



Arduino Measurements in Science



Advanced Techniques and Data Projects

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Richard J. Smythe

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Data Projects**

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Apress®

Arduino Measurements in Science: Advanced Techniques and Data Projects

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Wainfleet, ON, Canada

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Table of Contents

About the Authorxvii

About the Technical Reviewerxix

Acknowledgementsxxi

The Author’s Preface to Arduino Measurements in Science.....xxiii

Foreword for the Book’s Exercisesxxix

Chapter 1: Capacitance and Charge 1

 Capacitor Characteristics..... 7

 Leakage Currents..... 7

 Experiment A: Continuous Display of Lower Capacitance Values (< 10 μ F)..... 8

 Circuit: A Simple 555 Timer-Based Capacitance Meter 8

 Circuit Schematic 11

 Software 12

 Experiment B: Measurement of Higher Capacitance Values (> 1000 μ F or mF) 14

 Circuit 14

 Software 15

 Observations..... 17

 Experiment C: Autoranging Measurements for Capacitance..... 18

 Introduction 18

 Software Code for Arduino Uno 18

 Observations..... 20

 Discussion 20

 Calibration of Capacitance Measurements..... 21

TABLE OF CONTENTS

Capacitance Measurement with the Raspberry Pi.....	21
Experiment	22
Observations.....	22
Discussion	23
Measurement of Large Capacitance Values with Python and Raspberry Pi.....	24
Experiment	24
Observations.....	26
Discussion	28
Code Listings for Capacitance Measurement	30
Summary.....	43
Chapter 2: Current	45
Experiment.....	51
Hardware	52
Current Shunts	54
Observations	56
Discussion.....	59
Current Measurements with Raspberry Pi and Python	60
Experiment: Typical and Lower Electronic Circuit Currents	60
Observations	62
Discussion.....	63
Experiment: Higher Current Measurement with Shunts	64
Experiment	64
Observations.....	65
Discussion	66
Code Listings	67
Summary.....	72
Chapter 3: Heat and Temperature	73
Temperature Measurement.....	73
Subambient and Low Temperatures	80
Thermistor: Sensitive High-Resolution Temperature Measurements.....	82

Transition Metal Oxide Thermistors -40°C to 150°C	82
Experiment Part A: Metal Oxide NTC Thermistors.....	84
Hardware	84
Software	88
Observations and Calibration	90
Discussion	94
Experiment Part B: Silicon Carbide Thermistors -20°C to 450°C	97
Experiment: 555 Timer Frequency Shift Temperature Measurements.....	98
Observations.....	98
Discussion	100
Experiment: SiC NTC Temperature Measurement with a Wheatstone Bridge	101
Experiment	102
Observations.....	104
Discussion	104
Non-Contact Infrared Temperature Determination.....	106
Experiment	106
Observations.....	109
Discussion	110
Thermocouple Temperature Determination	111
Experiment	114
Hardware	117
Software	119
Observations.....	119
Discussion	121
Heat Transfer and Basic Thermodynamics.....	123
Experiment	124
Observations.....	125
Discussion	125
Thermoelectricity.....	127
Thermoelectric Heating and Cooling.....	129

TABLE OF CONTENTS

Experiment	129
Observations.....	133
Discussion	134
Measurement of Heat and Temperature with Raspberry Pi and Python	134
Experiment	136
Observations.....	137
Discussion	139
Non-Contact Temperature Measurement.....	141
Experiment	141
Observations.....	142
Discussion	143
Thermocouple Measurements with the Raspberry Pi.....	144
Experiment	144
Observations.....	145
Discussion	150
Passive Infrared (PIR) Heat Sensors.....	151
Experiment	151
Observations.....	153
Discussion	153
Code Listings	154
Summary.....	170
Chapter 4: Light, Optics, and Photoelectric Effects	171
Electro-Optical Components	174
Light Dependent Resistors (LDR).....	174
Photodiodes.....	175
Phototransistors	175
Electro-optical Applications.....	176
Experiment.....	178
A Simple Miniature Optical Bench	178

