A detailed look at the real world
of microcomputer-based instrumentation
and control systems

HANDBOOK OF MICROCOMPUTER-BASED INSTRUMENTATION AND CONTROLS

JOHN D. LENK

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This book is happily dedicated to Irene, Karen,
Tom, Brandon, Justin,
Cathy, and Michael. And a special dedication to our little Lambie.

PREFACE

This book is a "crash course" in digital or microcomputer-based instrumentation and control systems. The book is written with five classes of readers in mind. First, there is the engineer who must design with (and program) microcomputer-based systems. Next is the technician who must service digital instrumentation and control systems. Then there is the programmer/analyst who wants to relate programs and software to microcomputer-based equipment. Finally, but not of least importance, are students and hobbyists who want an introduction to microprocessor-based equipment.

The various classes of readers start from a different learning point. Obviously, engineers and technicians understand electronics, but they may have little knowledge of programmed devices or no knowledge of control and instrumentation systems. Programmer/analysts may be expert in computer language and systems but know nothing of control and instrumentation systems, particularly microprocessor-based systems. The student/hobbyists may have only an elementary knowledge of electronics and no understanding of digital or programmed equipment.

This book bridges the gaps by bringing all these readers up to the same point of understanding. This is done in a unique manner, following the tradition of the author's best-sellers. The descriptions of how the devices operate are technically accurate (to satisfy the technicians and engineers) but are written in simple, nontechnical terms wherever possible (for the benefit of programmers/students/hobbyists).

The first half of the book is devoted to the basic elements and theory of both instrumentation/control equipment and microcomputers. This first half is written in review or summary form to cover the widest possible range of subjects. The second half of the book describes actual control and instrumentation systems now in use throughout the industry. The second half also describes the programs and programming methods for this equipment. Thus, the book gives the reader both a detailed look at the real world of microcomputer-based instrumentation and control, and the background necessary to understand the equipment.

Chapter 1 provides an introduction to microprocessor-based control and instrumentation systems.

Chapter 2 reviews and summarizes the sensing elements and transducers found in control and instrumentation systems. The chapter also describes the basics of signal conditioning, measurement circuits, and control elements (actuators, transmitters, etc.) common to typical industrial control automation systems.

Chapter 3 reviews and summarizes microcomputers and microprocessor-based digital equipment. Although the review is thorough, the subjects discussed in this chapter are those necessary to understand the equipment described in Chapters 4 and 5.

Chapter 4 discusses and actual system that combines the two basic functions of control/instrumentation (Chapter 2) and microcomputer operation (Chapter 3).

Chapter 5 discusses how the system discussed in Chapter 4 can be programmed to perform the various control and instrumentation functions. The discussion includes block diagram descriptions, programming techniques, and sample programs for the system.

Many professionals have contributed their talent and knowledge to the preparation of this book. The author gratefully acknowledges that the tremendous effort required to make this book such a comprehensive work is impossible for one person, and he wishes to thank all who have contributed directly and indirectly.

Special thanks are due to the following: Dick Harmon and Glenn Green of Hewlett-Packard; Lothar Stern of Motorola Semiconductor Products, Inc.; Debra Siefert of Tektronix; Steve Bourque of Texas Instruments Incorporated; and Cheryl Gartenberg of United Technologies Mostek.

The author extends his gratitude to Dave Boelio, Hank Kennedy, John Davis, Jerry Slawney, Art Rittenberg, and Don Schaefer of Prentice-Hall. Their faith in the author has given him encouragement, and their editorial/marketing expertise has made many of the author's books best-sellers. The author also wishes to thank Joseph A. Labok of Los Angeles Valley College for his help and encouragement.

