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What Is Your Favorite Book on Classical Control?

Responses to an Informal Survey

DANIEL E. DAVISON, JIE CHEN, SCOTT R. PLOEN, and DENNIS S. BERNSTEIN

As part of this special section on classical control, we asked control experts in academia and industry about their favorite textbook on classical control. The survey was informal and not meant for statistical purposes, but it did result in some interesting replies. Due to the large number of responses, not all are included here, and many responses have been edited for length.

If you did not contribute to this survey, we invite your responses for a follow-up article. Interesting and memorable stories about your favorite classical control textbook, course, or instructor are most welcome.

CURRENT TEXTBOOKS FIRST PUBLISHED MORE THAN 35 YEARS AGO

Not surprisingly, many responses refer to textbooks that have been around for decades but are still in print. Some favor the textbook written originally by Dorf and now coauthored with Bishop:

» I have used the textbooks by the following authors over the past 20 years: Dorf and Bishop, Kuo, Ogata, Franklin, Powell, and Emami-Naeini, D'Azzo and Houpis, Philips and Harbor, and Nise. Each has strengths and weaknesses. However, among all of them, I prefer the first one. My main reasons are as follows: The book covers the control topics in a logical fashion; each chapter explains the subject in a simple way; the derivations of the formulas are complete and convince the students; tables, figures, and illustrations are excellent and useful for better understanding of the subjects; the numerous examples and problems represent all fields; the book shows the students the applicability of control systems to many facets of real life. The book makes the students aware that control systems are multidisciplinary. The modeling of many diverse systems taken from different applications are either derived or referenced for further investigation. This approach makes it easy for the students to realize that real systems can be modeled by differential equations, transfer functions, or a state variable description. The students are convinced that models are useful for analysis and design phases. There is a fair balance between design based on transfer function and state-space methods. The integration of Matlab and Simulink in the book over the past few years has enhanced the quality of this book. The division of exercises, problems, design problems, and Matlab problems make the students comfortable learning step-by-step theoretical concepts from simple situations to more complex cases. *Bahram Shafai, Northeastern University, Boston, Massachusetts*

» I feel slightly dated seeing that my favorite text falls in the "more than 35 years ago category"! In any event, I learned classical control in the fall of 1977 from Dorf's book in a graduate-level course at the University of Michigan in the Computer, Information, and Control Engineering Program. The course was taught by Bill Powers before he left to head up research at Ford. I was fascinated by the beauty and simplicity

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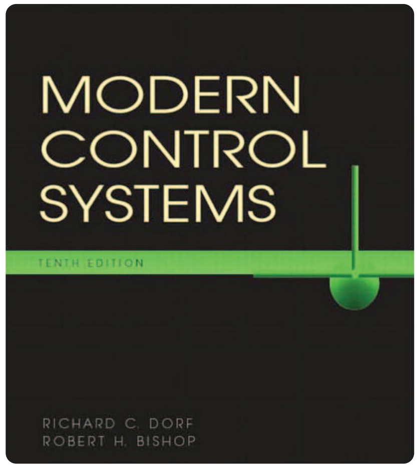
of the block diagrams as well as their ability to capture the dynamics of systems ranging from spacecraft to human speech. Bill had a gentle way of teaching math to engineers: He always used the word "property" instead of "theorem," and he presented ideas with great clarity. I remember the long elastic band with a weight on the end that he brought to class to demonstrate amplification and phase shift. That simple demonstration made the concept easy to grasp, and I still think of the demo every time I teach the topic. Getting back to Dorf's book, every so often I flip through it, realizing how difficult it is to teach this subtle subject. Nowadays, I teach classical control within the context of flight mechanics. The ideal book that merges these topics is waiting to be written. *Dennis Bernstein, University of Michigan, Ann Arbor*

