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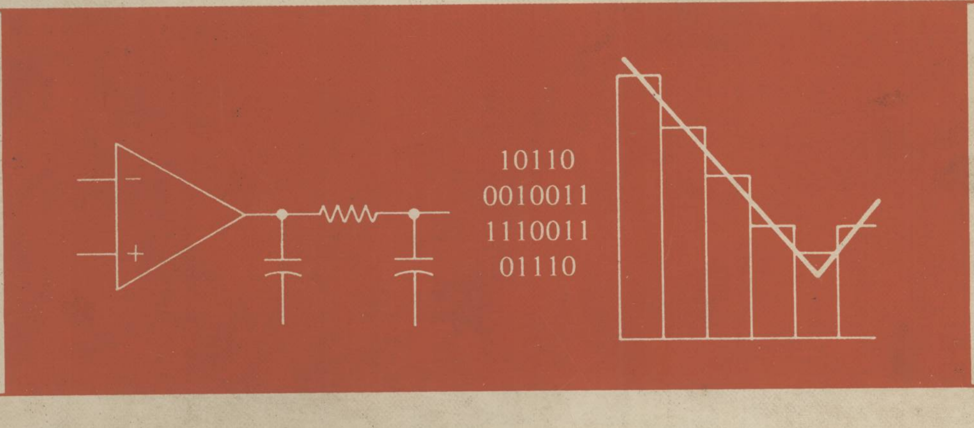
Computer Interface Engineering for Real-Time Systems

A Model-Based Approach



PATRICK H. GARRETT

Computer Interface Engineering for Real-Time Systems: A Model-Based Approach

Patrick H. Garrett

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Preface

Progress in the application of computer systems to the purposes of data acquisition, digital control, and communications functions has been widespread following the first real-time minicomputer implementation for process measurement and control in 1958, and especially rapid since the introduction of the microcomputer a decade and a half later. Since the integration of these systems may be defined with respect to the design of their computer interfaces, it is remarkable that such designs continue to be based essentially on empirical methods and circuit considerations. However, economic and performance accountability requirements have recently prompted the search for improved interface understanding in pursuit of a more quantitative methodology.

The motivation for this book accordingly was to address these needs through the definition of quantitative methods capable of characterizing the design and analysis of computer I/O systems. Subsequently, this led to the derivation and proofing of comprehensive mathematical models for describing device and system elements and their combination in terms of a unified input-to-output error budget. This provides an efficient integration tool for defining the performance of computer interfacing systems, including their sensitivity to component and system choices. The use of these accountability measures imposes needed organization on the design of computer I/O systems to achieve precision signal acquisition and accurate data conversion. The translation of these models into a software CAE program in Chapter 7 further provides for the automation of the many detailed calculations to speed the analysis of existing computer interfacing products and the optimization of new designs.

These methods therefore constitute a paradigm for quantitatively describing real-time I/O systems for digital computers, and the allocation of interface resources required to achieve the performance of interest including scale-up to many interconnected systems such as encountered in automated manufacturing.

This book presents a compendium of topics organized into ten chapters in a logical progression from input sensors to signal conditioning through digital conversion and output signal recovery elements, including extensions to advanced interfacing for sensor-based artificial intelligence applications and distributed I/O systems. A fundamental concern throughout is the accuracy of the data from the analog input circuits through the data conversion devices and output reconstruction components. The chapters are arranged according to the accompanying table into the three divisions of analog, conversion, and digital topics. The balance between theory and practice provides a usefulness for design applications that a more formal approach might lack. The book is intended as an extension to a computer engineering sequence, and to augment instrumentation, manufacturing, or digital control courses at the senior and first-year graduate level.

