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Practical Interfacing in the Laboratory

Using a PC for Instrumentation, Data Analysis, and Control

This text describes in practical terms how to use a desk-top computer to monitor and control laboratory experiments. The author clearly explains how to design electronic circuits and write computer programs to sense, analyze, and display real-world quantities, including displacement, temperature, force, sound, light, and biomedical potentials. The book includes numerous laboratory exercises and appendices that provide practical information on microcomputer architecture and interfacing, including complete circuit diagrams and component lists. Topics include analog amplification and signal processing, digital-to-analog and analog-to-digital conversion, electronic sensors and actuators, digital and analog interfacing circuits, programming, and data analysis and control. Only a very basic knowledge of electronics is assumed, making it ideal for college-level laboratory courses and for practicing engineers and scientists.

Stephen E. Derenzo is Professor-in-Residence in the Department of Electrical Engineering and Computer Sciences at UC Berkeley and a Senior Scientist at the Lawrence Berkeley National Laboratory. He has been teaching courses on electronic circuits, electronic transducers, and microcomputer interfacing for over 15 years and this book was developed from those courses. He has authored and co-authored over 150 technical publications, was awarded the 1992 Annual Merit Award and the 2001 Radiation Instrumentation Outstanding Achievement Award of the Nuclear and Plasma Sciences Society of the IEEE, and is a Fellow of the IEEE.

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Stephen E. Derenzo
University of California, Berkeley, California

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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

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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

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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 $\leftrightarrow$ 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

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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.

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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.

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