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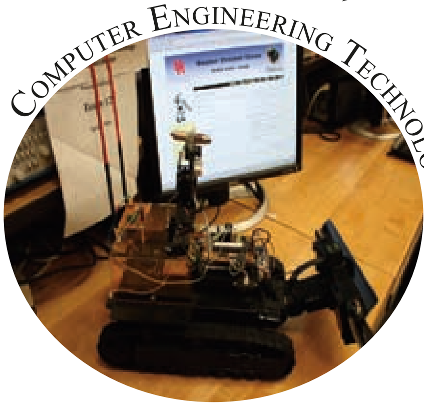

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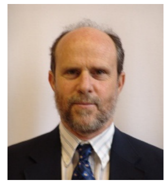

Philip Weinsier, IJME Manuscript Editor

IAJC Journals

Due to the overwhelming success of the International Association of Journals and Conferences' flagship journal—IJME—over the last nine years, IAJC launched its second journal, IJERI, in 2009. After only two printings, the International Journal of Engineering Research and Innovation already seems to be as popular as IJME. Combining the power and potential of these two journals with the diversity of the 14 partner journals is making IAJC and the IJME biennial international conference a magnet for some of the best research studies anywhere. Please look through our extensive web site (www.iajc.org) for information on conferences, chapters, membership and benefits, journals and more.

Current Issue

After an exhaustive review process—with a final acceptance rate of 25%—nine outstanding papers were accepted for publication in this issue of IJME. Both IJME and IJERI are available online (www.ijme.us & www.ijeri.org) and in print. We hope that you enjoy this issue and continue to support these journals, IAJC, and the biennial IJME conference.

IAJC, the parent organization of IJME and IJERI, is a first-of-its-kind, pioneering organization acting as a global, multilayered umbrella consortium of academic journals, conferences, organizations, and individuals committed to advancing excellence in all aspects of education related to engineering and technology.

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IJME is steered by IAJC's distinguished board of directors and is supported by an international review board consisting of prominent individuals representing many well-known universities, colleges, and corporations in the United States and abroad.

To maintain this high-quality journal, manuscripts that appear in the *Articles* section have been subjected to a rigorous review process. This includes blind reviews by three or more members of the international editorial review board—with expertise in a directly related field—followed by a detailed review by the journal editors.

2010 IJME International Conference

The third biennial IJME conference is scheduled for the fall of 2010. However, drawing on the success of the last IJME conference that was a joint venture with the National Association of Industrial Technology (now the Association of Technology, Management, and Applied Engineering), the next conference may again be offered jointly with another organization. Please watch for upcoming details in the spring issue of IJME and on the IJME web site.

The conference generally has three divisions: Engineering, Engineering Technology, and Industrial Technology. Presentation papers selected from the conference are considered for publication in one of the IAJC journals or member journals. Oftentimes, these papers, along with manuscripts submitted at-large, are reviewed and published in less than half the time of other journals.

Editorial Review Board Members

If you are interested in becoming a member of the IJME editorial review board, go to the IJME web site (Submissions page) and send me—Philip Weinsier, Manuscript Editor—an email. Contact me also if you are interested in joining the conference committee.

Acknowledgment

Listed here are the members of the editorial board, who devoted countless hours to the review of the many manuscripts that were submitted for publication. More than a simple thumbs-up or thumbs-down response, manuscript reviews require insight into the content, technical expertise related to the subject matter, and a professional background in statistical tools and measures. Furthermore, revised manuscripts typically are returned to the same reviewers for a second review, as they already have an intimate knowledge of the work. So I would like to take this opportunity to thank all of the members of the review board. Happy holidays and I look forward to working with you again in the New Year.

MULTIDISCIPLINARY ROBOTICS EXPERIMENT: LEGO MINDSTORMS NXT BLUETOOTH CONVOY

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Abstract

This work describes an innovative laboratory experiment designed for an introductory mechatronics course employing discovery-based learning. Robotic vehicles are constructed using new LEGO Mindstorms NXT sets. One of the moving robots is equipped with sensors and programmed to follow a prescribed path on an enlarged city map. The other robots have no sensors and are programmed to follow the first robot. Programming of the robots is accomplished using the LEGO Mindstorms NXT educational software and the National Instruments LabVIEW Toolkit for LEGO Mindstorms NXT. The inter-robot communication necessary for the robots that are programmed to follow uses Bluetooth wireless technology.

Introduction

LEGO Mindstorms NXT Bluetooth Convoy is a six-hour engineering design experiment implemented as a part of an introductory mechatronics course. Its major function is to promote discovery-based active learning and knowledge systematization. Robot building is a powerful motivational tool for students [1]. This experiment builds on segments of the Defense Advanced Research Project Agency's (DARPA) Urban Challenge held in 2007, an autonomous vehicle challenge to complete 60 miles in traffic in less than six hours, with a prize of $2 million [2]. Mimicking and adding new features to this actual multimillion-dollar robotic prize competition further enhances student motivation. A set of new tools like the LEGO Mindstorms Education Base Set with NXT technology (made available in August 2006) and the National Instruments LabVIEW Toolkit for LEGO Mindstorms NXT (made available for downloads in mid-December 2006) are implemented in this novel engineering design experiment. Built-in Bluetooth technology is used for robot-to-robot communication and control.

Previous Work and Justification

The LEGO Mindstorms NXT Bluetooth Convoy experiment is a part of the pedagogical system implemented in the Introduction to Mechatronics course and the Mechatronics curriculum. This pedagogical system is based on McCarthy's [3] version of the Kolb [4] learning cycle and was motivated in part by work presented by Harb et al. [5]. According to Kolb and McCarthy, one can learn new concepts by following a pattern (the learning cycle) exemplified by the questions why, what, how, and what if. A set of activities is associated with each part of the learning cycle. Active discovery-based learning is considered an important part of this learning cycle, particularly in the field of engineering [6]. Bruner [7] defines discovery learning as a cognitive instructional model whereby students are empowered and encouraged to learn concepts and principles through active hypothesis testing and discovery. He states, "The student will have to explore examples and from them 'discover' the principles or concepts which are to be learned [7]."

Engineering laboratory courses also use active learning. Depending on the course objectives, the laboratory experiments are either of a cookbook type (where students follow a set of instructions and all produce similar results), an organized project type (where the instructions are not precise and allow for some creativity), an open-ended project type (where the course instructor has a reasonable knowledge of the final outcome), or research (where neither the students nor the instructor know the final outcome of the experiments). Often, open-ended projects are used as powerful pedagogical tools to implement discovery-based learning. By using low-cost plastic parts and enforcing reusability of parts to minimize the time to build prototypes as well as the cost of such projects, many instructors adopted LEGO bricks and LEGO computerized systems as educational tools. There are hundreds of papers describing the use of LEGO bricks in engineering research [8]. Many papers use LEGO Mindstorms RCX with the Robolab programming environment (RIS 2.0) based on National Instruments LabVIEW software for various projects and courses such as robot competitions [9], [10], programming [11], [12], and project-based learning [13 - 19]. The literature reviewed shows positive results, such as an increase in students' enthusiasm towards engineering, perceptual and actual knowledge of their field of study, and development of design and team skills. However, some evaluators of LEGO Mindstorms RCX found it to be restrictive for more advanced projects in both hardware and software. A number of third-party solutions were proposed to increase its flexibility [12], [20].

LEGO's response to a need for an improved microcontroller system is addressed in their new LEGO Mindstorms NXT product. LEGO Mindstorms RCX, introduced in 1998, is already over ten years old, and LEGO stopped its production along with any further developments in favor of its new product, LEGO Mindstorms NXT. Furthermore, there is no hardware or software compatibility between the two systems. The only exception is with the old sensors, which can be connected to the new system with conversion cables and programmed using downloadable software modules. Even though the support for the old system will continue and the warehouses have a number of the old systems left, LEGO urges new users to buy NXT sets. While the ideas from the literature that reference the old LEGO Mindstorms RCX sets will still be valid, the implementations are quickly becoming dated. Since a recent literature search did not reveal any education research articles about implementing the new LEGO Mindstorms NXT with its improved hardware and software capabilities, this report will note some of the new, interesting, and possibly useful features.

Curriculum Context of Lego Mindstorms NXT Bluetooth Convoy Experiment

Introduction to Mechatronics is a two-hour lecture, two-hour laboratory, one-semester junior-standing course that is part of the Bachelor of Science in Engineering with specialization in Mechatronics (BSE-Mechatronics) program at Colorado State University - Pueblo. The LEGO Mindstorms NXT Bluetooth Convoy experiment is developed for this course. The lecture portion of the course covers the basic elements of a mechatronic system (e.g. actuators, sensors, data acquisition subsystems, and various controllers), their underlying principles, and mechatronic systems case studies.

During laboratory sessions, students use the National Instruments (NI) LabVIEW programming environment and NI ELVIS prototyping boards to verify characteristics of a few chosen actuators and sensors and interface these devices to a PC-controlled data acquisition and control subsystem. In addition, three lab sessions are used to build students' proficiency in programming Microchip's PIC16 microcontrollers for embedded applications.

To add an encompassing system's view to the course through discovery-based learning and to promote further development of graphical programming skills, a three-session project, entitled LEGO Mindstorms NXT Bluetooth Convoy, has been designed and implemented into the course. A specific discovery-based learning objective for this project is to increase the practical knowledge of basic robot controls and inter-robotic communications.

Since this is the last experiment in the course, students are already familiar with graphical programming concepts through LabVIEW and microcontrollers. Additionally, as part of the Introduction to Engineering course, they also have been exposed to an older LEGO Mindstorms RCX environment, allowing them to transfer some of the experience to the new system. So, the only background activities for this robotics project consists of a short lecture on LEGO Mindstorms NXT capabilities and a demonstration that includes the installation and use of the software, development and uploading of a simple program to a LEGO brick, and execution of the program. Additional tutorials are included with the LEGO Mindstorms Education NXT software and are available to students for further exploration.

Experiment grading is based on fulfilling two basic criteria, line following and robot following, and on fulfilling some additional criteria from the DARPA Urban Challenge announcement [2]. Final reports are also required.

Laboratory Assignment and Hardware Specifications

This robotics project is designed to further develop student engineering design and graphical programming skills, and to specifically provide practical experience with basic robotic controls and inter-robotic communications. The inspiration for the experiment comes from DARPA's Urban Challenge and from the Bluetooth wireless communication capability of the new LEGO programmable bricks. The experiment requires three or four LEGO Mindstorms NXT sets per group.

A. Laboratory Task

Mobile robots are to be constructed - one with sensory inputs (master) and the others without (slaves). The master should include at least two sensors: one light sensor for line following and one ultrasonic sensor for sensing any obstacles on the road (parked toy cars). A large map of the area with "START" and "FINISH" positions as well as the desired path will be provided. The robots are to operate as follows:

1. After placing the robots at the START position one behind the other, robots should be turned on, Bluetooth communication should be initialized, and appropriate programs should be executed.
2. Then, the master robot should follow the prescribed path (line following). The type and number of sensors can be decided on an individual basis.
3. The slave robots should follow the master robot by receiving commands from the master robot.
4. When they reach the FINISH position, robots will execute a parking maneuver resulting in the robots being parked one behind the other.
5. If the master robot detects an obstacle, it should stop and wait for it to clear before continuing.

Robot programming can be accomplished using LEGO Mindstorms NXT software. For more complicated tasks and added functionality National Instruments LabVIEW Toolkit for LEGO Mindstorms NXT [21] can be used to create and import modules into NXT programs.

Depending on the size of a group, two or three slave robots will be built so that each student can build a robot.

The hardware and software designs to be used are not specified. Students are allowed to use existing designs and modify them to satisfy the project requirements.

B. LEGO Mindstorms NXT Specifications

At $250, LEGO Mindstorms NXT includes one NXT Intelligent Brick with four input ports and three output ports, four sensors (a light sensor, a touch sensor, a sound sensor, and an ultrasonic sensor), three servo motors, and various connecting elements. Each servo motor has a built-in rotation sensor that measures speed and distance, thus allowing precise motor control within one degree of accuracy. Each NXT Intelligent Brick includes two microcontrollers: one 32-bit ARM7 microcontroller with 4 KB FLASH and 64 KB RAM, and one 8-bit AVR microcontroller with 4 KB FLASH and 512 B RAM. Apart from a major change in microcontroller hardware, when compared to the previous LEGO Mindstorms RIS 2.0 version, NXT has more memory, is Bluetooth enabled, has an additional input port, has an 8-bit 12-16 KHz sample rate sound channel with external speaker, and is MAC compatible. A USB 2.0 port allows fast program transfer. A quick-start program can get students started three times faster than with the RIS 2.0. LEGO Mindstorms NXT is not compatible with any older versions of LEGO Mindstorms except for the sensors, which can be reused with an adaptor.

The available ultrasonic sensors are able to detect objects from a distance of 0 cm to 255cm and return the range with a precision of +/- 3 cm. They can be used to avoid collisions with parked robots and other obstructions.

Implementation Results

Hardware implementation is relatively simple. All robots are modeled from the quick-start guide supplied with the LEGO Mindstorms NXT set. The master robot is then equipped with two sensors: an ultrasonic sensor pointing forward and one or more light sensors pointing down. The master and slave robot configurations (Figure 1 and Figure 2) are used in the project. While there is a set of articles [22 - 24] that describe other simple configurations, they are not used since the LEGO's in-the-box solution is sufficient and available.

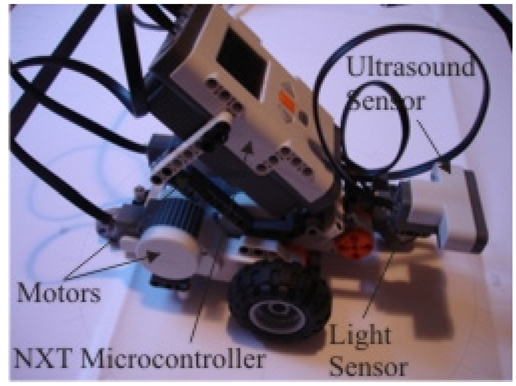

Figure 1. Master robot configuration

Figure 2. Slave robot configuration

A map of the area around campus with a desired path is downloaded from the Web [25], enlarged, printed on 12 sheets (8 ½ x 11 inch), and taped together. Figure 3 depicts the robots on the path on the map.

The program designed for line-following was modified from one of the educational tutorials supplied with the LEGO Mindstorms Education NXT software package. The set of programs designed for robot following (one for each robot) uses an array block (customized LabVIEW NXT block) adopted from Hassenplug [26].

In a single light sensor configuration, the master robot sweeps left and right in widening arcs until the sensor locates the line. Then, it moves forward until the line is lost. At this time the search begins again. After traveling a great enough distance (approximately two wheel revolutions), directions are transmitted via Bluetooth to a slave robot to bring it into close proximity of the master. If a line is not found within a ninety-degree arc during the line-searching process, the end of the line (FINISH) is assumed. Then, the master robot moves forward another two wheel revolutions to allow slave robots to move right behind it. The motion of the master robot is interrupted if the ultrasonic sensor encounters an obstacle. The master robot program consists of a main program, nine My Blocks, and the array object, which is not shown due to its complexity.

A simple slave robot program is shown in Figure 4. In this program, the slave robot waits until a signal is received through one of two Bluetooth mailboxes. An acknowledgement is sent back to the master robot. The top loop is used for moving straight, while the lower loop is for turning. If straight movement is indicated, the wheels move for the number of fractional rotations sent via a signal to the slave robot. If turning, the signal is converted from a number into text, which displays on the robot's screen, and used to rotate the robot a given number of degrees left or right depending on whether the signal is negative or positive.

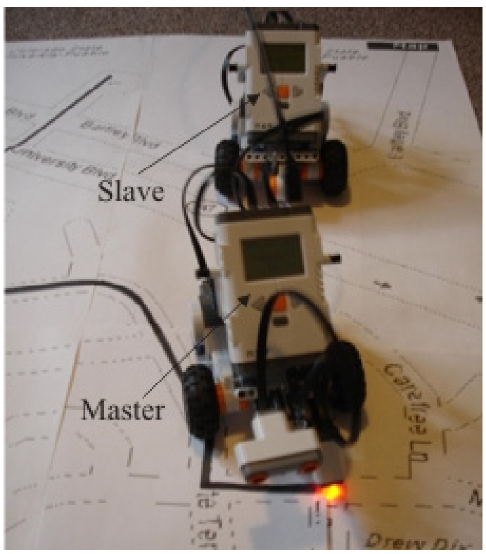

Figure 3. Robotic convoy following the path on the map

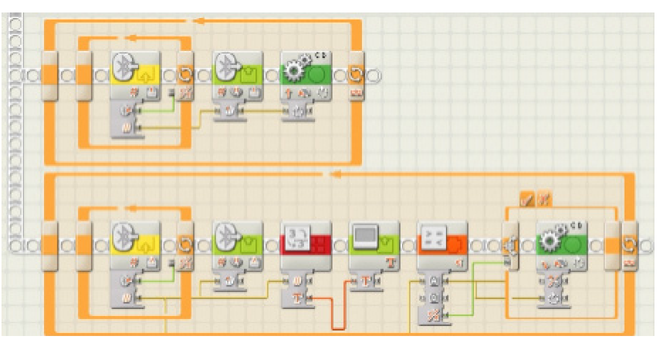

Figure 4. Slave robot program

Student Performance Results

During the project, students worked in groups of three or four. In each group, every student built a slave robot. Then, each group equipped one of their robots with sensors, thus creating one master robot per group. Since the Mindstorms NXT Bluetooth communication package has a limit of three simultaneous connections that create a convoy of four robots, the upper limit on group size was four students.

All students were successful in assembling working robots. At the beginning, designs within groups were different. However, students learned quickly that standardizing designs within groups was important to applications such as the convoy. Apart from obvious benefits, such as transparency of programs or easy hardware design change implementations, students learned that differences in robot weights, weight distributions, wheel dimensions, or distances between wheels would cause robots to behave differently when executing the same command.

All groups created master robots with appropriate programs capable of traversing a prescribed path. All master robots used the ultrasonic sensors supplied with the kits to detect obstacles on the path. All collision avoidance algorithms worked reliably (i.e. each master robot stopped before hitting an obstacle and continued moving after the obstacle was removed from the path). However, when a toy car obstacle was substituted with a small cardboard box, placed so that one edge of the box faced a master robot, the box was not detected. This was attributed to the nature of the ultrasonic sensor whereby the box's orientation did not allow the transmitted waves to reflect back from the box to the sensor.

Inter-robot Bluetooth communication was somewhat cumbersome to program and execute. Students felt the need for more instruction describing the protocol in detail. Some of them believed that the Mindstorms NXT help files where not helpful enough. All groups were fairly successful when dealing with only one slave robot. At this stage, the problems encountered included runs where some slave robots would bump into the master during parking, would continue with their last motion even after their master parked, or would otherwise not follow their master correctly.

Four-robot convoys were even more unpredictable. Students realized that slight differences in robot hardware designs and starting positions would compound errors in the slave robots' motions. Even the quality of the path surface was a challenge. Sometimes, one of the robot's wheels would slip during a turn and introduce an error in the robot's motion. One can conclude that students were partially successful with four-robot convoys. The robots were able to communicate. Messages were sent from master robots and received by the slave robots, and the commands were executed successfully. The inherent problems with dead reckoning were observed (i.e. without the appropriate feedback, slave robots could not sense if they moved as much as commanded).

The learning objectives for the project such as increasing the practical knowledge of basic robot controls and inter-robotic communications, as well as developing visual programming skills, were achieved. Students gained practical knowledge of a typical robotic platform consisting of motors, sensors, embedded processors, and a robotic architecture, a visual programming environment like Mindstorms NXT, and the Bluetooth wireless technology used for inter-robotic communication.

Lessons Learned

This robotics project presents an effective discovery-based learning educational tool. Overall, students seemed satisfied with the assignment. While the knowledge they gained of practical mechanics was not that significant (except in the area of mechanisms), since students do not fabricate their own robotic parts, they gained a significant amount of knowledge gain in visual programming and inter-robotic communications.

The six laboratory hours dedicated for the LEGO Mindstorms NXT Bluetooth Convoy project are not adequate for a project of this magnitude. A considerable amount of laboratory time is needed to complete the project. The project would be better served in a five- to seven-week time frame.

The LEGO Mindstorms NXT software presents the easiest way for novice programmers to access the robots. An ability to create customized Mindstorms NXT blocks via LabVIEW is another advantage of this package. However, while easy to use for simple tasks, the LEGO Mindstorms NXT software is somewhat cumbersome for more demanding tasks. The main problem is that the software requires state-of-the-art PCs to run, otherwise, it is too slow. If students have a working knowledge of more traditional programming languages like C or Java, a different text-based programming platform could be used. Since some of the students had a working knowledge of Java, those students were encouraged to use Lejos, Java for LEGO Mindstorms NXT [27], in the future.

Bluetooth wireless technology is also addressed in networking courses. A laboratory exercise on the implementation of Bluetooth for inter-robotic communication to achieve a group robotic task, such as robotic line dancing, will be developed and implemented in a networking course.

Conclusions

This paper presented a mechatronics laboratory design project on implementing a new hardware/software environment (the LEGO Mindstorms NXT). The project combines a traditional robotic line-following task, an obstacle detection task, and a robot-following task. The robot-following task includes up to three slave robots following a master robot. The communication between robots is established using Bluetooth wireless technology. During the project, learning objectives implementing discovery-based learning methods and dealing with robot controls and inter-robot communications were satisfied. Student comments were positive, and the project setup was cost effective (about $250 per robot).

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Biographies

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ENGINEERING COMMUNICATION – EXECUTIVE PERSPECTIVES ON THE NECESSARY SKILLS FOR STUDENTS

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Garlie A. Forehand, Georgia Institute of Technology

Abstract

Researchers at the Workforce Communication Program of the Georgia Tech Stewart School of Industrial and Systems Engineering conducted a qualitative study to understand how senior executives view the impact of communication skills in the hiring process. We drew on engineering and communication literature to create a series of questions for executive interviews and panel participation. The executives provided valuable information about how communication skills translate into the hiring process in their organizations. They additionally described the communication skills they consider critical for employment and professional advancement. The executives' comments cluster around a theme of non-technical skills in the hiring process. We summarize the executives' advice in terms of seven recurring themes: (1) the concept of communication, (2) communication with senior management, (3) presentation, (4) business writing, (5) messaging, (6) face-to-face communication, and (7) cross-cultural communication. We embed these skills into course instruction in Senior Design classes and make them available as a resource for confirming or expanding communication curriculum.

Introduction

Communication skills are now widely accepted as essential to engineering practice [1]-[2]. In 2000, the Georgia Institute of Technology Stewart School of Industrial and Systems Engineering (ISyE) started a high-impact Workforce Communication Program. Faculty built the program on information collected from interviews with senior executives, practicing engineers and their supervisors [3]-[12]. The approach is designed to help motivate and engage students as they learn communication tasks, and to help meet their need to transfer their communication skills to the workforce [13]. We conducted 11 phone interviews and posed questions to 28 executives in a series of panel presentations on workforce communication. The executives represented a variety of industries including health care, utilities, manufacturing, consulting, engineering, construction, real estate, delivery services, bottling, and home supply. All of the executives' companies employed engineers. Most of them were heads of companies; others were one or two levels below. Our goal was to extract the communication skills valued by the executives and to identify commonalities that can be translated into meaningful themes. The executives emphasized the importance of non-technical skills in the hiring process and provided a detailed description of the engineering communication skills they value.

