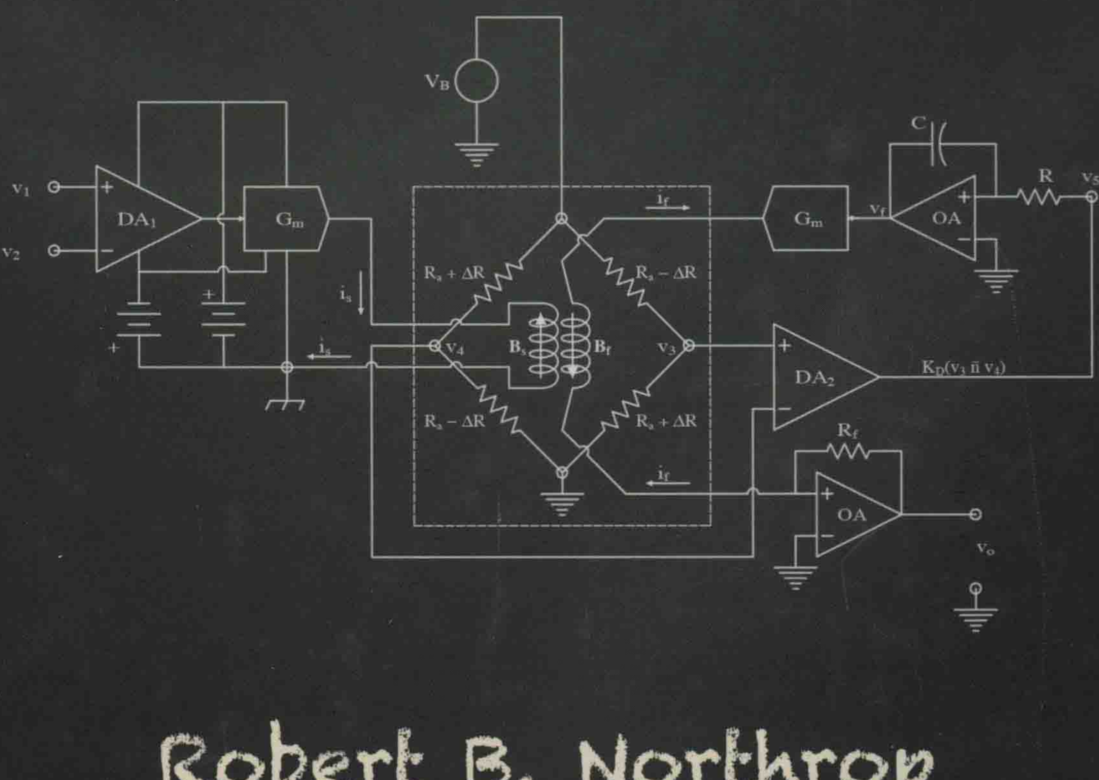
INTRODUCTION TO INSTRUMENTATION AND MEASUREMENTS

THIRD EDITION



Robert B. Northrop

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INTRODUCTION TO INSTRUMENTATION AND MEASUREMENTS

Third Edition

I dedicate this third edition to my wife and daughters, Adelaide, Anne, Kate, and Victoria, who have always believed in my writing.

Preface

Purpose

This text is intended to be used in a classroom course for engineers and scientists. It covers the theory, science, and art of modern instrumentation and measurements (I&M). There is more than enough material to support two semesters' work. Thus, the instructor has the option of choosing those topics and the depth of coverage that suit his or her interests and curriculum. Because of its breadth, *Introduction to Instrumentation and Measurements, Third Edition*, will also be useful as a reference for the practicing engineer and scientist interested in I&M.

Why have a classroom course in I&M? In the United States, over the past three or four decades, many electrical engineering departments have discontinued classroom courses on the theory and practice of I&M. In the past decade, we have also seen the swift development of new and exciting means of measurement using new technologies, the adoption of new standards, and, concurrently, the lack of development of a coherent educational base to support their understanding and use. Using an instrument in the laboratory is not the same as understanding the physical and electronic principles underlying its design, and its functional capabilities and limitations. Clearly, there is now more than ever a need for classroom experience in the new I&M that will give students the necessary technical background to use and design sensors, signal conditioning systems, and I&M systems. I feel that this text supports that need.

This text was written based on my 40 years of experience in teaching a classroom course (EE 230) on electrical instrumentation to juniors and seniors in the Electrical and Computer Engineering Department at the University of Connecticut, Storrs. Obviously, in more than 40 years, we have seen the field of I&M evolve with the rest of electrical engineering technology. Because of the rapid pace of technical development, it generally has been difficult to find an up-to-date text for our electrical instrumentation course. After years of frustration in trying to match a text to course content, I decided to write one that would not only encompass the *traditional* aspects of I&M, but also include material on such topics as modern integrated circuit (IC) and photonic sensors, micro-electromechanical (MEM) and nano-electromechanical (NEM) sensors, chemical and radiation sensors, signal conditioning, noise, data interfaces, basic digital signal processing (DSP), etc.