Hardware	181
Software	182
Observations	184
Discussion	186
A CdS or Phototransistor Detector Solid-State Colorimeter	188
Experiment: CdS or Phototransistor Colorimeters	190
Observations	194
Discussion	195
Implementing Optical Bench Techniques with Raspberry Pi and Arduino	197
Experiment	199
Colorimetric Light Intensity Determinations	209
Observations	217
Discussion	222
A Six Wavelength Spectrograph Using Reverse Biased LEDs	224
Experiment: Light Source Assembly and Calibration	229
Experiment: Selective Color Light Sensing with Reverse Biased LED	231
Observations	241
Discussion	242
Lighting by Fluorescence	246
Computer Imaging	246
Experiment	247
Discussion	248
Code Listings	250
Summary	265
Chapter 5: Magnetics, Magnetoresistance, and Hall Effects	267
Hall Effect Measurements	271
Magnetoresistance Magnetic Field Measurements	272
Magnetic Field Lines and Field Strengths	274
Experimental: Hall Effect Sensors	276

TABLE OF CONTENTS

Allegro Microsystems LLC 276

Software 277

NVE Corporation AA005 Analog Magnetic Sensor..... 278

Honeywell HMC 1001 Single-Axis Magnetic Field Sensor..... 280

Observations 281

Allegro Microsystems 281

NVE Corporation AA005 282

Honeywell HMC 1001 282

Discussion 283

Allegro Microsystems LLC: Linear Hall Effect Sensors A1324, A1325, and A1326 284

NVE Corporation Magnetometers 285

Honeywell HMC 1001 286

Creation, Control, and Measurement of Magnetic Fields 286

Experiment..... 287

 A. Magnetic Suspension/Levitation with an Analog Computing System 287

 B. Microcontroller Magnetic Suspension/Levitation..... 289

Discussion..... 293

Magnetic Field Measurement with the Raspberry Pi and Arduino..... 294

Experiment..... 294

Observations 295

Discussion..... 295

Natural Magnetic Fields and the Magnetometer Compass..... 296

Experimental 296

 Adafruit Industries, Inc.: LSM303DLHC (\$15 CDN)..... 296

 Compass Headings RPi and Python..... 298

 Observations..... 298

Discussion..... 300

Code Listings 300

Summary..... 307

Chapter 6: Motion and Vibration.....	309
Distance on a Grand Scale	310
Dead Reckoning.....	310
Inertial Navigation	310
Global Positioning System (GPS)	311
Reflective Distance Determinations	311
Distance on a Visible Scale	312
Range Finders	312
Distance in the Invisible Scales	312
Strain Gauge	313
Capacitor Distance Measurement	314
Velocity and Speed.....	314
Acceleration.....	314
Vibration	315
Continuous.....	315
Discrete Steps	315
Vibration Detectors and Generators	315
Crystals and Plastic Polymers	316
Experiment: Distance, Time, Velocity, and Acceleration.....	316
Observations.....	324
Discussion	327
Experiment: Electronic Distance Measurements	328
Ultrasonic Distance Measurement	328
Experiment	328
Observations.....	329
Discussion	330
Infrared Electromagnetic Proximity Sensors and Distance.....	331
Rangefinders	331
Experiment: Proximity Sensing	331
Observations.....	333

TABLE OF CONTENTS

Discussion	333
Experiment: IR Time-of-Flight Distance Measurement	334
Observations.....	335
Discussion	339
Three-Dimensional Positioning and Motion	340
Accelerometers, e-Compass, and Tilt Correcting	340
Observations.....	340
Discussion	342
Raspberry Pi Motion Detection, Recording, and Visualization.....	343
Experiment	344
Observations.....	345
Discussion	347
Repetitive Motions and Vibration	348
Experiment	349
Observations.....	350
Discussion	351
Measurement of Vibration Motions at Higher Frequencies	352
Experiment	353
Observations.....	356
Discussion	357
Code Listings	358
Summary.....	367
Chapter 7: Resistance and Conductivity.....	369
The Experimental Measurement of Resistance	371
Experimental Measurement of Fractional and Low Ohmic Values.....	372
Method 1	372
Observations	373
Method 2	374
Observations	375