ANALOG TOPICS	CONVERSION TOPICS	DIGITAL TOPICS
Chapter 1 Sensors	Chapter 5 Conversion Devices	Chapter 9 Processor I/O
Chapter 2 Amplifiers	Chapter 6 Sampled Data	Chapter 10 Distributed Systems
Chapter 3 Filters	Chapter 7 System Design	
Chapter 4 Signal Conditioning	Chapter 8 Advanced Interfacing	

Many of the developments described in this book have not been presented either in other books or literature. Notable are the derivations of component errors, such as average filter error, and system errors including the signal conditioning improvement of signal quality and the intersample error representation of sampled-data signals. Development of the device and system models occurs with each chapter relevant to the subjects addressed and are combined in complete system examples in the later chapters. The author accepts responsibility for the ideas presented and any shortcomings, including the software development, and is especially indebted for the assistance and many helpful discussions with John P. Brockman and the software development efforts of Lawrence P. Ochs.

COMMENTS ON ENCLOSED SOFTWARE DISC

The computer-assisted interface analysis software disc, program listing, and its use are described in Section 7-4 to support the design of data conversion systems. This software tool automates the detailed calculations associated with the quantitative models developed in this book. The floppy disc is formatted to run on all IBM PC/XT/AT computers including PC compatibles supported by MS-DOS. Also enclosed is an address for inquiries related to this program.

Patrick H. Garrett

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Sensors, Excitation, and Linearization

1

1-0 INTRODUCTION

Modern technology leans heavily on the science of measurement. The control of industrial processes and automated systems would be very difficult without accurate sensor measurements. The widespread use of microelectronics and computers is having a profound effect on the design of sensor systems. Signal processing functions increasingly are being integrated within sensors, and digital-type sensors directly compatible with computer inputs are emerging. Nevertheless, measurement is an inexact science requiring the use of reference standards and an understanding of the energy translations involved more directly as the need for accuracy increases.

This chapter presents electrical sensor/transducer techniques and devices useful for both industrial and laboratory measurements. Basic principles are discussed preliminary to examination of a variety of devices applicable to sensor-based data acquisition systems. Emphasis is on contemporary sensors supporting motion, ultrasonics, imaging, and chemical measurements as well as the traditional engineering measurements of temperature, pressure, flow, force, and level. Excitation and linearization circuits also are developed with an interest in minimizing the sensor error contribution to a data acquisition or control system. In practice, the words *sensor* and *transducer* are used interchangeably, although the former more accurately describes the device and the latter the principle involved.

1-1 BASIC PRINCIPLES

A transducer is a device that transfers energy between two systems as in the conversion of thermal into electrical energy by the Seebeck-effect thermocouple. Transducer excitation more often is required as in the case of a bridge sensor element. Figure 1-1 describes a basic sensor circuit and its relationship to the measurement quantity. Transducers are classified by the electrical principle involved in their operation. The actual functioning of a particular transducer is of less concern here than the parameters associated with its output signal as a representation of the measurement. Six descriptive parameters applicable to sensors are found in the following. Sensor error typically is dominated by the nonlinearity of the sensor transfer characteristic, which may be minimized by linearization methods developed in a later section.

Accuracy:	the closeness with which a measurement approaches the true value of a measurand, usually expressed as a percent of full-scale output
Error:	the deviation of a measurement from the true value of a measurand, also usually expressed as a percent of full-scale output
Precision:	an expression of a measurement over some span described by the number of significant figures available
Resolution:	an expression of the smallest quantity to which a quantity can be determined
Span:	an expression of the extent of a measurement between any two limits
Range:	an expression of the total extent of possible measurement values

A general convention is to provide sensor measurements in terms of signal amplitudes as a percent of full scale, or %FS, where minimum-maximum values correspond to 0 to 100%FS. This range may correspond to analog signal levels between 0 and 10 V (unipolar) with full scale denoted as 10 V_{FS}. Alternately, a signal range may correspond to ±50%FS with signal levels between ±5 V (bipolar) and full scale denoted as ±5 V_{FS}.

