

Smartphone-Based Real-Time Digital Signal Processing

Second Edition

Synthesis Lectures on Signal Processing

Editor

José Moura, *Carnegie Mellon University*

Synthesis Lectures in Signal Processing publishes 80- to 150-page books on topics of interest to signal processing engineers and researchers. The Lectures exploit in detail a focused topic. They can be at different levels of exposition—from a basic introductory tutorial to an advanced monograph—depending on the subject and the goals of the author. Over time, the Lectures will provide a comprehensive treatment of signal processing. Because of its format, the Lectures will also provide current coverage of signal processing, and existing Lectures will be updated by authors when justified.

Lectures in Signal Processing are open to all relevant areas in signal processing. They will cover theory and theoretical methods, algorithms, performance analysis, and applications. Some Lectures will provide a new look at a well established area or problem, while others will venture into a brand new topic in signal processing. By careful reviewing the manuscripts we will strive for quality both in the Lectures' contents and exposition.

Smartphone-Based Real-Time Digital Signal Processing, Second Edition

Nasser Kehtarnavaz, Abhishek Sehgal, and Shane Parris
2018

Anywhere-Anytime Signals and Systems Laboratory: From MATLAB to Smartphones, Second Edition

Nasser Kehtarnavaz, Fatemeh Saki, and Adrian Duran
2018

Anywhere-Anytime Signals and Systems Laboratory: From MATLAB to Smartphones

Nasser Kehtarnavaz and Fatemeh Saki
2016

Smartphone-Based Real-Time Digital Signal Processing

Nasser Kehtarnavaz, Shane Parris, and Abhishek Sehgal
2015

An Introduction to Kalman Filtering with MATLAB Examples

Narayan Kovvali, Mahesh Banavar, and Andreas Spanias
2013

Sequential Monte Carlo Methods for Nonlinear Discrete-Time Filtering

Marcelo G.S. Bruno

2013

Processing of Seismic Reflection Data Using MATLAB™

Wail A. Mousa and Abdullatif A. Al-Shuhail

2011

Fixed-Point Signal Processing

Wayne T. Padgett and David V. Anderson

2009

Advanced Radar Detection Schemes Under Mismatched Signal Models

Francesco Bandiera, Danilo Orlando, and Giuseppe Ricci

2009

DSP for MATLAB™ and LabVIEW™ IV: LMS Adaptive Filtering

Forester W. Isen

2009

DSP for MATLAB™ and LabVIEW™ III: Digital Filter Design

Forester W. Isen

2008

DSP for MATLAB™ and LabVIEW™ II: Discrete Frequency Transforms

Forester W. Isen

2008

DSP for MATLAB™ and LabVIEW™ I: Fundamentals of Discrete Signal Processing

Forester W. Isen

2008

The Theory of Linear Prediction

P. P. Vaidyanathan

2007

Nonlinear Source Separation

Luis B. Almeida

2006

Spectral Analysis of Signals: The Missing Data Case

Yanwei Wang, Jian Li, and Petre Stoica

2006

© Springer Nature Switzerland AG 2022
Reprint of original edition © Morgan & Claypool 2019

All rights reserved. No part of this publication may be reproduced, stored in a retrieval system, or transmitted in any form or by any means—electronic, mechanical, photocopy, recording, or any other except for brief quotations in printed reviews, without the prior permission of the publisher.

Smartphone-Based Real-Time Digital Signal Processing, Second Edition
Nasser Kehtarnavaz, Abhishek Sehgal, and Shane Parris

ISBN: 978-3-031-01412-3 paperback

ISBN: 978-3-031-02540-2 ebook

ISBN: 978-3-031-00333-2 hardcover

DOI 10.1007/978-3-031-02540-2

A Publication in the Springer series
SYNTHESIS LECTURES ON SIGNAL PROCESSING

Lecture #16

Series Editor: José Moura, *Carnegie Mellon University*

Series ISSN

Print 1932-1236 Electronic 1932-1694

Smartphone-Based Real-Time Digital Signal Processing

Second Edition

Nasser Kehtarnavaz, Abhishek Sehgal, and Shane Parris
University of Texas at Dallas