Communication skills are a very important part of the hiring process, according to the executives. In some cases, the applicant's communication skills are the deciding factor in the hiring decision. The executives commented, "Communication is part of the first impression… [in applicants' interviews]"; "it is a substantial part of the weighting process," and "[it is] important that [an applicant's] communication is excellent." The executives also identified key communication skills critical for professional advancement. We have grouped these skills into seven distinct communication themes: (1) the concept of communication, (2) communication with senior management, (3) presentation, (4) business writing, (5) messaging, (6) face-to-face communication, and (7) cross-cultural communication. These results are made available to confirm that communication instruction for engineering students includes these themes. Academic departments may consider expanding their curricula or course materials if they are not sufficiently covered. The instruction may also become more engaging and credible by identifying executive input on these skills and including relevant quotes and examples.

Background

A number of universities involve alumni or workforce professionals in their graduate and undergraduate courses. Experienced professionals offer a valuable perspective and are especially credible to career-oriented students [14]-[15]. Recent literature has reported experience with such programs at California State University at Sacramento (CSUS), Maryland Technology Enterprise Institute, the Milwaukee School of Engineering, Western New England College, and Vanderbilt University. In one project at CSUS, industry advisors helped electrical engineering masters students design and build integrated circuits. The industry advisors gave feedback on student presentations and on program effectiveness [16]. In other work, undergraduate engineering students interested in entrepreneurship attended seminars given by entrepreneurs and experts in venture concepts and practices [17]. In engineering capstone design courses, industry-partnered active learning is now commonly employed to involve industry in student projects. The interaction between students and their industry advisors often includes help identifying a project, guidance throughout the project, referral to other professionals in their company, and feedback with respect to the final report and presentation [18]-[21].

Several recent studies describe the interaction between alumni or workplace professionals to enhance engineering workplace communication skills. In one study, undergraduates view a professional engineer interviewing a volunteer student for a job. After the interview, the students and the professional discuss the strengths and weaknesses of the interviewee and offer suggestions for improvement [22]. In other work, faculty pair engineering undergraduates with recent engineering alumni as part of their orientation to college life. Students and mentors use a set of expectations to guide their interaction. Through virtual classroom and face-to-face interaction, the alumni mentor students by providing information, advice, and life experience. At Vanderbilt University [23]-[24], engineering undergraduates take a Technical Communication course and contact alumni and other professionals to interview them about the communication demands of their jobs. Each small group of students selects its own questions, such as "How important do you feel technical communication is in your occupation? What percentage of your time is spent on oral communication? Who is your most common audience?" [24]. The students write a report on their findings.

Alumni and industry professionals can be generous with their time while interacting with students and report benefiting by the interaction [25]. The workforce communication work done at Georgia Tech over the past six years relies on this generosity. The program director regularly interviews senior executives about critical communication skills. She gleans information from these interviews and incorporates it into student instruction on communication. Additionally, each semester students interact with senior executives during scheduled Executive Panels on Communication. This interaction is part of a workforce-centered approach to teaching communication. Executive-student contact creates rapport between engineering students and senior workforce professionals. The program has incorporated a number of successful approaches since its inception in 2000. These include (1) Workforce interview, (2) Executive panels on communication and (3) Capstone design courses.

Workforce interviews with senior executives serve to provide concrete information about workforce communication that can be incorporated into instruction. The interview results focus the educators' attention on communication skills that senior workforce professionals consider important for the engineering students.

Executive Panels on Communication are also a component of the Senior Design course. Panels consist of two to six senior executives who have substantial dealings with engineers. The panelists address students and answer questions about communication requirements of engineers. The students are motivated to learn from the panelists because for the first time many are engaged in professional workforce communication, and because the panelists are prestigious and credible mentors [10].

Capstone design courses provide hands-on-experience with projects in real companies addressing real problems. These courses are especially valuable as a means of presenting instruction in communication. Students learn to communicate their ideas as well as perform technical analysis. In addition, they encounter firsthand the communication demands of teamwork and client relations. Communication advice that may seem abstract in the classroom takes on enhanced significance. At Georgia Tech, Senior Design is the ISyE's capstone course. It is a major locus for communication instruction. In this course, we translate data from workforce interviews into techniques for use in audience analysis, presentation, and writing.

Accessing Executive Input

Serving as a panelist or interviewee requires an investment of the senior executive's time. Building a network of senior executives who are able and willing to make that investment requires some significant work and cooperation on the part of educators. We offer the following suggestions from this study and from previous research initiatives of the Georgia Tech ISyE program team [10]. First, enlist assistance from alumni associations and advisory boards. Many universities and departments within universities have groups of alumni who advise educators on important educational matters. These groups are often sensitive to issues of effectiveness of recent graduates in the workplace. In ISyE at Georgia Tech, the Advisory Board took the initiative to identify the need for a program in Workforce Communication. Their attention to workplace communication needs is equally evidenced by the emphasis placed on communication in Accreditation Board of Engineering and Technology (ABET) criteria [20], [26]-[27]. Second, engage some champions. There are frequently members of alumni advisory groups who are enthusiastic advocates of improved communication by engineers and engineering students. They can be catalysts for recruiting participation by others. Third, seek referrals. Faculty members, alumni, previous speakers, and interviewees can recommend other executives who would be interested and effective. When we identified the executives to approach, we asked for a very small amount of time at the executive's convenience. We interviewed senior executives by phone for one-half hour at the most (unless they decided to take more time). When the panelists came to Georgia Tech, they spent no more than two hours on the panel discussion.

Communication Skills in Hiring

In telephone interviews with executives, we asked how communication skills translate into the hiring process. Executives described it as playing a very active part in the hiring process. For example, in many cases companies have formal matrices or questionnaires that include communication skills as the first part of the hiring process. We learned that some firms ask applicants to weight their own communication skills by answering questions about whether they regularly make presentations to large audiences and whether they regularly present to rooms of executives. The executives shared distinct approaches they used to assess the communication skills of potential new employees. We share these approaches here. Each approach describes the level of executive involvement in the communication skills assessment in the hiring process.

In the first approach, typical in larger firms, the human resource department pre-screens the applicants. They stress communication skills as part of this screening. They report the use of a competency matrix or questionnaire to assess verbal and non-verbal communication. Division heads, or other more senior-level managers, sometimes follow with subsequent interviews. Based on these reviews, finalists are selected and invited to interview directly with the executives. In a second approach, typically characteristic of a smaller firm, the executive participates early in the interview process. The executive uses the opportunity to evaluate the interaction, all the while "watching for communication skills." Applicants that communicate well are introduced to department heads for more job-specific interaction. In a third approach, a committee that includes the executive interacts with the applicant. In these interviews, a situation is often described where communication is important. The committee asks the applicant how he or she would respond. In a fourth scenario, the hiring manager provides a written job description that includes executive-endorsed communication skills. In one particular situation, the executive pointed out, "the closer to the customer, the more important soft skills are." And, in almost every case, executives will conduct face-to-face interviews with their potential direct hires (those individuals reporting directly to them).

The executives are looking for a wide range of communication skills. In interviews with applicants, they look for concise verbal interaction in which topics tie together well and detail is included as needed. They also look for an individual's ability to get his or her point across, and to communicate verbally by email or on paper with his team members. For example, one executive uses this approach: "Tell me about a problem you had in this job and how you solved it. How were other people informed?" She also asks, "What activities do you do to make sure your team has the same goals and objectives?" During the interview, executives also look for the applicant's ability to sell himself, to communicate his ideas positively to a range of audiences, and to listen well and read his audience or customers.

Skills Valued by Executives

The results of the executive interviews indicated that an essential part of an engineer's job is communicating results or recommendations to his or her audience. Non-technical skills and workplace communication was identified as a meaningful theme of the executive input. An engineering job is not finished until it is successfully communicated. The engineer's audience is diverse, including clients and colleagues in management, manufacturing, technology, marketing and sales. Participating executives offered advice for responding to a diverse and challenging communication environment. We summarized their advice in terms of seven communication themes: (1) The concept of communication, (2) Communication with senior management, (3) Presentation, (4) Business writing, (5) Messaging, (6) Face-to-face communication, and (7) Cross-cultural communication.

The Concept of Communication

The executives have a wide variety of perspectives and a wide range of expressive styles. From their input, however, there emerged a consistent concept of communication as an element of organizational functioning. Executives emphasized the engineer's need to integrate communication with management decision-making. Several kinds of insight and advice stemmed from this integrated concept of communication. We list and describe the sub-themes below:

Selling: The comments by the executives suggested that communication is selling the engineer's idea. It is a form of persuasive communication that has direct bearing on outcomes. An engineer who is giving a report or presentation may have only one chance to sell his or her idea. The executives advised that the focus must remain on the idea or recommendation rather than on the amount of detailed work completed. Communication, like the research process, requires its own planning and preparation.

Listening: Good communication requires good listening. Executives noted that newly graduated engineers frequently neglect the listening component. They fall into the assumption that communication is what they say, not what they hear. Effective communicators are active listeners who repeat, clarify and summarize. They draw information out, using such phrases as "tell me about," and "what you're telling me is…" Executives encouraged engineering students to apply their techniques of listening to new personal contacts: in social situations, they should single out a few people and try to get to know them. One might start by asking others about themselves – what they do, what is important to them, what they think about a current topic or issue. Practicing listening skills is an integral part of becoming a successful listener.

Audience: Executives found that audience analysis is very important. Each audience member has a focus, a set of responsibilities that dominate his or her perception. It is the communicator's responsibility to understand the perspectives of audience members. More important than what the engineer says is what the audience perceives. Principles of audience analysis used in mass communication, such as knowing audience demographics, attitudes, and values, are relevant. In the workforce, audience analysis is frequently much more direct and immediate. What is important to the individual? What does he or she expect of the presentation? Are there conflicts among audience members? A number of executives suggested face-to-face interactions with key audience members before giving a presentation. The skills of active listening can be used to gain understanding of the audience members' perspectives.

Conciseness: The idea of a concise message, or "Keep it crisp" philosophy, permeated the advice from executives. They used different adjectives to describe the desired outcome: simple, short, succinct, clear, concise, and crisp. Their message was consistent: use as few words as possible to get your message across. Some executives recounted personal experiences that students identified with. One executive, as a young engineer, was asked to reduce a long, good report to one page. He stated that he felt like it was "tearing out his guts" because he had to leave out "so much good stuff". Engineers have a tendency to over-communicate. When an engineer has done a lot of analysis, executives point out that he or she often produces a weighty document. If the engineer tries to present all of it, he or she loses the audience quickly. A general rule is to ask the question: If I took this sentence out, what would happen? Would the audience have a lower level of understanding?

Correctness: Executives strongly emphasized the importance of correct spelling and grammar. Mistakes create an impression of poor quality, no matter how meritorious the content. The panelists recommended the use of grammar and spell-check tools, but also urged the communicators to go further in order to catch problems that the tools will miss, such as homonyms. Engineers should review their work several times and get input from their colleagues. The extra time spent in perfecting mechanics will pay off in effectiveness.

Trust: Over time, the executives stressed that a sense of trust develops with certain engineers and other professionals. Since they do not have time to know all of the necessary detail in each project, they count on action steps suggested by others. The executives interviewed made note that a small mistake, such as a misspelling, damages trust. The executives may start to wonder if there are other errors as well.

Communicating with Senior Management

Executives are a critically important category of audience. The senior manager focuses on decisions in contrast with facts and process. It is typical for a new graduate to look at a project and do the analysis. Then, in preparation for presentation, have thousands of bits of data and stacks of slides ready. The graduate has to figure out what is necessary to get his or her point across without overwhelming the audience. Several interviewees described a funnel. The executives' concern is at the narrow end, where the decision lies. Engineers may deal with hundreds of factors, but only a few of them bear on the executives' decision-making process. It is the responsibility of the engineer/communicator to understand the relative importance of these factors. Effective communication clarifies the actions to be taken, and presents fact-based recommendations.

What should an engineer do about the detail? The data and analysis the engineer uses to arrive at recommendations are too important to ignore. The executives suggested using detail for technical communication with team members and consultants, in order to back up recommendations. In presentations, engineers should be prepared with the detail but they should not plan to present it. It is part of the engineer's arsenal, available for answering questions and discussing alternatives, but called on only when needed. In written reports, executives again recommended placing the supporting detail in appendices or accessible databases.

Presentation

The previously summarized suggestions from the executives cut across genres and communication methods. Executives also offered practical advice for specific kinds of communication. Many placed considerable emphasis on oral presentation using slides, a ubiquitous mode of engineering communication. Because of these suggestions, presentation is the third of our seven recurring communication themes. We describe the sub-themes below:

Planning presentations: The executives we interviewed commented on the opportunity created in the presentation planning phase. The presenter can tailor a message to a specific audience and thereby learn something of the audience. Often the presenter will know what specific people will be present; if not the specific people, he or she will be able to learn the organizational levels and responsibilities of the audience. Senior executives indicated that the planning stage is the time to identify the focus of each audience member, understand his or her individual roles in the decision-making process, and tailor the presentation. Specific advice offered about planning presentations includes: (1) tell the audience where the presentation is going immediately, (2) put the results up front, (3) formulate the message to communicate and make sure each slide supports the message, and (4) provide insight and recommendations. Be prepared to support recommendations with detail, but hold the detail unless needed.

Slides: Presentation slides are the presenter's primary visual resource for structuring the presentation and focusing the audience's attention. Often the slides will have a life of their own, with hard copies providing the primary documentation for the presentation. Slides, therefore, deserve major preparation time and effort. Executives emphasized making sure each slide has a point and is clear and concise. The executives cited many bad examples, including slides with 20 points on a page, font so small the audience couldn't read it, and complex organization that the audience could not process during the meeting. Additional advice included putting the interpretation or conclusion on the chart with the data instead of making the audience interpret. Executives reinforced the idea that the presenters should not read the slides aloud; instead use them as cues and focus attention on the audience. We often assume engineering students know this information. The feedback from the executives suggests that additional focus may be necessary.

Responsibilities of the presenter: It is a presenter's responsibility to provide a well-planned and succinct presentation. Executives recommended that a presentation needs to be on-point, well-structured, and free of grammatical and spelling errors. The presenter should make it apparent that he or she spent time and effort on preparation. They should be attuned to the needs, values, and expectations of the audience.

Business Writing

Engineers on occasion have to produce a wide range of written documents. So our fourth theme is business writing. The executives emphasized the importance of documents that communicate with management rather than technical reports and manuals. The documents mentioned by the executives include market analyses, product/service descriptions, business plans, and proposals. Executives identified a number of levels of analysis and urged preparation of reports at the appropriate level. We summarize their comments by focusing on three levels of analysis: the executive summary, the body of the document, and the appendices.

Executive summaries: Executive summaries are critical. Executives sometimes insist on a one-page executive summary; almost all assume that it will be less than two pages. Senior management indicated that an executive summary should include: (1) what the reader needs to know, (2) what the reader needs to act on, and (3) why it is important. Executives frequently observed that key audience members may read only the executive summary. If communication is selling one's ideas, the executive summary may be the sole opportunity. It follows that the executive summary deserves intensive preparation time and effort. It cannot be an afterthought.

Body of the document: Senior executives also stressed that business documents should be brief and succinct. Different executives cited examples of a four- to six-page document. They suggested that documents be separated into one-half to one-page sections that report findings critical to the decision, such as market analysis, product/service description, financial projections, and the support needed to implement the recommendations. The biggest mistake noted is to write too much. The senior managers advised that engineers allow enough time to condense their writing since communicating ideas in fewer pages takes longer.

Appendices: The executives stressed that engineers should place anything that does not fall into the executive summary or the body of the document into an appendix. The appendix should be tabbed for easy access. Examples of appendix material described by the executives include: information summarizing data and analyses, the basic details of financials, a list of the exact resources needed, and examples illustrating the implementation of action plans. The various types of information should be referred to in the body of the document in case the reader wants more details.

Messaging

In addition to formal written and oral communication, executives placed a great deal of emphasis on day-to-day task-oriented communication. Technology rapidly impacts the opportunity and methods of getting messages to colleagues; the changes occur faster than people can develop communication skills for using the technology. Therefore, our fifth theme is messaging. Executives continually addressed the following three main areas of messaging in the series of interviews and panel discussions.

Email: Executives described email as a form of communication that requires skill and planning. The advantage and disadvantage of email is that it is instantaneous. Engineers are sometimes tempted to "dash off" an email without reviewing the quality and implications of the message. One executive received an email intended to say: "I will definitely be at the meeting." Instead, it read, "I will defiantly be at the meeting." The senior managers stressed the following: Email shares with other forms of communication the need to understand audience perspectives, to anticipate receivers' reactions, and to be considerate of the receivers' time and attention. As with more formal communication, it is the communicator's responsibility to understand the bearing of the message on decisions and to present recommendations clearly and succinctly. Engineers writing email need to keep in mind that it omits non-verbal cues, tone, and inflection. Executives indicated that, because of this, personal meetings are still needed to complement email communication. Additionally, email to nearby people can waste time and result in missing a chance to interact. The technical capability of creating long email chains can be of value in documenting messages, but executives said they do not read all of the messages. Therefore, if knowledge of only some of the messages is important, the sender needs to summarize the others.

Voice mail: Voice mail is another innovation that carries responsibilities for effective use. Executives advised new engineers to plan their voice mail, rather than improvise when the signal comes. For example, "here are three things I need to talk to you about …"; "this is what I need to know…" Briefness in voice mail shows respect for the person's time, but courtesy is always expected as in other forms of communication. Executives also said that a brief email can serve as a reminder of the response needed from the voice mail.

Personal notes and letters: To the surprise of many of our undergraduate engineering students, executives pointed out that personal notes and letters are still very important. Engineers need to know how to write them according to convention. Individuals find it rewarding to receive a personal letter following a contact. Thank-you letters were especially stressed, after such occasions as mentoring, advising, or providing a letter of support or recommendation. A personal note should be sent out in a timely manner, senior managers said, and they will be especially appreciated and remembered because this type of communication is rare.

Face-to-Face Communication

Many of the executives interviewed noted that media-based communication does not replace face-to-face communication. As a result, our sixth theme focuses on this type of communication. The senior managers pointed out that not every communication can be enhanced by technology. Engineers might miss key elements of the message without eye contact and facial expression showing the critical points in the communication. The executives also said that engineers may lose the opportunity to build a relationship with colleagues within or outside their environment if they never meet the person face-to-face. This type of communication can be one-on-one, in informal small groups, or in more formal meetings. Comments from executives focused repeatedly on the importance of good communication skills in meetings.

Meetings: Meetings are a primary setting for face-to-face communication. Much of the executives' advice regarding presentation is also pertinent to meetings. They placed special emphasis on the importance of knowing the perspectives and concerns of the individuals in the meeting. The senior managers stressed the following actions for successful meeting communication: (1) meet with meeting participants in advance in order to understand their perspectives, (2) identify the purpose of the meeting and try to learn in advance why certain individuals are in the audience, and (3) assess whether the meeting is for sharing information, discussion, or decision. Each attendee needs to determine if he or she is to play a specific role in the meeting, and who of the group is expected to do the talking. One executive described a new employee who spoke up in a meeting. The executive felt he didn't know enough about the organization yet to speak for them in a meeting. She and other executives emphasized the special importance of listening in a meeting environment. For example, one executive suggested that if the client is talking less than 70 to 80 percent of the time, the meeting is not going well.

Cross-Cultural Communication

Executives emphasized the importance of communication throughout the world. This is our final theme. Globalization creates a near certainty that engineers will have international exposure. This often begins with co-ops and internships for engineering students. Two main points stood out in the personal examples offered by the executives.

English language: Although English is often the language for international communication, the native English speaker cannot assume that all colleagues process English in the same way. The senior managers advised striving for English-by-the-book, the formal English that people of many backgrounds use and study. Engineers should avoid idioms (which might not translate with the same meaning to the non-native speaker) and slang. Listeners might not understand technical terms and acronyms. The key is to use the strategies suggested by the executives, described below, in frequent interaction with cross-cultural colleagues to test mutual understanding.

Cultural sensitivity: The second central point was the need for sensitivity to intercultural differences. People may interpret gestures in very different ways. For example, one executive inadvertently committed a faux pas by pointing in a setting where pointing was offensive. Cultural differences also affect interactive rituals such as the order in which to greet people, when to exchange personal information, and how to terminate a discussion. Since cross-cultural communication situations vary widely, it is desirable to apply strategies flexibly. The executives interviewed suggested the following strategies:

- Engineers will benefit by doing background research on cultural traditions in the countries they will be visiting. They should learn about interactive rituals, ways of expressing respect, and actions to avoid. When possible, the engineers should confirm with friends or colleagues who are native to the country.
- Engineers will be more successful if they learn some of the language; at minimum, key phrases of politeness and business interaction. If the engineers will be regularly interacting with speakers of another language, it is worth their long-term study of the language.
- Effective intercultural interaction requires learning to pay attention to feedback. Words and gestures expressing understanding or agreement may not have the same meaning to different participants. Engineers will benefit by learning to verify mutual understanding.
- Working with a translator when possible will enhance the engineers' communication and understanding.
- A local champion or partner is invaluable in helping the engineers convey their message and understanding others' messages.

Conclusion and Future Direction

As part of the Georgia Tech ISyE Workforce Communication Program for undergraduate engineers, we gathered executive input through phone interviews and participation in Executive Panels on Communication. Researchers made particular inquiries into how executives reflect on communication skills in the hiring process. We gained insight into the executive role in the hiring process and the importance of non-technical skills in engineering placement through interviews with executives of varying company size. After gathering the information, we extracted significant statements and commonalities. We analyzed this feedback and combined it into seven distinct themes of professional communication.

As executive interviews and panels on communication continue, new and yet-to-be-incorporated themes will emerge. Communication is not a static field. Audience needs and available tools change by time and situation. Communication concerns in cross-cultural communication, diversity, and emerging smart technologies offer areas for future investigation. Senior executives note that is it just as important for an engineer to be well-trained in professional communication skills as it is to be well trained in engineering skills. Technical and non-technical dimensions in engineering continue to intersect and expand the field. Engineering programs and curricula that foster interaction with industry will assist students in better understanding the importance of communication skills and its impact on the hiring practice.

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APPLIED ENGINEERING STIMULATES UNDERGRADUATE TECHNOLOGY STUDENTS' INNOVATIVE THINKING AND SUCCESS AT NATIONAL COMPETITIONS

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Abstract

The Experimental Vehicles Program (EVP) of the Engineering Technology Department at Middle Tennessee State University (MTSU) promotes innovative thinking through applied research projects. The various projects of the EVP allow engineering technology students to apply their innovative ideas and classroom knowledge to real-world problems. These projects—Baja SAE, Formula SAE, Moonbuggy, Solar Boat and Solar Vehicle—are novel in their variety, duration, and span across classes.

