Systems Design

Volume II of VLSI Systems Design for Digital Signal Processing

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Dedication

This book is dedicated to all "systems designers," those noble souls who reverse the natural laws of entropy and create structure in the universe.

Our approach to design is predicated on a natural law which we jointly discovered,

> If you don't know where you are going,
> you won't know when you get there

with several corollaries, the most notable being

> C:1 (Brown's corollary):
> It won't matter in which direction you go.
>
> C:2 (Bowen's observation)
> Murphy will be your travelling companion.

Thus, what is contained in this book is a simple message: You can't design (or choose) a complex piece of hardware to execute a complex algorithm unless you know what you want done—in detail.

This book offers designers four things:

A *methodology* for charting your course;
A *tactical arsenal* for getting you there;
Some *mechanisms* for helping you along the way; and
Some *means* of proving that you have arrived.

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There are many others who survived several graduate courses based on emerging notes, and we acknowledge the influence of everyone with whom we talked (perhaps the word is harangued) about our philosophy and approach. As we may have influenced them, they profoundly influenced us.

Introduction to Volume II

This volume is devoted to establishing the following: first, that the design of systems is a process; and, second, that an appropriate design methodology, with all the support mechanisms, is necessary to overcome many of the problems inherent in this process. Most emphatically, this volume is not concerned with myriad implementation details at the electrical level. It is concerned with the logical progression of steps from the initial requirements analysis to the choice of the functional components. Below this, another kind of expertise is required, which is beyond the scope of this volume.

In Volume I, an extensive tutorial review of signal processing theory was presented. This review exposed the computational requirements of signal processing algorithms, as derived from the underlying mathematical studies. A cursory review of processors was also undertaken to demonstrate the mechanisms used to achieve high performance, constrained by technology and perhaps by fundamental architectural concepts.

In Volume II, we present an additional set of essential concepts which are a necessary part of every system designer's arsenal. We believe it is exceedingly important that the reader appreciate both the perspective that generated the design philosophy and the structure of the material to be presented before he/she proceeds. To achieve this appreciation, Chapter 1 restates the major elements of the material presented in Chapter 5 of Volume I, followed by an examination of the structure and philosophy of this volume.

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Preface

In Volume I the basis of digital signal processing and high-performance digital processor architectures was reviewed. In this volume we introduce a comprehensive design methodology for creating digital signal processing systems; this design methodology is self-contained and applies to the design of processing systems in general.

Design involves, at many stages, an "intellectual leap" in order to conceive and create new structures where none existed before. This leap cannot be taught. In a sense, all that can be taught is the location and the structure of sound platforms from which to leap—and also, perhaps, how to recover gracefully from landing in a swamp.

Many portions of this book represent attempts to convey a philosophy of systems design. Philosophical discourse, as with other such high-level human affairs, is difficult and will invariably provoke disagreements. In a very large sense, it is unimportant whether you agree with our approach or not—the important issue is that, as a systems designer, you must establish such a perspective. Disagreeing with someone else's approach often provides the synergism for establishing your own version.

The success of your designs will provide the final judgment: You can't argue with the facts, although you can occasionally cloud the issue.

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From Processing to Processors—An Overview

1.0 INTRODUCTION

This book is the second of a two-volume set. The overall purpose of these two volumes is to present a coherent philosophy and methodology for the design of high-performance digital signal processing systems that exploit the advances being made in very large scale integration (VLSI) circuit technology.

In Volume I, we presented an overview of the basic theory of digital signal processing, an introduction to the basic concepts of high-performance processors, and a brief examination of the evolution of digital signal processors and integrated circuit technology growth trends. In this volume, we are concerned with bridging the gap between theoretical problem analysis and the physical implementation of the theory, through a systematic process of systems design.

Part A of Volume I examined the basic concepts of digital signals and the mathematical theory on which digital signal processing is based. We also reviewed some common techniques and algorithms of digital signal processing. Part A concluded with a discussion of the general attributes of any particular digital signal processing application area and introduced the overall problem of moving from theory to implementation.

The observation that the majority of digital signal processors implement a small set of basic processing operations leads to a particular perspective of the design problem. These processing operations have traditionally been further broken down to expose their dependence on the repetitious execution of the fundamental arithmetic operations of multiplication and addition. However, recent advances in integrated circuit technology have led to the availability of components of far greater complexity than simple multipliers and adders.

