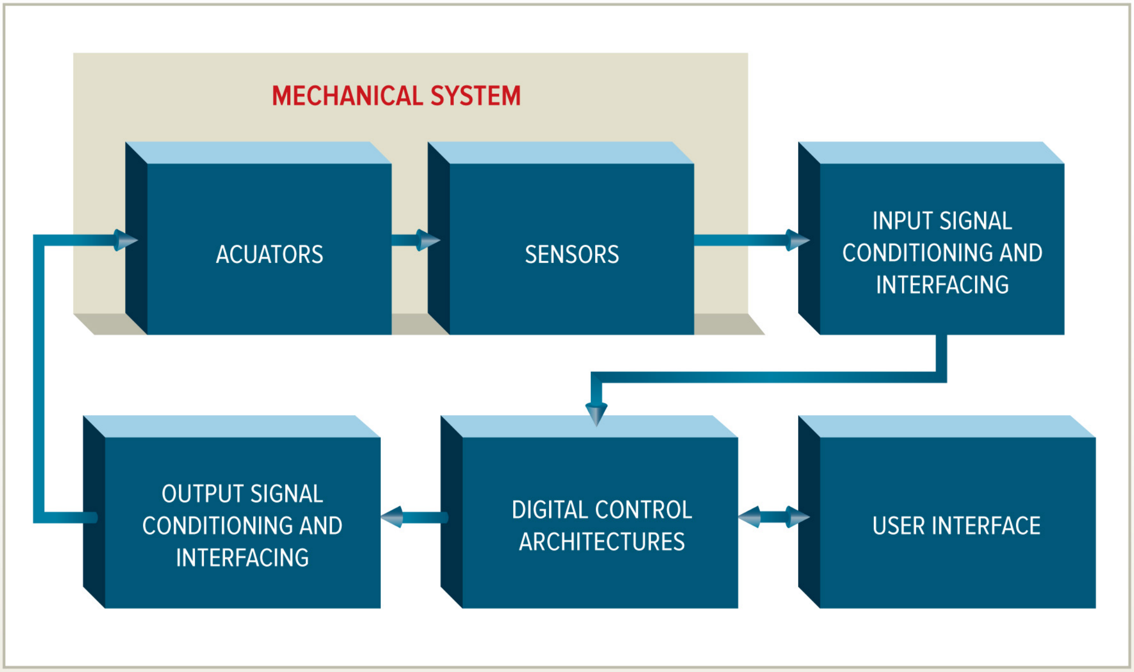
Introduction to MECHATRONICS and MEASUREMENT SYSTEMS

Fifth Edition

David G. Alciatore



Mc Graw Hill Education

Introduction to Mechatronics and Measurement Systems

Fifth Edition

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INTRODUCTION TO MECHATRONICS AND MEASUREMENT SYSTEMS, FIFTH EDITION

Published by McGraw-Hill Education, 2 Penn Plaza, New York, NY 10121.

This book is printed on acid-free paper.

1 2 3 4 5 6 7 8 9 QVS 21 20 19 18

ISBN 978-1-259-89234-9 (bound edition)
MHID 1-259-89234-4 (bound edition)
ISBN 978-1-260-04870-4 (loose-leaf edition)
MHID 1-260-04870-5 (loose-leaf edition)

Senior Portfolio Manager: *Thomas Scaife, PHD*
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Senior Buyer: *Sandy Ludovissy*
Content Licensing Specialist: *Lorraine Buczek*
Cover Images: *©McGraw-Hill Global Education Holdings, LLC*
Compositor: *SPi Global*

Library of Congress Cataloging-in-Publication Data

Names: Alciatore, David G., author.
Title: Introduction to mechatronics and measurement systems / David G. Alciatore, Department of Mechanical Engineering, Colorado State University.
Description: Fifth edition. | New York, NY : McGraw-Hill Education, [2019] | Includes index.
Identifiers: LCCN 2017049798| ISBN 9781259892349 (alk. paper) | ISBN 1259892344 (alk. paper)
Subjects: LCSH: Mechatronics. | Measurement.
Classification: LCC TJ163.12 .H57 2019 | DDC 621—dc23
LC record available at https://lccn.loc.gov/2017049798

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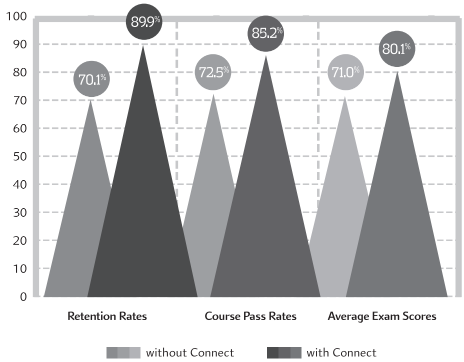

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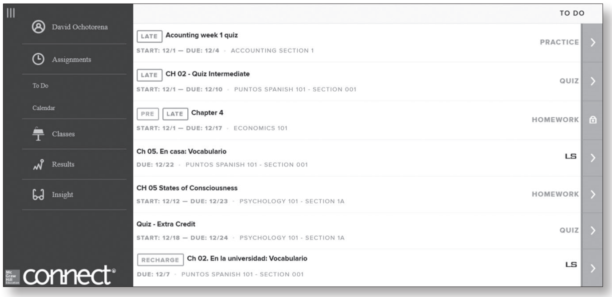

