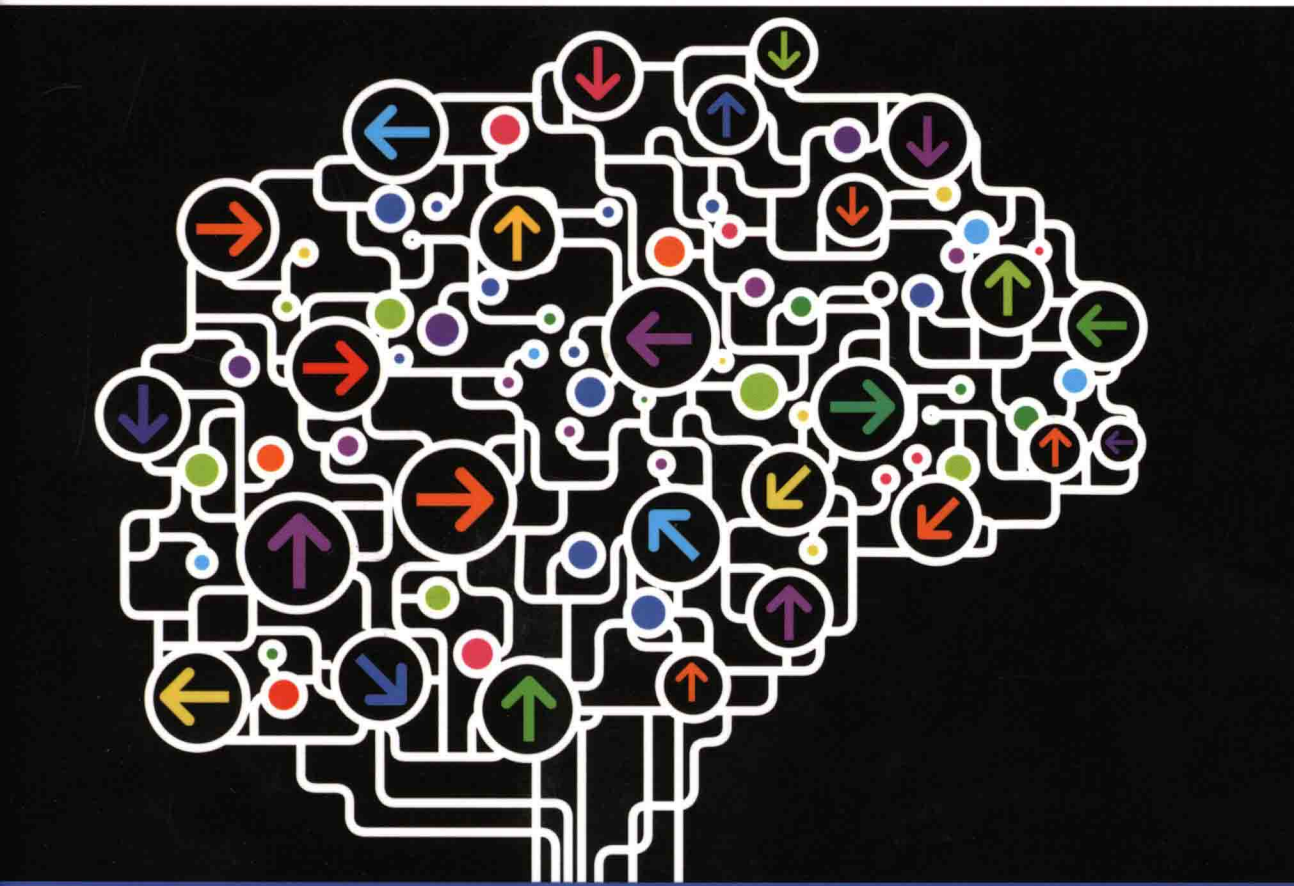
GLOBAL EDITION

Feedback Control of Dynamic Systems

SEVENTH EDITION

Gene F. Franklin • J. David Powell • Abbas Emami-Naeini



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Feedback Control of Dynamic Systems

