ROBERT L. NORTON

DESIGN OF MACHINERY

third edition

An Introduction to the Synthesis and Analysis of Mechanisms and Machines

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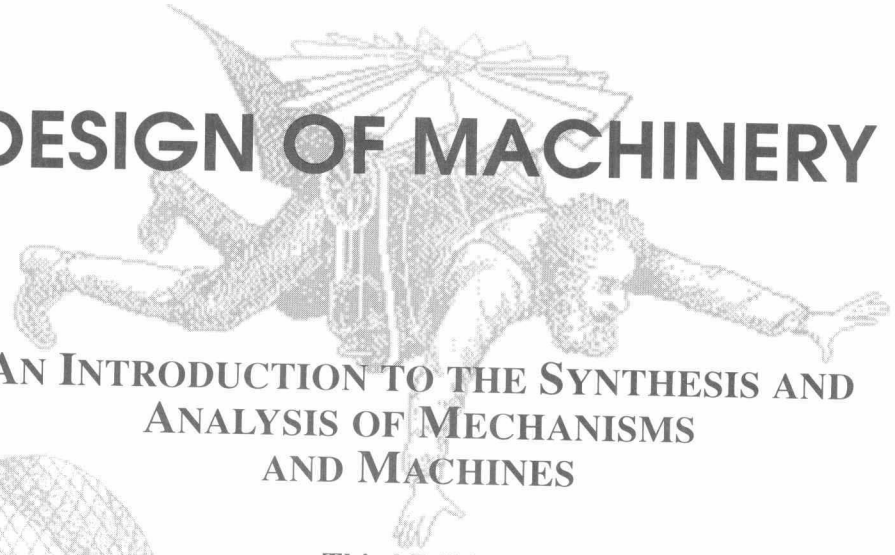


