ELECTRONIC INSTRUMENTATION

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Electronic Instrumentation

Under the editorship of Dr. Irving L. Kosow

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To my wife, Dinah

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Preface

The development of electronic instruments for measurement, test, and control purposes has experienced an impressive growth in recent years, and the scope of this instrumentation keeps on expanding. Not only do we observe a greater number of electronic instruments in use, but we also find them employed in a greater variety of ways. The electronic instruments have overflowed from the laboratory and are now found in widely different applications, ranging from the monitoring and recording of temperatures and pressures in an industrial process to the transmission from an orbiting satellite of data relating to speed, the kind of radiation encountered, and even the heart-rate of the astronaut in the space capsule.

The large number of instruments, and the great variety of uses to which they are put, make it increasingly important to concentrate on the electronic principles basic to the operation of this diverse assortment of instruments. This approach, stressing principles, has become all the more imperative because the rapid spurts of growth in this field have left unfilled gaps in the educational literature. Contrasted to the comparatively orderly development of text material on *electrical measurements*, at all levels, the instructional material on *electronic instruments* has not kept pace with the rapid advances. On the practical *operational level*, material has necessarily been made available in the form of manufacturers' instruction and maintenance manuals. Concurrently, *professional instruction* has gone ahead on the level of specialized electronic engineering. The wide intermediate area between practical operation and specialized electronic design, however, has not been so well developed. This area has become a matter of study by the Instrument Society of America[1] and has become recognized as a problem by many industrial groups. Many progressive industries are concerned about their need for competent technical workers, or "professional instrument technicians" if you will, whose competence should be acknowledged as including abilities considerably beyond the level of the practical maintenance worker or "service-man" type of technician.

In line with the prevailing recommendations of these groups, this text is aimed at that intermediate level, which might be termed "engineering associate" or "semiprofessional technician" for want of a better designation. This level of personnel, although short of the design responsibilities of the instrument engineer, requires a thorough understanding of the *basic electronic principles underlying instrument function.* To be of value to both the undergraduate engineering student and the semiprofessional technical student, the instructional material should include sufficient analysis of the full capabilities (and inherent limitations) of the electronic instrument and should provide for adequate understanding of the functional aspects that determine effective performance.

This text, therefore, aims to go beyond the necessarily simple *operating instructions* and the stating of *general principles of operation* in order to present a study of *instrument function* in sufficient depth to clarify the significant factors, such as equipment tolerances and precise calibration procedures, that are related to the effective performance of the instrument.

The instruments discussed in the text include both the *service and laboratory types.* The discussion of the service-type instrument is limited mainly to the testing principles involved. The major emphasis in the text is on the laboratory type instruments — whether used in the shop, school, or industrial and research laboratories.

The presentation of this book is directed toward the level of second or third year college students and students in industrial-training courses. Thus, the material is suitable for use in the second year of a two-year technical-institute course, in the junior year of a four-year college engineering course, or at some equivalent level.

To attain the stated aim, the text endeavors to make the following three points about each major type of instrument.

(1) To state why it works by establishing the *fundamental operating principle* of the instrument.

(2) To explain how it works by examining a *representative example* and explaining the *specific functions* of the instrument.

[1] "ISA Study of Instrument Technician Definitions and Job Classifications," Instrument Society of America, Education Committee, 313 Sixth Avenue, Pittsburgh 22, Pennsylvania.

(3) To illustrate where it works best by discussing *practical applications* of the instrument.

The reader's knowledge of basic electronics is assumed. The mathematics employed in the text is at a level appropriate to this assumption and is introduced freely wherever helpful, more for the purpose of providing a clearer interpretation of instrument function than for the purpose of either formula derivation or instrument design. For those who might need it, an explanation of the helpful *Thevenin-theorem approach* is included as Appendix A.

The book is roughly divided into thirds. The first third (made up of six of the 19 chapters) is devoted to the groundwork of electric and electronic measurement fundamentals. The second third discusses the primary group of general purpose electronic instruments, such as the electronic voltmeters, oscilloscopes, signal generators, and recorders with their accompanying transducers. The last third of the book studies the more highly developed instruments, along with accepted testing and specific instrumentation procedures. It includes examples from the fields of communication, radiation detection, counting and digital display, analog computation, and representative examples from specialized applications in the chemical and bio-medical fields and in the areas of automation and telemetry.