» I was introduced to control engineering at the University of Manchester in 1956 by John C. West, and so I was weaned on his textbook *Servomechanisms*, published in 1953, a distinctive text on which I based my first lectures. After moving to Canada in 1962, I changed the content of my course to be more in line with courses in the United States, covering what I regarded as classical control. Three of the books in common use were those by Savant, D'Azzo and Houpis, and Dorf. Eventually I based my lectures on the book by Dorf, *Modern Control Systems*, since it covered the appropriate topics, it was about the right length, it had a good selection of examples, it had many problems based on simplified practical situations, it had a solution manual, and I believe it was written to motivate students. The current version, like the majority in the field, is much longer and,



although making use of modern computational facilities, has not, in my opinion, had the content streamlined in response to these changes in software availability. *Derek Atherton, University of Sussex, United Kingdom*

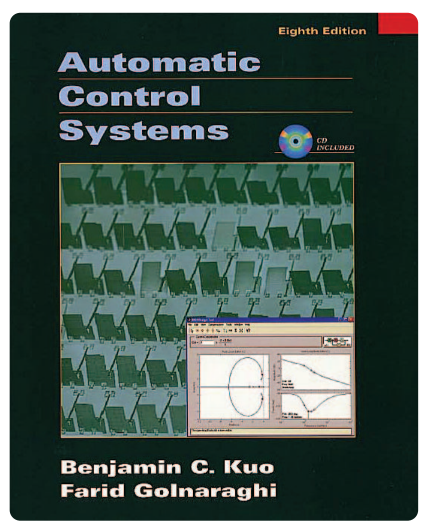
The book by Ogata is another textbook that has served multiple generations of control students, and it also received much praise:

» My favorite classical control text is *Modern Control Engineering*, by Katsuhiko Ogata, the first edition, published in 1970. This book was used in a second course on control that I took from Prof. Jorge Aravena in 1982 when I was a student at Louisiana State University. As an impressionable young EE student, I had learned Laplace transforms in the standard signals and systems course and already had a first course in control under my belt based on another favorite of mine—*Modern Control Systems*, third edition, by Richard Dorf. But not until I read Ogata's *Modern Control Engineering* did I understand how control theory crossed, and, I would submit, transcended the boundaries between the traditional engineering disciplines. What drove this home to me, and the reason Ogata is still one of my favorite books, is Chapter 5 in the first edition, which presented a variety of nonelectrical ways to generate basic control actions, such as a pneumatic PID controller. This chapter just blew me away, and I still show my students these examples to illustrate the generalist nature of control engineering. Of course, many books and new editions of books have come and gone since the 1970 publication of Ogata, but my copy of this book, with its tattered cover and taped binding, is kept front and center on my bookshelf. *Kevin Moore, Colorado School of Mines, Golden*

» Ogata's book is one of my favorites. We used an early edition of his book when I was taught classical feedback theory. I like this book because it contains many worked-out examples and ample exercises, which spurred more and deepened my interest in the subject. *Jie Chen, University of California, Riverside*

Finally, many survey responses recognize one of the eight editions of Kuo's textbook now coauthored with Golnaraghi as their favorite:

» I took my first course on classical control in 1972 in India. The textbook we followed was *Automatic Control* by Benjamin Kuo. If I remember right, that book in those days was a skinny one and had only about 100 pages. It is my favorite book. It is because of the professor who



taught me control the first time using that book that I ended up choosing control for my career. I am glad that I chose this profession and the book played a major role in my life. *Siva S. Banda, Air Force Research Laboratory, Wright-Patterson AFB, Ohio*

» I followed the footsteps of my brother who had studied in the same institute as I did five years earlier. He told me not to go into strength of materials since it's empirical and too simple, not to go into aerodynamics since it's PDEs and too difficult, but to go into control since it's ODEs and thus manageable. My criteria for classical control books are how they explain the root-locus method and Nyquist criterion. Along with the Russian book that I used in my undergraduate days, I can mention the book *Automatic Control Systems* by B. Kuo, which has survived eight editions. Both books are very good in terms of the above criterion. *Sergey G. Nersesov, Villanova University, Villanova, Pennsylvania*