The purpose of the projects is to support innovative thinking throughout the region and to provide experiences which give EVP students a valuable edge in the job market upon graduation. MTSU engineering technology students must function together as a team to design, build, test, promote, and race each vehicle in national and international competitions. The teams disseminate their knowledge to local middle and high schools to promote interest in engineering. The innovative projects have increased interest in engineering, incorporated classroom learning into hands-on experiences, and fostered an atmosphere of "peer-led team-learning" which has benefited the students both personally and academically.

Introduction

The Experimental Vehicles Program (EVP) was introduced in 2004 to the Engineering Technology department at Middle Tennessee State University. It was founded by the local student chapters of the American Society of Mechanical Engineers (ASME) and the Society of Automotive Engineers (SAE) [1]. Since the inception of the program, the department's enrollment and retention rates have noticeably increased [2]. In fact, enrollment has nearly doubled over the lifetime of these projects (Figure 6).

The various projects of the EVP allow engineering technology students to apply their innovative ideas and classroom knowledge to real-world problems. The program was developed to include several applied undergraduate research projects which involve designing and constructing vehicles from scratch and competing with the finished product at specific design competitions. Through these projects, students are able to learn and sharpen the critical skills necessary to prepare them for a successful career before they graduate [3].

The EVP is funded both internally and externally. EVP project teams submit proposals to MTSU's student government association. The proposals include details about manufacturing, cost of parts, travel expenses, and educational benefits. Because of the positive public attention brought to the university from these project competitions, the teams' efforts also receive funding from the Dean of the College of Basic and Applied Sciences (CBAS) and the Chair of Manufacturing in the Department of Engineering Technology. For external funding, EVP team members make contact with local companies. The CBAS Director of Development and Fundraising helps the students create professional letters conveying funding opportunities. Several local companies are delighted to support the teams because of their dedication to the projects and their record of winnings. Companies who do not support the teams financially do so through manufacturing consultation, mentoring, and parts donations. Students assume full responsibility for fundraising and are benefited by learning this important step in project development.

Paired with the teams' fundraising efforts are actions to cut costs. Transportation expenses to the competitions are reduced by carpooling and asking for group discounts at hotels. The teams manufacture the vehicles with their own hands. Not only does this cut costs, but working together strengthens the team as a whole. It also gives the students a deeper sense of pride when they see their vehicles cross the finish line. The construction costs can be further reduced by utilizing some parts from previous vehicles.

A major incentive for the students to participate in the EVP projects is the chance to bring their vehicles to national and international design competitions. Students form teams to represent each vehicle. Juniors and seniors pair together with freshmen or sophomores to facilitate a greater learning environment for collaboration. This environment is called peer-led team-learning, and has proven beneficial to the students both personally and academically. Many seniors within the engineering technology program also use elements of the projects for their capstone research course [4].

Project Design and Implementation

EVP research projects include the Baja SAE, Formula SAE, Moonbuggy, Solar Boat, and Solar Car [Figures 1-5].

Figure 1. Baja SAE

Figure 2. Formula SAE

Figure 3. Moonbuggy

Figure 4. Solar Boat

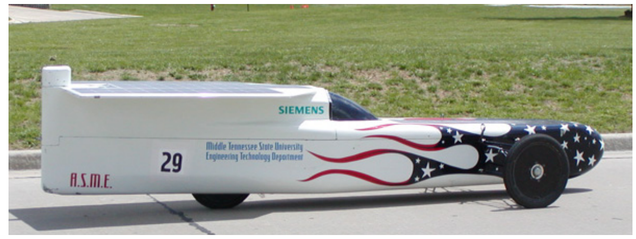

Figure 5. Solar Vehicle

Over the past several years, EVP team members have competed in a variety of national and international events. Each year, the students create a new, increasingly efficient, well-made vehicle for each of the projects. Success at this level not only means winning awards, but it is primarily the reflection of the innovation and dedication of students.

The unique research projects provide great benefits for the professional development of engineering and engineering technology students. Hands-on learning is a direct application of classroom concepts. In addition, these particular projects help students learn to think innovatively, communicate professionally, manage projects efficiently, and work in a team environment [5]. The competitions are also an opportunity for MTSU students to associate with other students from engineering schools around the country and globe [4].

Although most participants represent engineering and engineering technology majors, students from various disciplines have participated within the program. Students think creatively to design their blueprints, construct each vehicle from scratch, and enter each project into its respective competition. Each competition is composed of several events, providing a unique set of challenges along with racing against some of the top engineering schools in the nation including Georgia Institute of Technology (4th ranked Engineering school in the U.S.), the University of Illinois Urbana-Champaign (ranked 5th), and Cornell University (ranked 11th) [6].

The program provides a large range of students with a diverse collection of projects to facilitate excellence in engineering technology education and to encourage undergraduate participation through innovative, competitive research.

Students work diligently on these projects and incorporate skills needed in the workforce: project management, decision making, leadership, critical analysis, and problem solving. EVP participants learn the value of research, teamwork, and effective communication. They learn to incorporate innovative ideas into a single goal, complete projects, and excel at competitions. In addition, the national and international design competitions provide valuable exposure for Middle Tennessee State University [4].

Examples of each project type, along with competition judgment and innovative merit evaluation, are described below:

A. Baja SAE

The Baja SAE is designed as a rugged, single-seat, off-road vehicle that is intended for recreational use and to be marketed to amateur off-road fanatics. The Baja SAE is entered into the Baja SAE Collegiate Design Competition.

The Baja competition is an annual SAE-sponsored event. Baja provides many distinctive engineering challenges. Entries are judged in two different categories: 1) static inspection, including design and safety: and 2) dynamic events including mud bog, acceleration, rock crawl, hill climb, and land and water maneuverability. The dynamic events culminate in a grueling four-hour endurance race.

Student teams compete against one another to have their design accepted for manufacture by a fictitious firm. Students must document their efforts to design, build, test, promote, and race a vehicle within the limits of the rules, as well as their generation of financial support for their project. The teams present their efforts as a part of the competition. From 2006 to 2009, the Baja SAE has placed in the top 15th, 25th, and 40th percentile overall, as well as 30th in the sled-pull event and 6th in the mud-bog event. It has won awards for rookie-of-the-year, outstanding participation and performance, and presentation. The Baja SAE design was quite unique the year the team designed a clear glass covering for the transmission, allowing all to view the elements and how they worked.

B. Formula SAE

The Formula SAE is an open-wheeled, formula-style race car which is entered into the SAE Formula Competition. Vehicles are built to be a single-seat off-road recreational vehicle that is safe, fun to drive, easy to maintain, and has the ability to be mass produced and sold to the public. The vehicle must survive the severe punishment of rough terrain, mud, and water.

Formula SAE is a formula-style race sponsored by SAE. The vehicles are open-wheeled racers which are not only judged on their performance on the track, but also their technical and engineering innovation, manufacturability, project budget, and timeline.

MTSU's Formula SAE designs are unique in that, excluding the motor, the students design and build the entire vehicle in the machine shop. From 2006 to 2008, the Formula SAE has placed 9th in acceleration and 10th in endurance. It has won awards for successfully completing all events.

C. Moonbuggy

The Moonbuggy is designed to be a compact, lightweight, flexible and durable "all-terrain vehicle." Each Moonbuggy must be human-powered and carry two students, one female and one male, over a half-mile simulated lunar terrain course including craters, rocks, lava ridges, inclines, and lunar soil. The Moonbuggy is entered into the NASA-sponsored Great Moonbuggy Race.

An international competition, the Great Moonbuggy Race, is sponsored by NASA and held annually at the Marshall Space Flight Center in Huntsville, Alabama. Entries are judged on performance over a half-mile simulated lunar-terrain course that includes craters, rocks, lava ridges, and inclines. Design is also considered in the judging.

The Moonbuggy team works diligently each year to come up with a new and innovative design for their vehicle. Its design is unique in its fiber carbon composite, allowing it to be light enough for moon travel. From 2003 to 2009, the Moonbuggy has placed 4th, 5th, 7th, and 9th nationwide, as well as 1st in Tennessee. It has won awards for its design, safety, and the participation of the team.

D. Solar Boat

The Solar Boat is powered completely by batteries and a solar array. It must be very efficient hydro-dynamically as well as use its power extremely effectively. The Solar Boat competes at the American Society of Mechanical Engineers (ASME) Solar Splash.

The annual American Society of Mechanical Engineers (ASME) Solar Splash is the World Championship of solar-electric boating. Entries are judged on technical design as well as on-water competitions including sprint, maneuverability, endurance and speed competitions.

MTSU's Solar Boat designs have been unique in light, aerodynamic hull design. From 2006 to 2009, the Solar Boat has placed 11th, 12th, and 14th overall. It has won awards for perseverance, drive train design, participation, and outstanding hull design. Its team has won awards for workmanship, technical design/report, and teamwork.

E. Solar Vehicle

The Solar Vehicle is powered by both solar energy and batteries. It is designed to have a super-lightweight, low-drag carbon fiber body, efficient NiMH batteries, and advanced power management and remote monitoring systems. The Solar Vehicle is entered into a competition called the Solar Bike Rayce USA.

The annual Solar Bike Rayce USA is an international racing event sponsored by the Formula Sun Education Foundation. The race itself is part endurance and part sprint (vehicles approach speeds of 60km/hr and travel distances up to 100km) with the objective of stimulating interest in science, technology, and alternative energy.

MTSU's Solar Vehicles have been unique in their aerodynamic and attractive designs. From 2003 to 2006, the Solar Vehicle has placed 2nd and 3rd overall and in its division, 1st and 2nd in sprints, and 1st, 2nd, and 3rd in distance. It has won awards for design and sportsmanship.

Background and Innovativeness

Project-based learning is not a novel concept in the field of engineering. Engineering is a notoriously difficult degree which requires students to seek stimulation outside of the classroom to succeed. Some have tried to expose freshmen to hands-on engineering projects, but it was found that there was not enough prior course knowledge for the projects to be beneficial [7]. Others have experimented with senior engineering projects [8], but this may not give students enough time to develop sufficient teamwork skills. A project providing engineers with hands-on training in progressive vehicles, the EcoCar, combined students from seventeen different universities [9]. The experience was beneficial, but the mixture of student backgrounds did not allow for evaluation of specific university enrollment or retention rates.

What is novel about MTSU's program is its variety, duration, and span across classes. Other schools such as The Ohio State University, the State University of New York, and the University of Arizona have established programs similar to MTSU's Experimental Vehicles Program, but none match the variety of experimental vehicles MTSU regularly produces. EVP teams have constructed race cars, all-terrain vehicles, solar-powered boats, cars, and bikes, as well as vehicles fit for travel on the moon's surface. This variety offers a niche for all types of engineering students, as well as the opportunity to work on separate, diverse projects. Vehicle variety has attributed to the success of the program.

The EVP at MTSU is novel in its duration. The amount of dedication devoted to each of the projects requires commitment for at least two semesters; therefore, students who participate in the projects tend to remain within their chosen discipline. Students design and build the vehicles themselves. There are many original design plans proposed, but the students must function together as a team to design, build, test, promote, and race each vehicle. The longer duration provides students the opportunity to focus on product development, a key concept in engineering. The EVP exposes students frequently, and for extended periods of time, to the product development process, which is greatly beneficial [7].

MTSU extends the span of the EVP across all classes; upperclassmen and lowerclassmen are involved on teams together. The duration of the project allows newer students to be introduced to more seasoned students in the program who are often willing to help with homework and studying. This peer-support network has been shown to increase retention rates among Engineering Technology concentrations [3]. The combination of all three of these novel characteristics (variety, duration, and span) has formed the perfect environment for peer-led team-learning.

Methods: Peer-Led Team-Learning

The EVP projects have been modeled after the Peer-Led, Team-Learning (PL-TL) model, supported by the National Science Foundation. The established PL-TL model has proven successful mostly in mathematics, biology, and chemistry. The model's critical component is the relationship between the workshops and specific courses [10].

MTSU's EVP projects are an adaptation to the PL-TL model. Although EVP students gain critical hands-on experience which reinforces their coursework, the projects are not directly tied to a required course. However, an upper-division elective course, taught by the EVP's faculty advisor, offers an opportunity to gain academic credit for EVP projects. This course may count towards the core engineering curriculum if the student uses it to complete his or her capstone project. Students counting the elective as capstone projects must be team leaders and have major defined responsibilities as well as complete their own design reports, models, and presentations. Most students participate in the EVP as an extracurricular activity. Regardless of whether they receive academic credit for their participation or not, all students appreciate the projects which provide real-world application for their engineering courses.

The EVP projects essentially define what interdisciplinary education should be, necessitating that students possess strong skills in both mechanics and communication. This has been especially good for international students who speak English as a second language (ESL). One professor at MTSU watched several of his students struggle with presentations in class. By encouraging them to participate in one of these projects, he found that all ESL students' presentations and interpersonal communication skills increased substantially from working in the teams. Only about forty percent of them were able to deliver satisfactory presentations before the project. The students still struggled with grammar, but their confidence sky-rocketed. As a result, crucial presentation skills such as eye-contact and voice projection were very much improved [11].

Student learning is focused around textbook knowledge, but there is no substitute for hands-on learning. Peer-led team-learning at MTSU combines a hands-on learning approach and student-centered learning [12] with open communication between upper- and lower-classmen. These projects create a learning atmosphere which enables students to develop knowledge of what a future in the engineering and engineering technology fields requires. The PL-TL model at MTSU creates an internal support group as well as a mentoring program that has aided in sustaining the success of the ET department.

EVP's adapted PL-TL Model:

1. Create unique engineering-related projects to drive student interest.
   — The Experimental Vehicle Program has entered five different vehicles into competition.
2. Establish project teams.
   — Each team consists of about 15 students and must be a mix of upper- and lower-classmen.
3. Establish timelines.
   — Timelines correspond to the vehicle competitions, starting the semester before the competition registration deadline.
4. Foster student-centered, collaborative research.
   — A team leader works closely with his or her group.
   — The faculty advisor exists for consultation.
5. Expose teams to national and international competitions.
   — The competitions instill pride in engineering and a close student network.

EVP's PL-TL Goals (adapted from De la Hoz, 2009):

- Improvement of oral and written communication skills.
- Application of classroom knowledge to workroom settings.
- Encouragement of teamwork through shared and defined responsibility.
- Promotion of ethical, professional attitudes.
- Development of self-motivation.

At the completion of each project competition, the student team leaders and the faculty advisor have several meetings to discuss the highs and lows of the project. They talk about different ways the team can improve in design, machinery, fundraising, teamwork collaboration, and team leadership. In this way, they complete a type of student evaluation which will benefit the next competing team.

The Experimental Vehicles Program at Middle Tennessee State University creates an environment that allows upper level students' knowledge to be tested while stimulating freshmen and sophomores into learning the fundamentals of engineering. Freshmen students are paired with senior mentors; together these teams are required to complete all aspects of the projects. Modern mentoring relationships have expanded to include focusing on the development of job-related skills [13]. Seniors acquire leadership and project management skills, while exercising their engineering creativity based upon their prior knowledge of practical workings. Freshmen and sophomores gain multiple hands-on experiences and are able to see the engineering principles taught in the classroom being put into practice.

The essential factor of the EVP retaining students in the Engineering Technology department lies in the infrastructure of the PL-TL model which enables students to create a bond on the basis of similar interests. Through close interaction and daily activities, members create a support unit within themselves which creates a strong team. The design of the PL-TL model encourages mentoring in that upper-level students advise younger students on a wide variety of subjects. When members sense they are a part of something exceptional, they are compelled to continue even when they are faced with tough obstacles. The support that each member gives and receives is essential to the retention rates of the department.

Industry needs experienced engineers. "The U.S. Bureau of Labor Statistics predicts that industrial engineering will be among the fastest growing engineering disciplines in the next two years, with a growth of 20 percent over the decade" [14]. MTSU is doing its part to supply industry and help meet this need. To the best of the department's knowledge, those who were involved in the EVP have 100% job placement. This statement is reinforced through personal contact maintained between the faculty advisor and former students. Students found that during the job interview, they were frequently asked questions regarding their experience with projects, especially how they performed within team settings.

According to the enrollment record of the Engineering Technology Department at MTSU, undergraduate enrollment has been on the rise since success spread about the first EVP project in 2003 [15] (Figure F).

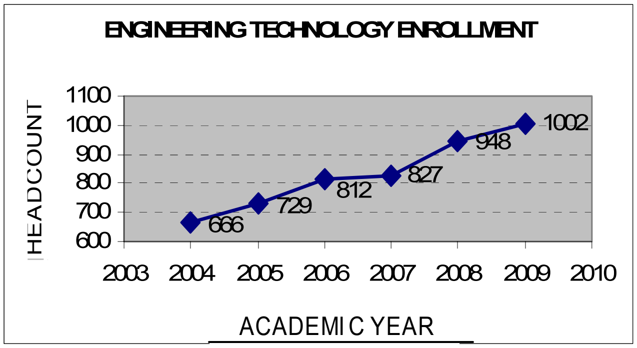

Figure 6. Engineering Technology Enrollment, 2004-2009

Competition Results and Benefits

A key benefit of this program is the element of national competition. Along with prestige, it offers far more excitement and demands much more innovative thinking than the usual undergraduate project. Hands-on research requires the students to think innovatively to design new, competitive projects each year. They must employ quality communication skills in order to collaborate with the team and be successful. Students learn the value of perseverance, the pride associated with a job well-done, and the joy of sharing their excitement with others.

The Solar Vehicle was MTSU's first experimental vehicle project to be entered for competition. After years of using different parts and equipment, the 2003 Solar Vehicle team placed first within its division at the international Solar Bike Rayce. The Bike's components are similar to those used in more recent models. A competition of this caliber is not only a fun experience, but the innovative thinking skills and dedication required for this achievement carry far into a student's career. This first successful competition has provided incentive for future projects, which in turn provides more valuable skills and recognition for résumés [4]. Therefore, these experimental vehicle projects help students attain the career of their choice. A student's active involvement in the EVP equates to one or two years of hands-on experience in the field of engineering.

Through the EVP, students are able to apply the following knowledge and skills learned from a variety of their undergraduate engineering technology courses:

- Acceleration and Braking
- Alternative Energy
- Electrical Components
- Water and Land Maneuvering
- Suspension and Stability
- Mechanical Components
- Top Speed
- Endurance
- Teamwork
- Hill Climbing
- Design
- Cost Report

These special research projects are an excellent way for students to relate real-life concepts to engineering and engineering technology classes. Students learn to design and implement new initiatives within the university and industrial partnerships, while exploring new technologies and practicing skills that meet real-world challenges. The projects are not merely technically challenging, but involve project management challenges in the form of teamwork, planning, and resource allocation [7]. Engineering professors are able to tailor the projects to meet the needs of their own students which provide them a real-world experience. Such experiences greatly add to a résumé because they show that the students are capable of completing a task from start to finish [4].

Apart from the excitement of competitions, students also benefit from the projects through development of professional communication skills. Effective communication is crucial between team members who design and construct the experimental vehicles. Team members must also communicate with the judges of national and international competitions as their vehicles are presented. The professional communication skills developed benefit the students as they are working on the projects as well as when they graduate and are searching for a job [4]. Employers are interested in well-rounded individuals who are able to conduct research, complete a project, and effectively communicate their ideas to others. The EVP reinforces these qualities in each team member [5].

The experimental vehicle projects benefit everyone involved: students, department, university, and local industry. The undergraduate research experience EVP participants gain exemplifies how they perform and is valuable on résumés. Positive media attention has been brought to MTSU's Engineering Technology department through the EVP, and the projects have become a powerful recruitment tool between undeclared students at MTSU and transfer students from other colleges and universities. Local industries that support the teams either with parts, donations, or both are allotted advertisement space on the vehicles when they compete. EVP is a win-win situation for all [4].

Dissemination

To disseminate their engineering experiences, the EVP teams host visits by area middle and high schools to teach the students about various elements of the vehicles. The teams have also visited the schools to give demonstrations with the vehicles. Regardless of where the demonstrations are given, young students are always excited about the vehicles and eager to learn more. By showcasing these eye-catching, real-world examples of engineering and engineering technology to local schools, the EVP has increased the number of students wishing to pursue a career in this field. The vehicles help introduce students to the innovative applications of math and science, as well as related career possibilities [4].

Demonstrations, seminars, and summer research workshops are examples of some events that the EVP has hosted for local middle- and high-school students. The unique vehicles always garner enthusiasm and interest from the audience. Sometimes the students are even able to operate the Solar Vehicle or Moonbuggy. The engineering technology faculty plan to expand the number of such events, not only because they inspire young minds to think innovatively but also because they have a direct effect on enrollment within the department.

The EVP has formed many partnerships between the university and local industries. Students participating in the EVP have become familiar with some of these industries through collaboration on the projects. Local industries have awarded stipends, internships, and future job placements for upper-level students. Contacts made can also lead to partnerships on future projects [4].

In the future, the EVP will take strides to expand upon and form new partnerships with area high schools, universities, and industries in order to encourage the community to think innovatively. Engineering Technology faculty members at MTSU believe that the generation of enthusiasm among potential students and the proper training of current students for careers in science and technology are two important ingredients of success for education within this discipline [4].

Summary and Conclusion

The Experimental Vehicles Program (EVP) of the Engineering Technology Department at Middle Tennessee State University (MTSU) promotes innovative thinking through applied research projects. These projects are novel in variety, duration, and span across student ages. These three innovative characteristics of the program enable a method of Peer-Led Team-Learning (PL-TL) to be utilized. PL-TL, in turn, enhances the engineering education of each student as well as fosters growth of the department.

The Experimental Vehicles Program not only enhances classroom learning but also teaches students things they ordinarily would not learn in a class, like organizational, leadership, and communication skills. The EVP students take the innovative thinking skills they have perfected through the projects and teach other students so that they may also think innovatively and succeed. Recruitment levels in ET have increased largely due to on-campus events hosted by the EVP, including high-school events that focus on stimulating interest in science and technology. The EVP members are able to give advice to high-school students and display opportunities that the program has opened up to them. These events expose students who are undecided about a major to the Engineering Technology department.

These projects provide students with an opportunity to experience hands-on research, to share their innovative projects with the community, to compete in national and international competitions, and to develop important thinking skills applicable to future jobs in the engineering technology field. Perhaps most importantly, the projects provide a niche for modern creative minds which are yearning for more opportunities to think innovatively.

The skills learned through participating with the EVP help propel students to graduate, and provide a solid foundation for a future career. Overall, the Experimental Vehicles Program at MTSU inspires innovative thinking and benefits all who are involved.

