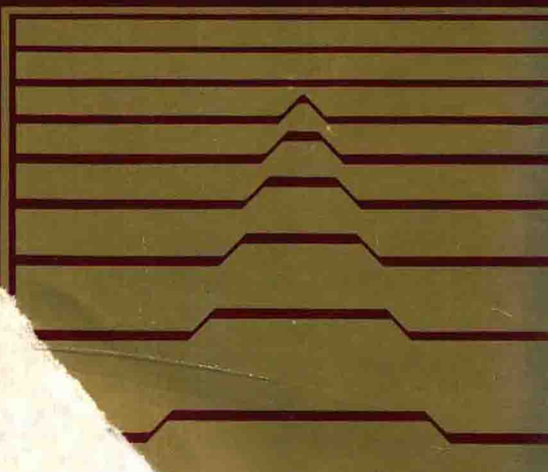
DATA ACQUISITION AND CONTROL

MICROCOMPUTER APPLICATIONS FOR SCIENTISTS AND ENGINEERS



JOSEPH J. C

DATA ACQUISITION AND CONTROL

MICROCOMPUTER APPLICATIONS FOR SCIENTISTS AND ENGINEERS

JOSEPH J. CARR

TAB Professional and Reference Books

Division of TAB BOOKS Inc.
P.O. Box 40, Blue Ridge Summit, PA

FIRST EDITION

FIRST PRINTING

Printed in the United States of America

Library of Congress Cataloging in Publication Data

Carr, Joseph J.
Data acquisition and control : microcomputer applications for scientists and engineers / by Joseph J. Carr.
p. cm.
Includes index.
ISBN 0-8306-2956-4
1. Physical measurements—Data processing. 2. Mensuration—Data processing. 3. Microcomputers. I. Title.
QC39.C36 1988
530.8'5—dc19
88-2205
CIP

Questions regarding the content of this book should be addressed to:

Reader Inquiry Branch
TAB BOOKS Inc.
Blue Ridge Summit, PA 17294-0214

Introduction

DATA-ACQUISITIONS SYSTEMS ARE USED TO electronically monitor or gather data from the external physical environment. These systems differ from regular data processing systems in that the data is typically derived from transducers, sensors, and other devices automatically, or at least semiautomatically. In this same category of equipment is are also included simple control systems, process controllers, and others.

Most of the systems discussed as examples in this book are oriented towards medicine, the life sciences, and biology. This emphasis is because of my own professional involvement with biomedical engineering for many years. The principles, however, are almost universally applicable and so may be extrapolated to your own area of professional involvement rather easily.

There is a collection of computer programs in the Appendix A of this book. For information on diskettes for these programs on IBM-PC or Apple IIe formatted disks, write to:

FTA
Joseph J. Carr
c/o TAB BOOKS, Inc.
Blue Ridge Summit, PA 17294-0214

Contents

Chapter 1

Data-Acquisition Systems: Scope and Approach

DATA-ACQUISITION SYSTEMS ARE DESIGNED TO interface a computer to the correct circuits or equipment in order to collect data from external sources. I limit this activity to those that collect data from external transducers, as opposed to data-processing systems. In data acquisition systems, the input devices will be sensors and transducers of several assorted types, and will measure parameters such as temperature, pressure, displacement, nuclear radiation, biopotentials, and so forth.

In this book I will cover a wide variety of topics. I assume that the reader is not an electronics engineer but is a person who is sophisticated in one or the other sciences or other technical disciplines. Examples of this model reader vary from the plant engineer keeping track of process control parameters, to the life scientist making measurements of bipotentials, to the physicist who savours odd exotica and wants to make a computerized study of it, to the chemist performing a laboratory experiment. You will need to know a certain amount about electronics to use this book, but true professional depth in that discipline is not critical.

Part of the book is devoted to a discussion of typical transducers and other sensors used in collecting analog data. We will take a look at temperature transducers, including the newer forms of integrated circuit pn-junction device. We will also look at pressure/force transducers, light transducers, flow transducers and other kindred types. Two chapters are devoted to biomedical-signals acquisition. Part of this emphasis evolved out of my own professional involvement in biomedical engineering, and also from the fact that a lot of scientists are involved in this type of research.

