

Contents

Preface	xv
1 Introduction to Real-Time Digital Signal Processing	1
1.1 Basic Elements of Real-Time DSP Systems	2
1.2 Analog Interface	3
1.2.1 Sampling	3
1.2.2 Quantization and Encoding	7
1.2.3 Smoothing Filters	8
1.2.4 Data Converters	9
1.3 DSP Hardware	10
1.3.1 DSP Hardware Options	10
1.3.2 DSP Processors	13
1.3.3 Fixed- and Floating-Point Processors	15
1.3.4 Real-Time Constraints	16
1.4 DSP System Design	17
1.4.1 Algorithm Development	18
1.4.2 Selection of DSP Processors	19
1.4.3 Software Development	20
1.4.4 High-Level Software Development Tools	21
1.5 Introduction to DSP Development Tools	22
1.5.1 C Compiler	22
1.5.2 Assembler	23
1.5.3 Linker	24
1.5.4 Other Development Tools	25
1.6 Experiments and Program Examples	25
1.6.1 Experiments of Using CCS and DSK	26
1.6.2 Debugging Program Using CCS and DSK	29
1.6.3 File I/O Using Probe Point	32
1.6.4 File I/O Using C File System Functions	35
1.6.5 Code Efficiency Analysis Using Profiler	37
1.6.6 Real-Time Experiments Using DSK	39
1.6.7 Sampling Theory	42
1.6.8 Quantization in ADCs	44
References	45
Exercises	45

2	Introduction to TMS320C55x Digital Signal Processor	49
2.1	Introduction	49
2.2	TMS320C55x Architecture	50
2.2.1	Architecture Overview	50
2.2.2	Buses	53
2.2.3	On-Chip Memories	53
2.2.4	Memory-Mapped Registers	55
2.2.5	Interrupts and Interrupt Vector	55
2.3	TMS320C55x Peripherals	58
2.3.1	External Memory Interface	60
2.3.2	Direct Memory Access	60
2.3.3	Enhanced Host-Port Interface	61
2.3.4	Multi-Channel Buffered Serial Ports	62
2.3.5	Clock Generator and Timers	65
2.3.6	General Purpose Input/Output Port	65
2.4	TMS320C55x Addressing Modes	65
2.4.1	Direct Addressing Modes	66
2.4.2	Indirect Addressing Modes	68
2.4.3	Absolute Addressing Modes	70
2.4.4	Memory-Mapped Register Addressing Mode	70
2.4.5	Register Bits Addressing Mode	71
2.4.6	Circular Addressing Mode	72
2.5	Pipeline and Parallelism	73
2.5.1	TMS320C55x Pipeline	73
2.5.2	Parallel Execution	74
2.6	TMS320C55x Instruction Set	76
2.6.1	Arithmetic Instructions	76
2.6.2	Logic and Bit Manipulation Instructions	77
2.6.3	Move Instruction	78
2.6.4	Program Flow Control Instructions	78
2.7	TMS320C55x Assembly Language Programming	82
2.7.1	Assembly Directives	82
2.7.2	Assembly Statement Syntax	84
2.8	C Language Programming for TMS320C55x	86
2.8.1	Data Types	86
2.8.2	Assembly Code Generation by C Compiler	87
2.8.3	Compiler Keywords and Pragma Directives	89
2.9	Mixed C-and-Assembly Language Programming	90
2.10	Experiments and Program Examples	93
2.10.1	Interfacing C with Assembly Code	93
2.10.2	Addressing Modes Using Assembly Programming	94
2.10.3	Phase-Locked Loop and Timers	97
2.10.4	EMIF Configuration for Using SDRAM	103
2.10.5	Programming Flash Memory Devices	105
2.10.6	Using McBSP	106
2.10.7	AIC23 Configurations	109
2.10.8	Direct Memory Access	111
	References	115
	Exercises	115