» I suppose it would be Ben Kuo's book, not for any special reason except that I studied from it as an undergrad. Yes, there were books back in those days, not just stone tablets! I have to admit that since I don't teach this stuff these days, my rereading on the subject is rather limited. I tend to look at the Schaum's outline on classical control when I need something. I like Boris Lurie's book and would use it as a reference were I forced back into the dark past to teach this topic. *Mark Balas, University of Wyoming, Laramie*

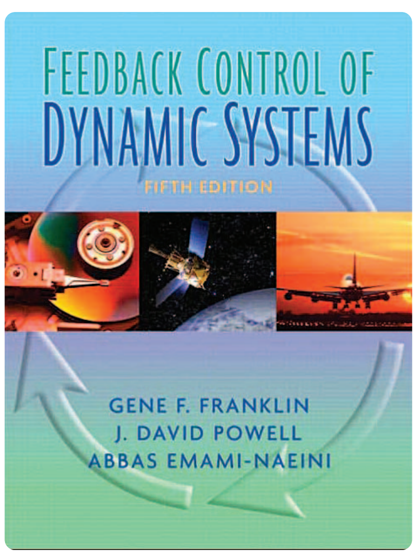
MORE RECENT TEXTBOOKS THAT ARE IN PRINT

Many people singled out Franklin, Powell, and Emami-Naeini's book as their favorite:

» My favorite book is G.F. Franklin, J.D. Powell, and A. Emami-Naeini, *Feedback Control of Dynamic Systems*, fifth edition. The outstanding features of the book include an overview of the brief history of feedback control of dynamic systems that give students a sense of the origin of feedback control; modeling of practical dynamic systems such as mechanical and electrical systems that show how real control problems in practice can be formulated; integration of PID control and classical control designs that equip students with useful control design skills; and many case studies that demonstrate applications of feedback control in real life. *Gary Feng, City University of Hong Kong*

» My preferred book is Franklin, Powell, and Emami-Naeini, *Feedback Control of Dynamical Systems*. The reason is that the book uses simple controllers to illustrate the concept of feedback very early in the development. This feature makes it much more suitable for courses with labs in which students have closed loops within the first session or two. *Roy Smith, University of California, Santa Barbara*

» My favorite classical control book is *Feedback Control of Dynamic Systems*, fourth edition, by Gene F. Franklin, J. David Powell, and Abbas Emami-Naeini. The major appeal of this book is in the clarity of exposition and the lucidity of treatment of topics and their relationships. This clarity reflects the authors' 360° view of the field, both in a theoretical perspective and in real-world applications. Let me mention three specific aspects that certainly impress the reader: perfect balance, homogeneity, and freshness in the presentation of root locus, frequency response, and state variable analysis and design techniques; appropriate mathematical level in covering all topics (the book is an essential prerequisite for graduate courses in digital and optimal control); and special attention to the description of modern case studies (a good tradeoff is achieved here between system description accuracy and simplified modeling for feedback control design). *Antonio Vicino, Università di Siena, Italy*



» My favorite contemporary book on classical control is the one by Franklin, Powell, and Emami-Naeini. I believe that this book reflects developments in the field over the last 20 years better than some other popular undergraduate textbooks. As it happens though, I never teach the undergraduate control class, so I cannot claim to have teaching experience with the text. A sentimental favorite is the first edition of the Schaum's Outline by Stubberud and DiStefano. I learned the subject by reading this book while in graduate school. *Jim Freudenberg, University of Michigan, Ann Arbor*

» At the University of New Mexico, the electrical engineering program requires one introductory course in feedback control. This course is transfer function based and includes standard tools such as root locus, the Nyquist stability criterion, and the Routh-Hurwitz test. Over the past few years we have been using the text of Franklin, Powell, and Emami-Naeini, *Feedback Control of Dynamic Systems*. We selected this text because it covers most of the topics we include in our course, and the material is well presented with good design examples and homework problems. The department also offers an optional follow-on course that includes the following topics, not covered in the first course: state-space methods, digital control, analytic design, and nonlinear systems. For the analytic design theory developed in the 80s, we use my monograph, *Analytic Feedback System Design—An Interpolation Approach*. *Peter Dorato, University of New Mexico, Albuquerque*