Sensor signals typically vary in amplitude with time to represent the information content of a measurement. However, a minimum frequency re-

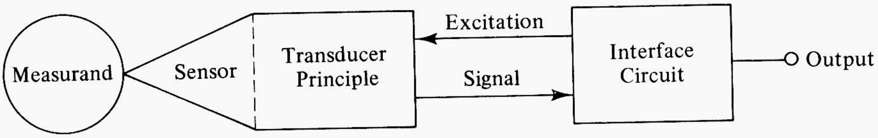

Figure 1-1. Sensor Circuit Elements

sponse or bandwidth must be provided by the data acquisition system to accommodate signal spectral occupancy requirements. The Fourier transform is a convenient method of describing the information bandwidth requirements of a signal. Of interest is the rate at which the Fourier spectral components diminish with increasing frequency. We can acquire insight into this matter by examining the waveforms of Figure 1-2 and their frequency spectrums. Pro-

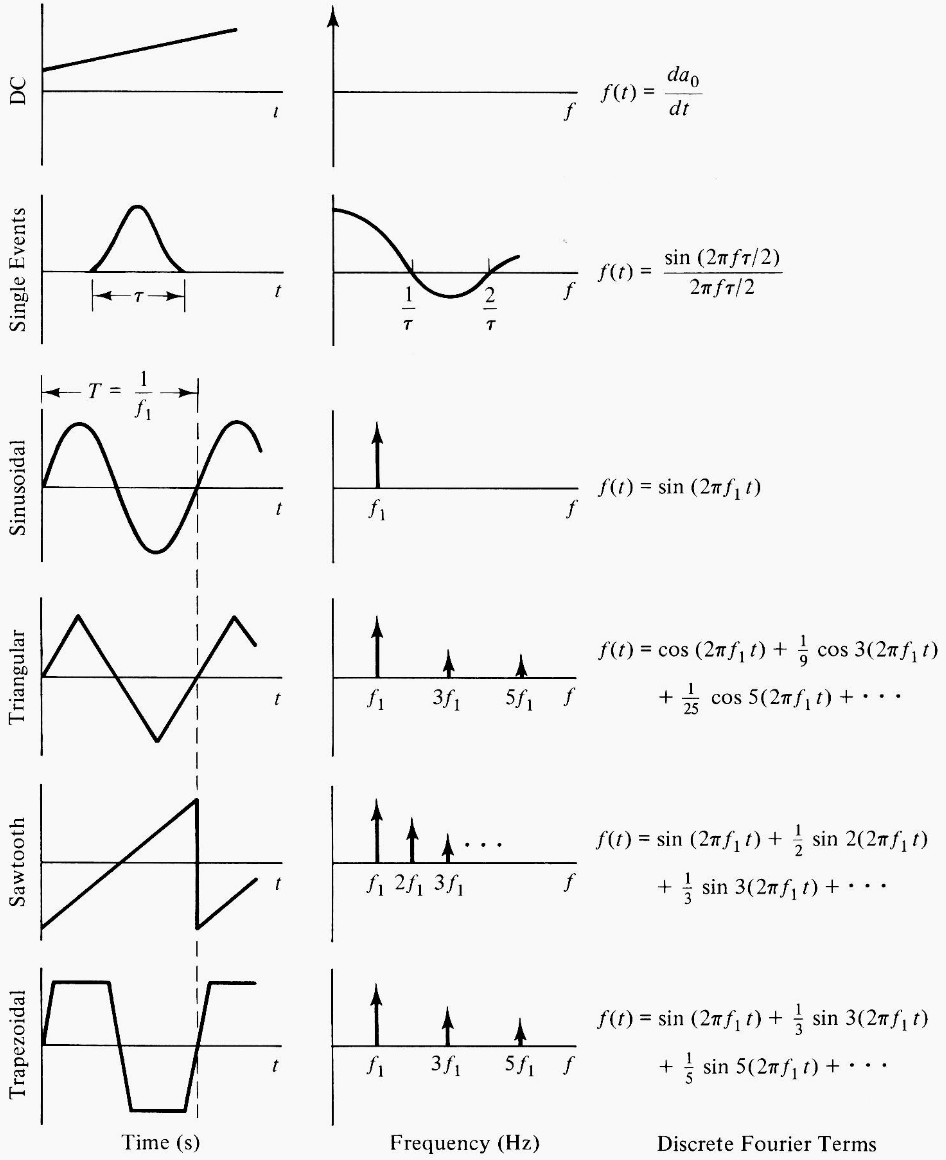

Figure 1-2. Instrumentation Signal Waveform Classifications

TABLE 1-1 SIGNAL BANDWIDTH REQUIREMENTS

Signal	Bandwidth (Hz)
dc	$dV_s/\pi V_{FS}dt$
Sinusoidal	1/period
Harmonic	10/period
Single events	2/width τ

viding signal bandwidth for spectral components until their amplitude diminishes to 5 percent of the fundamental-frequency amplitude value generally is adequate, and will accommodate the typical −20 dB/decade rolloff of complex harmonic signals. The more severe signal classification should be applied when signals are hybrid combinations of the waveforms shown to ensure adequate bandwidth. Table 1-1 summarizes the minimum bandwidth requirements for instrumentation signals, where dc signal rate of change is equated to its sinusoidal equivalent frequency in Hz.