CONTENTS

vii

3 DSP Fundamentals and Implementation Considerations	121
3.1 Digital Signals and Systems	121
3.1.1 Elementary Digital Signals	121
3.1.2 Block Diagram Representation of Digital Systems	123
3.2 System Concepts	126
3.2.1 Linear Time-Invariant Systems	126
3.2.2 The z -Transform	130
3.2.3 Transfer Functions	132
3.2.4 Poles and Zeros	135
3.2.5 Frequency Responses	138
3.2.6 Discrete Fourier Transform	141
3.3 Introduction to Random Variables	142
3.3.1 Review of Random Variables	142
3.3.2 Operations of Random Variables	144
3.4 Fixed-Point Representations and Quantization Effects	147
3.4.1 Fixed-Point Formats	147
3.4.2 Quantization Errors	151
3.4.3 Signal Quantization	151
3.4.4 Coefficient Quantization	153
3.4.5 Roundoff Noise	153
3.4.6 Fixed-Point Toolbox	154
3.5 Overflow and Solutions	157
3.5.1 Saturation Arithmetic	157
3.5.2 Overflow Handling	158
3.5.3 Scaling of Signals	158
3.5.4 Guard Bits	159
3.6 Experiments and Program Examples	159
3.6.1 Quantization of Sinusoidal Signals	160
3.6.2 Quantization of Audio Signals	161
3.6.3 Quantization of Coefficients	162
3.6.4 Overflow and Saturation Arithmetic	164
3.6.5 Function Approximations	167
3.6.6 Real-Time Digital Signal Generation Using DSK	175
References	180
Exercises	180
4 Design and Implementation of FIR Filters	185
4.1 Introduction to FIR Filters	185
4.1.1 Filter Characteristics	185
4.1.2 Filter Types	187
4.1.3 Filter Specifications	189
4.1.4 Linear-Phase FIR Filters	191
4.1.5 Realization of FIR Filters	194
4.2 Design of FIR Filters	196
4.2.1 Fourier Series Method	197
4.2.2 Gibbs Phenomenon	198
4.2.3 Window Functions	201

4.2.4	Design of FIR Filters Using MATLAB	206
4.2.5	Design of FIR Filters Using FDATool	207
4.3	Implementation Considerations	213
4.3.1	Quantization Effects in FIR Filters	213
4.3.2	MATLAB Implementations	216
4.3.3	Floating-Point C Implementations	218
4.3.4	Fixed-Point C Implementations	219
4.4	Applications: Interpolation and Decimation Filters	220
4.4.1	Interpolation	220
4.4.2	Decimation	221
4.4.3	Sampling-Rate Conversion	221
4.4.4	MATLAB Implementations	224
4.5	Experiments and Program Examples	225
4.5.1	Implementation of FIR Filters Using Fixed-Point C	226
4.5.2	Implementation of FIR Filter Using C55x Assembly Language	226
4.5.3	Optimization for Symmetric FIR Filters	228
4.5.4	Optimization Using Dual MAC Architecture	230
4.5.5	Implementation of Decimation	232
4.5.6	Implementation of Interpolation	233
4.5.7	Sample Rate Conversion	234
4.5.8	Real-Time Sample Rate Conversion Using DSP/BIOS and DSK	235
	References	245
	Exercises	245
5	Design and Implementation of IIR Filters	249
5.1	Introduction	249
5.1.1	Analog Systems	249
5.1.2	Mapping Properties	251
5.1.3	Characteristics of Analog Filters	252
5.1.4	Frequency Transforms	254
5.2	Design of IIR Filters	255
5.2.1	Bilinear Transform	256
5.2.2	Filter Design Using Bilinear Transform	257
5.3	Realization of IIR Filters	258
5.3.1	Direct Forms	258
5.3.2	Cascade Forms	260
5.3.3	Parallel Forms	262
5.3.4	Realization of IIR Filters Using MATLAB	263
5.4	Design of IIR Filters Using MATLAB	264
5.4.1	Filter Design Using MATLAB	264
5.4.2	Frequency Transforms Using MATLAB	267
5.4.3	Design and Realization Using FDATool	268
5.5	Implementation Considerations	271
5.5.1	Stability	271
5.5.2	Finite-Precision Effects and Solutions	273
5.5.3	MATLAB Implementations	275

