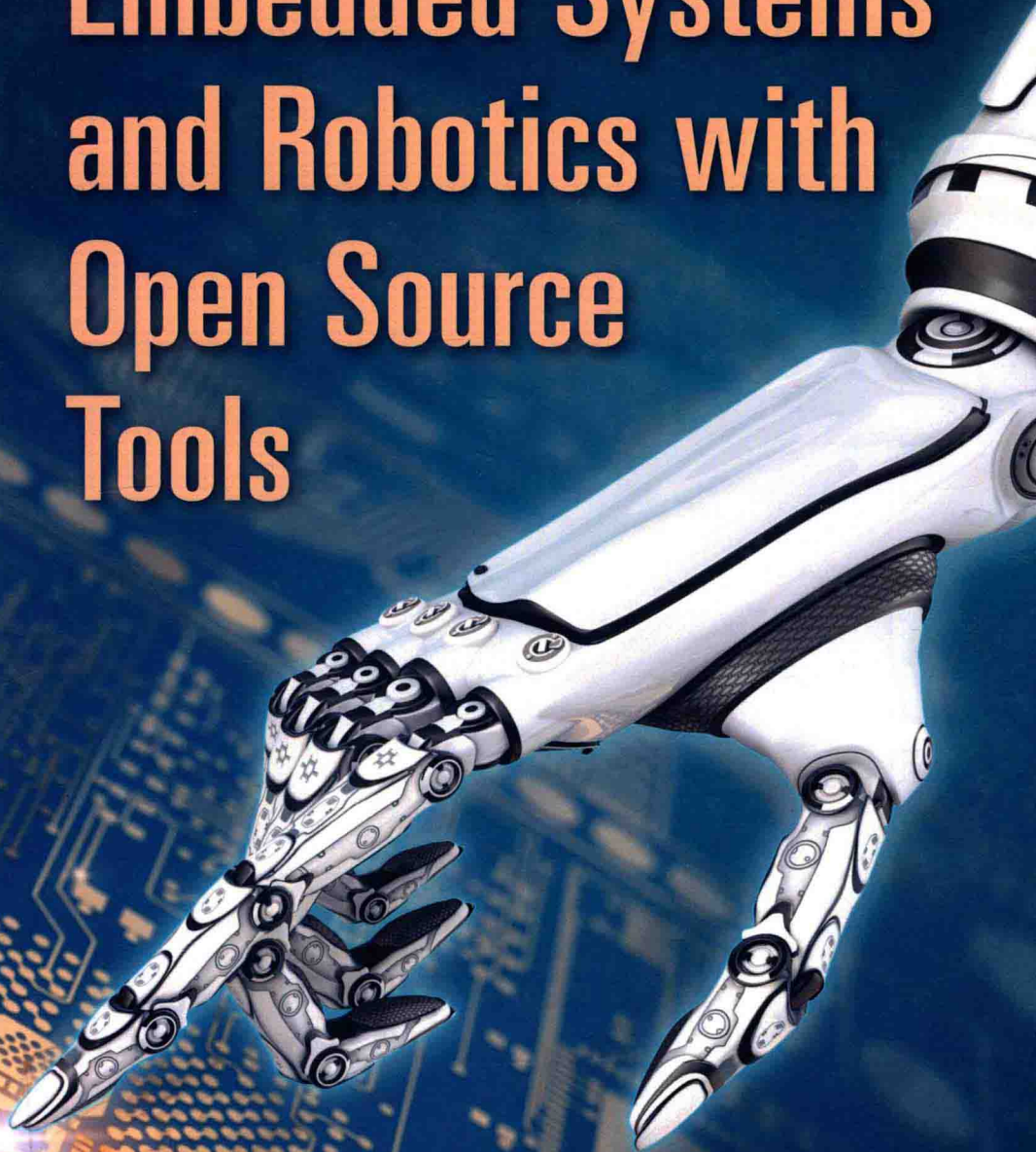


Embedded Systems and Robotics with Open Source Tools



Nilanjan Dey
Amartya Mukherjee



CRC Press
Taylor & Francis Group

Embedded Systems and Robotics with Open Source Tools

Nilanjan Dey
Amartya Mukherjee



CRC Press

Taylor & Francis Group

Boca Raton London New York

CRC Press is an imprint of the
Taylor & Francis Group, an **Informa** business

CRC Press
Taylor & Francis Group
6000 Broken Sound Parkway NW, Suite 300
Boca Raton, FL 33487-2742

