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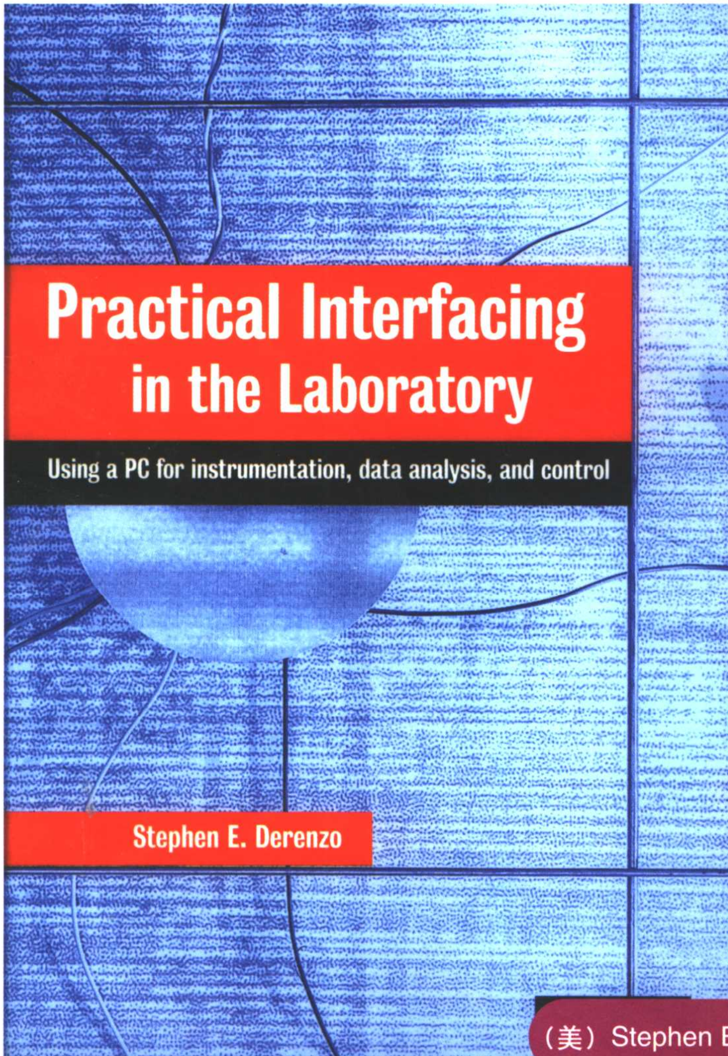

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Practical Interfacing in the Laboratory

Using a PC for Instrumentation, Data Analysis, and Control

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Stephen E. Derenzo : Practical Interfacing in the Laboratory : Using a PC for Instrumentation, Data Analysis, and Control (ISBN:0-521-81527-4).

Originally published by Cambridge University Press in 2003.

This reprint edition is published with the permission of the Syndicate of the Press of the University of Cambridge, Cambridge, England.

本书版权登记号：图字：01-2003-7040

图书在版编目（CIP）数据

微机接口技术实验教程（英文版）/（美）德兰佐（Derenzo, S. E.）著；-北京：机械工业出版社，2004.1

（经典原版书库）

书名原文：Practical Interfacing in the Laboratory : Using a PC for Instrumentation, Data Analysis, and Control

ISBN 7-111-13129-0

I. 微 … II. 德… III. 微型计算机-接口-实验-教材-英文 IV. TP364.7-33

中国版本图书馆CIP 数据核字（2003）第087876号

机械工业出版社（北京市西城区百万庄大街22号 邮政编码 100037）

责任编辑：迟振春

北京昌平奔腾印刷厂印刷 · 新华书店北京发行所发行

2004年1月第1版第1次印刷

787mm × 1092mm 1/16 · 39.25印张

印数：0 001-3 000册

定价：59.00元

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Dedicated to:

My mother, Alice, and my father, Stanley
for their lifelong support and encouragement

My brother, David
for our good times together

My wife, Carol
for being my partner, wife, friend, and adviser

My children, Jennifer and Julia
for reminding me of the joy of youth

My students and teaching associates
who, over the years, helped improve the laboratory exercises and pointed out my errors

Preface

This text describes in practical terms how to use the microcomputer to sense real-world quantities such as temperature, force, sound, light, etc., to analyze the data rapidly, to display the results, or to use the results to perform a control function. It was written for practicing engineers and scientists, and as a textbook for laboratory courses in electronic transducers and microcomputer interfacing.

