Integration of DSP Theory, Experiments, and Design: Report of a 7-Year Experience with an Undergraduate Course

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1. Summary

The senior technical-elective digital signal processing (DSP) course and lab at Cal Poly State University has become popular among electrical and computer engineering students. The goal of the courses is to teach digital signal processing for applications. Therefore, emphasis is placed on teaching and learning DSP through real-time, real-world examples. The approach is to “learn DSP by doing,” with synthesis and design as the main vehicle.

The course integrates classical DSP theory, structured experiments, and design projects. It requires prior knowledge of continuous and discrete-time signals and systems analysis, and familiarity with concepts and techniques such as linear time-invariant systems, convolution, correlation, and Fourier transforms. The course runs for a quarter of the academic year and includes three hours of lecture presentations, eight experiments and a design project. In all of the above activities, students work together in groups of two or three. Each experiment includes pre-lab, design, implementation, testing and evaluation of DSP algorithms and their application. Each design project requires effort equivalent to the completion of three or four regular experiments.

The laboratory uses Texas Instruments' DSP boards and software development tools and industry-standard computation engines, simulation, data analysis and display packages such as DADiSP and Matlab. The laboratory is also used in conjunction with four graduate courses in DSP and image processing, individual studies, senior projects, Master’s theses, and DSP research. The development of the course and the lab was supported by NSF/ILI grants, as well as by Cal Poly and donations from industry.

It is believed that the results of our successful experience during the last seven years at Cal Poly could be valuable to other engineering educational institutions interested in offering DSP activities. The present paper describes the course coverage, the experiment, and examples of student projects. The aim is to disseminate the results achieved at Cal Poly and to present a roadmap for similar activities elsewhere.

2. Background

In 1991-92 a learning environment for an application-oriented, advanced undergraduate course and design activities in digital signal processing was developed at Cal Poly with support from NSF, Cal Poly and donations from Texas Instruments, IBM, Sun Microsystems and Digital Equipment Corporation . Since the Spring of 1994, an undergraduate DSP course (including laboratory and project components) has been offered by the EE department regularly in the spring quarters as a technical elective. The course has been well received and has always been impacted with an average class size of 35. Since the1997-98 academic year, the course has been offered twice: in the winter and spring quarters. With additional support provided by an NSF/ILI grant and donations from industry, the DSP laboratory was recently renovated and expanded. All PC workstations in the laboratory have been upgraded and additional platforms dedicated to image processing are added. Our previous experience in developing the DSP platforms was greatly helpful in the recent expansion. In addition to serving the undergraduate DSP course (which is the topic of the present paper) the laboratory also supports other activities in digital signal processing such as senior projects, individual studies, Master's theses and research. A previous report presented at the 1998 ASEE conference [1] describes the objectives of the course, students' background, laboratory facilities and a summary example of the experiments. An updated summary is given below.

Prior to taking the DSP course, students have taken a course in discrete-time signals and systems and are familiar with concepts and techniques such as linear time-invariant systems, convolution, correlation, and Fourier transforms. They have had a course in the C language for computer programming. Most of them are comfortable with, some of them being very proficient in, using windows-based PC workstations and software packages for computation and graphics. A few have developed Windows applications. The lab has a network of six Vectra-Xu PCs from Hewlett-Packard which serve experiments and developments in off-line signal and image processing. These are equipped with software packages that are used for computation, explorations, simulations, data display and design. The lab also has a second set of six PC-based DSP workstations running under Windows 98 and equipped with Texas Instruments' TMS320 C30 EVM boards for real-time operations. They also accommodate many of the Texas Instruments' DSP starter kits through parallel and serial ports. Presently, the EVM boards constitute the main workhorse for real-time DSP experiments and applications. The starter kits are available to students for implementing their projects. Two powerful new additions to the family of hardware platforms are Texas Instrument's EVM TMS320 6000 and Pentium-based PCs with real-time DSP capabilities. These are used by students for development and implementation of their projects.

3. Pedagogical and Technical Considerations

The course has two sets of objectives. One is pedagogical, the other technical. On the pedagogical side, the course requires interaction, sharing of results, cooperation, competition and division of labor among students. These objectives are considered to be important not only for achieving the technical objectives but also in preparing the graduating engineer for a productive and satisfying professional career. Organizing students in groups of two or three is necessary, but by itself is not sufficient to achieve some of the above objectives. The strategy is to suggest and assign group activities that illustrate the need and benefits of interaction, sharing of experiences and cooperation.

On the technical side, digital signal processing is like the elephant. From a mathematical and computational point of view, the core of DSP is transformation of sequences of numbers to other sequences. From the engineers' point of view, the heart and the soul of DSP is its applications in communication, control, pattern recognition, instrumentation, speech, video, data transmission and so on. The DSP course at Cal Poly has three main components: theory, experiments, and design. DSP theory and discrete mathematics are not the goals of the course. They are used as tools for real-life applications. Interfacing with the real-time world of analog signals and systems is, therefore, emphasized. This places emphasis on the role of laboratory experiments and design projects. The strategy is to integrate the above three components, linking theory with application. If done successfully, the integration would present students with a comprehensive and unified picture of DSP. The interrelation between hardware and software is another technical aspect of the course, described in the succeeding sections.