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A WIRELESS MESH NETWORK BASED AUTOMATIC UTILITY DATA COLLECTION SYSTEM

Jin Zhu, University of Northern Iowa; Recayi Pecen, University of Northern Iowa

Abstract

In this paper, we propose a novel Automatic Meter Reading (AMR) system using the IEEE 802.15.4-compliant wireless networks. The mesh network-based automatic utility data collection system (AUDCS) provides a cost-efficient solution by exploring the self-organization, self-healing capabilities of the mesh networks and utilizing the state-of-art semiconductor chips and radio transceivers compliant with IEEE 802.15.4 standard. An IEEE 802.15.4 network may operate in either the star topology or the peer-to-peer topology. The peer-to-peer mode is chosen for the AUDCS system because it is more flexible and robust than the centralized implementation, based on the star topology. In the AUDCS system, each node has the capability of two-way communications and may relay or forward the data for the neighboring nodes within the transmit range, hence eliminating the need to install dedicated communication nodes to collect data. In addition, mesh networking provides the self-healing function by automatically re-routing via other neighboring nodes. The application data characteristics are exploited in the data gathering and dissemination to achieve better energy efficiency. Experimental results of the prototype test-bed will be presented and discussed.

Introduction

Automatic Meter Reading (AMR) is an electronics system that provides functionalities of remote meter reading of usage rate of electricity, gas, and water and generates billing to charge customers according to supplied amounts for energy suppliers. Utility service providers are increasingly interested in taking the advantages of AMR [1-4]. The majority of the current AMR is implemented by collecting data walk-by or drive-by, which limits the additional services to be added. With the rapid advancement in semiconductor and communication technology, it is possible and feasible to have a metering network to gather data remotely and efficiently. Most recently, smart meter reading using ZigBee Technology has drawn much attention [5-7]. Smart metering via an advanced metering infrastructure (AMI) has been a hot trend in the utility industry because of the promises of AMI technologies in enhanced customer service and greater energy efficiencies [6]. This not only benefits the utility company, it also allows customers to monitor their daily energy usage and optimize their energy usage.

In the AMR systems, the collected data can be transmitted through the power line carrier (PLC), the existing wired Internet infrastructure, and RF wireless communications [2, 3]. The PLC communication system uses a built-in power modem that receives and transmits data over the power lines. The carrier can communicate voice and data by superimposing an analog signal over the standard 50 or 60 Hz alternating current (AC). The PLC method is good for low-density scenarios, such as in rural areas. The utility company may also use the existing Internet network to communicate to the meter, by either making use of the consumer's personal computer modem or integrating a modem to the metering system. The utility company will dial the modem to start transferring data. The shortcoming of this method is that the existing Internet service has to be available.

In comparison with the PLC and wired Internet, wireless communications have the advantages of cable-free, easy, flexible installation and maintenance. One commonly used method is to use the existing cellular network. For example, GSM (Global System for Mobile communications) systems support Short Message Service (SMS) [2, 8] or the 3G data service for data transmission from the meters. The meters are either built with a data network interface or connected to a local area network, which uses a communication gateway to access the cellular network. This method requires the availability of the digital cellular SMS or data service. The data interface module is also relatively expensive. Another restriction is that you have to subscribe to the SMS service from the wireless company, which adds extra cost and may prevent the system from real-time monitoring. Alternatively, we propose a wireless mesh network-based AMR system that is more cost efficient and able to collect real-time data.

Automatic Utility Data Collection System Using Mesh Networks

In this paper, we propose an automatic real-time utility data collection system using wireless mesh networks (AUDCS-mesh). The proposed system utilizes the two-way communication between AMR nodes to forward the readings back to a collection center or AMR server in a mesh network. Because the meters at residential areas are not far away from each other, each AMR node is able to relay or forward the data for its neighboring nodes to the direction of the collection center via short-range wireless communication. Data will eventually reach the collection center. The system will not be limited by the service availability of the cellular networks. The conceptual system design is illustrated in Figure 1.

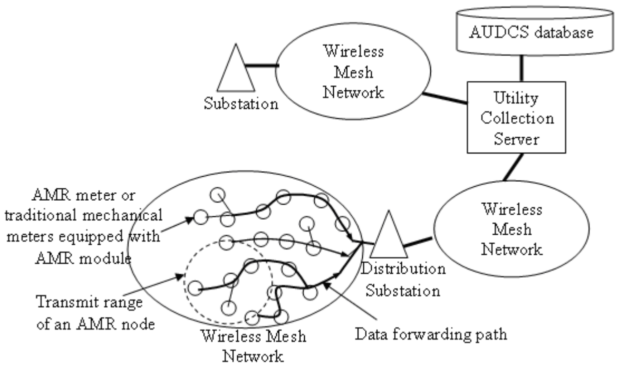

Figure 1. AUDCS Mesh Network System

The ad hoc communication mode is used in the self-organizing AUDCS mesh networks. Unlike the other centralized implementation, the mesh network implementation is more flexible and robust [9, 10]. In this system, each node has the capability of two-way communications and can forward the data for the neighboring nodes within the transmit range. It eliminates the installation of dedicated communication nodes to collect data. The self-organization feature means AMR nodes will become connected and start to collect data without human intervention once they are deployed. Each node selects appropriate relay neighbors based on specified criteria.

In addition, mesh networking also provides the self-healing function by automatically re-routing via another neighboring node. For the centralized approach, once a specific communication node fails, such as the AMR node equipped with a wireless adapter, all the nodes belonging to this cluster will not be able to transmit meter readings back to the collection center. Figure 2 illustrates the self-healing capability of mesh networks. In Figure 2-(a), the data of end node 1 are transmitted back to the collection center via the route 1-2-3-4-5; when a node fails (here assuming node 3, as shown in Figure 2-(b)), the communication links associated with node 3 cannot be used anymore, and the data from node 1 will be automatically rerouted back to the collection center via another path 1-6-7-8-5.

The AMR module prototype adopts the IEEE 802.15.4-compliant transceivers and ZigBee stacks. Before we continue to explain the implemented system, we will briefly discuss the IEEE 802.15.4 standard and ZigBee protocol stacks.

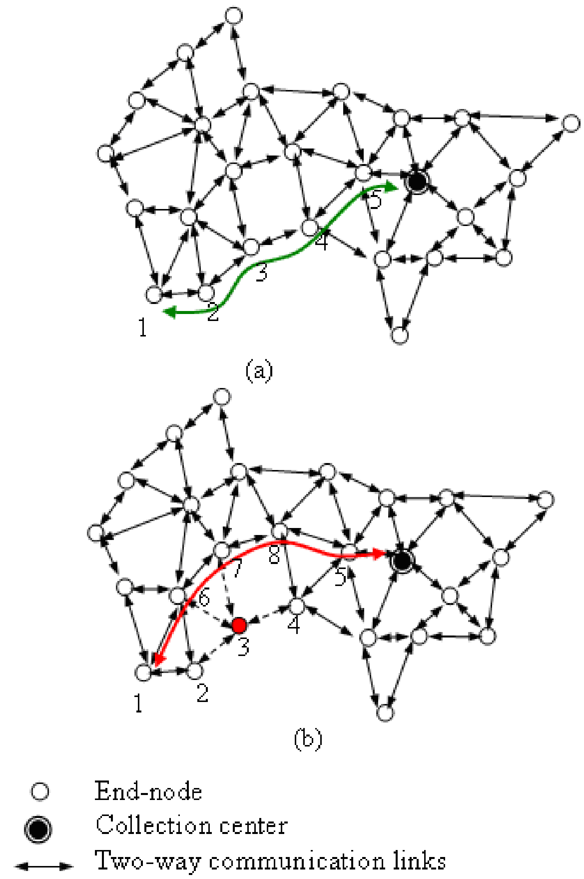

Figure 2. Self-healing of Wireless Mesh Networks

IEEE 802.15.4 Standard and ZigBee

The IEEE 802.15.4 standard defines the protocol and interconnection of devices via radio communication in a personal area network (PAN) [11]. It operates in the ISM (Industrial, Science, and Medical) radio bands, at 868 MHz in Europe, 915 MHz in the United States, and 2.4 GHz worldwide. The purpose is to provide a standard for ultra-low complexity, ultra-low cost, ultra-low power consumption, and low-data-rate wireless connectivity among inexpensive devices [11]. The standard uses carrier sense multiple access with a collision-avoidance, medium-access mechanism and supports star and peer-to-peer topologies. The media access is contention based, and it is possible to allocate time slots via the PAN coordinator to devices with time-critical data. The maximum raw data rate is 250 kilo-bits per second (kbps), which can satisfy various industry control and automation needs for wireless communications. The data rate may be scalable down to the needs of sensors to 20 kbps with extended transmission range.

While IEEE 802.15.4 standard specifies the physical layer and media access control protocols, the upper layers protocols are not covered. ZigBee Alliance [12] is an industrial consortium that promotes IEEE 802.15.4 standard-based technologies and addresses interoperation among different manufacturers. It publishes a specification set of high-level protocols based on the IEEE 802.15.4 standard (2003). ZigBee technology may be used in various applications in industrial controls, embedded sensors, medical devices, smoke and intruder alarms, building and home automation, and others. The network is designed to use very small amounts of power so that individual devices might run for one year or more with a single alkaline battery. They may use a mesh or star topology that allows low-power consumption over the sensor network. Based on these features provided by IEEE 802.15.4/ZigBee, the ZigBee technology is very suitable for our application.

Hardware Design and Implementation

To implement the mesh network, the existing electromechanical meters or the mechanical gas/water meters have to be modified or provide related data for AMR. The traditional meters may be attached with a retrofit module that is capable of converting meter readings to digital signals and transmitting the data back to collection centers. The main components are illustrated in Figure 3. A disk-type electrometrical meter includes a mechanical counter and a gear assembly, and the number of disk revolutions per KWh is fixed for a meter. To get the reading from the dial-meter, we can count the revolution of the disk with the help of a sensor. Possible solutions are using Hall-effect sensors/switches or opto-electronic sensors to generate a pulse for each disk cycle. The pulse is further counted and converted to digital signals by the microcontroller. A microprocessor is needed to process the data, and a radio module is needed for wireless communications.

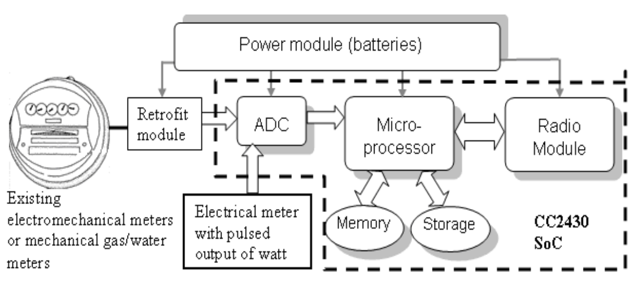

Figure 3. AMR End Node Architecture

The widely used diaphragm gas meter and the nutating disc water meter can also use the same mechanism to obtain the readings. As we can see in Figure 3, several meters located at the same location may be connected to the one AMR module so that cost may be further reduced. To achieve our design objectives, up-to-date, low-cost, ultra-low power consumption ICs and the IEEE 802.15.4-compliant radio transceivers will be considered.

A. Transceiver and System-on-chip Solution

In our prototype design, we adopt the IEEE 802.15.4 standard-compliant transceiver CC2430 from Texas Instruments [13]. CC2430 provided a system-on-chip (SoC) solution for 2.4GHz IEEE802.15.4/ZigBee. It combines the excellent performance of the leading CC2420 RF transceiver with an industry-standard enhanced 8051 microcontroller (MCU), with 128 KB flash memory and 8 KB RAM. Both the embedded 8051 MCU and the radio components have very low power consumption, as shown in Table 1. The CC2430 also includes digital RSSI/LQI (Receive Signal Strength Indicator/Link Quality Indication) support and a 12-bit ADC (Analog-to-Digital Converter) with up to eight inputs and configurable resolution. Combined with the ZigBee protocol stack (Z-Stack) from TI, the CC2430 is one of the most competitive ZigBee solutions. The cost of the chip is approximately $5. For larger volumes, the cost may be even lower. It enables the AMR node with ZigBee wireless communication to be built with very low total bill-of-material costs.

Table 1. Power Consumption of CC2430EM Reference Design with VDD = 3.0V and 25°C [13]

Operation Mode	Typical Current Consumption
MCU Active, 16 MHz, Low MCU Activity	4.3 mA
MCU Active, 32 MHz, Medium MCU Activity	10.5 mA
MCU Active Receive Mode	26.7 mA
MCU Active Transmit Mode (0dBm)	26.9 mA
Power Mode 1: Digital Regulator on, Power on Reset and Sleep Timer Active	190 μA
Power Mode 2: Digital Regulator off, Power on Reset and Sleep Timer Active	0.5 μA
Power Mode 3: No Clock. Power on Reset Active	0.3 μA

Several 2430EM boards are used to develop the system [13]. EM is shown on the SmartRF04 Development Board in Figure 4. This board is used for programming EM and serving as an emulator to present EM’s features directly, such as range testing, RF measurements, and prototype development. Battery board is used to power the EM with the use of two AA batteries. The battery board is 1.5 inches by 1.5 inches. The EM battery board is used in the end node prototype to collect data from the electric meter.

Figure 4. TI CC2430EM Module on the SmartRF Development Board

B. AMR Node Prototype

Each prototype of the implemented AMR nodes includes a Multitek kilowatt hour meter, a battery board with CC2430, and several loads. The coordinator node is connected to a PC via a serial port to display and store the collected meter readings. The Multitek kilowatt hour meter has pulsed analog output of instantaneous watts. The analog signal is converted to digital signal by the ADC module in CC2430 using differential analog inputs for further processing. A sample small mesh network with five nodes has been set up to test the system.

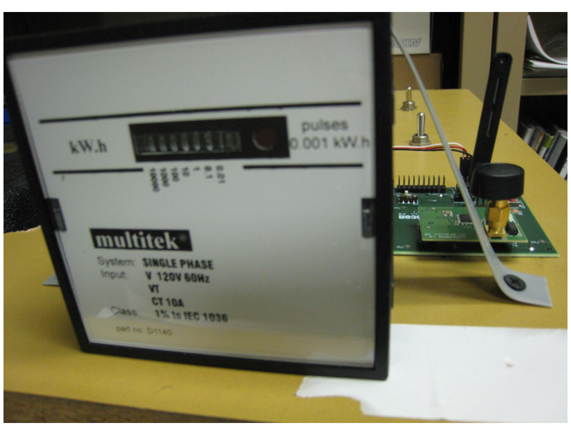

Figure 5. End Node Prototype -- CC2430EM Battery Board Used to Collect Power Usage Data from a Kilowatt Meter

Communication Protocol Design and Implementation

To put the mesh networks into operation for real-time data collection, appropriate communication protocols have to be designed and implemented. Many energy-efficient data-gathering and dissemination approaches have been proposed in literature for wireless sensor networks (for example in [14-16]). The basic concepts of the self-healing automatic routing selection are described as follows. Each node detects pilot signals from its neighboring nodes and determines which communication link to use for data transmission. When a node fails, its neighbors will remove it from the relay list and select another neighbor node for communication based on certain criteria, such as signal strength, distance from the collection center, or the available energy. Different algorithms may be implemented to determine the optimal path for data collection.

The data-gathering/collection approach may be carried out on a cluster-based, tree constructive-based, or chain-based mesh network. The selection of appropriate network organization depends on the physical location of AMR nodes and the data features. In addition, distributed data compression and aggregation methods may be implemented to improve the efficiency of data gathering. The scalability and fault-tolerance of the protocols are also important issues that need to be addressed.

The communication protocol is developed using IAR Embedded Workbench EW8051 based on TI's Z-stack. The routing protocol implementation is summarized as follows. Each node has an ID, address, distance (number of hops to coordinator), and neighbor list. The neighbor list consists of the neighbor's ID, neighbor's address and distance, and optional signal strength. Each node broadcasts its ID, address and distance periodically, so every node updates its neighbor list accordingly. When a node wants to send data, it will directly communicate with the center if its distance is 1 hop away from the coordinator. Otherwise, it will choose the neighbor with the smallest distance.

For the application of utility data monitoring, nodes may send the readings periodically, so a node waits and listens to the medium for a period before starting to send. Although, theoretically, a period can be a few seconds, it is reasonable in practice if a period ranges from 5 to15 minutes. When a period ends, the node changes its state to transmission. In this state, data read from meter via sensors and ADC are prepared to send. An acknowledgment packet must be received after each transmission to make sure that the transmission is made without any problem. The node re-transmits until ACK is received.

Power Consumption Estimation of the AMR Node

Along with the energy-efficient network protocol design, it is possible for an individual device to run for several months to years with a pair of AA batteries, depending on the data sampling or reading rate. Assume that the meter will be read every 5 seconds by the microcontroller, and every 2 minutes the collected readings will be sent back to the collector. Assume it takes 200 ms for each meter reading and 200 ms for other computations. Consider that each meter reading is represented using 2 bytes and the data packet header is 15 bytes, then the time needed to transmit those data every 2 minutes is

$$T_{tx} = (15\,\text{bytes header} + 2\,\text{bytes} \times (\,\#\,\text{of readings}))/\text{data rate}$$
$$= (15 + 2 \times 2 \times 60/5) \times 8\text{bits}/250\text{kbps} = 2.016\,\text{ms}$$

Assume the average transmission for forwarding other nodes' data is three times that of the transmission time for itself, and on average, each node spends a similar amount of time for receiving data $T_{rx} = 2.016 \times 3 = 6.048$ ms. So the overall average current consumption (using the data in Table 1 above) in the 2 minutes is

$$(400\text{ms} \times 10.5\text{mA} \times \frac{2\text{minutes}}{5\text{s}} + + 2.016\text{ms} \times 26.9\text{mA}$$
$$+ 6.048\text{ms} \times (26.9\text{mA} + 26.7\text{mA}))/2\text{minutes} = 0.843\text{mA}$$

Assuming a NiMN AA battery has the capacity of 4800 mAHour, then the lifetime for the each individual device is around 4800mAHour/0.843mA ≈ 237 days. This estimation is based on the assumption that the utility meter is read every 5 seconds.

Conclusions and Future Work

In this paper, we proposed an AUDCS using IEEE 802.15.4-compliant wireless mesh networks. We have discussed the hardware design and software implementation aspects of a five-node system. We will work on a larger network with more nodes for extensive mesh network performance evaluation and comparison with other systems, as well as explore more advanced data aggregation algorithms. Security issues are also a big challenge for mesh networks and need to be addressed. While the AES security co-processor is included in CC2430, it has not been utilized and implemented in the current prototype and will be investigated in the future.

Acknowledgments

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SELLS: A SPACE EFFICIENT LOCAL LOOK-UP SEARCH PEER-TO-PEER PROTOCOL FOR TRUSTWORTHY KEY DISTRIBUTION

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Anthony Weaver, Youngstown State University

Abstract

Unstructured Peer-to-Peer (P2P) networks for content distribution are decentralized and robust. Searching for content in the network is based on the Gnutella protocol. The broadcast search paradigm used by Gnutella is inefficient and generates much traffic overhead from query messages. The Broadcast Updates Look-up Search Protocol (BULLS) based on Gnutella can reduce traffic overhead at the expense of a space inefficient global data structure. Improving BULLS can be achieved by the use of a Bloom Filter (BF). A BF is a space efficient probabilistic data structure for membership queries widely used in protocols and applications. That is, they can be used to efficiently determine if a file is stored at a host. The cost is a small, bounded probability of error called false positive. The false positive rate can be tuned according to application requirements. In this paper, we introduce the use of bloom filters in the design and evaluation of a P2P protocol that enables a Space Efficient Local Look-up Search (SELLS). A space efficient local look-up search is enabled by including bloom filters in the BULLS protocol. SELLS stores all the shared files in the network in a data structure called Inverse Bloom Filter (IBF). Because the bloom filter summarizes the files shared at a particular host, SELLS maintains the confidentiality of the files shared, is space efficient, and reduces traffic overhead by locally searching for files. We also explore the application of SELLS for trustworthy key distribution.

Introduction

Popular unstructured Peer-to-Peer (P2P) networks such as Gnutella distribute content (files) in a decentralized manner, are self-organized, and are robust [1]. Additionally, the advent of wireless and mobile communication has enabled more people to exchange or share files anywhere, anytime on any device. Evidently, for P2P to be widely adopted and deployed on any device, it is of great importance to design space efficient protocols with reduced traffic overhead.

The broadcast search paradigm used by Gnutella is inefficient and generates much traffic overhead from query messages [3,4]. Users in a Gnutella file sharing P2P network search for files by broadcasting queries or flooding the network with queries [9]. Much of the traffic is overhead from the flooding of query messages and the associated queryhit response messages from searches for popular files [3,5]. Many P2P protocols focus on limiting query flooding and do not allow hosts to know what files are shared by other hosts [2].

Recent P2P file sharing networks like FastTrack (i.e., Kazaa) use the concept of supernodes or ultrapeers to proxy search requests from other hosts called leaves and limit flooding [2,4]. Limiting flooding excludes the leaves with low probability of responding the queries from file searches. Ultrapeers store the directory of the files shared by each of its assigned leaves [9]. Although, ultrapeers know the files shared by its leaves, they do not know what files are shared by other ultrapeers. The BULLS protocol, unlike FastTrack, can allow each ultrapeer to determine the entire set of files shared in the network at the cost of a space inefficient global data structure [1]. BULLS' global data structure can be improved to be space efficient by representing the files shared by each host with a Bloom Filter (BF). A BF is a space efficient probabilistic data structure for membership queries widely used in protocols and applications. That is, a BF can be used to efficiently determine if a file is stored at a host. The cost is a small probability of error called a false positive. The upper bound of the false positive rate can be tuned according to application requirements [7,8].

If traffic overhead is reduced and each ultrapeer can efficiently store all the files shared in the network, then flooding would become suitable for a wide range of applications that have not been explored by existing P2P networks. In particular, it is of interest to study a novel P2P application that allows the distribution of secret keys instead of files. A P2P application for distributing secret keys will allow communication between users to be secure and independent of a central authority [11].

In this paper, a new design and evaluation of the BULLS protocol is investigated. The new protocol is called Space Efficient Local Look-up Search (SELLS). SELLS has all the desirable properties of BULLS and a space efficient data structure that stores the shared files. SELLS stores all the shared files in the network in a data structure called Inverse Bloom filters (IBF). IBF uses a Global Bloom Filter (GBF) and a set of Local Bloom Filters (LBF). The GBF stores the files that are improbable to be found or downloaded from the network. Additionally, there is one LBF per host in the network. Each LBF stores the shared files of a given host. Because the bloom filter summarizes the files shared of a particular host, SELLS maintains the confidentiality of the files shared, is space efficient and reduces traffic overhead by locally searching for files. Also, a novel application of SELLS for trustworthy key distribution is discussed.

Protocol Description

Current popular P2P protocols based on Gnutella use the concept of ultrapeers and leaves to reduce the query/queryhit messages exchanged or overhead traffic [2]. Although, the BULLS protocol reduces overhead traffic in most cases when compared to Gnutella, it can be improved by including in its design the new concept of ultrapeers described in the Gnutella protocol version 0.6 [1, 9]. The new protocol description of BULLS which SELLS is based on is represented using a Finite State Machine (FSM). The notation for the FSM diagram used in this paper show the states as vertical lines and transitions as horizontal arrows showing the direction of the transition. The transitions are triggered when the input or condition specified above the arrow is met. The output or actions are specified below the arrow and occur simultaneously while making the transition. The dotted arrows are the initial and final transitions in the FSM. The initial transition does not have an originating state, and final transitions do not have a destination state.

