
CONTENTS

Preface	xv
Introduction	xvii
Acknowledgments	xix

CHAPTER

1 Elements of Embedded Design	1
1.1 Abstraction Levels	2
1.1.1 Transistors to Programs.....	2
1.1.2 Mixed Level Hardware	3
1.1.3 Design Specification.....	4
1.2 Embedded System Design Flow	4
1.2.1 Hardware/Software Partitioning	4
1.2.2 Hardware Part	5
1.2.3 Software Part	6
1.2.4 Interconnection Specification.....	6
1.2.5 Common Hardware/Software Simulation	6
1.2.6 Hardware Synthesis	7
1.2.7 Software Compilation	7
1.2.8 Interconnection Hardware Generation	8
1.2.9 Design Integrator.....	8
1.3 Design Tools	9
1.3.1 Block Diagram Description	9
1.3.2 HDL and Other Hardware Simulators.....	9
1.3.3 Programming Language Compilers.....	9
1.3.4 Netlist Simulator	9
1.3.5 Instruction Set Simulator	10
1.3.6 Hardware Synthesis Tool	10
1.3.7 Compiler for Machine Language Generation.....	10
1.3.8 Software Builder and Debugger.....	10
1.3.9 Embedded System Integrator	10
1.4 New Hardware Design Trends	10

1.4.1	Configurable Processors	11
1.4.2	Standard Bus Structure	11
1.4.3	Software Programming	11
1.4.4	Software Utilities.....	11
1.5	Summary.....	11
2	Logic Design Concepts	13
2.1	Number Systems	14
2.1.1	Binary Numbers.....	14
2.1.2	Hexadecimal Numbers	15
2.2	Binary Arithmetic.....	16
2.2.1	Signed Numbers.....	16
2.2.2	Binary Addition.....	16
2.2.3	Binary Subtraction	17
2.2.4	Two's Complement System	17
2.2.5	Overflow	18
2.2.6	Fixed Point Numbers.....	18
2.2.7	Floating Point Numbers	19
2.3	Basic Logic Gates and Structures	20
2.3.1	Logic Value System.....	20
2.3.2	Logic Function Representation	21
2.3.3	Transistors	22
2.3.4	CMOS Inverter.....	23
2.3.5	CMOS NAND	23
2.3.6	CMOS NOR	24
2.3.7	AND and OR gates.....	24
2.3.8	XOR gate	25
2.3.9	MUX gate	25
2.3.10	Three-State Gates.....	26
2.3.11	Look-up Tables (LUT).....	28
2.4	Designing Combinational Circuits	28
2.4.1	Boolean Algebra	28
2.4.2	Karnaugh Maps	32
2.4.3	Don't Care Values	35
2.4.4	Minimal Coverage.....	36
2.4.5	Iterative Hardware	38
2.4.6	Multiplexers and Decoders.....	41
2.4.7	Activity Levels.....	43
2.4.8	Enable / Disable Inputs	44
2.4.9	A High-Level Design.....	44
2.5	Storage Elements.....	45
2.5.1	The Basic Latch	46
2.5.2	Clocked D Latch.....	47
2.5.3	Flip-Flops	48
2.5.4	Flip-Flop Control.....	49