© 2016 by Taylor & Francis Group, LLC
CRC Press is an imprint of Taylor & Francis Group, an Informa business

No claim to original U.S. Government works

Printed on acid-free paper
Version Date: 20151116

International Standard Book Number-13: 978-1-4987-3438-7 (Hardback)

This book contains information obtained from authentic and highly regarded sources. Reasonable efforts have been made to publish reliable data and information, but the author and publisher cannot assume responsibility for the validity of all materials or the consequences of their use. The authors and publishers have attempted to trace the copyright holders of all material reproduced in this publication and apologize to copyright holders if permission to publish in this form has not been obtained. If any copyright material has not been acknowledged please write and let us know so we may rectify in any future reprint.

Except as permitted under U.S. Copyright Law, no part of this book may be reprinted, reproduced, transmitted, or utilized in any form by any electronic, mechanical, or other means, now known or hereafter invented, including photocopying, microfilming, and recording, or in any information storage or retrieval system, without written permission from the publishers.

For permission to photocopy or use material electronically from this work, please access www.copyright.com (<http://www.copyright.com/>) or contact the Copyright Clearance Center, Inc. (CCC), 222 Rosewood Drive, Danvers, MA 01923, 978-750-8400. CCC is a not-for-profit organization that provides licenses and registration for a variety of users. For organizations that have been granted a photocopy license by the CCC, a separate system of payment has been arranged.

Trademark Notice: Product or corporate names may be trademarks or registered trademarks, and are used only for identification and explanation without intent to infringe.

Library of Congress Cataloging-in-Publication Data

Names: Dey, Nilanjan, 1984- author. | Mukherjee, Amartya.
Title: Embedded systems and robotics with open source tools / Nilanjan Dey and Amartya Mukherjee.
Description: Boca Raton : CRC Press, 2016. | Includes bibliographical references and index.
Identifiers: LCCN 2015042967 | ISBN 9781498734387
Subjects: LCSH: Autonomous robots. | Embedded computer systems--Programming. | Open source software.
Classification: LCC TJ211.495 .D485 2016 | DDC 006.2/2--dc23
LC record available at <http://lcn.loc.gov/2015042967>

Visit the Taylor & Francis Web site at
<http://www.taylorandfrancis.com>

and the CRC Press Web site at
<http://www.crcpress.com>

Embedded Systems and Robotics with Open Source Tools

Nilanjan Dey
Amartya Mukherjee



CRC Press

Taylor & Francis Group

605 Third Avenue, New York, NY 10158

CRC Press is an imprint of Taylor & Francis Group

For more information on this title please go to the publisher's website at www.crcpress.com

*In loving memory of the
late Mihir Kumar Mukherjee*

Contents

Preface	ix
Author's Note	xv
Abbreviations	xvii

When the tools of production are available to everyone, everyone becomes a producer.

—Chris Anderson

1.1 Introduction	1
1.2 Why a Second-Cut Book?	2
1.3 Philosophical Goal of the Book	3
1.4 Main Topics	4
1.5 Information	5
1.6 How to Use This Book	6

