

CAPACITIVE SENSORS

Design and Applications

Larry K. Baxter



IEEE
PRESS



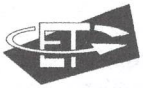
IEEE Press Series on Electronics Technology
Robert J. Herrick, Series Editor

IEEE Industrial Electronics Society, Sponsor

Capacitive Sensors

Design and Applications

Larry K. Baxter



IEEE Press Series on Electronics Technology
Robert J. Herrick, Series Editor

Published under the Sponsorship
of the IEEE Industrial Electronics Society



The Institute of Electrical and Electronics Engineers, Inc.
New York

This book may be purchased at a discount from the publisher when ordered in bulk quantities. Contact:

IEEE PRESS Marketing
Attn: Special Sales
P.O. Box 1331
445 Hoes Lane
Piscataway, NJ 08855-1331
Fax: (732) 981-9334

For more information about IEEE PRESS products, visit the IEEE Home Page:
<http://www.ieee.org/>

© 1997 by the Institute of Electrical and Electronics Engineers, Inc.
3 Park Avenue, 17th Floor, New York, NY 10016-5997

*All rights reserved. No part of this book may be reproduced in any form,
nor may it be stored in a retrieval system or transmitted in any form,
without written permission from the publisher.*

10 9 8 7 6 5 4 3 2 1

ISBN: 0-7803-5351-X
IEEE Order Number: PP5594

The Library of Congress has catalogued the hard cover edition of this title as follows:

Baxter, Larry K.

Capacitive sensors: design and applications / Larry K. Baxter.

p. cm.

Includes bibliographical references and index.

ISBN 0-7803-1130-2

1. Electronic instruments—Design and construction.
2. Capacitance meters—Design and construction. I. Title.

TK7870.B3674 1997

621.37'42—dc20

96-15907

CIP

Contents

Preface xiii

BASICS

Chapter 1—Introduction 1

Sensor trends 1

 Market 1

 Technology 2

 Integration 2

 Intelligence 3

 Sensor bus 3

Applications of capacitive sensors 3

 Proximity sensing 3

 Measurement 4

 Switches 4

 Communications 5

 Computer graphic input 5

Chapter 2—Electrostatics 6

Approximations 6

Charges and fields 7

 Coulomb’s law 7

 Conduction and displacement current 9

 Induced charge 11

 Superposition 11

 Charge images 12

Capacitance 13

 Calculating Capacitance 14

 Multielectrode capacitors 17

Analytical solutions	20
Effect of Gap Width.....	20
Planar Geometries	21
Cylindrical Geometry.....	23
Approximate solutions	24
Sketching field lines.....	24
Teledeltos paper.....	25
Finite element analysis.....	27
FEA plot.....	28
Fringe fields	29
Crosstalk.....	31
Moving shield	34
Proximity detector	35
Chapter 3—Capacitive sensor basics	37
Basic electrode configuration	37
Motion sensing plate configurations.....	38
Spacing variation	38
Area variation.....	39
Matching the circuit to the sensor.....	40
Spacing variation with low-Z amplifier.....	40
Spacing variation with high-Z amplifier.....	41
Area variation with low-Z amplifier	42
Area variation with high-Z amplifier	43
Area variation with feedback amplifier	44
Electrode configuration table.....	45
Limits to precision	46
Noise	46
Stability	46
Chapter 4—Circuit basics	48
Linearity	48
Measuring capacitance	49
Circuit comparison.....	49
Direct DC.....	51
Oscillator	51
Synchronous demodulator	54
Amplifiers.....	54
High-Z amplifier	54
Low-Z amplifier.....	56
Feedback amplifier.....	55
DC restoration	56
Single-ended circuits.....	57
Bridge circuits.....	57
Wheatstone bridge	57
Capacitance bridge.....	57
Bridge vs. single-ended	58
Excitation	58

