2006-1246: INTEGRATION OF A DSP HARDWARE-BASED LABORATORY INTO AN INTRODUCTORY SIGNALS AND SYSTEMS COURSE

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Abstract

Signal processing concepts are often presented in a very mathematical and abstract format. This can discourage students from further exploration because of the apparent irrelevance to real-world problems. A common solution is to provide a hands-on laboratory to illustrate applications of abstract concepts. However, hardware-based digital signal processing (DSP) laboratories – which are typically incorporated into senior-level signal processing courses – usually emphasize programming the DSP chip rather than exploring algorithms and applications. While suitable for students with a strong interest in signal processing, this type of laboratory experience may not generate enthusiasm or spark curiosity in a younger student being introduced to DSP for the first time.

This paper reports on a project in which application-driven laboratory exercises were implemented as part of a required sophomore/junior-level introductory signal processing course. Students entered the course with a solid foundation in MATLAB but with no experience programming in C or Assembly languages. This constrained the choice of laboratory platform, in that students were to spend their time developing, implementing, and testing signal processing algorithms, not learning a new programming language. The Texas Instruments C6713 DSK platform, which can be programmed using SIMULINK (The Mathworks, Inc.), met this constraint. Four laboratory projects were implemented: Digital Sound Effects, Touch-Tone Dialing, a Voice Scrambler/Descrambler, and an exploration of Sampling and Aliasing in the context of the Telephone System. Each presented fundamental concepts, such as sampling and aliasing, in the context of a realistic problem. Students experienced the effects of signal processing manipulations aurally, visually, and in real-time, solidifying their understanding and increasing their engagement in the material.

1. Introduction

Digital signal processing (DSP) is central to modern Electrical and Computer Engineering (ECE) undergraduate curricula. The discipline of signal processing combines an extensive mathematical background with practical design skills. To prepare for a successful career in signal processing, whether in industry or academia, students should develop expertise in two domains: the theoretical understanding of signal processing problems and the design of devices or algorithms to solve those problems. As part of its ongoing curriculum reform, the ECE department at Duke University has implemented a new DSP laboratory that impacts student instruction in multiple courses. The overall vision for this vertically-integrated, application-driven laboratory has been presented previously[1]. This paper described the motivation for integrating a hardware-based laboratory into the introductory *Signals and Systems* course, the specific laboratory experiments that were conducted, and an assessment of the impact of the laboratory experience.

1.1 Pedagogical motivation and innovation

Prior to the implementation of the new laboratory in Fall 2005, Duke ECE undergraduates received instruction in DSP principles within two courses. In the required sophomore-level *Signals and Systems* course, students learned about introductory signal processing concepts like frequency domain representation, sampling, and modulation. Complementing the primary lecture instruction were several student projects, including a music synthesis exercise that required students to use MATLAB (Mathworks, Inc.) to generate a musical selection of their choice. When creating their musical excerpts, all students learned the basic concepts of signal generation and manipulation, sampling, and frequency harmonics, while the more advanced students incorporated signal processing techniques like modulation to enhance their composition. Other projects included a very basic MATLAB simulation of source detection in which the students studied correlation, a simple modulation simulation done in MATLAB, and the construction and testing of a working AM radio. While these experiences provided students with a strong grounding in signal processing theory, they had only limited practical components.

Hardware-based laboratories have been integrated into *individual* Digital Signal Processing courses at many universities[2-7]. Such laboratories typically include exercises that familiarize students with the hardware and programming requirements of the DSP chip, covering topics such as hardware interrupts and Assembly Language programming. Although concepts such as FIR/IIR filtering and sampling are also covered in laboratory exercises, the emphasis often remains on the mechanics of hardware implementation so that these topics are not presented in the context of realistic applications. While such an approach may be ideal for senior-level students, it is not suitable for less-experienced students, as the perceived (or real) technical difficulty of such a course may deter students who do not immediately grasp the relevance of the material[8]. In a pedagogical model developed by Wright et al.[8], interactive demonstrations, MATLAB simulations, and real-time DSP programming are used to supplement the theory presented to the students. Their experience indicates that this approach results in a more thorough understanding of DSP topics, in turn making DSP more accessible to a broad range of students. The laboratory at Duke is based on the typical hardware-based signal processing laboratories and incorporates the pedagogical model of Wright et al. [8], while introducing two innovative features.