2. Basics of Embedded Systems	11
2.1 Introduction	11
2.2 Characteristics of Embedded Systems	12
2.3 Microprocessors	13
2.4 Microcontrollers	14
2.5 Application-Specific Processors	15
2.6 Sensors and Actuators	16
2.6.1 Sensors	16
2.6.2 Actuators	17
2.7 Embedded Systems in the Automobile	18
2.7.1 Engine Control	18
2.7.2 Transmission Control	19
2.7.3 ABS (Anti-Lock Braking System)	20
2.7.4 ESP (Electronic Stability Program)	21
2.8 Real-Time Operating Systems	22
2.8.1 Hard Real-Time Systems	22
2.8.2 Soft Real-Time Systems	23
2.8.3 Thread-Oriented Design	24
2.9 System Examples	25
2.9.1 Robot Arms Technology	25
2.9.2 Aircraft Autopilot System	26

3. Basics of Real-Time Systems	27
3.1 Introduction	27
3.2 Real-Time Concepts	28
3.3 Design of Real-Time Systems	29
3.4 Forward Scheduling	30
3.5 Backward Scheduling	31

Preface

In the world of computer science, software and hardware are deeply inter-related. A computer system is a combination of the functions of several electronic devices that act collaboratively with the help of software systems. Nowadays, the computer system is not limited to a desktop PC, laptop, palm-top, or a workstation server. The definition of a computer has been changed by the smart phone revolution. Starting from a basic video-gaming device to a more sophisticated unmanned aerial vehicle, everywhere we realize the presence of high-performance embedded computing.

This era is also well known for the open-source revolution. Technological enhancements have been achieved through both open-source software and hardware platforms. One of the very popular tools today is the rapid prototyping environment, which consists of a combination of hardware and software suites. With the help of high-performance microprocessors, microcontroller, and highly optimized algorithms, one can develop smarter embedded applications.

This book aims to present some cutting-edge open-source software and hardware technology and the practical applications of such smarter systems that take the technology to the next level. The chapters are designed in a way to help readers who are not familiar with advanced computing technologies easily understand and learn as they read deeper into the book. The book includes eight high-end, real-time projects for evaluation of the rapid prototype development skill. These projects are properly verified and tested so that one can easily deploy them soon after learning. The book will serve as a guide to undergraduate and postgraduate engineering students, researchers, and hobbyists in the field.

Nilanjan Dey

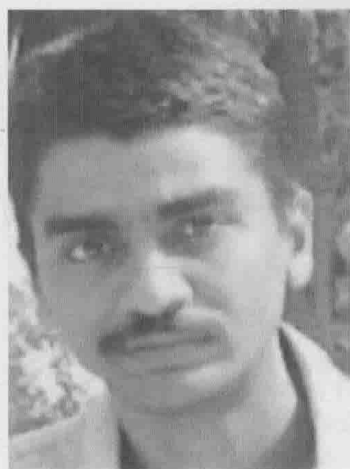
Amartya Mukherjee

Acknowledgments

This book itself is an acknowledgment to the technical and innovative competence of many individuals who have contributed to this domain. First, we thank our colleagues and coresearcher(s), especially Sayan Chakrabarty, Souvik Chatterjee, and Soumya Kanti Bhattacharaya, for their technical support in all regards. We thank Dr. Amira S. Ashour, vice-chairperson, Department of Computer Science, College of Computers and Information Technology, Taif University, Taif, Kingdom of Saudi Arabia, for extending her expertise in upgrading the literary quality of this book. We also thank Eshita Mazumder Mukherjee for her support in writing the book and our students Anant Kumar, Manish Kumar, and Masoom Haider.

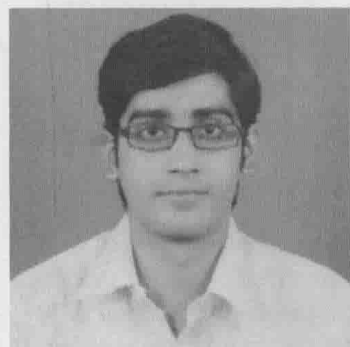
Finally, we thank our parents, wives, and children for their continuous support.