Seventh Edition

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To the memory of Gene F. Franklin

Contents

**Sections with (W) indicates that additional material is located on the web at www.FPE7e.com.

List of Appendices on the web at www.fpe7e.com

Preface

In this Seventh Edition we again present a text in support of a first course in control and have retained the best features of our earlier editions. For this edition, we have responded to a survey of users by adding some material (for example, gears in Chapter 2) and moved other little-used material from the printed book (for example, digital control in the early chapters) to a website that is fully accessible to readers. We have also updated the text throughout so that it uses the improved features of Matlab®. But perhaps the biggest jolt to our readers is that we succumbed to the times, and changed the notation used for the state-space description from **(F, G, H, J)** to **(A, B, C, D)**! In past editions, our loyalty to the early pioneers in the state-space approach overwhelmed our ability to accept reality, and we stayed with the classical notation. However, for this edition, we decided the time has come to accept the reality that the dominant notation in the field today is **(A, B, C, D)** as is the notation in Matlab. We have also added a section on feedfoward control to Chapter 4 and a model-following section to Chapter 7. In addition, the presentation of PID control has been improved as has some of the Laplace transform material. We strive to equip control system designers with the theory, basic design methods, and an introduction to computer-aided design methods. At the same time, we also strive to equip designers with a basic understanding so that computer results can be guided and verified. The case studies in Chapter 10 have been retained and updated where needed. Finally, in order to guide the reader in finding specific topics, both in the text and on our website, we have expanded the table of contents to include entries for material that is on the website as well as in the printed book.

The basic structure of the book is unchanged and we continue to combine analysis with design using the three approaches of the root locus, frequency response, and state-variable equations. The text continues to include many carefully worked out examples to illustrate the material. As before, we provide a set of review questions at the end of each chapter with answers in the back of the book to assist the students in verifying that they have learned the material.

In the three central chapters on design methods we continue to expect the students to learn how to perform the very basic calculations by hand and make a rough sketch of a root locus or Bode plot as a sanity check on the computer results and as an aid to design. However, we introduce the use of Matlab early on in recognition of the universal use of software tools in control analysis and design. Furthermore, in recognition of the fact that very few instructors were using the early material on Digital Control in Chapters 4, 5, and 6 in the sixth edition, that material was moved to our website and Chapter 8 was modified so that it provides a stand-alone introduction to Digital Control. For those instructors wanting to include the digital implementation of controllers early in their teaching, the material can

www.FPE7e.com QR Code

be downloaded and used without change from the order that existed in the sixth edition or the students can be directed to the material in Chapter 8. As before, we have prepared a collection of all the Matlab files (both "m" files and Simulink® "mdl" files) used to produce the figures in the book. These are available along with the advanced material described above at our website at *www.FPE7e.com*

New to this Edition

We feel that this Seventh Edition presents the material with good pedagogical support, provides strong motivation for the study of control, and represents a solid foundation for meeting the educational challenges. We introduce the study of feedback control, both as a specialty in itself and as support for many other fields.

A more detailed list of the changes is:

- Added new section on Fundamentals to Chapter 1
- Added new section on Gears to Chapter 2
- Updated Matlab commands throughout the book in order to utilize current capabilities of the software
- Rewrote section on the Laplace transform and frequency response in Chapter 3
- Rewrote section on PID control in Chapter 4
- Added section on Feedforward control in Chapter 4
- Moved the section on digital control in Chapter 4 to a dedicated website for the book (www.FPE7e.com)
- Revised section in Chapter 4 on the effect of zeros on a system
- Moved the sections on digital control and time delay in Chapter 5 to the website
- Moved the sections on digital control in Chapter 6 to the website
- Rewrote sections on stability and compensation in Chapter 6 for clarity and consistency with current standards in the industry
- Expanded discussion of Nichols plots in Chapter 6
- Moved sections of digital control in Chapter 7 to the website
- Revised notation of the state-space system from (**F, G, H, J**) to (**A, B, C, D**) in Chapters 7, 9, and 10.
- To prevent any ambiguity, the notation for the compensation was changed from $D(s)$ to $D_c(s)$ throughout the text because of the change in the state-space notation