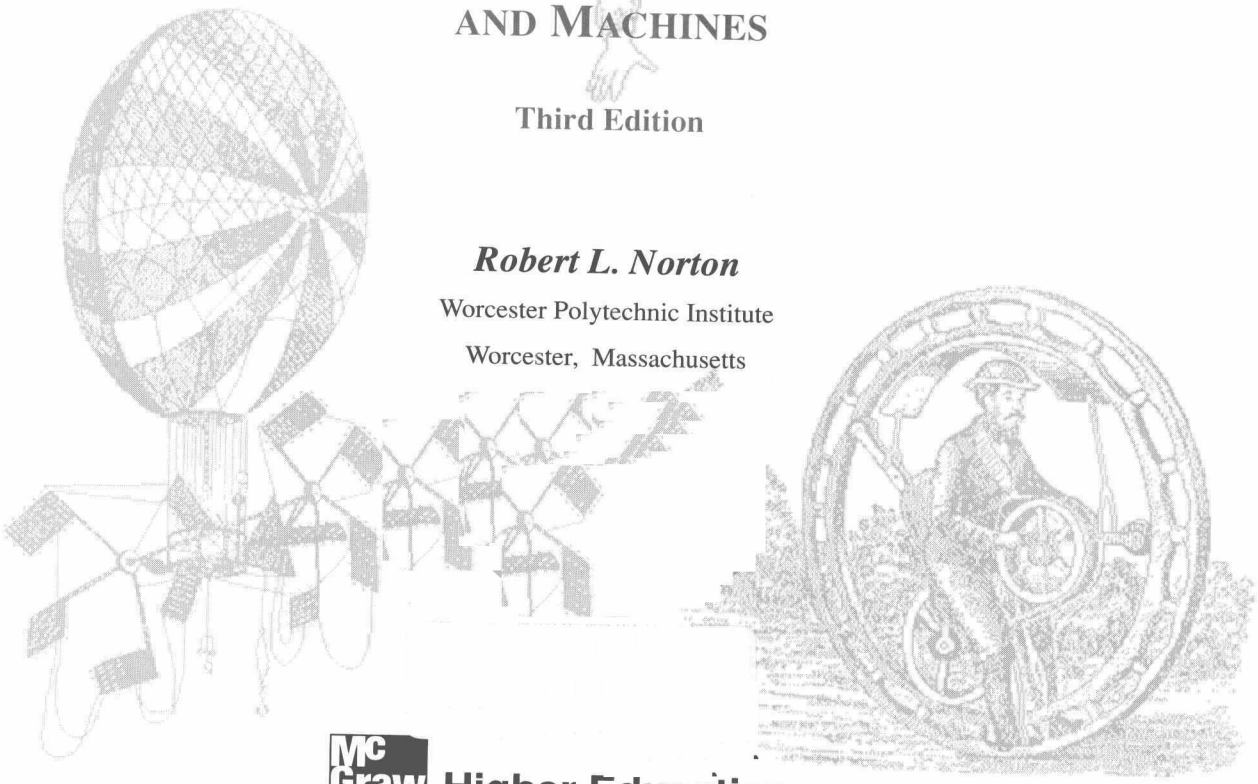
AN INTRODUCTION TO THE SYNTHESIS AND ANALYSIS OF MECHANISMS AND MACHINES

Third Edition

Robert L. Norton

Worcester Polytechnic Institute

Worcester, Massachusetts



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ABOUT THE AUTHOR

Robert L. Norton earned undergraduate degrees in both mechanical engineering and industrial technology at Northeastern University and an MS in engineering design at Tufts University. He is a registered professional engineer in Massachusetts. He has extensive industrial experience in engineering design and manufacturing and many years experience teaching mechanical engineering, engineering design, computer science, and related subjects at Northeastern University, Tufts University, and Worcester Polytechnic Institute.

At Polaroid Corporation for 10 years, he designed cameras, related mechanisms, and high-speed automated machinery. He spent three years at Jet Spray Cooler Inc., designing food-handling machinery and products. For five years he helped develop artificial-heart and noninvasive assisted-circulation (counterpulsation) devices at the Tufts New England Medical Center and Boston City Hospital. Since leaving industry to join academia, he has continued as an independent consultant on engineering projects ranging from disposable medical products to high-speed production machinery. He holds 13 U.S. patents.

Norton has been on the faculty of Worcester Polytechnic Institute since 1981 and is currently professor of mechanical engineering, head of the design group in that department, and the director of the Gillette Project Center at WPI. He teaches undergraduate and graduate courses in mechanical engineering with emphasis on design, kinematics, vibrations, and dynamics of machinery.

He is the author of numerous technical papers and journal articles covering kinematics, dynamics of machinery, cam design and manufacturing, computers in education, and engineering education and of the texts *Machine Design: An Integrated Approach* and the *Cam Design and Manufacturing Handbook*. He is a Fellow of the American Society of Mechanical Engineers and a member of the Society of Automotive Engineers. Rumors about the transplantation of a Pentium microprocessor into his brain are decidedly untrue (though he could use some additional RAM). As for the unobtainium* ring, well, that's another story.

* See Index.

This book is dedicated to the memory of my father,

Harry J. Norton, Sr.

who sparked a young boy's interest in engineering;

to the memory of my mother,

Kathryn W. Norton

who made it all possible;

to my wife,

Nancy Norton

who provides unflagging patience and support;

and to my children,

Robert, Mary, and Thomas,

who make it all worthwhile.

PREFACE

to the Third Edition

The third time is the charm.
ANONYMOUS

The third edition is an evolutionary improvement over the second edition, which was an extensive revision of the first edition. See the updated *Preface to the First Edition* (overleaf) for more detailed information on the book's purpose and organization. Throughout this third edition many small improvements have been made to the discussion of a variety of topics in every chapter, based largely on user feedback, and all known errors have been corrected. The major change is the addition of 231 new problem sets, a 46% increase over the second edition, bringing the total to 731 problems, plus 88 larger scale project assignments. Many problem figures have been redrawn and enhanced as have some in the text body. All of the problem figures are now included as PDF files on the CD-ROM so that students can easily obtain hard copies to work the solutions on.

Some new material also has been added. An introduction to compliant mechanisms and MEMS is provided in Chapter 2. Chapter 3 adds a section on "Other Useful Linkages" that solve common problems in industry. The treatment of cams in Chapter 8 has been both condensed and enhanced with new material. Chapter 9's discussion of transmissions is enhanced and expanded. The treatment of engine dynamics in Chapters 13 and 14 has been improved.

