An undergraduate research mentoring model in digital signal and image processing

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Abstract This work presents a research-mentoring framework to train undergraduate students in a hands-on setting in the area of digital signal and image processing (DSIP). It is intended to encourage undergraduate students to pursue research and to add to their knowledge in information technology and enhance their active-learning and problem-solving skills.

Keywords digital signal/image processing; undergraduate research

Recent advances in information technology are allowing more applications for digital signal and image processing (DSIP) to be added to the list. These applications include entertainment industry (video on demand and video games), medical (tele-medicine, medical instruments and different modalities of medical imaging), security and surveillance systems (object/face recognition and activity recognition), military applications (target recognition and/or detection), Communications (wireless and multimedia communications), and different industries (quality control, robot vision, intelligent transportation systems and vehicles, and nondestructive testing). These examples and many others involve digital information processing, compression, storage, visualization, analysis, and transport.

With the continued advancements in hardware, software, and the Internet, and with the rapid developments of information technology, the need for people with experience and research abilities in DSIP will grow exponentially. Furthermore, the competition around the globe is at its highest for advancements in DSIP applications. For example, digital signal processors (DSP) are the most rapidly expanding sector of the semiconductor market at a 30% annual growth rate since 1990. Since many industries have been making increasing demands for engineers with training in DSIP, educators must make available the necessary skills and opportunities to their students by expanding DSIP training.[1] This training may include offering advanced DSIP courses and/or offering research experiences to undergraduate students. These offerings should be designed with the aim of encouraging undergraduate students to pursue advanced degrees and research careers. It also should aim to teach undergraduate students research through their senior level classes.

Recognizing the importance and intellectual challenges of this field, academic classes were initially taught at the graduate level and have more recently become core undergraduate classes for electrical and computer engineering programmes.[2] The concepts, theory, and basic algorithms of digital signal and image processing have been established and applied for over thirty years.[1] Typically, two approaches have been implemented in teaching these concepts to undergraduate students. It is accomplished through either classroom lectures and homework assignments, or a set of hands-on experiments with heavy reliance on programming. The model presented in this paper is different from both approaches because it is structured on research projects that accomplish the students' learning of DSIP in real time while engaged in a meaningful research experience that demonstrates the different stages of the research process. Consequently, motivating students to pursue graduate degrees, research careers, or advanced industry work in the DSIP area.

Furthermore, the project-based learning experience is different from the senior design experience in many aspects. Senior design is a capstone experience that reinforces all the concepts covered in the curriculum using a comprehensive design project. No discovery is involved. On the other hand, DSIP research projects involve new discoveries and concepts not typically covered in courses/curriculum. It involves working on problems/issues that have not been solved typically and it involves reading journal and conference research papers. In a senior design course, teams are mandatory, while in this research model individuality is expected. This allows for individual initiative and creativity. It also prevents the typical situation where team members did not work on the project equally. Additionally, students are required to take the senior design, while they elect to take the model discussed in this paper. The students favour the idea that they are different from their classmates and that they can elect to take advantage of work that is challenging. They all strived to produce scholarly work that could be published. Indeed, this issue appeared to motivate the students.

The digital signal and image processing curriculum at Western Michigan University (WMU) has been developed with strong emphasis on the theoretical and simulation aspects of signal processing. At the undergraduate level, it comprises a series of courses that provide a cohesive plan of study beginning with linear systems and random processes in the junior year followed by digital signal processing and digital communications in the senior year.[3] For students with further interest in DSIP, independent study or faculty-directed research opportunities are available through both a project-based course ECE 490 and senior design capstone projects ECE 481/ECE 482 sequence. The project-based senior level course as well as a National Science Foundation (NSF) Research Experiences for Undergraduate (REU) supplemental grant has been utilized to develop the framework for the research-mentoring model discussed in this paper. Teaching students research turned out to be a challenging task, particularly as undergraduate students do not typically choose to conduct research. In other words, undergraduate students are used to being provided with information rather than seeking it.

This paper focuses on research mentoring in the DSIP area at the undergraduate level. The following section presents the objectives of teaching undergraduates DSIP research. Software and hardware systems used by the young investigators are then presented. The next section describes the research process used to train undergraduate students along with a sample list of research projects and their learning objectives. Students' evaluations and an assessment of the experience are presented in the fifth section, and conclusions are provided in the final section.