JOHN D. LENK

CONTENTS

PREFACE xi

1 INTRODUCTION TO MICROCOMPUTER-BASED INSTRUMENTATION AND CONTROLS 1

1-1. Relationships among the elements of a microcomputer-based control and instrumentation system, *4*
1-2. Types of control and instrumentation systems, *6*

2 ELEMENTS OF CONTROL AND INSTRUMENTATION SYSTEMS 13

2-1. Basic measuring and control systems, *13*
2-2. Basic transducer definitions and methods, *15*
2-3. Motion and force sensors, *20*
2-4. Fluid sensors, *32*
2-5. Moisture and humidity sensors, *40*

2-6. Light and radioactivity sensors, *44*
2-7. Temperature sensors, *50*
2-8. Thickness sensors, *56*
2-9. Proximity sensors, *59*
2-10. Density and specific gravity sensors, *60*
2-11. Chemical sensors, *61*
2-12. Basic signal conditioning circuits, *63*
2-13. Measurements in control and instrumentation systems, *74*
2-14. Basic control devices, *81*

3 ELEMENTS OF MICROCOMPUTER AND MICROPROCESSOR-BASED SYSTEMS **103**

3-1. Digital number systems and alphanumeric codes, *103*
3-2. Basic digital logic, *108*
3-3. Microcomputer terms, *124*
3-4. Elements of a microcomputer, *125*
3-5. Microcomputer circuit functions, *128*
3-6. Microcomputer hardware, *137*
3-7. Memory hardware, *140*
3-8. Input/output hardware, *148*
3-9. Basic microcomputer system, *150*
3-10. Microcomputer timing and synchronization, *162*
3-11. Machine language versus assembly language, *164*
3-12. Peripherals for microcomputer control systems, *166*

4 INTRODUCTION TO THE MULTIPROGRAMMER **173**

4-1. Hewlett-Packard 6940B/6941B multiprogrammer, *173*
4-2. Input/output card functions, *177*
4-3. Multiprogrammer capabilities, *193*
4-4. Multiprogrammer applications, *196*
4-5. Multiprogrammer operating features, *202*
4-6. Multiprogrammer basic principles of operation, *210*
4-7. Interface basic principles of operation, *234*

5 MULTIPROGRAMMER FUNCTIONS AND PROGRAMMING FUNDAMENTALS 249

5-1. Basic multiprogrammer system block diagram, *249*
5-2. Multiprogrammer output modes, *252*
5-3. Multiprogrammer input modes, *257*
5-4. HP-IB programming fundamentals, *261*
5-5. Plug-in card descriptions and programs, *267*
5-6. D/A voltage converter card, 69321B, *268*
5-7. Power supply/amplifier control cards, 69325A-69328A, *269*
5-8. Relay output card, 69330A, *272*
5-9. Digital output card, 69331A, *274*
5-10. Open-collector output card, 69332A, *274*
5-11. Stepping motor control card, 69335A, *275*
5-12. D/A current converter card, 69370A, *278*
5-13. Breadboard output card, 69380A, *279*
5-14. Voltage monitor card, 69421A, *280*
5-15. Isolated digital input card, 69430A, *282*
5-16. Digital input card, 69431A, *283*
5-17. Relay output with readback, 69433A, *286*
5-18. Event sense card, 69434A, *287*
5-19. Pulse counter card, 69435A, *289*
5-20. Process interrupt card, 69436A, *290*
5-21. Breadboard input card, 69480A, *291*
5-22. Resistance output cards, 69500A-69513A, *292*
5-23. Programmable timer card, 69600B, *292*
5-24. Frequency reference card, 69601B, *294*
5-25. Multiple-card programs, *295*
5-26. Voltage scanning and measurement (multiplexing), *295*
5-27. Frequency measurement, *298*
5-28. Time-interval measurement, *300*

INDEX **303**

1

INTRODUCTION TO MICROCOMPUTER-BASED INSTRUMENTATION AND CONTROLS

Microcomputer-based instrumentation and control systems can be very complex, or relatively simple, depending on the application. For example, at the relatively simple end of the scale, the fuel injection system of an automotive engine contains sensors to monitor engine and driving conditions such as compression, altitude, rotation, and speed. Information from those sensors is converted into control signals by a computer or computer-like device such as a microprocessor or controller. In turn, the signals are converted into commands that control the engine's performance. The commands regulate fuel air-gasoline mixture, amount of fuel, rate of fuel flow, and so on. Thus, the engine is controlled or adjusted for optimum performance despite constantly changing operating conditions.

