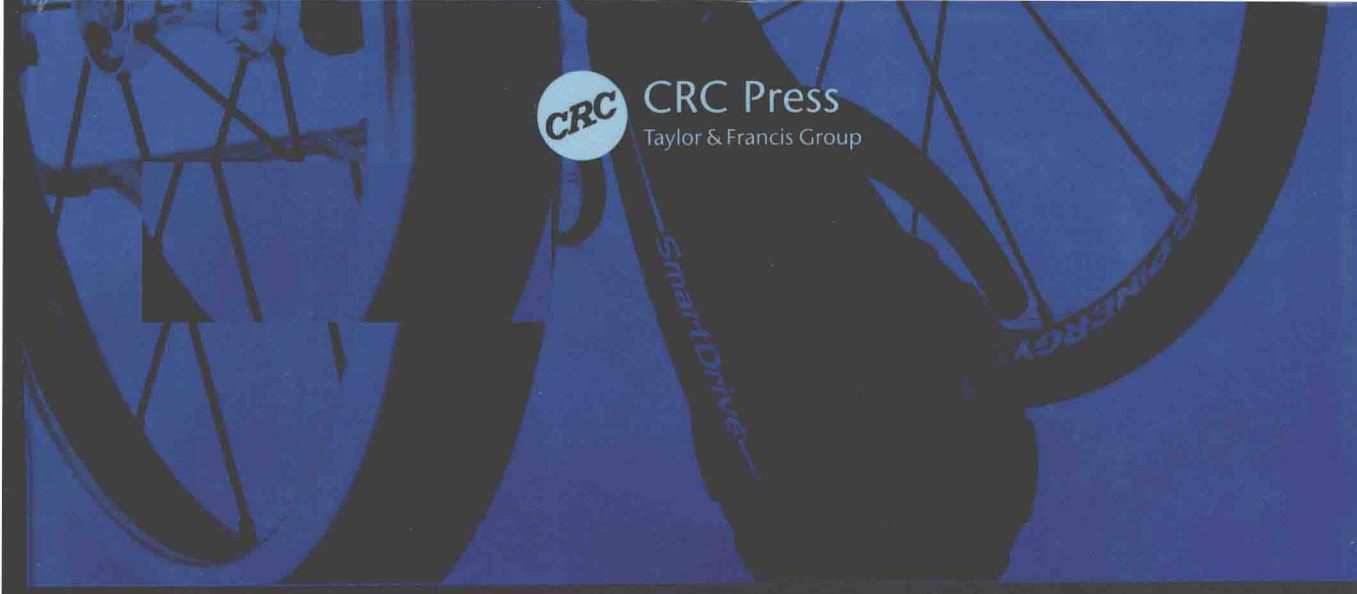

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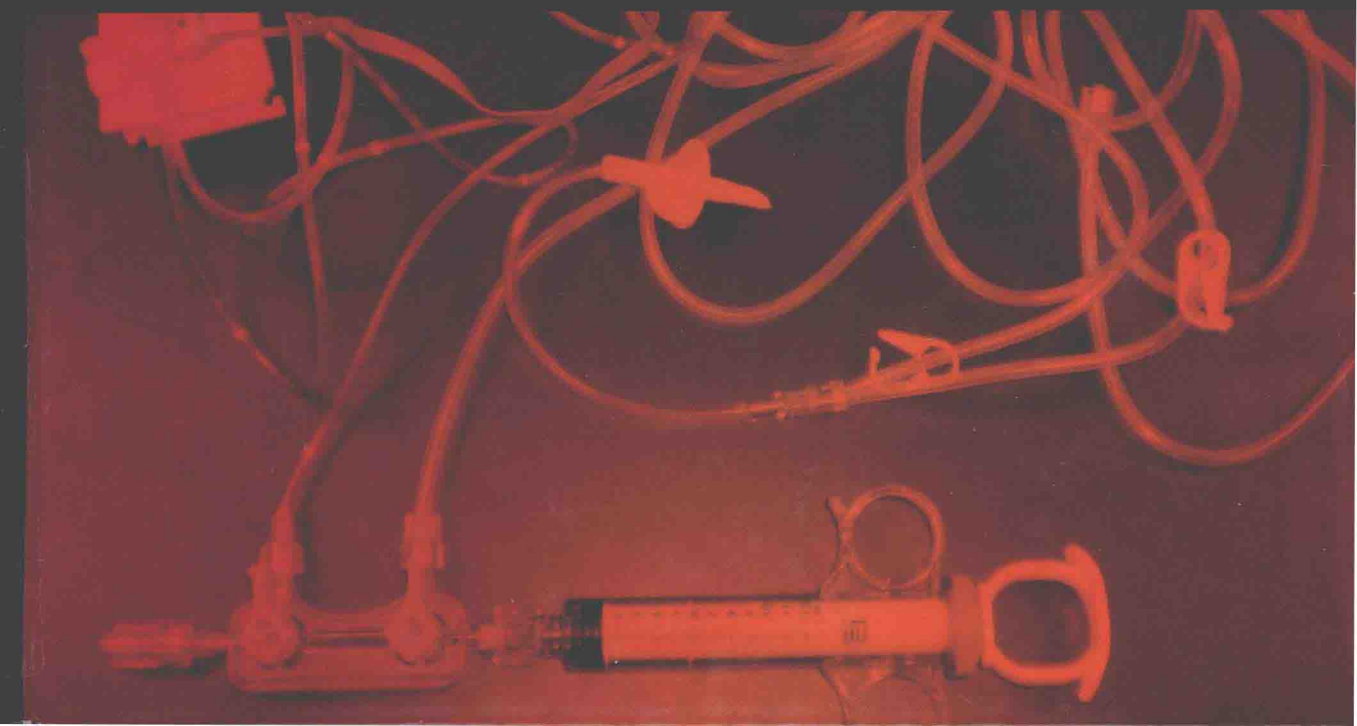
THIRD EDITION

DESIGN OF BIOMEDICAL DEVICES AND SYSTEMS

Paul H. King • Richard C. Fries • Arthur T. Johnson



Biomedical Engineering

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THIRD EDITION

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King • Fries • Johnson

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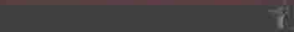
THIRD EDITION



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THIRD EDITION

DESIGN OF BIOMEDICAL DEVICES AND SYSTEMS

To

Sue

my wife and best friend

Paul H. King

To my wife

June

whose friendship, support, and love

make me whole

Richard C. Fries

and

In appreciation for the special people in my life who have greatly helped me to get this far.

Arthur T. Johnson

Preface

The design and functional complexity of medical devices and systems have increased during the past 50 years, evolving from the use of a metronome circuit for the initial cardiac pacemaker to functions that include medical bookkeeping, electrocardiogram analysis, delivery of anesthesia, laser surgery, magnetic resonance imaging, and intravenous delivery systems that adjust dosages based on patient feedback. As device functionality becomes more intricate, concerns arise regarding efficacy, safety, and reliability. Both the user and the patient want the device to operate as specified, perform in a safe manner, and continue to perform over a long period without failure. To be successful, the designer of medical devices must ensure that all devices meet these requirements.