CONTENTS

ix

5.6	Practical Applications	279
5.6.1	Recursive Resonators	279
5.6.2	Recursive Quadrature Oscillators	282
5.6.3	Parametric Equalizers	284
5.7	Experiments and Program Examples	285
5.7.1	Floating-Point Direct-Form I IIR Filter	285
5.7.2	Fixed-Point Direct-Form I IIR Filter	286
5.7.3	Fixed-Point Direct-Form II Cascade IIR Filter	287
5.7.4	Implementation Using DSP Intrinsic	289
5.7.5	Implementation Using Assembly Language	290
5.7.6	Real-Time Experiments Using DSP/BIOS	293
5.7.7	Implementation of Parametric Equalizer	296
5.7.8	Real-Time Two-Band Equalizer Using DSP/BIOS	297
	References	299
	Exercises	299
6	Frequency Analysis and Fast Fourier Transform	303
6.1	Fourier Series and Transform	303
6.1.1	Fourier Series	303
6.1.2	Fourier Transform	304
6.2	Discrete Fourier Transform	305
6.2.1	Discrete-Time Fourier Transform	305
6.2.2	Discrete Fourier Transform	307
6.2.3	Important Properties	310
6.3	Fast Fourier Transforms	313
6.3.1	Decimation-in-Time	314
6.3.2	Decimation-in-Frequency	316
6.3.3	Inverse Fast Fourier Transform	317
6.4	Implementation Considerations	317
6.4.1	Computational Issues	317
6.4.2	Finite-Precision Effects	318
6.4.3	MATLAB Implementations	318
6.4.4	Fixed-Point Implementation Using MATLAB	320
6.5	Practical Applications	322
6.5.1	Spectral Analysis	322
6.5.2	Spectral Leakage and Resolution	323
6.5.3	Power Spectrum Density	325
6.5.4	Fast Convolution	328
6.6	Experiments and Program Examples	332
6.6.1	Floating-Point C Implementation of DFT	332
6.6.2	C55x Assembly Implementation of DFT	332
6.6.3	Floating-Point C Implementation of FFT	336
6.6.4	C55x Intrinsic Implementation of FFT	338
6.6.5	Assembly Implementation of FFT and Inverse FFT	339
6.6.6	Implementation of Fast Convolution	343
6.6.7	Real-Time FFT Using DSP/BIOS	345
6.6.8	Real-Time Fast Convolution	347
	References	347
	Exercises	348

7	Adaptive Filtering	351
7.1	Introduction to Random Processes	351
7.2	Adaptive Filters	354
7.2.1	Introduction to Adaptive Filtering	354
7.2.2	Performance Function	355
7.2.3	Method of Steepest Descent	358
7.2.4	The LMS Algorithm	360
7.2.5	Modified LMS Algorithms	361
7.3	Performance Analysis	362
7.3.1	Stability Constraint	362
7.3.2	Convergence Speed	363
7.3.3	Excess Mean-Square Error	363
7.3.4	Normalized LMS Algorithm	364
7.4	Implementation Considerations	364
7.4.1	Computational Issues	365
7.4.2	Finite-Precision Effects	365
7.4.3	MATLAB Implementations	366
7.5	Practical Applications	368
7.5.1	Adaptive System Identification	368
7.5.2	Adaptive Linear Prediction	369
7.5.3	Adaptive Noise Cancellation	372
7.5.4	Adaptive Notch Filters	374
7.5.5	Adaptive Channel Equalization	375
7.6	Experiments and Program Examples	377
7.6.1	Floating-Point C Implementation	377
7.6.2	Fixed-Point C Implementation of Leaky LMS Algorithm	379
7.6.3	ETSI Implementation of NLMS Algorithm	380
7.6.4	Assembly Language Implementation of Delayed LMS Algorithm	383
7.6.5	Adaptive System Identification	387
7.6.6	Adaptive Prediction and Noise Cancellation	388
7.6.7	Adaptive Channel Equalizer	392
7.6.8	Real-Time Adaptive Line Enhancer Using DSK	394
	References	396
	Exercises	397
8	Digital Signal Generators	401
8.1	Sinewave Generators	401
8.1.1	Lookup-Table Method	401
8.1.2	Linear Chirp Signal	404
8.2	Noise Generators	405
8.2.1	Linear Congruential Sequence Generator	405
8.2.2	Pseudo-Random Binary Sequence Generator	407
8.3	Practical Applications	409
8.3.1	Siren Generators	409
8.3.2	White Gaussian Noise	409
8.3.3	Dual-Tone Multifrequency Tone Generator	410
8.3.4	Comfort Noise in Voice Communication Systems	411
8.4	Experiments and Program Examples	412
8.4.1	Sinewave Generator Using C5510 DSK	412
8.4.2	White Noise Generator Using C5510 DSK	413