First, the laboratory will be vertically-integrated throughout the curriculum, enhancing or replacing existing simulation exercises in both introductory and advanced signal processing courses. Students will progress from the development of signal processing algorithms (to be implemented on the chip) to programming the chip directly. This approach will particularly benefit students in the introductory *Signals and Systems* course who do not have the theoretical or technical background necessary for direct programming of DSP chips. Recently developed software programs (such as the *MATLAB Link for Code Composer Studio* and *Embedded Target for TI C6000 DSP*; Mathworks, Inc.) will minimize this obstacle by allowing students to implement designs on DSP chips using more familiar and/or intuitive software tools such as MATLAB and SIMULINK. This approach will allow even beginning students to gain hands-on experience with DSP hardware and equipment at the same time they learn the theoretical fundamentals of signal processing[8,9].

Second, an application-based approach will be adopted. The laboratory exercises will illustrate fundamental signal processing concepts using real-world examples and applications, thus complementing theoretical material presented in the classroom and MATLAB simulations assigned for homework. Linking the theory to a real application and allowing students to determine and test their own system specifications will be more likely to stimulate students' interest in the material when compared to more standard, abstract laboratory exercises. As student feedback has indicated, application-driven exercises enhance the appeal of signal processing without compromising learning of theoretical concepts or precluding more specialized instruction in DSP design and programming.

1.2 Goals and Expected Outcomes

The principles of vertical integration and application-driven exercises were adopted for two reasons: to improve students' conceptual understanding of course material and to elevate their interest in the subject area. Common student complaints about undergraduate laboratory exercises, in general, are that they are irrelevant, busy work, and unconnected to lecture material. To counter these sorts of complaints, the laboratory exercises were designed to enhance the lecture component of the course by being well-integrated with classroom activities and homework assignments. Finally, the laboratory materials were designed to have open-ended problems and challenges, rather than step-by-step instructions, to encourage students to think critically about the concepts and their application. To make this approach possible, the exercises were grounded in real-world examples rather than abstract problem statements, allowing students to derive relevant system parameters directly and logically from the challenge set before them.

2. Hardware-based *Signals & Systems* Laboratory

2.1 Physical Laboratory Environs

The laboratory has 12 stations each composed of 1) a PC with a microphone, speakers, and headphones and 2) test and measurement equipment, including a function generator, a digital oscilloscope, a multimeter, and a power supply. For our purposes, it was important to select a DSP board that could easily interface with MATLAB and SIMULINK to minimize the technical challenges a beginning student might encounter when first learning to program the chip in Assembly or C. Not only did the Texas Instruments' TMS320C6713 DSP Starter Kit (DSK) satisfy this criterion, but TI also expressed an interest in the development of our laboratory and provided hardware through their University Program. Software available on each PC includes a C Compiler/Assembler/Linker, debugger, and simulator; MATLAB 7 with Signal Processing, Image Processing, Data Acquisition, and Filter Design Toolboxes (The Mathworks, Inc.); SIMULINK with DSP and Communications Blocksets (The Mathworks, Inc.); MATLAB Link for Code Composer Studio and Embedded Target for TI C6000 DSP (The Mathworks, Inc.); Real-Time Workshop (The Mathworks, Inc.); and Goldwave Digital Audio Editor.

2.2 Laboratory Exercises

Students entered *Signals and Systems* with a basic knowledge of MATLAB and a fundamental understanding of test and measurement equipment. However, they had no experience with SIMULINK programming or with the DSP hardware used in the laboratory. As this course provided an introduction to signal processing and system design, they also had no prior knowledge of these topics.