Reader Background

The reader is assumed to have taken core EE curriculum courses or their equivalents. He or she should be skilled in basic, linear circuit theory, that is, should have mastered Thevenin's and Norton's theorems, Kirchoff's laws, superposition, dependent sources, and ideal op-amps, and should know how to describe DC and AC steady-state circuits in terms of linear loop and node equations. An *introductory systems course* should have given him or her familiarity with both time- and frequency-domain methods of describing linear dynamic systems characterized by ordinary, linear, differential, or difference equations, including state space, Fourier, Laplace and z-transforms, transfer functions, steady-state frequency response of systems, as well as Bode plots. From physics or an *EE course in electromagnetics*, the reader should have a basic knowledge of electric and magnetic fields, inductance, capacitance, reluctance, transformers, etc. There should also be some familiarity with electromagnetic waves, Maxwell's equations, transmission lines, and polarization. From a *first course in electronics*, there should be basic knowledge of bipolar junction transistors (BJTs), junction field-effect transistors (JFETs), diodes, and photodiodes and their simple linear circuit models.

Scope of the Text

A major feature of this book is its breadth of coverage. Throughout the text, a high level of mathematical analytical detail is maintained. It is not a *picture book;* we have assumed that readers have already had contact with basic electrical instruments, including oscilloscopes and meters in their introductory EE and physics labs.

In the following paragraphs, we give an overview of the contents:

Chapter 1, *Measurement Systems,* is an introductory chapter, which illustrates typical measurement system architecture and describes sensor dynamics, signal conditioning, and data display and storage. Errors in measurements are discussed, including the meaning of accuracy and precision, limiting error, etc. The recent (1990) quantum standards adopted for the volt and the ohm are described, as well as other modern electrical and physical standards.

In Chapter 2, *Analog Signal Conditioning in Instrumentation,* we describe, largely at the systems level, means of conditioning the analog outputs of various sensors. Op-amps, differential, instrumentation, autozero, and isolation amplifiers are covered. Applications of op-amps in active filters, differential instrumentation amplifiers, charge amplifiers, phase-sensitive rectifiers, etc., are shown. We also give practical consideration to errors caused by offset voltage, bias currents, input impedance, slew rate and gain × bandwidth product, etc. There is also a section on nonlinear signal processing with op-amps.

Noise and Coherent Interference in Measurements are treated in depth in Chapter 3. A heuristic yet rigorous approach is used in which we define and use one-sided, noise voltage and current power density spectra to describe the effect of noise in instruments and measurement systems. Noise factor and figure are defined, and output signal-to-noise ratios are used to evaluate measurement system resolution. Examples are given of calculations of the noise-limited resolution of the quantity under measurement (QUM). Techniques are shown for the minimization of coherent interference.

The traditional topics of *DC Null Methods of Measurement* and *AC Null Measurements* are covered in Chapter 4 and Chapter 5, respectively. Wheatstone and Kelvin bridges and potentiometers are described in Chapter 4, and the major AC bridges used to measure inductance, Q, capacitance, and D are treated in Chapter 5. Material in this chapter includes a description and analysis of the *Anderson current loop* method of reading sensor outputs.

A *Survey of Sensor Mechanisms* is presented in Chapter 6. This is a large and substantive chapter covering a broad range of sensor mechanisms and types. Of special note is the introduction of certain fiber-optic and electro-optic sensors, as well as selected chemical and ionizing radiation sensors. The Sagnac effect is introduced, and the basic fiber-optic gyro is described. New material in Chapter 6 includes a description and analysis of sensors based on the giant magnetoresistive effect (GMR) and the anisotropic magnetoresistive (AMR) effect. Pyroelectric IR sensors are also introduced. Means of measuring the rotation of linearly polarized light is presented. A substantive section on photomultiplier tubes and channel-plate photomultipliers is also provided.

Chapter 7, *Applications of Sensors to Physical Measurements*, presents a detailed analysis of mechanical gyroscopes, clinometers, and accelerometers. It covers the Doppler effect in ultrasonic velocimetry and laser Doppler velocimetry. It also provides an introductory section on the global positioning system (GPS), a section on optical interferometry, and an extensive introduction to spectrophotometry, sonoluminescence, and surface plasmon resonance used for substance quantification. The measurement of force, pressure, and torque is also covered.