Our approach takes full advantage of the availability of relatively low-cost microcomputers that are powerful enough to support high-speed parallel input/output (I/O) ports, data-acquisition circuit boards, graphical operating systems, high-level programming languages, and fast double-precision calculations. This book shows in practical terms the range of problems in data acquisition, analysis, display, and control that can be tackled in a cost-effective manner without delving into the bus protocol or native language of a particular microprocessor.

The book contains five chapters, covering digital tools, analog tools, conversion between analog and digital signals, sensors and actuators, and data analysis and control. The 27 laboratory exercises can be used either in a college-level laboratory course or as working examples for practicing engineers and scientists who wish to apply sensor, low-level amplification, and microcomputer principles in their work in a practical and immediate way.

This material was developed for two one-semester laboratory courses in the Electrical Engineering and Computer Science Department at the University of California in Berkeley, EECS 145L: "Electronic Transducer Laboratory" and EECS 145M: "Microcomputer Interfacing Laboratory." The purpose of these two courses is to provide upper-level undergraduate students with the tools needed to sense and control "real-world" quantities, such as temperature and force, as well as to display the results of "real-time" analyses, such as least-squares fitting, the Student's *t* test, fast Fourier transforms, digital filtering, etc. **It is assumed that the students have had some exposure to elementary analog and digital electronics, differential calculus and linear algebra, and the C programming language.**

Over the years, we have used several different microcomputer systems in the laboratory, and the laboratory exercises were designed to be as machine-independent as possible. Special instructions (such as Appendices E and F) were provided for the particular counter/timer, parallel I/O port, and data-acquisition board that were used. A recent advance is software support in the form of C-callable drivers that make it relatively easy to perform single-word and block-data acquisitions and transfers in the Windows NT environment.

The C programming language was chosen because it is available for almost all microcomputers and is well-suited to data acquisition, analysis, and control. It provides word and byte I/O, bit manipulation, powerful conditional branching and data structures, a wide choice of accuracy and bit length for integer and floating point numbers, and high-speed execution.

Chapter 1, "Digital tools," briefly describes the overall organization of the microcomputer, binary and 2's complement number systems, and the digital components needed to perform data acquisition and control, such as digital timers, latches, registers, tri-state buffers, and parallel I/O ports. It goes on to describe the digital and control aspects of several data-acquisition procedures, and discusses the level of handshaking needed for various applications.

Laboratory Exercise 1 introduces the Windows NT operating system, the C compiler/editor, and the many ways that binary bit patterns can be interpreted as numerical quantities. Laboratory Exercise 2 provides examples using the microprocessor timer to measure human reaction times, and Laboratory Exercise 3 introduces the parallel I/O ports, reading switches, and controlling lights.

Chapter 2, "Analog tools," covers commonly used op-amp circuits, the instrumentation amplifier used for low-level differential amplification of sensor signals, noise sources, and the analog signal processing that can be used to enhance the signal-to-noise ratio. It goes on to describe a class B power amplifier that can be used to drive actuators.

Laboratory Exercises 4 and 5 explore op-amp circuits, instrumentation amplifiers, differential amplification, and noise sources, including electromagnetic interference. Laboratory Exercise 6 explores analog signal processing using the op amp, including active high-pass, low-pass, and notch filters.

Chapter 3, "Analog ↔ digital conversion," covers the data-conversion components needed to perform data acquisition and control, such as digital-to-analog (D/A) and analog-to-digital (A/D) converters, the sample-and-hold amplifier, and the comparator. It describes the commonly used methods for data sampling and introduces the notion of frequency aliasing resulting from inadequate sampling. (Considerations of aliasing in the Fourier domain are deferred to Chapter 5.) Chapter 3 lists and describes several commercially available circuit boards.

Laboratory Exercise 7 uses a commercial analog I/O board to provide an overview of both digital-to-analog and analog-to-digital conversion for those students who will not be doing Laboratory Exercises 8 and 9. The conversion between analog and digital is explored in Laboratory Exercises 8 and 9, using D/A and A/D integrated circuit chips. Laboratory Exercise 8 involves interfacing a D/A converter to a parallel input port and waveform generation. Laboratory Exercise 9 involves interfacing an A/D converter to a parallel output port, using a hardware "strobe" and "ready for data" and "data available" handshaking protocol. Laboratory Exercise 10 uses a commercial data-acquisition board for the periodic sampling of waveforms and demonstrates the concept of frequency aliasing in the time domain.