Four laboratory exercises were developed for the pilot offering in the Fall of 2005 and are described in the following sections. The exercises included Digital Audio Effects, a Dual-Tone Multi-Frequency System, a Voice Scrambler and Descrambler, and Sampling and Aliasing. Each exercise was conducted by students working in groups of two during one 2.5-hour laboratory session with a full report due the following week. Inspiration for some of the exercises came from several sources[3,5,10-13].

2.2.1 Digital Audio Effects

In this assignment, students explored simple digital audio effects to complement classroom instruction in basic signals and signal manipulations. The purpose of this exercise was to enable them to manipulate audio signals and aurally "experience" the effect of different processing algorithms. The algorithms were implemented using a digital signal processor so that the input signals (both speech and music) could be processed in real-time. While this is not a necessary component to the learning experience, it facilitated comparisons between original and modified signals and added to the "coolness" factor. The effects explored included a simple echo generation, flanging, and reverberation.

The objectives of this projects were for the student to:

- Become familiar with the hardware and software
- Implement a simple audio I/O system using Simulink and a digital signal processor
- Implement several simple audio effect algorithms (difference equations) in real-time using a digital signal processor
- Manipulate system parameters to explore the effect on the audio output

To become familiar with the hardware and software tools used throughout the semester, students designed, built, and implemented a basic audio processor using the DSK and SIMULINK. Step-by-step instructions were provided, guiding students through the initialization of the DSK, exploration of SIMULINK (with which few had previous experience), and the design and implementation of a simple I/O system consisting of an ADC and DAC. Students were then asked to explore the range of input and output options, including microphone input, and line input from both the function generator and the line out of the computer (e.g., a stored .wav file). Output was sent to headphones, an oscilloscope, or stored in a computer file which could be played using an audio player (such as RealPlayer) or loaded into MATLAB for analysis.

Following this basic introduction to SIMULINK and its interface with the DSK, students were asked to examine and implement several audio effects algorithms. The first, a simple echo, extended the basic I/O system previously implemented by adding delay and gain blocks to the system (see Figure 1).

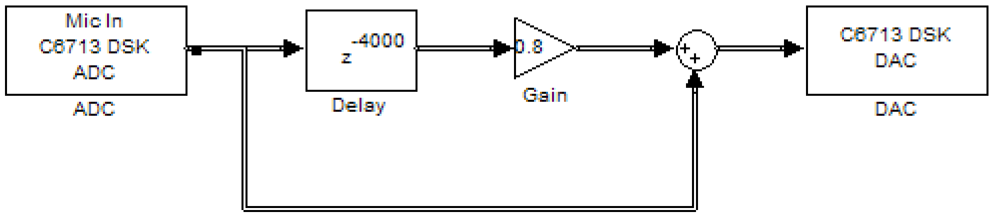

FIGURE 1. SIMULINK block diagram for a single echo filter

Students were instructed to compile and download the system onto the DSK and to experiment with various input signals (e.g., speech through the microphone, pre-recorded music files) to experience the audio effect. The difference equation describing this system was provided and students were asked to relate the block diagram to the equation, to modify the parameters of the system, and to describe mathematically and aurally how those changes affected the signal. As students were beginning to learn about impulse responses in class, they were also asked to derive the impulse response of this system and to interpret their answer in terms of the system behavior. Similar experiments were performed to explore flanging and reverberation.

2.2.2 Dual-Tone Multi-Frequency System

The next project presented an practical application of correlation and illustrated a use of basic sinusoidal signals: a dual-tone multi-frequency (DTMF) encoder/decoder. Using MATLAB, SIMULINK, and a TI DSK, students designed and implemented a real-time DTMF system that simulated the standard touch-tone phone system.