Sine wave	58
Square wave	59
Filtering	59
Lowpass filter	59
Bandpass filter	60

APPLICATIONS

Chapter 5—Capacitive micrometers	61
Circuits	62
Two-plate micrometer	62
Three-plate micrometer	63
Circuit comparison	65
Chapter 6—Proximity detectors	66
Applications	66
Technology	67
Inductive sensors	67
Magnetic sensors	68
Optical sensors	68
Ultrasonic sensors	68
Capacitive proximity detectors	69
Limits of proximity detection	71
Maximum detection range	72
Proximity sensing equivalent circuit	74
Stray fields	75
Phase detectors	76
Capacitive limit switches	78
Vanes	78
Limit switch circuits	80
Chapter 7—Motion encoders	83
Applications	83
Absolute	83
Incremental	83
Technology	84
Capacitive motion encoders	86
Electric potential sensors	87
Alternate ways to generate a linear electric field	88
Convolution	92
The convolution integral	92
Sampled data convolution	93
Examples of inverse convolution	95
Rectangular to polar conversion	98
Plate geometry	99
Spacing change effects	100
Wireless coupling	103
Chapter 8—Multiple plate systems	105
Capacitive multiple plate systems	105

Rotary encoders	106
Multiple plate counting	109
Debounce	110
Tracking circuits	112
Tracking algorithms	113
Three-phase drive	113
Plate construction	113
Printed circuit board techniques	113
Other techniques	115
Dielectric substrate	118
Chapter 9—Miscellaneous sensors	122
Pressure sensors	122
Differential pressure transducer	122
Absolute pressure sensors	123
Silicon pressure sensors	123
3 cm linear transducer	124
Linear multiplate motion sensor	127
Motor commutator	129
Commutation	129
Ripple torque	129
Water/oil mixture probe	131
Simple probe	132
Improved probe	133
Touch switch	134
Keypad	135
CMOS and ESD	136
Keypad software	137
Touchpad	138
Sensing Technique	138
Accurate two-dimensional sensor	139
Spacing measurement	139
Liquid level sense	140
Dielectric liquids	140
Conductive liquids	141
Low-Z amplifier	142
Liquid level switch	143
Six-axis transducer	144
Demodulator	145
Clinometers	145

DESIGN

Chapter 10—Circuits and components	147
Capacitor dielectrics	147
Classical dielectric models	147
Modified dielectric model	148
Other dielectrics	150

Capacitor measurement	152
Capacitor models	152
Bridges	153
Pickup amplifiers	154
High-Z amplifier	154
Rise time effects	159
Discrete amplifiers	160
Low-Z amplifier	162
Feedback amplifier	164
Wireless connection	165
Noise performance	167
Circuit noise	168
Components	169
Operational amplifiers	169
Resistors	171
Carrier	171
Demodulators	173
180° drive circuits	173
90° drive circuits	175
Chapter 11—Switched capacitor techniques	177
Alternate design techniques	177
Digital signal processing	177
Charge coupled devices, bucket brigade devices	178
Packaged switched capacitor filters	178
Component accuracy	179
MOS vs. bipolar processes	179
BiCMOS process	180
MOS vs. discrete component accuracy	180
Sampled signals	181
Filters	182
Lowpass filter, RC	183
Lowpass filter, switched capacitor	184
Integrator	185
Instrumentation amplifier	186
Demodulator	187
Switched capacitor circuit components	188
Switch	188
Operational amplifiers	189
Accuracy	191
Capacitor ratios	191
Amplifier accuracy	191
Parasitics	191
Charge injection	192
Balanced differential-input demodulator	193
Alternate balanced demodulator	195

Chapter 12—Noise and stability	197
Noise types	197
Resistor noise	199
FET noise	200
High-impedance amplifier	204
Limiting displacement	205
Limiting displacement of three-plate micrometer	205
Maximizing limiting displacement	206
Shielding	207
Grounding	209
Ideal ground	209
Stability	211
Temperature	211
Stability with time	212
Stability with humidity	213
Chapter 13—Hazards	214
Leakage	214
Guarding against leakage	214
Static discharge	217
To combat static discharge	217
Static charge	219
Crosstalk in silicon circuits	219

PRODUCTS

Chapter 14—Electret microphone	221
Electret microphone construction	221
Equivalent circuit	223
Miller capacitance	224
Chapter 15—Accelerometer	226
Accelerometer design	226
Surface micromachining vs. bulk micromachining	226
Force balance	227
Capacitive feedback in silicon accelerometers	228
ADXL50	228
Chapter 16—StudSensor	231
Block diagram	232
Circuit diagram	232
Low cost display	233
Increased sensitivity	233
Self calibration	234
Modified circuit diagram	234
Chapter 17—Proximity detector	236
Block diagram	236
Lossy capacitance	236
Construction	237
Carrier	238