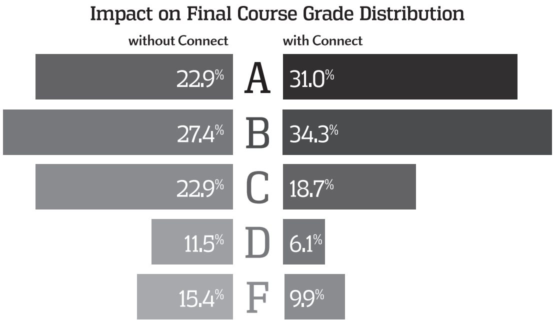

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PREFACE

APPROACH

The formal boundaries of traditional engineering disciplines have become fuzzy following the advent of integrated circuits and computers. Nowhere is this more evident than in mechanical and electrical engineering, where products today include an assembly of interdependent electrical and mechanical components. The field of mechatronics has broadened the scope of the traditional field of electromechanics. *Mechatronics* is defined as the field of study involving the analysis, design, synthesis, and selection of systems that combine electronic and mechanical components with modern controls and microprocessors.

This book is designed to serve as a text for (1) a modern instrumentation and measurements course, (2) a hybrid electrical and mechanical engineering course replacing traditional circuits and instrumentation courses, (3) a stand-alone mechatronics course, or (4) the first course in a mechatronics sequence. The second option, the hybrid course, provides an opportunity to reduce the number of credit hours in a typical mechanical engineering curriculum. Options 3 and 4 could involve the development of new interdisciplinary courses and curricula.

Currently, many curricula do not include a mechatronics course but include some of the elements in other more traditional courses. The purpose of a course in mechatronics is to provide a focused interdisciplinary experience for undergraduates that encompasses important elements from traditional courses as well as contemporary developments in electronics and computer control. These elements include measurement theory, electronic circuits, computer interfacing, sensors, actuators, and the design, analysis, and synthesis of mechatronic systems. This interdisciplinary approach is valuable to students because virtually every newly designed engineering product is a mechatronic system.

NEW TO THE FIFTH EDITION

The fifth edition of *Introduction of Mechatronics and Measurement Systems* has been improved, updated, and expanded beyond the previous edition. Additions and new features include:

- Arduino resources and examples added to supplement PIC microcontroller programming.
- Matlab solutions added for all MathCAD analysis files provided in previous editions.
- More microcontroller programming and interfacing examples, including serial communication.
- Expanded coverage of practical circuit and microcontroller-project debugging and troubleshooting advice.

- New section dealing with diode applications.
- New coverage of how to use an A/D reconstruction filter to produce high-fidelity representations of sampled data.
- Expanded section dealing with virtual instrumentation and the NI ELVIS Laboratory Platform.
- More website resources, including Internet links and online video demonstrations, cited and described throughout the book.
- Additional end-of-chapter questions throughout the book provide more homework and practice options for professors and students.
- Corrections and many small improvements throughout the entire book.

Also, the Laboratory Exercises Manual that supplements and supports this book is now available on-line for free and unlimited use by faculty and students. It is located, along with video demonstrations, on the Lab Book web page at: ***mechatronics.colostate.edu/lab_book.html***

CONTENT

Chapter 1 introduces mechatronic and measurement system terminology. Chapter 2 provides a review of basic electrical relations, circuit elements, and circuit analysis. Chapter 3 deals with semiconductor electronics. Chapter 4 presents approaches to analyzing and characterizing the response of mechatronic and measurement systems. Chapter 5 covers the basics of analog signal processing and the design and analysis of operational amplifier circuits. Chapter 6 presents the basics of digital devices and the use of integrated circuits. Chapter 7 provides an introduction to microcontroller programming and interfacing, and specifically covers the PIC microcontroller and PicBasic Pro programming. Chapter 8 deals with data acquisition and how to couple computers to measurement systems. Chapter 9 provides an overview of the many sensors common in mechatronic systems. Chapter 10 introduces a number of devices used for actuating mechatronic systems. Finally, Chapter 11 provides an overview of mechatronic system control architectures and presents some case studies. Chapter 11 also provides an introduction to control theory and its role in mechatronic system design. The appendices review the fundamentals of unit systems, statistics, error analysis, and mechanics of materials to support and supplement measurement systems topics in the book.

It is practically impossible to write and revise a large textbook without introducing errors by mistake, despite the amount of care exercised by the authors, editors, and typesetters. When errors are found, they will be published on the book website at: **mechatronics.colostate.edu/book/corrections_5th_edition.html.** You should visit this page now to see if there are any corrections to record in your copy of the book. If you find any additional errors, please report them to *David.Alciatore@colostate.edu* so they can be posted for the benefit of others. Also, please let me know if you have suggestions or requests concerning improvements for future editions of the book. Thank you.

LEARNING TOOLS

Class discussion items (CDIs) are included throughout the book to serve as thought-provoking exercises for the students and instructor-led cooperative learning activities in the classroom. They can also be used as out-of-class homework assignments to supplement the questions and exercises at the end of each chapter. Hints and partial answers for many of the CDIs are available on the book website at **mechatronics.colostate.edu.** Analysis and design examples are also provided throughout the book to improve a student's ability to apply the material. To enhance student learning, carefully designed laboratory exercises coordinated with the lectures should accompany a course using this text. A supplemental Laboratory Exercises Manual is available for this purpose (see **mechatronics.colostate.edu/lab_book.html** for more information). The combination of class discussion items, design examples, and laboratory exercises exposes a student to a real-world practical approach and provides a useful framework for future design work.