The objectives of this project were for the student to:

- Gain an understanding of the standard DTMF phone dialing system
- Design and implement a software-based DTMF tone generator (encoder)
- Design and implement a hardware-based DTMF receiver (decoder)

These objectives were achieved through the design and implementation of the two major subsystems: a DTMF encoder and a DTMF decoder. The encoder was implemented using software, for simplicity. Students wrote MATLAB code capable of generating the tones representing an arbitrary phone number. For the decoder, students designed a system (using a SIMULINK block diagram) that enabled the DSK to translate the tones back into numbers, using the on-board LEDs to display the decoded phone number.

The standard touch-tone telephone system operates using dual-tone multi-frequency (DTMF) signals to transmit information. When any key on the telephone key pad is pressed, a pair of sinusoids are generated and added together, producing a "dual tone." For example, when you press the "6" key, a signal containing the sum of 770 Hz and 1477 Hz is generated (as shown in

Table 1). The particular tones selected for the touch-tone system provided an ideal discussion topic regarding harmonics, signal distortion, and the importance of designing robust systems.

TABLE 1. DTMF frequencies

Freqs	**1209 Hz**	**1336 Hz**	**1477 Hz**
697 Hz	1	2	3
770 Hz	4	5	6
852 Hz	7	8	9
941 Hz	*	0	#

DTMF decoding can be done in a number of ways. One way is to implement a series of band pass filters, each of which is tuned to one of the DTMF frequencies. To detect which key has been pressed, the decoder would look at the output of each filter and choose the two frequencies whose filters have the greatest output (since each DTMF tone consists of two summed sinusoids). Since the students had not learned about filters, a second approach utilizing correlation was used to decode the DTMF tones.

