MICROCOMPUTER-BASED DESIGN

JOHN B. PEATMAN

MICROCOMPUTER-BASED DESIGN

JOHN B. PEATMAN
Professor of Electrical Engineering
The Georgia Institute of Technology

McGRAW-HILL BOOK COMPANY

New York St. Louis San Francisco Auckland Bogotá Düsseldorf
Johannesburg London Madrid Mexico Montreal New Delhi Panama Paris
São Paulo Singapore Sydney Tokyo Toronto

MICROCOMPUTER-BASED DESIGN

1234567890 KPKP 783210987

This book was set in Melior by Progressive Typographers.
The editors were Peter D. Nalle and Matthew Cahill;
the copy editor was Susan Sexton;
the proofreader was Mary Ann Rosenberg;
the designer was Anne Canevari Green;
the production supervisor was Charles Hess.
The drawings were done by J & R Services, Inc.
Kingsport Press, Inc., was printer and binder.

Library of Congress Cataloging in Publication Data

Peatman, John B
Microcomputer-based design.

Includes bibliographical references.
1. Miniature computers. I. Title.
TK7888.3.P37 001.6'4'04 76-29345
ISBN 0-07-049138-0

PREFACE

This book is directed toward the engineer interested in obtaining an integrated understanding of the design of "smart" microcomputer-based instruments and devices. It opens the door to the many applications of microcomputers. It differs from many books in that it develops fundamental design capability while keeping this breadth of application in mind.

An effective digital designer requires at least three distinct capabilities. First, the designer must have a fundamental understanding of available components. This begins with the microprocessor chips, memory chips, and I/O chips which make up a microcomputer. It extends to the keyboards and switches for setting up an instrument or device, transducers for sensing inputs, actuators for control, devices for communicating with computers and other instruments, devices providing extensive storage capability, and printers and displays for informing the user of results. Furthermore, for a designer to be effective, this understanding must extend beyond the framework of only simplified and idealized devices. For example, since the proper use of a printer requires careful observance of timing considerations, the designer is aided by having systematic ways to design with microcomputers so as to maintain control over these timing considerations.

Second, the designer must thoroughly understand the algorithmic processes required by each aspect of the design and be able to translate these into the language of the microcomputer. For example, an instrument which automatically carries out several measurements and then must fit the resulting data with a sinusoid requires the designer to develop a Fourier analysis algorithm and then be able to implement it as a sequence of microcomputer instructions.

Third, the designer must understand how the extensive requirements of an instrument or device can be broken down into manageable parts. The hardware must be selected and configured. Where tradeoffs occur between hardware and software, these will usually be resolved so as to minimize hardware. The software requirements of each aspect of the design must then be met, be they the reading and interpreting of a keyboard, the development of a data-averaging algorithm, or the control of a stepper motor. Finally, the software parts must be put together into a coordinated whole so that the overall goals of the instrument are met.

This book attempts to organize and unify the development of these three capabilities: to understand and use components, to exploit powerful algorithmic processes, and to realize an effective organization of hardware and software so as to meet the specifications for an instrument or device.

From another point of view, this book is directed toward a specific goal of engineering studies—the development of creative design capability. With the development of microcomputers, design capability has centered upon the understanding and use of a limited number of complex but well-defined microcomputer chips. The various requirements of an instrument or device have largely become translated into software. Thus, the development of creative design capability has largely been translated into the domain of microcomputer instructions and is measured by the simplicity and clarity of algorithms. This evolution of digital technology provides a beautiful opportunity to develop design capability under rather ideal conditions: the specifications for each aspect of a design can be made both real and unambiguous; only a few microcomputer chips need be understood to meet the hardware needs of these design goals; and the amount of read-only memory required to hold the microcomputer instructions used by the student to carry out each aspect of a design provides a specific, real, cost criterion for measuring the quality of a design. To take advantage of this opportunity, most chapters close with a broad variety of problems having a design flavor.