For an example of a more complex control and instrumentation system, consider an automated plant such as a petroleum refinery. The basic elements of such a system are shown in Fig. 1-1. Special devices called *transducers* or *sensors* (or possibly "pickups," although that is a slang term) are installed at many points along the refining process. The transducers measure the conditions or state of *process variables* at those points. Typical process variables could include temperature, pressure, rate of flow, chemical content, density, and so on, of the petroleum being refined. Any deviation from normal measurement (abnormal temperature, incorrect pressures, etc.) must be corrected instantly to

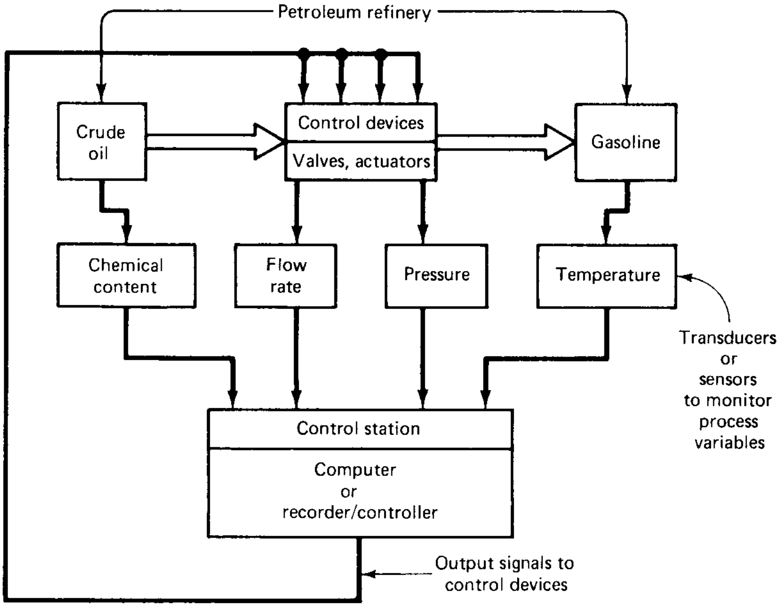

FIGURE 1-1 Basic elements of an instrumentation and control system for a petroleum refinery.

keep the petroleum flowing without interruption and to ensure that the refinery output is of proper quality.

The output from each transducer or sensor is transduced, or converted, to a corresponding signal (usually electric but possibly pneumatic in some older systems) and sent to a control center. That is, a process variable (temperature, pressure, etc.) is converted to a corresponding electrical signal in a form that can be accepted by a control station or device.

There are many types of control stations. In the older, noncomputer systems, some form of *recorder-controller* is often used as the basic element. A recorder-controller prints a continuous record of the condition or state of a process variable and compares the condition with a normal or desired value (often called a *set point*) expected at that stage in a process. Any deviation from normal produces an output signal from the recorder-controller that corresponds to the *amount of deviation* as well as the *phase of deviation*. That is, the signal indicates whether the condition or state of the process variable is above or below the value indicated by the set point, and by how much. The recorder-controller output signal is sent to an *actuator* such as an electromagnetic valve or possibly a motor-driven device, which restores the process variable to the normal value.

In a large control system such as a petroleum refinery, there usually is a complex interrelationship among the process variables. This means that if one variable changes, that change usually affects all other variables. For example, an increase in the temperature of a liquid in a refining tank could also raise the pressure on that liquid in the tank. Thus, if one variable changes, the set point of all the controllers should be readjusted to compensate for those changes. So complex is the interrelationship, however, that even an experienced operator cannot make all the readjustments required for the most efficient and profitable operation.

To overcome these problems, some form of digital computer is used in most present-day control and instrumentation systems. These can be conventional larger computers or the new and smaller microcomputer or minicomputer. Similarly, there are some systems that use a microprocessor-based instrument as the basic control element. Whichever type of computer is used, signals from the transducers are converted to corresponding numerical quantities that are fed to the computer. This relationship is shown in Fig. 1-2. That is, a physical quantity (pressure, temperature, etc.) is converted to an electrical signal by the transducer. In turn, an electrical signal is converted to a numerical quantity in a form suitable for the computer.

