Circuit Design for Electronic Instrumentation

ANALOG AND DIGITAL DEVICES FROM SENSOR TO DISPLAY

Darold Wobschall

Circuit Design for Electronic Instrumentation

ANALOG AND DIGITAL DEVICES FROM SENSOR TO DISPLAY

Darold Wobschall
Associate Professor, Electrical Engineering
State University of New York at Buffalo

McGRAW-HILL BOOK COMPANY
New York St. Louis San Francisco Auckland Bogotá
Düsseldorf Johannesburg London Madrid
Mexico Montreal New Delhi Panama
Paris São Paulo Singapore
Sydney Tokyo Toronto

Library of Congress Cataloging in Publication Data

Wobschall, Darold.
Circuit design for electronic instrumentation.

Includes index.
1. Electronic instruments—Design and construction. I. Title.
TK7878.4.W62 621.3815'3 79-9084
ISBN 0-07-071230-1

1234567890 KPKP 7865432109

The editors for this book were Tyler G. Hicks and Joseph Williams, the designer was Naomi Auerbach, and the production supervisors were Sally Fliess and Paul A. Malchow.
It was set in Baskerville by University Graphics, Inc.

Printed and bound by The Kingsport Press.

Preface

Electronic instrument design is now a widely practiced craft. Its increase in popularity in recent years with both professional and amateur engineers can be attributed to the wide variety of integrated circuits which reduce the cost and complexity of implementing a design approach.

With the proliferation of electronic devices there has been a corresponding expansion of electronic literature and a subdivision into areas of specialization which treat only certain aspects of instrument design. As a consequence, students and non-specialists may spend more effort in finding electronic design information than in designing it, or may not even become aware of standard techniques. I have attempted to simplify the design process by gathering and describing standard devices and techniques in a single, reasonably compact book. The designer can then go to a single source for ideas and approaches to an electronic design problem.

The objective of this book is to provide guidance in the design of complete electronic instruments, from input to output or sensor to readout. Therefore, interfacing and interrelation of circuits is emphasized. All the parts of a digital thermometer, for example, which include a thermosensor, an analog amplifier, an A/D converter, and digital displays, are described.

Sections of the text cover temperature, electrooptical, and displacement transducers or sensors, analog and digital devices, analog and digital signal processing, digital displays, analog-to-digital conversion, data transmission, and data recording. Many or most instruments in use today utilize several of these circuits or devices.

While microprocessor systems are not covered in full detail, many microprocessor-based instruments employ the circuits described here as peripheral devices. The discussions of multiplexing and data transmission are especially appropriate. The chapter on microprocessors expands on the background by describing the interfacing of microprocessors to external devices.

Coverage of a wide variety of topics in compact form requires brevity and careful selection. Preference is given here to more basic and useful circuits. Sufficient explanation is included to allow the reader to understand circuit operation, but extensive mathematical treatment and detailed descriptions of specialized topics are avoided. Should an interest in understanding the details of specific circuits be kindled, I expect that most readers will prefer, as I do, to consult specialized texts or to analyze the circuit themselves.

Students of electronics engineering design will find this book a useful reference text. In one sense, design is not taught by books but through practice and laboratory experience. It must be done by the student. A text can only complement the process by providing guidelines and the basic circuits which are the building blocks of electronic instruments. This text is intended to do so while not relieving the student of exercise by leaving no detail unsaid. Students in a senior-level electronic design course, for which this book was developed, design, analyze, construct, and test instruments on an individual basis as a part of the course requirements. Such projects, even in the academic environment, provide experience akin to that encountered industrially, which is widely recognized as a valuable facet of an engineer's education. Several examples of how the various circuits are combined to form complete instruments are given in the text. Design problems are also included to provide further design exercise for students.

I am indebted to many students who have used earlier drafts of this book and whose suggestions and encouragement have resulted in the present version. I also wish to thank the typists who worked on the various drafts, particularly Kay Ward and my daughter, Tina. Finally, I thank my wife, Katrina, for proofreading when she would rather be planting tulips.

