Effective Use of Projects in DSP Laboratory Instruction

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July 14, 2000

Abstract

With the recent growing interest in digital signal processing at the undergraduate level, a laboratory course addressing the fundamentals of real-time signal processing implementation is becoming a necessity for a well-rounded DSP education. We have found that incorporating an open-ended project component into DSP laboratory instruction is highly beneficial in achieving these objectives. However, because of the limited time in a one-semester lab, careful attention must be paid to temper the open-endedness of the project with sufficient guidance to ensure that the students' time is efficiently spent. In this paper we highlight the project phase of the real-time DSP lab course developed at the University of Illinois and discuss how creating an effective project experience has affected recent course development.

1 Introduction

The importance of digital signal processing courses in undergraduate electrical engineering curricula has grown tremendously. As more and more students are exposed to introductory signal processing theory, laboratory instruction is becoming almost essential as part of a well-rounded DSP curriculum.

A DSP laboratory can potentially serve many educational purposes, both DSP-specific goals and more general curricular objectives [1]. A partial list of DSP-specific topics includes

- DSP theory
- Real-time DSP
- DSP implementation issues (e.g., quantization, fixed point, hardware and software)
- DSP applications
- Advanced topics in DSP

More general educational goals potentially well addressed via a DSP laboratory course include

- Microprocessor architecture, design, and applications
- Assembly language programming
- Ability to connect the theory with the implementation
- Oral and written communication skills
- Teamwork

- Research experience
- Open-ended design experience and project management

Many DSP laboratory courses consist primarily of a series of structured weekly laboratory exercises. This approach effectively addresses many of the above educational objectives. However, substantial, open-ended laboratory projects can greatly enhance many of these goals and are uniquely effective at addressing some of them. A project component of the lab course provides students the opportunity for open-ended design, research experience, and implementation practice as well as the chance to exercise their communication skills through oral project demonstrations and a formal written research report at the end of the term. Additionally, as more advanced signal processing theory courses become available at the undergraduate level, a carefully designed project-oriented laboratory can provide an introduction to some of the material covered in these more advanced classes as well as valuable hands-on experience which they can relate back to as they progress through the expanding DSP curriculum.

Open-ended laboratory projects can be a uniquely effective teaching tool, but must be carefully organized to obtain maximal utility. Particular attention must be paid to the students' varying needs for theoretical instruction in advanced topics, for individual guidance and organization, as well as to the provision of laboratory equipment to support a variety of student interests. In the remainder of this paper, we discuss some of the specific objectives and issues associated with the project phase of a DSP lab course at the University of Illinois, and how these project objectives have impacted recent course and hardware development.

2 A Project-Oriented Lab Course

The growing interest in DSP at the undergraduate level has been evident in the evolution of ECE 320, a senior-level DSP lab at the University of Illinois. This elective lab class currently serves nearly a third of the electrical and computer engineering undergraduates, and its popularity is largely due to the project-oriented structure of the class.

All of the educational objectives listed above are at least secondary goals of ECE 320. Within the current curriculum, the primary educational goals of ECE 320 are

- Enhanced understanding of DSP theory
- Real-time, real-world DSP implementation
- Open-ended design experience in an advanced DSP application

We note that the first two goals are most efficiently achieved through a series of structured weekly lab assignments, whereas the latter goal is only achieved through a substantial project. In addition, many students have specific DSP application interests prior to enrolling, so a flexible structure accommodating different interests better serves the students. Accordingly, the course has been roughly divided into two eight-week halves: first a series of weekly laboratory assignments that review the introductory DSP theory and address real-time implementation issues, followed by a project phase where the students research and complete an application of their choosing. However, to enable students to accomplish a significant advanced DSP implementation in a single semester, the weekly assignments must simultaneously prepare the students for rapid progress in the project phase, making the project the ultimate focus of the course for the students throughout the semester. As most of the students have little experience in microprocessor systems, engineering design, and DSP applications, this preparation includes programming and use of a real-time DSP microprocessor system, basic DSP algorithms and applications, and proper design methodology.

Weekly lab topics include an introduction to a real-time DSP microprocessor system, FIR filtering and filter design, multi-rate processing, IIR filtering and fixed-point implementation issues, modulation theory, and FFT usage. Each assignment consists of a high-level system simulation in MATLAB followed by real-time implementation of the task on the DSP in assembly language. Requiring that a significant portion of the lab assignments be completed at the assembly language level provides remedial instruction in this area and gives all students a deeper understanding of the architectural issues involved in digital signal processors as well as an appreciation for efficient machine-level implementation. Evaluation of the students' performance on lab assignments and project completion is done via oral examination, where students are individually quizzed. This places the emphasis on the students' ability to demonstrate both the theoretical and practical aspects of the assignment. Although time-consuming for the instructor(s), this personalized oral quiz format provides instantaneous feedback to the students using the working lab as a tool to illustrate the concepts in a real-time environment.

By the end of the structured lab assignments, students must select a project in an application of their choice and spend the remainder of the semester researching and implementing it. A formal project proposal as well as a demonstration of and written report describing their projects helps develop oral and written communication. Students are also encouraged to work on their projects in groups to provide experience in teamwork and project management.