The last third of the text encounters the ever-present problem of an overabundance of material, not only of the instruments in current use, but also of those continually coming on the scene. Although the objective of adhering to fundamental principles is effective in keeping the large amount of material under control, the author feels that this alone is not enough. In order to develop the student's ability to analyze practical circuits of major developments, the general principles must also be fortified by significant practical applications. Considerable effort has been made, therefore, to include examples and simplified functional circuits — not only from the field of standard instruments — but also from the area of the newer and more highly developed instruments. Since such a large order is necessarily constrained by space limitations, an extensive list of text and literature references is given at the end of each chapter. These references, together with others of a general nature, are collected in an extensive *Bibliography* list in Appendix B. As an additional aid for obtaining much available practical information, a listing is given of *Manufacturers' Literature*, Appendix C, providing specific listing of such sources, both from the manufacturers of all the instruments illustrated in the text and from buyer's-guide references to other manufacturers. A *Glossary of Instrument Terms* is listed in Appendix D. Problems and questions are provided at the end of each chapter.

Acknowledgment is gratefully made of the valuable help received from

many sources. Credit lines identify the many manufacturers who obligingly supplied photographs and helpful instructional material from the literature cited and identified in footnotes. Grateful thanks for personal help are owed to Mr. Fred Shunaman, editor of *Radio Electronics* and Mr. Edward Grazda, editor of *Electronic Design* for their journalistic mentoring; to the late Mr. Ricardo Muniz (last with Magnavox) for the benefit of his extensive industrial experience coupled with friendly advice; also to Mr. George Ehrlich, and Mr. Carl H. Penziner for kindly counseling. Skillful secretarial help was cheerfully given by the Misses Joyce Kessler and Sheila Greenwald. Very special thanks are owed to the perceptive manuscript reading and comments by Professors Maucie Miller, Ignatius E. Lawlor, and Dean Harold Rothbart of Fairleigh Dickinson University and to the editorial help and kind encouragement of editor Matthew Fox of Prentice-Hall.

Finally, permit me to assure my wife, Dinah, that the dedication of the book to her is not meant to completely balance out my entire debt for the vast amount of understanding patience on her part.

Sol D. Prensky

Teaneck, New Jersey

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1

General Instrumentation

1-1. GENERAL DESCRIPTION OF INSTRUMENTATION

Instruments of many kinds have the common purpose of supplying information concerning some variable quantity (sometimes called a *parameter**) that is to be measured. This information is generally obtained as a deflection of a pointer on a meter, and in this general way the instrument performs an *indicating function.* In many cases the instrument also provides a chart record of the instantaneous indications, thus performing a *recording function.* A third important instrument function, particularly in industrial-process situations, is accomplished when the information is used by the instrument to *control* the original measured quantity. We can thus classify instruments by function into three main groups: the large, general group that has only the one indicating function; another large group of indicator/recorders; and finally the specialized group that performs all three functions of indicating, recording, and controlling.

The last-named group that includes the control function forms the basis of automatic systems, wherein a process is automatically controlled by the information fed back by the monitoring instrument. This leads to more complicated but very useful *automated systems* (*or automation*), a

*A quantity that is experimentally varied in a series of steps (see Glossary of Instrument Terms, Appendix D).

specialized field that is rapidly extending to science and industry its benefits of minimizing repetitive work.

This text will emphasize the more general instrument functions of *indicating and recording*, especially in those instruments that supply information for *measurement and test purposes;* the control function will be examined in those cases where controlling enters as an integral part of the indicating and recording functions of electronic instrumentation. (Sources for the further study of the control function are listed separately at the end of this chapter.)

1-1.1 General Measurement and Test Methods

Many methods are available for obtaining a given measurement; some measurements are made by *mechanical* means, as where the force exerted by a gas under pressure is measured by means of a Bourdon-tube pressure gage; other methods are primarily *electrical*, as in a measurement of solution conductivity by a current meter; and still other methods are *electronic*, as for example in the vacuum-tube voltmeter, where electron devices contribute amplification to provide more sensitive detection of the measured quantity.*

The use of electronic amplification together with electrical measurement methods offers means of electronic measurement having significant advantages. The use of amplification to produce *highly sensitive indications* is valuable in detecting small physical changes, while the ability to obtain this *indication at a remote location* helps in monitoring inaccesible or dangerous locations. Heightening the effectiveness of the electronic method of measurement is the fact that it can be extended to a wide variety of nonelectrical fields by the action of *transducers*. These are devices that convert other forms of energy to an electrical form. The many available types of transducers enable us to measure many forms of energy in terms of electrical signals; these transducer types are studied in a separate chapter.