Intermediate or Moderate Resistance Value Measurements	376
Measurements of High Resistance Values	378
Discussion.....	379
Conductivity	381
Conductivity in Solids.....	382
Conductors	382
Insulators.....	382
Semiconductors.....	383
Conductivity in Liquids.....	383
Ionic Electrolytes	383
Non-Ionic Liquids.....	384
Capacitively Coupled Contactless Conductivity Detection (C4D)	384
Conductivity in Gases	385
Arc and Spark Discharges	385
Flame Ionization	385
Glow Discharges.....	386
Applications of Gas Conductivity in Chemical Analysis.....	386
Inductively Coupled Argon Plasma Optical Emission Spectroscopy and Mass Spectrometry	386
Ion Mobility Spectrometry (IMS): Plasma Chromatography	387
Photoionization	387
Experiment.....	388
Electrolytic Conductivity Measurements in Aqueous Solutions.....	388
Experiment.....	391
Preparation of Ionic Solution Standards.....	394
Electrolytic Conductivity Measurements: 555 Timer	397
Electrolytic Conductivity Measurements: Microcontroller	398
Observations	399
Discussion.....	402
Conductivity: Relative Humidity	405

TABLE OF CONTENTS

Experiment.....	406
Assembly of an Equilibrium Vapor Pressure Chamber	408
Silica Gel Desiccant Preparation	410
Observations	412
Discussion.....	413
Water Activity.....	414
DAQFactory Serial Port I/O Data Parsing Code.....	416
Summary.....	416
Chapter 8: Voltage	419
Static Electrical Charge and Measurement.....	422
Inverse Square Laws.....	425
Solid-State Devices for Static Voltage Measurements.....	427
Reported Static and Electric Field Detectors.....	430
Quantitative Measurement of Accumulated Static Charges	435
Experiment.....	440
FET and MOSFET Static Electric Field Sensors.....	440
MOSFET Calibration	441
High Sensitivity Electric Field Measurements	448
Observations	449
Recording Electrostatic Effects with Arduino and Raspberry Pi	452
Discussion.....	453
Detecting and Measuring Static Electric Accumulations.....	456
Code Listings	457
Summary.....	460
Chapter 9: Weight, Mass, and Force	461
Determination of Weight and Mass.....	462
Development History	463
Experiment.....	469
Variation of Dielectric Composition, Discrete Plates, and Metalized Plastic Films	472
Aluminum Foil and Sheet Polyethylene	472

Papers, Treated Papers, and Cellulose Films	473
Aluminized Mylar Film	473
Software	475
Slope or First Derivative Software	476
Observations	477
Simple Systems: Aluminum–Polyethylene Sheet	477
Simple Systems: Aluminum–Cellophane Sheet	481
Simple Systems: Aluminum–New and Used Newsprint	482
Complex Systems: Aluminum-Mylar Composite	484
Complex Shaped Systems	486
Experimental Refinements of Tapered MPCLC Devices	490
Augmentation of Force Created by Weighing Operation	496
Design Parameters for a Weighing Device	498
Discussion	505
Static Friction and Self-Compression	505
Determining Self-Compression and Angle of Inclination	506
Device Capacitance	508
Materials of Construction	511
Weight Manipulation, Data Generation, and Interpretation	512
Measurement of Force	513
An Experimental Anemometer and Wind Pressure Gauge	513
Experiment	514
Variable Speed Wind Generator	516
Observations	520
Discussion	521
Pressure	523
Measurements of Pressure	523
Part C: Sensor Construction, Calibration, and Optimization	528
Sensor Construction	528
Sensor Calibration	530

TABLE OF CONTENTS

Weight or Force Sensor Optimization.....	536
Experiment.....	539
Observations	546
Discussion.....	550
Code Listings	552
Summary.....	564
Chapter 10: Data Collection, Storage, and Networking.....	565
Time Measurement	566
Data Storage	568
SD Class	569
File Class	570
Liquid Crystal Displays (LCD).....	571
Experiment.....	574
Hardware	574
Real-Time Clock and Breakout Board.....	574
SD Card Holder and Breakout Board	576
Liquid Crystal Display	577
Software.....	578
Observations	586
Data Logging with RPi	590
Networking.....	590
Connecting Arduino to a Network.....	594
Simple Web Pages	595
Experiment.....	596
Creating a Simple HTML Web Page	596
Network Device Locations.....	598
Reading Data from an Experiment Attached to an Arduino Server	598
Discussion.....	601
Code Listings	602
Summary.....	616