1-2 TEMPERATURE SENSORS

Thermocouples are widely used temperature sensors because of their ruggedness and broad temperature range. Two dissimilar metals are used in the Seebeck-effect temperature-to-emf junction with transfer relationships described by Figure 1-3. Proper operation requires the use of a thermocouple reference

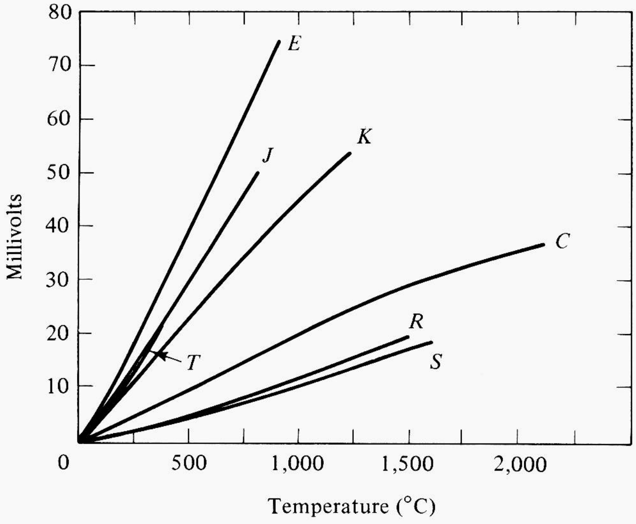

Figure 1-3. Temperature-Millivolt Graph for Thermocouples (*Courtesy Omega Engineering, Inc., an Omega Group Company*)

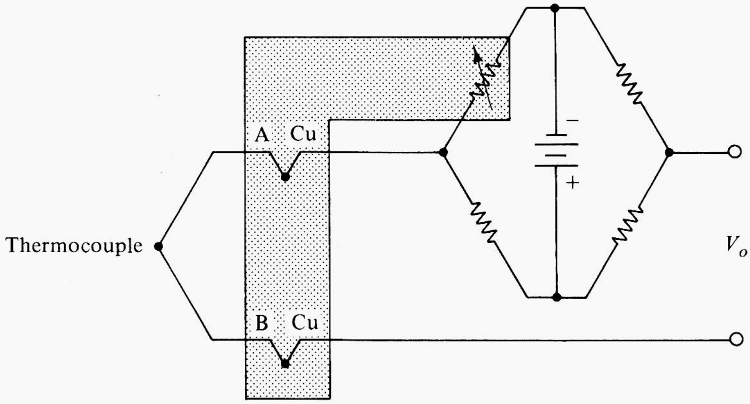

Figure 1-4. Electrical Reference Junction

junction in series with the measurement junction to polarize the direction of current flow and maximize the measurement emf. Omission of the reference junction introduces an uncertainty evident as a lack of measurement repeatability equal to the ambient temperature. Figure 1-4 describes an elementary electrical-bridge reference junction. This incorporates a temperature-sensitive resistor as one leg of a bridge circuit that is thermally integrated with the reference-junction thermocouple where the leads of the measurement-junction thermocouple are referenced to copper. However, the requirement for an isolated supply or battery excitation is an implementation disadvantage of this cold-junction reference method.

