MECHANICAL ENGINEERS' HANDBOOK

Volume 2

Design, Instrumentation, and Controls »

MYER KUTZ EDITOR

FOURTH EDITION

WILEY

Mechanical Engineers' Handbook
Fourth Edition

Design, Instrumentation, and Controls

Edited by
Myer Kutz

WILEY

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Mechanical Engineers' Handbook

To Arlene, Bill, Merrilyn, and Jayden

Preface

The second volume of the fourth edition of the *Mechanical Engineers' Handbook* is comprised of two parts: Part 1, Mechanical Design, with 14 chapters, and Part 2, Instrumentation, Systems, Controls and MEMS, with 11 chapters. The mechanical design chapters were in Volume I in the third edition. Given the introduction of 6 new chapters, mostly on measurements, in Volume I in this edition, it made sense to move the mechanical design chapters to Volume II and to cull chapters on instrumentation to make way for the measurements chapters, which are of greater use to readers of this handbook. Moreover, the mechanical design chapters have been augmented with 4 chapters (updated as needed) from my book, *Environmentally Conscious Mechanical Design*, thereby putting greater emphasis on sustainability. The 4 chapters are Design for Environment, Life-Cycle Design, Design for Maintainability, and Design for Remanufacturing Processes. They flesh out sustainability issues that were covered in the third edition by only one chapter, Product Design and Manufacturing Processes for Sustainability. The other 9 mechanical design chapters all appeared in the third edition. Six of them have been updated.

In the second part of Volume 2, Instrumentation, Systems, Controls and MEMS, 5 of the 11 chapters were new to the third edition of the handbook, including the 3 chapters I labeled as "new departures": Neural Networks in Control Systems, Mechatronics, and Introduction to Microelectromechanical Systems (MEMS): Design and Application. These topics have become increasingly important to mechanical engineers in recent years and they are included again. Overall, 3 chapters have been updated for this edition. In addition, I brought over the Electric Circuits chapter from the fifth edition of *Eshbach's Handbook of Engineering Fundamentals*. Readers of this part of Volume 2 will also find a general discussion of systems engineering; fundamentals of control system design, analysis, and performance modification; and detailed information about the design of servo actuators, controllers, and general-purpose control devices.

All Volume 2 contributors are from North America. I would like to thank all of them for the considerable time and effort they put into preparing their chapters.

Vision for the Fourth Edition

Basic engineering disciplines are not static, no matter how old and well established they are. The field of mechanical engineering is no exception. Movement within this broadly based discipline is multidimensional. Even the classic subjects, on which the discipline was founded, such as mechanics of materials and heat transfer, keep evolving. Mechanical engineers continue to be heavily involved with disciplines allied to mechanical engineering, such as industrial and manufacturing engineering, which are also constantly evolving. Advances in other major disciplines, such as electrical and electronics engineering, have significant impact on the work of mechanical engineers. New subject areas, such as neural networks, suddenly become all the rage.

In response to this exciting, dynamic atmosphere, the Mechanical Engineers' Handbook expanded dramatically, from one to four volumes for the third edition, published in November 2005. It not only incorporated updates and revisions to chapters in the second edition, published seven years earlier, but also added 24 chapters on entirely new subjects, with updates and revisions to chapters in the Handbook of Materials Selection, published in 2002, as well as to chapters in Instrumentation and Control, edited by Chester Nachtigal and published in 1990, but never updated by him.

The fourth edition retains the four-volume format, but there are several additional major changes. The second part of Volume I is now devoted entirely to topics in engineering mechanics, with the addition of five practical chapters on measurements from the Handbook of Measurement in Science and Engineering, published in 2013, and a chapter from the fifth edition of Eshbach's Handbook of Engineering Fundamentals, published in 2009. Chapters on mechanical design have been moved from Volume I to Volumes II and III. They have been augmented with four chapters (updated as needed) from Environmentally Conscious Mechanical Design, published in 2007. These chapters, together with five chapters (updated as needed, three from Environmentally Conscious Manufacturing, published in 2007, and two from Environmentally Conscious Materials Handling, published in 2009) in the beefed-up manufacturing section of Volume III, give the handbook greater and practical emphasis on the vital issue of sustainability.

Prefaces to the handbook's individual volumes provide further details on chapter additions, updates and replacements. The four volumes of the fourth edition are arranged as follows:

Volume 1: Materials and Engineering Mechanics—27 chapters

- Part 1. Materials—15 chapters
- Part 2. Engineering Mechanics—12 chapters

Volume 2: Design, Instrumentation and Controls—25 chapters

- Part 1. Mechanical Design—14 chapters
- Part 2. Instrumentation, Systems, Controls and MEMS —11 chapters

Volume 3: Manufacturing and Management—28 chapters

- Part 1. Manufacturing—16 chapters
- Part 2. Management, Finance, Quality, Law, and Research—12 chapters

Volume 4: Energy and Power—35 chapters

Part 1: Energy—16 chapters

Part 2: Power—19 chapters

The mechanical engineering literature is extensive and has been so for a considerable period of time. Many textbooks, reference works, and manuals as well as a substantial number of journals exist. Numerous commercial publishers and professional societies, particularly in the United States and Europe, distribute these materials. The literature grows continuously, as applied mechanical engineering research finds new ways of designing, controlling, measuring, making, and maintaining things, as well as monitoring and evaluating technologies, infrastructures, and systems.

