

Embedded Microcomputer Systems

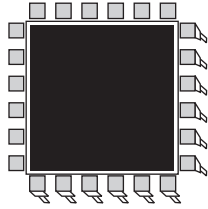
Real Time Interfacing
Second Edition

Jonathan W. Valvano

University of Texas at Austin



Australia • Canada • Mexico • Singapore • Spain • United Kingdom • United States



Contents

1 Microcomputer-Based Systems 1

- 1.1** Computer Architecture 2
- 1.2** Embedded Computer Systems 6
- 1.3** The Design Process 10
 - 1.3.1 Top-Down Design 10
 - 1.3.2 Bottom-Up Design 14
- 1.4** Digital Logic and Open Collector 15
- 1.5** Digital Representation of Numbers 20
 - 1.5.1 Fundamentals 20
 - 1.5.2 8-Bit Numbers 22
 - 1.5.3 Character Information 23
 - 1.5.4 16-Bit Numbers 23
 - 1.5.5 Fixed-Point Numbers 25
- 1.6** Common Architecture of the 6811 and the 6812 27
 - 1.6.1 Registers 28
 - 1.6.2 Terminology 29
 - 1.6.3 Addressing Modes 30
 - 1.6.4 Numbering Scheme Used by Freescale for the 6811 and the 6812 33
- 1.7** 6811 Architecture 33
 - 1.7.1 6811 Family 33
 - 1.7.2 MC68HC711E9 35
 - 1.7.3 MC68HC11D3 37
- 1.8** 6812 Architecture 37
 - 1.8.1 6812 Family 37
 - 1.8.2 MC9C12C32 38
 - 1.8.3 MC68HC812A4 41
 - 1.8.4 MC68HC912B32 42
- 1.9** Parallel I/O Ports 43
 - 1.9.1 Basic Concepts of Input and Output Ports 43
 - 1.9.2 Introduction to I/O Programming and the Direction Register 46
 - 1.9.3 Our First Design Problem 47

- 1.10** Choosing a Microcontroller 53
- 1.11** Exercises 54
- 1.12** Lab Assignments 56

2 Design of Software Systems 58

- 2.1** Quality Programming 58
 - 2.1.1 Quantitative Performance Measurements 59
 - 2.1.2 Qualitative Performance Measurements 59
- 2.2** Assembly Language Programming 60
 - 2.2.1 Introduction 60
 - 2.2.2 Assembly Language Syntax 62
 - 2.2.3 Memory and Register Transfer Operations 64
 - 2.2.4 Indexed Addressing Mode 66
 - 2.2.5 Arithmetic Operations 69
 - 2.2.6 Extended Precision Arithmetic Instructions on the 6812 74
 - 2.2.7 Shift Operations 75
 - 2.2.8 Logical Operations 77
 - 2.2.9 Subroutines and the Stack 78
 - 2.2.10 Branch Operations 82
 - 2.2.11 Assembler Pseudo-ops 84
 - 2.2.12 Memory Allocation 88
- 2.3** Self-Documenting Code 91
 - 2.3.1 Comments 91
 - 2.3.2 Naming Convention 94
- 2.4** Abstraction 95
 - 2.4.1 Definitions 95
 - 2.4.2 6811 Timer Details 96
 - 2.4.3 6812 Timer Details 96
 - 2.4.4 Time Delay Software Using the Built-in Timer 97
 - 2.4.5 Moore Finite State Machine Traffic Light Controller 98

xiv ■ Contents

2.4.6	Mealy Finite State Machine Robot Controller	101
2.5	Modular Software Development	104
2.5.1	Local Variables in Assembly Language	104
2.5.2	Modules	109
2.5.3	Dividing a Software Task into Modules	113
2.5.4	Rules for Developing Modular Software in Assembly Language	116
2.6	Layered Software Systems	118
2.7	Device Drivers	119
2.7.1	Basic Concept of Device Drivers	119
2.7.2	Design of a Serial Communications Interface (SCI) Device Driver	121
2.8	Object-Oriented Interfacing	122
2.8.1	Encapsulated Objects Using Standard C	122
2.8.2	Object-Oriented Interfacing Using C++	123
2.8.3	Portability Using Standard C and C++	124
2.9	Threads	126
2.9.1	Single-Threaded Execution	126
2.9.2	Multithreading and Reentrancy	126
2.10	Recursion	128
2.11	Debugging Strategies	128
2.11.1	Debugging Tools	128
2.11.2	Debugging Theory	129
2.11.3	Functional Debugging	131
2.11.4	Performance Debugging	133
2.11.5	Profiling	136
2.12	Exercises	137
2.13	Lab Assignments	141

