

EMBEDDED SYSTEMS:

REAL-TIME INTERFACING TO ARM[®]
CORTEX[™]-M MICROCONTROLLERS

Volume 2
Fourth Edition,
June 2014

Jonathan W. Valvano

Fourth edition

June 2014

ARM and uVision are registered trademarks of ARM Limited.

Cortex and Keil are trademarks of ARM Limited.

Stellaris and Tiva are registered trademarks Texas Instruments.

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: Real-Time Interfacing to ARM® Cortex™-M Microcontrollers, <http://users.ece.utexas.edu/~valvano/>, ISBN: 978-1463590154, 2014.

Copyright © 2014 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: 978-1463590154

ISBN-10: 1463590156

Table of Contents

Preface to Third Edition	vii
Preface to Fourth Edition	vii
Preface.....	viii
Acknowledgements	ix
1. Introduction to Embedded Systems.....	1
1.1. Computer Architecture.....	2
1.2. Embedded Systems.....	10
1.3. The Design Process	16
1.4. Digital Logic and Open Collector	29
1.5. Digital Representation of Numbers.....	40
1.6. Ethics.....	56
1.7. Exercises.....	58
1.8. Lab Assignments.....	62
2. ARM Cortex-M Processor.....	63
2.1. Cortex™-M Architecture.....	64
2.2. Texas Instruments LM3S and TM4C I/O pins	71
2.3. ARM® Cortex™-M Assembly Language	87
2.4. Parallel I/O ports	109
2.5. Phase-Lock-Loop.....	122
2.6. SysTick Timer	125
2.7. Choosing a Microcontroller	126
2.8. Exercises.....	128
2.9. Lab Assignments.....	129
3. Software Design.....	131
3.1. Attitude	132
3.2. Quality Programming	134
3.3. Software Style Guidelines.....	135

3.4. Modular Software	150
3.5. Finite State Machines	163
3.6. Threads	174
3.7. First In First Out Queue	177
3.8. Memory Management and the Heap	185
3.9. Introduction to Debugging	188
3.10. Exercises	200
3.11. Lab Assignments	202
4. Hardware-Software Synchronization	203
4.1. Introduction	204
4.2. Timing	209
4.3. Petri Nets	214
4.4. Kahn Process Networks	217
4.5. Edge-triggered Interfacing	219
4.6. Configuring Digital Output Pins	222
4.7. Blind-cycle Interfacing	223
4.8. Busy-Wait Synchronization	235
4.9. UART Interface	240
4.10. Keyboard Interface	249
4.11. Exercises	254
4.12. Lab Assignments	256
5. Interrupt Synchronization	259
5.1. Multithreading	260
5.2. Interthread Communication and Synchronization	263
5.3. Critical Sections	271
5.4. NVIC on the ARM® Cortex-M Processor	275
5.5. Edge-triggered Interrupts	280
5.6. Interrupt-Driven UART	283
5.7. Periodic Interrupts using SysTick	287
5.8. Low-Power Design	291
5.9. Debugging Profile	292

5.10. Exercises	292
5.11. Lab Assignments	297
6. Time Interfacing	299
6.1. Input Capture or Input Edge Time Mode.....	299
6.2. Output Compare or Periodic Timer	313
6.3. Pulse Width Modulation	317
6.4. Frequency Measurement	320
6.5. Binary Actuators.....	326
6.6. Integral Control of a DC Motor	339
6.7. Exercises	341
6.8. Lab Assignments.....	343
7. Serial Interfacing.....	345
7.1. Introduction to Serial Communication.....	346
7.2. RS232 Interfacing	352
7.3. RS422/USB/RS423/RS485 Balanced Differential Lines	357
7.4. Logic Level Conversion	362
7.5. Synchronous Transmission and Receiving using the SSI.....	363
7.6. Inter-Integrated Circuit (I ² C) Interface	374
7.7. Introduction to Universal Serial Bus (USB).....	387
7.8. Exercises.....	394
7.9. Lab Assignments.....	397
8. Analog Interfacing	399
8.1. Resistors and Capacitors	399
8.2. Op Amps.....	402
8.3. Analog Filters.....	418
8.4. Digital to Analog Converters	421
8.5. Analog to Digital Converters	433
8.6. Exercises.....	446
8.7. Lab Assignments.....	448
9. System-Level Design.....	449
9.1. Design for Manufacturability	449

9.2. Power	451
9.3 Tolerance	458
9.4. Design for Testability	460
9.5. Printed Circuit Board Layout and Enclosures	461
9.6. Exercises	464
9.7. Lab Assignments	464
10. Data Acquisition Systems	465
10.1. Introduction	465
10.2. Transducers	470
10.3. Discrete Calculus	482
10.4. Data Acquisition System Design	484
10.5. Analysis of Noise	490
10.6. Data Acquisition Case Studies	499
10.7. Exercises	511
10.8. Lab Assignments	515
11. Introduction to Communication Systems	517
11.1. Fundamentals	517
11.2. Communication Systems Based on the UARTs	521
11.3. Wireless Communication	525
11.4. Internet of Things	530
11.5. Exercises	544
11.6. Lab Assignments	545
Appendix 1. Glossary	546
Appendix 2. Solutions to Checkpoints	563
Index	571
Reference Material	583

Preface to Third Edition

There are a new features added to this third edition. The new development platform based on the TM4C123 is called Tiva LaunchPad. Material in this book on the TM4C also applies to the LM4F because Texas Instruments rebranded the LM4F series as TM4C (same chips new name), and rebranded StellarisWare™ as TivaWare™. These new microcontrollers run at 80 MHz, include single-precision floating point, have two 12-bit ADCs, and support DMA and USB. A wonderful feature of these new boards is their low cost. As of December 2013, the boards are available on TI.com as part number EK-TM4C123GXL for \$12.99. They are also available from \$13 to \$24 at regular electronics retailers like arrow.com, newark.com, mouser.com, and digikey.com. The book can be used with either a LM3S or TM4C microcontroller. Although this edition now focuses on the M4, the concepts still apply to the M3, and the web site associated with this book has example projects based on the LM3S811, LM3S1968, and LM3S8962.

Preface to Fourth Edition

This fourth edition includes the new TM4C1294-based LaunchPad. Most of the code in the book is specific for the TM4C123-based LaunchPad. However, the book website includes corresponding example projects for the LM3S811, LM3S1968, LM4F120, and TM4C1294, which are ARM® Cortex™-M microcontrollers from Texas Instruments. There are now two lost-cost development platforms called Tiva LaunchPad. The EK-TM4C123GXL LaunchPad retails for \$12.99, and the EK-TM4C1294XL Connected LaunchPad retails for \$19.99. The various LM3S, LM4F and TM4C microcontrollers are quite similar, so this book along with the example code on the web can be used for any of these microcontrollers. Compared to the TM4C123, the new TM4C1294 microcontroller runs faster, has more RAM, has more ROM, includes Ethernet, and has more I/O pins. This fourth edition switches the syntax from C to the industry-standard C99, adds a line-tracking robot, designs an integral controller for a DC motor, and includes an expanded section on wireless communication and Internet of Things.