Most professional-level mechanical engineering publications tend to be specialized, directed to the specific needs of particular groups of practitioners. Overall, however, the mechanical engineering audience is broad and multidisciplinary. Practitioners work in a variety of organizations, including institutions of higher learning, design, manufacturing, and consulting firms, as well as federal, state, and local government agencies. A rationale for a general mechanical engineering handbook is that every practitioner, researcher, and bureaucrat cannot be an expert on every topic, especially in so broad and multidisciplinary a field, and may need an authoritative professional summary of a subject with which he or she is not intimately familiar.

Starting with the first edition, published in 1986, my intention has always been that the Mechanical Engineers' Handbook stand at the intersection of textbooks, research papers, and design manuals. For example, I want the handbook to help young engineers move from the college classroom to the professional office and laboratory where they may have to deal with issues and problems in areas they have not studied extensively in school.

With this fourth edition, I have continued to produce a practical reference for the mechanical engineer who is seeking to answer a question, solve a problem, reduce a cost, or improve a system or facility. The handbook is not a research monograph. Its chapters offer design techniques, illustrate successful applications, or provide guidelines to improving performance, life expectancy, effectiveness, or usefulness of parts, assemblies, and systems. The purpose is to show readers what options are available in a particular situation and which option they might choose to solve problems at hand.

The aim of this handbook is to serve as a source of practical advice to readers. I hope that the handbook will be the first information resource a practicing engineer consults when faced with a new problem or opportunity—even before turning to other print sources, even officially sanctioned ones, or to sites on the Internet. In each chapter, the reader should feel that he or she is in the hands of an experienced consultant who is providing sensible advice that can lead to beneficial action and results.

Can a single handbook, even spread out over four volumes, cover this broad, interdisciplinary field? I have designed the Mechanical Engineers' Handbook as if it were serving as a core for an Internet-based information source. Many chapters in the handbook point readers to information sources on the Web dealing with the subjects addressed. Furthermore, where appropriate, enough analytical techniques and data are provided to allow the reader to employ a preliminary approach to solving problems.

The contributors have written, to the extent their backgrounds and capabilities make possible, in a style that reflects practical discussion informed by real-world experience. I would like readers to feel that they are in the presence of experienced teachers and consultants who know about the multiplicity of technical issues that impinge on any topic within mechanical engineering. At the same time, the level is such that students and recent graduates can find the handbook as accessible as experienced engineers.

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PART 1

DESIGN

CHAPTER 1

COMPUTER-AIDED DESIGN

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1 INTRODUCTION TO CAD

Computers have a prominent, often controlling role throughout the life cycle of engineering products and manufacturing processes. Their role is vital as global competitive pressures call for improvements in product performance and quality coupled with significant reductions in product design, development, and manufacturing timetables. Design engineers vastly improve their work productivity using computers. For example, performance of a product or process can be evaluated prior to fabricating a prototype using appropriate simulation software.

Computer-aided design (CAD) uses the mathematical and graphic processing power of the computer to assist the engineer in the creation, modification, analysis, and display of designs. Many factors have contributed to CAD technology being a necessary tool in the engineering world for applications including shipbuilding, automotive, aerospace, medical, industrial, and architectural design, such as the computer's speed in processing complex equations and managing technical databases. CAD at one time was thought of simply as computer-aided drafting, and its use as an electronic drawing board is still a powerful tool in itself. Geometric modeling, engineering analysis, simulation, and the communication of the design information can also be performed using a CAD system. However, the functions of a CAD system are evolving far beyond its ability to represent and manipulate graphics. The CAD system is being integrated into the overall product life cycle as part of collaborative product design, sustainability impact analysis, product life-cycle management, and product data management.

1.1 Historical Perspective on CAD

Graphical representation of data, in many ways, forms the basis of CAD. An early application of computer graphics was used in the SAGE (Semi-Automatic Ground Environment) Air Defense Command and Control System in the 1950s. SAGE converted radar information into computer-generated images on a cathode ray tube (CRT) display. It also used an input device, the light pen, to select information directly from the CRT screen.

Another significant advancement in computer graphics technology occurred in 1963, when Ivan Sutherland, in his doctoral thesis at MIT, described the SKETCHPAD (Fig. 1) system. A Lincoln TX-2 computer drove the SKETCHPAD system. SKETCHPAD is a graphic user interface that enables a design to be input into a computer using a light pen on the CRT monitor. With SKETCHPAD, images could be created and manipulated using the light pen. Graphical manipulations such as translation, rotation, and scaling could all be accomplished on-screen using SKETCHPAD. Computer applications based on Sutherland's approach have become known as interactive computer graphics (ICG), which are the foundation of CAD design processes. The graphical capabilities of SKETCHPAD showed the potential for computerized drawing in design.