Medical device design is a complex process that requires careful integration of diverse disciplines, technical activities, standards, regulatory requirements, and administrative project controls. The need for systematic approaches to product development and maintenance is necessary to ensure a safe and effective device for the user and the patient, an economical and competitive success for the manufacturer, and a reliable, cost-effective investment for the user.

This third edition of the book is aimed generally at senior bioengineering students who are in the formative stages of deciding what to do for a senior design project and who need to consider what the societal factors are that may or may not impact their project now or in the future if brought to a useful conclusion. Portions of the book may be used in lower level classes, such as the sections on brainstorming and elementary idea generation techniques. Portions of the book may be used in early graduate level classes if one has had little exposure to the Food and Drug Administration (FDA) and CE mark information. The book is meant to be fairly comprehensive, so that the needs of a variety of students working on a variety of topics (from databases to process analysis to device improvement) may have adequate information to begin a fairly comprehensive project. Additionally, it is aimed at design engineers new to the medical device industry who have not had access to such a comprehensive book or course in their background. This book should prove to be an excellent resource for those individuals as they enter the workforce.

The emphasis of the book is on the practical, hands-on approach to device design. The layout of the book follows the typical design process. The mathematics included here is that which is necessary to conduct everyday tasks. Equations, where needed, are merely given, not derived. It is assumed that the reader has a basic knowledge of statistics. References are given at the end of each chapter for those wishing to delve more deeply into the subject.