Objectives of the research mentoring model

A key factor in motivating students to pursue advanced degrees and research careers in science and engineering is to expose them to a meaningful research experience at the undergraduate level. One of the recommendations of the NSF Curricular Developments in the Analytical Science Workshop was 'more students be offered hands-on learning opportunities'.[4,5] To achieve this, the workshop suggested providing undergraduate research opportunities with faculty as a means for developing familiarity and comfort with the scientific method and analytical process, and as a means for building skills in problem solving and critical thinking. Therefore, the objectives of the WMU's DSIP research mentoring model described in this paper are to:

- create an interest in research as early as possible through active involvement in a research project and through interactions with graduate students and faculty;
- provide undergraduate students with opportunities to conduct independent DSIP research projects, to learn the research process, and to become familiar with the scientific method in problem solving;
- emphasize the importance of graduate education and research by introducing the students to the world of research through the scholarly work that they are learning and/or by introducing them to the opportunities that they can contribute through publications; and
- provide the students with hands-on training in DSIP in real-life applications.

DSIP research environment

The DSIP research laboratory consists of PC-based workstations equipped with specialized DSIP hardware and software. Three different types of workstations are available in the laboratory. The first type includes real-time signal processing workstations (DSP) that are equipped with TI TMS320C6701 Evaluation Module (EVM) boards, as shown in Fig. 1. The EVM board is supported by the Code Composer Studio (CCS) package developed by Texas Instruments specifically for their processors and evaluation boards.[6] CCS enables students to develop programs in C within a user supportive framework. The students use real signals and they can see and hear the results in real time.

The second type includes real-time image processing workstations equipped with TI TMS320C6711 processors and capture/display daughter-boards with composite video input (NTSC or PAL), as shown in Fig. 2. Also, this type of workstation has an RGB monitor output (565 VGA or SVGA) for display of real-time processing results. The camera is NTSC/PAL compatible. Students use this type of workstation for real-time image processing projects.

The third type includes workstations equipped with several software packages to support research in the DSIP area, such as MATLAB, with a collection of tool kits that are suitable for DSIP algorithms. MATLAB has been increasingly used in the undergraduate curriculum at WMU, and thus it was a natural choice for the simula-

Fig. 1 *Real-time signal processing workstation.*

tion environment for these projects. Other software packages that are also available include digital filter design packages such as DSPWorks and QEDesign. DSPWorks is a signal processing package that provides an extensive library of digital signal processing (DSP) algorithms and functions for signal generation and capture. QEDesign is a filter design and simulation package, and it provides time domain processing, convolution, and correlation. Both packages have been used for learning practical aspect of DSP algorithms.

DSIP research mentoring model

Undergraduate students at WMU are introduced to research in DSIP in a non-traditional teaching approach. Students elect to register for a problem-based senior elective course, ECE490: Independent Research and Development. The syllabus for ECE 490 is shown in Fig. 3. An undergraduate research project for ECE 490 is typically designed to span one or two semesters. The programme is comprised of research projects that achieve certain objectives and have research outcomes represented by technical reports and professional articles in journals and conferences. The syllabus is designed with great flexibility to suit different student abilities and backgrounds. This flexibility is based on several factors, with the following meant to serve as examples only:

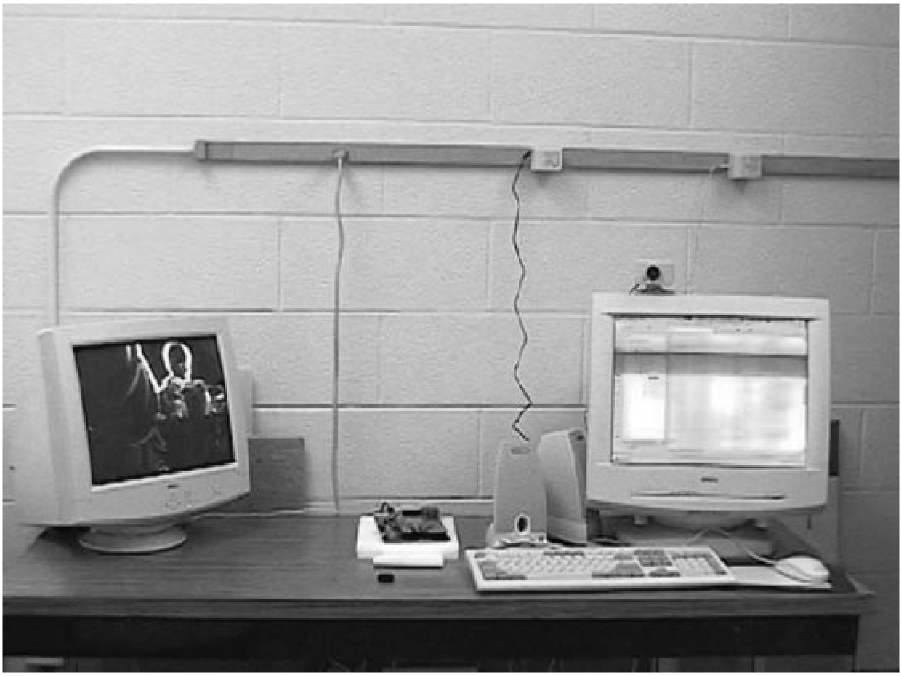

Fig. 2 *Real-time image processing workstation.*

- The student can choose the topic to be in the signal processing or in the image processing area.
- The student can choose the programming environment that he is comfortable with. Some students choose to work with C, MATLAB, MATHEMATICA, and assembly language. Currently, one student has chosen to work on an image processing problem using the Texas Instruments 6711 and MATLAB where he is using the MATLAB linker to the code composer.
- The student has the flexibility of choosing the research topic closest to her/his interests and knowledge. For example, some students prefer to work on transforms such as Fourier transform, a topic that is well known to them, as opposed to other students who choose to work on wavelets, a topic that is new to them.
- The student has flexibility with the timetable of progress, within certain limits, as opposed to submitting homework assignments weekly and predetermined exam dates as in the classical course structure. The students were responsible for meeting with their mentor for questions and to report on their progress but they were not penalized if they had a week with nothing to report due to other commitments. At times, they worked on their projects at nights, weekends, and/or holidays.

ECE490
Projects in Digital Signal and Image Processing (DSIP)

Objectives:
You will be assigned a topic in DSIP. You are to learn a DSIP algorithm that has certain applications and some problem solving capabilities. Objectives of this research experience include:

- Creating an interest in DSIP research through active involvement in a DSIP research project,
- Providing opportunities to conduct independent DSIP research projects and to learn the research process, and
- Emphasizing the importance of graduate education and research by interacting with graduate students and faculty mentors.

Outcomes:

- You will write a technical report on your assigned topic.
- You will also develop a software simulation for your assigned algorithm.
- Depending on the project and the results, professional articles may also be developed with you as a co-author.

Readings Guidelines:

- Reading materials should include textbooks, technical papers (journals and conference proceedings), and reports. These are available in my library and at the main University library.
- Start with a general reading in the area of signal or image processing, depending on your project, to get an understanding of the type of data and signals that you will work with. I will assign this reading to you.

Report Guidelines:

- You must write a technical report using professional formats (see me for format).
- Provide a detailed description of the signal/image topic that is assigned to you and the recent advances in that area.
- Provide full details of your assigned algorithm (usage, advantages and disadvantages).
- List all references you looked at. You are expected to write your own understanding of the topic (DO NOT COPY). You can always quote from references. Also, reference citations need to be listed next to text in the report whenever possible.
- Write your comments and discussion of the results, and state your conclusions

Software and Hardware Simulations Guidelines:

- Go through the tutorials provided by Texas Instruments for their processor and by MATLAB.
- Write your code using C or MATLAB. However, you may also use any language or software package available in the laboratory.
- Test your algorithm with sufficient data (signals or images) and comment on the results (advantages and/or limitations of your algorithm).
- Hardware implementation will be assigned based on the student and the nature of the assigned algorithm.

Fig. 3 *Syllabus for the research mentoring course at WMU.*

Initially, the students are given a background in DSIP through reading assignments, small experiments/simulation exercises, and through discussion meetings with the mentor. Then, each student is given one or two references relevant to his/her project and they are encouraged to continue with the literature search as necessary. At this point students are eager to start working on real images or signals and report the results. Students are directed to obtain other references and to consult with all legal sources that may aid in their project and/or troubleshooting. Some students need more time to train themselves on the software and/or hardware. Since project difficulty and expectations are high, enrollment in the class is restricted by grade point average.

Sample research projects

The following list provides descriptions of some of the ongoing or recently completed research projects undertaken by undergraduate students at WMU.