Schematic	239
Excitation	239
Input amplifier	239
Demodulator	240
Power supply	241
Noise and stability	241
Performance	242
Chapter 18—Vernier caliper	243
6 in caliper	243
Circuit description	246
CMOS ASIC	247
Problems	248
Chapter 19—Graphic input tablet	250
Specifications	250
Generating the electric field	250
One dimension	250
Two dimensions, resistive sheet	251
Potentiometer wire	253
Pickup	253
Reverse sensing	254
Excitation	255
Demodulation	255
Chapter 20—Camera positioner	257
Specifications	258
Motor	258
DC brush motor	260
DC brushless motors	261
Permanent magnet step motors	261
Hybrid step motors	262
Transmission	262
Servo system	263
Chapter 21—Digital level	265
Specifications	266
Sensor	266
Sensor construction	269
Circuit description	270
Calibration	270
Chapter 22—References	271
Appendix 1—Capacitive sensors in silicon technology	279
Appendix 2—Dielectric properties of various materials	287
Index	299

1

Introduction

Capacitive sensors electronically measure the capacitance between two or more conductors in a dielectric environment, usually air or a liquid. A similar technique is electric field measurement, where the electrostatic voltage field produced by conductors in a dielectric environment is picked up by a probe and a high impedance amplifier.

A high frequency excitation waveform is normally used, as the reactive impedance of small plates in air can be hundreds of megohms at audio frequencies. Excitation frequencies of 100 kHz or more reduce the impedance to a more easily handled kilohm range.

Some systems use the environment as a return path for capacitive currents; a person, for example, is coupled capacitively to the building or the earth with several hundred pF. More often, the return path is a wire.

The range of applications is extreme. At the small end, silicon integrated circuits use the capacitance between micromachined silicon cantilevers to measure micrometer displacements. The dimensions are on the order of 100 μm , and the gap can be a μm or less. At the large end, capacitive personnel and vehicle detectors have plate dimensions of several meters. Capacitive sensors have been used for video-rate signals in one of the early video disk storage technologies. At the sensitive end, one researcher [Jones, p. 589] reports on an instrument with movement sensitivity of 10^{-11} mm.

1.1 SENSOR TRENDS

1.1.1 Market

The world market for sensors [Control Engineering, 1993] is over \$2.3 billion, growing at an annual rate of 10%. Consumer products, including imaging sensors, make up 64% of the market, with accelerometers accounting for 19% and a variety of specialized sensors completing the total.

Venture Development Corp., Natick, MA, (508)653-9000, in *The U.S. Market for Proximity, Photoelectric, and Linear Displacement Sensors* (1995), forecasts that market segment's size to grow from \$429.6 million in 1995 to \$548 million in 1999. U.S. consumption in 1999 is forecasted as

Magnetic	1.2%
Ultrasonic	1.9%
Capacitive	3.1%
Magnetic-actuated	4.7%
Inductive	42.2%
Photoelectric	46.9%

1.1.2 Technology

Sensor technology is in the process of a slow migration from discrete "dumb" instruments, expensive and inflexible, to smart, self-calibrating, silicon-based units, and the measurement method of choice for silicon devices as well as for discrete instruments is moving from a variety of transducer technologies, such as magnetic, optical, and piezoelectric, to capacitive.

Capacitive sensors can be used for many different applications. Simple sensors are used for go-no go gaging such as liquid level in reservoirs, where their ability to detect the presence of a dielectric or conductor at a distance allows them to work through a nonconducting window. Similar devices (StudSensor) can find wood studs behind plaster walls. Very high analog accuracy and linearity can be achieved with two- or three-plate systems with careful construction, or multiple-plate geometries can be used with digital circuits to substitute digital precision for analog precision.

Capacitive sensors are also useful for measuring material properties. Materials have different values of dielectric constant as well as dielectric loss, and the values of both properties (particularly dielectric loss, or "loss tangent") change with temperature and frequency to give a material a characteristic signature which can be measured at a distance. Appendix 2 lists the dielectric properties of different materials vs. frequency.