CONTENTS**xi**

8.4.3	Wail Siren Generator Using C5510 DSK	414
8.4.4	DTMF Generator Using C5510 DSK	415
8.4.5	DTMF Generator Using MATLAB Graphical User Interface	416
	References	418
	Exercises	418
9	Dual-Tone Multifrequency Detection	421
9.1	Introduction	421
9.2	DTMF Tone Detection	422
9.2.1	DTMF Decode Specifications	422
9.2.2	Goertzel Algorithm	423
9.2.3	Other DTMF Detection Methods	426
9.2.4	Implementation Considerations	428
9.3	Internet Application Issues and Solutions	431
9.4	Experiments and Program Examples	432
9.4.1	Implementation of Goertzel Algorithm Using Fixed-Point C	432
9.4.2	Implementation of Goertzel Algorithm Using C55x Assembly Language	434
9.4.3	DTMF Detection Using C5510 DSK	435
9.4.4	DTMF Detection Using All-Pole Modeling	439
	References	441
	Exercises	442
10	Adaptive Echo Cancellation	443
10.1	Introduction to Line Echoes	443
10.2	Adaptive Echo Canceller	444
10.2.1	Principles of Adaptive Echo Cancellation	445
10.2.2	Performance Evaluation	446
10.3	Practical Considerations	447
10.3.1	Prewhitening of Signals	447
10.3.2	Delay Detection	448
10.4	Double-Talk Effects and Solutions	450
10.5	Nonlinear Processor	453
10.5.1	Center Clipper	453
10.5.2	Comfort Noise	453
10.6	Acoustic Echo Cancellation	454
10.6.1	Acoustic Echoes	454
10.6.2	Acoustic Echo Canceller	456
10.6.3	Subband Implementations	457
10.6.4	Delay-Free Structures	459
10.6.5	Implementation Considerations	459
10.6.6	Testing Standards	460
10.7	Experiments and Program Examples	461
10.7.1	MATLAB Implementation of AEC	461
10.7.2	Acoustic Echo Cancellation Using Floating-Point C	464
10.7.3	Acoustic Echo Canceller Using C55x Intrinsic	468
10.7.4	Experiment of Delay Estimation	469
	References	472
	Exercises	472

11	Speech-Coding Techniques	475
11.1	Introduction to Speech-Coding	475
11.2	Overview of CELP Vocoders	476
11.2.1	Synthesis Filter	477
11.2.2	Long-Term Prediction Filter	481
11.2.3	Perceptual Based Minimization Procedure	481
11.2.4	Excitation Signal	482
11.2.5	Algebraic CELP	483
11.3	Overview of Some Popular CODECs	484
11.3.1	Overview of G.723.1	484
11.3.2	Overview of G.729	488
11.3.3	Overview of GSM AMR	490
11.4	Voice over Internet Protocol Applications	492
11.4.1	Overview of VoIP	492
11.4.2	Real-Time Transport Protocol and Payload Type	493
11.4.3	Example of Packing G.729	496
11.4.4	RTP Data Analysis Using Ethereal Trace	496
11.4.5	Factors Affecting the Overall Voice Quality	497
11.5	Experiments and Program Examples	497
11.5.1	Calculating LPC Coefficients Using Floating-Point C	497
11.5.2	Calculating LPC Coefficients Using C55x Intrinsic	499
11.5.3	MATLAB Implementation of Formant Perceptual Weighting Filter	504
11.5.4	Implementation of Perceptual Weighting Filter Using C55x Intrinsic	506
	References	507
	Exercises	508
12	Speech Enhancement Techniques	509
12.1	Introduction to Noise Reduction Techniques	509
12.2	Spectral Subtraction Techniques	510
12.2.1	Short-Time Spectrum Estimation	511
12.2.2	Magnitude Subtraction	511
12.3	Voice Activity Detection	513
12.4	Implementation Considerations	515
12.4.1	Spectral Averaging	515
12.4.2	Half-Wave Rectification	515
12.4.3	Residual Noise Reduction	516
12.5	Combination of Acoustic Echo Cancellation with NR	516
12.6	Voice Enhancement and Automatic Level Control	518
12.6.1	Voice Enhancement Devices	518
12.6.2	Automatic Level Control	519
12.7	Experiments and Program Examples	519
12.7.1	Voice Activity Detection	519
12.7.2	MATLAB Implementation of NR Algorithm	522
12.7.3	Floating-Point C Implementation of NR	522
12.7.4	Mixed C55x Assembly and Intrinsic Implementations of VAD	522
12.7.5	Combining AEC with NR	526
	References	529
	Exercises	529