1-1.2 Energy Conversion by Transducers

The action of transducers may be profitably examined here in terms of energy conversion. For example, we have the familiar microphone used to convert *sound* energy to an electrical signal; the *thermocouple* for converting heat energy to an equivalent electrical voltage; the *photocell* for converting light energy to electricity; the *Geiger-Mueller tube* for the conversion of nuclear radiation into electrical pulses; and a host of transducers for obtaining electrical outputs from *mechanical forms of energy*, such as force, pressure, displacement, flow acceleration, and the like.

*An excellent appraisal of the state of the art is given by D. B. Sinclair, "The Measuring Devices of Electronics," in the voluminous and valuable 50th anniversary issue of *Proc. I.R.E.* (May 1962).

1-1.3 Electronic vs. Electrical Instruments

The newer developments in electronic instruments have been built up on the base of the older, electrical instruments, and so the instrument forms at present are thoroughly mixed. We will see more clearly the role played by the electronic — as opposed to electrical — instruments if we identify the unique features the former contribute. Basically, the *electronic instrument includes in its make-up some electron device,* such as a vacuum tube, semiconductor diode, transistor, or gas tube, while the purely electrical instrument does not. Thus, electronic voltmeters, whether of the vacuum-tube or transistor variety, are obviously electronic instruments, while the common d-c voltmeter, based on the moving-coil meter movement is clearly an electrical instrument. There are instances, however, where this distinction may not be so clear cut, as in some solid-state applications; but it is clear enough, generally speaking, to be a very useful guide.

For example, the *greater speed* inherent in the electronic switching method (using tubes or transistors) is easily observed in comparison with the electromechanical method using relays; similarly, the electron instruments that incorporate some degree of *amplification of the input signal* in the circuit arrangement stand out clearly as more sensitive than their purely electrical counterparts. In addition to speed and amplification, specific features, contributed by electron devices in instruments are discussed more fully in Chapter 6.

Summarizing, it may be said in general that the *use of electronic principles provides instruments having higher sensitivity, faster response, and greater flexibility* than their mechanical or purely electrical counterparts in *indicating, recording,* and, where required, *controlling* the measured quantity.

1-2. DEVELOPMENT OF ELECTRONIC INSTRUMENTATION

A brief glance at some steps in the development of our knowledge and control of the electron will help us to understand the potentialities of the present electron devices. At the turn of the century (in 1906) the Nobel Prize was awarded to Joseph J. Thomson for his discovery of the electron. At that time, too, the very first three-element electron tube, the "audion," was introduced by its inventor, Dr. Lee DeForest. Thereafter, electronic amplifiers and circuits developed at a rapid rate; communication and radar circuit developments were spurred by wartime necessities in 1914 and 1941. Peacetime uses for entertainment purposes were first given a great impetus by the broadcast-radio receiver introduced as a "music-box" by David Sarnoff (forming the basis for the huge Radio Corporation of America); then again by Dr. Allen B. DuMont's development of the cathode-ray tube, culminating in Major Armstrong's later developments in FM reception. These were followed by developments from many manufacturers of television receivers.

The accent on communication developments in AM and FM radio, and television, suitable for mass distribution, was a powerful factor in making electronic components available at reasonable cost. As a result of these civilian and military developments, industrial applications developed concurrently.

The significant point is the success that was achieved in such a relatively short time in harnessing the potentialities of electron devices. Developers were quick to sense the versatile properties of the electron and to incorporate them in devices able to respond quickly and faithfully to the slightest impulse in the form of an electrical signal.

A few examples from the abundance of possible instances may be cited to illustrate electron-device capabilities:

(1) In the field of medical electronics, the faithful recording by the electroencephalograph* of minute electrical impulses generated in the body in the form of brain waves indicates the extremely *sensitive response* made possible by electronic amplification.