The FSM that describe the new protocol behavior of BULLS is only related to the exchange of messages (i.e., query, queryhits, and updates) as this is considered to be the overhead traffic. Low data rate message exchanges from connectivity maintenance (i.e., ping and pong messages) are not considered in the FSM. File downloads (one per queried file found) are not considered because not only have these been already studied and improved upon [2] these are non-overhead traffic that is useful.

BULLS

BULLS is a P2P Gnutella based protocol that reverses the broadcast search paradigm and explores broadcasting file updates instead of queries. Figure 1 is the BULLS FSM based on Gnutella protocol version 0.6 (Gnutella version 0.6). The FSM shown in Figure 1 only describes the behavior of an ultrapeer host. Ultrapeer hosts, and not leaf hosts, exchange overhead messages (i.e., query and queryhit messages). The behavior of a leaf host in BULLS is the same as in Gnutella; that is, only generating query message overhead traffic. The queryhit message response from an ultrapeer to a query message from one of its leaves is omitted from the FSM because it does not impact the overall overhead queryhit traffic. In addition, the data structure used by BULLS is only stored by ultrapeer hosts. Each ultrapeer host stores in the data structure its own share file listing (set of shared files) and the shared file listing of the leaf hosts connected to it.

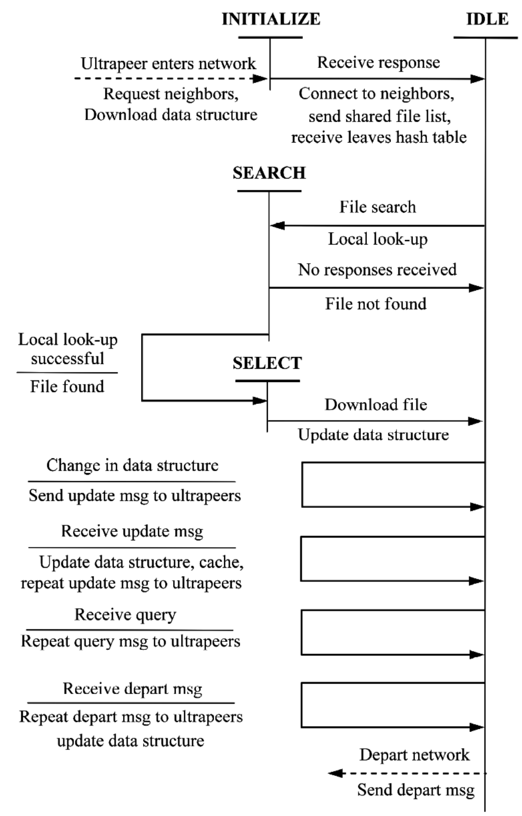

Figure 1. BULLS FSM based on Gnutella version 0.6

The four states for the improved version of BULLS with ultrapeers are defined as in [1]. They are **INITIALIZE**, **IDLE**, **SEARCH**, and **SELECT**. The detailed description of the states and transitions is given below:

• **INITIALIZE**: An ultrapeer host entering the network can be in this state by requesting to receive neighbor addresses of ultrapeers (neighbors) or leaves and downloading the data structure from a specialized bootstrapping host. On the reception of a response with the requested neighbor addresses, the ultrapeer host connects to its neighbors, forwards its own shared file list (one update message per file shared) and the share file listing of the leaves (one update message per file shared) to ultrapeer neighbors (neighbor host that are ultrapeers) only and transitions to **IDLE**.

• **IDLE**: In this state an ultrapeer host can 1) make a file search by a local look-up in the data structure and transition to **SEARCH**, 2) detect a change in the data structure, repeat to ultrapeer neighbors via an update message the changes in data structure (one update per change) and remain in **IDLE**, 3) receive an update message, modify the data structure with the update received, store it in the cache, repeat it (send update message to all ultrapeers neighbors except the one from which the message was received), and remain in **IDLE**, 4) receive a query message from a leaf host, repeat the query to all of its ultrapeer neighbors, and remain in **IDLE**, 5) receive a depart message, update data structure by modifying departing host's row entry and repeat depart message to ultrapeer neighbors, or 6) disconnect from the network by sending a depart message.

• **SEARCH**: In this state the ultrapeer host waits for results from a local look-up and it can 1) transition to **SELECT** if local look-up is successful or 2) transition to **IDLE** if local look-up does not return results.

• **SELECT**: In this state a host is selected from which to download a file (the host can be an ultrapeer or a leaf). The set of possible hosts to select from is returned by the successful local look-up executed in the **SEARCH** state. The ultrapeer host downloads the file, updates its shared files, updates its data structure, and transitions to **IDLE**.

The transitions that impact the amount of overhead traffic generated are the same five transitions that impact the overhead traffic in [1]. The transitions that impact the amount of overhead traffic cause the broadcast of the shared file list and the broadcast of updates when the shared file list is modified, that is when a file is added, deleted or downloaded. Also, the data structure used by the improved BULLS remains the same as described in [1].

SELLS

The behavior of the SELLS protocol is very similar to the BULLS protocol behavior described in Figure 1. SELLS differs from BULLS in the data structure used to store the share file listing (the files shared by each host). SELLS uses a bloom filter to represent the list of shared files by each ultrapeer host and can be used to performed file look-ups in the bloom filter to obtain the list of IP address or hosts from which the desired file can be downloaded.

A bloom filter is a compact randomized data structured for representing a set and supports membership queries (i.e., does an element belong to set S?). A bloom filter has the drawback of allowing a rate of false positives in membership queries [7,8]; that is, a membership query incorrectly recognizes a non-element as a member of a set. A bloom filter is a set $S = \{s_1, s_2, ..., s_n\}$ of n elements and a m-bit array that uses k independent hash functions $h_1, h_2, ..., h_k$ each with range between $\{1, ..., m\}$ where $m > n$ [7,8]. Initially the m-bit array has all bits set to zero. The i^{th} bit in the m-bit array is set to one if and only if there exits an element e in S and some j^{th} hash function such that $h_j(e) = i$. The m-bit array used for the bloom filters may yield a false positive when determining membership of elements and can be used to determine when an element does not belong to a set. If an element v is not in set S, then there is at least one bit in the position in $\{h_1(v), ..., h_k(v)\}$ of the m-bit array that is equal to zero. The probability of a false positive fp for an m-bit bloom filter for a set of n elements and k independent hash functions is

$$fp = (1-p)^k \text{ where } p \approx e^{-kn/m} \text{ [7,8].} \quad (1)$$

The rate of false positives can be controlled to a given tolerance by setting the parameters k, n, and m properly. There is a clear tradeoff between the size of the bloom filter and the rate of false positives. A good practical estimate for k that can yield a wise and low false positive rate is

$$k = \ln 2(m/n) \text{ [7,8].} \quad (2)$$

Thus, to design a bloom filter we only need to know the number of elements to be represented and the size of the bloom filter.

Bloom filters allow the data structure used by SELLS to be more space efficient than BULLS. SELLS uses a compact probabilistic representation or bloom filter for all the files shared by each host instead of representing each file as a separate item. Also, a global bloom filter is used to filter searches with low probability of success. The SELLS's data structure is called an Inverse Bloom filters (IBF). The two components that make the IBF are a set of Local Bloom Filters (LBF) and a Global Bloom Filter (GBF). The IBF used by SELLS is described in Figure 2 and explained in detail below:

• **LBF**: The first component shown in Figure 2 is a table with each row representing the data stored for a host in the network. The columns of the table in Figure 2 are the two basic types of data stored. The first column is the hostname and it is used to identify a host in the network (IP address or host identification number). The second column is the bloom filter representing the file share listing (set of filenames shared) of a host.

• **GBF**: The second component shown in Figure 2 is a bloom filter constructed by applying a generalization of the logical operations (i.e, and, or, and xor). That is, these operations are applied to the bloom filters stored in LBF. The operations will create a bloom filter that will stored the improbable files to be found in the network or the files that are not stored by any host in the network.

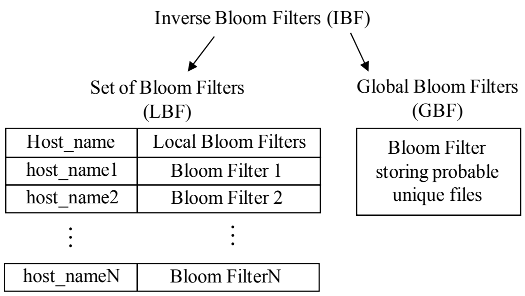

Figure 2. SELLS data structure

When a SELLS host inserts a file in the file shared list, the corresponding bloom filter will be updated by setting the bits obtained from hashing the name of the file inserted. Contrary to a file being inserted in the file shared list, the deletion of a file causes the bloom filter to be reconstructed. That is, each element in the file shared list is inserted in a new bloom filter that will substitute the first one.

Additionally, because SELLS stores the shared file list as a single item instead of separate items, when an ultrapper host enters the network it behaves different from BULLS. That is, forwards its own shared file list (one update message or one bloom filter per shared file list) and the share file listing of the leaves (one update message or one bloom filter shared file list) to ultrapeer neighbors (neighbor host that are ultrapeers) only and then transitions as BULLS does to the **IDLE** state.

Flow Model

The flow models developed in this section result in expressions that are statistics for the storage requirement of the data structure of BULLS (S_{bulls}) and SELLS (S_{sells}) in bytes. Also, expressions for the overhead traffic per host in messages per second for Gnutella version 0.6 ($X_{gnutella}$), improved BULLS (X_{bulls}), and SELLS (X_{sells}) are developed. The flow model for Gnutella version 0.6 (Gnutella) is included as the baseline comparison for theoverhead traffic.
BULLS and SELLS are both based on the same FSM shown in Figure 1. The difference in the overhead traffic between BULLS and SELLS is that BULLS stores a file shared list per host while SELLS stores one bloom filter per host and a single global bloom filter. All flow models are developed as a function of the independent variables described in [1] and the independent variables (N_{lbf}) and (N_{gbf}) representing the size (bytes) of the bloom filters in the data structure used by SELLS. All assumptions for the flow models not explained in this paper are assumed to be as in [1]. The five assumptions for this work are explained below:

1. The flow model for Gnutella and BULLS described in [1] defines the total number of files shared in the network to be $M_{files}N_{hosts}$ given that each host shares M_{files} files [1]. Thus, for the improved BULLS protocol and SELLS, it is assumed that at least M_{files} files are shared by each ultrapeer host. Also, it is assumed that N_{hosts} is the total number of ultrapeer hosts in the network since ultrapeers are the hosts that generate the overhead traffic.

2. For simplicity, it is assumed that there are an equal number of leaves connected to each ultrapeer and that the total number of files shared by all leaves connected to an ultrapeer is M_{files}. The total number of files shared by all the leaves in the network is $M_{files}N_{hosts}$ as each group of leaf hosts connected to an ultrapeer shares the same number of files as the ultrapeer itself. This is a reasonable assumption given that the ultapeer capacity must at least be equal to the aggregated capacity of its leaves. The total number of files in the network is $2M_{files}N_{hosts}$.

3. It is also assumed that ultrapeers have a degree D(total number of ultrapeer hosts connected to an ultrapeer) and that the number of leaves connected to any ultrapeer is approximately $5D$[2,3,6,8].

4. The rate of file searches per host (ultrapeer or leaf), R_{search}, corresponds to the total file query search activity initiated by the user at a host (successful and unsuccessful searches). It is assumed that search activity is the same for a leaf and ultrapeer host. Search activity depends on the user and not on the host capability.

5. In the improved version of BULLS and SELLS, $2M_{files}$ messages are required to broadcast the entire shared file list of an ultrapeer (M_{files} files) and the entire shared file list of all the leaves (M_{files} files) of the ultrapeer. Additionally, the ultrapeers have the rate of updates as $R_{updates}$ but a leaf update rate is less than that of an ultrapeer. It is a requirement that ultrapeers have more bandwidth available than leaves [9]. Thus, it is reasonable to assume that leaves have half or less the rate of updates of an ultrapeer, that is $0.5R_{updates}$.

Storage Requirements of BULLS and SELLS

In the improved BULLS version described above, each host must store the data structure that contains all of the names of all files stored in the network by all hosts (ultrapeers and leaves). The total number of files shared by all the leaves in the network is $M_{files}N_{hosts}$ and the total number of files shared by all ultrapeers in the network is $M_{files}N_{hosts}$. Thus, the total number of files shared in the network is $2M_{files}N_{hosts}$. The size of this data structure (in bytes) for BULLS with ultrapeers or the improved BULLS is

$$S_{bulls} = N_{hosts}\left(N_{hostname} + 2M_{files}N_{filename}\right). \quad (3)$$

The first term is the number of bytes required to store all the *hostnames*. The second term is the total number of bytes necessary to store the *filenames* of all the files shared by each host.

For SELLS the size of this data structure (in bytes) is

$$S_{sells} = N_{hosts}\left(N_{hostname} + N_{lbf}\right) + N_{gbf}. \quad (4)$$

The first terms is the number bytes required to store the *hostnames*. The second term is the total number of bytes used to store the set of *filenames* shared by each host. Because each set of *filenames* shared by a host is represented by a bloom filter of size N_{lbf} bytes, the total number of bytes necessary to store all the *filenames* shared by all host in the network is $N_{hosts}N_{lbf}$. The third term is the total number of bytes (N_{gbf}) of the bloom filter (GBF) representing the improbable files to be found in the network.

Overhead Traffic of Gnutella, BULLS, and SELLS

The overhead message rate for Gnutella, BULLS, and SELLS are based on the overhead traffic equations described in [1]. The overhead message rate per ultrapeer host for Gnutella is

$$X_{gnutella} = R_{search}D\left(N_{hosts} - 1\right) + R_{search}DN_{hosts} + R_{search}N_{hops}P\left(N_{hosts} - 1\right). \quad (5)$$

The first term is the rate of query messages seen by each ultrapeer host and initiated by an ultrapeer host. Each ultrapeer host receives D copies of each query message sent by every other ultrapeer host. The second term is the rate of query messages seen by each ultrapeer host and initiated by a leaf host. Each ultrapeer receives D copies of each query message. The third term is an approximation of the rate of queryhit response messages seen by each ultrapeer host. Queryhit messages are returned via the backward path a query message was received, thus each queryhit message travels on average N_{hops} and thus is received by N_{hosts} ultrapeer hosts.

The overhead message rate per ultrapeer host for BULLS is

$$X_{bulls} = 0.5R_{update}D(1.5N_{hosts} - 1) + D\left(N_{hosts}/T_{stay}\right)\left(2M_{files} + 1\right) \quad (6)$$

The first term is the rate of flooded directory update messages seen by each ultrapeer host as a result of ultrapeer hosts adding or deleting a shared file. The second term is the rate of flooded directory update messages seen by each ultrapeer host as a result of leaf hosts adding or deleting a shared file. When all searches are successful (i.e., a file is found) and files are not otherwise added or deleted to a host (ultrapeer or leaf), $R_{updates}$ will be the same as R_{search}. The third term is the rate of flooded update messages seen by each ultrapeer host as a result of hosts entering the network (flooding their entire listing of shared files and share files list of its leaves to all ultrapeer hosts) and from depart messages from departing ultrapeer hosts. It is assumed, as in [1], that the rate in which hosts enter and depart the network is the same. For BULLS, the total number of update messages is the same as the total number of files shared in the network ($2M_{files}$) plus the depart message. Thus, the overhead message rate per ultrapeer host for SELLS is

$$X_{sells} = 0.5R_{update}D(1.5N_{hosts} - 1) + D\left(N_{hosts}/T_{stay}\right)\left(5D + 3\right). \quad (7)$$

The first term and second term, as in BULLS, corresponds to the update messages from an ultrapeer host or leaf adding or deleting a shared file. The third term in SELLS as in BULLS is the rate of flooded updated messages resulting from a host entering or departing the network. SELLS in contrast to BULLS does not flood the network with the entire listing of shared files and share files list of its leaves. SELLS floods the network with one update message representing the complete listing of shared files of a host. Thus, the total number of update messages is the total number of shared file list by an ultrapeer ($5D+1$) and one update message for the GBF. Also, as in BULLS we must add one additional update message for the depart message.

Performance Evaluation

The performance evaluation is based on the flow models previously described and the representative case explained in [1]. The numerical values selected for the overhead traffic variables of Gnutella, BULLS and SELLS are the same values used [1]. The overhead traffic rate is studied as a function of the rate of hosts entering (and leaving) the network for the flow models. The variables $M_{files}, P, D,\ N_{hosts}$, R_{search}, and R_{update} are fixed and T_{stay} (amount of time a host stays connected to the network) is varied from a couple of hours to days.

The numerical results in Figure 3 demonstrate the difference between Gnutella, BULLS, and SELLS overhead traffic as a function of T_{stay}. Figure 3 shows that SELLS has a lower overhead traffic rate than Gnutella and BULLS. From Figure 3, it can be determined that

- SELLS reduces Gnutella's overhead traffic by a minimum of 6% and a maximum of 42%.
- SELLS reduces BULLS's overhead traffic by a minimum of 5% and a maximum of 66%.

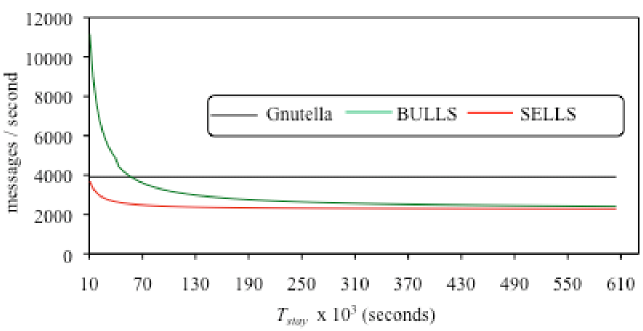

Figure 3. Impact of T_{stay} in overhead traffic

The numerical values for the storage requirements of BULLS and SELLS are based on the values in [1]. We haves selected values for the size of the bloom filters that yield an acceptable false positive rate (i.e., less 0.1 %) and we have selected to use of four hash functions. The size in bytes of the bloom filters are:

- N_{lbf} = 512 bytes or 4096 bits (assuming that the average host stores about 100 files) and the false positive rate is 7.50 x 10^{-5}, this is much less that 0.1%.
- N_{gbf} = 1 Mb or 8,388,608 bits (assuming the total number of files share is less than 8 million files) and the false positive rate is 5.1 x 10^{-20}, which can be considered negligible.

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The numerical results for the representative values used in [1] with T_{stay} = 8 hours and equations 3, 4, 5, 6, and 7 are:

- $X_{gnutella}$ = 3908 messages/second
- S_{bulls} = 7.83 x 10^8 bytes
- X_{bulls} = 5755 messages/second
- S_{sells} = 0.42 x 10^8 bytes
- X_{sells} = 2793 messages/second

The data structure size for BULLS and SELLS corresponds to 747 MB and 40 MB, respectively. Given that memory stick sizes are usually 1 GB or larger, the SELLS storage requirement can easily be satisfied at a cost of less than $40. The message rate corresponds to less than 200 Kb/sec, 350 Kb/sec, and 150 Kb/sec for Gnutella, BULLS, and SELLS respectively, which is reasonable for broadband connections with a data rate of several Mb/sec. If T_{stay} = 8 hours then the SELLS overhead traffic rate is 34% less than Gnutella and 39% less than BULLS. In addition, SELLS reduces BULLS storage requirement by 94% at the expense of a false positive rate less than 0.1%.

Trustworthy Key Distribution using P2P networks

P2P networks lack security and protocols to establish trust between peers. Establishing trustworthy key distribution with SELLS requires that each LBF store the trustworthy keys exchanged by a host in the network and that the GBF stores the improbable trustworthy keys. Thus, a host will accept a secure trusted connection if the key is found in at least one LBF and is not found in the GBF. SELLS assumes the existence of a host (Trusty) who has previously securely exchanged secret keys with other hosts (seed hosts). It is assumed that seed hosts have previously exchanged secret keys using a public key exchange protocol. Thus, connecting to the network for the first time has two steps: 1) connect to Trusty and download the GBF and LBF, and 2) establish a trusted communication with the host using the LBF from Trusty.

The feasibility of the key exchange between Trusty and other hosts is can be achieved using the Diffie-Hellman protocol or any other public key exchange protocol [10,11].

Conclusions

SELLS is a new space efficient protocol based on the BULLS protocol. SELLS, like BULLS, reverses the query broadcast paradigm by building a local data structure and enabling local look-up search in a host (i.e., without a broadcast query). The SELLS data structure is more space efficient than the BULLS structure due to the compact representation of the shared file listing using bloom filters. Futhermore, today's Information Technology (IT) systems require protocols like BULLS that are efficient and can be used to establish a trusted communications. In particular, SELLS can be used in IT systems that communicate over the Internet and need to exchange secret keys with geographically disperse/remote users. This allows users to establish a trustworthy communication that will decrease security risks.

The SELLS protocol was designed and evaluated using flow models. Numerical results based on a representative case show that SELLS needs 94% less storage than BULLS and that SELLS has less overhead traffic when compared to Gnutella and BULLS.

For a representative case, it was shown that SELLS reduces Gnutella's overhead traffic by a minimum of 6% and a maximum of 42%. Also, SELLS reduces BULLS's overhead traffic by a maximum of 66% and a minimum of 5%. The SELLS protocol was also designed with the goal of enabling a novel application for trustworthy key distribution.

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Biographies

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A REAL-TIME DSP-BASED OPTICAL CHARACTER RECOGNITION SYSTEM FOR ISOLATED ARABIC CHARACTERS USING THE TI TMS320C6416T

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Abstract

Optical Character Recognition (OCR) is an area of research that has attracted the interest of researchers in the past forty years. Although the subject has been the center topic for many researchers along the years, it remains one of the most challenging and exciting areas in pattern recognition. Since Arabic is one of the most widely used languages in the world, the demand for a robust OCR for this language could be commercially valuable. There are varieties of software available for Arabic OCR. However, there is little work done in the area of hardware implementation of Arabic OCR where speed is a factor. In this research, a robust DSP-based OCR is designed for recognition of Arabic characters. Since the scope of this research is focused on hardware implementation, the system is designed for recognition of isolated Arabic characters. An efficient recognition algorithm based on feature extraction and using a Fuzzy ART Neural Network as well as the hardware implementation is also proposed in this research. A recognition rate of 95% is achieved.

Introduction

Optical Character Recognition, usually referred to as OCR, is the process of converting the image obtained by scanning a text or a document into machine-editable format. OCR is one of the most important fields of pattern recognition and it has been the center of attention for researchers in the last forty years [1].

The goal is to process data that normally could be processed only by humans with computers. One of the apparent advantages of computer processing is dealing with huge amounts of information at high speed [2]. Some other advantages of OCR are: reading postal addresses off envelopes, reading customer-filled forms, archiving and retrieving text, digitizing libraries, etc. Using OCR, the handwritten and typewritten text could be stored in computers to generate databases of existing texts without using the keyboard.

The modern version of OCR appeared in the middle of the 1940's with the development of digital computers [3]. Since then several character recognition systems for English, Chinese and Japanese characters have been proposed [4, 5, 6]. On the other hand, developing OCR systems for other languages such as Arabic didn't receive the same amount of attention.