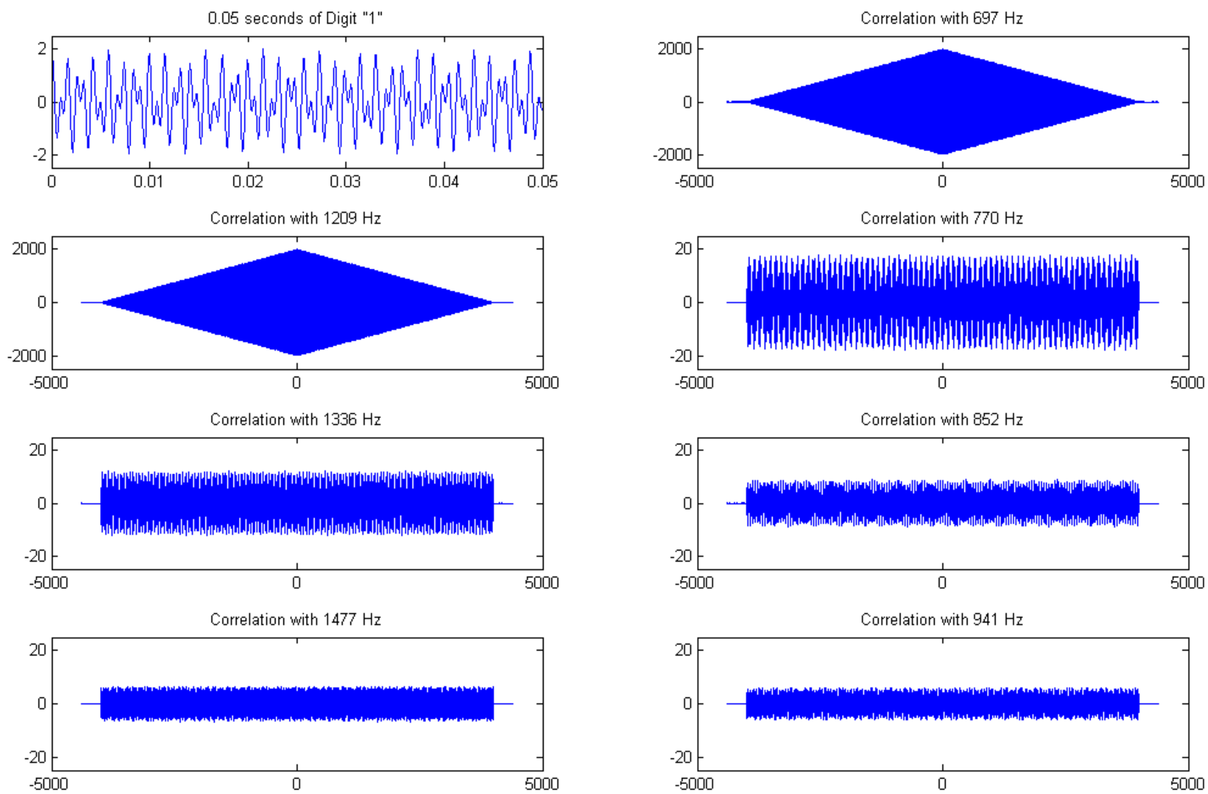

FIGURE 2. Correlation of digit '1' with individual DTMF tones.

Students began by generating files corresponding to several digits and plotted the correlation of each digit signal with the seven individual DTMF tones. An example, using the digit "1", is shown in Figure 2. Students observed that correlation was greatest when correlating the digit with the two tones composing that particular number (in this example, 697 Hz and 1209 Hz, from Table 1). Examination of the fine structure of the correlation revealed an interesting (sinusoidal) pattern which required students to think carefully about their signals and correlation in order to interpret the results.

Based on their observations, students were asked to develop and test a software-based decoding algorithm which they then used to identify a mystery digit in a pre-recorded file. After finalizing the algorithm, students were then required to implement the decoder on the DSK. This required students to use new blocks and to translate their understanding of the decoding algorithm into an actual system. Finally, students were able to generate a phone number using their software-based encoder and use their hardware-based decoder to translate the DTMF tones into a pattern of LEDs representing the original phone number.

2.2.3 Voice Scrambler/Descrambler

Thus far, the laboratory exercises had focused on exploring the effects of manipulating signals in the time domain. With the introduction of the Fourier Series and the Fourier Transform, students were now ready to explore the effects of signal manipulations on both the time and frequency domain representations of a signal.

The objectives of this project were for the student to:

- Design a simple filter given the desired specifications
- Design a system that scrambles a message signal
- Design a system that descrambles the message signal

In this project, students explored what happens to the frequency content when two signals were multiplied in the time domain. Using SIMULINK and two TI DSKs, students designed and implemented a real-time system that scrambled a message signal (such as speech or music) and then descrambled the same signal using very simple signal manipulations. This project also provided an opportunity to explore filter design, a topic only briefly addressed in the lectures.

To verify proper operation of the frequency-inverting Scrambler, students had to consider the implication of using various input signals and design their system such that distortion was minimized. This required filters to be used both for anti-aliasing and to eliminate high-frequency artifacts resulting from the modulation process (as seen in the block diagram in Figure 3.)