2.5.5 Registers	51
2.6 Sequential Circuit Design.....	51
2.6.1 Finite State Machines	52
2.6.2 Designing State Machines.....	53
2.6.3 Mealy and Moore Machines	58
2.6.4 One-Hot Realization	59
2.6.5 Sequential Packages	59
2.7 Memories	63
2.7.1 Static RAM Structure.....	64
2.8 Bidirectional IO	64
2.9 A Comprehensive Example: Serial Adder.....	65
2.9.1 Problem Statement	65
2.9.2 Design Partitioning.....	65
2.9.3 Datapath Design	66
2.10 Summary	70
3 RTL Design with Verilog	71
3.1 Basic Structures of Verilog	72
3.1.1 Modules	73
3.1.2 Module Outline	74
3.1.3 Module Ports	75
3.1.4 Module Variables	76
3.1.5 Logic Value System.....	78
3.1.6 Wire (net) Resolutions	79
3.2 Combinational Circuits	80
3.2.1 Gate Level Combinational Circuits	80
3.2.2 Gate Level Synthesis	85
3.2.3 Descriptions by Use of Equations	87
3.2.4 Instantiating Other Modules	90
3.2.5 Synthesis of Assignment Statements	92
3.2.6 Descriptions with Procedural Statements	93
3.2.7 Combinational Rules	98
3.2.8 Synthesizing Procedural Blocks.....	98
3.2.9 Bussing	100
3.3 Sequential Circuits.....	100
3.3.1 Basic Memory Elements at the Gate Level.....	101
3.3.2 Memory Elements Using Procedural Statements	102
3.3.3 Flip-flop Synthesis	106
3.3.4 Registers, Shifters and Counters.....	108
3.3.5 Synthesis of Shifters and Counters	111
3.3.6 State Machine Coding	111
3.3.7 State Machine Synthesis.....	121
3.3.8 Memories	123
3.4 Writing Testbenches.....	125
3.4.1 Generating Periodic Data.....	126

3.4.2	Random Input Data	127
3.4.3	Timed Data.....	127
3.5	Sequential Multiplier Specification.....	128
3.5.1	Shift-and-Add Multiplication Process	129
3.5.2	Sequential Multiplier Design.....	131
3.5.3	Multiplier Testing.....	137
3.6	Synthesis Issues	140
3.7	Summary.....	141
4	Computer Hardware and Software	143
4.1	Computer System	143
4.2	Computer Software.....	146
4.2.1	Machine Language.....	146
4.2.2	Assembly Language	146
4.2.3	High-Level Language	147
4.2.4	C Programming Language	148
4.3	Instruction Set Architecture	160
4.4	SMPL-CPU Design	162
4.4.1	CPU Specification	162
4.4.2	Single-Cycle Implementation.....	164
4.4.3	Multi-Cycle Implementation	177
4.5	SAYEH Design and Test.....	187
4.5.1	Details of Processor Functionality.....	188
4.5.2	SAYEH Datapath.....	190
4.5.3	SAYEH Verilog Description	193
4.5.4	SAYEH Top-Level Testbench / Assembler	193
4.5.5	SAYEH Hardware Realization	195
4.6	Summary.....	195
5	Field Programmable Devices	197
5.1	Read Only Memories	197
5.1.1	Basic ROM Structure	197
5.1.2	NOR Implementation	199
5.1.3	Distributed Gates.....	199
5.1.4	Array Programmability	201
5.1.5	Memory View	202
5.1.6	ROM Variations	203
5.2	Programmable Logic Arrays	206
5.2.1	PAL Logic Structure	208
5.2.2	Product Term Expansion.....	209
5.2.3	Three-State Outputs.....	210
5.2.4	Registered Outputs.....	211
5.2.5	Commercial Parts	211
5.3	Complex Programmable Logic Devices	214
5.3.1	Altera's MAX 7000S CPLD	215

5.4	Field Programmable Gate Arrays	216
5.4.1	Altera's FLEX 10K FPGA	217
5.4.2	Altera's Cyclone FPGA	223
5.5	Summary	241
6	Tools for Design and Prototyping	243
6.1	Hardware Design Flow.....	243
6.1.1	Datapath of Serial Adder	244
6.1.2	Serial Adder Controller	245
6.2	HDL Simulation and Synthesis.....	247
6.2.1	Pre-Synthesis Simulation.....	248
6.2.2	Module Synthesis.....	254
6.2.3	Post-Synthesis Simulation	260
6.3	Mixed-Level Design with Quartus II	263
6.3.1	Project Specification	265
6.3.2	Block Diagram Design File	265
6.3.3	Creating and Inserting Design Components.....	267
6.3.4	Wiring Design Components.....	275
6.3.5	Design Compilation	275
6.3.6	Design Simulation	276
6.3.7	Synthesis Results.....	279
6.4	Design Prototyping	284
6.4.1	UP3 Board Specification.....	284
6.4.2	DE2 Board Specification.....	291
6.4.3	Programming DE2 Cyclone II	299
6.5	Summary	303
7	Design of Utility Hardware Cores	305
7.1	Library Management	305
7.2	Basic IO Device Handling	306
7.2.1	Debouncer.....	306
7.2.2	Single Stepper	310
7.2.3	Utilizing UP3 Basic IO	312
7.2.4	Utilizing DE2 Basic IO	314
7.3	Frequency Dividers	315
7.4	Seven Segment Displays	315
7.4.1	SSD Driver	315
7.4.2	Testing DE2 SSD Driver	316
7.5	LCD Display Adaptor	317
7.5.1	Writing into LCD	317
7.5.2	LCD Initialization.....	319
7.5.3	Display Driver with Initialization	320
7.5.4	Testing the LCD Driver (UP3)	321
7.5.5	Testing the LCD Driver (DE2)	322