Because of the high speed involved, the computer or microprocessor-

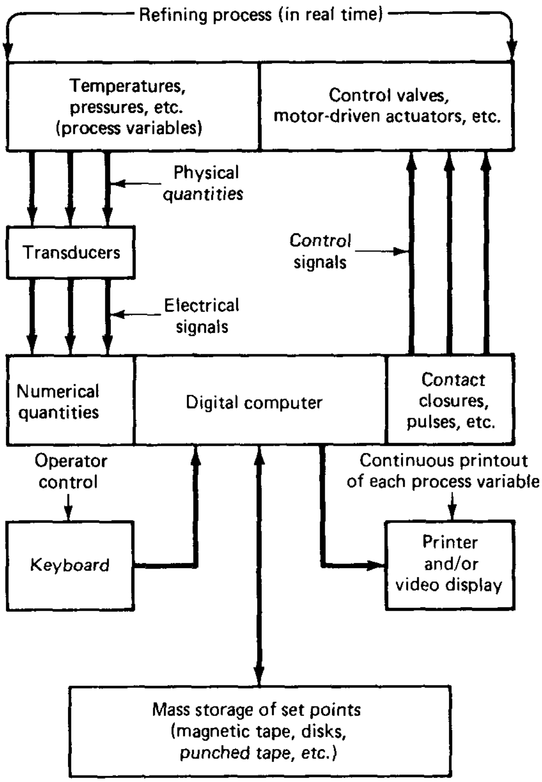

FIGURE 1-2 Basic elements of a computer-based instrumentation and control system.

based controller is able to calculate the effects of every change in the interrelationship among the variables and quickly produce output signals that adjust the set point of each controller to produce the most efficient operation. In the more sophisticated systems discussed in this book, the computer replaces the older recorder-controller completely. In these advanced systems we describe here, the computer continuously prints out the condition or state of each process variable (usually on a printer similar to that of a business computer or work processor), stores the various set points in memory (typically on magnetic tape, disks, and punched tape), and adjusts the set points as required. The computer then compares the input signals from the transducers with the readjusted set points and sends appropriate signals to the various actuators.

1-1 RELATIONSHIPS AMONG THE ELEMENTS OF A MICROCOMPUTER-BASED CONTROL AND INSTRUMENTATION SYSTEM

There are at least three, and possibly four, elements in any control and instrumentation system, in addition to the basic control element (computer, microprocessor, etc.). These elements include the sensing elements or transducers, the measurement and signal conditioning elements, the control devices or actuators, and possibly instrumentation devices.

1-1.1 Sensing Elements and Transducers

A typical automatic control system starts with a primary sensing element (sensor or transducer) that senses a condition, state, or value of a process variable and produces an output that reflects a condition. Typically, the electrical signal output is an *analog* of the process variable condition. For example, the output could be a voltage where 1 volt represents 1 pound of pressure, or a current where a 1-milliampere change in current represents a 1-degree change in temperature. There are many types of transducers used in present-day control systems. Among them are sensors of motion and force (acceleration, attitude, displacement, force, torque, pressure, speed, velocity, strain), fluid conditions (flow, pressure, and liquid level), humidity, moisture, light, radioactivity, temperature, and sound. Such transducers are discussed in Chapter 2. Although every possible type or variation of transducer or sensor cannot be included in one book, the coverage does include a full cross section of transducers used in present-day control systems. For a more complete presentation of transducer basics, your attention is called to the author's *Handbook of Controls and Instrumentation* (Englewood Cliffs, N.J.: Prentice-Hall, Inc., 1980).

1-1.2 Measurement and Signal Conditioning Elements

Measurement is an important part of any control and instrumentation system. For example, we measure the temperature and pressure of a process variable, the rate of flow, the acidity, and much more. The measurement is needed not only to learn the condition or quantity of a variable, but also to get a value that can be compared with a standard value (the set-point value) to obtain an *error signal.* The error signal is used to operate an actuator, which causes the process variable to return to a predetermined value.