- ***Image analysis for crack detection in bridges:*** Bridge monitoring and maintenance is an expensive yet essential task in maintaining a safe nationwide infrastructure. Traditional monitoring methods use visual inspection of bridges on a regular basis. This often requires inspectors to travel to the bridge of concern and determine the deterioration level of the bridge. The automation of this process could result in great monetary savings and a safer infrastructure. One aspect of this automation is the detection of cracks and deterioration of the bridge. This project is a comparison of the effectiveness of the fast Haar transform (FHT) to several traditional edge-detection techniques in identifying cracks in concrete bridge images. The algorithms were implemented in MATLAB and simulated using a sample of 50 bridge images (25 with cracks and 25 without) taken from concrete bridges in the Kalamazoo, Michigan area. The results show that the FHT was significantly more reliable than the fast Fourier transform, Sobel, and Canny edge-detection techniques in identifying cracks.
- ***Voice recognition using MATLAB:*** Automatic speech recognition (ASR) is an extremely important research topic with numerous applications. In this project, a brief background on the many ASR applications and algorithms is prepared. Then, a detailed description of vector quantization with the utilization of mel-frequency cepstrum coefficients is presented. A code using MATLAB simulation of a speaker verification system based on mel-frequency cepstrum coefficients is developed. Also, a set of simulations is developed using real signals with different signal-to-noise ratio (SNR). Finally, a discussion of the results and conclusions are provided.
- ***Real-time edge detection using wavelets:*** Edge detection is a cornerstone in any computer, robotic or machine vision system. The edge image contains critical information about the scene. In this project a real-time edge detection algorithm in grayscale images is developed. The algorithm will be implemented in real time using the TI TMS320C6711 DSP processor. The hardware also includes a daughter board for communication between the main DSP processor and the video camera. The algorithm, which is based on the Haar Wavelet, divides the image frame into low and high frequency components in a multi-level decomposition and displays the image edges corresponding to the high frequency coefficients in real time. The multi-level decomposition improves the results obtained from noisy images. Wavelets-based algorithms are taking the place of traditional algorithms, especially the Haar wavelet because of its simplicity. Results show that execution time is low while edge results are accurate, thus presenting a suitable algorithm for on-line vision systems such as industrial assembly lines,

surveillance systems (intruder detection), and on-line hand-written document reading.

- **Mammogram compression and transmission via Internet2:** Medical images are different from all other types of information because of the huge amount of data that needs to be processed in a short time for each examination. Technology developments in communications and transmission allow the dream of telemedicine and remote surgery to become a reality. Internet2 is the infrastructure for which applications and services are being designed by researchers. Medical applications mandate rapid and accurate access to national health and medical databases and to expert discussion groups for special medical cases. Investigate and understand the performance of existing compression algorithms, including JPEG2000, and transmission over Internet2 for mammograms. Use these results to develop data sets of the compression rates, bandwidth requirements, transmission speed, and most importantly, the accuracy of the received and reconstructed mammograms.

Learning objectives and outcomes

The projects were designed in two tracks. One introduces student to advanced concepts in DSP that are beyond the topics covered in the undergraduate curriculum. The second track deals with introducing students to the basics of digital image processing concepts and techniques, since such a course is not formally offered at WMU. In both tracks, learning research in DSIP is the main objective. Having the students work in real time and/or with real signals helps them better understand the theory.[3,7,8] Also, having the students read about recent advances in the DSIP area from conferences and journal papers allows them to gain experience that is beyond the typical classroom setting. Below is a summary of the specific learning objectives from the different research projects that have been taken by the participants in this programme.

- Learn the research process (literature search, experiment setup, data collection, data analysis, ups and downs of the research process, presentation of results in a report/paper and orally).
- Learn the difference between theory (as in a classroom setting) and practice (as in real-time implementation of algorithms).
- Learn independence in acquiring knowledge, in thinking, and in drawing conclusions.
- Learn digital signal/image processing (image analysis, compression, digital filters, speech processing).
- Learn advanced topics in digital signal/image processing.
- Learn how to use MATLAB and other software packages in real applications and signals.
- Learn how to use DSP boards and other peripherals to process signals and images in real time.

The participants in this research-mentoring model were required, at minimum, to present their results in technical reports and professional presentations. However, some technical reports were then modified and published in conference proceedings and/or refereed journals. A sample of publications that resulted from this research framework work is listed in the references section[9–19] where the young researchers names are identified by *.

Evaluation and assessment

An assessment of the DSIP research experiences was accomplished by a questionnaire, shown in Fig. 4, and completed at or near the conclusion of each project. Table 1 summarizes the responses to the questionnaire shown in Fig. 4. The students are all in agreement that learning real-time DSIP is very important to their careers. Further supporting this impression, many of the students have been interviewed by industry for permanent or internship opportunities specifically because of their hands-on experience with DSP processors. All participants agreed on the fact that teaching them DSIP topics using a project-based approach forces them to tie the theory to the real world by solving an actual problem using real data. Also, teaching DSIP in this manner has given the students an opportunity for creativity (80% agree).

