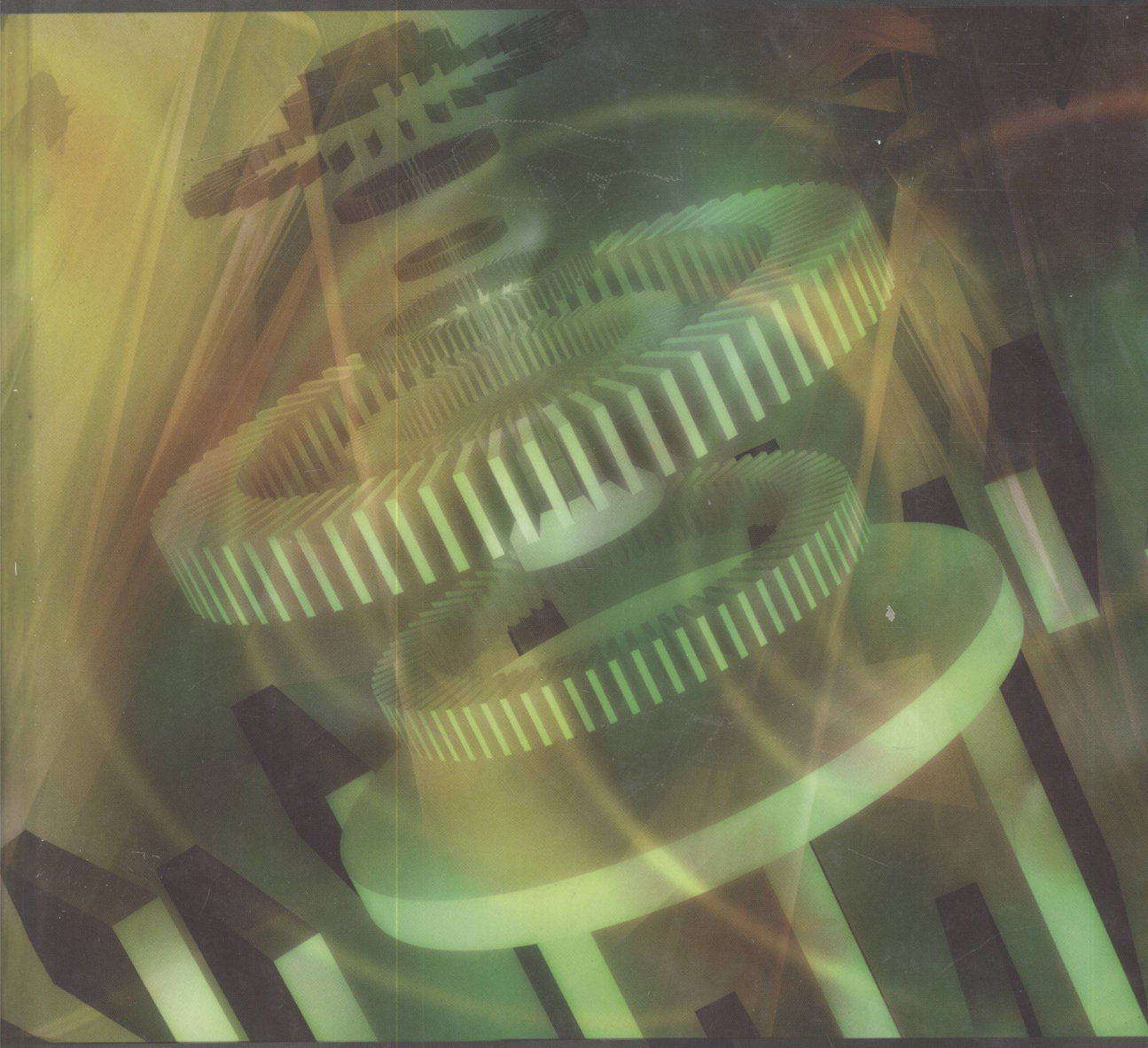
Modeling and Control of Engineering Systems