DAROLD WOBSCHALL

Contents

Preface ***ix***

Part One Semiconductor Devices and Basic Circuits

1. An Approach to Electronic-Instrument Design 3

1-1	The Parts of an Electronic Instrument	3
1-2	Circuit Design and Refinement	4
1-3	Integrated-Circuit Advantages	6
1-4	Interfacing and Matching Sections	7
1-5	To Build or To Buy?	8
1-6	Analog or Digital?	9
1-7	The Role of Circuit Analysis	9

2. Discrete-Device Characteristics 11

2-1	Basic Diode Characteristics	11
2-2	Special-Purpose Diodes	13
2-3	Bipolar Junction Transistors (BJT)	15
2-4	Field-Effect-Transistor (FET) Characteristics	17
2-5	The SCR and Triac	20
2-6	Programmable Unijunction Transistors (PUT)	22
2-7	Lamp and Relay Drivers	23

3. Operational-Amplifier Characteristics 26

3-1	Ideal Op-amps	26
3-2	Inside the Voltage-controlled Op-amp	27
3-3	Nonideal Op-amp Characteristics	29
3-4	Types of Op-amps	36
3-5	Measurement of Characteristics	38
3-6	Feedback Fundamentals	40
3-7	Stability and Compensation	43

4. Operational-Amplifier Configurations 45

4-1	Noninverting Amplifier	45
4-2	Inverting Amplifier	47
4-3	Differential Amplifier	48
4-4	Summing Amplifier	48
4-5	Integrator	49
4-6	Current-to-Voltage Converter	51
4-7	Bridge Amplifier	53
4-8	Instrumentation Amplifier	55
4-9	Logarithmic Amplifier	56
4-10	OTA Multiplier or Gain Control	59
4-11	Current-Differencing-Amplifier (CDA) Configurations	60
4-12	Voltage-Offset–DC and Bias-Adjustment Methods	62
4-13	Comparator	63
4-14	Multivibrators	63
4-15	Peak Reader	66
4-16	Output Limiting and Clipping	67

5. Basic Digital Devices: TTL and CMOS 69

5-1	Inverter-Drivers	70
5-2	OR, NOR, and XOR Gates	70
5-3	AND and NAND Gates	71
5-4	Transmission Gates	71
5-5	Set-Reset *(SR)* Flip-Flops	72
5-6	*JK* Flip-Flops	73
5-7	Binary Counters	75
5-8	Decimal (BCD) Counters	76
5-9	Type-*D* and Related Flip-flops	79
5-10	Special-Purpose Counters	80
5-11	Inside TTL Integrated Circuits	82
5-12	Inside CMOS Integrated Circuits	85
5-13	TTL and CMOS Characteristics	87
5-14	Comparison of Digital Families	88
5-15	Diode Gates	89
5-16	Op-amp–TTL–CMOS Interfacing	90
5-17	Schmitt Triggers	93
5-18	Line Receivers	93
5-19	Digital Comparators	95
5-20	Negative-Logic Notation	96
	Basic-Circuit Design Examples	98
	Basic-Circuit Design Problems	100

Part Two Transducers

6. Temperature Sensors 105

6-1 Thermistors 105
6-2 Other Resistance Thermometers 109
6-3 Bridge Amplifier for Resistance Sensors 110
6-4 Thermocouples 111
6-5 Additional Thermosensors 113
6-6 IC Temperature Transducer 114

7. Electrooptical Devices 115

7-1 Optical Spectra and Energy Relations 115
7-2 Photodiodes 118
7-3 Light-emitting Diodes 120
7-4 Semiconductor Photocells and Related Devices 122
7-5 Photomultipliers 123
7-6 Optical Isolators 125
7-7 Digital Displays 127

8. Displacement Transducers 131

8-1 Strain Gages 131
8-2 Electromagnetic Velocity Sensors 133
8-3 Inductive Transducers 136
8-4 Capacitive Transducers 138
8-5 Digital Displacement Transducers 140
8-6 Other Displacement Transducers 141
8-7 Magnetic Proximity Detectors 143

9. Fluid-Measurement Gages 146

9-1 Pressure Gages 146
9-2 Flow Gages 147
9-3 Vacuum Gages 149
9-4 Moisture and Humidity Sensors 151
9-5 Liquid-Level Gages 153

10. Chemical and Biological Electrodes 157

10-1 Reversible Electrodes 157
10-2 Reference Electrodes 160
10-3 Membrane Potentials 161
10-4 pH Meters 162
10-5 Specific-Ion Electrodes 163
10-6 Microelectrodes 165
10-7 Skin Electrodes 167
10-8 Differential Electrode Preamplifiers 169
10-9 Electric-Shock Hazards 172
Transducer Design Examples 174
Transducer Design Problems 176