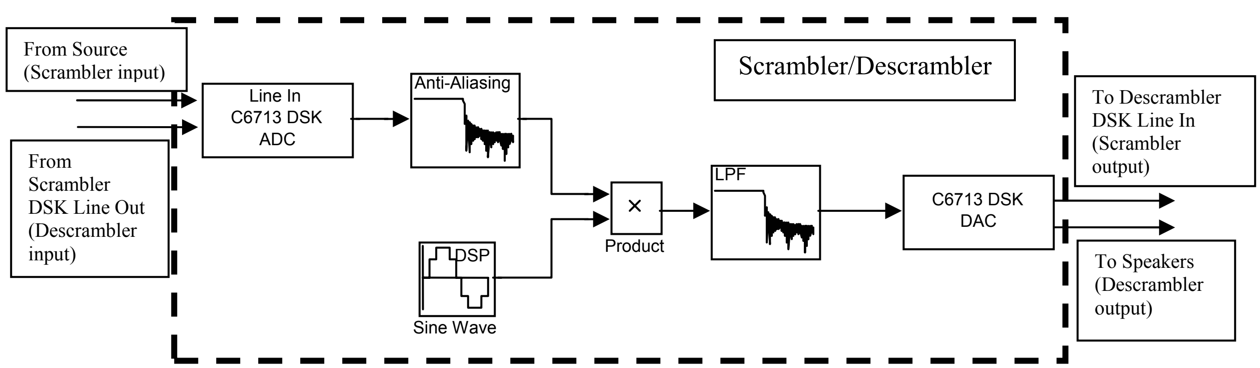

FIGURE 3. SIMULINK block diagram for Scrambler/Descrambler

Students quickly realized that the Descrambler could be implemented using the same system as the Scrambler. Students downloaded the system onto one DSK, which was then disconnected from the computer so that the system could be downloaded onto the second DSK. This emphasized the fact that the system was actually running on the DSK itself, in real-time, making it portable. Students verified that their Descrambler decoded the scrambled message signal and explored the limitations of the system. Through these explorations, students were able to gain a better understanding of the importance of anti-alias filtering and the limitations imposed by the Nyquist sampling theorem.

2.2.4 Sampling and Aliasing

In the final hardware-based project, students investigated the effects of aliasing that can arise when digitally processing a continuous-time signal. By collecting theoretical, visual, and aural observations, students realized that anti-aliasing filters could improve the quality of the signal.

The objectives of this project were for the student to:

- Examine (visually/aurally) effects of aliasing in the sampling of continuous-time signals
- Examine (visually/aurally) effects of an anti-aliasing filter
- Explain why anti-aliasing pre-filtering is often necessary

In order to digitally process any continuous-time signal, one must convert that analog signal into a digital signal through *sampling*, to create discrete time samples, and *quantization*, to create discrete amplitudes. Both sampling and quantization can introduce errors, or distortion, into the signal being processed. These errors become evident when, after processing, the digital signal is converted back to an analog signal through a process known as *reconstruction*.

One interesting real-world application in which a continuous-time signal is processed digitally is telephone transmission. To motivate the study of sampling and aliasing, students were introduced to the basic design and operation of the telephone system. Topics included the analog-to-digital and digital-to-analog conversion processes and the determination of the sampling rate of the system. Students learned that the standard telephone system uses an 8 kHz sampling rate, which works well assuming speech signals are to be transmitted. Students were asked to consider what would happen if something other than speech (e.g., music) was transmitted over the phone system. They came to the conclusion that if the signal contained frequencies above 4 kHz, aliasing would occur and the resulting distortion might compromise the signal quality. Thus, students realized that their system would need an additional step of processing (pre-filtering) to ensure that aliasing was avoided. In this lab, students first explored what would happen if this pre-filtering operation were not in place. Then, the pre-filtering was put in place and comparisons were made between the two systems.

3. Assessment

In order to evaluate the impact of the new laboratory exercises and the degree to which project objectives were met, assessment activities focused on four primary criteria: conceptual learning, retention and enrollment, student interest, and quality of materials. First, a primary hypothesis of the project is that hands-on laboratory experience will improve students' ***conceptual***

understanding of the course material. This was quantified via conceptual exam questions and student self-assessment. Second, it was also hypothesized that hands-on experience would aid in ***retention and enrollment*** by increasing the probability that students would remain in (or convert to) an ECE major and choose Signal Processing as an area of concentration. Although a longitudinal study is required to collect quantitative data to assess students' choice of major and area of concentration, qualitative data regarding students' intentions can be assessed using a student questionnaire. Third, critical factors in determining whether students choose to pursue ECE or, more specifically, Signal Processing are their ***interest in the material*** and intellectual motivation. We obtained qualitative data via a student questionnaire measuring student perception of the laboratory and its integration within the course and relation to real-world challenges. Finally, we asked students to evaluate the ***appropriateness and clarity of the materials*** developed for each exercise.