Clarence W. de Silva

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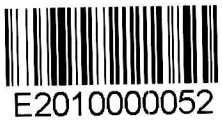

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Modeling and Control of Engineering Systems

To all my students, present and past

"Education is just the progressive realisation of our ignorance"

–Albert Einstein

Preface

This is an introductory book in the subject of modeling and control of engineering systems. It serves as both a textbook for undergraduate engineering students and entry-level graduate students, and a reference book for practicing professionals. As a textbook, it is suitable for courses in: modeling of dynamic systems, feedback control systems, control engineering, and design and instrumentation of control systems. There is adequate material in the book for two 14-week courses, one at the junior (third-year undergraduate) or senior (fourth-year undergraduate) level and the other at the first-year graduate level. In view of the analytical techniques, computer and software tools, instrumentation details, design methods, and practical considerations that are presented in the book, and in view of the simplified and snap-shot style presentation of more advanced theory and concepts, the book serves as a useful reference tool for engineers, technicians, project managers, and other practicing professionals in industry and in research laboratories, in the fields of control engineering, mechanical engineering, electrical and computer engineering, manufacturing and production engineering, aeronautical and aerospace engineering, and mechatronics.

A control system is a dynamic system that contains a controller as an integral part. The purpose of the controller is to generate control signals, which will drive the process to be controlled (the plant) in the desired manner—to meet a set of performance specifications. Actuators are needed to perform control actions as well as to directly drive/operate the plant. Sensors and transducers are necessary to measure output signals (process responses) for feedback control; to measure input signals for feedforward control; to measure process variables for system monitoring, diagnosis and supervisory control; and for a variety of other purposes. Design is a necessary part as well, for it is design that enables us to build a control system that meets the performance requirements—starting, perhaps, with basic components such as sensors, actuators, controllers, compensators, and signal modification devices. The book addresses all these issues, starting from the basics and systematically leading to advanced concepts.

Control engineers should be able to model and analyze individual components or an integrated control system, design controllers, identify and select components for a control system, and choose parameter values so that the control system will perform the intended functions of the particular system while meeting a set of specifications. Proper control of an engineering system requires an understanding and a suitable "representation" of the system—a "model" of the system. Any model is an idealization of the actual system. Properties established and results derived are associated with the model rather than the actual system, whereas the excitations are applied to and the output responses are *measured* from the actual system. Modeling is often an essential task in control engineering. For instance, a good understanding of the system to be controlled may be gained through modeling and associated analysis and computer simulation. In fact a controller may be designed and its performance can be studied through modeling and computer simulation even before a physical controller is developed. Such an approach is often more economical and time effective. Furthermore there are control techniques called "model-based control" for which modeling is a requirement.

Important aspects of laboratory experimentation and instrumentation are included in the book. There are numerous worked examples, problems, and exercises, many of which are related to real-life situations and practical applications. Augmenting their traditional

role, the problems at the end of each chapter serve as valuable sources of information not found in the main text. In fact, the student is strongly advised to carefully read all the problems in addition to the main text. Complete solutions to the end-of-chapter problems are provided in a *Solutions Manual*, which is available to instructors who adopt the book.

The manuscript for the original book evolved from the notes developed by the author for mandatory undergraduate courses in dynamic system modeling and feedback control, and entry-level graduate courses in control system instrumentation and modern control engineering for students in electrical and computer engineering, mechanical engineering, and chemical engineering at Carnegie Mellon University. During the development of the material for those courses, a deliberate attempt was made as well to cover a major part of the syllabuses for similar courses offered in the Department of Mechanical Engineering at the Massachusetts Institute of Technology. At the University of British Columbia, the original material was further developed, revised, and enhanced for teaching courses in dynamic system modeling, control systems, intelligent control, mechatronics, and control sensors and actuators. The material in the book has acquired an application orientation through the author's industrial experience at places such as IBM Corporation, Westinghouse Electric Corporation, Bruel and Kjaer, and NASA's Lewis and Langley Research Centers.