In a typical control system, we start by using a sensor to translate the condition or quantity of a process variable to an electrical or pressure output signal. Chapter 2 concerns some of the methods generally used to measure such signals. Typical values to be measured include current, voltage, resistance, capacitance, inductance, frequency, and pulse rate. In microcomputer-based systems, the measurement process also involves conversion from analog values (where voltage represents pressure, etc.) to digital values, and vice versa. This is because computers use digital pulses, and require both analog-to-digital (A/D) and digital-to-analog (D/A) circuits. The basic functions of such circuits are discussed in Chapter 2.

1-1.3 Control Devices and Actuators

In most instances, the final stage of any control system consists of (1) a switch or contact that may be opened or closed, (2) a valve that may be fully opened or closed or adjusted to some position between the two extremes, (3) an electromagnetic device that may be energized by an electrical current to perform some mechanical or electrical function, and (4) a motor that may be started, stopped, or reversed (typically in steps) or whose running speed may be varied.

Between a primary sensing element, which initiates a control function, and a final actuator there may be many control elements, each performing a definite function in the system. Such devices are switches, valves, solenoids, relays, electron tubes, and (in most present-day systems) solid-state control elements. Chapter 2 covers some of the most commonly used elements, explains their operation, and shows how they fit into modern control systems.

1-1.4 Instrumentation, Readout Devices, and the Computer

In a sense, all the devices described in this book could be called instruments or instrumentation. However, we reserve these terms to those devices that indicate, transmit, or record signals between other elements in a system. In older and simpler systems, the indicators are basic pressure gauges, thermometers, electrical meters, panel lights that indicate an event (such as a red light that flashes when the fluid in a tank has reached a certain level), and similar devices. In computer-based systems, the indicators usually take the form of digital readouts, or possibly displays on a video terminal, or a printout on an output printer. In Chapters 4 and 5 we discuss a system where the printout is on a desktop calculator (which also functions as the controller terminal).

Because of the complexity of even a simple microcomputer, a full description of computers is beyond the scope of this book. However, Chapter 3 discusses the elements of microcomputers, particularly as they apply to a control and instrumentation system. For a full presentation of modern computer basics, your attention is called to the author's best-selling *Handbook of Microprocessors, Microcomputers, and Minicomputers* (Englewood Cliffs, N.J.: Prentice-Hall, Inc. 1979) or the *Handbook of Digital Electronics* (Englewood Cliffs, N.J.: Prentice-Hall, Inc., 1981).

If you are already familiar with the basics of control and instrumentation systems, including transducers, signal conditioning, and actuators, you can skip Chapter 2. Similarly, if you fully understand microprocessor-based computer systems, you can pass over Chapter 3. However, it is recommended that you at least skim through these two chapters before getting into detailed discussions of present-day systems and circuits found in the remaining chapters.

1-2 TYPES OF CONTROL AND INSTRUMENTATION SYSTEMS

Each industry or specialized field has its own set of automatic control systems suited to its particular requirements, and there are many variations of each system. However, all control systems (both computer and noncomputer types) fall into either of two general groups: *open-loop* or *closed-loop* systems. Furthermore, these two basic groups can be classified as *continuous* or *discontinuous* systems. In the following sections, we describe each of these four basic systems, followed by an explanation of a simple yet complete system that incorporates all the basic elements of a typical microcomputer-based control and instrumentation system (sensor, signal conditioner, indicator, recorder, controller, actuator, etc.).

1-2.1 Basic Discontinuous Open-Loop Control System

In any open-loop system, a controlling device operates independently of a process variable that is being controlled. An example of a discontinuous open-loop system is shown in Fig. 1-3. The switch is the controlling device. The room temperature is the "process variable." When the switch is closed, current flowing through the heater raises the room temperature. When the switch is opened, the room temperature starts to fall. Because operation of the switch is not af-

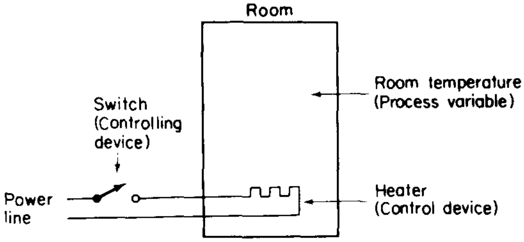

FIGURE 1-3 Basic discontinuous open-loop control system.

fected by room temperature (or the condition of the process variable) the system is open-loop. Similarly, because the control circuit can be opened and closed, the system is discontinous.

