

EMBEDDED SYSTEMS:

INTRODUCTION TO ROBOTICS

First Edition,

July 2019

Jonathan W. Valvano

First edition
1st printing
July 2019

ARM and uVision are registered trademarks of ARM Limited.
Cortex and Keil are trademarks of ARM Limited.
Code Composer Studio is a trademark of Texas Instruments.
All other product or service names mentioned herein are the trademarks of their respective owners.

In order to reduce costs, this college textbook has been self-published. For more information about my classes, my research, and my books, see <http://users.ece.utexas.edu/~valvano/>

For corrections and comments, please contact me at: valvano@mail.utexas.edu. Please cite this book as: J. W. Valvano, Embedded Systems: Introduction to Robotics, <http://users.ece.utexas.edu/~valvano/>, ISBN: 978-1074544300, 2019.

Copyright © 2019 Jonathan W. Valvano

All rights reserved. No part of this work covered by the copyright herein may be reproduced, transmitted, stored, or used in any form or by any means graphic, electronic, or mechanical, including but not limited to photocopying, recording, scanning, digitizing, taping, web distribution, information networks, or information storage and retrieval, except as permitted under Section 107 or 108 of the 1976 United States Copyright Act, without the prior written permission of the publisher.

ISBN-13: 978-1074544300

ISBN-10:

Table of Contents

Preface	viii
Acknowledgements	ix
1. Introduction to Embedded Systems	1
1.1. Computer Systems	2
1.2. Embedded Systems	9
1.3. The Design Process	13
1.4. The Software Development Process	26
1.5. Ethics	27
2. Introduction to Electrical Engineering	29
2.1. Electrical Circuits	29
2.2. Resistors and Capacitors	31
2.3. Voltage, Current, Power, Energy	33
2.4. Measurement of Voltage and Current	38
2.5. Transistor Circuits	39
2.6. Op Amps	42
2.7. Interfacing with Digital Logic	47
2.8. Logic Level Conversion	54
3. ARM Cortex-M Architecture	55
3.1. Digital Representation of Numbers	56
3.2. ARM Cortex™-M Processor	63
3.3. ARM Cortex-M Assembly Language	67
3.4. First Example Project	93
3.5. Nonvolatile Storage	96
4. Software Design	99
4.1. Introduction to C	99
4.2. Modular Design using Abstraction	121
4.3. Functional Debugging	132
5. Power Sources and Voltage Regulation	135

5.1. Power Sources	135
5.2. Battery Power.....	136
5.3. Voltage Regulators	139
6. General Purpose Input Output.....	143
6.1. Texas Instruments MSP432 I/O pins	143
6.2. Software Access to GPIO ports.....	152
6.3. Configuring Digital Output Pins	159
6.4. Debugging Tools	160
7. Finite State Machines	169
7.1. Arrays and Strings.....	169
7.2. Indexed Addressing and Pointers.....	170
7.3. Function Pointers in C.....	173
7.4. Structures.....	174
7.5. Finite State Machines with Linked Structures.....	176
7.6. Line Tracking Robot	185
7.7. Stepper Motor Interface.....	188
8. Interfacing Input and Output.....	197
8.1. Introduction to Interfacing	197
8.2. Switch Interfacing.....	198
8.3. LED Interfacing	201
8.4. Debugging monitor using an LED.....	204
8.5. Solid State Relays.....	205
8.6. IR Communication Beacon	206
9. Managing Time.....	207
9.1. Clock System	207
9.2. SysTick Timer	212
9.3. Two-wheel Stepper Motor Robot.....	213
9.4. Introduction to Pulse Width Modulation.....	217
9.5. Profiling with a Debugging Dump	220
10. Concurrent Multithreading	221

10.1. Multithreading	221
10.2. Interthread Communication and Synchronization.....	225
10.3. Critical Sections.....	227
10.4. NVIC on the ARM Cortex-M Processor	231
10.5. Interrupts using SysTick.....	235
10.6. Two-wheel Stepper Motor Robot (redesigned)	238
10.7. Debugging Profile.....	239
11. Serial Port Interfacing.....	241
11.1. Synchronizing the software with the state of the I/O.....	241
11.2. Introduction to Serial Communication.....	245
11.3. Synchronous Communication using the SPI.....	249
11.4. Inter-Integrated Circuit (I ² C) Interface.....	253
11.5. Asynchronous Communication using the UART.....	265
11.6. Nokia 5110 Graphics LCD Interface	271
11.7. Fixed-point numbers	273
11.8. Floating-point numbers.....	276
11.9. Recursion.....	279
12. Motor Interfacing.....	283
12.1. Physics of a Brushed DC motor.....	283
12.2. Electromagnetic and Solid State Relays	286
12.3. Solenoids	287
12.4. Electrical Interfacing	288
12.5. DC Motor Differential Drive Robot.....	294
12.6. Servos.....	296
12.7. Brushless DC Motor	298
13. Timers	301
13.1. Basic Principles	301
13.2. Periodic Interrupts using the Timer	302
13.3. Pulse Width Modulation	307
13.4. Timer32.....	309
14. Real-Time Systems	311

14.1. Performance Measures for Real-time Systems	311
14.2. Edge-triggered Interfacing	315
14.3. Real-time Profiling	319
15. Data Acquisition Systems	323
15.1. Introduction	323
15.2. Analog Filters	332
15.3. Sampling.....	334
15.4. Digital to Analog Converters	336
15.5. Analog to Digital Converters	338
15.6. Introduction to Digital Signal Processing.....	343
15.7. Noise	349
15.8. IR Distance Measurement	353
15.9. Audio Input/Output	354
16. Tachometer Interfacing	359
16.1. Input Capture Basic Principles	359
16.2. Period Measurement.....	364
16.3. Pulse Width Measurement	366
16.4. Frequency Measurement.....	368
16.4. Odometry.....	369
17. Control Systems	371
17.1. Introduction to Digital Control Systems	371
17.2. Bang-Bang Control Systems	372
17.3. Incremental Control Systems	374
17.4. Integral Control Systems	376
17.5. PID Control Systems	377
17.6. Fuzzy Logic Control.....	382
18. Communication Systems	391
18.1. Fundamentals	391
18.2. First In First Out Queue.....	395
18.3. Interrupt-Driven UART.....	402
18.4. Communication Systems Based on the UARTs.....	405

19. Wireless Communication	409
19.1. Introduction to Wireless Communication	409
19.2. ZigBee	410
19.3. Bluetooth Fundamentals	414
19.4. CC2650 Solutions	420
19.5. Network Processor Interface (NPI)	423
20. Internet of Things	429
20.1. Basic Concepts	429
20.2. Layered Model	431
20.3. Message Protocols	433
20.4. UDP communication over wifi	434
20.5. Client-Server Paradigm	438
20.6. Access a Weather Server using TCP	440
20.7. Other CC3100 Applications	442
Appendix 1. Glossary	445
Appendix 2. Solutions to Checkpoints	461
Index	467
Reference Material	477