Arabic is the official language of all countries in North Africa and most of the countries in the Middle East and is spoken by 234 million people [7, 8]. It is the sixth most commonly used language in the world. While spoken Arabic varies across regions, written Arabic, sometimes called "Modern Standard Arabic" (MSA), is a standardized version used for official communication across the Arab world [9]. The characters of Arabic script and similar characters are used by a much higher percentage of the world's population to write languages such as Arabic, Farsi (Persian), and Urdu [10]. Therefore, an efficient way to automate the process of digitizing Arabic documents such as books, articles, etc., would be highly beneficial and commercially valuable. A 2006 survey cites that the first modern Arabic OCR approach took place in 1981 where Parhami and Taraghi presented their algorithm which achieved a character recognition rate of 85 percent. Since then, many attempts have been taken place and there have been numbers of commercial OCR products available in the market. However, there is little effort done in implementing a hardware-based Arabic OCR device that has a smallfoot print and could be easily carried around.

This research aims to design and implement an efficient hardware-based OCR using image processing and DSP techniques. The advantages of this OCR system include, but are not limited to the following:

- Small footprint
- Light and easy to carry
- Low power consumption
- High speed performance

Characteristics of Arabic Script

One of the reasons for slow advancement in Arabic OCR is the characteristics of this script that make it more challenging than other languages. Some of these characteristics are listed below:

- The Arabic script is cursive.

- Characters can have different shapes in different positions of a word.
- Most letters have one, two, or three dots.
- A word is composed of sub-word (s).

In addition to the above characteristics, the Arabic font is written/read from right to left. These characteristics have made the progress of Arabic OCR more complex and difficult than OCR for other languages.

Preview of Existing Work

Typewritten vs. Handwritten Recognition

The problem of character recognition can be divided into two major categories: typewritten and handwritten. As their names describe their natures, typewritten recognition recognizes a document that has been previously typed and scanned prior to the recognition progress. Such a system would be used as a way to digitize books, documents and papers in libraries, government, or companies. In handwritten recognition however, the system attempts to recognize a text that has been written by a human (not a machine). This is usually harder due to the fact that there is no standard way of writing and the handwriting of each person is different from the others. As a result, the recognition rate achieved for handwritten recognition systems is lower than the typewritten.

Offline vs. Online Text Recognition

Character recognition systems may be further categorized as offline and online recognition systems. In offline recognition, the image of the type or handwritten text is acquired through scanning using regular optical scanners. The image then is read by the system and is analyzed for recognition. In online recognition systems the input is an image of a hand-printed text which is usually acquired from a tablet computer or pen-based devices such as cell phone and sign pad. Online recognition is a fast growing technique for convenient human computer interface and it has a lot of advantages. For example, it could be used to help people such as computer novices and old people to conveniently use a computer. It also makes a small portable computer (PDA, handheld PC, palm PC, etc.) possible because there is no need for keyboard or keypad. In this research, the developed system is designed for typewritten, offline character recognition; therefore the discussion will be focused on this area.

Basic OCR System's Architecture

Any offline OCR system contains of all or part of the following steps:

- Image Acquisition
- Preprocessing
- Line Segmentation
- Word Segmentation
- Character Segmentation
- Recognition
- Post Processing

Proposed Algorithm

Figure 1 shows the block diagram of the proposed algorithm.

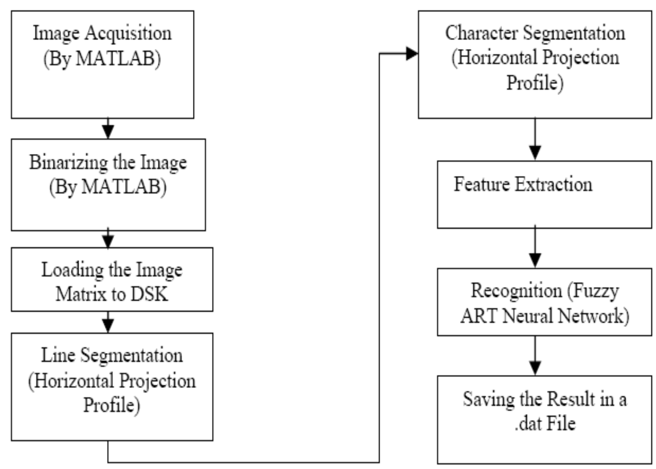

Figure 1. The block diagram of the proposed algorithm

Image Acquisition

The process starts by acquiring the image. The text is scanned using a 300 dpi scanner and the image of the text is saved as a .bmp file in a computer running MATLAB program. MATLAB is used to read the image and convert it to a black and white format. The pixel values of the binary image are saved in a text file. The pixel values are then used to create a header file to represent the image in the main program. As shown in figure 2, the scanned image always contains noise that usually appears as an extra pixel (black or white) in the character image. If the noise is not taken into consideration, it could lead the process to produce an incorrect answer.

Figure 2. Letter "faa" corrupted by noise

Line Segmentation

When the image matrix is ready to be processed, the first step is to isolate each line of the text from the whole document. A horizontal projection profile technique is used for this purpose. The program scans the image horizontally to find the first and last black pixels in a line. Once these pixels are found, the area in between these pixels represents the line that may contain one or more characters. Using the same technique, the whole document is scanned and each line is detected and saved in a temporary array for further process.

Character Segmentation

Once each line of the text is stored in a separate array, using vertical projection profile, the program scans each array, this time vertically, to detect and isolate each character within each line. The first and last black pixels that are detected vertically are the borders of the character. It possible that when the characters are segmented, there is a white area above, below, or both above and below the character, except for the tallest character such that its height is equal to the height of the line. Since the edges of each character box are needed for recognition purposes, another horizontal scan is run to detect the top and bottom of the character and isolate the area that contains only the pixels of the character.

Feature Extraction and Recognition

At this point, the program has isolated each character in the document and the matrix representation of each character is ready to be processed for recognition purposes. In this research, several methods are examined to find the most suitable method for recognition. Additionally, several factors determine the efficiency of the recognition algorithm. The most important factors are the speed of the process and the accuracy of the result. Feature extraction, as discussed earlier, at this time of the process is a matrix of pixel values which contains the four borders of each character image is extracted by the program and has to be recognized as shown in figure 3.

Feature selection is one of the most critical issues in character recognition as the recognition rate is dependent on the choice of features. Every character has some features that distinguish it from the other characters. Some of the famous features used for character recognition are loops, holes, strokes, vertical lines, cusps, etc. The majority of previous works used these features, as they appeal to human intuitive logic. These works suffer a common drawback, namely, exhaustive processing time. The solution to this issue lies in the selection of an algorithm which effectively reduces image processing time. An optimal selection of features, which categorically defines the details of the character and does not take a long processing time, is implemented to extract some features from the character to be recognized prior to recognition.

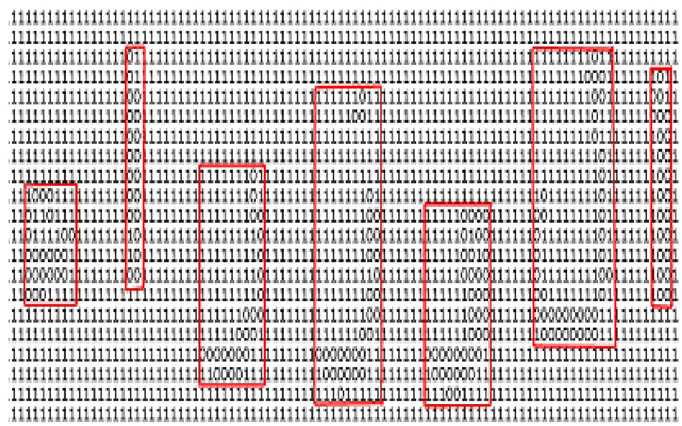

Figure 3. Extracted characters

This way, each character is distinguished with a set of features which are unique for each character and train the Neural Network to learn and use these features to find the result rather than inputting all the pixel values for each character. The features extracted have the following properties:

- Easy to extract, which reduces the complexity of the program
- Distinct, which eases the Neural Network's recognition process
- Independent of font type and size, which is a big advantage since the system is capable of recognizing any font type with any size

There are a total of 14 features extracted from the character in which four are for the whole image as listed below:

1. Height / Width
2. number of black pixels / number of white pixels image
3. number of horizontal transitions
4. number of vertical transitions

The horizontal and vertical transition is a technique used to detect the curvature of each character and found to be effective to serve this purpose. The procedure runs a horizontal scanning through the character box and finds the number of times that the pixel value changes from 0 to 1 or from 1 to 0 as shown in figure 4. The total number of times that the pixel status changes is horizontal transition. A similar process is used to find the vertical transition.

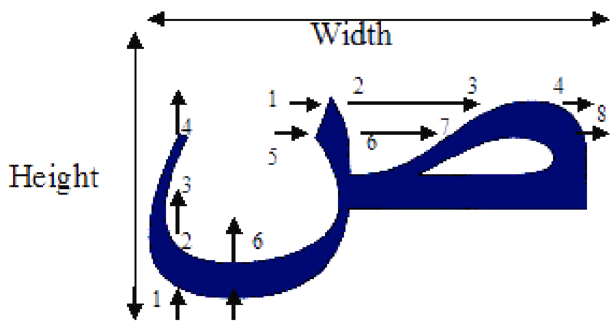

Figure 4. Horizontal and vertical transitions

Furthermore, the image is divided into four regions as shown in figure 5, and the following features are extracted from these regions:

- Black Pixels in Region 1 / White Pixels in Region 1
- Black Pixels in Region 2 / White Pixels in Region 2
- Black Pixels in Region 3 / White Pixels in Region 3
- Black Pixels in Region 4 / White Pixels in Region 4
- Black Pixels in Region 1 / Black Pixels in Region 2
- Black Pixels in Region 3 / Black Pixels in Region 4
- Black Pixels in Region 1 / Black Pixels in Region 3
- Black Pixels in Region 2 / Black Pixels in Region 4
- Black Pixels in Region 1 / Black Pixels in Region 4
- Black Pixels in Region 2 / Black Pixels in Region 3

These features are found to be efficient enough to distinguish between different characters. The extracted feature vector is to train the Neural Network.

ART Neural Network

The training set database has to be generated for the network to be trained. We chose 700 sample characters from the most popular Arabic fonts and sizes to generate the database. The 14 features explained above are extracted from this set of characters using MATLAB, and the results are saved in a text file which could be used by Professional II/PLUS as the training set.

The Fuzzy ART neural network has the following architecture: 14 Input, 1 Output, 60 F2 Layer, 0.0000 Vigilance. The network is trained for 20,000 times and tested using different samples to calculate the performance. The test results showed that the network was able to predict about 95% of the input characters correctly. This accuracy range is an average since it varies depending on the resolution and the font type and size. If the input font is the same as the fonts available in the database (which are used to train the network), the accuracy goes up to + 98%, but if the font is unknown for the network, the error may go up to 8%, i.e., an accuracy of 92%. Since most of the popular Arabic fonts are defined in the training set, the network should be able to achieve a high accuracy rate in most cases.

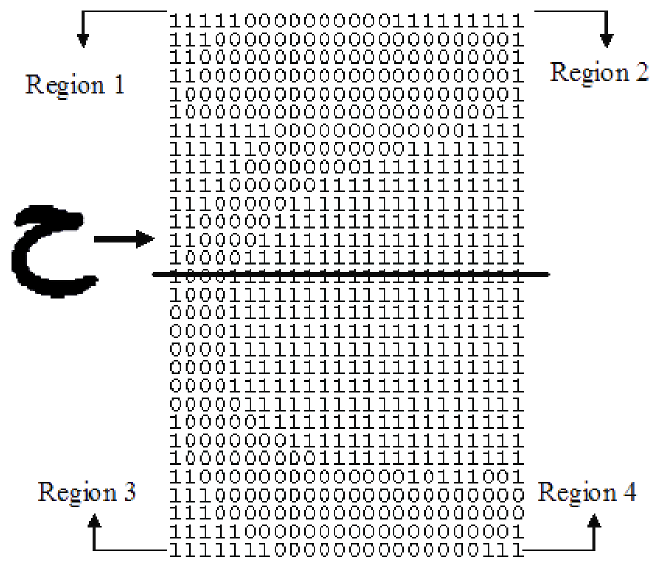

Figure 5. Dividing the image to 4 regions and extracting features

After the network is fully trained and tested and when the satisfactory result is achieved, the C source code is generated using *the flashcode* option, which is a utility available in Professional II/PLUS.

Hardware Implementation and Results

This project is fully written in C language in Code Composer Studio, which is a fully integrated development environment (IDE) supporting Texas Instruments (TI) industry-leading DSP platforms. A C6416T DSP Starter Kit (DSK), which is a standalone development platform that enables users to evaluate and develop applications for the TI C64xx DSP family, is used to run the application. The 6416 DSK is an all-in-one evaluation platform for the TMS320C6416T

Digital Signal Processor from Texas Instruments. It includes a target board that can be used as a reference design for interfacing the DSP to common devices such as SDRAM, Flash and a codec as well as a special introductory version of TI's Code Composer Studio development tools. An on-board JTAG emulator allows debug from Code Composer Studio through a PC's USB port. The Neural Network is designed in Professional II/PLUS software. The project is built and run on C6416T DSK and the result is saved on computer as a .dat file. The images are obtained through scanning different texts with a 300 dpi scanner and presented to the system.

Conclusion and achievements

The aim of the thesis is to implement a hardware-based Optical Character Recognition system for printed Arabic characters. The goal is achieved using DSP techniques. The following points summarize the conclusions of the thesis:

- Arabic character recognition is a research area involving many concepts and research points.
- A Fuzzy ART Neural Network is implemented and tested.
- A complete hybrid hardware-based system for isolated Arabic character recognition is proposed and tested for performance.
- A noble and efficient recognition method with a high accuracy (plus 95%) is successfully developed and tested in this thesis.

Future work

The implemented system suffers from some constraints and needs further work to become a reliable and commercially valuable product. The following list mentions the limitations and suggested solutions for future research on this project:

- As discussed earlier, the image is read by MATLAB outside the program and after preprocessing (converting to binary, etc.), its pixel values are transferred to the project as a header file. The possible solution for this limitation is to write C code to read the image from the computer .
- Since the scope of this research is focused on the recognition problem and hardware implementation, the current system assumes that the characters are already isolated and the algorithm can only recognize the isolated characters. For this project to have commercial value, the system should be able to isolate the connected characters from a word. Since there are techniques already developed for isolating Arabic characters, this system could be integrated with one of the existing character segmentation algorithms to overcome this limitation.
- The system is developed using a general-purpose DSP board (TMS320C6416T DSK); however, the algorithm could be developed on a single chip and a smaller board which is designed only for this purpose.
- A multi-language Optical Character Recognition hardware could be developed if several OCR applications for several languages are programmed on the same chip using the same board.
- The board could be integrated with a built-in scanner (like the scanners used to scan the bar code of the products) for image acquisition. This way, the system would work independently of any computer or host device. Such a board can scan a document and perform OCR without the need for any computer.

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MAKING STEEL SCULPTURE AVAILABLE ONLINE TO STUDENTS IN DEVELOPING COUNTRIES

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Abstract

Steel connections play important roles in the integrity of structures, and many structural collapses are attributed to connection failures. In recent years, in order to help civil engineering students visualize various connection types and to understand their importance, many schools in the United States, including Minnesota State, have acquired steel-connection-sculptures. A steel-connection-sculpture is a physical structure that shows forty-eight types of connections that are found in standard construction practices. The sculpture weighs nearly 2500 pounds. The American Institute of Steel Construction and their corporate members incur the cost of materials, fabrication, and transportation to a campus site. Unfortunately, because of its high cost, the steel sculpture is not available to civil engineering students studying abroad in developing countries. To provide the same learning opportunities for these students, we have created an online, interactive version of our steel-connection-sculpture. The virtual steel sculpture shows the close-up view of each connection, a brief description, potential failure modes, field examples, and sample design calculations. It is available twenty-four hours a day to interested students. To measure the effectiveness of the virtual steel sculpture, we collaborated with Kwame Nkrumah University of Science and Technology in Ghana, West Africa. We asked their civil engineering students to examine the helpfulness of this tool. In this paper, we describe how this interactive tool can be used to enhance student's learning in a steel design class.

Introduction

In almost all civil engineering programs in the United States, a student is required to take at least one structural design course. Steel design and reinforced concrete design are examples of two courses that are typically offered in a civil engineering program. A student who takes a structural design course has already taken courses in statics, mechanics of materials, and structural analysis. Moreover, a student usually takes the steel design course during his/her junior or senior year. It could be the student's first introduction to a formal design course. A traditional introductory-level steel design course includes the following topics: load combinations with appropriate load factors; sizing of tension, compression, and flexural members; and design of tension connections using mechanical fasteners as well as welds. Time permitting, an instructor may also cover additional topics such as shear-moment connection design. For a typical 15-week long course, approximately two weeks is devoted to tension connection design for both mechanical fasteners and welds.

The lack of emphasis in connection design is by no means a reflection of the significance of connections to the integrity of a structure. Instead, it is due to the time constraint in a semester and the common belief that connections are standardized details that should be left to fabricators. However, the connections are the glue that holds a structure together. Historically, connection failures have contributed to many structural failures, for example, the Hartford Civic Center in 1977 [1], the Hyatt Regency Hotel in Kansas City in 1980 [2], and more recently, the I-35W bridge in Minneapolis [3]. Since the Hyatt Regency failure, many state licensing boards have placed the connection design responsibility with the engineer-of-record. Furthermore, there are occasions wherein standard connection types are not applicable, and an engineer is required to design "special" connections and specify all details. For these reasons, it is critically important that a student gains a complete understanding of connection design and assembly concepts.

Steel connections are typically designed as 2-dimensional elements despite the fact that their load-bearing behavior is 3-dimensional. For students who are learning design for the first time and have no prior experience or knowledge of steel connection designs, it is difficult to visualize a three-dimensional connector. For example, when two beams (Girder B3 and Beam B3A) are oriented normal to each other as illustrated in Figure 1, we often use two angle sections to connect them. One of the angles will be in the front face of beam B3A, and the other angle will be placed at the back face of beam B3A. The bolts will then connect all three elements together as shown in Figure 1 – View B.

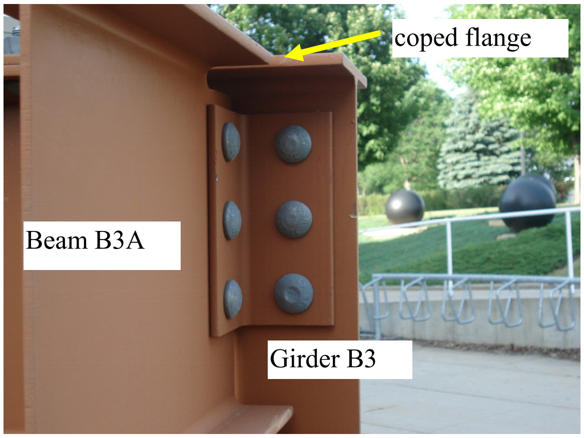

Figure 1 – View A   Double bolted-angle shear connection

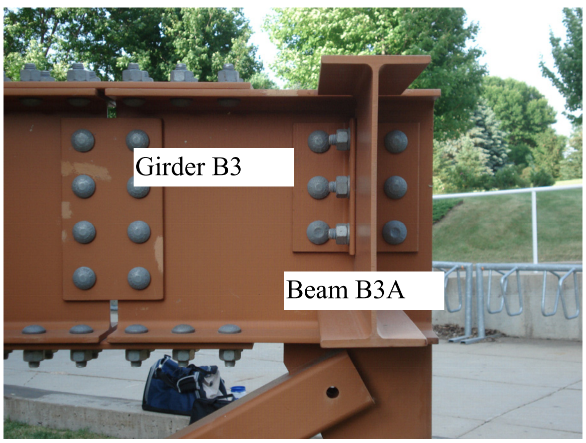

Figure 1 – View B   Double bolted-angle shear connection

Figure 1 shows various views of the shear connections between a girder and two beams (Beams B3A and B3B connect to Girder B3). If we were shown only view A, we would then conclude that the connection is a single-angle bolt connection. If we were given view B, then it is obvious to a structural engineer that it is a double-angle bolt connection. However, further examination of the connection reveals that it is actually a two-double angle bolt and bolt-weld connection. View C shows the back side of view B. It would be difficult to show all the details of this connection on a blackboard. As for this connection, it would be difficult for students to visualize the existence of an angle at the back face of Beam B3A in Figure 1-View A. This could lead to two common problems. First, students would not realize the significance and necessity of the second angle because of its absence in the diagram. Second, due to the visual absence of the second angle, the students would forget to include it in the design calculations, and this could affect the safety and

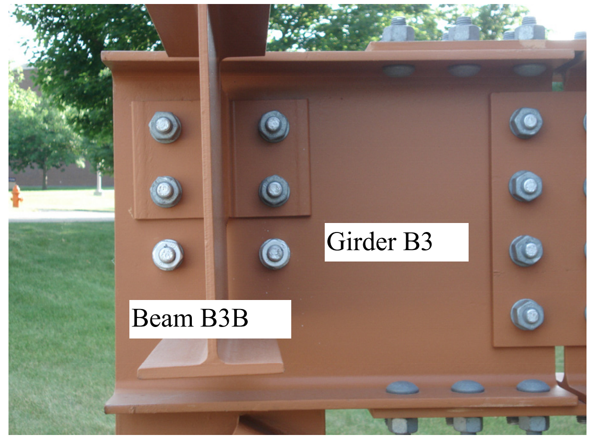

Figure 1 – View C   Double bolted-welded-angle shear connection, back of View B

integrity of a structure. Furthermore, the sculpture shows that the flange of Beams B3A and B3B must be coped to meet the top-of-steel-elevation requirement often specified in the design – *i.e.* the top face of the beam and girder flanges must be at the same elevation so that the roof deck or floor deck can be placed on them. From the first author's experience, the coping detail is particularly difficult for students to comprehend from 2-D sketches. On the other hand, the true configuration of this shear connection can easily be observed using a virtual sculpture.

To increase students' understanding of connections, one can take them to actual construction sites to see for themselves various steel connection types. Although this is a good approach, finding appropriate construction projects in close proximity and during the term that the design course is taught is challenging. Often, liability issues also prevent the faculty from taking students to construction sites. Because of these issues, many faculty members have resorted to taking photographs of connection types from construction sites and have shown them to their students. Unfortunately, the photographs still do not show the true 3-dimensional nature of connections.

In the summer of 1985, after seeing the inability of his students to visualize even simple connections, Professor Duane Ellifritt of the University of Florida designed a steel connection sculpture as a visual aid to teach his students about the many ways steel members are connected. Steel Fabricators, Inc. underwrote the cost of this project. This sculpture has now been duplicated and has sprouted over 135 campuses across the United States. At Minnesota State, we acquired a replica of the sculpture in 2005. The material and fabrication of our sculpture (shown in Figure 2) were donated by the steel industry. In addition to the physical

Figure 2. The 8-ft tall steel connection sculpture at Minnesota State University

sculpture, AISC also has prepared a teaching guide [4], which can be downloaded from the AISC website.