The third edition is also enhanced by the addition of much new software on the attached CD-ROM. New student versions of the author-written programs, FOURBAR, FIVEBAR, SIXBAR, SLIDER, DYNACAM, ENGINE, and MATRIX have been revised, enhanced, and improved. All now provide larger screens and many new features. These programs undergo frequent revision with added features and enhancements. Instructors who adopt the book for a course may download the latest student versions of the programs from http://www.designofmachinery.com.

Professor Shih-Liang (Sid) Wang of North Carolina A&T has added many models to his included package, *Mechanism Simulation in a Multimedia Environment*. It now contains over 100 *Working Model* (*WM*) files based on the book's figures and 19 *Matlab*® models for kinematic analysis and animation. These *WM* models bring the text's figures to life with animation, graphs, and numerical output. For each of Professor Wang's simulations, a video file of the mechanism can be played independently of the *Working Model* program. Microsoft Internet Explorer is used to navigate among hyperlinked HTML files that contain text, picture, video, *Matlab*, and *Working Model* files.

The *Working Model* 2D *Version* 5.2 *Textbook Edition* (*WM*) program is included on the CD-ROM and is a newer version than in the second edition. The student can open, run, modify, and interact with the many *WM* simulation files provided on the CD-

ROM. Students also may build and test new mechanisms in the *WM* Textbook Edition provided on the CD-ROM, but the Textbook Edition as supplied does not allow the user to save or print the model. However, instructors who adopt the text for a class and require its purchase by their students may call 800-766-6615 or 650-381-3395 to obtain information on how to expand the capabilities of the *WM* Textbook Edition for their student's class assignments. For separate information on printing high-quality graphics from either edition of *WM*, follow the instructions at http://www.workingmodel.com/faqlist.html#print.

Some of the *Matlab* files supplied will analyze fourbar, slider crank, and inverted slider crank linkages and animate their motion. Other *Matlab* files calculate the tooth profile of an involute spur gear, show the geometric generation of an involute and the motion of an elliptic trammel. *Matlab* source code is provided. The *Matlab* program is not. Extensive comments are provided within each *Matlab* file identifying the equations used from the text by number. The student can modify these models for other applications.

ACKNOWLEDGMENTS The sources of photographs and other nonoriginal art used in the text are acknowledged in the captions and opposite the title page, but the author would also like to express his thanks for the cooperation of all those individuals and companies who generously made these items available. The author is indebted to, and would like to thank, a number of users who kindly notified him of errors or suggested improvements. These include: Professors *Eben Cobb* of WPI, *Diego Galuzzi* of University of Buenos Aires, *John R. Hall* of WPI, *Shafik Iskander* of U. Tennessee, *Richard Jakubek* of RPI, *Cheong Gill-Jeong* of Wonkwang Univ., Korea, *Swami Karunamoorthy* of St. Louis University, *Pierre Larochelle* of Florida Tech, *Scott Openshaw* of Iowa State, *Francis H. Raven* of Notre Dame, *Arnold E. Sikkema* of Dordt College, and *Donald A. Smith* of U. Wyoming.

Professors *Melvin R. Corley* of Louisiana Tech, *R. Devashier* of U. Evansville, *Krishna Gupta* of U. Illinois-Chicago, *Michael Keefe* of U. Delaware, *John Steffen* of Valparaiso University, *Douglas Walcerz* of York College, and *Lindsey Wells* of U. Texas at Tyler also provided useful suggestions or corrections. Reviewers of this edition also included: Professors *Kurt Anderson* of RPI, *Steve de Bruyn Kops* of U. Washington, *Marek Kujath* of Dalhousie University, *Mark Nagurka* of Marquette University, *Tim Nye* of McMaster University, and *Bob Williams* of Ohio University. The author also thanks the many others who responded to the survey on the second edition.

Professors *Larry L. Howell* of BYU, *G. K. Ananthasuresh* of U. Penn, and *Yong-Mo Moon* of WPI kindly supplied photographs of compliant mechanisms. Professor *Cosme Furlong* of WPI generously supplied MEMS photos and information.