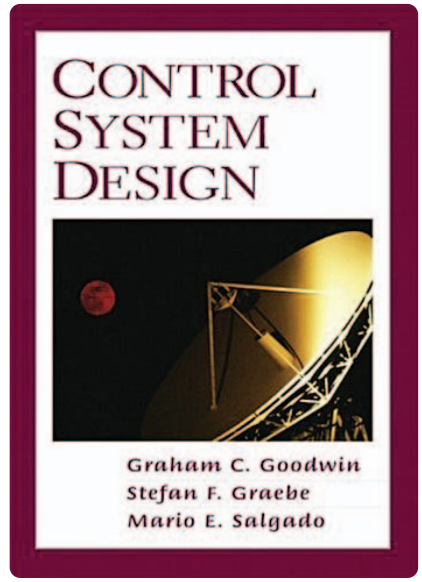
However, plenty of other favorite textbooks are still rolling off the printing presses:

» My favorite book is *Linear Control System Analysis and Design* by J.J. D'Azzo and C.H. Houpis. The main merit of this book is that it provides an introduction to control systems that can be enjoyed at different levels. The undergraduate students can find a simple, yet detailed, treatment of the basic tools for control system analysis and design, both in the time and frequency domains. Engineers working in the control field can use it as a reference manual for the classical control techniques needed in most practical applications. Researchers and professors appreciate the clear and direct introduction to advanced topics such as multivariable control and QFT techniques. *Andrea Garulli, Universita' degli Studi di Siena, Italy*

» My favorite control book is *Control Systems Engineering* by Norman A. Nise. What distinguishes this book from others is the emphasis on design. Classical control is an art form that can only be learned by design applications. Other books do an adequate job of teaching the tools of the trade such as root locus analysis, Bode and Nyquist plots, and state space, but none does as good a job teaching the application of these techniques to the design of a control system. Students who grasp the theory and design covered by Nise should be able to apply the art of control in real-life applications. *Michael J. Piovoso, Penn State University, State College*

» As an undergraduate in the late 1960s I learned the subject of control from *Modern Control Systems* by Dorf. In that book the subject was all technique: how to sketch a root locus plot and how to get 60° phase margin by lead compensation. Plants did not have performance limitations, and therefore designs did not involve tradeoffs; and Bode's beautiful sensitivity integral formula was not relevant, nor was his gain-phase formula that shows there's a maximum rolloff rate through crossover. Times have changed, and there are now texts that develop relevant theory and then use it to develop sensible design methods. Of these, the one I like to teach from is *Multivariable Feedback Control: Analysis and Design* by Skogestad and Postlethwaite. *Bruce Francis, University of Toronto, Canada*

» My favorite classical control book is *Control System Design* by G.C. Goodwin, S.F. Graebe, and M.E. Salgado. This book is unique in that it leads the reader all the way from the basic



ingredients of control including feedback, modeling, signals, and systems to the most advanced concepts of multivariable control design. The book contains all that is needed for a basic control course but offers a lot more. Major advantages are the emphasis on motivation, design issues, elaborate case studies, and the comprehensive website support. *Michel Gevers, Université Catholique de Louvain, Louvain la Neuve, Belgium*

» My favorite book is by Lurie and Enright, *Classical Feedback Control*. This volume is a deep book that many engineers at the Jet Propulsion Laboratory have found to be indispensable for designing real-world controllers. The first part of the book is suitable for use in an undergraduate course and develops the Bode integral relationships from first principles. Until I was exposed to this book in the late 1990s, I liked the book *Linear Control Systems* by Melsa and Schultz the best since I was taught from this book while an undergraduate in the Department of Applied Mechanics and Engineering Sciences at UCSD. It is very well written and blends the modern and classical approaches. *Scott Ploen, Jet Propulsion Laboratory, Pasadena, California*