The diversity of student interests ensures a wide variety of projects each semester, and the popularity of the course as a whole is due in large part to the creative projects students have pursued in the past. In the audio field, students have successfully implemented digital crossovers, audio effects such as concert hall reverberation, active surround-sound decoding, active sub-woofer control, and wavetable and FM music synthesis. Speech projects have included single word recognition, speaker verification, and speech synthesis and coding. Students with an interest in communication systems have completed a variety of projects including QPSK transmitter/receiver pairs complete with carrier and symbol-timing recovery, a decoder for the time and date information on the WWV radio signal, and slow-scan NTSC video processing. Other types of projects have included signal processing for a proton precession magnetometer and LMS adaptive filtering applied to active noise control and mechanical system identification. Some teams have had the opportunity to explore hardware issues including adding a MIDI control to a music synthesis system, a video camera interface, and an all-digital amplifier. Many more teams do significant user interface programming in MATLAB or some other language to provide attractive and configurable front-ends to their projects.

In past years, the project phase was almost entirely self-paced. However, certain problems consistently arose that led to many students' failure to successfully complete their projects; as discussed in the following section, some changes have recently been introduced to improve the effectiveness of this portion of the course.

3 Recent Project-Driven Modifications

The project has been an educationally effective and popular component of our DSP laboratory course for many students. However, each semester some students have failed to successfully complete their projects or to gain valuable experience from the effort. Over the years, three types of problems have consistently arisen that often lead to failure:

- putting off project work until too late,
- poor strategy for approaching open-ended design, and
- lack of background knowledge on the project topic.

We have recently introduced several new elements in the project phase in an attempt to mitigate these common problems. Intermediate milestones, including a formal design review and the project labs (discussed later), require substantial, regular progress early in the project phase. At the design review, which occurs approximately half way through the project phase, students present a detailed description of their project, their proposed implementation, and MATLAB simulation results to both their peers and selected faculty members. In addition to receiving valuable feedback and alternative suggestions for completing their proposed projects, this formal design review contributes to the overall real-world, industrial-style design experience.

Many students approach design in a haphazard way, for example by beginning assembly-language coding before fully understanding their application, developing a system-level description, or performing any high-level simulations to confirm the correctness of their approach. Such students often invest an immense amount of effort only to find at the end that their approach fails or that they cannot debug their system. This is immensely frustrating both for the students and the instructors. To partially alleviate this problem and to better train students in proper design methodology, a greater emphasis is now placed on on end-to-end, high-level simulation in an environment such as MATLAB. As mentioned above, MATLAB or similar simulations are required at the time of the design review. Together, these modifications have substantially reduced the failures due to the first two causes.

The final major problem (students' lack of advanced knowledge in the project area) has been another major challenge to overcome. We strongly encourage students to choose a project area in which they have a particular interest regardless of their background. For example, many students desiring to implement a digital communication system in the DSP laboratory project have not yet taken a course in communications theory! Even those with previous coursework generally have not yet learned about many of the more challenging aspects of a real-world system (such as frequency and timing synchronization in a communications system). Simply sending students off to the library for independent study, while a desirable and necessary aspect of the project experience, is often insufficient. However, limiting students' ambitions to simple projects in areas covered by previous coursework is demotivating and largely defeats the purpose of an open-ended design experience.

We have addressed this challenge by introducing two weekly "project labs" in four specific topical areas early in the project phase. As a transition period between the programmed exercises of the first half of the course and the open-ended design of the second half, the students work through exercises in one of several tracks which mirror the predominant project topics. These assignments efficiently cover specific key system components and serve both to introduce students to a few basic principles in their project area and to help them through certain tricky components (e.g., phase-locked loops in a communications system) that have often been barriers to success for inexperienced students.

There is obviously a trade-off between the relevance of the project labs to specific student projects and the staff effort involved in developing multiple parallel tracks. Through twelve years of experience, we have observed that the vast majority of student-selected projects fall in four general categories, for which we have developed specific assignments relevant to most projects in that area. We currently have project tracks covering adaptive filtering, audio, communications systems, and speech processing. We emphasize that our goal is not to suppress the individual research component or open-ended nature of the project. Instead, these additional project lab exercises should act as a springboard to provide background in the theoretical and implementational issues likely to be encountered by the student, as well as suggest areas of extended research.

Audio-related topics have long been a popular choice for projects, and two exercises have been provided for those students who are interested in some of the fundamentals of digital audio processing. These exercises include an introduction to surround-sound processing, the use of extended memory for buffering long audio samples, interpolation techniques required in professional-quality audio effects, and information on using the DSP development system's serial port to develop user-friendly "stand-alone" applications whose parameters can be updated in real-time.

For students interested in an adaptive filtering project we have designed two exercises to introduce them to the LMS adaptive filtering algorithm. After completing these exercises the students have a basic understanding of how adaptive FIR filters can be applied to system identification problems. They gain some intuitive insights into the theory of random processes and the part it plays in analyzing the performance of adaptive systems. As part of their completed projects, students are encouraged to explore more advanced adaptive filtering concepts like delayed LMS updates, system equalization, or active noise cancellation.