CONTENTS

xiii

13 Audio Signal Processing	531
13.1 Introduction	531
13.2 Basic Principles of Audio Coding	531
13.2.1 Auditory-Masking Effects for Perceptual Coding	533
13.2.2 Frequency-Domain Coding	536
13.2.3 Lossless Audio Coding	538
13.3 Multichannel Audio Coding	539
13.3.1 MP3	540
13.3.2 Dolby AC-3	541
13.3.3 MPEG-2 AAC	542
13.4 Connectivity Processing	544
13.5 Experiments and Program Examples	544
13.5.1 Floating-Point Implementation of MDCT	544
13.5.2 Implementation of MDCT Using C55x Intrinsic	547
13.5.3 Experiments of Preecho Effects	549
13.5.4 Floating-Point C Implementation of MP3 Decoding	549
References	553
Exercises	553
14 Channel Coding Techniques	555
14.1 Introduction	555
14.2 Block Codes	556
14.2.1 Reed–Solomon Codes	558
14.2.2 Applications of Reed–Solomon Codes	562
14.2.3 Cyclic Redundant Codes	563
14.3 Convolutional Codes	564
14.3.1 Convolutional Encoding	564
14.3.2 Viterbi Decoding	564
14.3.3 Applications of Viterbi Decoding	566
14.4 Experiments and Program Examples	569
14.4.1 Reed–Solomon Coding Using MATAB	569
14.4.2 Reed–Solomon Coding Using Simulink	570
14.4.3 Verification of RS(255, 239) Generation Polynomial	571
14.4.4 Convolutional Codes	572
14.4.5 Implementation of Convolutional Codes Using C	573
14.4.6 Implementation of CRC-32	575
References	576
Exercises	577
15 Introduction to Digital Image Processing	579
15.1 Digital Images and Systems	579
15.1.1 Digital Images	579
15.1.2 Digital Image Systems	580
15.2 RGB Color Spaces and Color Filter Array Interpolation	581
15.3 Color Spaces	584
15.3.1 $YCbCr$ and YUV Color Spaces	584
15.3.2 CYMK Color Space	585

15.3.3	YIQ Color Space	585
15.3.4	HSV Color Space	585
15.4	$YCbCr$ Subsampled Color Spaces	586
15.5	Color Balance and Correction	586
15.5.1	Color Balance	587
15.5.2	Color Adjustment	588
15.5.3	Gamma Correction	589
15.6	Image Histogram	590
15.7	Image Filtering	591
15.8	Image Filtering Using Fast Convolution	596
15.9	Practical Applications	597
15.9.1	JPEG Standard	597
15.9.2	2-D Discrete Cosine Transform	599
15.10	Experiments and Program Examples	601
15.10.1	$YCbCr$ to RGB Conversion	601
15.10.2	Using CCS Link with DSK and Simulator	604
15.10.3	White Balance	607
15.10.4	Gamma Correction and Contrast Adjustment	610
15.10.5	Histogram and Histogram Equalization	611
15.10.6	2-D Image Filtering	613
15.10.7	Implementation of DCT and IDCT	617
15.10.8	TMS320C55x Image Accelerator for DCT and IDCT	621
15.10.9	TMS320C55x Hardware Accelerator Image/Video Processing Library	623
	References	625
	Exercises	625
Appendix A Some Useful Formulas and Definitions		627
A.1	Trigonometric Identities	627
A.2	Geometric Series	628
A.3	Complex Variables	628
A.4	Units of Power	630
	References	631
Appendix B Software Organization and List of Experiments		633
Index		639