In an anonymous survey administered at the conclusion of the laboratory, students were asked to evaluate each exercise in terms of the degree to which the experience complemented and enhanced classroom activities, whether the exercise successfully illustrated a real-world application of course concepts, and the extent to which the laboratory activity improved their conceptual understanding of the course material. Students were also asked to answer several more general questions aimed at gauging the impact of the laboratory experience on their interest in ECE and Signal Processing. Of the 23 students enrolled in the course, a total of 15 responded to the survey. Table 2 presents the student questionnaire along with the percentage of students (N = 15) who Strongly Agreed (SA), Agreed (A), Neither Agreed nor Disagreed (N), Disagreed (D), or Strongly Disagreed (SD) with each statement.

TABLE 2: Student assessment of laboratory activities

Question	**SA**	**A**	**N**	**D**	**SD**
The **REAL-TIME AUDIO EFFECTS** laboratory exercise…					
…incorporated concepts from the lecture.	20	53.3	20	6.7	0
…illustrated real-world applications.	20	80	0	0	0
…increased my understanding of the material.	13.3	53.3	20	13.3	0
The **DTMF** laboratory exercise…					
…incorporated concepts from the lecture.	26.7	60	6.7	6.7	0
…illustrated real-world applications.	46.7	46.7	0	0	6.7
…increased my understanding of the material.	33.3	53.3	6.7	6.7	0
The **VOICE SCRAMBLER/DESCRAMBLER** laboratory exercise…					
…incorporated concepts from the lecture.	40	40	6.7	6.7	6.7
…illustrated real-world applications.	26.7	66.7	6.7	0	0
…increased my understanding of the material.	33.3	40	6.7	20	0
The **SAMPLING & ALIASING** laboratory exercise…					
…incorporated concepts from the lecture.	46.7	53.3	0	0	0
…illustrated real-world applications.	46.7	33.3	6.7	13.3	0
…increased my understanding of the material.	53.3	33.3	0	13.3	0
OVERALL ASSESSMENT					
Overall, the laboratory exercises increased my interest in signal processing.	26.7	53.3	6.7	6.7	6.7
The overall laboratory experience increased my interest in completing the Signal Processing and Communication course sequence.	20	33.3	33.3	6.7	6.7
	Sig. Incr.	**SL.Incr.**	**N**	**Sl.Decr.**	**Sig. Decr.**
As a result of the <u>*laboratory experience*</u>, my interest in EE/ECE as a (first or second) major has:	20	40	33.3	0	6.7

The majority of students consistently Agreed or Strongly Agreed that all four laboratory exercises incorporated concepts from the lecture (73.3, 80, 86.7, and 100%). Thus, the project objective of ensuring coherent integration between lecture and laboratory components of the course was met. This is significant because one of the most common complaints from students regarding their undergraduate experience is that laboratory sections are often seen as irrelevant. If students perceive that the laboratory experience is more relevant to the course, it is likely that they will commit more time and effort to the experience.

All of the exercises were overwhelmingly judged to successfully illustrate real-world applications of the theoretical concepts introduced in the lecture, with students almost unanimously Agreeing or Strongly Agreeing that this goal was achieved (100, 93.4, 93.4, and 80%). As one objective of the project was to motivate the students by providing them the opportunity to apply their knowledge to realistic signal processing problems, this result is also very encouraging.

When queried about the impact of the laboratory exercises on their conceptual understanding, results were more variable across projects and across students. Both the Sampling & Aliasing and the DTMF exercises received very high marks for enhancing the students' understanding of the material (86.6% Strongly Agreed or Agreed). However, fewer students found the Voice Scrambler/Descrambler or the Digital Audio Effects exercises helpful (73.3% and 66.6% Strongly Agreed or Agreed, respectively). As the percentages steadily increased from the first project to the last project, it is possible that the benefit of the earlier projects was muted due to the learning curve associated with using the DSP hardware. Anecdotally, several students commented on the challenges of learning to use the hardware, even going as far as to suggest that debugging the software/hardware sometimes obscured the conceptual learning objective.