Chapter 4, "Sensors and actuators," covers the sensors (the first element in many data-acquisition systems), the real-world quantities that they sense, the nature of the signals (and the noise) that they produce, and actuators (essential in any control system).

Laboratory Exercises 11–14 explore the basic electronic transducers used to measure position, temperature, strain, force, and light. The thermoelectric heat pump is explored in Laboratory Exercise 15. Laboratory Exercise 16 investigates the ac and dc electrical properties of bare metal and Ag(AgCl) electrodes. Laboratory Exercises 17–19 explore physiological signals from the heart, skeletal muscles, and eyes.

Chapter 5, "Data analysis and control," covers data analysis, including statistical analysis; Student's *t* test; least-squares and Chi-squared fitting; continuous, discrete, and fast Fourier transforms, and some algorithms used for the control of real-world quantities.

Laboratory Exercise 20 explores analog-to-digital conversion for the storage of analog signals, digital-to-analog conversion for the analog recovery of those signals, and least-squares fitting for determining the accuracy of signal recovery. Laboratory Exercise 21 involves the sampling of sine, square, and triangle waves and the computation of their fast Fourier transforms (FFT). These techniques are applied in Laboratory Exercise 22 to the sampling and FFT of the human voice. Laboratory Exercise 23 compares analog to real-time digital filtering and Laboratory Exercise 24 demonstrates how the microcomputer can measure the impulse response of a linear, time-invariant system and use FFT techniques to determine the digital filter that can compensate for signal distortion caused by the system, provided that the frequency response of the system meets certain requirements. Laboratory Exercise 25 provides experience with analog temperature sensing and control. Laboratory Exercise 26 provides experience with computer-based digital temperature sensing and control using an electrical resistance oven and several algorithms. Laboratory Exercise 27 is similar to Laboratory Exercise 26, except that a thermoelectric heat pump is used with both the ability to heat and cool actively. An essential component is the LM12 power op amp.

In several laboratory exercises, a number of related circuits are built and examined. The *equipment* lists at the beginning of these exercises include all the parts needed for the students to build all the circuits before coming to the laboratory. As laboratory time is usually very limited, this approach works better than providing only the minimum number of parts needed and having the students dismantle one circuit during the laboratory period before they can build the next.

Each chapter is provided with problems derived from those used in midterm and final examinations.

Defined terms appear in the index followed by the word (definition) and the page number where they are first used. On that page, the term appears in bold face in the text that defines it.

Appendix A provides some physical and electronic units and constants for the problems at the end of the chapters, and Appendix B discusses issues of error propagation, and electrical shielding and grounds. Appendix C summarizes some hints useful in C programming. Appendix D provides C code listings and flow charts of some numerical methods, including the fast Fourier transform, nonlinear function minimization (used to fit curves to data), numerical integration using adaptive quadrature, and function inversion using both Newton's method and quadratic approximation. A program to compute the probability of exceeding Student's t is given as an example.

Appendix E describes the hardware and software needed to use the Data Translation DT3010 PCI plug-in board, and Appendix F describes how to use HP VEE to record waveforms on a digital oscilloscope. Appendix G discusses some potential electrical hazards and methods used to prevent them. Appendix H lists standard resistor and capacitor values and provides resistor color codes. Appendix I lists the ASCII character codes. Last is a glossary defining the technical terms used in the book.

Guide for the instructor

Although the entire book would serve for a full-year course, it is also possible to cover portions of the material in separate one-semester courses, as we do at Berkeley.

A one-semester course on ***digital interfacing, data analysis, and control*** would include Chapters 1, 3, and 5, and Laboratory Exercises 1–3, 8–10, 20–24, and 26 or 27.

A one-semester course on ***sensors, low-level amplification, and analog signal processing*** would include Chapters 2 and 4, and Laboratory Exercises 4–6 and 11–19. Portions of Chapter 5 and Laboratory Exercise 25 would provide an introduction to analog control.

