Preface

This monograph is concerned with the problem of designing low-order/fixed-structure feedback controllers for uncertain dynamical systems. Feedback controllers are required to reduce the effect of unmeasured disturbance acting on the system and to reduce the effect of uncertainties related to the system dynamics. This requires some knowledge about the system in order to design an effective feedback controller. The available knowledge is generally expressed as a mathematical description of the real system which is called the model of the system. However, the model thus obtained is always an approximation of the reality and is thus subject to some uncertainties. Therefore, the design of an effective feedback controller for the real system must take into account model uncertainties. A controller is said to be robust if the stability and/or the desired performance of the closed-loop system are not affected by the presence of bounded modeling uncertainties.

Uncertainty and Robustness

Since the early 1940s, robustness has been recognized of paramount importance when designing a feedback controller. Indeed, in the classical control theory of Black–Nyquist–Bode, plant uncertainties are taken into account via gain and phase margins which are measures of stability in the frequency domain. These stability margins confer to the closed-loop system fairly good robustness properties. However, classical control is mainly concerned with single-input single-output systems.

The transition to the so called modern control theory was done in the early 1960s by the development of optimal control. The basic principle is to determine the controller that minimizes a given performance index. This approach applies to multivariable systems represented in the time domain by a set of first order ordinary differential equations called a state space model. In the context of linear systems, the main result of this theory is certainly the Wiener–Hopf–Kalman optimal regulator, also known as the Linear Quadratic Gaussian (LQG) regulator. An inherent limitation of LQG control is that uncertainties are considered only in the form of exogenous stochastic disturbances having known statistical properties, while the system is assumed to be perfectly described by a linear, possibly time-varying, state space representation. These assumptions are so strong that the LQG control leads to poor performance when applied to systems for which no precise model is available. The need of a control theory capable of dealing with modeling errors and disturbance uncertainty thus became very clear.

A major step toward a robust control theory was taken in 1981 when Zames introduced the optimal $\mathbf{H}_\infty$ control problem. It was soon recognized that the $\mathbf{H}_\infty$ norm can be used to quantify not only disturbance attenuation but also robustness against modeling errors. Since then, many contributions in robust control theory have been made such as the introduction of structured singular value, the two-Riccati-equation method, the $\mathbf{H}_\infty$ loop-shaping and the linear matrix inequality approach, to cite only the most important advances. Nowadays optimal robust control is a mature theory and can be applied to a number of industrial problems which were beyond the scope of both classical control theory and LQG control theory. This is due to the fact that robust control theory provides a systematic treatment of robustness against modeling errors and disturbance uncertainty for both scalar and multivariable systems.

Limitations

A weakness of traditional robust control is that the controller obtained is of full order, in other words, the order of the controller is always greater than or equal to the dimension of the process model itself which can be very high. This is a serious limitation especially when the memory and computational power available are limited, in embedded controllers. Moreover, traditional robust control is unable to incorporate constraints into the structure of the controller. This is also a strong limitation especially when the control law must be implemented on commercially available controllers that have inherently a fixed structure such as PID or lead–lag compensators.

All these reasons justify the need for designing robust reduced-order/fixed-structure controllers. Unfortunately, the problem of designing a robust controller with a given fixed structure (e.g. a PID) remains an open issue. This is mainly due to the fact that the set of all fixed-order/structure stabilizing controllers is non-convex and disconnected in the space of controller parameters. This is a major source of computational intractability and conservatism. Nevertheless, due to their practical importance, some new approaches for structured control have been proposed in the literature. Most of them are based on the resolution of Linear Matrix Inequalities LMIs or Riccati equations. However, a major drawback with this kind of approach is the use of Lyapunov variables, whose number grows quadratically with the system size. For instance, if we consider a system of order 70, this requires, at least, the introduction of 2485 unknown variables whereas we are looking for the parameters of a fixed-order/structure controller which contains a comparatively very small number of unknowns. It is then necessary to introduce new techniques capable of dealing with the non-convexity of optimization problems arising in automatic control without introducing extra unknown variables.

Stochastic Optimization via HKA

The main optimization tool used in this book to tackle the problem of non-convexity is the so-called Heuristic Kalman Algorithm (HKA). The main characteristic of HKA is the use of a stochastic search mechanism to solve a given optimization problem. From a computational point of view, the use of a stochastic search procedure appears essential for dealing with non-convex problems.

The HKA method falls into the category of the so-called "population-based stochastic optimization techniques". However, its search heuristic is entirely different from other known stochastic algorithms such as genetic algorithm (GA) or particle swarm optimization (PSO). Indeed, HKA explicitly considers the optimization problem as a measurement process designed to give an estimate of the optimum. A specific procedure, based on the Kalman estimator, is utilized to improve the quality of the estimate obtained through the measurement process. HKA shares with GA and PSO interesting features such as: ease of implementation, low memory and CPU speed requirements, a search procedure based only on the values of the objective function, and no need for strong assumptions such as linearity, differentiability, convexity etc., to solve the optimization problem. In fact it could be used even when the objective function cannot be expressed in an analytic form; in this case, the objective function is evaluated through simulations. The main advantage of HKA compared to other stochastic methods, lies in the small number of parameters that need to be set by the user (only three). In addition these parameters have an understandable effect on the search procedure. These properties make the algorithm easy to use for non-specialists.