The first three chapters are a general introduction to the subject. Chapter 1 introduces the reader to biomedical engineering design. Chapter 2 is an outline of some fundamental ideas, generation techniques, and design decision and comparison tools with a brief introduction to the process of inventive (TRIZ) problem solving. Fundamental to successful design processes is the generation of a good design team and the management thereof; this is introduced in Chapter 3. This section then naturally sequences into the need for documentation techniques and requirements, and the use of databases in this endeavor. Reporting techniques are briefly covered in discussion on posters, oral presentations, and progress reports.

Fundamental to a good design is correct and customer-driven product definition. Chapter 4 summarizes the product definition process, and reiterates and concludes on the use of QFD in this process.

Product documentation, record keeping, and levels of effort mandated by FDA quality regulations and medical device regulations are discussed in Chapter 5.

Chapter 6 gives an overview of hardware and software design techniques that ensue from the earlier product specification tasks. Specifically covered is the FDA concept of the product development

process, which outlines the links from product requirements to design transfer, with intermediate links such as design verification and validation.

Hardware development methods and tools are reviewed in Chapter 7. Overviewed are such topics as design for Six Sigma, robust design, failure modes and effect considerations, axiomatic design, design improvements via component derating, reliability prediction and improvement, and several design for "X" methodologies. The chapter concludes with a discussion of design reviews.

Chapter 8 is an introduction to software development methods and tools. Because software differs from hardware, methods and tools used for software development are very different from those used in hardware development, but constraints on verification and validation as mandated by the FDA are paramount.

Chapter 9 overviews human factor issues. Several of the techniques used to guard against human-caused errors are reviewed, as are techniques to increase usability. Workstation design and human expectations are also discussed, as are the methods used to test these in use.

Chapter 10 discusses industrial design, including developing user interface concepts, designing a conceptual model, developing screen templates and a screenplay, and testing the design.

Biomaterials and materials selection are the theme of Chapter 11, with heavy coverage of the various FDA (and some international) tests and test methods used for materials that may come into contact with users. Tests for toxicity, hemocompatibility, irritation, reactivity, and sensitization are summarized.

Chapter 12 covers risk analysis of devices and systems, including some safety topics not dealt with elsewhere in the text, specifically addressing safety as a component of the design process and one of several structured approaches to the consideration of safety in a design.

Once the design is completed, it must be tested to prove whether it meets its requirements. The subject of testing is summarized in Chapter 13. Types of tests, parsing test requirements, establishing a test protocol, and defining failure are all discussed in detail. The chapter also discusses the methodology for determining test sample size and test length.

Once the testing is completed, the test data must be analyzed to determine the success or failure in testing. Chapter 14 explains the mathematical basis of analyzing test data. Metrics that are covered here include failure rate, reliability, mean time between failures, confidence level, confidence limits, and minimum life. There is also a discussion of graphical analysis of data, including Pareto charts.

Chapter 15 discusses the legal ramifications of medical device development and failure. Topics include negligence, breach of warranty, failure to warn of dangers, accident reconstruction, and forensics.

Chapter 16 discusses the FDA and its role in the regulation of medical devices. Device classification, manufacturer registration, and types of registration and listing are among the topics discussed.

Chapter 17 discusses FDA history and relevant nondevice regulations. A comprehensive history of the FDA is followed by a discussion of drug enforcement and postproduction oversight and enforcement.

Chapter 18 discusses biological engineering design. The emphasis of the chapter is on biological systems impacted by engineering.

Chapter 19 discusses international regulations and standards. Medical devices sold in the United States must meet FDA regulations and US standards. Those devices sold in other parts of the world must meet regulations and standards from those areas where they will be sold.

Good design will likely generate intellectual property. Chapter 20 gives a summary of the protection of intellectual property, including licensing, patents, copyrights, and trademarks.

Chapter 21 covers manufacturing and quality control. This chapter discusses manufacturing processes and how quality control issues continue during this phase of the design process and how they must be addressed.

Chapter 22 covers a few miscellaneous issues not relevant to other chapters, specifically such issues as learning from failure and designing for failure.

Chapter 23 is a brief synopsis of professional issues that must be considered by the biomedical professional. Specifically, membership in professional societies, licensure, and professional ethics are discussed. Forensics and consulting are also briefly covered.