3 Interfacing Methods 142

3.1	Introduction	142
3.1.1	Performance Measures	142
3.1.2	Synchronizing the Software with the State of the I/O	143
3.1.3	Variety of Available I/O Ports	146
3.2	Handshake protocols	148
3.2.1	6811 Handshake Protocol	148
3.2.2	MC68HC812A4 Key Wakeup Interrupts	149
3.2.3	MC9S12C32 Key Wakeup Interrupts	150
3.3	Blind Cycle Counting Synchronization	151
3.3.1	Blind Cycle Printer Interface	151
3.3.2	Blind Cycle ADC Interface	152
3.4	Gadfly or Busy Waiting Synchronization	153
3.5	Parallel I/O Interface Examples	155
3.5.1	Blind Cycle Printer Interface	156
3.5.2	Blind Cycle ADC Interface	157

3.5.3	Gadfly Keyboard Interface Using Latched Input	158
3.5.4	Gadfly ADC Interface Using Simple Input	159
3.5.5	Gadfly External Sensor Interface Using Input Handshake	161
3.5.6	Gadfly Printer Interface Using Output Handshake	163
3.5.7	Gadfly Synchronous Serial Interface to a Temperature Sensor	164
3.6	Serial Communications Interface (SCI) Device Driver	173
3.6.1	Transmitting in Asynchronous Mode	174
3.6.2	Receiving in Asynchronous Mode	175
3.6.3	6811 SCI Details	177
3.6.4	6812 SCI Details	178
3.6.5	SCI Device Driver	179
3.7	Exercises	181
3.8	Lab Assignments	187

4 Interrupt Synchronization 189

4.1	What Are Interrupts?	190
4.1.1	Interrupt Definition	190
4.1.2	Interrupt Service Routines	191
4.1.3	When to Use Interrupts	192
4.1.4	Interthread Communication	192
4.2	Reentrant Programming	197
4.3	First-In–First-Out Queue	204
4.3.1	Introduction to FIFOs	204
4.3.2	Two-Pointer FIFO Implementation	205
4.3.3	Two-Pointer/ Counter FIFO Implementation	208
4.3.4	FIFO Dynamics	209
4.4	General Features of Interrupts on the 6811/6812	210
4.4.1	6811 Interrupts	212
4.4.2	6812 Interrupts	213
4.5	Interrupt Vectors and Priority	214
4.5.1	MC68H11E Interrupt Vectors and Priority	214
4.5.2	MC68HC812A4 Interrupt Vectors and Priority	216
4.5.3	MC68HC912B32 Interrupt Vectors and Priority	217
4.5.4	MC9S12C32 Interrupt Vectors and Priority	218
4.6	External Interrupt Design Approach	219
4.7	Polled Versus Vectored Interrupts	221
4.8	Keyboard Interface Using Interrupts	223

- 4.9** Printer Interface Using IRQ Interrupts 226
- 4.10** Power System Interface Using $\overline{\text{XIRQ}}$ Synchronization 229
- 4.11** Interrupt Polling Using Linked Lists 231
 - 4.11.1 6811 Interrupt Polling Using Linked Lists 232
 - 4.11.2 6812 Interrupt Polling Using Linked Lists 234
- 4.12** Fixed Priority Implemented Using One Interrupt Line 235
- 4.13** Fixed Priority Implemented Using XIRQ 237
- 4.14** Round-Robin Polling 238
- 4.15** Periodic Polling 238
 - 4.15.1 MC68HC711E9 Periodic Interrupts 240
 - 4.15.2 MC68HC812A4 Periodic Interrupts 243
 - 4.15.3 MC9S12C32 Periodic Interrupts 245
- 4.16** Exercises 249
- 4.17** Lab Assignments 254