FAVORITE TEXTBOOKS THAT HAVE GONE OUT OF PRINT

About half of those who responded to the survey chose a textbook that is no longer in print. The collection is quite broad:

» I was taught classical control from Fortmann and Hitz, *An Introduction to Linear Control Systems*. It has a good mix of classical material and a fairly solid mathematical treatment. As Konrad Hitz said when teaching from it, some of the math involved in deriving some of the classical results is quite sophisticated. For example, try completing all of the complex analysis you need to properly prove the principle of the argument and the Nyquist theorem. Oh, another reason is that Tom Fortmann left an endowment to the University of Newcastle. Unfortunately, he couldn't afford to endow a chair, so we have the Tom Fortmann endowed stool of electrical engineering. I believe it is still in the lab. *Richard H. Middleton, University of Newcastle, Australia*

» The book I like, that one I would call pre-state space, was by Page S. Buckley, *Techniques of Process Control*, published in 1979. Unfortunately, I no longer have this text. I am definitely remiss for not taking better care of this book, which by the way was given to me by someone who was retiring from DuPont. One sentence on why I like it: the book deals with real control techniques for real chemical processes. The book has insights into inverse and dead-time processes that you just don't learn from the more popular and better-written textbooks on my shelf. I also admire Page's patience to do difficult and sometimes tedious calculations without the power of the computer and the tools we have today, while providing analysis using intuition and common sense. I think some of the useful rules of thumb in today's chemical processes are due to his work. Although I never knew Page, his work has been quoted to me by other engineers, operators, educators, and process-control vendors. *Karlene A. Hoo, Texas Tech University, Lubbock*

» Doyle, Francis, and Tannenbaum's small blue book *Feedback Control Theory* is one of my favorites. I disliked it strongly when I was taught a course from it as an undergraduate student, mainly because of the frustrations of trying to design a loop-shaping controller when I could barely sketch a first-order Bode plot! Now, however, I find that I refer to the book regularly. The book has no fluff, and it concisely gets across the points it is making. It's a great introductory book about SISO robust control and performance limitations that arise in feedback control. *Dan Davison, University of Waterloo, Canada*

» My favorite book is Takahashi, Rabins, and Auslander, *Control and Dynamic Systems*. I used this book as a graduate student at UC Berkeley, and I have always gone back to refer to it as a very readable introduction to almost any topic in control, ranging from modeling, to bond graphs, to logic control, to distributed systems, to nonlinear systems, to time delays, to stochastic systems, to optimal control. *Galip Ulsoy, University of Michigan, Ann Arbor*

» My favorite classical control book is by O.J.M. Smith, *Feedback Control Systems*. This book, written and taught by my M.S. and Ph.D. thesis supervisor at Berkeley, was not very popular because it is long and difficult. However, students that were brave enough to go through it obtained a superb understanding of all of the issues related to classical SISO feedback control design. Special emphasis was given to performance and robustness specifications in the L-Plane using frequency-domain concepts. The book also contained other key ideas like the Smith predictor, widely used later in process control, as well as anticipation of time-domain concepts related to bang-bang control. *Michael Athans, Massachusetts Institute of Technology, Cambridge*

» As I glance through my library I see at least several books on classical control that I might call favorites, but I suppose the most special is *Control System Synthesis* by John Truxal. I say this not so much based on its content but rather by the good memories it provokes of the friends and times at Rockwell, Seal Beach, California. *Mike Borrello, Luminous Medical, Carlsbad, California*

» My favorite book is *Servomechanisms and Regulating System Design* by Harold Chestnut and Robert W. Mayer. The two volumes were a great blend of theoretical development and practical application, and they were written during the postwar heyday of classical control. *Ed Corbett, M.I.T. Lincoln Laboratory, Lexington, Massachusetts*

