Preface

This book is intended to be a thorough introduction to the properties of linear, time-invariant models of dynamical systems, as required for further work in feedback control system design, power system design and analysis, communications, signal processing, robotics, and simulation. The state-space model is used throughout, since it is a fundamental conceptual tool, although the background analysis applies to other models. The material is based on a course which has been taught for several years to motivated electrical and computer engineering undergraduates at the University of Waterloo, most of them in the first term of their senior year. Beginning graduate students from the same department, as well as from other departments, often have attended. The course has two goals: first, to give a thorough grounding in linear state-space modeling and, second, to give a mature understanding of some applications of the required background, which often has been learned quickly and used little. The content is presented in thirteen weeks, usually supplemented by a modest computational project.

The required background is working knowledge of linear algebra, differential equations, Laplace transforms, and $\mathcal{Z}$ transforms. The new material is supplemented with many examples, some of which extend the theory. There is also a good dose of proofs, to promote logical thinking and to show the elegance of some of the techniques, but hints about practicalities and floating-point numerical computation are also given, where it is possible without greatly extending the material.

I have attempted to emphasize the algebra common to a diversity of applications rather than specialized analysis, and where theoretical details have been omitted, they usually have been those of lesser application. Consequently, two themes recur: the importance of the Markov sequence in defining external system behavior, and the importance of the normal form of a matrix, and its generalizations, for matrix-related analysis. In setting the context of LTI systems, time-varying and nonlinear systems are mentioned, but not treated in detail.

Many good books containing similar subject material have appeared over the years. However, we have had difficulty adapting them to our requirements, often because the content is intended exclusively as an introduction to theoretical work, because their volume is far in excess of a one-semester course, or because they contain specialized analysis or design that does not fit with the objective of an introductory course applicable in a diversity of disciplines. Consequently, it has been convenient to tailor a package at a suitable level and of suitable size.

How to use this book: Some choices are available in reading or presenting the material in these chapters. Chapters 1 to 4 can be covered in a different order than presented here. However, provided that care is taken to motivate the use of state-space models, the details of their derivation from physical laws and other model forms are covered most economically by using both time-domain solutions and transform methods. Consequently, the book steps directly into solutions in Chapters 2 and 3 before the detailed modeling of Chapter 4. Not all of the material and examples included here can be covered in a typical course of thirteen weeks. Rather, slightly more material is included to allow customization. Not all of the sections of Chapter 4 are essential for understanding later material, and sections of Chapters 8 to 10 can also be omitted without major difficulty. In Chapter 4 for example, only one of the sections on electric circuits and Euler-Lagrange equations might be covered. The second half of Chapter 8 on stability might be omitted in order to cover the algebraic applications in Chapter 10. A selection from the examples can be made, depending on desired emphasis. Some of the material not explicitly covered in class can be used as a source of computational projects.

I recommend that the reader skim most of the examples and problems, since many of them embellish the main theoretical points of the text, although it is not necessary to examine each of them in detail.

Traditional texts present material on matrices and vector spaces either at the beginning or in appendices rather than in the middle, as done here in Chapters 5–7. Because we include the material in class, I have put it in the body and in the location at which we usually cover it, although a different order of presentation could be chosen.

Some readers might be surprised at seeing the B. L. Ho algorithm in an introductory course. In fact this algorithm is at once a natural application of the normal form of a matrix and of the Cayley-Hamilton theorem, an introduction to system identification and the concept of minimality, and an application of the singular-value decomposition. The proof contains moderate detail but no particular difficulty. This material could be covered in conjunction with minimality in Chapter 9 but I find it a motivating real-world application of the normal form, which has just been introduced in Chapter 5.

In the later chapters, it is useful to distinguish between essential theoretical constructions, especially the Jordan form and the Smith form, and more reliable computations. Hints are given in examples and problems.

The material is self-contained, although at the end of each chapter there is a section on further reading. The references are inevitably a personal selection from publications over four decades, but I have attempted to include some classics, under the philosophy that it is better to read the masters than their students, together with a selection of contemporary material.

The theory given here can only be applied easily with the assistance of a computer and software for floating-point computation, although for small systems, exact symbolic computation can be helpful. An excellent computing-laboratory tool for this material is the commercial MATLAB software, which provides easy invocation of professional-quality numerical routines, a programming language, and a graphical model-building environment. I encourage students to learn to use this or comparable software, and to develop a healthy sense of caution about its blind use on inexact floating-point data, especially for results that depend on the computed rank of a matrix. I usually assign one or more modest computational projects, such as implementing the Ho algorithm or testing other types of system identification. Many of the examples and problems are easily performed by using MATLAB and its toolboxes. However, the hints provided are intended to apply equally to floating-point arithmetic in embedded software, as well as to design computations conducted on an engineering workstation. A thorough introduction to the concepts of condition and the floating-point stability of algorithms is beyond the scope of this book, even if such an introduction is essential prior to the professional use of floating-point implementations of the theoretical material given here. For this as for other topics, I have attempted to provide the essentials, without attempting to be encyclopedic.

This book was produced by using LaTeX and PSTricks. The diagrams were prepared with the m4 macro processor, the dpic interpreter for the pic language, and PSTricks.

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have been sources of professional help and advice at the other end of an email connection.

These notes have been greatly influenced by the demanding and perceptive attention of students over several years. I hope that the transparency of exposition approaches the clarity of their questions.

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