DIGITAL SIGNAL PROCESSING

Using the ARM® Cortex®-M4

Donald S. Reay

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Published by John Wiley & Sons, Inc., Hoboken, New Jersey
Published simultaneously in Canada

Library of Congress Cataloging-in-Publication Data:

Reay, Donald (Donald S.), author.
Digital signal processing using the ARM Cortex-M4 / Donald Reay.
pages cm
Includes bibliographical references and index.
ISBN 978-1-118-85904-9 (pbk.)
1. Signal processing–Digital techniques. 2. ARM microprocessors. I. Title.
TK5102.9.R4326 2015
621.382′2–dc23

2015024771

Typeset in 10/12pt TimesLTStd by SPi Global, Chennai, India

Printed in Singapore by Markono Print Media Pte Ltd

10 9 8 7 6 5 4 3 2 1

1 2016

PREFACE

This book continues the series started in 1990 by Rulph Chassaing and Darrell Horning's *Digital Signal Processing with the TMS320C25*, which tracked the development of successive generations of digital signal processors by Texas Instruments. More specifically, each book in the series up until now has complemented a different inexpensive DSP development kit promoted for teaching purposes by the Texas Instruments University Program. A consistent theme in the books has been the provision of a large number of simple example programs illustrating DSP concepts in real time, in an electrical engineering laboratory setting.

It was Rulph Chassaing's belief, and this author continues to believe, that hands-on teaching of DSP, using hardware development kits and laboratory test equipment to process analog audio frequency signals, is a valuable and effective way of reinforcing the theory taught in lectures.

The contents of the books, insofar as they concern fundamental concepts of digital signal processing such as analog-to-digital and digital-to-analog conversion, finite impulse response (FIR) and infinite impulse response (IIR) filtering, the Fourier transform, and adaptive filtering, have changed little. Every academic year brings another cohort of students wanting to study this material. However, each book has featured a different DSP development kit.

In 2013, Robert Owen suggested to me that hands-on DSP teaching could be implemented using an inexpensive ARM® Cortex-M4® microcontroller. I pointed out that a Texas Instruments C674x processor was very significantly more computationally powerful than an ARM Cortex-M4. But I also went ahead and purchased a Texas Instruments Stellaris LaunchPad. I constructed an audio interface using a Wolfson WM8731 codec and successfully ported the program examples from my previous book to that hardware platform.

This book is aimed at senior undergraduate and postgraduate electrical engineering students who have some knowledge of C programming and linear systems theory, but it is intended, and hoped, that it may serve as a useful resource for anyone involved in teaching or learning DSP and as a starting point for teaching or learning more.

I am grateful to Robert Owen for first making me aware of the ARM Cortex-M4; to Khaled Benkrid at the ARM University Program and to the Royal Academy of Engineering for making possible a six-month Industrial Secondment to ARM during which teaching materials for the STM32f01 platform were developed; to Gordon McLeod and Scott Hendry at Wolfson Microelectronics for their help in getting the Wolfson Pi audio card to work with the STM32f01 Discovery; to Sean Hong, Karthik Shivashankar, and Robert Iannello at ARM for all their help; to Joan Teixidor Buixeda for helping to debug the program examples; to Cathy Wicks at the TI University Program and Hieu Duong at CircuitCo for developing the audio booster pack; and to Kari Capone and Brett Kurzman at Wiley for their patience. But above all, I thank Rulph Chassaing for inspiring me to get involved in teaching hands-on DSP.

DONALD S. REAY

Edinburgh
2015

To Reiko

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ARM® CORTEX®-M4 DEVELOPMENT SYSTEMS

1.1 INTRODUCTION

Traditionally, real-time digital signal processing (DSP) has been implemented using specialized and relatively expensive hardware, for example, digital signal processors or field-programmable gate arrays (FPGAs). The ARM® Cortex®-M4 processor makes it possible to process audio in real time (for teaching purposes, at least) using significantly less expensive, and simpler, microcontrollers.