This book will typically be used in a one-semester or two-quarter course in introductory microcomputer-based design at the senior level. It may be used at the junior level if it is deemed worthwhile to trade off the increased engineering experience of seniors for the opportunity to follow this course with other design-oriented courses. Because the design process is so dependent upon the characteristics and use of the specific microcomputer selected for its implementation, this book is dependent upon a parallel study of the characteristics of at least one specific microcomputer. To support such a study, appendixes are included on each of six microcomputers. Furthermore, any one of the appendixes can be used as a guide for culling through the manufacturer's information on some other microcomputer so as to pick out the data most immediately important for design purposes.

Although the content of the book is electrical, each component is sufficiently explained to permit the book to be used in a variety of curricula as an introduction to microcomputer-based design. The incentive to so use the book lies in the diverse applications of microcomputers, many of which are described in the first chapter.

An attempt has been made to make many of the parts of the book self-contained. Consequently, one way in which the book might be used is to study the "bare bones" of each chapter in order to obtain an accelerated route toward the overall instrument or device design picture. The remaining sections of each chapter can be studied at a later time as the need arises or in a subsequent course. Such an accelerated route through the study of *microcomputer software* might begin with Sections 2-1 to 2-9, perhaps using examples from Sections 7-6 and 7-7. At the same time, the register and data manipulation viewpoint of a specific microcomputer might be studied, using one of the appendixes. This might include the conventions inherent in the assembly language for the microcomputer, as presented in the manufacturer's assembly language user's manual. An accelerated study of *microcomputer hardware* might begin with Sections 3-1, 3-4, 3-6, 3-7, 3-9, 4-1, 4-2, 5-1, and 5-2. With this as a basis, the interactions between hardware and software are best exemplified by a study of the specific I/O devices of Sections 5-4 to 5-8. Chapter 6 then provides an overview of a variety of alternatives for actually carrying out the hardware and software development of an instrument.

It has been my good fortune to become involved with instrument design and the use of microcomputers through my work with some of the outstanding engineers of Hewlett-Packard Company, particularly with Ed Donn during two summers in Colorado Springs and David Dack during a year in Scotland. I am deeply indebted to my students at Georgia Tech who, through their design problem work, have also been my teachers.

My learnings and my activities have been fostered by several able administrators. Dr. Demetrius Paris has been instrumental in his support of my microcomputer-based design course and laboratory at Georgia Tech, while Dar Howard, Chuck House, and Bob Coackley have each in their own way opened new vistas for me within Hewlett-Packard. Finally, I am grateful to my wife, Marilyn, for sharing herself and her own career with her devotion to me and my career, and for typing the manuscript.

John B. Peatman

CONTENTS

1

THE ROLE OF THE MICROCOMPUTER

1-1 MERITS OF MICROCOMPUTER-BASED DESIGN

The creation of the microcomputer is revolutionizing instrument* design. Not only are traditional instruments becoming "smart," but entirely new kinds of instruments are appearing. With their extensive computing capability contained in a very few small integrated circuits, microcomputers have invaded the minds of design engineers, as in Fig. 1-1. In this section, we will consider ways in which this computing capability is enhancing instrument capability.

Simplified data entry is exemplified by the marked-sense card reader built into the point-of-sale terminal shown in Fig. 1-2. Each row of the card lists one of the items sold. Each column lists a quantity (1 to 9). Thus, to total an order requires only the filling in of appropriate marks for the quantity of each item purchased. The card reader senses these pencil marks and computes the total cost. In this way, pricing is handled automatically.

Sophisticated transduction permits a sales clerk to enter product-

* We will use the term *instrument* in a general sense. We will mean a self-contained, standalone device, not a rack full of equipment.