In addition to the analysis Examples and design-oriented Design Examples that appear throughout the book, Threaded Design Examples are also included. The examples are mechatronic systems that include microcontrollers, input and output devices, sensors, actuators, support electronics, and software. The designs are presented incrementally as the pertinent material is covered throughout the chapters. This allows the student to see and appreciate how a complex design can be created with a divide-and-conquer approach. Also, the threaded designs help the student relate to and value the circuit fundamentals and system response topics presented early in the book. The examples help the students see the "big picture" through interesting applications beginning in Chapter 1.

ACKNOWLEDGMENTS

To ensure the accuracy of this text, it has been class-tested at Colorado State University and the University of Wyoming. I'd like to thank all of the students at both institutions who provided me valuable feedback throughout this process. In addition, I'd like to thank my many reviewers for their valuable input.

YangQuan Chen *Utah State University*
Meng-Sang Chew *Lehigh University*
Mo-Yuen Chow *North Carolina State University*
Burford Furman *San José State University*
Venkat N. Krovi *State University of New York, Buffalo*
Satish Nair *University of Missouri*
Ramendra P. Roy *Arizona State University*
Ahmad Smaili *Hariri Canadian University, Lebanon*
David Walrath *University of Wyoming*

I'd also like to thank all of the users and readers who have sent in corrections and recommendations for improvement via email. This input has helped me make the new edition of the book better and as error-free as possible for everyone.

ABOUT THE AUTHOR

Dr. David G. Alciatore has been a mechanical engineering professor at Colorado State University (CSU) since 1991. Dr. Dave, as his students know him, is a dedicated teacher and has received numerous awards for his contributions, including the university-wide Board of Governors "Excellence in Undergraduate Teaching Award." His major research, consulting, and teaching interests include modeling and simulation of dynamic systems, mechatronic system design, high-speed video motion analysis, and engineering education. Over his career, Dr. Dave has done research and consulting dealing with robotics, computer graphics modeling, rapid prototyping (3D printing), sports mechanics, and mechatronics.

Dr. Dave has a PhD (1990) and an MS (1987) in Mechanical Engineering from the University of Texas at Austin, and a BS (1986) in Mechanical Engineering from the University of New Orleans. He has been an active member of the American Society of Mechanical Engineers (ASME) since 1984 and has served on many ASME committees, boards, and task forces. He also served as an ASME *Distinguished Lecturer*, and is a *Fellow* of the society. He is also a Professional Engineer.

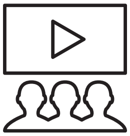
In addition to his interest in mechatronics, Dr. Dave is passionate about the physics and engineering of billiards equipment and techniques. He is author of the book: *The Illustrated Principles of Pool and Billiards* and has published numerous instructional-video DVDs dealing with understanding and playing the wonderful game of pool. He also writes a monthly column for *Billiards Digest* magazine and has a very active pool-related YouTube Channel. Dr. Dave incorporates his passion for pool into the engineering classroom every chance he gets (e.g., when he teaches Advanced Dynamics).

If you have used this book in the past, you will notice that a second author is no longer listed. Dr. Dave co-authored earlier editions of this book with Michael B. Histand. Dr. Histand retired in 2005 after a 37-year career at Colorado State University. Dr. Dave has worked on the last two editions of this book on his own; but in the early editions, Dr. Histand contributed a wealth of knowledge and experience dealing with electronics, sensors, and instrumentation. Dr. Dave will always cherish the time he spent with Mike, and he sincerely thanks him for the many enjoyable years working together. He and Mike are good friends and still see each other on a regular basis.

SUPPLEMENTAL MATERIALS ARE AVAILABLE ONLINE AT:
mechatronics.colostate.edu

Cross-referenced visual icons appear throughout the book to indicate where additional information is available on the book website at **mechatronics.colostate.edu.**

Shown below are the icons used, along with a description of the resources to which they point:

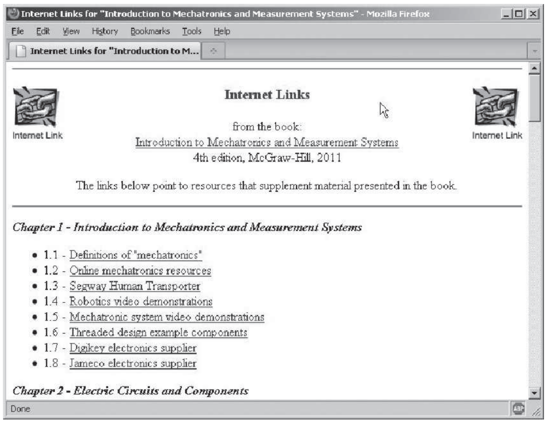


Video Demo

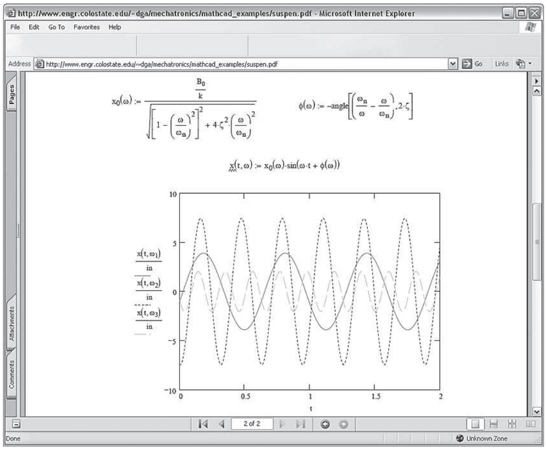
This sign indicates where an online video demonstration is available for viewing. The online videos are YouTube videos or Windows Media (WMV) files viewable in an Internet browser. The clips show and describe electronic components, mechatronic devices and system examples, and as well as laboratory exercise demonstrations.