Chapter 11: Powering Experiments	617
Batteries.....	617
Alkaline	622
Lead Acid	622
Lithium Batteries.....	625
Rechargeable Lithium-Ion Electrochemistry	625
Lithium-Ion Cobalt.....	626
Lithium-Ion Manganese	626
Lithium-Ion Nickel Manganese Cobalt	626
Lithium-Ion Phosphate.....	627
Nickel Cadmium.....	627
Nickel Metal Hydride.....	628
Zinc Carbon.....	629
Zinc Manganese.....	630
Recharging Secondary Cell Power Sources.....	630
Photovoltaic Cells.....	634
Wind- and Water-Powered Generators.....	638
Thermoelectric Power.....	643
Creation, Control, and Measurement of Higher Voltage, Low-Current Electricity	644
Introduction	644
High-Voltage Power Supply Components	645
High-Voltage Measurement.....	649
Experiment.....	649
Determining the Internal Resistance of Power Sources	649
Photovoltaic Panels and Arrays	652
Power Generation from Mechanical Action	653
Observations.....	656
Internal Resistance of PV Panels	658
Internal Resistance of a Stepper Motor Magneto/Generator	659

TABLE OF CONTENTS

Discussion..... 661

 Batteries 661

 Photovoltaic Cells 664

 Mechanical Energy 665

Summary..... 667

Appendix 1: List of Abbreviations and Acronyms..... 669

Appendix 2: List of Suppliers..... 677

Index..... 681

About the Author



Richard J. Smythe attended Brock University in Ontario and graduated with a four-year honors degree in chemistry with minors in mathematics and physics. He attended the University of Waterloo for a master's degree in analytical chemistry and computing science and a doctorate in analytical chemistry.

After a post-doctoral fellowship at the State University of New York at Buffalo in electro-analytical chemistry, Richard went into business in 1974 as Peninsula Chemical Analysis Ltd.

Richard is fluent in several computer languages and scripting codes. His professional career includes being a consulting analytical chemist, a civil forensic scientist at PCA Ltd., a full partner at Walters Forensic Engineering in Toronto, Ontario, and a senior scientist for Contrast Engineering in Halifax, Nova Scotia.

A large portion of Richard's professional career consists of devising methods for finding problem solutions that involve making fundamental measurements using equipment on hand or readily available off-the-shelf/out-of-the-box products.

About the Technical Reviewer



Roland Meisel holds a Bachelor of Science in physics from the University of Windsor, a Bachelor of Education in physics and mathematics from Queen's University, and a Master of Science in physics from the University of Waterloo. He worked at Chalk River Nuclear Laboratories before entering the world of education. He spent 28 years teaching physics, mathematics, and computer science in the Ontario secondary school system. After retiring from teaching as the Head of Mathematics at Ridgeway Crystal Beach High

School, he entered publishing, contributing to mathematics and physics texts from pre-algebra to calculus in various roles. He remains active in several organizations, including the Ontario Association of Physics Teachers, the Ontario Association of Mathematics Educators, the Canadian Owners and Pilots Association, and the Wainfleet Historical Society.

He has always had a strong interest in technology, mail-ordering his first personal computer, an Apple II with a 1 MHz CPU and 16 kB of memory, from California in 1979. He can be found piloting small airplanes, riding his bicycle or motorcycle, woodworking, and reading or playing the piano, among other instruments.

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Acknowledgements begin with the author's late parents, Richard H. Smythe and Margaret M. Smythe (nee Earle), who emigrated from the remains of London England after the war with their small family of three and eventually raised four children in Canada. Our parents instilled in us the need to be educated as much as possible in order for each of us to be self-sufficient and independent. That independence has led to the comfortable retirement of the middle two, the youngest continuing in her chosen occupation for close to a decade past retirement, and the oldest still actively engaged in the business of chemical analysis consulting and the practice of civil forensic science.