5 Threads 255

- 5.1** Multithreaded Preemptive Scheduler 256
 - 5.1.1 Round-Robin Scheduler 257
 - 5.1.2 Other Scheduling Algorithms 262
 - 5.1.3 Dynamic Allocation of Threads 262
- 5.2** Semaphores 262
 - 5.2.1 Spin-Lock Semaphore Implementation 263
 - 5.2.2 Blocking Semaphore Implementation 265
- 5.3** Applications of Semaphores 267
 - 5.3.1 Thread Synchronization or Rendezvous 268
 - 5.3.2 Resource Sharing, Nonreentrant Code or Mutual Exclusion 268
 - 5.3.3 Thread Communication Between Two Threads Using a Mailbox 268
 - 5.3.4 Thread Communication Between Many Threads Using a FIFO Queue 268
- 5.4** Fixed Scheduling 269
- 5.5** Exercises 274
- 5.6** Lab Assignments 275

6 Timing Generation and Measurements 276

- 6.1** Input Capture 276
 - 6.1.1 Basic Principles of Input Capture 276
 - 6.1.2 Input Capture Details 277
 - 6.1.3 Real Time Interrupt Using an Input Capture 281

- 6.1.4 Period Measurement 283
- 6.1.5 Pulse-Width Measurement 288
- 6.2** Output Compare 294
 - 6.2.1 General Concepts 294
 - 6.2.2 Output Compare Details 295
 - 6.2.3 Square-Wave Generation 298
 - 6.2.4 Pulse-Width Modulation 301
 - 6.2.5 Delayed Pulse Generation 303
- 6.3** Frequency Measurement 304
 - 6.3.1 Frequency Measurement Concepts 304
 - 6.3.2 Frequency Measurement with $\Delta f = 100\text{Hz}$ 305
- 6.4** Conversion Between Frequency and Period 306
 - 6.4.1 Using Period Measurement to Calculate Frequency 306
 - 6.4.2 Using Frequency Measurement to Calculate Period 307
- 6.5** Measurements Using Both Input Capture and Output Compare 307
 - 6.5.1 Period Measurement with $\Delta p = 1\text{ms}$ 307
 - 6.5.2 Frequency Measurement with $\Delta f = 0.1\text{Hz}$ 309
- 6.6** Pulse Accumulator 311
 - 6.6.1 MC68711E9 Pulse Accumulator Details 311
 - 6.6.2 MC9S12C32 Pulse Accumulator Details 312
 - 6.6.3 Frequency Measurement 313
 - 6.6.4 Pulse-Width Measurement 314
- 6.7** Pulse-width Modulation on the MC9S12C32 314
- 6.8** Exercises 318
- 6.9** Lab Assignments 323

7 Serial I/O Devices 326

- 7.1** Introduction and Definitions 326
- 7.2** RS232 Specifications 332
- 7.3** RS422/USB/RS423/RS485 Balanced Differential Lines 334
 - 7.3.1 RS422 Output Specifications 337
 - 7.3.2 RS422 Input Specifications 338
 - 7.3.3 RS485 Half-Duplex Channel 338
- 7.4** Other Communication Protocols 339
 - 7.4.1 Current Loop Channel 339
 - 7.4.2 Introduction to Modems 339
 - 7.4.3 Optical Channel 340
 - 7.4.4 Digital Logic Channel 340
- 7.5** Serial Communications Interface 341
 - 7.5.1 Transmitting in Asynchronous Mode 341
 - 7.5.2 Receiving in Asynchronous Mode 343
 - 7.5.3 MC68HC711E9 SCI Details 345
 - 7.5.4 MC9S12C32 SCI Details 346