In Chapter 8, *Basic Electrical Measurements*, the classic means of measuring electrical quantities are presented, as well as newer methods such as Faraday magneto-optic ammeters and Hall effect gaussmeters and wattmeters. Electronic means of measuring stored charge and static electric fields are also described.

Digital Interfaces in Measurement Systems are covered in Chapter 9. It begins with a description of the sampling theorem, aliasing and quantization. The traditional topics of hold circuits, digital-to-analog convertors (DACs), and many types of ADCs are covered. The chapter also deals with data buses. New material includes a section on dithering as a means to reduce quantization noise, a section on delta–sigma ADCs, and a section on the ubiquitous universal serial bus (USB). Virtual instruments and PCI eXtensions for Instrumentation (PXI) systems are also described.

Chapter 10, *Introduction to Digital Signal Conditioning in Instrumentation*, was written to acquaint the reader with this specialized field because digitized, measured data is processed and stored on computers in modern instrumentation practice. The *z*-transform and its use in describing filtering operations on discrete, digitized data in the frequency domain are introduced. Examples of FIR and IIR digital filters are given, including numerical integration and differentiation routines, viewed both in the time and frequency domain. The discrete and fast Fourier transforms are covered, and the effect of data windows on spectral resolution is discussed. Finally, the use of splines in interpolating discrete data sequences and in estimating missing data points is described.

An *all-new* Chapter 11, *Solid-State Chemical Microsensors and Wireless Instrumentation*, has been written to address these contemporary topics. Modern tin oxide gas sensors are described, as well as ChemFETs, ISFETs, and Schottky-diode-based chemical microsensors. Electronic noses (E-noses) are introduced. Wireless data transmission (WDX) protocols are described along with certain radio chips and their antennas, including a new section describing broadband, space-saving, fractal antennas. Energy-harvesting ICs and supercapacitors are described, as well as absorbable electronic circuits for temporary implants in living systems.

Chapter 12, *Introduction to Mechanical Microsensors*, is another all-new chapter covering mechanical microsensors (MEMS and NEMS). It covers micromachined electromechanical accelerometer designs, several MEM rate gyro designs, and cantilever-based MEMS. Resonant cantilevers are shown to make effective chemisensors.

In Chapter 13, *Examples of the Design of Measurement Systems*, four examples of complex measurement systems developed by my students and myself are given to illustrate design philosophy: (1) a self-nulling microdegree polarimeter to measure glucose concentration; (2) a system to detect and locate partial discharges on underground, high-voltage power cables; (3) the design of a laser velocity and distance measuring system; and (4) the design of capacitance sensors to detect hidden objects.

Home Problems

Chapters 1 through 12 are followed by problems taken from my extensive classroom experience in teaching courses in I&M at the University of Connecticut. The problems are doable; they are student tested. A home problem solutions manual is available from the publisher.

Glossary

This book has a comprehensive glossary covering the acronyms and abbreviations used in the broad field of I&M. It also describes and defines many terms used in the text.

References and Bibliography

The references cited encompass a wide time span, from the 1950s to the present. There are many recent entries of review articles and specialized texts that should lead the reader interested in pursuing a specialized area of I&M further into a particular field.

Index

A complete index allows the reader to access topics featured and not featured in the contents.

Features

Every chapter in this book has been revised to reflect modern technology. Traditional material has been retained, however. Two new chapters have been added containing contemporary material. They expand the scope of the text to include geophysical, chemical, micromechanical, and photonic instrumentation. Some of this unique new material includes the following:

- The Anderson current loop technology for conditioning the outputs of remote resistive and capacitive sensors is found in Chapter 4.
- The design of optical polarimeters and their application to polarization-responding sensors.
- Photonic measurements with photomultipliers and channel-plate photon sensors.

- The Sagnac effect and fiber-optic gyroscopes are introduced as a sensitive means of measuring angular velocity.
- Vibrating mass and vibrating disk rate gyros are introduced. The novel Humphrey air jet gyro is analyzed. Traditional pendulum as well as fluid-filled clinometers are described.
- The global positioning system (GPS) and the various modifications to improve its accuracy are described.
- Substance detection using photons is introduced in Chapter 7. Dispersive, nondispersive, and Fourier transform spectroscopy are described, as well as sonoluminescence and surface plasmon resonance.
- Chapter 9 on digital interfaces has new sections on dithering, delta-sigma ADCs, data acquisition cards, the USB, and virtual instruments and PXI systems.
- An all-new Chapter 11 describes solid-state chemisensors, including tin oxide gas sensors, Schottky diode chemisensors, chemFETs, ISFETs, and *E*-noses and introduces radio ICs for use in WDX. Broadband, compact, fractal antennas are also described.
- A new Chapter 12 covers micromachined IC accelerometers and rate gyros and describes resonant MEM cantilever chemisensors.