The material presented in the book provides a firm foundation in modeling and control of engineering systems, for subsequent building up of expertise in the subject—perhaps in an industrial setting or in an academic research laboratory—with further knowledge of control hardware and analytical skills (along with the essential hands-on experience) gained during the process.

Main Features of the Book

There are several shortcomings in existing popular books on modeling and control. For example, some books "pretend" to consider practical applications by first mentioning a real engineering system before posing an analytical or numerical problem. For example, it may describe an automobile (with a graphical sketch and even a photo) and then make a statement such as "let us approximate the automobile by the following transfer function." No effort is made to relate the model to the physical system and to address such issues as why a particular control technique is suitable for controlling the system. Some other books extensively use software tools for modeling and control system analysis without pointing out the fundamentals and the analytical basis behind the methodologies, ways of interpreting and validating the obtained results, and the practical limitations of the tools. While benefiting from the successes of the popular books, the present book makes a substantial effort to overcome their shortcomings. The following are the main features of the book, which will distinguish it from other popular textbooks in the subjects of modeling and control:

- Readability and convenient reference are given priority in the presentation and formatting of the book.
- Key concepts and formulas developed and presented in the book are summarized in windows, tables, and lists, in a user-friendly format, throughout the book, for easy reference and recollection.

- A large number of worked examples are included and are related to real-life situations and the practice of control engineering, throughout the book.
- Numerous problems and exercises, most of which are based on practical situations and applications, and carry additional useful information in modeling and control, are given at the end of each chapter.
- The use of MATLAB® (is a registered trademark of The MathWorks, Inc. For product information, please contact: The MathWorks, Inc., 3 Apple Hill Drive, Natick, MA 01760-2098 USA. Tel: 508 647 7000; Fax: 508-647-7001; E-mail: info@mathworks.com; Web: www.mathworks.com) Simulink®, and LabVIEW®, and associated toolboxes are described and a variety of illustrative examples are given for their use. Many problems in the book are cast for solution using these computer tools. However, the main goal of the book is not simply to train the students in the use of software tools. Instead, a thorough understanding of the core and foundation of the subject as facilitated by the book will enable the student to learn the fundamentals and engineering methodologies behind the software tools; the choice of proper tools to solve a given problem; interpret the results generated by them; assess the validity and correctness of the results; and understand the limitations of the available tools.
- Useful material that cannot be conveniently integrated into the main chapters is given in three separate appendices at the end of the book.
- The subject of modeling is treated using an integrated approach, which is uniformly applicable to mechanical, electrical, fluid, and thermal systems. An inspiration is drawn from the concept of equivalent circuits and Thevenin's theorem in the field of electrical engineering.
- The subject of intelligent control, particularly fuzzy logic control, is introduced. A chapter on control system instrumentation is included, providing practical details for experiments in an undergraduate laboratory.
- An *Instructor's Manual* is available, which provides suggestions for curriculum planning and development, and gives detail solutions to all the end-of-chapter problems in the book.

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Many individuals have assisted in the preparation of this book, but it is not practical to acknowledge all such assistance here. First, I wish to recognize the contributions, both direct and indirect, of my graduate students, research associates, and technical staff. Particular mention should be made of my PhD student Roland H. Lang, whose research assistance has been very important. I am particularly grateful to Jonathan W. Plant, Senior Editor, CRC Press/Taylor&Francis, for his interest, enthusiasm, and strong support, throughout the project. Other staff at CRC Press and its affiliates, in particular, Jessica Vakili, Arlene Kopeloff, Glenon Butler, Soundar Rajan, and Evelyn Delehanty, deserve special mention. I wish to acknowledge as well the advice and support of various authorities in the field—particularly, Professor Devendra Garg of Duke University, Professor Madan Gupta of the University of Saskatchewan, Professor Mo Jamshidi of the University of Texas (San Antonio), Professors Marcelo Ang, Ben Chen, Tong-Heng Lee, Jim A.N. Poo, and Kok-Kiong Tan of the National University of Singapore, Professor Max Meng of the Chinese University of Hong Kong, Dr. Daniel Repperger of U.S. Air Force Research Laboratory, Professor David N. Wormley of the Pennsylvania State University, and Professor Simon Yang of University of Guelph. Finally, my wife and children deserve much appreciation and apology for the unintentional "neglect" that they may have faced during the latter stages of the preparation of this book.