A section of this book is devoted to some elementary analog electronic circuits. The ubiquitous operational amplifier is covered in detail. It is impossible to be really knowledgeable about data acquisition problems without appealing to operational amplifiers to solve some of them. The staying power of the op amp over the years is due, in large part, to the fact that we can set gain on an operational amplifier with only two resistors. Just a little more knowledge allows you to contrive many devices using operational amplifiers.

There is a chapter on differentiators and integrators. Although modern data-acquisition systems tend to perform some of these functions in software, there is still quite a need for differentiator and integrator circuits in the analog subsystem of your computer. The design of practical circuits of this type is not as straightforward as some textbooks would have you believe, so some effort was made to let you know how to actually get the circuit working using regular, practical, operational-amplifier devices.

Signals-acquisition problems can make any effort a waste of time and money. Problems such as ground loops, noise, and extraneous high-voltage signals can foul up the best-laid plans. Therefore, some effort is needed to help you understand these problems and their usual solutions.

Because data-acquisition systems are built around programmable digital computers, I also cover the basics of interfacing these computers to other devices. Again, the emphasis is on practical circuits. Also covered in the same section of the book is material on analog-to-digital (A/D) converters and digital-to-analog converters (DAC). These devices allow the computer to be interfaced to what is still essentially an analog world. The A/D converts analog voltages or currents to a binary digital word that the computer can digest. Alternatively, the DAC converts binary digital words from the computer to a proportional analog voltage or current.

Finally, in the back of the book is material on certain peripherals that you will encounter in building data-acquisition systems. Topics covered include paper chart recorders, oscilloscopes, printers, and various forms of test equipment.

In the Appendix you will find a collection of BASIC computer programs suitable for data acquisitions use. Although these programs are designed to run on the IBM-PC and its clones, the BASIC language is broadly used, so conversion to other dialects should be an easy task.

Chapter 2

Basics of Instrumentation for Data Acquisition

AN ELECTRONIC INSTRUMENT IS AN APPARATUS consisting of a collection of circuits and mechanical and electromechanical devices that do some particular job of measurement or control. In the present context of data acquisition, both applications are typically found. The instrument might acquire a signal from a transducer of some sort and then process the signal to produce some numerical display or analog waveform at the output. Alternatively, it might take several different inputs, make some computations or comparisons, and then display the result or use them to perform some decision in a control circuit.

TYPES OF INSTRUMENTATION

Instrumentation can be analog, digital, or a synthesis of the two separate types. When high precision is mandatory or when extreme complexity might be required, the design is best left to qualified electronics engineers with experience in that area. The amateur, novice, or student designer can, though, perform chores in instrumentation that were once regarded as too difficult. So if you are the kind of person who enjoys designing and building his own from the electronics projects, there are a lot of sophisticated things you could do.

Two main areas of opportunity present themselves as ripe for such people: the creation of simple to moderately complex instruments, and interfacing two or more existing, commercially produced instruments or systems that were previously not compatible.

You will be surprised at the level of complexity that can be achieved by those whose competency is in other areas of expertise, although probably at the expense of some level of frustration in their earliest attempts. The frustration quotient, though, can be reduced considerably if the person is willing and able to seek advice from the professionals and the companies (too often overlooked!) who make and sell the products you plan to use.

Even where sophistication is modest, there is room for clever application of electronic circuits to save money. A physiologist, for example, might want to use a ×10 preamplifier to acquire cell action potentials. This instrument costs over $300 when purchased from a scientific instrument supplier, but can be duplicated exactly for about $40, and (using other, more modern, parts) duplicated in "form-fit-function" for about $20. Its chief claim to being a physiological amplifier, as opposed to other forms, is the fact that it has a high CMRR (common-made rejection ratio) and an input impedance

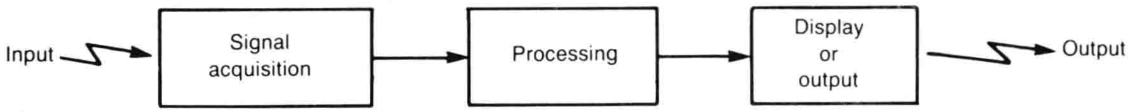


Fig. 2-1. Basics of an instrumentation system.

on the order of 100 billion ohms. But modern BiFET and BiMOS operational amplifiers will do the same job, but offer input impedances on the order or 1,500 billion ohms (1.5 teraohms).

Interfacing two existing commercial instruments may be as simple as constructing an appropriate patch cord, which would have the connector for one instrument on one end, and the connector for the other instrument on the other end. Alternatively, interfacing might involve designing electronic circuitry that makes the instruments compatible.