(2) In the TV broadcast station, the lightweight, almost inertia-free property of the electron is employed in the transmitter oscillator and amplifier tubes to provide extremely rapid alternations, calling for electron oscillations at rates greater than 200 million times each second. This VHF frequency (216 megacycles for TV channel 13) is not even close to the upper limit of *speed of electron response* employed in the microwave regions, where frequencies in the range of thousands of megacycles (gigacycles) are in common use.

(3) In the field of telemetry, we have an illustration of the great *flexibility* of electronic instrumentation; for example, in a space capsule over a dozen electrical signals monitor a like number of variable quantities, and these signals are then successfully multiplexed* on a single carrier to be received in intelligible form by a ground station.

Even a brief view of the field should include the important area of computers, both *analog* and *digital*, in which the electrical signals mentioned in the above examples can be further processed. Such examples serve to emphasize the great versatility that can be attained by applications of electronic instrumentation in the performance of highly sensitive and intricate tasks.

1-3. FORMS OF ELECTRONIC INSTRUMENTS

The general appearance of three electronic indicating instruments is illustrated in Fig. 1.01. Part (a) shows the familiar pointer-type *indicating*

*See Glossary, Appendix D.

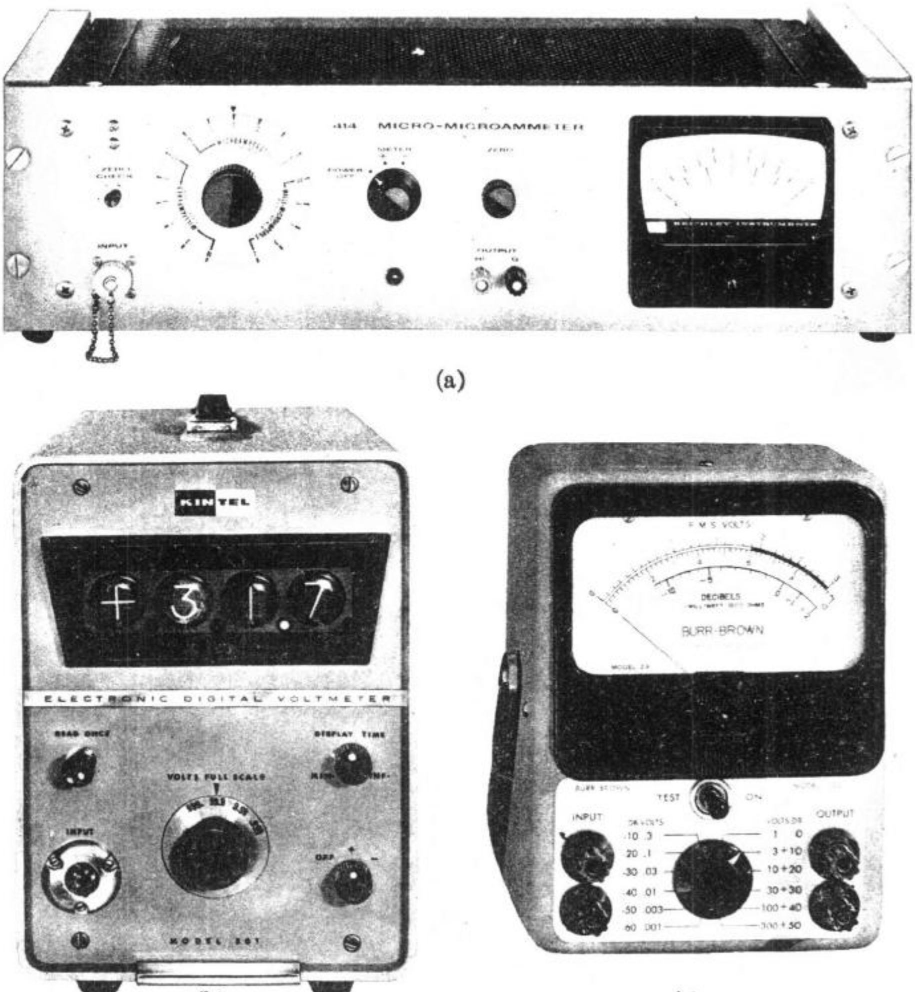

Fig. 1.01. Electronic indicating instruments: (a) electronic (vacuum-tube) microammeter (Kiethley, model 414); (b) digital voltmeter (DVM) with three digit display (KIN TEL, model 801); (c) transistor voltmeter (TVM) for a-c millivolts (Burr-Brown, model 300).

instrument in the form of a vacuum-tube micromicroammeter, capable of indicating 0.1 millimicroampere (1×10^{-10} amp) d-c, full scale; part (b) shows a digital voltmeter (DVM), and part (c) a transistor voltmeter (TVM). The general appearance of three *electronic recording instruments* is shown in Fig. 1.02, which illustrates a strip chart, a circular chart, and a transistorized recorder.