Virtual Steel Sculpture

The presence of the steel sculpture at Minnesota State has certainly helped our students to see for themselves examples of connections that are found in practice. The sculpture has also been used to teach students about other design considerations such as mechanical and electrical openings that are required in an actual structure. We also use tour and photographs of actual exposed steel structures as examples of practical application of the connections shown on the sculpture. The combination of the steel sculpture, tours, and photographs, as teaching aids, has greatly enhanced our students' understanding of the function of various connection types. Unfortunately, because of its high cost, the steel sculpture is not available to civil engineering students studying abroad, especially in developing countries. To provide the same learning opportunities for these students, we decided to create a virtual steel sculpture to show the close-up view of each connection with descriptions, potential failure modes, and field examples. We also decided that the virtual sculpture should be available twenty-four hours a day.

In addition, today's students are more computer savvy. A virtual sculpture would complement their learning style better [5]. Since the PowerPoint slides offer great flexibility in creating an interactive multimedia, as a starting point, the steel design class of spring 2006 was asked to produce PowerPoint slides of the steel sculpture as a class project. The students identified and labeled every connection on the sculpture. They presented the potential failure modes for each connection that engineers must consider in their designs. They also included actual field examples for many connections.

To further develop the virtual sculpture and to increase the database of the field examples, in the spring 2008, students in the steel design class were asked to create sample design calculations for some connection types and to add at least one field example.

The virtual sculpture now offers over 100 interactive PowerPoint slides, with half of the connection types having at least one field example. The creation of the virtual sculpture also increased students' interest in steel structures. It helped them develop a keen eye for recognizing various connection types.

Navigation of the Steel Sculpture

The virtual steel sculpture is highly interactive with links to four elevation views: north, south, east, and west (Figure 3). One can access the close-up of a connection and its potential failure modes by clicking on one of the connection numbers in an elevation view. From the close-up slide, by clicking on one of the buttons at the bottom of the slide, one can then move to field examples, sample calculations, or go back to the elevation view. The PowerPoint file also includes a user's navigation guide. The user can access this guide from the title slide. A detailed navigation description is found in [5].

It is important to note here that all the connections depicted in the steel sculpture are only intended to show how steel elements are assembled. Moreover, the sample calculations are intended to show the equations used in analyzing the limiting states of a connection. The results of sample calculations reflect the capacity of the connection based on the member sections, number of bolts and bolt size, or weld length and weld size. The sample calculations do not represent the design of a connection for an actual project.

Figure 3. East Elevation view. Other views can be seen by clicking the respective elevation button at the bottom of the slide

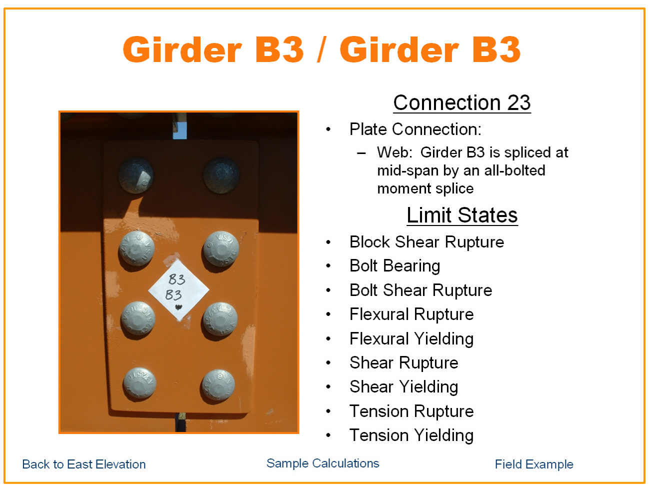

Figure 4. A close-up view of connection 23 and the list of limit states this connection should be designed for

Measuring the Effectiveness of Virtual Sculpture

In order to assess the effectiveness of the virtual steel sculpture, as a learning tool, we conducted a survey, which required the students to use the tool and answer a few questions. Groups of students from Minnesota State University (MSU) and Kwame Nkrumah University of Science and Technology (KNUST) in Ghana, West Africa participated in this assessment. Fifty-four students participated in the survey: 26 from MSU and 28 from KNUST.

The virtual sculpture was made available to students via Desire2Learn (MSU supported online teaching software), and a CD that was loaded into computers at KNUST. The MSU students had an opportunity to see a demonstration of the virtual sculpture in class. The KNUST students, however, had to rely on the procedures described in the user's guide. It is also important to note that the steel design specifications in the United States are based on the AISC Manual of Steel Construction [6] and U.S. customary units. On the other hand, in Ghana, the design specifications are based on the British system and SI units.

All students were asked to spend about an hour to navigate through the virtual sculpture and respond to the questions in the survey. In the survey, students were asked to

- rate the attributes related to the interactive tool (question 1);
- rate the effectiveness of the tool in enhancing their understanding of the connection design concepts (question 2);
- rate the overall usefulness of the tool (question 3); and
- evaluate the various components of the tool (question 5).

Summary of the survey results for questions 1, 2, and 5 are shown in Tables 1, 2, and 3, respectively. As shown in these tables, students were generally satisfied with the interactive steel connections. While students found the virtual steel sculpture satisfactory, there is a distinct difference between MSU and KNUST response in the "not satisfactory" category. In particular, the KNUST students found the navigation, calculations, and the design concept for electrical/mechanical usage "not satisfactory." All students with the exception of four with no responses rated the overall usefulness of the tool as "very satisfactory" or "satisfactory."

An explanation for the difference in responses is that when the KNUST students were asked to evaluate the virtual sculpture, they were exposed to the idea of steel sculpture for the first time. On the other hand, MSU students had seen the actual steel sculpture on campus and were also shown the slides that were created by the 2006 steel design class.

The main reason for the "not satisfactory" rating of the calculations by the KNUST students is the lack of familiarity with U.S. customary units and design specifications.

Furthermore, the students were asked to list three beneficial components of the virtual sculpture and the three areas in which the virtual sculpture could be improved. Examples of students' comments related to beneficial components include:

"*field examples – see the applications of various connections*"
"*sample calculations are helpful*"
"*see various types of connections*"

"*nice interaction between connection, field examples, and sample calculations*"

The students also suggested areas for improvement that included:
"*360° view of the connections*"
"*have sample calculations for more connections*"
"*show how the connections fit into the entire structure instead of just a close-up view of the connections in the field*"
"*link sample calculations from limit state in the connection description slide*"
"*file is too large; it takes too long to open from Desire2Learn*"

The KNUST students offered additional suggestions that are slightly different from the MSU students because of the design specifications, system of units, and their limited exposure to the steel sculpture. Their suggestions include:
"*use SI in sample calculations*"
"*need more explanation on sample calculations*"
"*more local field examples*"

Although the KNUST students appeared to be more critical of the quality of the virtual sculpture, the comments are valid and constructive. As previously discussed, KNUST students had never seen or heard of a steel sculpture until their instructor asked them to examine the virtual sculpture. The lack of familiarity with U.S. design specifications and the field examples also contributed to their suggestions for improvement.

Concluding Remarks

The 8-ft high, 2500 pounds, steel connection sculptures have been sprouting up on campuses in the United States. The steel sculpture is designed to help civil engineering students visualize various ways the steel members are assembled. To provide the same learning opportunities for students who do not have access to a steel connection sculpture, the authors, with the help of MSU students, have created an online interactive version of a steel sculpture. The virtual steel sculpture shows the close-up view of each connection with descriptions, potential failure modes, field examples, and sample design calculations. To assess the usefulness of the interactive sculpture, the authors conducted surveys in steel design classes at MSU and KNUST in Ghana. Both groups of students were asked to explore the virtual sculpture and complete a questionnaire regarding the effectiveness of the steel sculpture as a learning tool.

Table 1. Survey response for question 1

How would you rate the following attributes related to this interactive tool?

Attributes	MSU			KNUST			Total		
	V.S.	S.	N.S.	V.S.	S.	N.S.	V.S.	S.	N.S.
Images	15	11	0	21	7	0	36	18	0
Examples	5	21	0	9	18	1	14	39	1
Calculations	8	18	0	9	12	7	17	30	7
Navigation	15	9	2	6	14	8	21	23	10
Helpfulness	10	15	2	4	21	3	14	36	5
Other	1	8	2	2	13	1	3	21	3

V.S. = very satisfactory; S. = satisfactory; N.S. = not satisfactory

Table 2. Survey response for question 2

How would you rate the effectiveness of the tool in enhancing your understanding of these concepts?

Concepts	MSU			KNUST			Total		
	V.S.	S.	N.S.	V.S.	S.	N.S.	V.S.	S.	N.S.
Connect. types	13	13	0	16	12	0	29	25	0
Tension	5	18	3	4	19	5	9	37	8
Shear	9	16	1	4	21	2	13	37	3
Shear-moment	5	20	1	6	20	1	11	40	2
Anchorages	6	18	2	5	19	3	11	37	5
Assembly	4	18	2	5	20	1	9	38	3
Elec./Mech. usage	2	18	5	4	10	10	6	28	15

V.S. = very satisfactory; S. = satisfactory; N.S. = not satisfactory

Table 3. Survey response for question 5

How would you evaluate this education tool?

Attributes	MSU	KNUST	Total
Balanced	10	13	23
More types	6	1	7
More examples	8	5	13
More calculations	11	8	19
More assembly	5	7	12

In general, the responses from Minnesota and Ghanaian students were favorable. Their suggestions were also very constructive. For the virtual steel sculpture to be complete, we need to include the following items:

- sample calculations should be based on multiple design specifications (other international design specifications), not just based on AISC Manual of Steel Construction [6]
- field examples for every connection from projects around the globe
- international sample calculations for every connection type
- provide a means by which other educators would be able to submit field examples
- develop an efficient method on the internet to make the virtual sculpture available to students in developing countries with a limited internet bandwidth

To improve the virtual sculpture, a 360^{o} view of each connection is also necessary. Comments on practical application of each connection would be a great help to new graduates or engineers in training. For example, under what situation is one type of shear connection preferred over another? Based on the students' comments from Minnesota and Ghana, the concept of virtual sculpture is good, and the potential for it to be a great learning and reference tool is very high.

The virtual sculpture is available online at http://cset.mnsu.edu/steelsculpture. The authors are also currently seeking resources to develop the virtual sculpture further.

Acknowledgement

The authors are grateful to Dr. Mark Adom-Asamoah, Senior Lecturer at the Department of Civil Engineering, KNUST, Kumasi, Ghana, for his assistance in conducting the survey. We also appreciate the KNUST students' efforts in assessing the virtual sculpture. We also are indebted to our MSU students for their assistance in developing and assessing the virtual sculpture.

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ESTABLISHING AN ISO 17025 COMPLIANT LABORATORY AT A UNIVERSITY

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Michael R. Fisch, Kent State University

Abstract

The continuing need for industry to follow and use International Organization for Standardization (ISO) standards puts pressure on university organizations, which perform laboratory testing for outside organizations, to ensure that their results satisfy the required standards of the requesting organizations. The amount of outside testing of many university facilities makes full ISO 17025 certification economically unfeasible; however, such labs can be compliant to this standard, thus satisfying those that use the university's laboratory services. In this paper, we discuss our experiences in bringing our laboratory up to ISO 17025 compliance. The problems, time commitment, and personnel requirements as well as the advantages, both internally to the organization and to outside users, will be discussed. The contributions of our quality program to students as well as the students' contribution to the quality system are significant and benefit both parties. Finally, the need for continuous work on such a program will be discussed and put into perspective.

Introduction

There is a continuing and accelerating need for industries to demonstrate that their products or services meet a certain minimum standard. To minimize the number of different standards, most companies that have standards conform to those of the International Organization for Standardization (ISO). University laboratories are increasingly performing testing for outside companies, and as such they are under increasing scrutiny and may be encouraged to obtain ISO certification. In this paper we discuss some of the many aspects of establishing an ISO 17025–compliant laboratory in a university setting, with the goal of providing guidance to other university labs that may need to travel down the same road.

Our laboratory, the Middlefield Research and Testing Laboratory, (MRTL) is located roughly 40 minutes from the Kent Campus, within the NEO Beam facility. This facility is a joint venture between Kent State University and a local plastics company, Mercury Plastics, Inc. NEO Beam has a 150 kW, 5 MeV electron accelerator that is used for production and research. This joint venture gives both parties access to instruments and a facility that neither could justify individually. This arrangement allows our laboratory to provide basic and applied research for outside companies as well as university projects. In light of our relationship with a plastic company, we focus our external lab work on dosimetry (determining the dose a product absorbs) and the physical, chemical, and mechanical properties of polymers and plastics. Internally, we have active research in a number of areas [1]. The number of scientists and engineers at this facility varies over the year. It swells during the summer when students are present and is smaller during the academic year. Typically, we have 5–6 professional scientists during the academic year, and of this number, three to four are affiliated with the laboratory on a part-time basis. Thus, we are a rather small laboratory; and, as we will discuss, size is a determining factor in a number of our operational decisions.

Why should a university laboratory have a quality system? The establishment of our quality system began when a company asked about our quality system. Our first response was of the nature, "We are competent scientists with advanced degrees from highly ranked programs. We work at a major university using state-of-the-art equipment; of course we do quality work." From the perspective of the company, this answer is of the nature "true, true, true, but irrelevant." They want to know how it can be demonstrated. What is systematically being done that would lead them to accept the statement(s) about the quality of work? If we say the value of a parameter is x±y, can they stake their reputation on it? This exchange indicates the major reason for establishing a quality system—customers demand it.

We are certainly not the first university laboratory to establish and implement a quality system, and this is not the first report of such efforts. In 2005, Rodima et al. [2] summarized their experience in working under an ISO 17025 quality system at the University of Tartu in Estonia. Their particular laboratory acts as a gateway to other units of the university. They concluded that implementing such a system is possible and that it "gives significant added value to the university" by bringing industry and the university closer together and by introducing students to the real-world reality of such issues. Two years later in 2007, Zapata-García et al. [3] at the University of Barcelona describe their experience. They observe that it is a difficult task, but it can be accomplished, and that the system had a positive impact because it helped put university members in touch with the real world and it also impacted research and academic content. Earlier work by Pritzkow [4] and Halevy [5] discussed the practical benefits and experiences of implementing ISO 17025. This work focused on non-university settings.

Distinguishing features of our laboratory include its size, its variable number of personnel, and the opportunities and challenges that these bring to establishing an ISO 17025–compliant laboratory. The system that we will discuss in this paper is not our facility's first attempt at establishing a quality system. A few years ago, a former quality control manager from a local company who had joined the Kent State University faculty started on such a system. Full implementation of this system never took place, as the system was too cumbersome and required too many documents to work smoothly in a laboratory where the quality manager was not present 3 days per week. However, it did help us establish the role of management and the quality manager in quality systems and gave us the impetus for the present system. It also illustrates the important lesson that one needs to have a quality system that is the right size for the organization.

The major portion of this paper will discuss the specific issues, problems, and solutions that we developed as we implemented our quality system. There are many issues, and we have grouped them into five general areas: initial questions, implementation issues, forms, financial aspects, and continuing issues. Our purpose in each section is to describe what issues we encountered, show how we solved or avoided each issue, and finally explain why we opted for the process or answer that we used.

These five sections will be followed by a series of conclusions and recommendations. This final section will discuss the benefits and costs of such implementation, the advantages to students and faculty, the continuing nature of such implementation, and our view looking back after implementing our quality system.

Issues, Problems and Solutions

A. Initial Questions

In this section we discuss some of the questions we encountered as we began to develop our quality system. These basic questions need to be answered before the initial development of the quality system can take place. In our case, some of these issues were resolved in real time, and there is no question that this caused bruised egos and lengthened the time needed to develop and start using our system.

The first step is to determine if a quality system is required by your customers. Here it is important to realize that there are two issues: Does the company need data from a laboratory with a quality system? And if so, are they willing to pay extra for it? There is no question that implementing and maintaining a quality system is costly to the testing laboratory. This cost is seen both directly and in terms of the non-recoverable time people put into developing, testing, and checking the system.

A particularly important question in a university laboratory is whether the research at the lab requires a quality system or some part of it. In most university labs, older students teach newer students, and there is little thought of what might get lost in translation until there is a problem. Is this the best way to teach students in the laboratory, or should there be instruction and standard operating procedures (SOPs) so the new student gets the official lab technique for performing an operation? Our experience is that the use of SOPs greatly shortens the learning curves on many instruments for students and new faculty. The related issue of calibration of instruments comes into play here. Many university research labs do next to no calibration of their instruments, even when calibration requires no more than making measurements on a reference sample.

This last issue leads to a related question: How do you handle internal research and external testing in the same laboratory? If these operations use different equipment, what should the policy be? The easiest and most costly solution is to have all the equipment calibrated at periodic intervals. This is well beyond the financial means of a small university laboratory. In fact, since most university equipment is purchased without a service contract, this needs to be done either internally or by an expensive technician from the manufacturer. If performed internally, this may also require standards and related supplies. Our approach to this is to keep equipment that is used for outside testing calibrated through both internal and external means. The equipment that is used only for internal research is designated as "for reference only," indicating that it has not been calibrated recently. "For reference only" equipment includes most of our electronic meters, lock-in amplifiers, and similar equipment. Those instruments used for dosimetry and external polymer testing are calibrated at regular intervals. Calibration will be discussed in greater detail later as a continuing issue.

Once the lab has decided that it wants to be ISO 17025 compliant or certified, another issue immediately develops. Since our laboratory is small, everyone was asked to be part of the initial development. We found that it was extremely helpful to bring in an outside facilitator with a quality systems background (V. Fitzsimmons) to help with many of the remaining questions. For example, how large and complex of a system is necessary? The system needs to be simple enough to work, yet complete enough to comply with the standard. The system must also accommodate the other hats the quality manager wears in the lab and the day-to-day time commitment a quality system requires in practice. A good facilitator knows what is necessary and the level of detail that is needed. Once the committee chair or facilitator is chosen, the next question is whether the lab will be certified or only compliant. Certification is expensive, and it must be renewed periodically. If the customers require it and they provide sufficient income to cover certification, then go that route. If that is not the case and the university does not want to fund certification, then compliancy is the best the laboratory can achieve. In our case, no customer needed certification, and the university did not have the funds, so we are compliant to ISO 17025 and ready to become certified if necessary.

Regardless of the result of the central decision of certification, the decision to establish a quality system raises another set of issues. The first of these is: who owns the system? In many cases, when something is everyone's responsibility, it ends up being no one's. To prevent this, Fisch assigned K. Hullihen as quality manager and set up a system in which the three coauthors work together with consultation from the rest of the lab's members on various issues of particular interest to the specific lab member. The second question is: who controls the system? In the present system the quality manager and lab director work together, with as many decisions as possible made by the quality manager. The system is controlled by the quality manager, but there is managerial oversight. This is, in fact, how ISO 17025 should work [6].

B. Implementation Issues

Our basic system is available online [1]. The initial draft of this system was developed by Fitzsimmons and Fisch and then passed through several rounds of editing and meetings by all lab members. There was consensus on all aspects of this part of the plan. The SOPs were written by the faculty member most familiar with the equipment and edited by Hullihen and Fisch.

This section will discuss issues that occurred after the initial system was in place and when the initial steps of writing, editing, and using our SOPs became important. Some of these issues, such as how work is divided, are rather basic; while others, such as who can perform a test for an outside customer, are more complex.

One problem for a large project that has several participants with other commitments is how to divide the work so that the project can be completed in a timely manner. We used a three-step system with feedback. First, a faculty associate who was familiar with a given test or piece of equipment volunteered or was assigned to write a first draft of the SOP. The quality manager then forwarded a standard format for the SOPs for the assignee to complete. After the first version of the SOP was written, the copy was edited by the quality manager to ensure that formatting was uniform. The quality manager or another person then ran the procedure exactly as written and noted inconsistencies, missing steps, and similar problems. These problems were resolved by the quality manager and the person who wrote the SOP. The SOP was then forwarded to the lab director for reading and commenting and then sent back to the quality manager. After this edit, the quality manager had the writer check the final version. It was then sent once more to the lab director for final acceptance. In almost all cases, a student who was not familiar with the SOP was then asked to verify that the procedures were clear. This division of labor clearly requires significant time commitment on the part of the quality manager and more reasonable amounts on the writers and the lab director. We had no complaints about this system, and edited SOPs generally were returned in fairly short order. The time spent by the faculty associate was especially useful to them because it forced the faculty associates to look at the process carefully and thus made them more proficient at performing the task and teaching others.

Training is another time issue that can be difficult to include in schedules that are already overfilled. Questions such as who should train a new person, how many distinct aspects they should be trained on, and who is qualified to perform a test for customers all need to be answered [7]. Our small size, limited personnel, and focus on very precise SOPs have allowed us to take a piecemeal approach to the training. If a person needs training on a particular instrument, a faculty associate or the quality manager teaches them during normal operation of the instrument. Since there is little need to train someone in something they do not use, we focus the training on just the processes that a particular person will use. When testing is performed for an outside customer, we allow trained students to perform the test provided they are supervised by senior personnel qualified to run the test. This supervision is close enough to prevent large errors but sufficiently distant that students can learn self-checking and the other skills that go with being a professional doing quality work.

An important part of ISO 17025 compliance is establishing a policy for estimating the uncertainty of a measurement. This puts us at variance with some of our customers. For example, when we test according to ASTM standards, the standard may specify making two distinct measurements, but the customer may want just one measurement and may ask to use the second measurement for a different sample. The customer is generally right, so in this case, we explain that this is not the ASTM standard that we follow, and the best we can do on an uncertainty is the following estimate on a single sample. Other customers find that uncertainty clouds, rather than clarifies, the issue and do not care for nor want uncertainty. In other cases, as long as the uncertainty is below a certain value, there is no problem. Thus, while we can give estimates of uncertainty to our measurements, we place only a minimal focus on this aspect of the standard. This is part of our still-evolving system and, as in all compliance to standards, ultimately depends on the customer.

C. Forms

It was our experience and also that of another university lab [2] that in our first attempts at adapting a quality system we produced systems that required excess documentation. In practice, these systems were too top heavy in administrative details to work well and were dropped or reworked into more modest systems. This section will discuss the forms and formats that we use in our system. This is certainly not the last word but rather an example that we hope will be modified and used by others.

Our system consists of an introductory document that specifies five other documents and then a series of related documents that address specific issues related to calibration. The introductory document is titled "MRTL Quality Management System" and states the following:

"The purpose of the Middlefield Research and Testing Laboratory (MRTL) Quality Management System (QS) is to implement quality management methodology throughout the laboratory and associated processes in order to (1) Plan and perform laboratory operations in a reliable and effective manner to minimize the impact on the environment, safety, and health of the staff and the public; (2) Standardize processes and support continuous improvement in all aspects of laboratory operations; (3) Enable the delivery of products and services that meet customers' requirements and expectations."

This document goes on to define the roles of the individuals involved in the quality system and briefly describes the five documents that, to a large measure, define the fundamentals of our quality system. These are described in Table 1.