SYNTHESIS LECTURES ON SIGNAL PROCESSING #16

ABSTRACT

Real-time or applied digital signal processing courses are offered as follow-ups to conventional or theory-oriented digital signal processing courses in many engineering programs for the purpose of teaching students the technical know-how for putting signal processing algorithms or theory into practical use. These courses normally involve access to a teaching laboratory that is equipped with hardware boards, in particular DSP boards, together with their supporting software. A number of textbooks have been written discussing how to achieve real-time implementation on these hardware boards. This book discusses how to use smartphones as hardware boards for real-time implementation of signal processing algorithms as an alternative to the hardware boards that are used in signal processing laboratory courses. The fact that mobile devices, in particular smartphones, have become powerful processing platforms led to the development of this book enabling students to use their own smartphones to run signal processing algorithms in real-time considering that these days nearly all students possess smartphones. Changing the hardware platforms that are currently used in applied or real-time signal processing courses to smartphones creates a truly mobile laboratory experience or environment for students. In addition, it relieves the cost burden associated with using dedicated signal processing boards noting that the software development tools for smartphones are free of charge and are well-maintained by smartphone manufacturers. This book is written in such a way that it can be used as a textbook for real-time or applied digital signal processing courses offered at many universities. Ten lab experiments that are commonly encountered in such courses are covered in the book. This book is written primarily for those who are already familiar with signal processing concepts and are interested in their real-time and practical aspects. Similar to existing real-time courses, knowledge of C programming is assumed. This book can also be used as a self-study guide for those who wish to become familiar with signal processing app development on either Android or iPhone smartphones. A zipped file of the codes discussed in the book can be acquired from this third-party website <http://sites.fastspring.com/bookcodes/product/SignalProcessingBookcodesSecondEdition>.

KEYWORDS

smartphone-based signal processing, real-time signal processing using smartphones, smartphones as signal processing boards

Contents

Preface	xi
1 Introduction	1
1.1 Smartphone Implementation Tools	1
1.2 Smartphone Implementation Shells	2
1.2.1 Android Implementation	2
1.2.2 Iphone Implementation	3
1.3 Overview of ARM Processor Architecture	4
1.3.1 Data Flow and Registers	4
1.4 Organization of Chapters	6
1.5 Software Package of Lab Codes	8
1.6 References	9
2 Android Software Development Tools	11
2.1 Installation Steps	11
2.1.1 Java JDK	11
2.1.2 Android Studio Bundle and Native Development Kit	13
2.1.3 Environment Variable Configuration	14
2.1.4 Android Studio Configuration	15
2.1.5 Android Emulator Configuration	18
2.1.6 Android Studio Setup for Mac	24
L1 LAB 1:	
Getting Familiar with Android Software Tools	25
L1.1 Lab Exercise	37
3 iOS Software Development Tools	39
3.1 App Development	39
3.2 Setting-up App Environment	42
3.3 Creating Layout	42
3.4 Implementing C Codes	44
3.5 Executing C Codes Via Objective-C	45

3.6	Swift Programming Language	45
L2	LAB 2:	
	iPhone App Debugging	47
	L2.1 Lab Exercise	48
4	Analog-to-Digital Signal Conversion	51
4.1	Sampling	51
4.2	Quantization	55
4.3	References	56
L3	LAB 3:	
	Android Audio Signal Sampling	56
	L3.1 Demo Application	58
	L3.2 Application Code	59
	L3.3 Recording	60
	L3.4 Processing.Java	61
	L3.5 JNI Native C Code	62
	L3.6 Superpowered SDK	63
	L3.7 Multi-Threading	67
	L3.8 Multi-Rate Signal Processing	70
	L3.9 Lab Exercises	71
L4	LAB 4:	
	iPhone Audio Signal Sampling	71
	L4.1 App Source Code	72
	L4.2 App Code Discussion	72
	L4.3 Recording	73
	L4.4 Native C Code	77
	L4.5 Multi-Threading	77
	L4.6 Multi-Rate Signal Processing	78
	L4.7 Lab Exercises	78
5	Fixed-Point vs. Floating-Point	81
5.1	Q-Format Number Representation	81
5.2	Floating-Point Number Representation	85
5.3	Overflow and Scaling	86
5.4	Some Useful Arithmetic Operations	87
	5.4.1 Division	87
	5.4.2 Sine and Cosine	88

