

# **Smartphone-Based Real-Time Digital Signal Processing**

**Third 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, Third Edition

Nasser Kehtarnavaz, Abhishek Sehgal, Shane Parris, and Arian Azarang  
2020

## Anywhere-Anytime Signals and Systems Laboratory: from MATLAB to Smartphones, Third Edition

Nasser Kehtarnavaz, Fatemeh Saki, Adrian Duran, and Arian Azarang  
2020

## Reconstructive-Free Compressive Vision for Surveillance Applications

Henry Braun, Pavan Turaga, Andreas Spanias, Sameeksha Katoch, Suren Jayasuriya, and Cihan Tepedelenlioglu  
2019

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

Nasser Kehtarnavaz, Abhishek Sehgal, 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  
2017

**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 2020

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, Third Edition

Nasser Kehtarnavaz, Abhishek Sehgal, Shane Parris, and Arian Azarang

[www.morganclaypool.com](http://www.morganclaypool.com)

ISBN: 978-3-031-01415-4      paperback

ISBN: 978-3-031-02543-3      ebook

ISBN: 978-3-031-00336-3      hardcover

DOI 10.1007/978-3-031-02543-3

A Publication in the Springer series

*SYNTHESIS LECTURES ON SIGNAL PROCESSING*

Lecture #19

Series Editor: José Moura, *Carnegie Mellon University*

Series ISSN

Print 1932-1236    Electronic 1932-1694

# Smartphone-Based Real-Time Digital Signal Processing

Third Edition

Nasser Kehtarnavaz  
University of Texas at Dallas

Abhishek Sehgal  
University of Texas at Dallas

Shane Parris  
University of Texas at Dallas

Arian Azarang  
University of Texas at Dallas

*SYNTHESIS LECTURES ON SIGNAL PROCESSING #19*

## 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, thus providing 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 to enable 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 flexible 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. It 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 iOS smartphones/tablets. A zipped file of the codes discussed in the book can be acquired from this [third-party website](#).

## KEYWORDS

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

# Contents

<b>Preface</b> .....	<b>xiii</b>
<b>1 Introduction</b> .....	<b>1</b>
1.1 Smartphone Implementation Tools .....	2
1.2 Smartphone Implementation Shells .....	2
1.2.1 Android Implementation .....	2
1.2.2 iOS Implementation .....	3
1.3 Overview of ARM Processor Architecture .....	4
1.3.1 Data Flow and Registers .....	4
1.4 Organization of Chapters .....	5
1.5 Software Package of Lab Codes .....	8
1.6 References .....	9
<b>2 Android Software Development Tools</b> .....	<b>11</b>
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 .....	13
2.1.4 Android Studio Configuration .....	16
2.1.5 Android Emulator Configuration .....	16
2.1.6 Android Studio Setup for Mac .....	22
L1 LAB 1:	
Getting Familiar with Android Software Tools .....	28
L1.1 Lab Exercise .....	40
<b>3 iOS Software Development Tools</b> .....	<b>43</b>
3.1 App Development .....	43
3.2 Setting-Up App Environment .....	45
3.3 Creating Layout .....	46
3.4 Implementing C Codes .....	47
3.5 Executing C Codes via Objective-C .....	49



3.6	Swift Programming Language . . . . .	49
L2	LAB 2:	
	iPhone App Debugging . . . . .	52
L2.1	Lab Exercise . . . . .	53
<b>4</b>	<b>Analog-to-Digital Signal Conversion . . . . .</b>	<b>55</b>
4.1	Sampling . . . . .	55
4.2	Quantization . . . . .	57
L3	LAB 3:	
	Android Audio Signal Sampling . . . . .	60
L3.1	Demo Application . . . . .	62
L3.2	Application Code . . . . .	63
L3.3	Recording . . . . .	64
L3.4	Processing.java . . . . .	65
L3.5	JNI Native C Code . . . . .	66
L3.6	Superpowered SDK . . . . .	67
L3.7	Multi-Threading . . . . .	72
L3.8	Multi-Rate Signal Processing . . . . .	75
L3.9	Lab Exercises . . . . .	75
L4	LAB 4:	
	iPhone Audio Signal Sampling . . . . .	76
L4.1	App Source Code . . . . .	77
L4.2	App Code Discussion . . . . .	78
L4.3	Recording . . . . .	78
L4.4	Native C Code . . . . .	82
L4.5	Multi-Threading . . . . .	83
L4.6	Multi-Rate Signal Processing . . . . .	83
L4.7	Lab Exercises . . . . .	84
4.5	References . . . . .	84
<b>5</b>	<b>Fixed-Point vs. Floating-Point . . . . .</b>	<b>85</b>
5.1	Q-Format Number Representation . . . . .	85
5.2	Floating-Point Number Representation . . . . .	89
5.3	Overflow and Scaling . . . . .	90
5.4	Some Useful Arithmetic Operations . . . . .	91
5.4.1	Division . . . . .	91
5.4.2	Sine and Cosine . . . . .	92