Along the way, numerous individuals have served as an inspiration while teaching and mentoring this author, imparting knowledge, the art of rational thinking, tenacity, and in most cases valuable wisdom: From Merritton High School in St. Catharines Ontario, Mrs. E. Glyn-Jones, mathematics, Mr. J. A. Smith, principal, and Mr. E. Umbrico, physics. From Brock University in St. Catharines Ontario, Prof. E. A. Cherniak, Prof. R. H. Hiatt, Prof. F. Koffyberg, and Prof. J. M. Miller. From the University of Waterloo in Waterloo Ontario, Prof. G. Atkinson. From The State University of New York at Buffalo, Prof. S. Bruckenstein.

It may also be said that the seeds for the growth and development of this work began when as a parent the author made sure that both his daughters—Wendy and Christie—could read at a very early age and devised graphic teaching aids for them to learn and understand binary digital arithmetic.

Acknowledgements would not be complete without recognizing the person who has allowed me the time required to write, in spite of life's every day chaos in the country, my spouse Linda. She has suffered through many years of papers, notes, books, breadboards, wires, electronic components, and desktop experiments scattered everywhere in our home and when she wasn't looking, on the kitchen table! Thank You my love.

Although the author's career consists of solving essentially chemistry-based problems and writing reports explaining how the problem came into existence, how to correct its effects or avoid its recurrence, the author has never written a book. This work would not be possible without the help and guidance of editors at Apress—Ms. Natalie Pao, Ms. Jessica Vakili, and Mark Powers.

The Author's Preface to Arduino Measurements in Science

Arduino Measurements in Science introduces implementing the basic techniques that have been developed to engage in making experimental scientific measurements. I hope that this book can assist students—those new to or with limited backgrounds in electromechanical techniques or the physical sciences—to devise and conduct the experiments they need to further their research or education. I also hope that the book is useful where there are limited financial resources available to create and develop scientific programs based on experimental science.

Migrating or foraging animals and insects use daylight, near-infrared light, polarized light, celestial indicators, chemical traces in water, the earth's magnetic field, and other aids to navigate over the earth's surface in search of food or to return home to their breeding grounds.

Alphabetical classifications, such as astronomy, biology, chemistry, geology/geography, mathematics, and physics through zoology, are human concepts and classifications entirely unknown to travelers of the animal world. There are parallels between the animal kingdom's classless usage of physiochemical parameters and current scientific investigations.

A significant amount of new scientific knowledge is being revealed by investigators educated in one classifiable discipline using the unfamiliar experimental techniques from another. Although written by an analytical chemist, this book is a compilation of basic introductory techniques applicable to any scientific discipline that requires the experimental measurements of basic physiochemical parameters.

I am an analytical chemist who has worked with vacuum tubes, transistors, integrated circuits, mainframe, minicomputers, microcomputers, and microcontrollers. Computing technology transitioned from BASIC, Fortran, variations of C then into iterations of the open source systems such as Python, Processing (the basis of the Arduino microcontroller *integrated development environment* (IDE) language), and Linux operating systems used in the Raspberry Pi. New and revised open source versions of languages, IDEs, and operating systems are available free of charge from the Internet.

This book could be considered virtually obsolete as it is being written, but as with the science and technology that it describes, it is a starting point in an ever-changing subject. For the researcher and practicing scientist, the fundamentals of science are relatively constant and reasonably well understood, so a great deal of caution must be used when deciding that a concept or technique is “obsolete.”

The SCADA concept and its development significantly pre-date the PC. Some of the transistor and CMOS ICs and the 7400 series of integrated circuitry in heavy use today are from the 1970s. Chemical analysis and medical and physical measurement techniques taught and in use today date from the middle ages.

SCADA is the acronym for *supervisory control and data acquisition*. SCADA software allows a computer to supervise an electromechanical process by acquiring data from sensors monitoring the process being controlled. Many of the measurement techniques to be discussed can be considered as single element components that are not only a component of a SCADA system but may also be part of the developing technology being called the Internet of things (IoT).

HMI is the acronym for *human-machine interface*. The HMI can be an electronic device or construct that provides an interface between a computer, an experiment setup, and a human operator. (A graphical user interface (GUI) may serve as an HMI).

USB is the acronym for Universal Serial Bus, a written standard of specifications to which electromechanical hardware systems are expected to conform. The USB is a subsystem that lets a personal computer communicate with devices that are plugged into the universal serial bus. As this book was written, the USB was in its third iteration.