The ARM Cortex-M4 is a 32-bit microcontroller. Essentially, it is an ARM Cortex-M3 microcontroller that has been enhanced by the addition of DSP and single instruction multiple data (SIMD) instructions and (optionally) a hardware floating-point unit (FPU). Although its computational power is a fraction of that of a floating-point digital signal processor, for example, the Texas Instruments C674x, it is quite capable of implementing DSP algorithms, for example, FIR and IIR filters and fast Fourier transforms for audio signals in real-time.

A number of semiconductor manufacturers have developed microcontrollers that are based on the ARM Cortex-M4 processor and that incorporate proprietary peripheral interfaces and other IP blocks. Many of these semiconductor manufacturers make available very-low-cost evaluation boards for their ARM Cortex-M4 microcontrollers. Implementing real-time audio frequency example programs on these platforms, rather than on more conventional DSP development kits, constitutes a reduction of an order of magnitude in the hardware cost of implementing hands-on

Digital Signal Processing Using the ARM® Cortex® -M4, First Edition. Donald S. Reay.

DSP teaching. For the first time, students might realistically be expected to own a hardware platform that is useful not only for general microcontroller/microprocessor programming and interfacing activities but also for implementation of real-time DSP.

1.1.1 Audio Interfaces

At the time that the program examples presented in this book were being developed, there were no commercially available low-cost ARM Cortex-M4 development boards that incorporated high-quality audio input and output. The STMicroelectronics STM32F407 Discovery board features a high-quality audio digital-to-analog converter (DAC) but not a corresponding analog-to-digital converter (ADC). Many ARM Cortex-M4 devices, including both the STMicroelectronics STM32F407 and the Texas Instruments TM4C123, feature multichannel instrumentation-quality ADCs. But without additional external circuitry, these are not suitable for the applications discussed in this book.

The examples in this book require the addition (to an inexpensive ARM Cortex-M4 development board) of an (inexpensive) audio interface.

In the case of the STMicroelectronics STM32F407 Discovery board and of the Texas Instruments TM4C123 LaunchPad, compatible and inexpensive audio interfaces are provided by the Wolfson Pi audio card and the CircuitCo audio booster pack, respectively. The low-level interfacing details and the precise performance characteristics and extra features of the two audio interfaces are subtly different. However, each facilitates the input and output of high-quality audio signals to and from an ARM Cortex-M4 processor on which DSP algorithms may be implemented.

Almost all of the program examples presented in the subsequent chapters of this book are provided, in only very slightly different form, for both the STM32F407 Discovery and the TM4C123 LaunchPad, on the partner website `http://www.wiley.com/go/Reay/ARMcortexM4`.

However, in most cases, program examples are described in detail, and program listings are presented, only for one or other hardware platform. Notable exceptions are that, in Chapter 2, low-level i/o mechanisms (implemented slightly differently in the two devices) are described in detail for both hardware platforms and that a handful of example programs use features unique to one or other processor/audio interface.

This book does not describe the internal architecture or features of the ARM Cortex-M4 processor in detail. An excellent text on that subject, including details of its DSP-related capabilities, is *The Definitive Guide to ARM® Cortex®-M3 and Cortex®-M4 Processors* by Yiu [1].

1.1.2 Texas Instruments TM4C123 LaunchPad and STM32F407 Discovery Development Kits

The Texas Instruments and STMicroelectronics ARM Cortex-M4 processor boards used in this book are shown in Figures 1.1 and 1.2. The program examples presented in this book assume the use of the *Keil MDK-ARM* development environment, which is compatible with both development kits. An alternative development environment,