A CONTROL BOOK IN DISGUISE

» My favorite book is *Operational Amplifiers: Theory and Practice* by MIT professor James K. Roberge because it is a classical control book in disguise. The title suggests a textbook for analog circuit designers, but inside we find a complete treatment of root locus, the Nyquist criterion, the Nichols chart, lead and lag compensation, and describing functions. Also covered are integrated and discrete op-amp circuit design and applications, but op amps are used primarily as a vehicle for teaching feedback system design and compensation. The author has been quoted as saying that "feedback is so fundamentally important that analog engineers who don't understand it should be legally barred from circuit design," and I agree! *Kent Lundberg, Massachusetts Institute of Technology, Cambridge*

NOT JUST IN ENGLISH

A respondent rightly points out that some of the best classical control books were not printed in English:

» Not all of the great early texts of classical control originated as English publications. One of the earliest of all, in fact, was R.C. Oldenbourg and H. Sartorius's 1944 publication *Dynamik Selbsttätiger Regelungen*. This book not only presented some of the classic approaches to closed-loop, continuous-time linear systems but also described a way for analyzing sampled-data systems that looked forward to the z-transform. The book was lucky to see the light of day since, after it had been typeset, the printing works were bombed by the Allies. Fortunately, one of the authors had taken a set of proofs home, and the book was printed from these. Within a few years of the end of the war, the book was translated into English and Russian.

Another early German classic was Winfried Oppelts's 1947 book *Grundgesetze der Regelung*, which includes a version of what we now call the describing function for analyzing nonlinear systems. Oppelt's control texts went through many editions over the years, remaining in print for several decades in various extended versions. One of the most striking features right from the start was the presentation of a graphical taxonomy of closed-loop systems, giving both the frequency response and step response of various common topologies.

Turning to Russia, one of my favorites is V.L. Lossievskii's *Osnovy Avtomaticheskogo Regulirovaniya Tekhnologicheskikh Protsessov*, published in 1949. In many respects this book is similar to several other texts that disseminated classical control ideas just after WW2, but its most striking feature is the chapter that reviews stability criteria. Unlike most contemporary authors of any nationality, Lossievskii knew the work of all of the major contributors to stability theory from the mid-19th century onwards, including work from Routh in the United Kingdom; Vyshnegradskii, Lyapunov, and Mikhailov in Russia; work in Germany and Switzerland by Küpfmüller and Hurwitz; and work in the United States by Nyquist. The result was a remarkably comprehensive review for the late 1940s.

For more information about these and other seminal control texts from the classical era and earlier, have a look at my "Textbooks and subtexts," *IEEE Control Systems Magazine*, vol. 16, no. 2, April 1996, pp. 71–78; or "The classics revisited." Part I, *Measurement and Control*, vol. 32, June 1999, pp. 139–144, Part II, *Measurement and Control*, vol. 32, August 1999, pp. 169–173. *Chris Bissell, Open University, Milton Keynes, United Kingdom*

A BOOK OF PAPERS

One reader chose the book edited by T. Basar, *Control Theory: Twenty-Five Seminal Papers, 1932–1981:*

» My favorite book on classical control is not a book exactly, but rather a collection of several of the key papers in our field. Since these papers are now included in the above book, I can mention these papers and still fulfill the request to write about my favorite book.

One classic paper is Willems's "Dissipative Dynamical Systems-Part I: General Theory," published in 1972. Dissipative systems theory unifies many approaches to nonlinear control; for instance, the small gain and passivity theorems. It also provides a physical motivation in many cases for the analysis. The theory can now be found in many excellent textbooks on nonlinear control. However, because the background and motivation for the approach is nicely presented in this initial paper, I give this paper to many of my graduate students to read as an introduction to the field.