An electronic reference junction that does not require an isolated supply can be realized with an Analog Devices AD590 temperature sensor as shown in Figure 1-5. This reference junction usually is attached to an input terminal barrier strip in order to track the thermocouple-to-copper circuit connection thermally. The error signal is determined by the compensation resistor R values referenced to the Seebeck coefficients in mV/°C of Table 1-2, and provided as a compensation signal for ambient temperature variation. The single calibration trim at ambient temperature provides temperature tracking within a few tenths of a °C.

Resistance-thermometer devices (RTDs) provide greater resolution and repeatability than thermocouples, the latter typically being limited to approximately 1°C. RTDs operate on the principle of resistance change as a function of temperature, and are represented by a number of devices. The platinum resistance thermometer is frequently utilized in industrial applications because it offers good accuracy with mechanical and electrical stability. Thermistors are fabricated from a sintered mixture of metal alloys forming a ceramic that exhibits a significant negative temperature coefficient. Metal film resistors have an extended and more linear range than thermistors, but thermistors exhibit

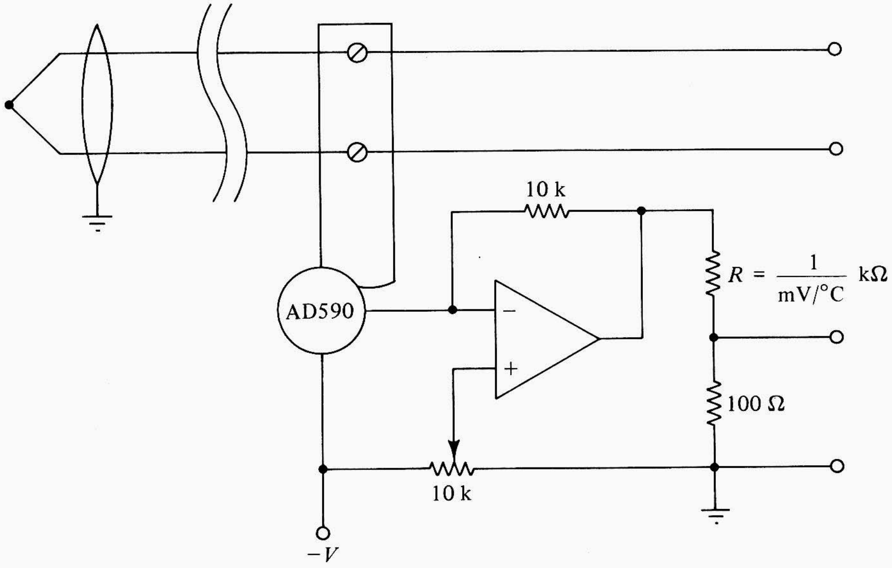

Figure 1-5. Electronic Reference Junction

approximately ten times the sensitivity. RTDs require excitation, usually provided as a constant-current source, in order to convert their resistance change with temperature into a voltage change. Figure 1-6 presents the temperature-resistance characteristic of common RTD sensors.

Optical pyrometers are utilized for temperature measurement when sensor physical contact with a process is not feasible, but a view is available. Measurements are limited to energy emissions within the spectral response capability of the specific sensor used. A radiometric match of emissions between a calibrated reference source and the source of interest provides a current analog corresponding to temperature. Automatic pyrometers employ a servo loop to achieve this balance as shown in Figure 1-7. Operation to 5,000°C is available.