There are two labs designed to introduce students to the fundamentals of speech processing, including an LPC-based exercise and suggestions for alternative methods of stable IIR implementation. Again there is an emphasis on treating the sampled signal as a random process and advanced linear algebra techniques are introduced for modeling the vocal tract as an all-pole system.

As the field of digital communications has become popular, we have introduced lab exercises covering the basics of carrier phase and symbol timing recovery for digital communication receivers. These labs focus heavily on the feedback control issues associated with basic recovery methods and provide students with practical techniques not covered in any of the advanced communications theory courses. The exercises encourage students to consider a variety of digital communications protocols and investigate the effects of noise on both the carrier and symbol recovery subsystems as well as the decision-making performance of the entire receiver.

Achieving the educational efficiency of structured laboratory assignments without sacrificing the creativity of an open-ended design experience has been a primary concern. Although on the surface the project labs might seem to detract from the open-ended individual design experience, they have been carefully constructed to introduce basic principles and key system components in each topical area without constraining the system design options or the students' creativity. In general, we have found that they accelerate rather than hinder the students' progress on their projects, have allowed students to tackle more ambitious projects with substantially higher success rates than in the past, and have not substantially reduced the open-ended nature of the design experience.

4 Hardware Selection

Although many development platforms are used for DSP instruction, the variety of project topics in ECE 320 requires careful selection of the DSP and its supporting hardware. This includes the development environment used for coding and debugging, as well as supplemental hardware such as audio-quality codecs and sufficient data/program memory. The development environment should expose students to systems they are likely to work with in an industrial setting while being flexible enough to offer prototype-level capabilities. One must strike a balance between an environment that is easy to learn and use and one that has sufficient performance to support a variety of projects. Just as a one-semester course cannot cover as many advanced DSP topics as one would like, no single evaluation platform is ideal for all of the possible project topics students might choose.

For ECE 320 we have selected the TMS320C549 evaluation board from Spectrum Digital, Incorporated. The primary benefits of this package are a fast (100 MHz) fixed-point processor capable of a variety of real-time algorithms, extended memory to support memory-intensive projects such as image processing or long audio buffers, and multiple interface options including a JTAG interface for efficient debugging and a serial interface for additional control. Additionally, this evaluation platform works with TI's Code Composer development/debugging environment, which supports both low-level (assembly language) and high-level (C source) code development.

In addition to the '549 EVM, we have incorporated a surround-sound module (also from Spectrum Digital) as part of the lab equipment. These multi-channel daughter boards feature audio quality, two-channel (one stereo signal) input and six-channel output via 20 bit A/D and D/A converters, as well as digital I/O for interfacing to DVD and CD players. A primary advantage of the surround-sound boards is the that it allows students (and instructors) to inspect the signals at many points in a system simultaneously to assist in debugging, as well as supporting the many projects in the popular area of audio.

5 Conclusion

In addition to contributing to the popularity of the course, the project-based lab format of ECE 320 has proven to be quite beneficial in meeting several key educational objectives. The open-ended nature of the projects allows students to tailor the class to their interests, and recent modifications to the course have helped broaden the students' experience. For example, although high-level system simulation has always been encouraged in the past, making it a requirement has significantly aided the successful completion of projects while providing a more balanced design and implementation experience.

The selection of the TI TMS320C549 DSP evaluation platform as the development environment has helped improve the project experience for the students. After comparing other DSP evaluation platforms we have found that the TI '549 EVM with the add-on multi-channel daughter-board can support a wide variety of student-selected projects. Although the mnemonic instruction set of the '549 processor is more cumbersome to teach than some other architectures, the ease of use of the debugging environment and the availability of high level C source development help make this environment very flexible.

The inclusion of the project-specific exercises has been very successful. We have found that having students spend two to three weeks working through the structured exercises focused on their projects has been significantly beneficial. Although this extra work may have cut into students' independent design time, proposing their final projects after completing the project lab exercises has resulted in higher expectations placed on the students with respect to the quality of research and implementation.

The project labs have also significantly improved the percentage of completed projects. In the past, many students had trouble getting started and spent a majority of the allotted project time on relatively trivial implementation issues. Using the application-specific lab exercises as an introduction to their chosen topic has greatly helped students get up to speed on their projects as well as offering guidance for completing the research and implementation.

The success experienced as a result of the project labs might suggest simply extending the weekly lab format to cover the entire semester, resulting in all students being introduced to a wider variety of advanced topics. To cover all of the advanced topics covered in the project labs, however, we would likely require more time than a one-semester course allows. More importantly, this all-lab format would detract from the open-ended design experience that has proven to be of significant benefit and interest to the students. Although offering a variety of project exercises in an attempt to cover the majority of project topics selected is time-consuming from an instructor perspective, the inclusion of the project labs has helped to introduce students to advanced signal-processing theory without requiring all students to work through the same advanced labs.

References

[1] D. L. Jones, "Effective DSP laborator course design," in *Proceedings of DSPS Fest*, 1999.