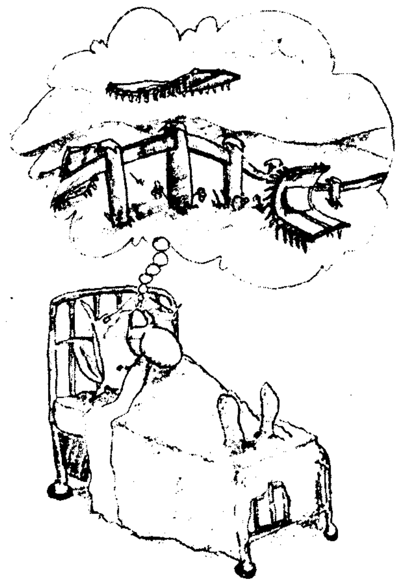


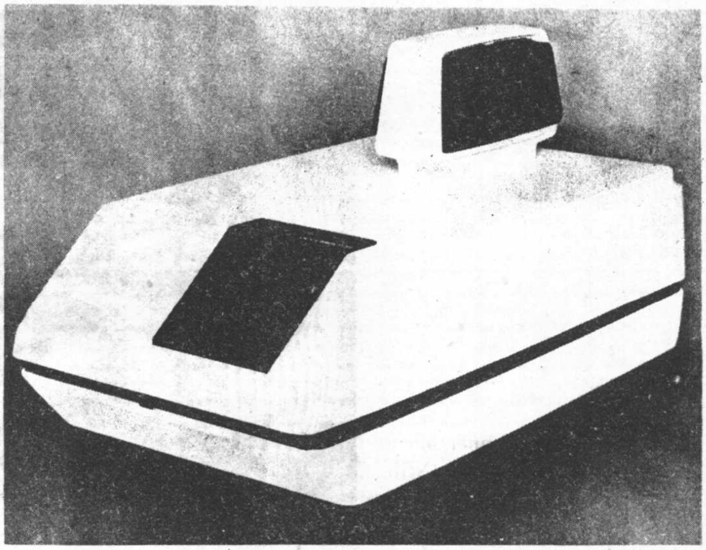
Figure 1-1. . . . . , 6797, 6798, 6799, . . . (Rand Renfroe.)

description information for each item sold into a point-of-sale terminal using the laser scanner shown in Fig. 1-3. As the laser beam scans the light and dark bands making up the Universal Product Code (UPC) symbol* on the item, the time durations for the succession of bands are normalized and converted into a UPC number. The terminal then looks this up in a table to convert it to a price for the product.

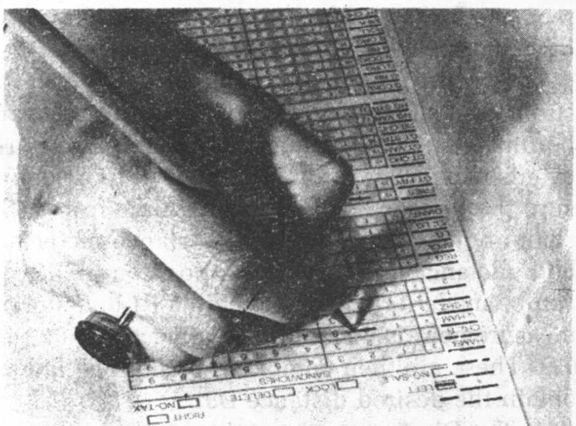
A microcomputer-based measuring instrument may achieve *high accuracy via repetitive measurements plus averaging of the results.* Thus the distance meter shown in Fig. 1-4 determines the distance to a passive reflector with an infrared light beam. It maintains an error of less than 1 in. in measurements up to 1 mile by taking 2000 measurements and comparing the standard deviation of these measurements against a preprogrammed limit. If the standard deviation is acceptable, it computes and displays the average distance. If it is not acceptable, it doubles the total number of measurements and checks the standard deviation against a new limit suitable for this number of measurements in order to meet the accuracy specification of the instrument. The instrument keeps trying for an acceptable standard by repeatedly doubling the number of measurements, up to a maximum of 32,000 (which takes less than 21 s). If an acceptable standard deviation is not attained after 32,000 measurements, an average is computed anyway, but it is *flashed* on the display.