Temperature measurement using a forward-biased *pn* junction is capable of accuracy to 0.1°C over a span of about ±100°C. Fortunately, many temper-

TABLE 1-2 THERMOCOUPLE COMPARISON DATA

Type	Elements, +/−	mV/°C	Range (°C)	Error (%FS)	Application
E	Chromel/constantan	0.063	0 to 800	0.5	High output
J	Iron/constantan	0.054	−250 to 700	0.75	Reducing atmospheres
K	Chromel/alumel	0.040	−250 to 1,200	0.75	Oxidizing atmospheres
R&S	Pt-Rh/platinum	0.010	0 to 1,400	0.25	Corrosive atmospheres
T	Copper/constantan	0.040	−250 to 350	1.0	Moist atmospheres
C	Tungsten/rhenium	0.012	0 to 2,000	0.5	High temperature

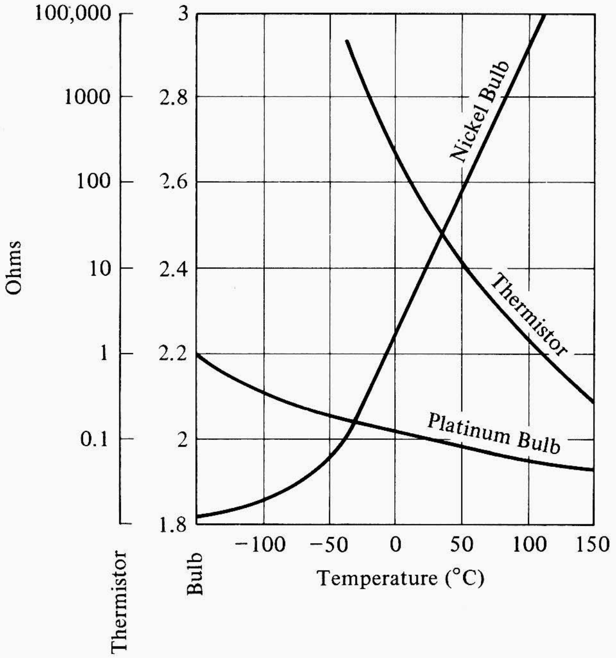

Figure 1-6. RTD Devices

ature measurements of interest fall within this range. The negative temperature coefficient of a diode-connected bipolar transistor can be made very linear by means of constant-current excitation as shown in Figure 1-8. The base-to-emitter forward voltage drop varies by −2.5 mV per plus degree Centigrade.

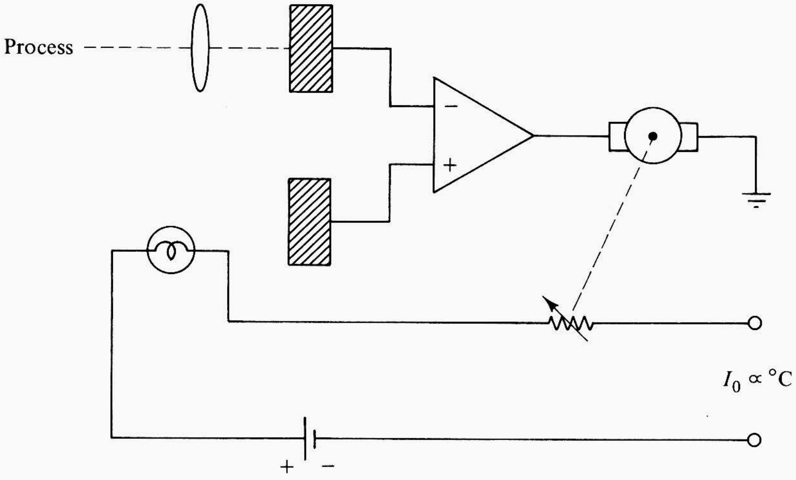

Figure 1-7. Automatic Pyrometer