Part Three Signal Amplification and Processing

11. Signal Filtering 181

11-1 Ideal Filters 181
11-2 Single-Stage High- and Low-Pass Filters 183
11-3 Integrator-Averager (Active Low-Pass) 185
11-4 Differentiator (Active High-Pass) 186
11-5 *LC* Bandpass Filters 187
11-6 Notch and Bandpass Filters 188
11-7 Butterworth Filters 191
11-8 Chebyshev and Other Active Filters 194
11-9 Gyrators 196
11-10 Derivation of Active-Filter Equations 197

12. Oscillators and Signal Sources 206

12-1 Wien-Bridge Oscillators 206
12-2 Phase-Shift Oscillators 208
12-3 Colpitts Sinusoidal Oscillator 209
12-4 Pulse Generators 210
12-5 Square-Wave Generators 211
12-6 Triangular-Wave Generators 212
12-7 Crystal Oscillators 213
12-8 DC-Signal Sources 215
12-9 IC Function Generator 215

13. High-Frequency Amplifiers 219

13-1 Higher-Frequency Op-amps 219
13-2 Wideband (Video) Amplifiers 220
13-3 Tuned RF Amplifiers 221
13-4 Limiting IF Amplifiers 222
13-5 Inside the Open-Collector RF-IF Amplifier 222
13-6 CMOS and TTL Inverters as Linear Amplifiers 223

14. Analog-to-Digital Conversion 226

14-1 D/A Converter Specifications 226
14-2 Voltage-to-Frequency Converters 228
14-3 IC Voltage-to-Frequency Converters 230
14-4 VFCs as A/D Converters 233
14-5 Ramp Converters 233
14-6 D/A Converters 236
14-7 Counter and Servo A/D Converters 238
14-8 Successive-Approximation A/D Converters 240

15. Modulation and Demodulation 242

15-1 Diode Rectifiers 242
15-2 AC-to-DC Converters 244
15-3 Phase-sensitive Detectors 247
15-4 Amplitude Modulation and Control 251

15-5 Frequency Modulation 253
15-6 FM Detectors 254
15-7 Phase-Locked-Loop Theory 255
15-8 PLL Integrated Circuits 259

16. Noise and Noise Reduction 261

16-1 Noise Sources and Terminology 261
16-2 Semiconductor Noise 263
16-3 Amplifier Noise 264
16-4 Bandwidth Limitation 267
16-5 Signal Averaging 269
Signal Amplification and Processing Design Examples 271
Signal Amplification and Processing Design Problems 272

Part Four Data Switching, Control, and Readout

17. Pulse Timers and Counters 277

17-1 IC Timers 277
17-2 Digital One-Shot Multivibrators 279
17-3 Triggered Sweep 281
17-4 Pulse-Delay Circuits 282
17-5 Bounceless Switches 283
17-6 Pulse Counters 285
17-7 Frequency Dividers and Multipliers 287
17-8 Digital Interval Timers 289
17-9 Frequency Counters 290
17-10 Decoders and Encoders 290
17-11 Pulse Sequencing 293

18. Multiplexing 294

18-1 Analog Switches 295
18-2 Analog Multiplexers and Demultiplexers 295
18-3 Latches 299
18-4 Digital Switches 300
18-5 Display Multiplexers 300
18-6 Serial and Parallel Digital-Data Conversion 301
18-7 Track-and-Hold Circuit 303
18-8 Charge-coupled Devices 304

19. Data Transmission and Recording 306

19-1 Analog Telemetry Techniques 306
19-2 Digital Telemetry and Recorders 310
19-3 MODEMs 313
19-4 UARTs 315
19-5 Keyboard and Character Generators 316
19-6 Tape Recorders 319

20. Introduction to Microprocessors 324

20-1 Microprocessor-System Organization 325
20-2 Memory-Address Organization 327
20-3 Arithmetic, Logic, and Branching Operations 330
20-4 Register Transfer Operations 333
20-5 Input/Output (I/O) Ports 334
20-6 Interrupt and Subroutine Transfers 338
20-7 Timing Diagrams 340
20-8 Memory (RAM and PROM) Circuits 341
20-9 Programming Methods 345
20-10 Microprocessor Types 346
Data Switching, Control, and Readout Design Example 347
Data Switching, Control, and Readout Design Problems 348