Authors



Nilanjan Dey is an assistant professor in the Department of Information Technology, Techno India College of Technology, Rajarhat, Kolkata, India. He holds an honorary position of visiting scientist at Global Biomedical Technologies Inc., California, and research scientist at the Laboratory of Applied Mathematical Modeling in Human Physiology, Territorial Organization of Scientific and Engineering Unions, Bulgaria. He is the editor in chief of the *International Journal of Rough Sets and Data Analysis*, IGI Global, US; managing editor of the *International Journal of Image Mining (IJIM)*, Inderscience; regional editor (Asia) of the *International Journal of Intelligent Engineering Informatics (IJIEI)*, Inderscience; and

associate editor of the *International Journal of Service Science, Management, Engineering, and Technology*, IGI Global. His research interests include medical imaging, soft computing, data mining, machine learning, rough set, mathematical modeling and computer simulation, modeling of biomedical systems, robotics and systems, information hiding, security, computer-aided diagnosis, and atherosclerosis. He has published 8 books and 160 international conferences and journal papers. He is a life member of the Institution of Engineers, Universal Association of Computer and Electronics Engineers, Internet Society as a Global Member (ISOC), etc. Detailed information on Nilanjan Dey can be obtained from <https://sites.google.com/site/nilanjandeyprofile/>.



Amartya Mukherjee, MTech, is an assistant professor at the Institute of Engineering and Management, Salt Lake, Kolkata, India. He holds a bachelor's degree in computer science and engineering from West Bengal University of Technology and a master's degree in computer science and engineering from the National Institute of Technology, Durgapur, West Bengal, India. His primary research interest is in embedded application development, including mobile ad hoc networking, aerial robotics, and Internet

of Things. He has written several papers in the field of wireless networking and embedded systems.

Contents

Preface.....	xv
Acknowledgments	xvii
Authors	xix
1. Introduction	1
1.1 Embedded Systems and Robotics	1
1.2 Fundamental Goal of Embedded Systems	1
1.3 Fundamental Goal of Robotics.....	2
1.4 Main Focus.....	2
1.5 Motivation	3
1.6 How to Use This Book.....	3
2. Basics of Embedded Systems	5
2.1 Introduction	5
2.2 Classifications of Embedded Systems.....	5
2.3 Microprocessors	6
2.4 Microcontrollers	8
2.5 Application-Specific Processors	9
2.6 Sensors and Actuators.....	11
2.6.1 Sensors.....	11
2.6.2 Examples of Sensors	11
2.7 Embedded Communication Interface	12
2.7.1 I2C Communication	12
2.7.2 SPI and SCI Communication.....	13
2.7.3 UART Communication.....	13
2.7.4 USB Communication.....	14
2.8 Real-Time Operating Systems	15
2.8.1 Hard Real-Time System.....	15
2.8.2 Soft Real-Time System.....	16
2.8.3 Thread-Oriented Design.....	16
2.9 Typical Examples.....	16
2.9.1 Smartphone Technology	16
2.9.2 Aircraft Autopilot Unit.....	17
3. Basics of Robotics	19
3.1 Introduction	19
3.2 Robot Kinematics	19
3.3 Degree of Freedom.....	20
3.4 Forward Kinematics	22
3.5 Algebraic Solution.....	22