xvi ■ Contents**7.6** SCI Software Interfaces 349

7.6.1 Full Duplex Serial Channel 349

7.6.2 Use of Data Terminal Ready (DTR) to Interface a Printer 352

7.6.3 Use of XON/XOFF to Interface a Printer 354

7.7 Synchronous Transmission and Receiving Using the SPI 355

7.7.1 SPI Fundamentals 355

7.7.2 MC68HC711E9 SPI Details 358

7.7.3 MC9S12C32 SPI Details 359

7.7.6 SPI Applications 361

7.8 Exercises 368**7.9** Lab Assignments 370**8** Parallel Port Interfaces 375**8.1** Input Switches and Keyboards 375

8.1.1 Interfacing a Switch to the Computer 375

8.1.2 Hardware Debouncing Using a Capacitor 377

8.1.3 Software Debouncing 381

8.1.4 Basic Approaches to Interfacing Multiple Keys 386

8.1.5 Sixteen-Key Electronic Piano 389

8.1.6 4 by 4 Scanned Keyboard 393

8.1.7 Multiplexed/Demultiplexed Scanned Keyboard 396

8.2 Output LEDs 398

8.2.1 Single LED Interface 400

8.2.2 Seven-Segment LED Interfaces 402

8.2.3 Scanned Seven-Segment LED Interface 402

8.2.4 Scanned LED Interface Using the 7447 Seven-Segment Decoder 405

8.2.5 Integrated LED Interface Using the MC14489 Display Driver 408

8.3 Liquid Crystal Displays 410

8.3.1 LCD Fundamentals 410

8.3.2 Simple LCD Interface with the MC14543 412

8.3.3 Scanned LCD Interface with the MC145000, MC145001 414

8.3.4 Parallel Port LCD Interface with the HD44780 Controller 416

8.4 Transistors Used for Computer-Controlled Current Switches 419**8.5** Computer-Controlled Relays, Solenoids, and DC Motors 421

8.5.1 Introduction to Relays 421

8.5.2 Electromagnetic Relay Basics 422

8.5.3 Reed Relays 424

8.5.4 Solenoids 424

8.5.5 Pulse-Width Modulated DC Motors 424

8.5.6 Interfacing EM Relays, Solenoids, and DC Motors 425

8.5.7 Solid-State Relays 430

8.6 Stepper Motors 431

8.6.1 Stepper Motor Example 431

8.6.2 Basic Operation 434

8.6.3 Stepper Motor Hardware Interfaces 438

8.6.4 Stepper Motor Shaft Encoder 441

8.7 Exercises 443**8.8** Lab Assignments 446**9** Memory Interfacing 448**9.1** Introduction 448**9.2** Address Decoding 451