Structure of the Book

This book focuses on the development of simple and easy to use design strategies for robust low-order/fixed-structure controllers. HKA is used to solve the underlying constrained non-convex optimization problems.

Chapter 1 introduces some basic definitions and concepts from the classical optimization theory and indicates some limitations of the classical optimization methods. The class of convex optimization problems is also briefly presented with an emphasis on semi-definite programs. Some aspects related to the optimization in engineering design are also introduced. After that, the main objectives of the book are presented.

Chapter 2 introduces some basic materials related to signal and systems norms. Many control objectives can be stated in terms of the size of some particular signals. Therefore, a quantitative treatment of the performance of control systems requires the introduction of appropriate norms, which give measurements of the sizes of the signals considered. Another concept closely related to the size of a signal, is the size of an LTI system. The latter concept is of great practical importance because it is at the basis of $\mathbf{H}_\infty$ control as well as the robustness analysis.

Chapter 3 introduces how a control design problem can be formulated as an optimization problem. To this end, the standard control problem as well as the notion of stabilizing controllers are first briefly reviewed. After that, some closed-loop system performance measurements are presented, they are essential to evaluate the quality of a given controller. These performances measurements are then used to formulate the optimal controller design problem which is multi-objective in nature. The resulting multi-objective problem is scalarized using the notion of ideal point. The last part of the chapter is dedicated to the case of structured controllers i.e., structural constraints have to be taken into account in the optimization problem. These structural constraints make the resulting optimization problem non-smooth and non-convex, which results in intractability. This is why the use of stochastic optimization methods is suggested to find an acceptable solution. The robustness issue is also briefly discussed. It is pointed out that the optimal robust control problem in addition to being non-smooth and non-convex is also semi-infinite. This means that the optimization problem has an infinite number of constraints and a finite number of optimization variables.

Chapter 4 introduces the notion of acceptable solution; after that, a brief overview of the main stochastic methods which can be used to solve continuous non-convex constrained optimization problems is presented i.e., Pure Random Search Methods, Simulated Annealing, Genetic Algorithm, and Particle Swarm Optimization. The last part is dedicated to the problem of robust optimization, i.e., optimization in the presence of uncertainties in the problem data.

Chapter 5 introduces a new optimization method, called Heuristic Kalman Algorithm (HKA). This algorithm is proposed as an alternative approach for solving continuous non-convex optimization problems. The performance of HKA is evaluated in detail through several non-convex test problems, both in the unconstrained and constrained cases. The results are compared to those obtained via other metaheuristics. These various numerical experiments show that the HKA has very interesting potentialities for solving non-convex optimization problems, especially with regard to the small number of parameters that need to be set by the user (only three parameters).

Chapter 6 deals with the concept of uncertain system. This is a key notion when designing a robust feedback controller. The objective is indeed to determine the controller parameters ensuring acceptable performance of the closed-loop system despite the unknown disturbances affecting the system as well as the uncertainties related to the plant dynamics. To this end, it is necessary to be able to take into account the model uncertainties during the design phase of the controller. In this chapter, we briefly describe some basic concepts regarding uncertain systems and robustness analysis. The last part of this chapter is dedicated to structured robust control for which a specific stochastic algorithm is developed.

In Chap. 7 we consider the design of fixed structure controllers for uncertain systems in the $\mathbf{H}_\infty$ framework. Although the design procedures presented apply for any kind of structured controller, we focus mainly on the most widely used of them, that is, the PID controller structure. Two design approaches will be considered: the mixed sensitivity method and the $\mathbf{H}_\infty$ loop-shaping design procedure.

Using these methods, the resulting PID design problem is formulated as an inherently non-convex optimization problem. The resulting tuning method is applicable both to stable and to unstable systems, without any limitation concerning the order of the process to be controlled. Various design examples are presented to give some practical insights into the methods presented.

Chapter 8 is concerned with the design of structured controller for uncertain parametric systems in the $\mathbf{H}_2$ and mixed $\mathbf{H}_2/\mathbf{H}_\infty$ framework. We restrict ourselves to the case of static output feedback (SOF) controllers; this is not restrictive because any dynamical controller can be reformulated as SOF for an augmented plant. Some design examples are presented to illustrate the design methods proposed.

Chapter 9 is devoted to the design of a nonlinear structured controller for systems that can be well described by uncertain multi-models. In a first part, the concept of multi-model is introduced and some examples are given to show how this works. After that, the problem of designing a nonlinear structured controller for a given uncertain multi-model is considered. A characterization of the set of quadratically stabilizing controllers is first introduced. This result is then used to design a nonlinear structured controller that quadratically stabilizes the uncertain multi-model, while satisfying a given performance objective. Some design examples are presented to illustrate the main points introduced in this chapter.

Finally, Chap. 10 concludes the book by recalling the general philosophy behind the approach developed from chapter to chapter as well as the difficulty we can encounter when designing a structured controller and thus the development that needs to be done.

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