3.6	Inverse Kinematics.....	23
3.7	Robots and Sensors.....	24
3.7.1	Motion Detection Sensor	24
3.7.2	Gyroscope and Accelerometer	24
3.7.3	Obstacle Detector.....	25
3.7.4	Location Tracking by GPS	25
3.8	Robots and Motors.....	26
3.8.1	DC Motor	27
3.8.2	Servo Motor	28
3.8.3	Stepper Motor.....	29
3.9	Robot Controller	29
3.10	Frames and Materials	30
3.11	Types of Robots	30
3.11.1	Industrial Robots	31
3.11.2	Medical Robots.....	31
3.11.3	Military Robots	32
3.11.4	Space Robots	33
3.11.5	Entertainment Robots	35
3.12	Summary.....	35
4.	Aerial Robotics.....	37
4.1	Introduction to Aerial Robotics	37
4.2	History of Aerial Robotics	37
4.3	Classification of Aerial Robots	38
4.3.1	Fixed-Wing Systems	38
4.3.2	Multirotor Systems	40
4.4	Sensors and Computers	41
4.5	Open Research Area	43
4.6	Aerial Sensor Networks	43
5.	Open-Source Hardware Platform	45
5.1	Introduction	45
5.2	Open-Source Hardware Features	45
5.3	Open-Source Hardware Licensing	47
5.4	Advantages and Disadvantages of Open-Source Hardware	47
5.5	Examples of Open-Source Hardware.....	48
5.5.1	Raspberry Pi Computer	48
5.5.2	BeagleBoard	49
5.5.3	PandaBoard.....	50
5.6	Summary.....	51
6.	Open-Source Software Platform.....	53
6.1	Introduction	53
6.2	Open-Source Standards	53
6.2.1	Open-Source Software Licensing	54
6.2.2	Free and Open-Source Software.....	54

6.3	Examples of Open-Source Software Products.....	55
6.4	Advantages and Limitations of Open-Source Software.....	56
6.5	Open-Source Future	58
7.	Automated Plant-Watering System.....	59
7.1	Introduction	59
7.2	Architecture of Plant-Watering Systems	59
7.2.1	Soil Moisture Sensor.....	60
7.2.2	Setting Up 433 MHz Radio Tx/Rx Module.....	61
7.2.3	Setting Up the Pumping Device	62
7.3	Arduino Programming Code.....	63
7.3.1	Arduino Code for the Radio Transmitter	63
7.3.2	Arduino Code for the Radio Receiver.....	64
7.4	Broadcasting Sensor Data to the Internet via Processing	65
7.5	Summary	69
7.6	Concepts Covered in This Chapter	69
8.	Device to Cloud System	71
8.1	Introduction	71
8.2	Temperature Sensor Data Logging System.....	71
8.2.1	Interacting with Cloud	71
8.3	Components	73
8.4	Temperature Sensor	73
8.5	Circuit Connections	75
8.6	Setting Up Zigbee Communication.....	76
8.6.1	Zigbee Basics	76
8.6.2	Configuring XBee Module.....	78
8.7	Sample Python Code for Serial Read	80
8.8	Sending Data to Cloud	80
8.8.1	More about Raspberry Pi	82
8.8.2	Main Components	83
8.9	Installation of Operating System and Python API in Raspberry Pi	83
8.9.1	OS Installation.....	83
8.9.2	pySerial Installation	84
8.9.3	Python Google Spreadsheet API Installation	84
8.10	Configuring Google Account	85
8.11	Python Code to Access Google Spreadsheet.....	86
8.12	Summary	87
8.13	Concepts Covered in This Chapter	88
9.	Home Automation System	89
9.1	Introduction	89
9.2	Home Automation System Architecture	89
9.3	Essential Components	89

9.4	Connection Detail	91
9.5	Setting Up the Web Server.....	92
9.6	Interaction with Server by Processing	95
9.7	Summary	100
9.8	Concepts Covered in This Chapter	100
10.	Three-Servo Ant Robot	101
10.1	Introduction	101
10.2	Tools and Parts Required	101
10.2.1	Ultrasonic Sensor	101
10.2.2	Servomotors	102
10.2.3	Leg Design	103
10.2.4	Mounting Ultrasonic Sensor	106
10.3	Programming the Leg Movement	106
10.4	Summary	110
10.5	Concepts Covered in This Chapter	110
11.	Three-Servo Hexabot	111
11.1	Introduction	111
11.2	System Architecture	111
11.3	Parts and Their Assembly	112
11.4	Programming Basic Moves.....	115
11.5	Summary	118
11.6	Concepts Covered in This Chapter	119
12.	Semi-Autonomous Quadcopter	121
12.1	Introduction	121
12.2	Structural Design	121
12.3	Component Description	122
12.4	Flight Controller Unit	124
12.4.1	MultiWii CRIUS SE2.5.....	124
12.4.2	Flight Controller Comparison.....	125
12.5	Assembling Parts	125
12.6	Sensor and Speed Controller Calibration	128
12.6.1	MultiWii Setup and Configuration	128
12.6.1.1	Configuring MultiWii Firmware	128
12.6.1.2	Sensor Calibration	129
12.6.1.3	ESC Calibration	131
12.6.2	Configure KK 5.5 Multicopter Board	131
12.7	Radio Setup and Calibration	132
12.8	Radio TX/RX Binding Technique.....	133
12.9	Connection with GUI Interface.....	134
12.9.1	PID Tuning.....	136
12.9.1.1	Basic PID Tuning	136
12.9.1.2	Advanced PID Tuning	136

