Preface

Since the early 1990's a variety of control design methods that are constructed directly upon batches of input-output data collected from the process to be controlled have appeared in the literature. These methods contrast with model-based control design mainly in two fundamental aspects: they are not based on the knowledge of a process model and they do not intend to freely determine the controller's transfer function. Instead, they make direct use of the information carried by the measured data in order to adjust the numerical parameters of a controller whose transfer function has a previously specified and fixed structure. Accordingly, these methods became known as *data-based*, in opposition to model-based, or alternatively as *data-driven* methods.

This same challenge of adjusting the parameters of a controller whose transfer function structure is given a priori, without ever obtaining a model for the process, has been undertaken in the context of adaptive control, since at least the 1960's. This has become known as the *direct approach* to adaptive control, in contrast with the *indirect approach*, in which the controller's parameters are adjusted through a model-based design, which is performed after the identification of the parameters of a process model and with the application of the certainty equivalence principle. Adaptive control has been a major field of research in control theory ever since, and colossal amounts of literature and successful applications of adaptive control have been developed over the past half-century. However, most quotidian industry applications do not seem to have assimilated this evolution. This gap between practical industry applications and the adaptive control theory, along with extraneous nonlinear behavior introduced by the adaptation mechanisms, propelled a surge of interest in the data-driven alternative for controller's adaptation, a surge that has been gaining momentum since its onset.

Attempts to delimit exactly the borders between model-based control, adaptive control, and data-driven control would most likely be unproductive; instead, let us propose a rather elastic definition of data-driven control. The term data-driven (or data-based) control refers to the methodologies whose aim is to design the parameters of a fixed-structure controller based on a reasonably large batch of input-output data, without any attempts to perform control design based on a process model.

Data-driven control is thus different from model-based control because the design is not based on a process model, even though approximative process models can be used for secondary purposes in some data-driven control methods. And data-driven control differs from adaptive control essentially by the fact that parameter adjustments are always based on large batches of data rather than on a single input-output sample or a few samples, as is usual in adaptive control. This one difference between data-driven control design and adaptive control has major implications, both theoretical and practical, and yet a substantial part of the theory in this book can be applied to direct adaptive control as well.

Some conceptually distinct data-driven approaches to control design appear in the literature. Yet, it seems fair to say that most of the methodologies are built around one of the most familiar concepts in control systems theory: the optimization of a performance criterion, where performance is measured by the H_2 norm of a particular signal in the loop. Representative of these methodologies are the pioneering works of Hjalmarsson, Gunnarsson and Gevers [3], Kammer, Bitmead and Bartlett [4], Campi, Lecchini and Savaresi [2], Karimi, Mišković and Bonvin [5], and Shi and Skelton [6]. These pioneering works later developed into sound design methodologies, as well as into applications, described in many other papers which constituted fundamental sources for the writing of this book. Each one of these methodologies has been baptized by their authors, respectively as: Iterative Feedback Tuning (IFT), Frequency Domain Tuning (FDT), Virtual Reference Feedback Tuning (VRFT), Correlation-based Tuning (CbT) and Markov LQG Control.

This is what this book is about: it intends to present a comprehensive analysis of this H_2 approach to data-driven control design, providing a common theoretical framework to these methodologies that have been presented separately in the literature since the early 1990's. This common theoretical framework also fits a large family of adaptive control methodologies, like Minimum Variance and Model Reference Adaptive Control. From this unified framework a number of shared properties become apparent, and solutions to shared problems emerge. This unification effort, which has been initiated in [1], is based on the analysis of the problem itself, namely the objective function(s) being minimized, the features of the data used for this purpose and the potential ways of performing the minimization, rather than on the algorithmic details of each particular solution.

The book is primarily intended for PhD students and researchers, whether senior or junior, in control engineering. It should serve as reference material for PhD theses, as well as teaching material for data-driven and adaptive control courses at the graduate level. We hope it will also be useful for advanced engineers willing to apply data-driven control design, by providing them with an understanding of the strengths and limitations of the existing data-driven methodologies and guidelines that will help coding these methods; but it is not a "how-to book".

The book starts with a formal delimitation of the problem and the class of systems treated. General definitions appear in Chap. 1, whereas the formal statement of the H_2 design problem is given in Chap. 2. Also in Chap. 2 is a presentation of the basic properties of the H_2 design problem and a discussion about the different control objectives and what are the designer's choices in choosing her/his performance criterion.

Once the designer has chosen the performance criterion, it must be minimized, which will be done using only input-output data collected from the system. It is possible in many situations to perform this minimization in only "one-shot", that is, with only one batch of data collected in only one operating condition. These "one-shot" solutions, which are the most convenient, are the subject of Chap. 3. In many other situations, however, it is necessary to resort to iterative procedures in which each iteration requires collecting more data, each time with a different controller in the loop. This may be necessary because the theoretical conditions required by the "one-shot" solutions are not met, or because operational constraints of the process require that only small adjustments to existing parameter settings can be made (a very common practical constraint). Accordingly, the subject of iterative optimization occupies the remaining of this book.

In Chap. 4 a general review of optimization is given, in order to set the stage for the chapters to follow. Then, starting in Chap. 5, the particularities of the H_2 cost functions minimized in data-driven control start being explored, bearing in mind that convergence to the globally optimal controller is sought. A number of properties of these particular cost functions and of some basic optimization algorithms when applied to them are presented in Chap. 5, along with guidelines for the optimization. Then, in Chap. 6, the *cost function shaping* concept is presented. Cost function shaping is the name we have given to a set of procedures and maneuvers that change the cost function so that it is more amenable to optimization.

Performing the optimization requires calculation of the cost function's derivatives, and this must be done only with the data collected from the system—no analytical expressions are available. It is only in Chap. 7 that this computing aspect—the calculation of these quantities—is discussed. In this chapter, three different methods are described in some detail and interpreted under the light of the theory presented in the previous chapters: IFT, FDT and CbT.

All along the book, simulation examples are presented that aim to illustrate and explain the concepts presented. These simulation studies do not have the purpose of demonstrating the practical application of these concepts, a task that is accomplished separately, in Chap. 8. There, numerous experimental results showing the data-driven design of controllers for processes of different natures are presented. These designs illustrate how the theory translates into the real world, showing that the methodologies are indeed effective, what are the designer's choices, and how he/she should make these choices taking into account the theoretical concepts presented in this book to obtain the best result from a real data-driven control design.

References

1. A.S. Bazanella, M. Gevers, L. Mišković, B.D.O. Anderson, Iterative minimization of H_2 control performance criteria. Automatica **44**(10), 2549–2559 (2008)
2. M.C. Campi, A. Lecchini, S.M. Savaresi, Virtual reference feedback tuning: A direct method for the design of feedback controllers. Automatica **38**, 1337–1346 (2002)

3. H. Hjalmarsson, S. Gunnarsson, M. Gevers, A convergent iterative restricted complexity control design scheme, in *33rd IEEE Conference on Decision and Control*, Lake Buena Vista, USA, 1994
4. L.C. Kammer, R.R. Bitmead, P.L. Bartlett, Direct iterative tuning via spectral analysis. Automatica **36**, 1301–1307 (2000)
5. A. Karimi, L. Mišković, D. Bonvin, Iterative correlation-based controller tuning. Int. J. Adapt. Control Signal Process. **18**, 645–664 (2004)
6. G. Shi, R.E. Skelton, Markov data-based LQG control. J. Dyn. Syst. Meas. Control **122**(3), 551–560 (2000)

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