- Added the model-following procedure to Chapter 7
- Several sections were rewritten in Chapter 8 for clarity
- Added section on the ZOH approximate method in Chapter 8
- Updated the engine control example and substantially revised the system biology case study in Chapter 10
- Approximately 20% of the problems in the book are revised or new in all chapters

Addressing the Educational Challenges

Some of the educational challenges facing students of feedback control are long-standing; others have emerged in recent years. Some of the challenges remain for students across their entire engineering education; others are unique to this relatively sophisticated course. Whether they are old or new, general or particular, the educational challenges we perceived were critical to the evolution of this text. Here we will state several educational challenges and describe our approaches to each of them.

- CHALLENGE *Students must master design as well as analysis techniques.*

Design is central to all of engineering and especially so to control systems. Students find that design issues, with their corresponding opportunities to tackle practical applications, are particularly motivating. But students also find design problems difficult because design problem statements are usually poorly posed and lack unique solutions. Because of both its inherent importance and its motivational effect on students, design is emphasized throughout this text so that confidence in solving design problems is developed from the start.

The emphasis on design begins in Chapter 4 following the development of modeling and dynamic response. The basic idea of feedback is introduced first, showing its influence on disturbance rejection, tracking accuracy, and robustness to parameter changes. The design orientation continues with uniform treatments of the root locus, frequency response, and state variable feedback techniques. All the treatments are aimed at providing the knowledge necessary to find a good feedback control design with no more complex mathematical development than is essential to clear understanding.

Throughout the text, examples are used to compare and contrast the design techniques afforded by the different design methods and, in the capstone case studies of Chapter 10, complex real-world design problems are attacked using all the methods in a unified way.

- CHALLENGE *New ideas continue to be introduced into control.*

Control is an active field of research and hence there is a steady influx of new concepts, ideas, and techniques. In time, some of these elements develop to the point where they join the list of things every control engineer

must know. This text is devoted to supporting students equally in their need to grasp both traditional and more modern topics.

In each of our editions we have tried to give equal importance to root locus, frequency response, and state-variable methods for design. In this edition we continue to emphasize solid mastery of the underlying techniques, coupled with computer-based methods for detailed calculation. We also provide an early introduction to data sampling and discrete controllers in recognition of the major role played by digital controllers in our field. While this material can be skipped to save time without harm to the flow of the text, we feel that it is very important for students to understand that computer control is widely used and that the most basic techniques of computer control are easily mastered.

- CHALLENGE *Students need to manage a great deal of information.*

The vast array of systems to which feedback control is applied and the growing variety of techniques available for the solution of control problems means that today's student of feedback control must learn many new ideas. How do students keep their perspective as they plow through lengthy and complex textual passages? How do they identify highlights and draw appropriate conclusions? How do they review for exams? Helping students with these tasks was a criterion for the Fourth, Fifth, and Sixth Editions and continues to be addressed in this Seventh Edition. We outline these features below.

FEATURE

1. *Chapter openers* offer perspective and overview. They place the specific chapter topic in the context of the discipline as a whole and they briefly overview the chapter sections.
2. *Margin notes* help students scan for chapter highlights. They point to important definitions, equations, and concepts.
3. *Shaded highlights* identify key concepts within the running text. They also function to summarize important design procedures.
4. *Bulleted chapter summaries* help with student review and prioritization. These summaries briefly reiterate the key concepts and conclusions of the chapter.
5. *Synopsis of design aids*. Relationships used in design and throughout the book are collected inside the back cover for easy reference.
6. *The color blue* is used (1) to highlight useful pedagogical features, (2) to highlight components under particular scrutiny within block diagrams, (3) to distinguish curves on graphs, and (4) to lend a more realistic look to figures of physical systems.
7. *Review questions* at the end of each chapter with solutions in the back to guide the student in self-study
8. *Historical perspectives* at the end of each chapter provide some background and color on how or why the material in that particular chapter evolved.