Zames's 1981 paper "Feedback and Optimal Sensitivity: Model Reference Transformations, Multiplicative Seminorms and Approximate Inverses," is credited with starting H_∞ control. The paper took the existing classical approach of SISO frequency response shaping and formalized it in terms of operators and norms. This approach provided a mechanism for generalizing design problems to multivariable control systems. The framework led to many developments in H_∞ controller synthesis, including the two-Riccati-equation state-space solution for multivariable problems. The theory is now very abstract, but reading this paper shows that H_∞ control is a natural development of classical control.

There are many other interesting papers in this book, starting with the first papers published on feedback. Each paper has an excellent introduction by Basar

(continued on page 99)

whenever the limit on the right hand side of (3) is finite, $y(t)$ approaches infinity in the order of

$$y(t) \sim \left(\frac{1}{\Gamma(\lambda+1)} \lim_{s \downarrow 0} s^{\lambda+1} \hat{y}(s) \right) t^{\lambda}.$$

Since $\Gamma(x)$ is positive, whether $y(t)$ approaches ∞ or $-\infty$ is determined by $\lim_{s \downarrow 0} s^{\lambda+1} \hat{y}(s)$.

The generalized final value theorem generalizes the extended final value theorem since $\hat{y}(s)$ need not be a rational function. To illustrate, consider $y(t) = \sqrt{t}$, which has the Laplace transform

$$\hat{y}(s) = \frac{1}{2s} \sqrt{\frac{\pi}{s}}.$$

The function $y(t)t^{-1/2}$ approaches 1 as $t \to \infty$, which is consistent with the calculation

$$\lim_{t \to \infty} \frac{y(t)}{\sqrt{t}} = \frac{1}{\Gamma(3/2)} \lim_{s \downarrow 0} s^{3/2} \hat{y}(s) = \frac{1}{\Gamma(3/2)} \frac{\sqrt{\pi}}{2} = 1.$$

CONCLUSIONS

For rational Laplace transforms with poles in the OLHP or at the origin, the extended final value theorem provides the correct infinite limit. For irrational Laplace transforms, the generalized final value theorem provides the analogous result.

Finally, we point to a detailed analysis of the final value theorem for piecewise continuous functions given in [6, chap. 12].

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» EDUCATION (continued from page 94)

that explains the importance and historical context of the paper. For instance, the U.S. Patent Office took nine years to approve Black's patent for the feedback amplifier because they did not believe it would work. The papers in this volume illustrate the difficulties and routes to fundamental results in control. *Kirsten Morris, University of Waterloo, Canada*

THOSE WITH NO FAVORITE BOOK

Many people who were surveyed said they could not think of a favorite book or were too busy to write up their thoughts. A few people explained why they have no favorite book:

» I have no favorite classical control book. I feel that we need a fresh approach to teaching classical control that, for either the institution or the instructor, provides a broader view of the field, reaches out to other disciplines such as biology and physics, incorporates more key ideas developed in the last 15–20 years on robustness, nonlinear control, and discrete event or hybrid systems, and includes a broader range of applications to demonstrate the richness and broad applicability of the concepts. *Kevin Passino, Ohio State University*

» To satisfy my teenage daughter's curiosity, I showed her my favorite textbook on classical control. Afterwards, she told her friends that I am a mathematician. To help me out, my physician wife explained to her the fine difference: a mathematician solves equations, but your dad creates his own equations. So, I need another favorite control book. It must be short and can be read during breakfast and on the train, by teenagers and physicians. It tells people that control is interesting and important, and we create systems, in addition to equations. It is a daunting task but achievable. *Leyi Wang, Wayne State University, Michigan*

» I'm sorry, but I didn't reply because I don't have a favorite. In fact, I don't have any that I particularly like. *Pablo Iglesias, John Hopkins University, Baltimore, Maryland*

THE FINAL WORD

We close with one of our favorite responses to the survey:

» I don't want to be quoted for this, but I have never read a book on classical control. The first book I ever read was *Linear Multivariable Control* by Murray Wonham, which was for years a bible for me. You can, however, not be further from the truth than claiming that this book is a book on classical control. Later, I realized the need to know about classical control, which I handled by sitting in on a lecture series. *An anonymous control engineer*