1-2.2 Basic Continuous Open-Loop Control System

A basic continuous open-loop system is shown in Fig. 1-4. Here the variable resistance is the controlling device. The resistance controls the amount of current flowing through the heater. In turn, the amount of current determines the room temperature. Again, the condition of the process variable (room temperature) does not affect operation of the controlling device (variable resistance), so the system is open-loop. However, because the control circuit is always closed and in operation, the system is continuous.

In most continuous open-loop systems, a *calibrated controlling device* must be used to place the process variable at the desired value. In the example shown in Fig. 1-4, the dial that operates the variable resistance can be calibrated in terms of desired room temperature. However, variations such as opening and closing windows and doors to the room affect such calibrations. From a practical standpoint, the variable resistance has no means for sensing such changes and making adjustments to meet them.

In most control systems, it is usually desired that the process variable be kept at a constant value. If an open-loop system such as that shown in Fig. 1-4

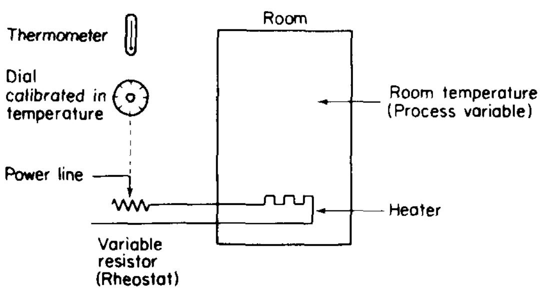

FIGURE 1-4 Basic continuous open-loop control system.

is used, an *indicating device* such as a thermometer must be used to show the condition of the process variable (room temperature) at all times. Then an operator must be posted at the controlling device to decrease the variable resistance (thus increasing current flow and heat) should the room temperature fall below the desired value (set point) or to increase the variable resistance should the temperature rise above that value.

1-2.3 Basic Discontinuous Closed-Loop Control System

An obvious disadvantage of an open-loop system is the lack of automatic control. That is, the process variable (or room temperature in our case) is not monitored constantly and is not maintained at a desired value, except by a human operator. Even a simple closed-loop system can overcome that disadvantage. Take the example of Fig. 1-5, which is a simplified version of a typical thermostat-controlled room heater. In this case, a gas heater is used. The flow of gas to the burners is controlled by a valve, which, in turn, is operated by current through a thermostat. (As a matter of interest, the current is usually generated by a *thermocouple* placed next to the heater's pilot element. Thermocouples are discussed in Chapter 2. For now, we are interested in how the gas burners are controlled by a thermostat.)

As shown in Fig. 1-5, a thermostat (or controlling device) is a bimetallic strip that bends in accordance with the temperature to which it is subjected. Two different metals are bonded together. Each metal expands and contracts (with changes in temperature) at a different rate, so the strip tends to bend when

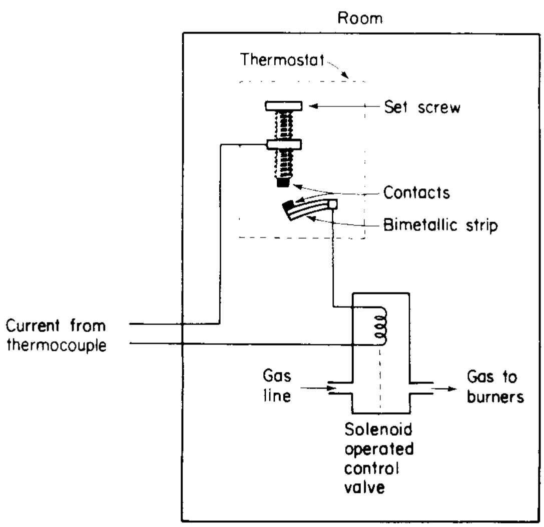

FIGURE 1-5 Basic discontinuous closed-loop control system.