9.2.1 Full-Address Decoding 452

9.2.2 Minimal-Cost Address Decoding 454

9.2.3 Special Cases When Address Decoding 457

9.2.4 Flexible Full-Address Decoder 458

9.2.5 Integrated Address Decoder on the MC68HC812A4 459

9.3 Timing Syntax 461

9.3.1 Available and Required Time Intervals 461

9.3.2 Timing Diagrams 463

9.4 General Memory Bus Timing 463

9.4.1 Synchronous Bus Timing 464

9.4.2 Partially Asynchronous Bus Timing 465

9.4.3 Fully Asynchronous Bus Timing 466

9.5 External Bus Timing 468

9.5.1 Synchronized Versus Unsynch-ronized Signals 468

9.5.2 Freescale MC68HC11A8 External Bus Timing 469

9.5.3 Freescale MC68HC812A4 External Bus Timing 472

9.5.4 Freescale MC9S12C32 External Bus Timing 477

9.6 General Approach to Interfacing 483

9.6.1 Interfacing to a 6811 483

9.6.2 Interfacing to a 6812 in Expanded Narrow Mode 484

9.6.3 Interfacing to a 6812 in Expanded Wide Mode 485

9.7 Memory Interface Examples 487

9.7.1 32K PROM Interface 487

9.7.2 8K RAM Interface 492

9.7.3 32K by 16-bit PROM Interface to a MC68HC812A4 505

9.7.4 8K by 16-bit RAM Interface 507

9.7.5 Extended Address Data Page Interface to the MC68HC812A4 509

9.7.6 Extended Address Program Page Interface to the MC68HC812A4 511

9.8 Dynamic RAM (DRAM) 514**9.9** Exercises 514**9.10** Lab Assignments 523

10 High-Speed I/O Interfacing 524

- 10.1 The Need for Speed 524
- 10.2 High-Speed I/O Applications 525
 - 10.2.1 Mass Storage 525
 - 10.2.2 High-Speed Data Acquisition 526
 - 10.2.3 Video Displays 527
 - 10.2.4 High-Speed Signal Generation 527
 - 10.2.5 Network Communications 527
- 10.3 General Approaches to High-Speed Interfaces 528
 - 10.3.1 Hardware FIFO 528
 - 10.3.2 Dual Port Memory 529
 - 10.3.3 Bank-Switched Memory 529
- 10.4 Fundamental Approach to DMA 530
 - 10.4.1 DMA Cycles 530
 - 10.4.2 DMA Initiation 531
 - 10.4.3 Burst Versus Cycle Steal DMA 531
 - 10.4.4 Single-Address Versus Dual-Address DMA 532
 - 10.4.5 DMA Programming 534
- 10.5 LCD Graphics 535
 - 10.5.1 LCD Graphics Controller 535
 - 10.5.2 Practical LCD Graphics Interface 538
- 10.6 Exercises 539
- 10.7 Lab Assignments 540

11 Analog Interfacing 541

- 11.1 Resistors and Capacitors 541
 - 11.1.1 Resistors 541
 - 11.1.2 Capacitors 542
- 11.2 Operational Amplifiers (Op Amps) 543
 - 11.2.1 Op Amp Parameters 543
 - 11.2.2 Threshold Detector 546
 - 11.2.3 Simple Rules for Linear Op Amp Circuits 547
 - 11.2.4 Linear Mode Op Amp Circuits 549
 - 11.2.5 Instrumentation Amplifier 553
 - 11.2.6 Current-to-Voltage Circuit 555
 - 11.2.7 Voltage-to-Current Circuit 555
 - 11.2.8 Integrator Circuit 556
 - 11.2.9 Derivative Circuit 556
 - 11.2.10 Voltage Comparators with Hysteresis 556
 - 11.2.11 Analog Isolation 557
- 11.3 Analog Filters 558
 - 11.3.1 Simple Active Filter 558
 - 11.3.2 Butterworth Filters 559
 - 11.3.3 Bandpass and Band-Reject Filters 560
- 11.4 Digital-to-Analog Converters 561
 - 11.4.1 DAC Parameters 561
 - 11.4.2 DAC Using a Summing Amplifier 563

- 11.4.3 Three-Bit DAC with an R-2R Ladder 564
- 11.4.4 Twelve-Bit DAC with a DAC8043 566
- 11.4.5 DAC Selection 567
- 11.4.6 DAC Waveform Generation 570

11.5 Analog-to-Digital Converters 573

- 11.5.1 ADC Parameters 573
- 11.5.2 Two-Bit Flash ADC 574
- 11.5.3 Successive Approximation ADC 575
- 11.5.4 Sixteen-Bit Dual Slope ADC 576
- 11.5.5 Sigma Delta ADC 577
- 11.5.6 ADC Interface 578

11.6 Sample and Hold 579

11.7 BiFET Analog Multiplexer 580

11.8 ADC System 582

- 11.8.1 ADC Block Diagram 582
- 11.8.2 Power and Grounding for the ADC System 584
- 11.8.3 Input Protection for High-Speed CMOS Analog Inputs 584

11.9 Multiple-Access Circular Queue 585

11.10 Internal ADCs 587

- 11.10.1 6811 ADC System 587
- 11.10.2 6812 ADC System 589
- 11.10.3 ADC Software 591

11.11 Exercises 593

11.12 Lab Assignments 595

12 Data Acquisition Systems 597

12.1 Introduction 597

- 12.1.1 Accuracy 599
- 12.1.2 Resolution 601
- 12.1.3 Precision 601
- 12.1.4 Reproducibility or Repeatability 602