Author

Dr. Clarence W. de Silva, P.E., Fellow ASME and Fellow IEEE, is a professor of Mechanical Engineering at the University of British Columbia, Vancouver, Canada, and occupies the Tier 1 Canada Research Chair professorship. Prior to that, he has occupied the NSERC-BC Packers Research Chair professorship in Industrial Automation since 1988. He has served as a faculty member at Carnegie Mellon University (1978–1987) and as a Fulbright Visiting Professor at the University of Cambridge (1987/1988).

He has earned PhD degrees from Massachusetts Institute of Technology (1978) and University of Cambridge, England (1998), and an honorary DEng degree from University of Waterloo (2008). De Silva has also occupied the Mobil Endowed Chair Professorship in the Department of Electrical and Computer Engineering at the National University of Singapore and the Honorary Chair Professorship of National Taiwan University of Science and Technology.

Other Fellowships: Fellow Royal Society of Canada; Fellow Canadian Academy of Engineering; Lilly Fellow; NASA-ASEE Fellow; Senior Fulbright Fellow to Cambridge University; Fellow of the Advanced Systems Institute of BC; Killam Fellow; Erskine Fellow.

Awards: Paynter Outstanding Investigator Award and Takahashi Education Award, ASME Dynamic Systems and Control Division; Killam Research Prize; Outstanding Engineering Educator Award, IEEE Canada; Lifetime Achievement Award, World Automation Congress; IEEE Third Millennium Medal; Meritorious Achievement Award, Association of Professional Engineers of BC; Outstanding Contribution Award, IEEE Systems, Man, and Cybernetics Society.

Editorial Duties: Served on 14 journals including *IEEE Transactions on Control System Technology* and *Journal of Dynamic Systems, Measurement and Control, Transactions ASME*; Editor-in-Chief, *International Journal of Control and Intelligent Systems*; Editor-in-Chief, *International Journal of Knowledge-Based Intelligent Engineering Systems*; Senior Technical Editor, *Measurements and Control*; and Regional Editor, North America, *Engineering Applications of Artificial Intelligence—IFAC International Journal of Intelligent Real-Time Automation*.

Publications: 16 technical books, 14 edited books, 32 book chapters, about 180 journal articles, about 200 conference papers.

Research and development Areas: Industrial process monitoring and automation, intelligent multi-robot cooperation, mechatronics, intelligent control, sensors, actuators, and control system instrumentation. Funding of over $5 million, as principal investigator, during the past 15 years.

Further Reading

This book has relied on many publications, directly and indirectly, in its development and evolution. Many of these publications are based on the work of the author and his co-workers. Also, there are some excellent books the reader may refer to for further information and knowledge. Some selected books are listed below.

Brogan, W.L. *Modern Control Theory*. Prentice Hall, Englewood Cliffs, NJ, 1991.

Chen, B.M., Lee, T.H., and Venkataramenan, V. *Hard Disk Drive Servo Systems*. Springer-Verlag, London, UK, 2002.

De Silva, C.W. and Wormley, D.N. *Automated Transit Guideways: Analysis and Design*. D.C. Heath and Co./Simon & Schuster, Lexington, MA, 1983.

De Silva, C.W. *Dynamic Testing and Seismic Quahfication Practice*. Lexington Books, Lexington, MA, 1983.