Internet Link

This sign indicates where a link to additional Internet resources is available on the book website. These links provide students and instructors with reliable sources of information for expanding their knowledge of certain concepts.



This sign indicates where Mathcad/Matlab files are available for performing analysis calculations. The files can be edited to perform similar and expanded analyses. PDF versions are also posted for those who do not have access to Mathcad/Matlab software.



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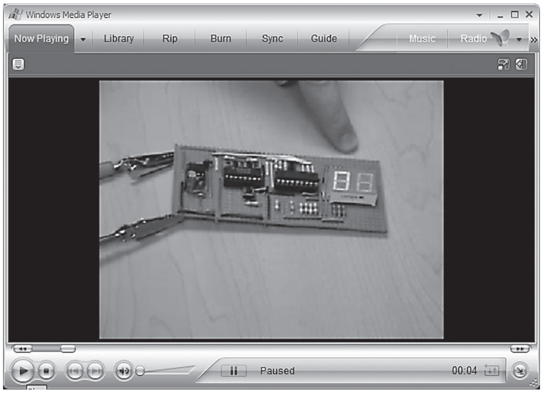
This sign indicates where a laboratory exercise is available in the supplemental Laboratory Exercises Manual that parallels the book. The manual provides useful hands-on laboratory exercises that help reinforce the material in the book and allow students to apply what they learn. Resources and short video demonstrations of most of the exercises are available on the book website. For information about the Laboratory Exercises Manual, visit **mechatronics.colostate.edu/lab_book.html.**



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ADDITIONAL SUPPLEMENTS

More information, including a recommended course outline, a typical laboratory syllabus, Class Discussion Item hints, and other supplemental material, is available on the book website.

In addition, a complete password-protected Solutions Manual containing solutions to all end-of-chapter problems is available at the McGraw-Hill book website at **www.mhhe.com/alciatore.**

These supplemental materials help students and instructors apply concepts in the text to laboratory or real-world exercises, enhancing the learning experience.

CHAPTER 1

Introduction

CHAPTER OBJECTIVES

After you read, discuss, study, and apply ideas in this chapter, you will be able to:

1. Define mechatronics and appreciate its relevance to contemporary engineering design
2. Identify a mechatronic system and its primary elements
3. Define the elements of a general measurement system

1.1 MECHATRONICS

Mechanical engineering, as a widespread professional practice, experienced a surge of growth during the early 19th century because it provided a necessary foundation for the rapid and successful development of the industrial revolution. At that time, mines needed large pumps never before seen to keep their shafts dry, iron and steel mills required pressures and temperatures beyond levels used commercially until then, transportation systems needed more than real "horse power" to move goods; structures began to stretch across ever wider abysses and to climb to dizzying heights, manufacturing moved from the shop bench to large factories; and to support these technical feats, people began to specialize and build bodies of knowledge that formed the beginnings of the engineering disciplines.

The primary engineering disciplines of the 20th century—mechanical, electrical, civil, and chemical—retained their individual bodies of knowledge, textbooks, and professional journals because the disciplines were viewed as having mutually exclusive intellectual and professional territory. Entering students could assess their individual intellectual talents and choose one of the fields as a profession. We are now witnessing a new scientific and social revolution known as the information revolution, where engineering specializations ironically seem to be simultaneously focusing and diversifying. This contemporary revolution was spawned by the engineering development of semiconductor electronics, which has driven an information and communications explosion that is transforming human life. To practice engineering today, we must understand new ways to process information and be able to utilize semiconductor electronics within our products, no matter what label we put on ourselves as practitioners. Mechatronics is one of the new and exciting fields on the engineering landscape, subsuming parts of traditional engineering fields and requiring a broader approach to the design of systems that we can formally call mechatronic systems.

Internet Link

1.1 Definitions of "mechatronics"

Then what precisely is mechatronics? The term **mechatronics** is used to denote a rapidly developing, interdisciplinary field of engineering dealing with the design of products whose function relies on the integration of mechanical and electronic components coordinated by a control architecture. Other definitions of the term "mechatronics" can be found online at Internet Link 1.1. The word mechatronics was coined in Japan in the late 1960s, spread through Europe, and is now commonly used in the United States. The primary disciplines important in the design of mechatronic systems include mechanics, electronics, controls, and computer engineering. A mechatronic system engineer must be able to design and select analog and digital circuits, microprocessor-based components, mechanical devices, sensors and actuators, and controls so that the final product achieves a desired goal.

Mechatronic systems are sometimes referred to as smart devices. While the term "smart" is elusive in precise definition, in the engineering sense we mean the inclusion of elements such as logic, feedback, and computation that in a complex design may appear to simulate human thinking processes. It is not easy to compartmentalize mechatronic system design within a traditional field of engineering because such design draws from knowledge across many fields. The mechatronic system designer must be a generalist, willing to seek and apply knowledge from a broad range of sources. This may intimidate the student at first, but it offers great benefits for individuality and continued learning during one's career.