Thus, digital signal processor design efforts must concentrate on achieving higher throughput rates for processors organized around the execution of more complex fundamental operations. We note, in addition, that the rate of advancement of integrated circuit technology has been exponential for over a decade, and projections indicate that it will remain so for at least the immediate future. Digital components of both very high execution speed and very high functional complexity are assured. Thus, the overall problem of processor design, or processing system design, seems more appropriately viewed in terms of an algorithm partitioning more closely aligned with the functional complexity of modern components, that is, viewed from the perspective of creating interconnected structures of VLSI components that in many cases are processors in their own right. From such a perspective emerges the design philosophy and methodology which forms the subject matter of this volume

In this chapter, we review the perspective, established in Volume I, of current trends in signal processing and signal processors and then outline the structure and philosophy of this volume.

1.1 THE REARVIEW MIRROR: A PERSPECTIVE OF VOLUME I

1.1.0 Introduction

The move from signal processing theory to physical implementation is invariably made within the context of some particular application area or range of related applications. Indeed, the number of specific fields, such as radar, sonar, image processing, speech processing, and digital communications, to name only a few, in which digital signal processing techniques are being applied has been steadily increasing. The primary reasons for this proliferation are, of course, the steadily increasing performance capabilities of digital systems and the declining cost/performance ratios.

In Chapter 5 of Volume I, we noted several general attributes of an intended application that influence the selection or design of implementation hardware. These attributes were categorized in terms of signal models, the functions required to manipulate the signals, and the performance requirements and constraints imposed. We will review, briefly, these attributes in the following.

1.1.1 Signal Modelling

Two general aspects of signal modelling influence implementation decisions: basic signal parameters and information content modelling. The basic signal parameters such as frequency content, dynamic range, and signal-to-noise ratio requirements drive decisions on digital signal representation such as sample rate, sample quantization, anti-alias filtering, etc. The information-content model assumed for a digital signal forms the basis for determining what processing operations are to be performed on it. The information-content model of a signal is directly related to the application and specifies such characteristics as whether the signal is considered to be a random or a deterministic signal. This form of signal modelling is often concerned with the assumed characteristics of the signal source, the transmission medium, and transducer characteristics. From these signal models come the definitions of the required processing algorithms. Modelling is, therefore, the most fundamental part of the whole structure of deriving a suitable processor. We will not be concerned with the activity of signal modelling in this book—however, this is not to understate its importance. Indeed, we shall see that system modelling is the fundamental basis of system design.

1.1.2 Basis Operations

Based on the signal models and the specific problems or goals of the various application areas, the required sequences of processing operations are formulated in terms of signal processing theory. This specification of processing requirements is carried out in terms of the basic mathematical tools of signal processing theory, as discussed in detail in Part A of Volume 1. In general, the specification of the signal processing requirements amounts to the specification of the order in which the signal is to be manipulated to get the information of interest into a desired form or representation. The actual signal manipulations tend to be based on a relatively small set of basic signal processing operations such as convolution, correlation, difference-equation calculations, discrete Fourier transform (DFT) coefficient calculations, vector or matrix arithmetic operations, etc. The problem at hand must be specified in terms of the appropriate combination of these operations to accomplish the required processing.

This view of processing requirements specification is of central importance, since it provides a common set of processing function types needed to carry out digital signal processing. These common processing functions, which we designate as the *basis operations* of digital signal processing (DSP), are summarized in the following list.

1. *Difference equation calculations*

$$y(n) = \sum_{k=0}^{N} a_k x(n-k) - \sum_{k=1}^{M} b_k y(n-k) \tag{1.1}$$

This equation represents the general computational requirement for a recursive or infinite impulse response (IIR) filtering operation, where $x(n)$ is the input sequence and $y(n)$ is the filtered output sequence. The parameters N, M, a_k, and b_k define the actual transfer function or equivalently the phase and amplitude response of the filter. If the coefficients b_k are all zero, then equation (1.1) reduces to the familiar form of a finite convolution sum representing a nonrecursive or finite impulse response (FIR) digital filtering operation:

$$y(n) = \sum_{k=0}^{N} a_k x(n-k) \tag{1.2}$$