Part Five Power Circuits

21. Power Supplies 353

21-1 Power-Supply Characteristics 353
21-2 Rectifier-Capacitor Input Section 355
21-3 Unregulated Supplies 359
21-4 Diode Voltage Regulators 360
21-5 Op-amp Regulators 361
21-6 Overvoltage Protection 363
21-7 Voltage-Regulator ICs 364
21-8 Single-to-Dual Supplies 365
21-9 DC-to-DC Converters 367
21-10 Batteries and Battery Chargers 368

22. Power Amplification and Control Circuits 373

22-1 Power-Output Transistor Configurations 373
22-2 Op-amp Output Boosters 376
22-3 AC Amplifiers 376
22-4 SCR and Triac Drivers 378
22-5 Small Motors and Drivers 380
22-6 Stepping Motor Drivers 382
Power-Circuit Design Examples 383
Power-Circuit Design Problems 384

Index 385

Part One

Semiconductor Devices and Basic Circuits

Chapter One

An Approach to Electronic-Instrument Design

The design of an electronic instrument consists largely of the creative arrangement of proved circuits and devices to achieve a chosen performance goal. Of course, technical requirements must be met in the choice and interconnection of subunits. A textbook cannot teach creativity, but it can describe the devices and circuits which are the ingredients of the design process. It also can provide examples. Actually experience is the best teacher. This chapter has been written as an aid to the inexperienced designer, who may lack confidence or general guidelines to instrument design.

1-1 The Parts of an Electronic Instrument

The purpose of an electronic instrument is typically the measurement and display of a physical parameter. Generally an instrument can be divided into the sections indicated by the block diagram of Fig. 1-1. An input transducer is a device with a measurable electrical parameter which is a function of, and often linearly proportional to, the physical parameter being measured. For example, the resistance change (electrical parameter) of a thermistor (transducer) is proportional to the temperature (physical parameter) at least over a limited range. Usually some type of read-in circuit is present, which converts the change in the electrical parameter of the transducer into an electrical signal which can be easily measured. Signal voltage or frequency, in particular, can be measured accurately. A transducer read-in or converter circuit may be quite simple. For the

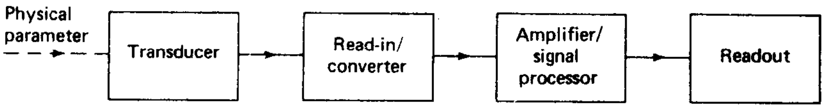

Fig. 1-1 General block diagram of an electronic instrument.

thermistor a dc voltage source and a resistor are all that is needed to convert the resistance change into a proportional voltage change (signal).

Amplification and perhaps further processing of the signal are often required before it is suitable for readout. Signal processing can be elaborate, involving separation into frequency components, timing of various segments, or conversion from ac into dc. Signal readout may consist of a panel meter, a digital display, or perhaps conversion into a form suitable for transfer to a digital computer. In addition to these parts, an instrument generally requires a power supply, which may be so standard that it needs no separate discussion, and control circuits, which may be an integral part of the blocks already discussed.

1-2 Circuit Design and Refinement

Instrument design consists in many cases simply of choosing an appropriate circuit for each block from a catalog of available circuits with due consideration to the matching or interfacing of these blocks. It is assumed, of course, that the function, performance characteristics, or specifications are known. A wide variety of transducers and circuits are available. More often than not the problem facing the designer is how to choose compatible circuits from the wide variety available rather than finding a circuit which performs a particular function. Compatibility between sections must be stressed since without it the required interfacing circuits can increase the complexity of the instrument and may require more effort than a careful selection of basic circuit blocks.

Circuits to perform a particular function can be obtained from a number of sources, e.g., a text like this, journals or magazines concerned with electronic instrumentation, electronic manufacturer's application notes, and local consultants or friends interested in this subject. An experienced designer also builds up a repertoire of circuits or bag of tricks on which to draw, together with a feeling for which circuits, singly or in combination, are easy to implement.

Sometimes a complete and detailed circuit is found to perform the task required, in which case no design is required; all that remains is construction and test of the instrument. More often than not the circuit found will be incomplete, have too many or too few functions, or otherwise not have quite the right specifications. The designer's task is then to edit, modify, or fill in missing parts of the circuit. Circuits found in textbooks or application notes generally have one or more components whose values are unspecified, but a formula or procedure is given so that appropriate values to fit a specific application can be chosen. For example, the gain A of a feedback amplifier might be determined by the ratio of two resistors ($A = R_b/R_a$), and the designer is free to set, within limits, the gain by the resistor selection.