4. DSP Theory

The theory and algorithms of DSP have been available for at least thirty years. It is the development and wide availability of VLSI chips for data acquisition and processing which have generated a tremendous expansion in the DSP field. Because of this, when it comes to designing and developing DSP tools and learning digital signal processing, the theory, hardware, software, and applications become strongly interrelated. Lectures are the main vehicle for discussing the theoretical component of the course. Because Cal Poly students have already taken a course in discrete-time signals and systems, the theoretical component of the DSP course emphasizes DTFT, DFT, digital filter design, optimization, and signal detection . The textbook is *Digital Signal Processing*, by Proakis and Manolakis, 3rd edition. Lecture notes are also made available by the instructor, when needed. A reference book is *Discrete-Time Signal Processing* by Oppenheim and Schafer.

The theory component includes simulation and problem solving using computational engines and data display software such as DADiSP, Matlab, Mathcad, and Maple. Real data such as speech, music and sound is used for this purpose. Students are encouraged to set up their own DSP platform at home and search the web for DSP tools and software packages and to study, examine and evaluate them. They are also encouraged to explore DSP capabilities of general purpose tools such as standard computer cards, simulation software packages and operating systems. This helps students bridge the gulf between potentials of DSP theory and their realization. It also makes theory less formidable. The seemingly dull mathematics may become the source of an interesting, and sometimes dazzling, experience without losing its rigor and accuracy.

5. Experiments

The laboratory manual is developed in-house. The latest laboratory manual, being revised for Spring 1999, contains 15 structured experiments. It includes brief outlines of theory from a practical point of view even when the subject of the experiment appears to be basic, fundamental, and theoretical. The following are examples of experiments included in the manual: Fourier analysis, Sampling, Analyzing voice and speech, Synthesizing sound, Real-time DSP, Correlation detection, Windowing, Notch filters, Lowpass FIR filter design by windowing, FIR filter design and real-time operation, IIR filter design and real-time operation.

Most of the experiments require the use of the TMS320 EVM DSP board. The DSP code for the board may be written in assembly, but is generally written in. It is then converted to machine code using the DSP chip C-compiler and assembler on the PC. The final code is then loaded onto the chip and run by it. Texas Instruments' user guides for DSP chips and boards, reference manuals for software development tools and application books are available in the lab. Examples of C source code are available in the optional reference book *Digital Signal Processing with C and the TMS320C30* by Rulph Chassaing . EVM and starter kits are used for several reasons. Initially, they were the only affordable individual platforms available for real-time DSP. The other reason was meeting one main objective of the course: to emphasize the design and utilization of hardware and software capable of doing real-time DSP.

Integration of theory, experimentation and synthesis is illustrated in the subject of sampling, which includes: i) sampling, by a strobe light, the rotational motion of a disk mounted on the axis of a fan, ii) simulation of the motion of the disk and observations on a PC, iii) using the EVM board on-line with the input coming from the function generator and the output displayed on the scope or heard through a speaker, iv) down converting high frequency signals in real-time using the EVM board (a 250 mV (rms) sine wave at 1700 Hz sampled at the rate of 1920 Hz, with the A/D and D/A low-pass filters set at 1512 Hz and the A/D high-pass filter set at 36 Hz generates a 200 Hz output sine wave which can be heard through a speaker), and v) observations on aliasing and frequency down-shifting on display devices such as a digital oscilloscope in real time and a data display software package. Students are then asked to synthesize similar experiences and design additional components for the experiment. This experiment is described in more detail in [1].

6. Design Projects

Synthesis and design are important vehicles for learning and the project provides such a vehicle in the DSP course. It is a required part of the course. Each group has its own project. The effort and time that is required to complete a project is comparable to three or four experiments. The ideas for projects come from students and are to be approved by the instructor. Projects are expected to provide students with a comprehensive experience. In terms of their complexity, novelty, challenge and relation to real-world applications, they vary. Some are done minimally to satisfy the requirement at the passing level. Some are innovative and sophisticated, indicating students' facility with the hardware, programming and advanced use of computers. Selected categories of projects done at Cal Poly's DSP Lab, including senior projects in this field are listed below.

i. Design and manufacture of DSP boards and systems (7).
ii. Applications in communication (16).
iii. Applications in control (5).
iv. Applications in image processing (4).
v. FIR, IIR and adaptive filters (many).
vi. Signal detection (5).
vii. Touch-tone dialing (6).
viii. Noise reduction (3).
ix. Linear predictive coding (4).
x. Speech and music, analysis and synthesis (6).

7. Discussion and Conclusions

Mathematics and the physical world may be linked together through an undergraduate course in digital signal processing, producing expertise that is currently much in demand by the industry. The course needs to keep up with the rapid developments in hardware and software tools. This requires frequent maintenance and upgrading of the lab and the course. It also requires the faculty to keep up with the new tools and techniques, not just in DSP hardware and software, but also in computers and interfacing with them. Students' familiarity with high-tech tools and computers makes it possible for them to explore and implement challenging DSP projects.

In planning and developing the DSP Laboratory at Cal Poly, we have learned how to spread and stretch our limited financial resources for optimum integration and maximum payoff. We believe that the results of the current Cal Poly project can be transplanted to other undergraduate engineering educational institutions with similar objectives and circumstances.

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