Overall, the laboratory experience increased the students' level of interest in the field of signal processing (80% Strongly Agreed or Agreed). Over half of the students surveyed indicated that the laboratory experience increased their interest in pursing a concentration in the field by taking two or more advanced Signal Processing courses in the future (53.3% Strongly Agreed or Agreed). Finally, 60% of the students responding indicated that the laboratory experience Significantly or Slightly Increased their interest in pursuing a first or second major in ECE.

Based on this feedback, the first three primary criteria were met to varying degrees. First, it appears that two of the laboratory exercises enhanced the ***conceptual understanding*** of the material for the majority of the students. The two other exercises, while still improving the understanding of a majority of the students, may need improvement and/or clarification in order to aid a greater portion of the students. ***Retention and enrollment*** seems to be positively correlated with the laboratory experience, based on students' professed intentions regarding their choice of major and area of concentration. A follow up study tracking the actual choices made by the students over the next 2 to 3 years is necessary to quantify this result. The increased level of ***interest*** in Signal Processing, indicated by these same results, can possibly be attributed to the students' perception that the laboratory exercises were well-integrated with the lecture and enhanced their experience by illustrating real-world examples and applications of signal processing concepts.

The assessment of the fourth primary criterion, ***appropriateness and clarity of the materials***, indicates that this is an area that needs improvement. Although a majority of the students (N=23 answered this questions) felt that the laboratory materials were clear and easy to follow and implement (26% strongly agreed; 48% agreed), the qualitative feedback indicated that this is an area that needs improvement. Much of the dissatisfaction stemmed from the Teaching Assistants' inability to answer all questions. This can be attributed both to the Teaching Assistants' inexperience (since the laboratory exercises were also new to them) and the challenges of debugging hardware and software. In addition, many students were frustrated with inconsistent and ambiguous documentation for the software and hardware which led to an often time-consuming debugging process. For a number of students, this process detracted from the learning objective and turned an otherwise interesting project into a chore. Students gave conflicting feedback regarding the clarity of the laboratory instructions, with some indicating the manual was "akin to spoon feeding" and others suggesting "a more precise lab manual".

4. Conclusions and Future Work

The pilot offering of the laboratory demonstrated that it is possible, and indeed beneficial, to integrate a DSP hardware-based laboratory into an introductory signal processing course. Through a careful selection of hardware and software, students with no prior knowledge of signal processing were able to design and implement processing algorithms, focusing on the signal process*ing*, rather than the signal process*or*. This enhanced the students' conceptual understanding because they were able to manipulate system parameters and to make visual and aural observations that reinforced the abstract, mathematical equations presented in lecture.

Based on the success of the pilot offering of the laboratory in the Fall of 2005, future offerings of *Signals and Systems* will incorporate the existing laboratory exercises. In addition to refining these exercises, new experiments will be developed and the hands-on component will be expanded. Assessment activities will be extended by using pre- and post-laboratory concept quizzes to better quantify the impact of the laboratory activities on students' understanding. Also, choice of major and course selection will be tracked to provide quantitative data to support or refute the qualitative conclusion: that the laboratory experience motivated students to pursue ECE, generally, and Signal Processing, specifically.

Based on the assessment results, the project successfully addressed the goals of improving students' understanding of the material and increasing interest in the subject area and ECE as a major. Students perceived that the laboratory was an important part of the learning experience and was well-integrated with classroom activities. Despite these successes, there are aspects that need improvement such as providing better-trained Teaching Assistants, improving the reliability of the hardware, and clarifying some of the laboratory instructions. These issues will be addressed as the laboratory is further developed.

Acknowledgments

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