Author

Robert B. Northrop, PhD, was born in White Plains, New York, in 1935. After graduating from Staples High School in Westport, Connecticut, he majored in electrical engineering (EE) at MIT, graduating with a bachelor's degree in 1956. At the University of Connecticut, he earned his master's degree in electrical and systems engineering in 1958. As the result of a long-standing interest in physiology, he enrolled in a PhD program at UCONN in physiology, doing research on the neuromuscular physiology of molluscan catch muscles. He received his PhD in 1964.

In 1963, he rejoined the UCONN EE Department as a lecturer and was hired as an assistant professor of EE in 1964. In collaboration with his PhD advisor, Dr. Edward G. Boettiger, Dr. Northrop secured a five-year training grant in 1965 from NIGMS (NIH), and started one of the first, interdisciplinary, biomedical engineering graduate training programs in New England. UCONN currently awards MS and PhD degrees in this field of study, as well as BS degrees in engineering under the BME area of concentration.

Throughout his career, Dr. Northrop's research interests have been broad and interdisciplinary and have been centered on biomedical engineering and physiology. He has done research (sponsored by the US Air Force Office of Scientific Research [AFOSR]) on the neurophysiology of insect and frog vision and devised theoretical models for visual neural signal processing. He also did sponsored research on electrofishing and developed, in collaboration with Northeast Utilities, effective working systems for fish guidance and control in hydroelectric plant waterways on the Connecticut River at Holyoke, Massachusetts, using underwater electric fields.

Still another area of Dr. Northrop's sponsored research (by NIH) has been in the design and simulation of nonlinear, adaptive digital controllers to regulate in vivo drug concentrations or physiological parameters, such as pain, blood pressure, or blood glucose in diabetics. An outgrowth of this research led to his development of mathematical models for the dynamics of the human immune system, which were used to investigate theoretical therapies for autoimmune diseases, cancer, and HIV infection.

Biomedical instrumentation has also been an active research area for Dr. Northrop and his graduate students: An NIH grant supported studies on the use of the ocular pulse to detect obstructions in the carotid arteries. Minute pulsations of the cornea from arterial circulation in the eyeball were sensed using a no-touch, phase-locked, ultrasound technique. Ocular pulse waveforms were shown to be related to cerebral blood flow in rabbits and humans.

More recently, Dr. Northrop addressed the problem of noninvasive blood glucose measurement for diabetics. Starting with a Phase I SBIR grant, he developed a means of estimating blood glucose by reflecting a beam of polarized light off the front surface of the lens of the eye and measuring the very small optical rotation resulting from glucose in the aqueous humor, which in turn is proportional to blood glucose. As an offshoot of techniques developed in micropolarimetry, he developed a magnetic sample chamber for glucose measurement in biotechnology applications. The water solvent was used as the Faraday optical medium.

He has written numerous papers in peer-reviewed journals, and twelve textbooks: *Analog Electronic Circuits* (Addison Wesley, 1990), and the following books published by CRC Press: *Introduction to Instrumentation and Measurements* (1997), *Endogenous and Exogenous Regulation* *and Control of Physiological Systems* (2000), *Dynamic Modeling of Neuro-Sensory Systems* (2001), *Noninvasive Instrumentation and Measurements in Medical Diagnosis* (2002), *Analysis and Application of Analog Electronic Circuits in Biomedical Engineering* (2004), *Introduction to Instrumentation and Measurements*—2nd edition (2005), *Introduction to Molecular Biology, Genomics & Proteomics for Biomedical Engineers* (with Anne N. Connor) (2008), *Signals and Systems Analysis in Biomedical Engineering*—2nd edition (2010), *Introduction to Complexity and Complex Systems* (2011), *Analysis and Application of Analog Electronic Circuits in Biomedical Engineering*—2nd edition (2012), and *Ecological Sustainability: Understanding Complex Issues* (with Anne N. Connor) (2013).

Dr. Northrop is a member of Sigma Xi, Phi Kappa Phi, Eta Kappa Nu, and Tau Beta Pi and a founding fellow, Connecticut Academy of Engineers (2003).

His current research interest lies in complex systems and sustainability.

Dr. Northrop was on the Electrical & Systems Engineering faculty at UCONN until his retirement in June 1997. Throughout this time, he was director of the Biomedical Engineering Graduate Program. As emeritus professor, he teaches graduate courses in biomedical engineering, writes texts, sails, and travels. He lives in Chaplin, Connecticut, with his wife and a smooth fox terrier.

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