Today, practically all mechanical devices include electronic components and some type of digital monitoring or control. Therefore, the term mechatronic system encompasses a myriad of devices and systems. Increasingly, microcontrollers are embedded in electromechanical devices, creating much more flexibility and control possibilities in system design. Examples of mechatronic systems include an aircraft flight control and navigation system (including those on consumer drones), automobile air-bag safety system and antilock brake systems, automated manufacturing equipment such as robots and numerically controlled (NC) machine tools, smart kitchen and home appliances such as bread machines and clothes washing machines, and even toys.

Internet Link

1.2 Online mechatronics resources

Figure 1.1 illustrates all the components in a typical mechatronic system. The actuators produce motion or cause some action; the sensors detect the state of the system parameters, inputs, and outputs; digital devices control the system; conditioning and interfacing circuits provide connections between the control circuits and the input/output devices; and a user interface enables manual inputs and provides graphical displays or visual feedback to the user. The subsequent chapters provide an introduction to the elements listed in this block diagram and describe aspects of their analysis and design. At the beginning of each chapter, the elements presented are emphasized in a copy of Figure 1.1. This will help you maintain a perspective on the importance of each element as you gradually build your capability to design a mechatronic system. Internet Link 1.2 provides links to various vendors and sources of information for researching and purchasing different types of mechatronics components.

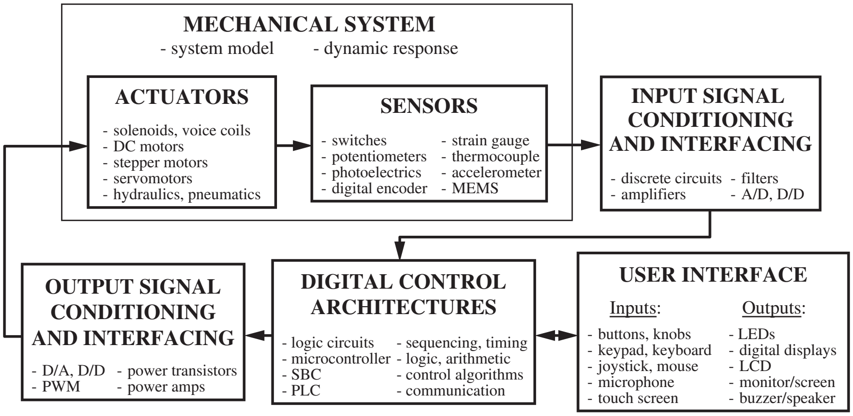

Figure 1.1 Mechatronic system components.

Internet Link

1.3 Segway human transporter

Video Demo

1.1 Adept One robot demonstration

1.2 Adept One robot internal design and construction

1.3 Honda Asimo Raleigh, NC, demonstration

1.4 Sony "Qrio" Japanese dance demo

1.5 Inkjet printer components

Example 1.1 describes a good example of a mechatronic system—an office copy machine. All of the components in Figure 1.1 can be found in this common piece of office equipment. Other mechatronic system examples can be found on the book website. See the Segway Human Transporter at Internet Link 1.3, the Adept pick-and-place industrial robot in Video Demos 1.1 and 1.2, the Honda Asimo and Sony Qrio humanoid-like robots in Video Demos 1.3 and 1.4, and the inkjet printer in Video Demo 1.5. As with the copy machine in Example 1.1, these robots and printer contain all of the mechatronic system components shown in Figure 1.1. Figure 1.2 labels the specific components mentioned in Video Demo 1.5. Video demonstrations of many more robotics-related devices can be found

Mechatronic System—Copy Machine — EXAMPLE 1.1

An office copy machine is a good example of a contemporary mechatronic system. It includes analog and digital circuits, sensors, actuators, and microprocessors. The copying process works as follows: The user places an original in a loading bin and pushes a button to start the process; the original is transported to the platen glass; and a high-intensity light source scans the original and transfers the corresponding image as a charge distribution to a drum. Next, a blank piece of paper is retrieved from a loading cartridge, and the image is transferred onto the paper with an electrostatic deposition of ink toner powder that is heated to bond to the paper. A sorting mechanism then optionally delivers the copy to an appropriate bin.

Analog circuits control the lamp, heater, and other power circuits in the machine. Digital circuits control the digital displays, indicator lights, buttons, and switches forming the user interface. Other digital circuits include logic circuits and microprocessors that coordinate all of the functions in the machine. Optical sensors and microswitches detect the presence or absence of paper, its proper positioning, and whether or not doors and latches are in their correct positions. Other sensors include encoders used to track motor rotation. Actuators include servo and stepper motors that load and transport the paper, turn the drum, and index the sorter.