When a personal computer runs supervisory control and data acquisition software with a human-machine interface connected via the universal serial bus system, then investigative science experiments or other processes, experimental apparatus or equipment setups, either “in the field” miles away or “on the bench” next to the computer/workstation or laptop, can be monitored and controlled in real time.

Laptop, stand-alone desktop, cabled or wireless networked workstations together with internet connections now allow unprecedented flexibility in laboratory or “in-field” monitoring of investigative science experiments.

The options available to the experimenters for implementing SCADA systems can essentially be divided into three categories based upon the amount of development work required to achieve a fully functional system.

Complete, finished, working software systems that can measure and control virtually any electro-optical-mechanical system are available from manufacturers such as National Instruments and Foxboro. Commercially available fully functional, basic, software-only systems can be expected to cost in the range of several thousands of dollars.

I chose to develop this book on three lower-cost options for SCADA implementation on experiment setups.

A moderately cost implementation strategy involving the following resources was used to develop the exercises in this book. These resources should also be adequate for further experimental development of new applications.

- A PC with SCADA software. Numerous systems are available. DAQFactory Express and the base-level DAQFactory version from AzeoTech are both used in this book. DAQFactory's base-level software costs approximately \$250 CDN.

There are freeware versions of SCADA systems available for those who can adapt the software and may require extended flexibility. AzeoTech provides an excellent scaled-down but fully workable version of DAQFactory called Express with a fully functioning plotting facility with limited paging and scripting capabilities.

- A USB HMI. Many devices are available from many manufacturers, and the device chosen for this book is the model U12 from the LabJack Corporation. (U12 costs approximately \$120. U3 was added later; it costs approximately \$110 USD.)

The LabJack devices are provided with software in the form of a working version of the DAQFactory program called Express. The LabJack software is excellent for its graphical display capabilities, and for many applications in investigative sciences is more than adequate.

The DAQFactory Express is limited to ten lines of script code, five script sequences, and two display pages. The extensive capabilities of DAQFactory's commercial version may be required for some of the project exercises in this book. If the software is to be purchased, the reader should start with the most basic program available and add upgrades as required.

- The third option is the newest and lowest cost approach to implementing a SCADA system that consists of the Raspberry Pi (RPI), its Linux operating system, the Python programming language with its Matplotlib library, and the Tkinter graphical user interface.

The Linux operating system, Python, and its modules are all open source projects and free for download from the Internet.

The Raspberry Pi project has made available the Raspberry Pi single-board computer (SBC) that can be purchased from many large electronics supply houses such as Digi-Key or Newark Element 14, to name only two, for \$35. The Raspberry Pi board requires an HDMI compatible TV or computer monitor, mouse, and keyboard to form a full function computing system. The Linux operating system software, the Python programming language, and its modules are open source software available for free downloading from the Internet.

In addition to the virtually no-cost software, the Raspberry Pi board contains its own general-purpose input/output (GPIO) bus in addition to its USB input/output connection. It contains its own HMI requiring no additional circuitry or expense to interface to external electronics or experimental setups. The Raspberry Pi board is manufactured with an Ethernet connection and is thus network capable. Numerous libraries are available online and free of charge from the Raspberry Pi Foundation that can interface the RPi to sensors, robots, devices, and instruments resident in the real world.

In 2008, an open source project called Arduino made available a series of USB-connected microcontroller boards that allowed designers, artists, hobbyists, and non-electronics specialists to interface optical-electro-mechanical devices to a computer.

A basic Arduino Uno Rev 3 board can be purchased from any major electronics supply house for approximately \$20. The software to program the microcontroller board is another open source project and is freeware that can be downloaded from the Internet. The Arduino board can be used with Windows or Linux-based operating systems. It is fully supported with an online forum, many tutorials, and an extensive range of example programs and applications. An Arduino can function as a smart interface for virtually any computing system.

Experiments using SCADA-type implementations can take the form of a complete commercially available package, useable as received with no required development time. A lesser cost system requiring a moderate amount of programming using the DAQFactory program and commercial HMI devices such as the LabJack series of interfaces is also possible. Finally an Arduino, or an assemblage of low-cost hardware and open source software freely available for download on the Internet can be used with added development time to form a working system.