As can be seen from the rear view of this distance meter, the microcom-

* Described in Sec. 5-5.



(a)



(b)

Figure 1-2. Data entry with a marked-sense card reader. (a) Card reader; (b) pencil-marked order card. (Documentor Division, Addressograph Multigraph Corp.)

Figure 1-3. Laser-scanner entry of product information. (NCR Corp.)

puter permits *simplicity of use.* It has only four switches (power off/on/self-test; feet/meters; signal strength for aiming/signal strength for measuring; set up/begin measurement), two knobs (correction for temperature and pressure; adjustment of signal strength), a meter (signal strength), and a display (distance). One of the challenges of "smart" instrument design is forestalling requests for "extra features" and maintaining the vision of a simple-to-use device, as was done for this distance meter.

An instrument can employ a microcomputer to *obtain a desired measurement indirectly by combining the measurements of several different parameters.* For example, a distance-measuring instrument for sporting events like discus throwing would be more convenient to use if it could measure the distance between two points from a third point. By combining a shaft-angle encoder with the distance meter of Fig. 1-4, a measurement of both distance D1 and angular position (relative to an arbitrary reference) $\theta 1$ can be made for one of the points P1 and stored in the instrument. Then a measurement is made for the other point P2, providing new values D2 and $\theta 2$. These are then combined using the "law of cosines," as in Fig. 1-5, to obtain the desired distance D3.

The Dioptron® automatic objective refractor of Fig. 1-6 helps determine the eyeglass prescription for a patient indirectly. As can be seen from the figure, it also provides the ultimate in simplicity of use, with only two push buttons. Pressing one illuminates the patient's eye for accurate alignment. Pressing the other initiates the measurement. The instrument detects blinks and interrupts the measurement for the duration of each blink. At the completion of the measurement, the refraction is printed out.

To understand how the instrument works, consider the simplified optical-system diagram of Fig. 1-7*a*. The image source can be thought of as

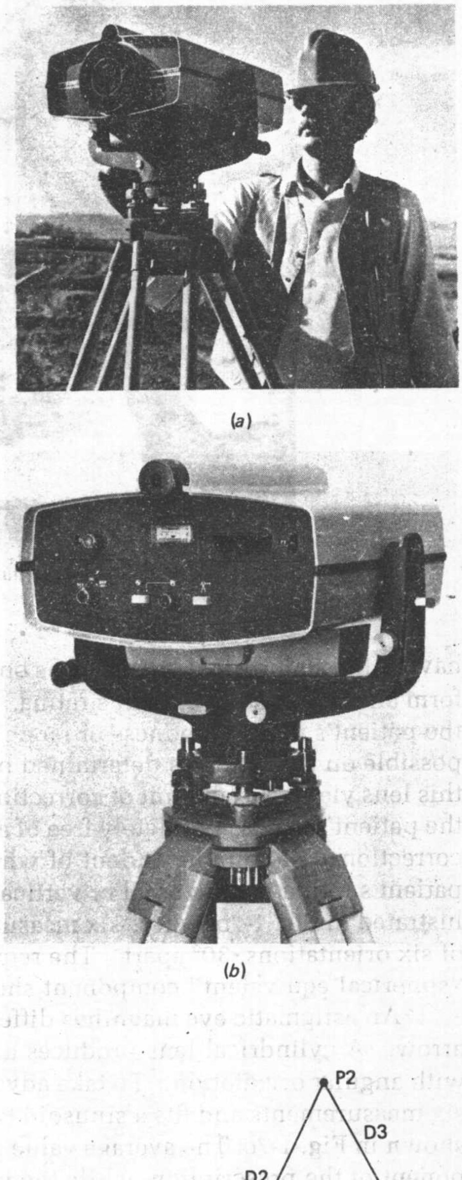
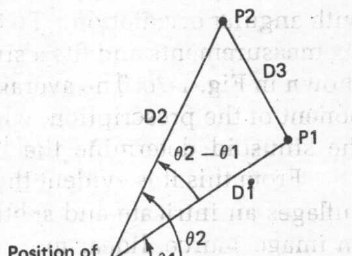


Figure 1-4. Distance meter. (a) Front view; (b) rear view. (Hewlett-Packard Co.)