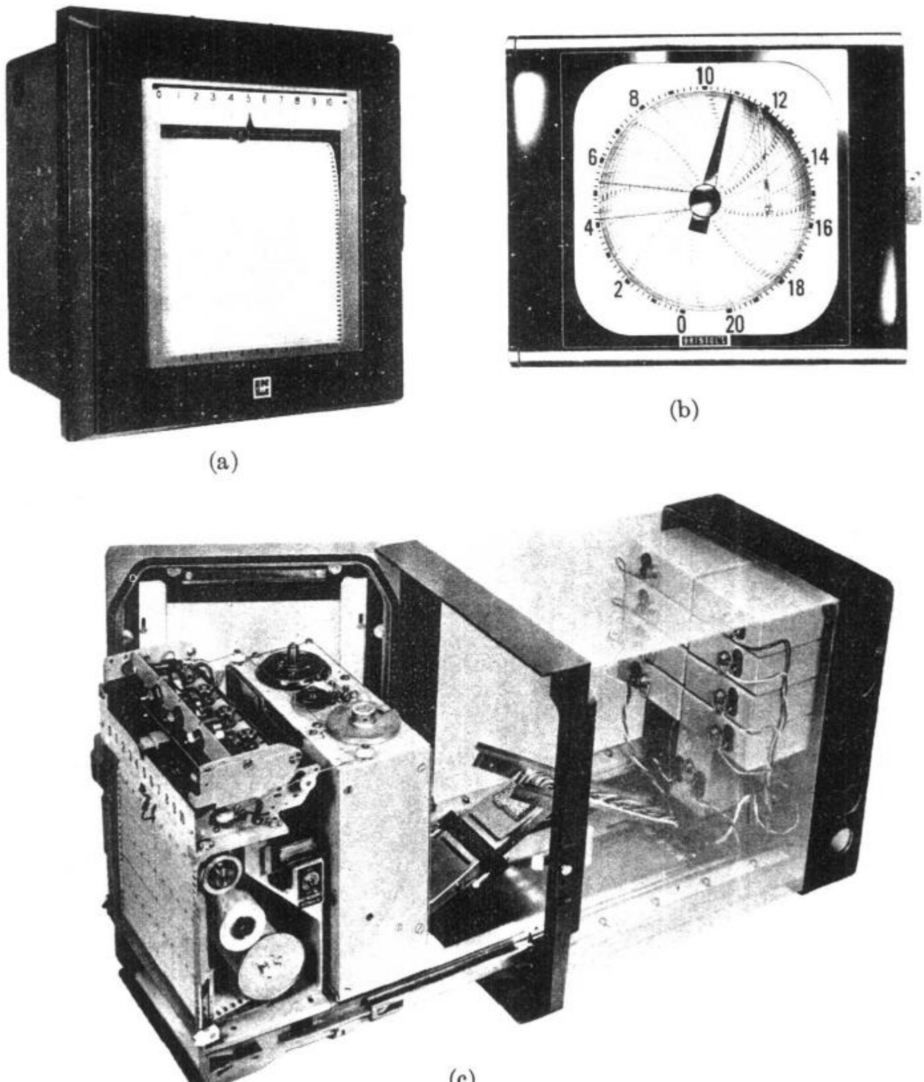

Fig. 1.02. Electronic recording instruments: (a) strip-chart recorder (Leeds & Northrup, "Speedomax," model G); (b) circular-chart form of recorder, Bristol's "Dynamaster" recorder; (c) transistorized strip-chart recorder (Honeywell, Electronik 17).

The study of electronic instruments, by its nature, must include a study of essential electrical principles. However, since this text emphasizes the electronic aspects of instrumentation, the reader is referred to other