Evaluation of Digital Signal and Image Processing DSIP Research Experiences

SA = Strongly Agree; A = Agree; N = Neutral; D = Disagree; SD = Strongly Disagree

1. The project provided me with a better understanding of DSIP concepts learned in theory.
   SA A N D SD

2. The project gave me the opportunity to demonstrate individual initiative and creativity.
   SA A N D SD

3. The project was clearly outlined and objectives are well explained.
   SA A N D SD

4. I believe that this research experience is very valuable to my professional future.
   SA A N D SD

5. Handouts and reading assignments were useful and informative.
   SA A N D SD

6. I recommend this experience to other students.
   SA A N D SD

Fig. 4 *Research experience evaluation form.*

TABLE 1 *Results of DSIP research experiences*

Question	% Agree (SA and A)	% Neutral	% Disagree (D and SD)
1. The project provided me with a better understanding of DSIP concepts learned in theory.	100	0	0
2. The project gave me the opportunity to demonstrate individual initiative and creativity.	80	20	0
3. The project was clearly outlined and objectives are well explained.	65	15	20
4. I believe that this research experience is very valuable to my professional future.	95	5	0
5. Handouts and reading assignments were useful and informative.	80	20	0
6. I recommend this experience to other students.	95	5	0

In one case, a successful ending of the project was not achieved, while in another, the project was not defined well for the student. However, all research projects were completed or 90% completed. Students learned that not every research project concludes as anticipated. They found that research is challenging and, at times, frustrating. Nevertheless, they spent many hours in the laboratory working hard on their projects. Moreover, students found themselves in an active learning environment and at times felt that they did not properly understand the theory until they had the opportunity to apply it (80% agree). As an overall assessment, the students enjoyed the research experience and valued the skills they acquired.

During the various DSIP research projects, students are exposed to and learn about fundamental differences between real-time and non-real-time signal/image processing. While software applications typically encountered by the students are executed and controlled by operating systems using a structured, predictable order and methodology, real-time processing requires the use of interrupts based on seemingly random events. The TI EVM combined with CCS provides a simple framework for teaching these differences and supports the development of real-time DSIP algorithms by the students.

Ultimately, students learned that the DSIP field is an ongoing and very dynamic research area and that a graduate must be involved in research and continuing education to keep up-to-date with the rapid developments in this field.

Students, in an informal way, commented on their interest in publishing as they were aiming to have their resumes stand out among the crowd. This was very clear with those students interested in graduate education.

For the mentor, mentoring undergraduates in DSIP research is a very time consuming process. Forcing the students to learn the principles on their own rather than directly answering their questions has been at times challenging to the mentor. The mentor found that most students would look for a quick answer more often than thinking and/or searching for an answer. It was much harder to direct students toward the right answer with hints and tips rather than spoonfeed it to them. The objective here is to make the students become active learners, involved in the learning and problem-solving process and not just executers of instructions. Active learning kept the students interested and enthusiastic about their projects. Moreover, it is a time consuming process for the mentor because of student demands to meet individually in addition to group meetings. Also, while all students take an undergraduate course in digital signal processing, they do not have any knowledge of image processing, thus adding more time and complexity to image processing projects. Projects need to be carefully selected to be appropriate to the student's level and background.

Concluding remarks

This paper has described the structure of a research-mentoring model in digital signal and image processing (DSIP) at Western Michigan University. The goals of this mentoring experience are to create an interest in DSIP research among electrical and computer engineering undergraduate students and to encourage them to pursue graduate studies and research careers in DSIP. Students who are interested in working in industry also found the experience invaluable because of the strong ties between DSIP and the state of the art in information technology.

This paper presented the framework used in mentoring undergraduate students in DSIP research using a research project-based approach. The students learn how to independently conduct research, how to find out what is the problem, and how to find a solution. Moreover, the students acquire excellent active learning skills, learn the science of DSIP, and learn the difference between software simulations and real-time processing. They also learn about the research process with its opportunities, challenges, joys, and disappointments. Learning digital signal and image processing with hands-on experiences reinforces the theoretical concepts and provides a better understanding of the mathematical basis on which the algorithms and systems are based. Combining the hands-on experiences with research-based learning as in this mentoring framework makes this experience invaluable to the students.

More of these research-mentoring programmes are needed to increase the number of individuals seeking graduate studies and research careers. This is particularly true in DSIP, where the number of individuals being trained in this field does not meet the demand. The DSIP undergraduate research mentoring model at Western Michigan University has been very successful and is a timely contribution to the many efforts aimed at providing students with excellent training to meet the demands of this field.

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