The author would like to express his special appreciation to Professor *Sid Wang* of NCAT for his efforts in creating the *Working Model* and *Matlab* files on the CD-ROM. Professor *Thomas A. Cook*, Mercer University (Emeritus) provided most of the new problem sets as well as their solutions in his impressive and voluminous solutions manual and its accompanying *Mathcad* ® solution files. The author is most grateful for Dr. Cook's valuable contributions.

Robert L. Norton
Mattapoisett, Mass.
May, 2004

If you find any errors or have comments or suggestions for improvement, please email the author at *norton@wpi.edu*. Errata as discovered, and other book information, will be posted on the author's web site at http://www.designofmachinery.com.

PREFACE

to the First Edition

When I hear, I forget
When I see, I remember
When I do, I understand
ANCIENT CHINESE PROVERB

This text is intended for the kinematics and dynamics of machinery topics which are often given as a single course, or two-course sequence, in the junior year of most mechanical engineering programs. The usual prerequisites are first courses in statics, dynamics, and calculus. Usually, the first semester, or portion, is devoted to kinematics, and the second to dynamics of machinery. These courses are ideal vehicles for introducing the mechanical engineering student to the process of design, since mechanisms tend to be intuitive for the typical mechanical engineering student to visualize and create.

While this text attempts to be thorough and complete on the topics of analysis, it also emphasizes the synthesis and design aspects of the subject to a greater degree than most texts in print on these subjects. Also, it emphasizes the use of computer-aided engineering as an approach to the design and analysis of this class of problems by providing software that can enhance student understanding. While the mathematical level of this text is aimed at second- or third-year university students, it is presented *de novo* and should be understandable to the technical school student as well.

Part I of this text is suitable for a one-semester or one-term course in kinematics. Part II is suitable for a one-semester or one-term course in dynamics of machinery. Alternatively, both topic areas can be covered in one semester with less emphasis on some of the topics covered in the text.

The writing and style of presentation in the text is designed to be clear, informal, and easy to read. Many example problems and solution techniques are presented and spelled out in detail, both verbally and graphically. All the illustrations are done with computer-drawing or drafting programs. Some scanned photographic images are also included. The entire text, including equations and artwork, is printed directly from the author's computer disk by laser typesetting for maximum clarity and quality. Many suggested readings are provided in the bibliography. Short problems, and where appropriate, many longer, unstructured design project assignments are provided at the ends of chapters. These projects provide an opportunity for the students *to do and understand.*

The author's approach to these courses and this text is based on over 40 years' experience in mechanical engineering design, both in industry and as a consultant. He has taught these subjects since 1967, both in evening school to practicing engineers and in day school to younger students. His approach to the course has evolved a great deal in that time, from a traditional approach, emphasizing graphical analysis of many structured problems, through emphasis on algebraic methods as computers became available, through requiring students to write their own computer programs, to the current state described above.

The one constant throughout has been the attempt to convey the art of the design process to the students in order to prepare them to cope with *real* engineering problems in practice. Thus, the author has always promoted design within these courses. Only recently, however, has technology provided a means to more effectively accomplish this goal, in the form of the graphics microcomputer. This text attempts to be an improvement over those currently available by providing up-to-date methods and techniques for analysis and synthesis that take full advantage of the graphics microcomputer, and by emphasizing design as well as analysis. The text also provides a more complete, modern, and thorough treatment of cam design than existing texts in print on the subject.

The author has written seven interactive, student-friendly computer programs for the design and analysis of mechanisms and machines. These programs are designed to enhance the student's understanding of the basic concepts in these courses while simultaneously allowing more comprehensive and realistic problem and project assignments to be done in the limited time available than could ever be done with manual solution techniques, whether graphical or algebraic. Unstructured, realistic design problems which have many valid solutions are assigned. Synthesis and analysis are equally emphasized. The analysis methods presented are up to date, using vector equations and matrix techniques wherever applicable. Manual graphical analysis methods are de-emphasized. The graphics output from the computer programs allows the student to see the results of variation of parameters rapidly and accurately and reinforces learning.