A one-semester course on ***bioengineering*** would include Chapters 2, 4, and 5, and selections from Laboratory Exercises 2, 4–7, 11–19, and 20–22, depending on course emphasis.

A solutions set is available for this book – contact solutions@cambridge.org for details.

Acknowledgments

I am indebted to Kenneth Krieg, who was the cofounder of EECS 145M "Microcomputer Interfacing Laboratory" and, as teaching associate over a period of several years, made important contributions to most of the laboratory exercises. I also thank the numerous teaching assistants and students who contributed to the improvement of the laboratory exercises.

Special thanks to Professor Ted Lewis for contributions to Chapter 4, derived from his course EECS 145A, "Sensors, actuators, and electrodes," and to Dr Thomas Budinger for contributions to Chapter 5, derived from his course EECS 145B, "Computer applications in biology and medicine." Some of the laboratory exercises were derived from EECS 182, "Biological signals and transducers," developed by Professors Ted Lewis and Ed Keller at Berkeley during the 1970s, and to them I am grateful. I also thank John Cahoon, Matt Ho, and William Moses for discussions of circuit design, Ronald Huesman and Gerald Lynch for discussions of statistical analysis and fitting, and to Orin Dahl for discussions of pseudo-random number generators.

Contents

1 Digital tools

1.1 Introduction

In the past few years, enormous advances have been made in the cost, power, and ease of use of microcomputers and associated analog and digital circuits. It is now possible, with a relatively small expenditure, to purchase a microcomputer system that will take data, quickly analyze them, and display the results or control a process. This has been made possible by the development of technology that can fabricate millions of transistors, diodes, resistors, capacitors, and conductors on a single silicon **integrated circuit chip**.

Normally, the microcomputer is equipped with a number of standard items: the microprocessor chip and associated circuits, random-access memory chips, removable floppy and cartridge disk drives, magnetic hard disk drives, optical disk drives, keyboards, video display screens, serial interfaces, printers, and x–y entry devices such as the mouse, trackball, joystick, bitpad, and touch-sensitive display screen. However, data acquisition and control require additional components, such as digital and analog input/output (I/O) ports, and counters/timers. Analog input ports contain analog multiplexers, sample-and-hold (S/H) amplifiers, and analog-to-digital (A/D) converters. Analog output ports contain digital-to-analog (D/A) converters.

Even for designs requiring only a microprocessor and a few additional circuits, there are considerable advantages to using the resources of the microcomputer during the development stage. These include program code editors and compilers, an operating system for the storage and manipulation of code and data files, and ample random-access memory.

In this chapter, we discuss digital interfacing concepts used in microcomputer-based data-acquisition and control systems (Figure 1.1), including parallel and serial input/output ports, handshaking, and digital counters/timers. Analog tools (amplification and filtering) are treated in Chapter 2, digital-to-analog and analog-to-digital conversion and sampling in Chapter 3, and sensors and actuators in Chapter 4.

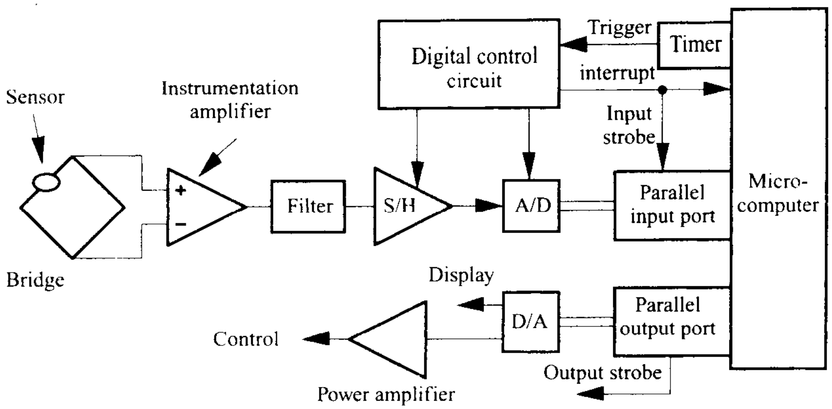

Figure 1.1 A microcomputer system interfaced to sensors and associated analog circuits for data acquisition, analysis, and control.