1.1.3 Integration

Tools are available to fabricate many different types of sensors on silicon substrates, including micromachining which etches silicon wafers into sensor structures like diaphragms and cantilevered beams (Chapter 15). The decision to integrate a sensor can be done in stages, with the sensor and its electronics integrated together or separately, and usually is considered when the volume reaches 250,000 per year for total integration. Advantages of integration on silicon [Keister, 1992] are

- Improved sensitivity
- Differential sensors compensate parasitic effects
- Temperature compensation
- Easier A-D conversion
- Batch fabrication for lower cost

- Improved reliability
- Size reduction
- Less assembly required
- Lower parasitic capacitances for smaller capacitive electrodes

Capacitive technology is particularly useful for integration, as it is temperature-stable and problems of parasitic capacitance, lead length, and high impedance nodes are more easily handled on a silicon chip than on a PC board.

1.1.4 Intelligence

Smart sensors increase their value to the system by handling low level tasks such as calibration, self-test, and compensation for environmental factors. The gage factor of smart sensors can be scaled automatically so that one sensor type can be used in many locations, and sensor-resident software may help with communications by managing its end of a sensor data bus.

1.1.5 Sensor bus

Most sensors use point-to-point connections to the host, with contact closure or TTL level digital signaling or 4-20 mA current loop or 1-5 V voltage signaling. As the sensors proliferate in an application, the difficulty of wiring and testing complex systems encourages a single-shared-wire bus connection. One effort to establish smart sensor bus standards is pursued by the IEEE Instrumentation and Measurement Society TC-9 committee [Ajiluni, 1994]. This group is drafting "Microfabricated Pressure and Acceleration Technology." A joint IEEE and National Institute of Science and Technology group is developing guidelines for standardization of protocol and interface standards for system designers and manufacturers.

Another proposal for a smart sensor bus is Fieldbus, from the Smar Research Corp. of Brazil [Ajiluni, 1994]. Fieldbus works with WorldFip and ISP protocols, and is defined for all layers of the ISO seven-layer communications structure.

1.2 APPLICATIONS OF CAPACITIVE SENSORS

Some different applications listed below show the variety of uses for capacitive sensors.

1.2.1 Proximity sensing

Personnel detection	Safety shutoff when machine operator is too close.
Light switch	A capacitive proximity sensor with 1 m range can be built into a light switch for residential use.
Vehicle detection	Traffic lights use inductive loops for vehicle detection. Capacitive detectors can also do the job, with better response to slow-moving vehicles.

1.2.2 Measurement

Flow	Many types of flow meters convert flow to pressure or displacement, using an orifice for volume flow or Coriolis effect force for mass flow [Jones, 1985]. Capacitive sensors can then measure the displacement directly, or pressure can be converted to a displacement with a diaphragm.
Pressure	With gases or compressible solids a pressure change may be measured directly as a dielectric constant change or a loss tangent change.
Liquid level	Capacitive liquid level detectors sense the liquid level in a reservoir by measuring changes in capacitance between parallel conducting plates which are immersed in the liquid, or applied to the outside of a nonconducting tank.
Spacing	If a metal object is near a capacitor electrode, the coupling between the two is a very sensitive way to measure spacing.
Scanned multiplate sensor	The single-plate spacing measurement concept above can be extended to contour measurement by using many plates, each separately addressed. Both conductive and dielectric surfaces can be measured.
Thickness measurement	Two plates in contact with an insulator will measure the thickness if the dielectric constant is known, or the dielectric constant if the thickness is known.
Ice detector	Airplane wing icing can be detected using insulated metal strips in wing leading edges.
Shaft angle or linear position	Capacitive sensors can measure angle or position with a multiplate scheme giving high accuracy and digital output, or with an analog output with less absolute accuracy but simpler circuitry.
Balances	A spring scale can be designed with very low displacement using a capacitive sensor to measure plate spacing. A similar technique can measure mass, tilt, gravity, or acceleration.

1.2.3 Switches

Lamp dimmer	The standard metal-plate soft-touch lamp dimmer uses 60 Hz excitation and senses the capacitance of the human body to ground.
Keyswitch	Capacitive keyswitches use the shielding effect of the nearby finger or a moving conductive plunger to interrupt the coupling between two small plates.