	5.4.3	Square Root . . . . .	92
L5		LAB 5:	
		Fixed-Point and Floating-Point Operations . . . . .	93
	L5.1	App Structure . . . . .	93
	L5.2	NEON SIMD Coprocessor . . . . .	94
	L5.3	Lab Exercises . . . . .	95
5.6		References . . . . .	95
<b>6</b>		<b>Real-Time Filtering . . . . .</b>	<b>97</b>
6.1		FIR Filter Implementation . . . . .	97
6.2		Circular Buffering . . . . .	99
6.3		Frame Processing . . . . .	102
6.4		Finite Word Length Effect . . . . .	104
L6		LAB 6:	
		Real-Time FIR Filtering, Quantization Effect, and Overflow . . . . .	104
	L6.1	Filter Design . . . . .	105
	L6.2	ARM Overflow Detection . . . . .	106
	L6.3	Lab Exercises . . . . .	112
6.6		References . . . . .	112
<b>7</b>		<b>Adaptive Filtering . . . . .</b>	<b>113</b>
7.1		Infinite Impulse Response Filters . . . . .	113
7.2		Adaptive Filtering . . . . .	114
L7		LAB 7:	
		IIR Filtering and Adaptive FIR Filtering . . . . .	115
	L7.1	IIR Filter Design . . . . .	115
	L7.2	Adaptive FIR Filter . . . . .	116
	L7.3	Lab Exercises . . . . .	118
7.4		References . . . . .	120
<b>8</b>		<b>Domain Transforms . . . . .</b>	<b>121</b>
8.1		Fourier Transforms . . . . .	121
	8.1.1	Discrete Fourier Transform . . . . .	121
	8.1.2	Fast Fourier Transform . . . . .	123
8.2		Leakage . . . . .	125
8.3		Windowing . . . . .	125
8.4		Overlap Processing . . . . .	126

8.5	Reconstruction .....	128
8.5.1	Inverse Fourier Transform .....	129
8.5.2	Overlap-Add Reconstruction .....	130
L8	LAB 8: Frequency Domain Transforms – DFT and FFT .....	130
L8.1	Lab Exercises .....	134
8.7	References .....	135
<b>9</b>	<b>Code Optimization .....</b>	<b>137</b>
9.1	Code Timing .....	137
9.2	Linear Convolution .....	138
9.3	Compiler Options .....	139
9.4	Efficient C Code Writing .....	140
9.5	Architecture-Specific Optimizations .....	142
9.5.1	Target Architecture .....	142
9.5.2	ARM Hardware Capabilities .....	143
9.5.3	NEON Intrinsics .....	144
L9	LAB 9: Code Optimization .....	146
L9.1	Compiler Options .....	146
L9.2	Target Architecture (Android Only) .....	147
L9.3	Code Modification .....	147
9.7	References .....	147
<b>10</b>	<b>Implementation via MATLAB Coder .....</b>	<b>149</b>
10.1	MATLAB Function Design .....	149
10.2	Test Bench .....	150
10.3	Code Generation .....	150
10.4	Source Code Integration .....	153
10.5	Summary .....	154
L10	LAB 10: Matlab Coder Implementation .....	155
L10.1	Lab Exercises .....	155
10.7	References .....	156
	<b>Authors' Biographies .....</b>	<b>157</b>
	<b>Index .....</b>	<b>159</b>

# 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 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 flexible (anywhere-anytime) 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. It 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 iOS smartphones/tablets. In this third edition, various updates are made to reflect the newer versions of the software tools used in the first and second editions.

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 an anywhere-anytime 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/SignalProcessingBookcodesThirdEdition>.

As a final note, I would like to thank my co-authors and former/current students Abhishek Sehgal, Shane Parris, and Arian Azarang, for their contributions in the first, second, and third editions.

Nasser Kehtarnavaz  
Summer 2020