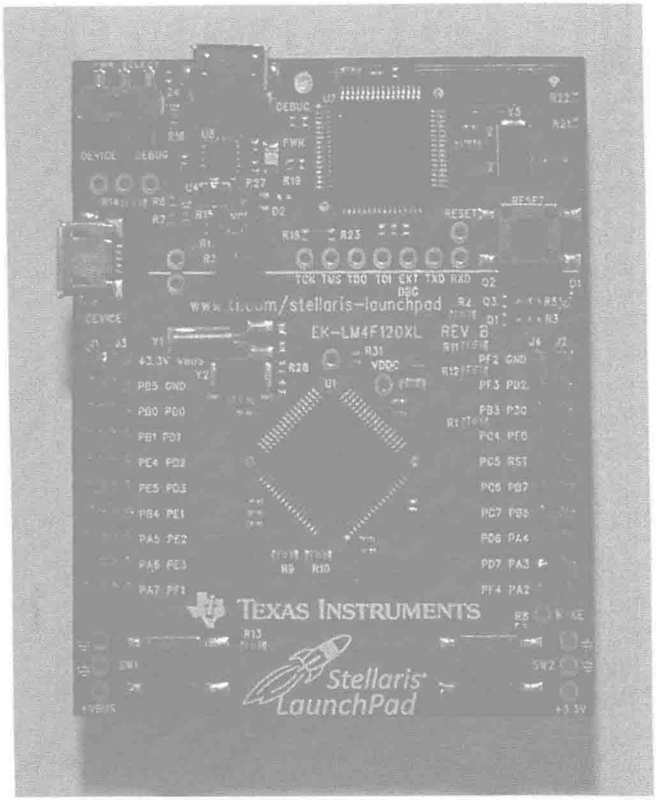

Figure 1.1 Texas Instruments TM4C123 LaunchPad.

Texas Instruments' *Code Composer Studio*, is available for the TM4C123 LaunchPad and the program examples have been tested using this. Versions of the program examples compatible with *Code Composer Studio version 6* are provided on the partner website `http://www.wiley.com/go/Reay/ARMcortexM4`.

The CircuitCo audio booster pack (for the TM4C123 LaunchPad) and the Wolfson Pi audio card (for the STM32F407 Discovery) are shown in Figures 1.3 and 1.4. The audio booster pack and the launchpad plug together, whereas the Wolfson audio card, which was designed for use with a Raspberry Pi computer, must be connected to the Discovery using a custom ribbon cable (available from distributor Farnell).

Rather than presenting detailed instructions here that may be obsolete as soon as the next version of *MDK-ARM* is released, the reader is directed to the "getting started" guide at the partner website `http://www.wiley.com/go/Reay/ARMcortexM4` and before progressing to the next chapter of this book will need to install *MDK-ARM*, including the "packs" appropriate to the hardware platform being used and including the CMSIS DSP library, download the program examples from the website, and become familiar with how to open a project in *MDK-ARM*, add and