Limit switch Limit switches can detect the proximity of a metal machine component as an increase in capacitance, or the proximity of a plastic component by virtue of its increased dielectric constant over air.

1.2.4 Communications

Wireless datacomm Data are capacitively coupled across a short gap in a device which replaces the optical isolator. RF propagation in the near field can be sensed by a receiver with a capacitive plate antenna.

1.2.5 Computer graphic input

x-y tablet Capacitive graphic input tablets of different sizes can replace the computer mouse as an x-y coordinate input device; finger-touch-sensitive, z-axis-sensitive, and stylus-activated devices are available.

ESD transients

The short transient produced by an ESD event is handled in software by resampling each input after a millisecond or two to reject transients. Interrupt-driven software can handle ESD problems as well as switch bounce.

9.8 TOUCHPAD

The mouse serves personal computers well as an input pointing device, but it has not been as popular for portable computers, where a number of solutions have been tried. Recently, small capacitive touch pads integrated into laptop computers are becoming popular. Several manufacturers make these products, including Philips, Symbios/Scriptel, Synaptics, and Alps.

Synaptics' touch pad is smaller than a business card, with a smooth mylar surface. It handles cursor control by finger position, and also substitutes for mechanical mouse switches by interpreting a finger tap as a switch closure. The standard size is 50×66 mm, with smaller sizes available, and thickness is less than 5 mm. The resolution is better than 500 dots/in, so that fine cursor control is achieved by rocking the finger slightly. As the device is sensitive to the total finger capacity which will vary with pressure, a degree of z-axis pressure response is available, which could be used to modulate line width in a paint program or control scroll speed in a word processor.

Electrostatic discharge performance is good, with soft failures occurring at 15 kV and hard failures at 20–25 kV.

9.8.1 Sensing Technique

The sensing technique, an analog version of the keypad above, uses an x-y grid of wires etched on the upper two layers of a four-layer printed circuit board (Figure 9.20a).

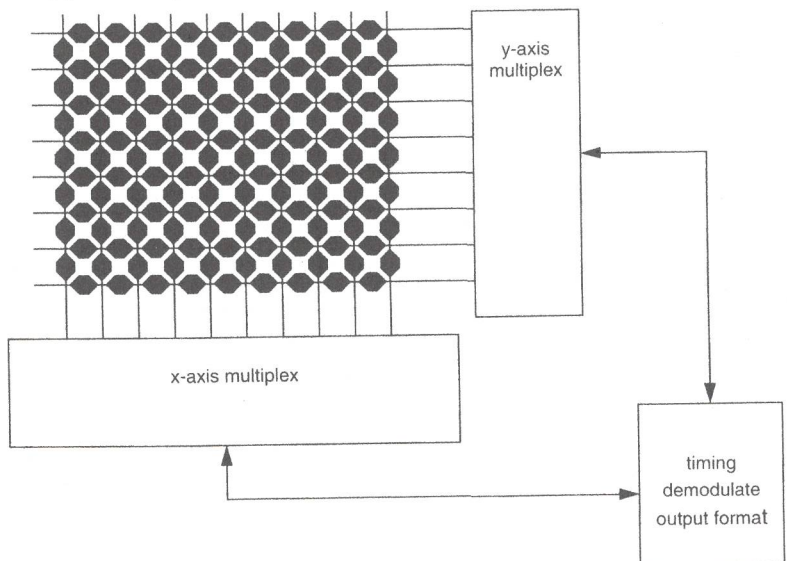


Figure 9.20a Example of the sensing technique

Capacitive coupling is improved by widening the traces, and finger capacitance is sensed as a decrease in coupling between adjacent electrodes caused by the shielding effect of the relatively high capacitance of the human body.

The electronics are surface-mount components on the bottom side of the board, including a mixed-signal ASIC and one or more digital chips if needed for special interface requirements. A combination of digital sensing and analog interpolation between wires is used to accurately determine finger location. The connections from the ASIC to the electrodes are designed to have equal capacitance despite unequal trace length.

Both the electronic and mechanical complexity of the touchpad are less than trackballs, and with no moving parts service life is much higher.