In both industrial and university laboratory environments, as well as certain amateur science endeavors, one may be asked to make a specially-built instrument or a collection of commercial instruments. You might buy or reallocate (i.e., steal) a cabinet such as a 19-inch relay rack, and then go about mounting the instruments and subassemblies. But before much progress can be made, it will be advisable to study each instrument to ascertain its capabilities. Input/output requirements and specifications, the function and range of each control, and the signal-flow path within the instrument. Any attempt at producing an instrumentation system without doing this will result in a less than optimum device, or at worst, might destroy one or more of the subassemblies.

Figure 2-1 shows the generalized block diagram of a "typical" instrument. There are three sections, which in real life might be anything from one device to a whole rackfull of devices. The input device is some sort of signals-acquisition device. It might be a set of biopotentials electrodes, a transducer for measuring a given parameter, or some other device that originates the signal for the system. Once the signal is acquired, it must be processed. This stage almost always consists of amplification, but might also contain filtering, logarithmic compression, or other functions. In today's microcomputer world, the signals processing might be in the form of digital-signal-processing program routines. Alternatively, it might be a sophisticated analog module. Burr-Brown Corporation, for example, produces a three-input device that has a transfer function on the order of:

$$V_o = V_x \times \frac{V_y}{V_z}^m$$

where:

V_o is the output voltage
V_x is the potential at the x-input
V_y is the potential at the y-input
V_z is the potential at the z-input
m is a factor determined by an external resistor network

The last section of our universal instrument is the output stages. This section might consist of a display device (oscilloscopes, paper recorders, digital meters, etc.), or a control system actuator (furnace turn-on controller, etc). In general, the device will be either an indicator/display or an actuator of some sort.

In this book you will learn a little bit about electronic instrumentation design, but much more about that form of electronics instrumentation unique or particularly applicable to data-acquisition situations.

CLASSES OF SYSTEMS

There are various forms of electronic systems that can be generically classed as data-acquisition systems. In this section I will classify these instruments into a few coherent categories.

Measurement. A measurement system is designed to examine some parameter and produce an output that indicates its value.

Control System. A feedback control system is designed to examine a parameter, determine its value, and then actuate some device or process that forces the parameter to a preset value or level. Perhaps the most common example of a feedback control system (and also the least sophisticated) is the thermostat and furnace in your home.

Data Logging System. This type of system is designed to collect data and store it in a form that is retrievable later on. Classical data loggers were either AM, dc, or FM/FM tape recorders. Models existed that used every form of tape from a microcassette to 35 millimeter, 32-channel versions. Modern data loggers are digital versions that store data on either magnetic media (diskettes) or in a form of volatile memory that does not lose its data when the instrument is turned off (a keep-alive memory battery is provided).

Chapter 3

The Role of the Microcomputer

PERHAPS NO OTHER FACTOR HAS SPAWNED THE sharp increase in data-acquisition systems than the invention of the microcomputer. Previously, such systems were terribly costly because they had to be based on large mainframe computers or stand-alone minicomputers. While the minicomputers were an order of magnitude lower in cost while still being more than sufficient for most data-acquisition problems, they were still very expensive. The microcomputer revolution changed this situation. The desk-top microcomputer, especially those types that allow plug-in modules or printed circuit cards, are easily adaptable to data-acquisition problems. It is now possible to buy, for about the price of a ten-year old used car, a microcomputer that is capable of running a factory, performing a scientific experiment, or crunching the data acquired.

The key aspect of the microcomputer that makes it useful for our problem is the fact that it is programmable. This means we can make the computer do a lot of different jobs just by changing the software. In Chapter 22 I will discuss in general terms how to select such a computer.

The microcomputer can do different jobs for us. Let's suppose that we are life scientists that want to do an experiment that will win the Nobel prize next year. Let's look at the kinds of jobs that can be done by the same microcomputer in our Quest for the Grand Prize.

Word Processor. We have to write the grant that will fund our basic research. The microcomputer is a dandy word processor. This book was written on a word processor (FinalWord Ver. 1.15, run on an IBM-PC), and I am very familiar with its utility. Not only will you have to write your grant application, you will also have to write up the results of the experiment for the peer review journal.