1.2 The microcomputer

In selecting a system for data acquisition and control, the **microcomputer** itself is a crucial component (Figure 1.2). The microcomputer is sufficiently small to fit on a laboratory bench (or desktop) and yet contains the following components:

1. The **microprocessor** is an integrated circuit that reads program instructions from memory and uses them to determine the sequence of actions that it performs. It is connected to memory and peripheral circuits by an address bus, a data bus, and control lines.

   These actions include reading data and instructions from memory, performing calculations, executing different instructions depending on the outcome of a calculation, printing data, and transferring data to and from peripheral devices such as hard disks. Microprocessors vary greatly in their speed and data-handling capability.
2. **Random-access memory (RAM)** usually consists of high-speed semiconductor memory chips that are used to store and retrieve program instructions and data. The highest data-acquisition speeds are achieved when external data are read directly into RAM, so the size of the RAM places a limit on the number of data values that can be sampled rapidly.
3. Common user interface devices are the keyboard, video display screen, printer, mouse, joystick, and trackball. Some systems provide voice input and synthesized speech output. The IEEE-1284 interface standard includes the standard parallel printer (SPP) port as well as other enhancements. The universal serial bus (USB) is the current standard for keyboards and pointing devices. For higher

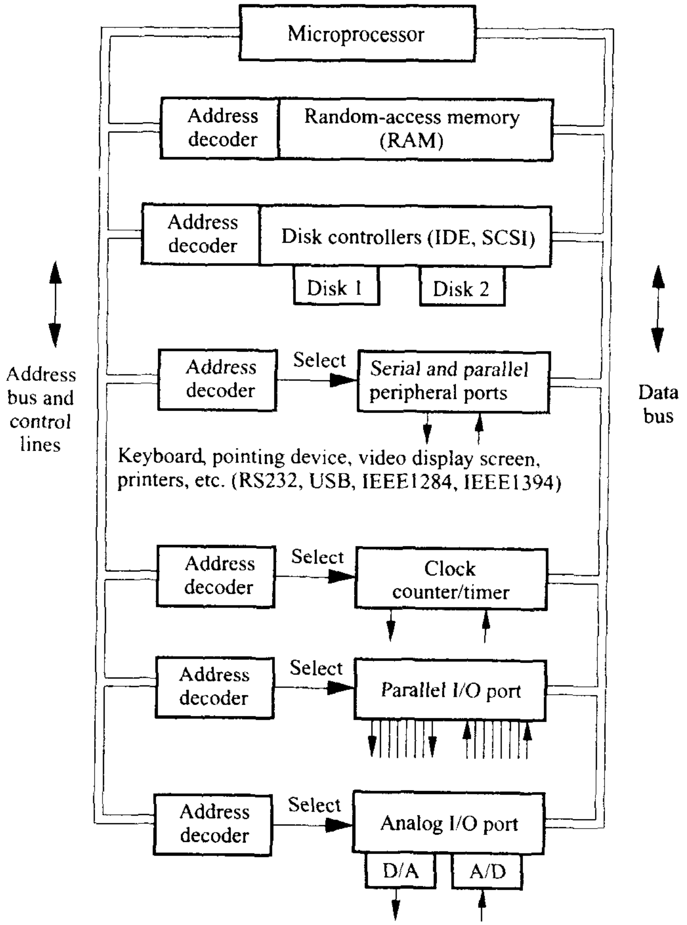

Figure 1.2 The microcomputer consists of a microprocessor that communicates with memory and input/output devices by address and data buses.

speed transfers (external hard drives, digital camcorders, HDTV), the IEEE-1394 standard (FireWire or i.Link) has recently been introduced.

4. **Magnetic disk memory** is used for the long-term storage of programs and data, and consists of one or more flat circular plates coated with a magnetic surface. Magnetic disk capacities range from 500 kbytes to 2 Mbytes for small removable floppy disks and from 1 to 20 Gbytes or more for hard disks. Access time consists of a fixed delay of tens of milliseconds (for the read/write head to locate the desired track) and a transfer time of typically 1 μs per 16-bit word.
5. **Optical disk memory** includes the CD-ROM and the DVD-ROM disks. The **CD-ROM** (compact disk-read-only memory) and DVD-ROM (digital versatile disk) drives use optical storage and retrieval technology that was developed for the music and entertainment industry. The capacity of the CD-ROM is over 600 Mbytes and about ten times larger for the DVD-ROM. Both are 12 cm in