9.8.2 Accurate two-dimensional sensor

A more accurate two-dimensional transducer can be built with similar techniques if the finger is replaced with a close-spaced plane pickup electrode. Bonse et al. [1994] describe an 85×60 mm unit using a 14×10 array of 6 mm^2 square electrodes on the stator and a moving 3×3 electrode pickup. This device, fabricated with printed circuit board technology, demonstrated a 100 nm resolution and 200 nm repeatability. Sine wave excitation and a synchronous demodulator were used, and the major contribution to inaccuracy was determined to be the stability and tolerance of the printed circuit board.

9.9 SPACING MEASUREMENT

The CMOS 555-type timer and the RC circuit form an oscillator which changes frequency as $1/RC$. As the capacitance C is proportional to $1/\text{spacing}$, the output frequency is directly proportional to plate spacing and may be easily measured by counting pulses for some fixed interval of time (Figure 9.21).

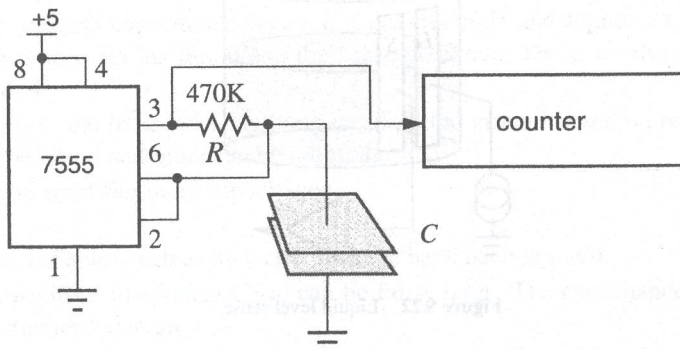


Figure 9.21 Spacing measurement system

If the plates are large and opened, a proximity detector is implemented which detects either dielectric or conductive material in the vicinity of the plates.

This circuit is not too accurate or sensitive, as the input capacitance of the 7555's pins 2 and 7 is about 15 pF and changes slightly with V_{CC} . For better performance, add a driven guard as described in Figure 4.3.

CAPACITIVE SENSORS

Design and Applications

A Volume in the IEEE Press Series on Electronics Technology
Robert J. Herrick, Series Editor

Accurate, inexpensive, and easily integrated with silicon chips, capacitive sensors have caused a "quiet revolution" in today's sensing technology. Capacitive sensors produce spectacular resolution of movement to one part in 10^{-10} meters and maintain exceptional long-term stability in hostile environments. They are increasingly used for a variety of jobs in consumer and industrial equipment, including wall stud sensors, keypads, lamp dimmers, micrometers, calipers, rotation encoders, and more.

The most focused, authoritative book available in the field, **CAPACITIVE SENSORS** brings you complete information on the research, design, and production of capacitive sensors. This all-in-one source provides detailed, comprehensive coverage of key topics, including underlying theory, electrode configuration, and practical circuits.

In addition, you'll find reviews of a number of tested systems never before published. **CAPACITIVE SENSORS** is a must-have for product designers and mechanical and electrical engineers interested in using this fast-developing technology to get top price and performance advantages.

ABOUT THE SERIES

The IEEE Press Series on Electronics Technology provides practical texts and references on major topics in the ever-changing areas of electronics technology and related technology fields. Designed to provide useful information on current practices and developments, the series was specifically created for the practicing engineer and technician who wants and needs timely, easily accessible information about the "what" and "how" of today's electronics and electrical technologies. Educators and students of applied engineering will also be interested in the real-world information.

ABOUT THE AUTHOR

Larry K. Baxter (BSEE, RPI '61), in a long career as a consulting engineer, has designed and built many products that use capacitive sensors. His expertise is in electromechanical design, analog circuit design, and embedded microcomputer systems. He has authored numerous articles on various system design projects, has more than 20 patents, and has been a founding partner in several startup companies, including ECHOLab, Inc., Kronos, Inc., and Everygame, Inc. He is now working as a consulting engineer at PictureTel, Inc. and answers e-mail at baxterl@pictel.com.



IEEE Press
445 Hoes Lane
Piscataway, NJ 08855-1331 USA
1-800-678-IEEE

IEEE Order No. PP5594

ISBN 978-0780353510



9 780780 353510