The digital computer will not only make it easier to draft and edit your grant applications, professional papers, reports to management and so forth, it can make them look really spiffy. Modern software, such as PageMaker and PrintShop, allow you to lay out pages that look like they were professionally designed and typeset. Although such software is available for the IBM-PC, the hands-down master at this type of job is the Apple MacIntosh machine. When coupled with a laser printer (which should also be used on non-Apple machines used for this purpose), the Apple "Desktop Publisher" package is supurb for professional typesetting. Although the quality is not up to the best in electronically typeset pages, it is close enough that some publishers are now using Desktop Publishing.

Financial Records. Any project that requires funding will benefit from the computer's ability to keep records. Various programs are available, including spreadsheet and dedicated accounting programs. The same computer that helped you write your grant application will now be useful in keeping track of the grant money, and indeed, will even write the checks for you . . . if you want it to.

Program Management. Various program management software offerings allow you to keep track of a multiple critical path project, vary the parameters, and spot troubles on the way. An example of this form of program is the *Harvard Program Manager.*

Experiment Control. The programable computer can be married with various plug-in and external circuits to actually control the experiment. You can interface assorted instruments to the computer, and then write a program that will allow the computer to control the instruments and how they work in the given experiment.

This type of system has a distinct advantage over manually operated systems: consistency. I can recall a case where a physician complained that he didn't need a computerized laboratory system because his technicians, most of whom he had personally trained, were good at their jobs. Besides, the computer had a 15-percent error rate. In other words, 15-percent of the time the computer gives a result that is outside of a predetermined quality control band of acceptability. It was argued that the technicians could do the job almost error free. That, however, was wishful thinking! Inspection of the actual situation showed that technicians made less than 1% errors at 0700 when their shift started, but by the end of the day were trucking along at about a 25% error. The computer gives predictable and benign errors, while the human error is totally unpredictable.

Interestingly enough, the human/machine interface can affect the perception of the system. One of the first automated electrocardiogram (ECG) reading programs was deemed inadequate by several emergency-room physicians. The problem turned out to be one of perception. The program searched a database of 25,000 confirmed pathologies to find the one(s) that most nearly fit(s) the incoming ECG waveform for the present patient. During the search period (two to three minutes sometimes), the efficient programmer decided that the machine could be used to output an analog rendition of the digitized waveform. In other words, a DAC was used to output the waveform to a strip-chart recorder. The problem was that the ER doctors would examine the strip, and make a tentative diagnosis. If the computer disagreed with him or her, then the doctor arrogantly assumed that the machine has erred, and that his or her diagnosis was the correct one. That actually rarely turned out to be the case: the computer won hands down. The solution to the perception problem was to delay outputting the analog waveform until the printed diagnosis from the database search was completed. The analog waveform then merely confirmed what the computer, in its wisdom, had determined.

Controling an experiment or other data acquisition event requires collecting the correct plug-ins and external equipment. For this reason I prefer computer models that allow plug-in printed-circuit boards to expand the capability of the machine. For this reason, the Apple IIe and the IBM-PC are well-suited (note: not all PC-clones accept plug-in cards).

Data Logging. If the experiment is one that does not easily lend itself to control applications, then the computer can still be used for data collection. A suitable array of analog-to-digital converters to input analog data to the computer is necessary. The computer can then collect and store a large array of data on the experiment automatically. Note that the computer can collect a lot more data than manual methods.

Number Crunching. Raw data collected during an experiment is rarely useful in its initial form. We have to perform assorted forms of statistical analysis and other jobs on the data before it can be used. The computer does this job magnificently. In fact, you can use the same data logged (see above) during the experiment; in some cases the statistical massaging can be done as the data is collected.

Chapter 4

Designing a System

THE ONE UNMISTAKABLE SIGN OF THE NOVICE DEsigner of electronic instruments is the tendency to jump right into the construction and testing phase of the project without the benefit of the least little bit of planning. Don't make this expensive, time-consuming mistake.

This thing called "design" is a logical process. Indeed, the very word "design" suggests activities like planning, thought, intent, and procedure. There is little that is really arcane in elementary electronic design, and anyone with a little knowledge can design adequate electronic instruments.

This is not to diminish the first-class design engineer, but merely suggests that almost anyone can get something working that will perform the chore at hand. A good designer exhibits intelligence, insight, knowledge, and that subjective property known as cleverness. Most of these attributes are obtained through one process: experience, i.e., the art of surviving repeated attempts at nailing you to the wall.