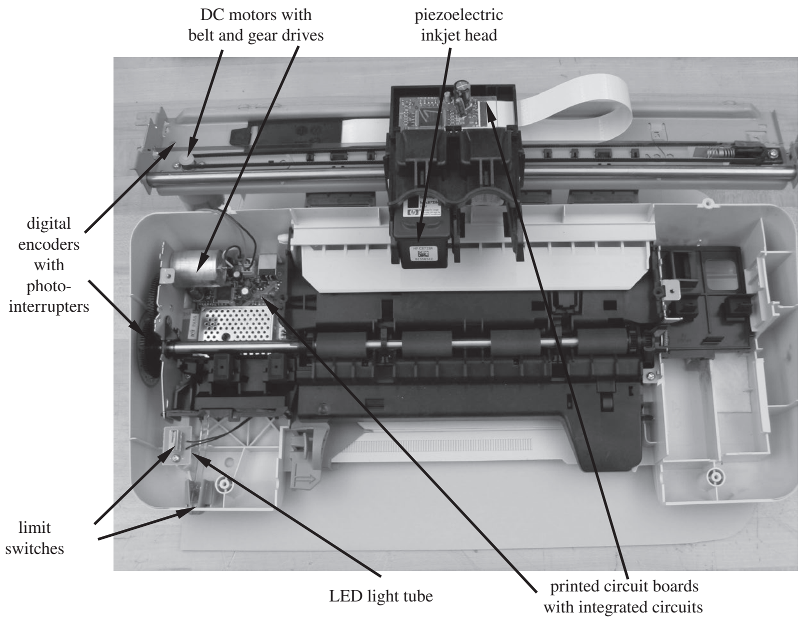

Figure 1.2 Inkjet printer components.
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Internet Link

1.4 Robotics video demonstrations

1.5 Mechatronic system video demonstrations

at Internet Link 1.4, and demonstrations of other mechatronic system examples can be found at Internet Link 1.5.

> ■ **CLASS DISCUSSION ITEM 1.1**
> ***Household Mechatronic Systems***
>
> What typical household items can be characterized as mechatronic systems? What components do they contain that help you identify them as mechatronic systems? If an item contains a microprocessor, describe the functions performed by the microprocessor.

1.2 MEASUREMENT SYSTEMS

A fundamental part of many mechatronic systems is a **measurement system** composed of the three basic parts illustrated in Figure 1.3. The **transducer** is a sensing element that converts a physical input into an output, usually a voltage. The **signal processor** performs filtering, amplification, or other signal conditioning on the transducer output. The term **sensor** is often used to refer to the transducer or to the combination of transducer and signal processor. Finally, the **recorder** is an instrument, a computer, or an output device that stores or displays the sensor data for monitoring or subsequent processing.

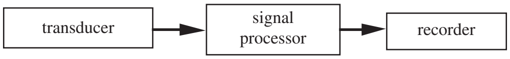


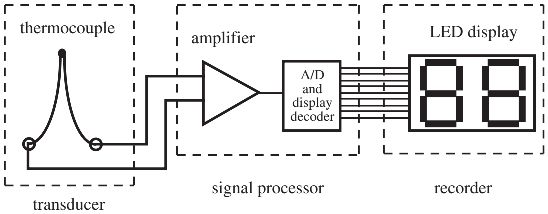
Figure 1.3 Elements of a measurement system.

These three building blocks of measurement systems come in many types with wide variations in cost and performance. It is important for designers and users of measurement systems to develop confidence in their use, to know their important characteristics and limitations, and to be able to select the best elements for the measurement task at hand. In addition to being an integral part of most mechatronic systems, a measurement system is often used as a stand-alone device to acquire data in a laboratory or field environment.

EXAMPLE 1.2

Measurement System—Digital Thermometer

The following figure shows an example of a measurement system. The thermocouple is a transducer that converts temperature to a small voltage; the amplifier increases the magnitude of the voltage; the A/D (analog-to-digital) converter is a device that changes the analog signal to a coded digital signal; and the LEDs (light-emitting diodes) display the value of the temperature.



Supplemental information important to measurement systems and analysis is provided in Appendix A. Included are sections on systems of units, numerical precision, and statistics. You should review this material on an as-needed basis.

1.3 THREADED DESIGN EXAMPLES

Throughout the book, there are Examples, which show basic analysis calculations, and Design Examples, which show how to select and synthesize components and subsystems. There are also three more complex Threaded Design Examples, which build upon new topics as they are covered, culminating in complete mechatronic systems by the end. These designs involve systems for controlling the position and speed of different types of motors in various ways. Threaded Design Examples A.1, B.1, and C.1 introduce each thread. All three designs incorporate components important in mechatronic systems: microcontrollers, input devices, output devices, sensors, actuators, and support electronics and software. Please read through the

Internet Link

1.6 Threaded design example components

1.7 Digikey electronics supplier

1.8 Jameco electronics supplier

following information and watch the introductory videos. It will also be helpful to watch the videos again when follow-on pieces are presented so that you can see how everything fits in the "big picture." The list of Threaded Design Example citations at the beginning of the book, with the page numbers, can be useful for looking ahead or reflecting back as new portions are presented.

All of the components used to build the systems in all three threaded designs are listed at Internet Link 1.6, along with descriptions and price information. Most of the parts were purchased through Digikey Corporation (see Internet Link 1.7) and Jameco Electronics Corporation (see Internet Link 1.8), two of the better online suppliers of electronic parts. By entering part numbers from Internet Link 1.6 at the supplier websites, you can access technical datasheets for each product.

THREADED DESIGN EXAMPLE

A.1 *DC motor power-op-amp speed controller—Introduction*

This design example deals with controlling the rotational speed of a direct current (DC) permanent magnet motor. Figure 1.4 illustrates the major components and interconnections in the system. The light-emitting diode (LED) provides a visual cue to the user that the microcontroller is running properly. The speed input device is a potentiometer (or pot), which is a variable resistor. The resistance changes as the user turns the knob on top of the pot. The pot can be wired to produce a voltage input. The voltage signal is applied to a microcontroller (basically a small computer on a single integrated circuit) to control a DC motor to rotate at a speed proportional to the voltage. Voltage signals are "analog" but microcontrollers are "digital," so we need analog-to-digital (A/D) and digital-to-analog (D/A) converters in the system to allow us to communicate between the analog and digital components. Finally, because a motor can require significant current, we need a power amplifier to boost the voltage and source the necessary current. Video Demo 1.6 shows a demonstration of the complete working system shown in Figure 1.5.

