion of nonadaptive approaches, in particular, to control systems with the highest derivative of the output signal and high gain in the feedback loop, control systems with state vector and high gain in the feedback loop, and control systems with sliding motions.

Chapter 4: Design of SISO continuous-time control systems. The problem of output regulation of SISO nonlinear time-varying control systems is discussed. The control system is designed to provide robust zero steady-state error of the reference input realization. Moreover, the controlled output transients should have some desired behavior. These transients should not depend on the external disturbances and varying parameters of the plant model. The insensitivity condition of the output transient behavior with respect to external disturbances and varying parameters of the system is introduced. The highest derivative in the feedback loop is used in proposed control law structures. The limit behavior of control systems with the highest derivative of the output signal in the feedback loop is discussed. Closed-loop system properties are investigated on the basis of the two-time-scale technique and, as a result, slow and fast motion subsystems are considered separately.

Chapter 5: Advanced design of SISO continuous-time control systems. Problems related to implementation of continuous-time control systems with the highest derivative in feedback are discussed. In particular, control accuracy and robustness of the control system, various design techniques for choosing controller parameters, the influence of high-frequency noisy measurements, and noise attenuation are considered.

Chapter 6: Influence of unmodeled dynamics. The peculiarities of SISO continuous-time control system design with the highest derivative in feedback are discussed on the assumption of uncertainty in the model description caused by unmodeled dynamics. These dynamics reflect errors on the

system degree (or relative degree). Their influences, such as a pure time delay in the feedback loop and the unstructured uncertainties, lead to a plant model in the form of perturbed and/or singularly perturbed systems of differential equations. Some particulars of control design in the presence of a nonsmooth nonlinearity in the control loop are discussed as well.

Chapter 7: Realizability of desired output behavior. The conditions of realizability of the desired output behavior are discussed in this chapter. These are connected with invertibility conditions, nonlinear inverse dynamics solutions, and the problem of internal behavior analysis. Concepts such as invertibility index (relative degree), normal form of a nonlinear system, internal stability analysis, degenerated system on condition of output stabilization, and zero-dynamics are discussed. The design methodology for SISO control systems with the relative highest derivative in feedback is considered in the presence of internal dynamics. Finally, the problem of switching controller design is discussed.

Chapter 8: Design of MIMO continuous-time systems. The problem of output regulation of MIMO nonlinear time-varying control systems is discussed. Here the goals of control system design are to provide output decoupling and disturbance rejection, i.e., each output should be independently controlled by a single input, and to provide desired output transient performance indices on the assumption of incomplete information about varying parameters of the plant model and unknown external disturbances. The design methodology for SISO control systems with the highest derivative in feedback are extended to cover MIMO nonlinear time-varying control systems. The control law structure with the relative highest derivative in feedback is used in order to provide desired dynamical properties and decoupling of the output transients in a specified region of the system state space. The systematic design procedure for the control laws with the relative highest output derivatives is presented. The output regulation problem is discussed on the assumption that the previously presented realizability of the desired output behavior is satisfied.

Chapter 9: Stabilization of internal dynamics. This chapter is devoted to consideration of control system design where the dimension of the control vector is large, as the dimension of the output vector and redundant control variables are used in order to obtain internal dynamics stabilization. By this, the presented design methodology may be extended to more general system types. The discussed problem of internal dynamics stabilization for linear time-invariant systems corresponds to the displacement of zeroes of the transfer function in the left half of the complex plane.

Chapter 10: Digital controller design based on pseudo-continuous approach. The design of digital controllers for continuous nonlinear time-varying systems is discussed. The control task is formulated as a tracking problem for the output variables, where the desired decoupled output transients are attained on the assumption of incomplete information about varying parameters of the system and external disturbances. A distinguishing feature of the approach is that a pseudo-continuous-time model of the control loop with a pure time delay is used, where the delay is the result of a zero-order-hold transfer function approximation. The linear continuous-time controller with the relative highest output derivatives in feedback is designed, where the control law parameters are selected in accordance with the requirements placed on output control accuracy and damping of fast-motion transients. In particular, the selection of the sampling period is provided based on the requirement placed on the phase margin of the fast-motion subsystem. Then the Tustin transformation is applied to calculate the parameters of a digital controller. In order to increase the sampling period, a control law with compensation of the pure time delay is introduced.

Chapter 11: Design of discrete-time control systems. The method of discrete-time control systems design to provide the desired output transients is introduced, and is related with the purely discrete-time systems. In the case of continuous-time plants, the first step to be performed is discretization of the plant model. As a result, the discrete-time model of the plant in the form of a difference equation is used. A procedure to analyze the fast and slow motions in the discrete-time control system is given. It has been shown that if a sufficient time-scale separation between the fast and slow modes in the closed loop system and stability of the fast motions are provided, then after damping of the fast motions the output behavior in the closed loop system corresponds to the reference model and is insensitive to parameter variations of the plant and external disturbances. The design methodology is the discrete-time counterpart of the previously discussed approach to continuous-time control system design with the highest derivative in feedback.

Chapter 12: Design of sampled-data control systems. In this chapter, a design methodology for the discrete-time control system with two-time-scale motions is extended for the purpose of sampled-data control system design, by taking into account the particulars of the model of a series connection between a zero-order hold and a continuous-time system with high sampling rate. As a result, an approach to derive an approximate discrete-time model for nonlinear time-varying systems preceded by zero-order hold (ZOH) in

the form of a difference equation with a small parameter is represented, where the small parameter depends on the sampling period. The design of SISO as well as MIMO sampled-data control systems is discussed.

Chapter 13: Design of control systems with distributed parameters. The main points of the extension of the previously presented methodology for control system design with the highest derivative in feedback for distributed parameter systems are highlighted, based on consideration of the parabolic-type system.

The book aims to disseminate new results in the area of control system design under uncertainty, and may be used as a course textbook. It contains numerous examples with simulation results, as well as assignments suitable for courses in nonlinear control system design. The core of the book is based on a translation of an earlier book [Yurkevich (2000a)] and lecture notes used by the author over the last ten years with students in the Automation and Computer Engineering Department at Novosibirsk State Technical University.

The design methodology may be useful for graduate and postgraduate students in the field of nonlinear control systems design. It will also be of interest to researchers, engineers, and university lecturers who are taking aim at real-time control system design in order to solve practical problems in the control of aircraft, robots, chemical reactors, and electrical and electro-mechanical systems.

Any comments about the book (including any errors noticed) can be sent to yurkev@mail.ru with the subject heading *book*. They will be sincerely appreciated.

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