During his time as a professor of electrical engineering at the University of Utah, Sutherland continued his research on head-mounted displays (HMDs), the precursor to virtual reality head displays. The field of computer graphics (Fig. 2), as we know it today, was born from among the many new ideas and innovations created by the researchers who made the University a hub for this kind of research. Together with Dave Evans, the founder of the University's

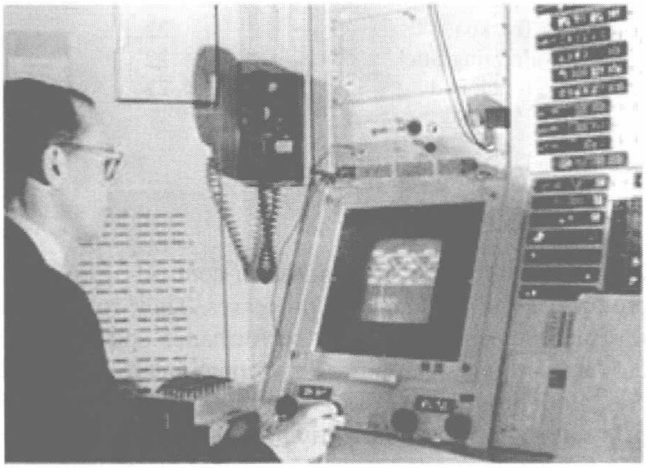

Figure 1 Ivan E. Sutherland and the SKETCHPAD system.

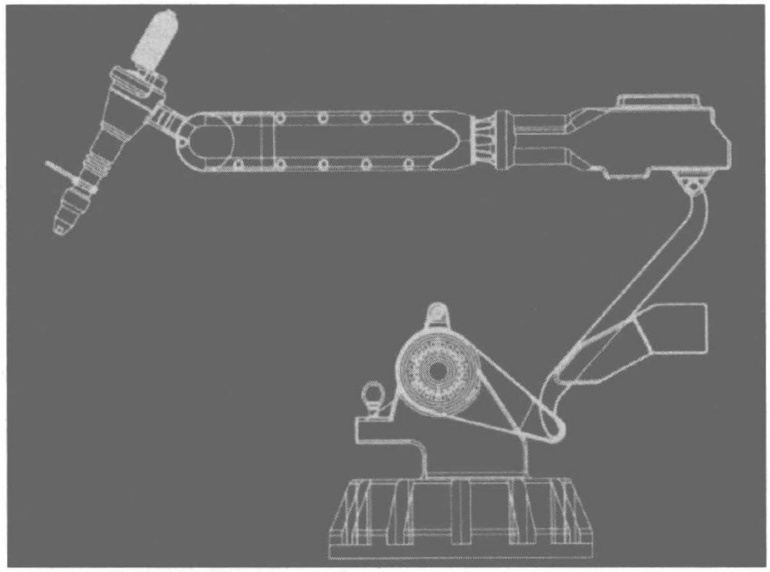

Figure 2 Image on a line drawing graphics display.

Computer Science Department, Sutherland co-founded Evans and Sutherland in 1968, which later went on to pioneer computer modeling systems and software.

While at the California Institute of Technology, Sutherland served as the chairman of the Computer Science Department from 1976 to 1980. While he was there, he helped to introduce the integrated circuit design to academia. Together with Professor Carver Mead, they developed the science of combining the mathematics of computing with the physics of real transistors and real wires and subsequently went on to make integrated circuit design a proper field of academic study. In 1980, Sutherland left Caltech and launched the company Sutherland, Sproull, and Associates. Bought by Sun Labs in 1990, the acquisition formed the basis for Sun Microsystems Laboratories.

The high cost of computer hardware in the 1960s limited the use of ICG systems to large corporations such as those in the automotive and aerospace industries, which could justify the initial investment. With the rapid development of computer technology, computers became more powerful, with faster processors and greater data storage capabilities. As computer cost decreased, systems became more affordable to smaller companies allowing entrepreneurs to innovate using CAD tools and technologies.

In more recent times, increased impact of computer-aided design has been facilitated by advances in Web-based technologies and standards, use of mobile computing platforms and devices, cloud-based storage, software as a service, and functional integration into enterprise-wide systems. Additionally, the proliferation of CAD systems running on a wide variety of platforms has promoted global collaboration as well as concurrent design and manufacturing approaches. In the view of many, CAD has become a necessary business tool for any engineering, design, or architectural firm.

1.2 Design Process

Before any discussion of computer-aided design, it is necessary to understand the design process in general. What is the series of events that leads to the beginning of a design project? How does the engineer go about the process of designing something? How does one arrive at