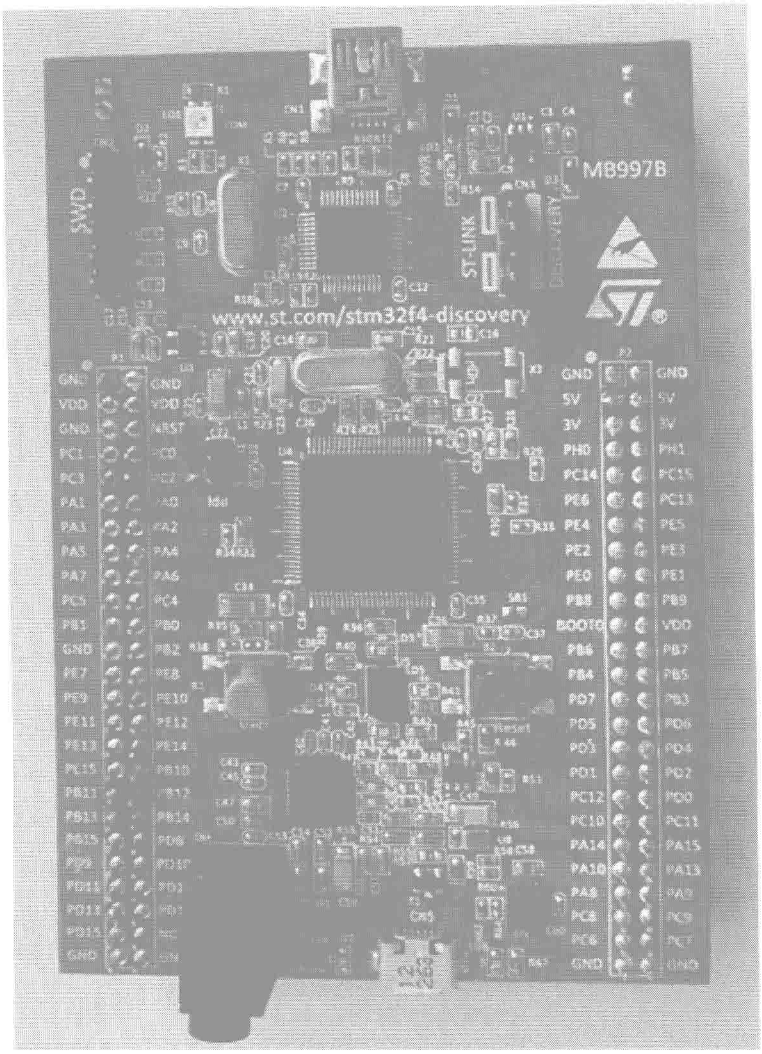

Figure 1.2 STMicroelectronics STM32F407 Discovery.

remove files from a project, build a project, start and stop a debug session, and run and halt a program running on the ARM Cortex-M4 processor.

Some of the example programs implement DSP algorithms straightforwardly, and with a view to transparency and understandability rather than computational efficiency or elegance. In several cases, ARM's CMSIS DSP library functions are used. These are available for both the STMicroelectronics and Texas Instruments processors as part of the *MDK-ARM* development environment. In appropriate circumstances, these library functions are particularly computationally efficient.

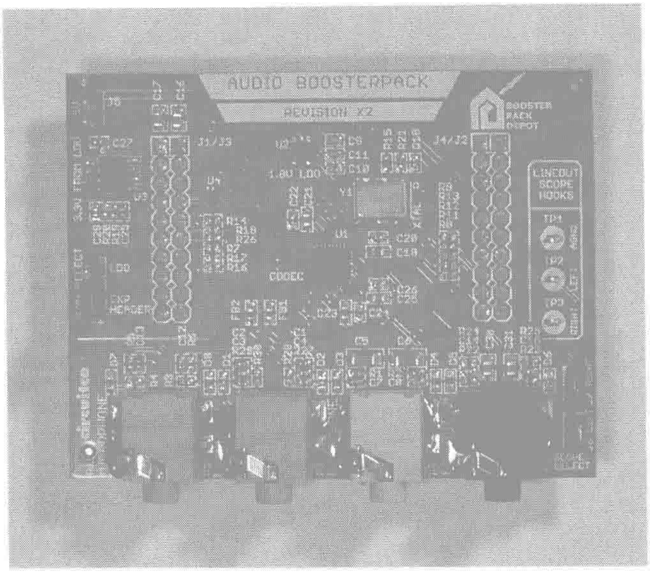

Figure 1.3 AIC3104 audio booster pack.