Chapter 24 is essentially a resource chapter. It is written to assist and advise you, the reader, in determining if you wish to take your concept as developed in your coursework, profession, or otherwise to a point where you decide to develop your final product.

Design of Biomedical Devices and Systems, 3rd edition, is the joint effort of three engineers, one with more than 40 years of teaching and research experience in biomedical engineering and 20 years as the sole instructor of a senior design course (King), another with more than 30 years of experience as a reliability engineer in the biomedical device industry (Fries), and the third with 34 years of experience in the department of bioengineering (Johnson).

With the publication of the third edition, the authors felt that an explanation of the history of this book might be in order. As such, the normal place for a history is here.

In 1991, author King was assigned the task of initiating the first required one-semester senior design course at Vanderbilt. With only a semester for lecturing and for project work, the didactic material for the course had to be very limited and was fairly much constrained to a quick overview of "who, what, where, why, and when"; a quick overview of codes; some discussion of the mechanics of generation of design projects; and requirements for completion of design projects.

Attendance circa 1993 at an National Science Foundation (NSF)-sponsored design teaching seminar based largely on the text by Pahl and Beitz (titled *Engineering Design, A Systematic Approach*) assisted in the formalization of the course as a structured lecture and design course with specific deadlines and requirements based upon the mechanistic approach advocated by Pahl and Beitz. This was especially helpful as by 1997, the course evolved into a two-semester sequence with the dropping of a local requirement for a database course. Given the extra time, roughly the first third of the course year became formal instruction from notes, and the latter two-thirds became design projects with weekly written and monthly oral reporting requirements.

In 1999, author King reviewed author Fries's textbook *Reliable Design of Medical Devices* for the *IEEE Engineering in Medicine and Biology Magazine*. He was impressed enough with the industrial material in the textbook to adapt the text for a period of 3 years while authors King and Fries worked on the first edition of this text and tested it on the Vanderbilt classes. The first edition of this text was published in 2002, the second in 2009. The texts are currently being used for senior design courses both in the United States and overseas.

In 2011, King reviewed author Johnson's textbook *Biology for Engineers*. The application of engineering design principles to problems in biology was an aspect of our editions that author King felt was lacking in the early editions. As a result, author Johnson was cajoled into adding a chapter on biological engineering design to this textbook in order to broaden the horizons of students who may work not just in the medical domain but also in the biological domains not previously covered.

Johnson also relied on his 35 years of experience in teaching a transport processes design course to biological engineers at the University of Maryland. His book entitled *Biological Process Engineering* that he developed for the course has many examples from multiple applications areas in biological engineering. It is from this course that he has selected many of the design examples used in this text.

Paul H. King
Richard C. Fries
Arthur T. Johnson

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We are deeply indebted to many people for their encouragement, help, and constructive criticism in the preparation of this book.

Author King wishes to thank his coauthors, the over 1200 students who have suffered through his lectures and who have performed over 500 projects in the 20-year history of his teaching engineering design in the Department of Biomedical Engineering at Vanderbilt. He wishes to thank the other (EE, ChE, ME) design instructors at Vanderbilt for their camaraderie and sharing of students on projects (both ways). He also wishes to thank others who have contributed in reviews and additions to various chapters and those who have contributed in other ways (such as coworkers in anesthesiology and the lawyers who have, on occasion, presented him with interesting consulting cases, some of which are presented here). Thanks also to the NSF and National Collegiate Inventors and Innovators Alliance (NCIIA) for support of the course and projects and to CRC Press/Taylor & Francis for publishing this text.

We want to thank the biomedical engineering students in senior design at Vanderbilt University for their review and constructive criticism of the first edition of this book. Their input made this a better text. We thank those of you who have adopted and/or reviewed the prior editions also. We appreciate the feedback from faculty users that has influenced the content of this third edition.

Authors

Paul H. King, PhD, PE, attended Case Institute of Technology for his BS and MS degrees and then obtained his PhD at Vanderbilt University in 1968 (mechanical engineering.) That same year, he became one of the founding members of the Department of Biomedical Engineering at Vanderbilt University. He was department chair/program director shortly thereafter for a period of 5 years. With the exception of a 1-year sabbatical at Oak Ridge Associated Universities, he was actively teaching and doing research and service in the department until approximately December 2011. Research endeavors included work in nuclear medicine, cardiology, orthopedics, urology, and anesthesiology (19 years). He developed and taught most of the early required coursework in the Department of Biomedical Engineering. In approximately 1991, he initiated the current senior design sequence in biomedical engineering; an accompanying senior design seminar for most majors was initiated in 2001. He was exclusive instructor of the biomechanical engineering (BME) design course for a period of 20 years. In approximately 2001 he and coauthor Richard Fries published the first edition of the textbook *Design of Biomedical Devices and Systems*. This textbook is being used in multiple universities in the United States and abroad.