De Silva, C.W. *Control Sensors and Actuators*. Prentice Hall, Englewood Cliffs, NJ, 1989.

De Silva, C.W. and MacFarlane, A.G.J. *Knowledge-Based Control with Application to Robots*. Springer-Verlag, Berlin, Germany, 1989.

De Silva, C.W. *Intelligent Control—Fuzzy Logic Applications*. CRC Press, Boca Raton, FL, 1995.

De Silva, C.W. (Editor). *Intelligent Machines: Myths and Realities*. Taylor & Francis, CRC Press, Boca Raton, FL, 2000.

De Silva, C.W. *Mechatronics—An Integrated Approach*. Taylor & Francis, CRC Press, Boca Raton, FL, 2005.

De Silva, C.W. (Editor). *Vibration and Shock Handbook*. Taylor & Francis, CRC Press, Boca Raton, FL, 2005.

De Silva, C.W. *Vibration Fundamentals and Practice*, 2nd Edition. CRC Press, Boca Raton, FL, 2007.

De Silva, C.W. *Sensors and Actuators—Control System Instrumentation*. Taylor & Francis, CRC Press, Boca Raton, FL, 2007.

De Silva, C.W. (Editor). *Mechatronic Systems—Devices, Design, Control, Operation, and Monitoring*. Taylor & Francis, CRC Press, Boca Raton, FL, 2007.

Dorf, R.C. and Bishop, R.H. *Modern Control Systems*, 9th Edition. Prentice Hall, Upper Saddle River, NJ, 2001.

Hordeski, M.F. *The Design of Microprocessor, Sensor, and Control Systems*, Reston Publishing Co., Reston, VA, 1985.

Jain, L. and de Silva, C.W. (editors), *Intelligent Adaptive Control: Industrial Applications*. CRC Press, Boca Raton, FL, 1999.

Karray, F. and de Silva, C.W. *Soft Computing Techniques and Their Applications*. Addison Wesley/Pearson, NY/UK, 2004.

Kuo, B.C. *Automatic Control Systems*, 6th Edition. Prentice Hall, Upper Saddle River, NJ, 1991.

Necsulescu, D. *Mechatronics*. Prentice Hall, Upper Saddle River, NJ, 2002.

Ogata, K. *Modern Control Engineering*. Prentice Hall, Upper Saddle Rivver, NJ, 2002.

Rowell, D. and Wormley, D.N. *System Dynamics—An Introduction*. Prentice Hall, Upper Saddle River, NJ, 1997.

Tan, K.K., Lee, T.H., Dou, H., and Huang, S. *Precision Motion Control*, Springer-Verlag, London, UK, 2001.

Van de Vegte, J. *Feedback Control Systems*. Prentice Hall, Englewood Cliffs, NJ, 1986.

Units and Conversions (Approximate)

1 cm	=	1/2.54 in=0.39 in
1 rad	=	57.3°
1 rpm	=	0.105 rad/s
1 g	=	9.8 m/s^2=32.2 ft/s^2=386 in/s^2
1 kg	=	2.205 lb
1 kg·m^2 (kilogram-meter-square)	=	5.467 oz·in^2 (ounce-inch-square)=8.85 lb.$in.s^2$
1 N/m	=	5.71×10^{-3} lbf/in
1 N/m/s	=	5.71×10^{-3} lbf/in/s
1 N·m (Newton-meter)	=	141.6 oz·in (ounce-inch)
1 J	=	1 N.m=0.948×10^{-3} Btu=0.278 kWh
1 hp (horse power)	=	746 W (watt)=550 ft·lbf
1 kPa	=	1×10^3 Pa= 1×10^3 N/m^2
	=	0.154 psi= 1×10^{-2} bar
1 gal/min	=	3.8 L/min

Metric Prefixes:

giga	G	10^9
mega	M	10^6
kilo	k	10^3
milli	m	10^{-3}
micro	μ	10^{-6}
nano	n	10^{-9}
pico	p	10^{-12}

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