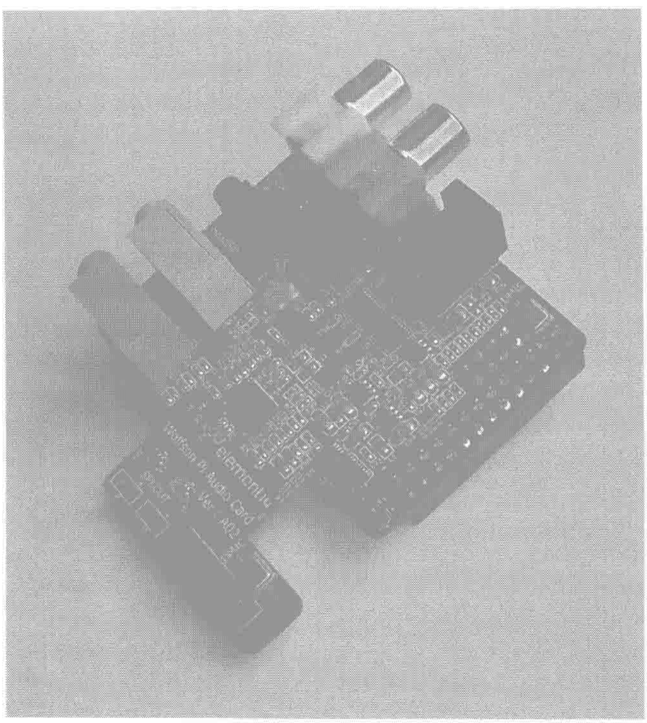

Figure 1.4 Wolfson Pi audio card.

This is useful in some of the program examples where the demands of running in real-time approach the limits of what is achievable with the ARM Cortex-M4. One difference between the two devices used in this book is that STM32F407 uses a processor clock speed of 168 MHz, whereas the TM4C123 clock speed is 84 MHz. As presented in the book, all of the program examples will run in real time on either device. However, if the parameter values used are changed, for example, if the number of coefficients in an FIR filter is increased, it is likely that the limits of the slower device will be reached more readily than those of the faster one.

All of the program examples have been tested using the free, code size-limited, version of *MDK-ARM*. The aim of hands-on DSP teaching, and the intention of this book, is not to teach about the architecture of the ARM Cortex-M4. The device is used because it provides a capable and inexpensive platform. Nor is it the aim of hands-on DSP teaching, or the intention of this book, to teach about the use of *MDK-ARM*. The aim of hands-on DSP teaching is to reinforce DSP theory taught in lectures through the use of illustrative examples involving the real-time processing of audio signals in an electrical engineering laboratory environment. That is to say where test equipment such as oscilloscopes, signal generators, and connecting cables are available.

1.1.3 Hardware and Software Tools

To perform the experiments described in this book, a number of software and hardware resources are required.

1. An ARM Cortex-M4 development board and audio interface. Either a Texas Instruments TM4C123 LaunchPad and a CircuitCo audio booster pack or an STMicroelectronics STM32F407 Discovery board and a Wolfson Microelectronics Pi audio card are suitable hardware platforms.
2. A host PC running an integrated development environment (IDE) and with a spare USB connection. The program examples described in this book were developed and tested using the *Keil MDK-ARM* development environment. However, versions of the program examples for the TM4C123 LaunchPad and project files compatible with Texas Instruments *Code Composer Studio* IDE are provided on the partner website `http://www.wiley.com/go/Reay/ARMcortexM4`.
3. The TM4C123 LaunchPad and the STM32F407 Discovery board use slightly different USB cables to connect to the host PC. The launchpad is supplied with a USB cable, while the STM32F407 Discovery is not.
4. Whereas the audio booster pack and the launchpad plug together, the Wolfson Pi audio card does not plug onto the STM32F407 Discovery board. Connections between the two can be made using a custom ribbon cable, available from distributor Farnell.
5. An oscilloscope, a signal generator, a microphone, headphones, and various connecting cables. Several of these items will be found in almost any electrical engineering laboratory. If you are using the STM32F407 Discovery and Wolfson Pi audio card, then a microphone is unnecessary. The audio card has built-in

digital MEMS microphones. The Wolfson Pi audio card is also compatible with combined microphone and headphone headsets (including those supplied with Apple and Samsung smartphones). Stereo 3.5 mm jack plug to 3.5 mm jack plug cables and stereo 3.5 mm jack plug to (two) RCA (phono) plugs and RCA to BNC adapters are the specific cables required.

6. Project and example program files from the partner website `http://www.wiley.com/go/Reay/ARMcortexM4`.

REFERENCE

1. Yiu, J., "The Definitive Guide to ARM® Cortex®-M3 and Cortex®-M4 Processors", Third Edition, Elsevier Inc., 2014.