With all three Threaded Design Examples (A, B, and C), as you progress sequentially through the chapters in the book you will gain fuller understanding of the components in the design.

Video Demo

1.6 DC motor power-op-amp speed controller

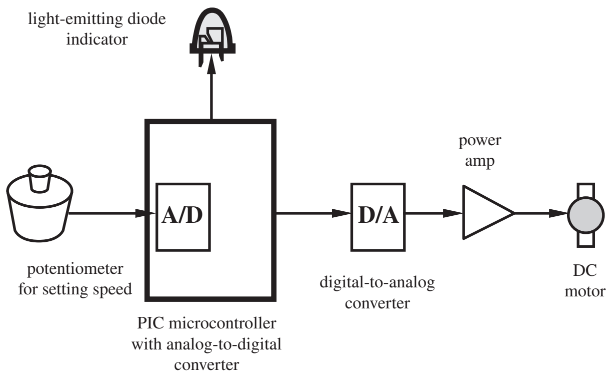


Figure 1.4 Functional diagram of the DC motor speed controller.

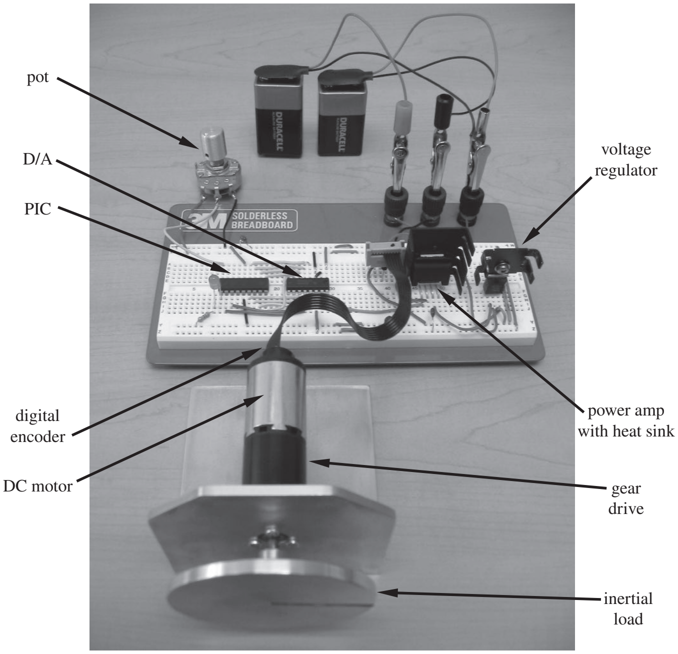


Figure 1.5 Photograph of the power-amp speed controller.
©David Alciatore

Note that the PIC microcontroller (with the A/D) and the external D/A converter are not actually required in this design, in its current form. The potentiometer voltage output could be attached directly to the power amp instead, producing the same functionality. The reason for including the PIC (with A/D) and the D/A components is to show how these components can be interfaced within an analog system (this is useful to know in many applications). In addition, the design serves as a platform for further development, where the PIC can be used to implement feedback control and a user interface, in a more complex design. An example where you might need the microcontroller in the loop is in robotics or numerically controlled mills and lathes, where motors are often required to follow fairly complex motion profiles in response to inputs from sensors and user programming, or from manual inputs.

THREADED DESIGN EXAMPLE

Stepper motor position and speed controller—Introduction B.1

This design example deals with controlling the position and speed of a stepper motor, which can be commanded to move in discrete angular increments. Stepper motors are useful in position indexing applications, where you might need to move parts or tools to and from various fixed positions (e.g., in an automated assembly or manufacturing line). Stepper motors are also useful in accurate speed control applications (e.g., controlling the spindle speed of a magnetic hard-drive or optical DVD player), where the motor speed is directly proportional to the step rate.

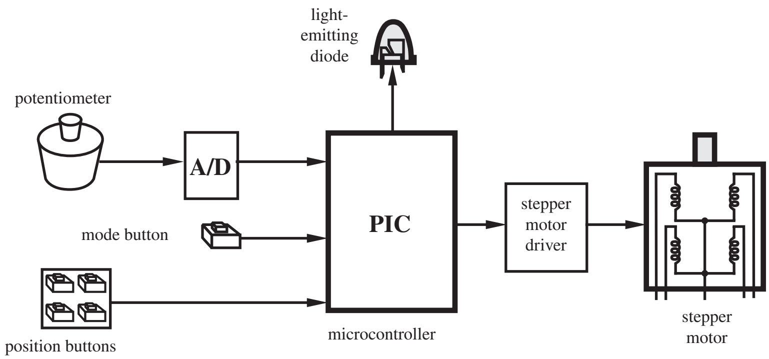
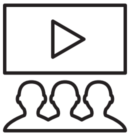


Figure 1.6 Functional diagram of the stepper motor position and speed controller.