Law of cosines:
$D3^2 = D2^2 + D1^2 - 2(D2D1)\cos(\theta 2 - \theta 1)$

Figure 1-5. Indirect measurement of distance.

Figure 1-6. Dioptron® automatic objective refractor. (Coherent Radiation.)

having the shape of an arrow. It is bounced off a semitransparent mirror to form an image on the patient's retina. A motor-driven lens compensates for the patient's nearsightedness or farsightedness to form as sharp an image as possible on the retina as determined by the focus detector. The position of this lens yields the amount of correction needed, measured in "diopters." If the patient's eye is completely free of astigmatism, the number of diopters of correction will be independent of whether the arrow-shaped image on the patient's retina is horizontal or vertical or anywhere in between. This is illustrated in Fig. 1-7*b*, where six measurements have been made, one for each of six orientations, 30° apart. The required correction consists solely of the "spherical equivalent" component shown.

An astigmatic eye magnifies differently for different orientations of the arrow. A cylindrical lens produces a correction which varies sinusoidally with angular orientation. To take advantage of this, the instrument takes its six measurements and fits a sinusoid to the resulting points as best it can, as shown in Fig. 1-7*c*. The average value gives the "spherical equivalent" component of the prescription, while the peak-to-peak value and phase angle of the sinusoid determine the "cylinder" and "cylinder axis" components.

From this it is evident that the simplicity of use of this instrument camouflages an intricate and subtle measurement process involving rotation of an image source, linear movement of a lens, and a determination of focus. It also camouflages a calculation of the Fourier components of a waveform represented by six points.