7.6	Keyboard Interface Logic	322
7.6.1	Serial Data Communication.....	322
7.6.2	Power-On Routine.....	325
7.6.3	Codes and Commands	325
7.6.4	Keyboard Interface Design.....	328
7.7	VGA Interface Logic	333
7.7.1	VGA Driver Operation.....	333
7.7.2	Monitor Synchronization Hardware.....	336
7.7.3	Character Display.....	338
7.7.4	VGA Driver for Text Data	342
7.7.5	VGA Driver Prototyping (UP3)	342
7.7.6	VGA Driver Prototyping (DE2)	343
7.8	Summary.....	344
8	Design with Embedded Processors.....	345
8.1	Embedded Design Steps.....	345
8.1.1	Processor Selection	346
8.1.2	Processor Interfacing.....	348
8.1.3	Developing Software.....	349
8.2	Filter Design	349
8.2.1	Filter Concepts.....	350
8.2.2	FIR Filter Hardware Implementation.....	354
8.2.3	FIR Embedded Implementation	356
8.2.4	Building the FIR Filter.....	361
8.3	Design of a Microcontroller	363
8.3.1	System Platform	363
8.3.2	Microcontroller Architecture.....	364
8.4	Summary.....	366
9	Design of an Embedded System	367
9.1	Designing an Embedded System	368
9.2	Nios II Processor	369
9.2.1	Configurability Features of Nios II	370
9.2.2	Processor Architecture.....	372
9.2.3	Instruction Set	378
9.2.4	Nios II Alternative Cores	381
9.3	Avalon Switch Fabric	381
9.3.1	Avalon Specification	381
9.3.2	Address Decoding Logic.....	384
9.3.3	Data-path Multiplexing.....	384
9.3.4	Wait-state Insertion.....	385
9.3.5	Pipelining	385
9.3.6	Endian Conversion	386
9.3.7	Native Address Alignment and Dynamic Bus Sizing ..	386
9.3.8	Arbitration for Multi-Master Systems	386

9.3.9	Burst Management	388
9.3.10	Clock Domain Crossing	389
9.3.11	Interrupt Controller.....	390
9.3.12	Reset Distribution.....	391
9.4	SOPC Builder Overview.....	391
9.4.1	Architecture of SOPC Builder Systems.....	391
9.4.2	Functions of SOPC Builder	393
9.5	IDE Integrated Development Environment	394
9.5.1	IDE Project Manager.....	394
9.5.2	Source Code Editor	395
9.5.3	C/C++ Compiler.....	395
9.5.4	Debugger	395
9.5.5	Flash Programmer.....	396
9.6	An Embedded System Design: Calculator	396
9.6.1	System Specification.....	396
9.6.2	Calculating Engine	397
9.6.3	Calculator IO Interface.....	398
9.6.4	Design of Calculating Engine.....	398
9.6.5	Building Calculator Software.....	408
9.6.6	Calculator Program	413
9.6.7	Completing the Calculator System.....	417
9.7	Summary	417

APPENDIX

A	Nios II Instruction Set.....	419
A.1	Data Transfer Instructions	419
A.2	Arithmetic and Logical Instructions	420
A.3	Move Instructions.....	421
A.4	Comparison Instructions.....	421
A.5	Shift and Rotate Instructions	422
A.6	Program Control Instructions.....	422
A.7	Other Control Instructions	423
A.8	Custom Instructions.....	424
A.9	No-Op Instruction.....	424
A.10	Potential Unimplemented Instructions	424
B	Additional Resources	425