	5.4.3 Square-Root	88
L5	LAB 5:	
	Fixed-Point and Floating-Point Operations	89
	L5.1 App Structure	89
	L5.2 NEON SIMD Coprocessor	90
	L5.3 Lab Exercises	91
5.6	References	91
6	Real-Time Filtering	93
6.1	FIR Filter Implementation	93
6.2	Circular Buffering	95
6.3	Frame Processing	98
6.4	Finite Word Length Effect	99
6.5	References	100
L6	LAB 6:	
	Real-Time FIR Filtering, Quantization Effect, and Overflow	100
	L6.1 Filter Design	100
	L6.2 ARM Overflow Detection	102
	L6.3 Lab Exercises	106
7	Adaptive Filtering	109
7.1	Infinite Impulse Response Filters	109
7.2	Adaptive Filtering	110
7.3	References	111
L7	LAB 7:	
	IIR Filtering and Adaptive FIR Filtering	111
	L7.1 IIR Filter Design	111
	L7.2 Adaptive FIR Filter	112
	L7.3 Lab Exercises	114
8	Frequency Domain Transforms	117
8.1	Fourier Transforms	117
	8.1.1 Discrete Fourier Transform	117
	8.1.2 Fast Fourier Transform	119
8.2	Leakage	121
8.3	Windowing	122
8.4	Overlap Processing	123

8.5	Reconstruction	125
8.5.1	Inverse Fourier Transform	125
8.5.2	Overlap-Add Reconstruction	126
8.6	References	126
L8	LAB 8:	
	Frequency Domain Transforms–DFT and FFT	126
L8.1	Lab Exercises	128
9	Code Optimization	131
9.1	Code Timing	131
9.2	Linear Convolution	132
9.3	Compiler Options	133
9.4	Efficient C Code Writing	134
9.5	Architecture-Specific Optimizations	136
9.5.1	Target Architecture	136
9.5.2	Arm Hardware Capabilities	137
9.5.3	Neon Intrinsics	138
L9	LAB 9:	
	Code Optimization	140
L9.1	Compiler Options	140
L9.2	Target Architecture (Android Only)	140
L9.3	Code Modification	140
9.7	References	141
10	Implementation Via Matlab Coder	143
10.1	Matlab Function Design	143
10.2	Test Bench	144
10.3	Code Generation	144
10.4	Source Code Integration	147
10.5	Summary	147
10.6	References	149
L10	LAB 10:	
	Matlab Coder Implementation	149
L10.1	Lab Exercises	150
	Authors' Biographies	151
	Index	153

Preface

Real-time or applied digital signal processing courses are offered as follow-up courses to conventional or theory-oriented digital signal processing courses in many electrical engineering curricula. The purpose of offering real-time or applied digital signal processing courses is to enable students to bridge the gap between signal processing theory and implementation aspects.

A typical real-time or applied digital signal processing course is normally held within the confines of a teaching laboratory room that is equipped with implementation hardware platforms and the accompanying software for those platforms. The fact that mobile devices, in particular smartphones, have become powerful processing platforms led to the development of this book toward enabling students to use their own smartphones as implementation platforms for running signal processing algorithms as apps considering that these days nearly all students possess smartphones. Changing the hardware platforms that are normally used in real-time applied signal processing courses to smartphones creates a truly mobile laboratory experience or environment for students. In addition, it relieves the cost burden associated with using dedicated signal processing hardware boards noting that the software development tools for smartphones are free of charge and are well-maintained by smartphone manufacturers.

This book is written in such a way that it can be used as a textbook for real-time or applied digital signal processing courses offered at many universities. Ten lab experiments that are commonly encountered in such courses are covered in the book. This book is written primarily for those who are already familiar with signal processing concepts and are interested in their real-time and practical aspects. Similar to existing real-time courses, knowledge of C programming is assumed. This book can also be used as a self-study guide for those who wish to become familiar with signal processing app development on either Android or iPhone smartphones. In this second edition, various updates are made to reflect the newer versions of the software tools used in the first edition.

The smartphone-based approach covered in this book eases the constraint of a dedicated signal processing laboratory for the purpose of offering applied or real-time signal processing courses as it provides a truly mobile platform for implementation of signal processing algorithms. A zipped file of the codes discussed in the book can be acquired from this third-party website <http://sites.fastspring.com/bookcodes/product/SignalProcessingBookcodesSecondEdition>.

xii PREFACE

As a final note, I would like to thank my co-authors and ex-students, Abhishek Sehgal and Shane Parris, for their contributions, in particular for the development of the lab codes, in the first and second editions of this book.

Nasser Kehtarnavaz
November 2018