These computer programs are distributed on CD-ROM with this book, which also contains instructions for their use on any IBM compatible, Windows 98/2000/NT capable computer. Programs SLIDER, FOURBAR, FIVEBAR and SIXBAR analyze the kinematics and dynamics of those types of linkages. Program DYNACAM allows the design and dynamic analysis of cam-follower systems. Program ENGINE analyzes the slider-crank linkage as used in the internal combustion engine and provides a complete dynamic analysis of single and multicylinder engine inline, V, and W configurations, allowing the mechanical dynamic design of engines to be done. Program MATRIX is a general purpose linear equation system solver.

All these programs, except MATRIX, provide dynamic, graphical animation of the designed devices. The reader is strongly urged to make use of these programs in order to investigate the results of variation of parameters in these kinematic devices. The programs are designed to enhance and augment the text rather than be a substitute for it. The converse is also true. Many solutions to the book's examples and to the problem sets are provided on the CD-ROM as files to be opened in these programs. Most of these solutions can be animated on the computer screen for a better demonstration of the concept than is possible on the printed page. The instructor and students are both encouraged to take advantage of the computer programs provided. Instructions for their use are in Appendix A.

The author's intention is that synthesis topics be introduced first to allow the students to work on some simple design tasks early in the term while still mastering the analysis topics. Though this is not the "traditional" approach to the teaching of this material, the author believes that it is a superior method to that of initial concentration on detailed analysis of mechanisms for which the student has no concept of origin or purpose.

Chapters 1 and 2 are introductory. Those instructors wishing to teach analysis before synthesis can leave Chapters 3 and 5 on linkage synthesis for later consumption. Chapters 4, 6, and 7 on position, velocity, and acceleration analysis are sequential and build upon each other. In fact, some of the problem sets are common among these three chapters so that students can use their position solutions to find velocities and then later use both to find the accelerations in the same linkages. Chapter 8 on cams is more extensive and complete than that of other kinematics texts and takes a design approach. Chapter 9 on gear trains is introductory. The dynamic force treatment in Part II uses matrix methods for the solution of the system simultaneous equations. Graphical force analysis is not emphasized. Chapter 10 presents an introduction to dynamic systems modeling. Chapter 11 deals with force analysis of linkages. Balancing of rotating machinery and linkages is covered in Chapter 12. Chapters 13 and 14 use the internal combustion engine as an example to pull together many dynamic concepts in a design context. Chapter 15 presents an introduction to dynamic systems modeling and uses the cam-follower system as the example. Chapters 3, 8, 11, 13, and 14 provide open ended project problems as well as structured problem sets. The assignment and execution of unstructured project problems can greatly enhance the student's understanding of the concepts as described by the proverb in the epigraph to this preface.

ACKNOWLEDGMENTS The sources of photographs and other nonoriginal art used in the text are acknowledged in the captions and opposite the title page, but the author would also like to express his thanks for the cooperation of all those individuals and companies who generously made these items available. The author would also like to thank those who reviewed various sections of the first edition of the text and who made many useful suggestions for improvement. Mr. John Titus of the University of Minnesota reviewed Chapter 5 on analytical synthesis and Mr. Dennis Klipp of Klipp Engineering, Waterville, Maine, reviewed Chapter 8 on cam design. Professor William J. Crochetiere and Mr. Homer Eckhardt of Tufts University, Medford, Mass., reviewed Chapter 15. Mr. Eckhardt and Professor Crochetiere of Tufts, and Professor Charles Warren of the University of Alabama taught from and reviewed Part I. Professor Holly K. Ault of Worcester Polytechnic Institute thoroughly reviewed the entire text while teaching from the pre-publication, class-test versions of the complete book. Professor Michael Keefe of the University of Delaware provided many helpful comments. Sincere thanks also go to the large number of undergraduate students and graduate teaching assistants who caught many typos and errors in the text and in the programs while using the pre-publication versions. Since the book's first printing, Profs. D. Cronin, K. Gupta, P. Jensen, and Mr. R. Jantz have written to point out errors or make suggestions that I have incorporated and for which I thank them. The author takes full responsibility for any errors that may remain and invites from all readers their criticisms, suggestions for improvement, and identification of errors in the text or programs, so that both can be improved in future versions. Contact norton@wpi.edu.

Robert L. Norton
Mattapoisett, Mass.
August, 1991

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