Video Demo

1.7 Stepper motor position and speed controller

Figure 1.6 shows the major components and interconnections in the system. The input devices include a pot to control the speed manually, four buttons to select predefined positions, and a mode button to toggle between speed and position control. In position control mode, each of the four position buttons indexes the motor to specific angular positions relative to the starting point (0°, 45°, 90°, 180°). In speed control mode, turning the pot clockwise (or counterclockwise) increases (or decreases) the speed. The LED provides a visual cue to the user to indicate that the PIC is cycling properly. As with Threaded Design Example A, an A/D converter is used to convert the pot's voltage to a digital value. A microcontroller uses that value to generate signals for a stepper motor driver circuit to make the motor rotate.

Video Demo 1.7 shows a demonstration of the complete working system shown in Figure 1.7. As you progress through the book, you will learn about the different elements in this design.

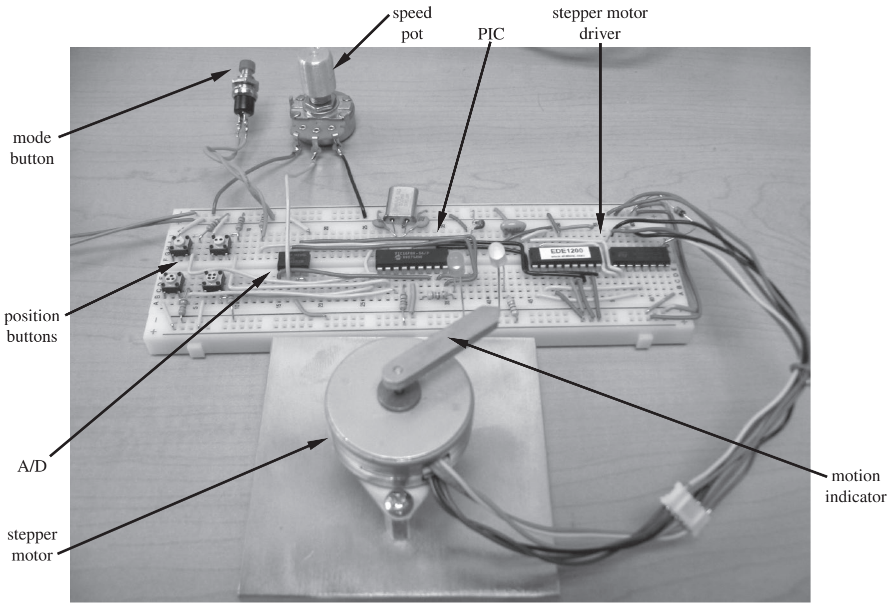


Figure 1.7 Photograph of the stepper motor position and speed controller.
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THREADED DESIGN EXAMPLE

DC motor position and speed controller—Introduction **C.1**

This design example illustrates control of position and speed of a permanent magnet DC motor. Figure 1.8 shows the major components and interconnections in the system. A numerical keypad enables user input, and a liquid crystal display (LCD) is used to display messages and a menu-driven user interface. The motor is driven by an H-bridge, which allows the voltage applied to the motor (and therefore, the direction of rotation) to be reversed. The H-bridge also allows the speed of the motor to be easily controlled by pulse-width modulation (PWM), where the power to the motor is quickly switched on and off at different duty cycles to change the average effective voltage applied.

A digital encoder attached to the motor shaft provides a position feedback signal. This signal is used to adjust the voltage signal to the motor to control its position or speed. This is called a servomotor system because we use feedback from a sensor to control the motor. Servomotors are very important in automation, robotics, consumer electronic devices, flow-control valves, and office equipment, where mechanisms or parts need to be accurately positioned or moved at certain speeds. Servomotors are different from stepper motors (see Threaded Design Example B.1) in that they move smoothly instead of in small incremental steps.

Two PIC microcontrollers are used in this design because there is a limited number of input/output pins available on a single chip. The main (master) PIC gets input from the user, drives the LCD, and sends the PWM signal to the motor. The secondary (slave) PIC monitors the digital encoder and transmits the position signal back to the master PIC upon command via a serial interface.

Video Demo 1.8 shows a demonstration of the complete working system shown in Figure 1.9. You will learn about each element of the design as you proceed sequentially through the book.

Video Demo

1.8 DC motor position and speed controller

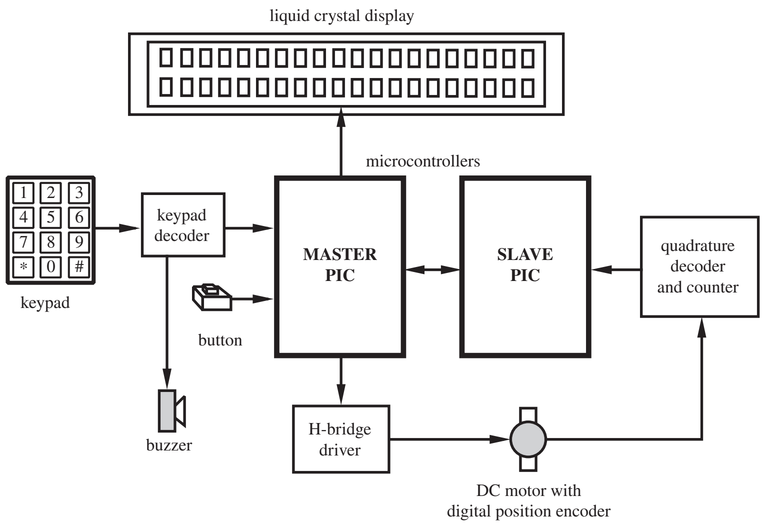

Figure 1.8 Functional diagram for the DC motor position and speed controller.