In addition to the software and hardware required to implement the monitoring and controlling system, additional ancillary equipment may be required in the form of the following list.

- A solderless breadboard system, appropriate power sources such as battery or electronic regulated supplies, and access to various IC and passive electronic components are required.
- A multimeter is required for troubleshooting. A stand-alone oscilloscope or an oscilloscope program for a PC may be required for more advanced work.

I presumed that you are not entirely new to this technology and can work through any of the measurement procedures with the aid of reference texts, online tutorials, and component manufacturer's datasheets. If additional aid is required, academic course outlines with exercises can be located online to help you understand the base knowledge to implement a specific measurement technique. All science is empirical, and this book is no different than real-life scientific work.

You must progress from the simple to the more complicated facets of a measurement project, verifying and validating each intermediate step in any multiple-stage measurement process.

As the title states, this book deals with monitoring and measuring physical-chemical parameters with integrated circuitry and physical computational systems. Inexpensive off-the-shelf components are used to monitor and control experimental setups that can measure data in the form of basic physiochemical parameters in many classified sciences—in some cases, with astounding sensitivity, flexibility, accuracy, and precision.

Disclaimer

- 110-volt electricity can be lethal and will start fires.
- Soldering irons are hot enough to cause serious burns.
- This book is only for educational purposes and presents concepts demonstrated through experimental formats. These setups have not been tested for robustness and are not designed or intended for any form of implementation in field service.

These concepts are the basis for education only. They are intended as being starting points for further R&D into instrumental methods of monitoring experimental scientific apparatus to gather data or make physical measurements.

- The concept for this book came to me in the mid-1960s. In the interim years, various portions were developed with the technology available.

Although the formal assembly of this book began in 2008 using the integrated circuitry, physical computing, and Internet information resources available at that time, the document continued to develop as it was written using new integrated circuits, physical computing software, and online information sources. The continued availability of software or electromechanical hardware is never assured, and hence the practitioners of this or any science must learn the art of the “workaround.”



Foreword for the Book's Exercises

Introduction

This work is not intended to be an introduction to data collection. Although motivated or enthusiastic investigators can plunge right in and try to pick up needed knowledge and skills on the fly, this guide is aimed at those who have at least some experience in working with electronic hardware and computer software. A basic familiarity with simple electronics and elementary programming in a structured language such as Python or C++ will shorten the time required to implement any of the measurement techniques presented.

The manufacturer's literature for most of the data collection hardware referred to in this guide provides guidance and elementary activities to familiarize a new user with its implementation. Online sources can also provide numerous practical applications using the hardware at hand.

This work is devoted to making experimental physio-chemical measurements with equipment assembled from readily available components and physical computing systems. This book offers written methodologies by which experimenters can make fundamental measurements with electronics, electro-optical, and simple mechanical systems. A series of experimental measurement procedures for the basic units of parameters such as temperature, distance, light intensity, sound frequency, relative humidity, and other fundamental measurements are described together with the methods for powering and controlling the experimental mechanisms.

The determinations or measurements of individual basic units of interest are unit operations that can be combined to measure or control more complex experimental investigations. The following techniques represent the unit operations that can be assembled in experiment setups to measure the fundamental parameters monitored in virtually any scientific discipline.

Project Management

The following is a suggested general procedure for developing a supervisory control and data acquisition/monitoring project.

1. In preparation for creating an experimental development project, whether for conducting one of the exercises in this book or for a new concept, you should review available up-to-date information. Collect published work relevant to your project if it adds to your depth of knowledge and helps you avoid unnecessary duplication of effort. Rough notes and drawings should be collected in a notebook (either on paper or in an electronic format).
2. Arrange the ideas into a logical sequence of development in a flow chart or process diagram. Common spreadsheet software and word processing programs contain flowcharting capabilities. In a flow chart, keep the main process flow downward in the middle of the sheet with forward branches to the left or right and the backward branches to the opposite side.
3. Revise the flow chart/process diagram until a final iteration is achieved.
4. Begin assembling the hardware/electronics and corresponding software from the project's simplest unit operations, debugging the individual modules and verifying operational status until the entire project functions as designed.