You will have to learn good design and laboratory techniques if your efforts are going to be efficient. You will also have to learn some of the more objective things such as the upper limits of devices (mostly to prevent a costly method of converting silicon to carbon. If you follow true to form, you will notice your mistake approximately 1 millisecond before a puff of smoke indicates that your one-of-a-kind sample just evaporated). Don't worry if your early efforts seem futile. They are not totally without merit, if only because you are afforded the opportunity to learn from your mistakes. This book lets you learn from some of mine and those of others.

Do not be impatient to get started building hardware. This is actually one of the last steps in any proper design activity. Unfortunately, other people may not see it that way. If you are designing some electronic widget as part of your employment, or to fulfill a requirement in a school course, then there might be pressure from above to start producing something that can be seen, felt, smelled or heard almost immediately. There always seems to be an impatient supervisor, overlord, or nervous customer who is only too willing to believe that you are not producing anything if you are not constantly spritzing and fussing with wires, capacitors, ICs, and other electronic paraphernalia. So despite primordial urges to the contrary, resist the temptation to jump in prematurely.

The very first step in any design process involves knowing and understanding the problem that you must solve. This advice may seem at first glance like a case of runaway cynicism, but in reality it is common sense based on observation. A remarkable number of people will begin something they call "designing" without really knowing what the device is supposed to do. Studying the problem will involve any or all of several activities including literature search, thinking, interviewing the end user, and interviewing other people who solved the same sort of problem before.

Do not underestimate the value of a literature search. Too many alleged designers shun this step for some reason. I suspect that they suffer "N.I.H." (Not Invented Here) syndrome. This well-known malady afflicts those whose misplaced pride prevents them from using perfectly good solutions from prior art in favor of attempting the new and unknown. They are embarrassed to admit that somebody else once had a good idea. If prior art will solve your problem, then use it. Your job is to solve the problem, and not necessarily to prove how clever you are with state-of-the-art designs.

The next step is to formulate an approach to solving the problem. This will involve trying to figure out several methods or circuits that might do the trick. There is seldom a single "best" way to perform any electronic design job. So be sure to consider several possible alternatives. The word "contingencies" looms large in this area.

Some wise souls will tell you that your first design in any given project is usually the poorest one that you will invent. If this is true even some of the time, then it might be wise to collect several approaches before actually starting to build anything.

One other thing to do prior to building anything is to make a drawing of the entire circuit and every critical mechanical part. I know several people who allege themselves to be "electronic instrument designers," who are often seen in their workshops with a semiconductor manufacturer's data book propped up on a vise or pile of books, copying fragments of their total circuit, first from one page, then another. This is an extremely poor practice, and inevitably leads to burned-out ICs, ragged tempers, unhappy customers, and the well-earned contempt of colleagues who are smarter and wiser. Even if you choose to duplicate a published electronic project, you should copy it *in toto* onto a working sheet of paper, especially if you plan to change the circuit, or any small part of it.

The drawing and other documentation will play a large role as you begin building and testing the first prototype. Keep detailed records of key voltages, signals, and other parameters that are important for the specific case. Change the master drawing to reflect any changes that you make in the circuit. Think with a pencil!

Also, please write an alignment and adjustment procedure that can be followed by someone less qualified than yourself. The procedure might be self-evident to you because you originated the concept, but to others it may be mysterious. Do not require your successors to use mental telepathy or the occult sciences to figure out how to adjust, align, or calibrate your creation.

Besides, six months or a year down the road, you may well be the one who is called on to make a repair or readjustment of the instrument. Guess who will then be neatly and properly nailed for not knowing how? Serves you right . . . good documentation is a fine save yourself tactic.

Use the laboratory notebook, or some other running design log. Most college bookstores, drafting supplies stores, or "engineering supplies" stores sell adequate, quadrilled laboratory notebooks. These, if kept properly, can be your file and may help you if a patentability question arises.

Another sign of the novice or inept designer is the tendency to commit even relatively complex or untried designs in final form without first breadboarding the circuit. Every new design cannot be considered "finished" until it has been tested properly and not found wanting. Every idea that you conceive must be considered merely hypothetical until it has been proven valid. It may appear that certain ideas will work, but when you connect them a big, nasty, smelly surprise is found waiting. This is the reason why laboratory breadboards are fast-selling items.

The final product will usually be built on a wireboard, DIP-board, PC board, or whatever works best and is most cost-effective. You will