Dr. King has been very active in the field of design as a result of his commitment to the course and its development elsewhere. This commitment has taken the form of this textbook and of the assistance in the formation of a current enterprise termed *BME-IDEA*. The BME-IDEA group currently meets biannually and is comprised of invited chairmen and/or design instructors from universities in the United States (primarily). The meeting site precedes the Biomedical Engineering Society meeting, planning is done by an ad hoc group, and funding comes from various sources including NSF, the NCIIA, and others.

In addition to his work in the area of design, Dr. King was and remains an Accreditation Board for Engineering and Technology (ABET) evaluator for bioengineering and biomedical engineering programs. He has evaluated approximately 12 programs in the past 12 years, both in the United States and abroad. "Officially" retired in 2011, he remains active in reviewing grants and papers and is involved in design projects and in updating this textbook.

Richard Fries, PE, CSQE, CRE, is a licensed professional engineer in the state of Wisconsin and certified by the American Society for Quality as a reliability engineer and a software quality engineer. He is also certified as a Six Sigma Green Belt, an ISO 9000 lead auditor, and a TickIT lead auditor. He is trained as a Six Sigma Black Belt and a HIPAA Professional. He has degrees from Loyola University in Chicago and Marquette University in Milwaukee. He has 40+ years experience in hardware and software reliability, software development, regulatory compliance, and device design. He is coinventor of the absorber switch locking device (patent 5,682,876). He has authored eight books and chapters in several others on reliability and regulatory compliance. He has also written numerous articles in professional journals on hardware and software reliability, human factors, standards and regulations, and engineering education. He is an ABET evaluator, a senior life member of Institute of Electrical and Electronic Engineers (IEEE), a senior member of American Society for Quality (ASQ), and a member of the Biomedical Engineering Society. He is a member of the IEEE Software Engineering Subcommittee. He was a member of the Association for the Advancement of Medical Instrumentation (AAMI) Medical Device Software Committee and the Technical Committees that developed ISO 13485 and IEC 62304.

Arthur T. Johnson attended Cornell University for his undergraduate and graduate degrees. His PhD was awarded in 1969, and he immediately began serving as an officer in the US Army,

eventually serving in Vietnam at the rank of captain. He was awarded the Army Commendation Medal and Bronze Star Medal. He joined the faculty of the University of Maryland in 1975 and was professor from 1986 until 2009, when he became professor emeritus. He was cochairman of the committee to found the American Institute for Medical and Biological Engineering (AIMBE) from 1988 to 1992, and served as the executive director of AIMBE in 2004. He has been president of the Alliance for Engineering in Medicine and Biology (1984–1988), Institute for Biological Engineering (1998), and International Society for Respiratory Protection (2004–2006). He was the Secretary of the Biomedical Engineering Society from 2004 to 2009. He has been on the board of directors of the American Society for Agricultural and Biological Engineers (1995–1997). He is a founding fellow of the AIMBE (1992), life fellow of the American Society for Engineering Education (1996), life fellow of the American Society for Agricultural and Biological Engineers (2002), fellow of the American Industrial Hygiene Association (2005), fellow of the Biomedical Engineering Society (2005), fellow of the Institute for Biological Engineering (2009), and the life fellow of the Institute for Electrical and Electronics Engineers (2010). He is a member of the honor societies Phi Kappa Phi, Sigma Xi, Tau Beta Pi, and Alpha Epsilon. He has written three books: *Biomechanics and Exercise Physiology: Quantitative Modeling*, *Biological Process Engineering*, and *Biology for Engineers*. His research interests are human performance wearing respiratory protective masks, respiratory mechanics and measurement, and transport processes. He has been most recently active in teaching electronic design, transport processes, and engineering in biology courses, and in working to continue development of the airflow perturbation device as a noninvasive measurement of respiratory resistance.