12.9.1.3	Standard Guideline for PID Tuning	138
12.9.1.4	General Guidelines	138
12.10	Position, Navigation, Level, and Magnetometer Performance Tuning	139
12.11	Additional Channel Assignments	140
12.12	Summary	141
12.13	Concepts Covered in This Chapter	142
13.	Autonomous Hexacopter System.....	143
13.1	Introduction	143
13.2	Structural Design of the Autonomous Hexacopter.....	143
13.3	Components.....	143
13.3.1	Frames	144
13.3.2	Motors and ESC.....	144
13.3.3	Radio Units	145
13.3.4	Autopilot Unit.....	147
13.4	Component Assembly	148
13.5	APM Ground Station Software Installation.....	150
13.6	APM Firmware Loading	152
13.7	Sensor and Radio Calibration	152
13.7.1	Accelerometer and Gyroscope Calibration	152
13.7.2	Compass Calibration	153
13.7.3	Radio Calibration.....	154
13.7.4	ESC Calibration	154
13.7.5	Motor Test	155
13.8	Flight Parameter Settings	155
13.9	Flight Modes	156
13.10	Mission Design.....	157
13.10.1	Using Ground Station.....	157
13.10.2	Waypoint Navigation Algorithm.....	158
13.10.3	GPS Glitch and Its Protection.....	160
13.11	Adding FPV Unit.....	161
13.12	Final Hexacopter UAV	162
13.12.1	Flight Path Visualization and Log Analysis	162
13.13	Summary	164
13.14	Concepts Covered in This Chapter	164
14.	Conclusion.....	165
14.1	Tools Used	165
14.2	Important Safety Notes	166
14.3	Frequently Asked Questions.....	168
14.4	Final Words.....	172
	Bibliography.....	173
	Index	177

1

Introduction

1.1 Embedded Systems and Robotics

Embedded systems and robotics are the most interrelated terms in this cutting-edge technological era. The revolution of smartphone, smart real-time operating system (RTOS), and system-on-chip technology provides a new dimension to the embedded hardware. In the past, the embedded system was a bit complicated to manage and a huge chunk of assembly-level code was to be written to program the whole system. But as things keep changing quite drastically, nowadays embedded systems act as a platform in the development of software/firmware, thus reducing the development time. The architecture of the system also keeps changing day by day so as to increase processing power and to decrease energy consumption. The enhancement of the RTOS-like Android gives another new dimension to embedded systems. On the contrary, robotics has evolved to higher-dimensional applications. In earlier years, robots were only used in industrial and scientific research, but today robotics has reached a new dimension, thanks to open-source hardware; starting from military to medical applications or maybe for entertainment or as a hobby, the concept of robotics has been widely spread. Robotics experts claim that by 2022 they will produce a robotic maid that will cost less than \$100,000.

1.2 Fundamental Goal of Embedded Systems

The growth of embedded systems depends on innovative engineers with exposure to robotic technology. Loosely defined, an embedded system, which is a computer system that is intended to be a general-purpose computer, is a programmable device that drives some specific set to the system. It might be connected with one or more number of sensors and actuators. The main task of the embedded system is to acquire data from the sensor. The system should be smart enough to process and analyze the data using its