Finally, the instrument carries out the entire measurement process on

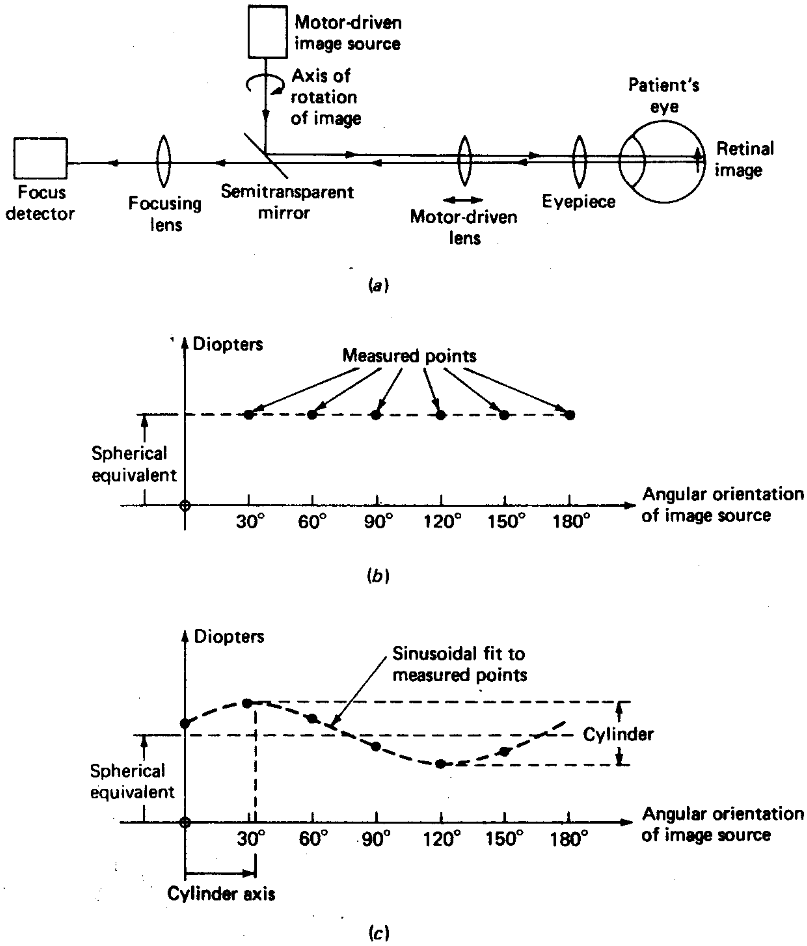


Figure 1-7. Eye refraction. (a) Optical system; (b) measurement of an eye having no astigmatism; (c) measurement of an eye having astigmatism.

each eye with an invisible, infrared image source while the patient views a visible, binocular target appearing to be located at infinity. More than anything else, it is this contrast between "what you see" and "what you get" which characterizes the "smart" instruments made possible by microcomputers.

Automatic calibration is a particularly valuable feature in a measuring instrument. It requires two capabilities:

1 The measuring circuit must be automatically switchable from the input transducer to either of two standard inputs, one which should give a "zero" measurement and one which should give a "full-scale" mea-

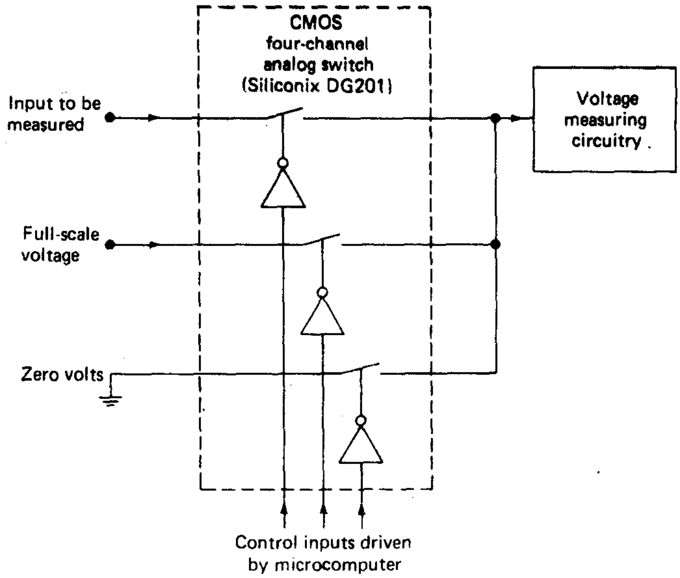


Figure 1-8. Autocalibration switching of a voltage input.

surement. Measurements are made and results stored for these two standard conditions.

2 Subsequent measurements must be normalized to these two stored results. The control required for the first step and the calculating capability required for the second are already built into a microcomputer-based instrument. The input switching for a voltage input can use complementary metal-oxide semiconductor (CMOS) analog switches for fast, reliable, solid-state switching, as in Fig. 1-8.

The grocer's scale shown in Fig. 1-9 furnishes a closely related capability. The grocer first places a container on the scale and presses a "tare" button. The microcomputer will zero the display of weight. Subsequent measurements are then calculated and displayed using this *arbitrary zero reference*.

Sophisticated handling of a device can be more easily achieved in a microcomputer-based instrument than otherwise. The microcomputer-based PROM programmer shown in Fig. 1-10 enters data into a programmable read-only memory (PROM). PROMs are extremely useful for storing the instructions which make up the software of a microcomputer-based instrument. They suffer from rather wide variations in the amount of current, or voltage, required to change the state of a specific bit during programming. As discussed in Sec. 4-1, the PROM programmer pulses the bits to be changed and monitors the results. Then it selects the number of pulses required for the programming of each bit on the basis of how many it actually