In all scientific reports, the documentation must be complete to the point at which any other researchers can duplicate the original experimental work and confirm the reported observations. Software code must be liberally commented for those attempting to duplicate the work being described and for the investigator to modify the code for more efficient operation or changes made to the electro-mechanical system under development.

To duplicate the work of another, clear definitions of units must exist. Caution is required in reading schematic diagrams and attempting to duplicate assembly. Discrete components and integrated circuitry are constantly decreasing in physical size or replaced with newer technology. The decrease in size means that identification markings on components are getting smaller also.

Resistor and capacitor markings may appear in several formats as combinations of numbers and letters, with the magnitude symbol sometimes replacing the decimal point. Surface mount technologies have a three-digit code in which the first two digits are the component value, and the third is the power of 10 of the value multiplier.

- Resistance is measured in units called ohms (Ω).
- A megohm ($M\Omega$) is 10^6 or 1,000,000 ohms; typical identifications may be, for example, 1.5M or 1M5.
- A kilohm ($k\Omega$) is 10^3 or 1,000 ohms; and typical identifications may be, for example, 1.2K or 1K2.
- R is 10^0 or 1 or 1 unit ohm; for example, 100 R or 100 since there is no decimal point to replace.
- A milliohm (m) is $1/1000$ or 10^{-3} ohms; for example, 0.052Ω is written as 52 $m\Omega$.

Capacitor units in older works were mainly limited to microfarad and picofarad designations. Most current capacitor notation usage seems to adhere to the three main fractional designations listed next but has recently been expanded to include the farad to avoid using thousands and millions in the micro term when describing ultra and supercapacitor devices.

- Capacitance is measured in units called farads (F).
- A microfarad (μ) is one millionth (10^{-6}) of a farad.
- A nanofarad (nF) is one billionth (10^{-9}) of a farad.
- A picofarad (pF) is one micro micro farad or (10^{-12}) of a farad.

When selecting the components required to assemble an experimental setup, a certain amount of caution must be exercised to ensure that the finished construct is suitable for the desired measurement. A case in point can be found in the creation of something as simple as a linearly changing voltage value. Modern electronics technology presents two simple methods for the creation of a voltage ramp in which the value of a voltage varies linearly with time between a lower and upper voltage value. In a linear system, the electrical potential can be deemed to “ramp up” or “ramp-down.”

FOREWORD FOR THE BOOK'S EXERCISES

If a 4-bit digital to analog converter is used, the values from 0 to 2^4 (0 to 15 or 16 digital values) can be created as incremental voltages. A 16 V signal applied to the digital to analog converter (DAC) can thus provide a series of discreet steps between the values of 0 V and 15 V in approximately 1 V increments. The one-volt steps may be adequate for positioning a robot or mirror in any one of 16 possible positions but may not be used in an electrochemical application.

In chemical reactions in which several metals are deposited from a solution at several different impressed non-integer voltage levels, it might be necessary to have a smooth voltage waveform whose voltage value continuously ramps between the desired levels. The smooth transition of continuously varying voltage values is an analog waveform. It must be generated by special methods, one of which uses a constant current source to charge a capacitor to produce a linear voltage change across the capacitor plates.

Although calculus demonstrates that by selecting a sufficiently large number of tiny steps, we can mimic an analog signal with a digital signal, a digital signal may not have the desired value for the application at hand. A continuously variable constant current-based capacitor charging methodology may be necessary. The selection of which variation technique to use for a problem depends on the voltage resolution needed and the availability of the required electronic components.

When working with electrical signals from a sensor or experimental apparatus, ensure that the output voltage level does not exceed the input voltage capability of the electronic components processing the signal. Most discrete integrated circuitry is limited to 5 V. Some op-amps operate at up to 18 V. Most surface mount technology operates at a nominal 3.3 V.

As with all scientific endeavors, a logical progression should be made from the simplest to the more complex. When developing software for a project, you should begin with the code required to connect the apparatus to the computing and display circuitry.

The simplest form of electrical signal transmission uses a series connection for both analog and digital signals.

Analog voltage signals are often connected directly to the input pins of integrated circuits that provide some form of signal processing. Digital signals are connected to pins that sense whether the signal is high or low. A large portion of sensor outputs are voltage based, but current sensing is also used in some sensor measurements.