Considerable design freedom is usually available, and the student who has been narrowly schooled in the analytical methods of circuit analysis is bothered by this extra freedom at first. A gain of 10 in the example above can be obtained with the combination $R_a = 100\ \text{k}\Omega$ and $R_b = 10\ \text{k}\Omega$, or $R_a = 20\ \text{k}\Omega$ and $R_b = 2\ \text{k}\Omega$, or an infinite number of other choices. Many analytically inclined students would like to see only one solution. They must learn to live with these extra degrees of freedom and even appreciate them.

Once a tentative circuit has been chosen, it should be analyzed, refined, and tested. This is an iterative process, as the flowchart of Fig. 1-2

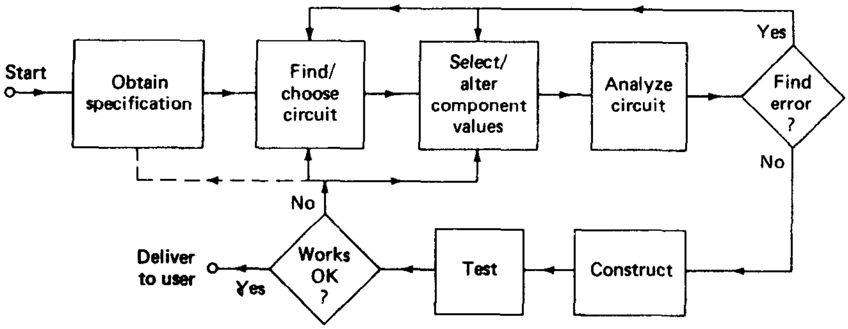

Fig. 1-2 Instrument-design flowchart.

suggests. In the analysis step, the voltage, current, gain, frequency response, or other appropriate parameters are examined quantitatively. This may only consist of a check on the compatibility of voltages between stages or may involve a more thorough mathematical analysis of the system response. A computer-aided design procedure may be used, especially in complicated high-frequency circuits. If errors or deviations from the given specifications are uncovered, the circuit component values are appropriately modified or if necessary a better circuit is found. These steps are repeated until no errors are apparent. In other words, the circuit should look good on paper before one proceeds to the next stages, the constructing and testing of the instrument. If problems are uncovered in the testing stage, as is usually the case, the component values may have to be modified, or in the worst case the circuit will have to be scrapped and a new one selected (back to the drawing board).

If the instrument does not meet the specifications provided, the possibility of changing the specifications to fit the actual performance should be considered. Often the specifications provided initially are unnecessarily stringent or unrealistic in some respects, but until the design is complete, the problem is not recognized. Quite possibly a particular requirement was set rather arbitrarily or with a very generous margin of safety which upon closer examination might be modified. Drawing up a complete and realistic set of specifications, in other words, is often part of the design problem and the iterative loop rather than an unalterable input.

1-3 Integrated-Circuit Advantages

Instrument design has been enormously simplified by the wide availability of integrated circuits (ICs). Circuits which might take hours to design using discrete transistors take only minutes with ICs. Further, the instrument with ICs will probably work much better, cost much less, and be much easier to construct. A beginner today can in some cases design and construct an amplifier in an hour which will outperform an amplifier requiring days to make by an electrical engineer one or two decades ago. With many IC configurations, the choice of components is simple, even cookbooklike. Novices are not likely to run into many problems with these configurations, and the more experienced designers also appreciate them because they take so little time. Of course, not all circuits involving ICs are easy to design or even understand; there is still an adequate challenge to the experienced engineer. The point is that the easy end of the circuit spectrum is easy indeed and should not be feared by the inexperienced.

An important advantage of most ICs is that they approach ideal behavior closer than the typical discrete circuit. They are more linear and insensitive to power-supply fluctuations, for example. Actually these desirable characteristics are achieved through external negative-feedback stabilization and internal regulation and stabilization circuits on the IC chip itself, which can be duplicated with discrete transistors. However an IC may have the equivalent of 10, 50, or even more transistors at less than the cost of a single transistor (not to mention the cost of wiring the equivalent circuit), and therefore the implementation of the equivalent circuit with discrete transistors is usually impractical.

It would be a mistake to leave the impression that all electronic func-