12.2 Transducers 602

- 12.2.1 Static Transducer Specifications 602
- 12.2.2 Dynamic Transducer Specifications 606
- 12.2.3 Nonlinear Transducers 607
- 12.2.4 Position Transducers 608
- 12.2.5 Velocity Measurements 609
- 12.2.6 Force Transducers 611
- 12.2.7 Temperature Transducers 612

12.3 DAS Design 617

- 12.3.1 Introduction and Definitions 617
- 12.3.2 Using Nyquist Theory to Determine Sampling Rate 618
- 12.3.3 How Many Bits Does One Need for the ADC? 621
- 12.3.4 Specifications for the Analog Signal Processing 621
- 12.3.5 How Fast Must the ADC Be? 626
- 12.3.6 Specifications for the S/H 626

12.4 Analysis of Noise 627

- 12.4.1 Thermal Noise 627

xviii ■ Contents

12.4.2	Shot Noise	630
12.4.3	1/f, or Pink Noise	630
12.4.4	Galvanic Noise	630
12.4.5	Motion Artifact	630
12.4.6	Electromagnetic Field Induction	631
12.4.7	Techniques to Measure Noise.	631
12.4.8	Techniques to Reduce Noise	633
12.5	Data Acquisition Case Studies	635
12.5.1	Temperature Measurement	635
12.5.2	EKG Data Acquisition System	639
12.5.3	Position Measurement System	642
12.6	Exercises	643
12.7	Lab Assignments	650
13	Microcomputer-Based Control Systems	652
13.1	Introduction to Digital Control Systems	652
13.2	Open-Loop Control Systems	653
13.2.1	Open-Loop Control of a Toaster	654
13.2.2	Open-Loop Robotic Arm	654
13.3	Simple Closed-Loop Control Systems	659
13.3.1	Bang-Bang Temperature Control	659
13.3.2	Closed-Loop Position Control System Using Incremental Control	661
13.4	PID Controllers	663
13.4.1	General Approach to a PID Controller	663
13.4.2	Design Process for a PID Controller	666
13.4.3	Velocity PID Controller	668
13.4.4	Proportional-Integral Controller with a PWM actuator	669
13.5	Fuzzy Logic Control	672
13.5.1	DAC, ADC Fuzzy Controller	675
13.5.2	PWM Fuzzy Controller	681
13.5.3	Temperature Controller Using Fuzzy Logic	687
13.6	Exercises	691
13.7	Lab Assignments	694
14	Simple Networks	696
14.1	Introduction	696
14.2	Communication Systems Based on the SCI Serial Port	698
14.3	Design and Implementation of a Controller Area Network (CAN)	700
14.3.1	The Fundamentals of CAN	700
14.3.2	Details of the 9S12C32 CAN	703
14.3.3	9S12C32 CAN Device Driver	706
14.4	Inter-Integrated Circuit (I²C) Network	709
14.4.1	The Fundamentals of the I ² C Network	709
14.4.2	I ² C Synchronization	712
14.4.3	9S12 I ² C Details	714
14.4.4	9S12 I ² C Single Master Example	717
14.5	Modem Communications	718
14.5.1	FSK Modem	718
14.5.2	Phase-Encoded Modems	721
14.5.3	Quadrature Amplitude Modems	722
14.6	X-10 Protocol	723
14.7	Universal Serial Bus (USB)	730
14.7.1	Introduction	730
14.7.2	Modular USB Interface	734
14.7.3	Integrated USB Interface	735
14.8	Exercises	735
14.9	Lab Assignments	739
15	Digital Filters	742
15.1	Basic Principles	743
15.2	Simple Digital Filter Examples	745
15.3	Impulse Response	752
15.4	High-Q 60-Hz Digital Notch Filter	755
15.5	Effect of Latency on Digital Filters	760
15.6	High-Q Digital High-Pass Filters	762
15.7	Digital Low-Pass Filter	763
15.8	Direct-Form Implementations	765
15.9	Exercises	766
15.10	Lab Assignments	767
Appendix 1		769
Appendix 2		789
Index		802