Table 1. Documents In Our Quality System

Document number and title	Purpose
QP 10 Document Control	Describes document control, nomenclature, destroying documents, etc.
QP 20 Review of Requests for Work	Procedures in checklist form for reviewing requests for work
QP 30 Control of Nonconforming testing and Calibration at MRTL	Procedures in checklist form for nonconforming measurements and/or calibration
QP 40 Corrective and Preventative Actions	Procedures in checklist form for corrective and preventative actions
QP 50 Document and Record Retention	Procedures in checklist form for retaining and destroying records

QP 10 describes document control, and nomenclature. An important part of this document is the method we developed for labeling documents. In this part of the system we tried to produce as few different types of documents as possible. Nevertheless, the sheer number rapidly became rather large. The letters used to designate a particular document type were chosen because they were appropriate and made sense to our lab. They may not be appropriate to all labs. Moreover, in many cases, we separated documents into categories that others may want to combine. For example, the measurement procedure and the measurement procedure sheet could be combined. We separated them so that the measurement procedure sheet could be printed by itself if needed. The measurement procedure could be left adjacent to the instrument at all times so that it could be referred to as necessary. The revision number is in the upper right of the header on all documents. When the revision number is less than one, the document is still under review, these documents may be used for reference only. Table 2 describes our nomenclature, which generally indicates the purpose of each document by its title.

Table 2. Nomenclature Used In Our Quality System

Prefix	Meaning	Explanation/example
EO#a	**E**quipment **O**perating Procedure	EO006 Equipment operation procedure 6
PR#a	**Pr**eventative Maintenance Procedure	PR006
MP#a	**M**easurement **P**rocedure	MP006
MPS#a	**M**easurement **P**rocedure (check-off and record) **S**heet	MPS006 Note that many measurement procedures have a measurement procedure sheet with the same number and revision number. For example, MP006 uses MPS006.
CE#a	**C**alibration procedure for **E**quipment	CE006
CS#a	**C**alibration procedure for **S**ystems	CS006
QP#	**Q**uality **P**rocedure	QP10

Most measurement procedures (MP), or more colloquially SOPs, have an associated measurement procedure sheet (MPS). An MP and its corresponding MPS have the same numbers. The MPS has checkboxes and fill-in spaces with the corresponding procedure step. This provides natural error checking for a person performing a test.

We use two calibration documents. CE documents describe the calibration of an individual piece of equipment, such as a differential scanning calorimeter (DSC). This generally requires specific procedures and reference standards or instruments. For example, in DSC calibration, the melting temperature and transition enthalpy of a standard substance (near room temperature for very pure indium) are determined. The instrument is said to be in calibration if the measured transition temperature and enthalpy are within specified deviations from those determined by national standards laboratories. Similarly, thermometers may be calibrated by comparing the temperature of the thermometer being calibrated to a calibrated thermometer and adjusting the calibrated thermometer's values so there is minimum deviation from the calibrated thermometer.

CS documents describe dosimetry system calibration procedures. These are necessary in our dosimetry lab, where we have several different dosimetry techniques that often require the use of more than one instrument and cross-calibration against standards from national or international standards laboratories such as NIST. The ISO/ASTM standards on dosimetry define a dosimetry system as "A system used for determining absorbed dose, consisting of dosimeters, measurement instruments and their associated reference standards, and procedures for the system's use [8]." Calibration of a dosimetry system requires (i) irradiation of dosimeters to a number of known, different absorbencies over the range of interest/validity. This is done at a standards laboratory. Then, (ii) the dosimeters are analyzed using calibrated equipment. Finally, (iii) a "calibration curve" is made that relates the analytic equipment response to the dose. This requires that both the standards and the instruments be calibrated.

We also separated equipment operating procedures (EO) from measurement procedures (MP) so that as the tests evolve, the basic operation of the instrument does not need to be explained in every procedure. If a person needs to review how to operate an instrument in general or wants to develop a new technique, they refer to the EO document. However, for a particular type of measurement for which we have already established a measurement procedure, they use the MP and MPS corresponding to the desired measurement.

An important feature of most of our documents is that they are in checklist form, so that the document serves as both the quality procedure and the checklist for what to do. This double-duty use reduces the number of forms and makes it clear what aspects of the procedures are very important. An example is part of the procedure section of QP 40 shown in Figure 1. These procedures are as simple as possible within the constraints of ISO 17025 and are written with the size of our laboratory in mind. This is important, as larger laboratories may want and need more formal and longer procedures.

MRTL	Program on Electron Beam Technology Middlefield Research and Testing Laboratory Corrective and Preventive Actions	Document # QP40	Rev 1.0 August 2006 Page 1 of 1

III. Procedure:

A. Annual Audit

☐ The Quality Manager (QM) is in charge of the annual audit in part to identify situations where preventive and/or corrective action is necessary.

☐ All situations identified in the audit as needing preventive and/or corrective action will be addressed by the QM as discussed in section C below.

B. Discovery of a potential need for action

☐ When an associate identifies potential sources of nonconformities in need of preventive and/or corrective action, he (she) will inform the QM of their observation as soon as possible.

C. Addressing the need for action

Figure 1. Part Of QP 40; The Use Of A Checklist In A Quality Procedure

There are a few documents that do not easily fit into this rubric. For example, the work order sheet is a two-sided, one-page document that includes a checklist to assure that the proper management procedures are followed. Similarly, many of our templates have no number. These templates indicate the major headings and information that must be generically provided on forms of a given type. An example is shown in Figure 2, the measurement procedure template. Item 9 on that template is included on all relevant documents so that it is clear that one must be trained and qualified by the quality manager to perform a measurement. Item 10 can include calculations, error analysis, and other relevant information.

Finally, we use form MPS666 to describe variances from our normal procedures that the customer wants and for which there is an understanding between our laboratory and the customer. For example, the customer that wants only one measurement when two are suggested has explained this to us, and we have agreed to just perform the measurement once.

In summary, even a simple system at a small lab has a remarkable amount of documentation. Much of it—for example, calibration reports—is behind the scenes. This section has illustrated our approach to keeping this collection as simple as possible. An important technique we found is to use checkboxes in procedures where possible so that a procedure can also serve as the template for what needs to be done.

EBEAM Program on Electron Beam Technology Laboratory	Kent State University Program on Electron Beam Technology Measurement Procedure (title)	Document # MP.a	Rev: b Page 1 of x

1 **Purpose**

The purpose of this procedure is to provide

2 **Scope**

This procedure applies to

3 **References**

4 **Definitions**

5 **Equipment**

6 **Materials**

7 **Environmental Conditions**

8. Procedure:

8.1 **(title)**

9 **Skills/Personnel**

9.1 Only trained personnel authorized by the Quality Manager are authorized to perform these procedures.

10 **Additional Information**

Written by: ____________ __/__/__ Approved by: ____________ __/__/__

Figure 2. The Measurement Procedure template. This is typical of all our templates and is designed for ease of use

D. Financial Aspects

The long-term commitment of financial and personnel resources to a quality system is another issue that must be considered. While certification is too expensive to consider for most university organizations, our experience indicates that there is also a heavy financial burden to running a lab that is compliant, but not certified. This section will describe some of the costs associated with our ISO-compliant lab. This will not be comprehensive, but it should give the reader a sense of the relative expenses.

The first and relatively easy-to-quantify expense is the cost associated with equipment calibration. This expense breaks down into three parts: expenses for external calibration, expenses for standards, and time required by lab personnel to calibrate and track calibration of the instruments.

The expense of external calibration is generally unavoidable. Even if the laboratory calibrates its own equipment, the standards used in the calibration must have known values. An example is the calibration of masses for calibrating balances. Calibrating a balance is not difficult, but it requires calibrated masses. These masses need to be recertified at periodic intervals. The issue is how often. Our approach has been to follow the manufacturer or supplier's recommendation for yearly time intervals 2–3 times and then examine the calibrated values graphically to search for a systematic variation in the calibrated quantity. If a systematic variation is observed, then we continue to follow the recommendation. In those cases where there is no systematic variation, or small random variation, we then extend the calibration interval. We do not have enough data to judge how long we can extend the interval. However, we anticipate no more than a factor of two to three times the recommendation. Our dosimetry standards need to be verified and calibrated once per year. This area also includes the expense of updating computer software and hardware to take advantage of the newer developments in a particular instrument.

The second area of expense is that of the standards for calibrating equipment. An example of this would be the samples to calibrate a differential scanning calorimeter or a thermogravitometric apparatus. These may be calibrated in our lab, but this is often costly. Once more, there is no easy way to avoid these expenses. If you want the equipment calibrated, you need standards. One frustration here is that materials from the manufacturer are often much more expensive than those from other suppliers, but those from other suppliers are not certified. Here one has to use experience and knowledge to decide if the extra money is well spent or if the less expensive material can be calibrated against the certified material to provide interim calibrations and hence reduce costs.

The final expense area is personnel. In the very large budget approximation, outside technicians can come in and calibrate equipment. In the real world, the lab has to develop the competence to calibrate equipment to the extent possible. This requires time, skill, and training. We have our quality manager in collaboration with associates doing as much of the calibration as possible. This puts the keeping of calibration records and related quality issues all under the purview of a single person.

The first two areas of equipment calibration costs can be easily quantified by review of the budget. In our lab, the cost varies from year to year, but it averages about $8,000/year. The cost of personnel to calibrate equipment and follow the calibration of standards and related issues can be quantified via detailed time cards. Our university laboratory's policy is not to require such detail in the accounting of time. Thus, we can only present an estimate, which is roughly 1/6 of the time of a fulltime BS-level laboratory coordinator. In our lab, the quality manager not only calibrates the equipment but also manages the quality system. This person spends roughly 1/3 of her time on the quality system. Thus, at present we have the equivalent of 1/2 a person totally involved in our quality system.

We discussed earlier that many of our customers do not need the full benefit of an ISO 17025 certified system, so part of this expense is not being borne by customers. At present, this is lab overhead and illustrates a largely hidden cost of having a quality system. The benefits of a quality system go beyond the work for our outside customers and the tangible benefits to students who have worked on and under our system. These benefits will be discussed in the last section on conclusions and recommendations, but include greater confidence and a better understanding of uncertainty in all our measurements.

E. Continuing Issues

Implementing a quality system and then using it in a laboratory requires continuous attention. The system is never complete and never runs on its own. A byproduct of this living nature is that the users of the system continually improve the system, and yesterday's problem is today's opportunity. At the same time, there are some issues that have no correct answer and continue to be a source of discussion. This section will discuss several of these issues and try to present several sides of our discussion of each issue. There is no particular order of importance within this section. We will discuss personnel issues, calibration and service issues, and some financial issues.

A number of personnel-related issues have arisen that are of a continuing nature. One aspect of routine laboratory testing is that it is routine and repetitive. This means that when the testing is performed by highly educated people with advanced degrees, they tend to get bored. With boredom comes the potential of errors. In the long term, we would like for most of our lab tests to be run by advanced undergraduate students or an AS/BS level employee. The difficulty with the former is that students come and go, and our early experience indicates that the learning curve and training time make this inefficient. The latter option works if there is sufficient work to justify hiring such a person. In a small laboratory such as ours, we are in the in-between state. Some tests are run by faculty members, some by our lab coordinator/quality manager, and some by students. Nevertheless, we are on constant watch through cross-checking to avoid errors due to lack of interest.

Different people will require different amounts of time for a given task. Is the slower person doing a better job than the faster person? Does the extra time, which is not charged in a flat fee test, provide benefits to the customer, such that the fee should be raised? Since the individuals of both speeds are similarly trained and nominally following the same measurement procedure, we presume there is no difference in the final product, but this is difficult to ascertain except in side-by-side tests. Finally, in our laboratory every nonstudent qualified on a particular measurement may take orders from customers to perform a given test. This is largely out of necessity; in a larger company there would be an order entry person. However, this policy has had the advantage that customers develop a one-to-one relationship with a given person that promotes the laboratory.

The second area has been touched on before—calibration and the costs of calibration. As stated earlier, we do not generally have service contracts because of their rather high price. This is simply an economic decision that at the present time makes good sense. But this needs to be examined continuously and for each instrument. The second issue is what to calibrate on a continuous basis. The secondary issues of why and how often come into play. To a certain extent, this depends on the test. In one test, we put 25.6 kg on a sample that is heated to 190°C and pushed through a small orifice. Other than a go/no-go test of the orifice size, we have done no calibration on this instrument. Clearly in a laboratory with greater resources, this instrument would be calibrated on a periodic basis.

Two procedural issues have not been tackled. The first concerns accessibility of the various forms. Our approach has been to have printouts of the procedures near the equipment and procedure forms available with the procedure and from the quality manager. Ideally, these should be in a database and accessible to everyone regardless of the form needed. We do not have sufficient IT support to use this approach and intend to follow this approach in the future. The other procedural issue is when to stop writing procedures. For example, does the procedure for measuring volume with a graduated cylinder need to be written? What about the techniques needed to make solutions of a given concentration? We assume that procedures that are part of the standard associate/bachelor degree program in chemistry, physics, or technology need not be covered. When problems do arise, we write procedures to ensure that the problem does not reoccur. For example, one instrument requires the use of a crimping tool to hold samples. In spite of reading the instructions and being shown several times, a particular student continually jammed the crimper. This was alleviated by further training and the production of a procedure to use the crimper.

In our laboratory, billing is handled by the lab director. This ensures that there is a central location that invoices customers. Once more, in a larger or different laboratory, this could be handled in a different way. However, by having completed test results go from the tester through the quality manager to the lab director, there is constant administrative review and oversight of the whole process. Another issue that arose was the extent to which a university should do pro bono work on projects. The argument for pro bono work is that the university should help companies and share their expertise. A counterargument is that there are real costs associated with a faculty member helping a company. We do not have a policy on this issue; both sides make excellent arguments.

Comments

This section will discuss our experiences and address question such as the following: Would you do it again? What are the benefits of your quality system? Does it make a difference? If so, how does it make a difference? How long will it take? Are there issues that cannot be resolved except by compromise? The purpose of this section is to try to anticipate some of the readers' questions and provide our answers. Some of these answers are tentative and may evolve with time. The important point that we reemphasize is that our quality system is simply an example, and our problems are representative, but certainly not all-inclusive. Establishing a quality system in a university laboratory is an adventure.

There must be benefits to establishing a quality system in our laboratory, or we would have stopped several years ago. Quality systems are not just academic exercises. As we mentioned earlier, to date we have had few customers that actually require ISO 17025 compliance. It is our hope and belief that in the longer term this will become more important to our customers and help the testing side of our laboratory expand. In the meantime, there is a continuing need to justify the time and expense of our quality system. One of the primary benefits is that by documenting procedures, we are much more isolated from a knowledge discontinuity if a faculty member leaves the lab. We also know that, to the best of our ability, everyone is doing the same measurement in the same way and has been taught by a person who knows the measurement. We are confident when we compare and combine measurements by multiple experimenters. Thinking about quality and performing measurements in a systematic and identical way every time has permeated our lab. Students that work in our lab learn very quickly that quality is not a meaningless adjective but something that can be quantified and practiced. This appears to have become part of some of the students' thought processes. We have had students work on the quality system, and the experience of working in a lab with an ISO 17025 program is different from coursework in a quality course [9]. In fact, the nonfinancial benefits to the laboratory are so significant that even if the hoped-for economic growth does not occur, the quality system will be worth the time and effort. Students need to see how the "real world" has metrics for quality, and the common undergraduate perception of quality being out there away from the university is outmoded. Fisch has run research labs in the past, and after this process, it is difficult for him to imagine a lab without a basic quality system—too much is left to happenstance in most academic research labs that can be systematically controlled. Thus, our answer to the question, "Would you do it again?" is a very positive yes.

While the time on a continuing basis has been discussed, the total time was not. The process described in this paper has been occurring continuously for two years, and we expect it to continue into the future. A quality system is never complete; continuous improvement is a goal of our system and that of all other labs. Through internal reviews and continuous monitoring, changes have been made and continue to be made. However, it is our expectation that after the initial large body of documentation and paperwork, the time necessary to devote to the system with be reduced. An issue that we discussed earlier continues to be the source of discussion and disagreement. The university embraces discussion and academic freedom. In practice, this makes establishing a policy and saying "This is the way it is" difficult. We have accepted some ambiguity in non-procedural parts of our system, not because we like the ambiguity, but because the solutions are considered worse than the problems.

Finally, how do you know your quality system is successful, i.e., that it works? A successful quality system is one that seems natural to the user. The system has been set up so that while there are procedures, paperwork, and calibrations, they are seen as simply part of the measurement and are not overwhelming or too numerous. The procedures make sense because the operator knows why every step is necessary. The forms make it straightforward, and he or she understands the importance and significance of the results to the customer or their research. The importance of calibration and preventative maintenance is also understood and appreciated by the operators, and because they have assisted in or performed these operations, they know that the instrument is within specifications. In a successful quality system, operators do not ask why something is done a specific way, or why something is recorded; rather, they ask how this can be made better, easier, or faster. In short, success is measured by the extent to which quality is a part of every operator's interaction with customers, the equipment, and themselves.

This paper has summarized our experiences in establishing an ISO 17025–compliant laboratory at a university. We have tried to address questions the interested reader might ask and defined a successful quality system. In spite of the time and cost, establishing a quality system at a university laboratory has many advantages, and we suggest that other university labs develop such a system, even those not yet considering a quality system. We have referenced our basic forms and will provide copies of specific documents to interested parties.

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STRUCTURE HEALTH MONITORING BY WIRELESS SENSOR NETWORK AND ITS INTEGRATION INTO ENGINEERING CURRICULUM

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Abstract

This paper describes a sensor network platform for structure health monitoring. Structures constantly face a harsh environment and loading conditions, which result in long-term deterioration and a significant amount of repair cost. For example, leaks and ruptures due to an aging and fast decaying pipeline system cost millions of dollars a year. This makes it clear the necessity for having continuous automatic monitoring systems that can provide early detections and give early warning of defects before they become major disasters. In this paper, we discuss how to use acoustic sensor networks to detect and locate defects. We demonstrate the feasibility of defect localization using multiple ultrasonic transducers in an educational laboratory. Finally, we discuss how to integrate the advances of sensor networks for structure health monitoring systems into an undergraduate engineering curriculum.

Introduction

Structures, including pipelines, aircraft, ships, bridges, buildings, dams, among others, are complex engineered systems that ensure society's economic and industrial prosperity. It is common that structures are often subjected to harsh loading scenarios and severe environmental conditions. As a result, long-term structural deterioration may occur. Researchers have been pursuing novel sensing technologies and analytical methods that can be used to rapidly identify the onset of structural damage in an instrumented structural system. Structural health monitoring (SHM) is a new paradigm that offers an automated method for tracking the health of a structure by combining damage detection algorithms with structural monitoring systems. Various sensor technologies have been used to implement SHM. Wireless sensor network (WSN) is an emerging technology that combines advanced sensing, data aggregation and processing, and data communication. Research has demonstrated that WSN can help advance the structural engineering field's ability to economically realize SHM.

In this paper, we present the research and educational activities related to structure health monitoring systems based on wireless sensor networks at the University of Maryland Eastern Shore. In particular, we demonstrate the problem of detection and the localization of defects on distributed pipelines using sensor network technologies. The focus of this research and educational activities include 1) Develop a guided wave-based structure defect numerical simulation model and signal processing algorithms; 2) Develop a LabView supported ultrasonic transducer network for defect target measurement experiments; and 3) Integrate sensor networks advances into an undergraduate engineering curriculum for SHM applications. In the next three sections, we discuss each of these topics.

Structure Defect Monitoring Using Acoustic Sensors

The working principle of an acoustic sensor is the piezoelectric effect. Piezoelectric effects occur in dielectric materials, causing physical dimension changes due to electric fields and, conversely, generating electric charges due to strain or stress. To inspect structure defects, acoustic sensors are mounted on structures to interrogate acoustic propagation waves scattered by defects. For example, in the distributed transmission pipeline monitoring and inspection, an impact caused by a third party on a pipe wall creates acoustic waves that travel upstream and downstream in the pipeline. Distributed passive acoustic sensors measure the timing and relative magnitude of these waves to determine the impact location and severity. Sensors can operate in a passive mode or active mode. Passive sensors provide limited functionality and are not adequate for structure inspection. Smart materials such as piezoelectric ceramic Lead Zirconate Titanate (PZT) can excite acoustic waves to adaptively probe structures. A PZT-based electro-mechanical impedance technique for structural health monitoring has been successfully applied to various engineering systems [1]-[2]. A PZT sensor can produce electrical charges when subjected to a strain field and conversely mechanical strain when an electric field is applied. PZT possesses the property of piezoelectricity that can be used to launch guided waves along a structure and to measure the corresponding response time signals. However, the conventional PZT materials are brittle and susceptible to cracking especially when the surface of the pipeline is curved. To address this issue, research has shown that flexible smart materials such as macro fiber composite sensors and active fiber composite sensors are the sensing and actuating devices that can adapt to the curved structure surfaces [1]-[4]. The composite materials are composed of ceramic fibers that can bend or flex when a current is applied to them; they can also generate a current when they are vibrated or flexed. These unique properties provide sensing flexibility for pipeline inspection by adjusting the size and spacing of the PZT sensors and the effective configuration along the circumference.

In structure health monitoring, Lamb waves that propagate on the surfaces of structures have attracted many researchers [5]-[10]. Lamb waves are guided ultrasonic waves capable of propagating relatively long distances without much attenuation in plates and laminated structures, such as airframe skins, storage tanks, and pressure vessels. This is because they are guided plane strain waves constrained by two free surfaces. The long sensing range makes Lamb waves attractive for damage inspection and diagnosis. Moreover, if a receiving sensor is positioned at a remote point on a structure, the received signal contains information about the integrity of the line between the transmitting and receiving sensors. The test therefore monitors a line rather than a point. Hence we save considerable testing time compared with the conventional ultrasonic inspection methods where each point of a structure needs to be scanned and tested.

However, the propagation of Lamb waves is complicated due to their dispersive and multimode characteristics. Their propagation properties in structures depend on the vibration frequency as well as on the thickness and material properties of the structure. For example, in thin plates, there exist two sets of modes called symmetric modes and anti-symmetric modes. The modes are generally dispersive, which means that the shape of a propagating wave changes with distance along the propagation path. Lamb waves exhibit velocity dispersion, i.e., their velocity of propagation c depends on the frequency (or wavelength), as well as on the elastic constants and density of the material. This phenomenon is central to the study and understanding of wave behavior in plates and tubes. There are two types of velocity dispersion for Lamb wave propagation: group velocity dispersion and multimode dispersion [5]-[7]. The group velocity dispersion is caused by the frequency dependency of a single Lamb wave mode. That is, the different frequency components in a single mode travel at different speeds. As a result, the group velocity dispersion causes spreading of the wave packets. The multimode dispersion exists because different modes at a given frequency travel at different speeds. Therefore, when an input acoustic waveform with a discrete frequency is applied to a thin medium, it is separated into multiple modes that travel at different speeds.

Ultrasonic Sensor Networks for Structure Damage Inspection

A sensor network is composed of a large number of geographically distributed sensor nodes [11]-[13]. Though each sensor is characterized by low power constraint and limited computation and communication capacities, potentially powerful networks can be constructed to accomplish various high level tasks via sensor cooperation, such as distributed estimation, distributed detection, and target localization and tracking. In structure health monitoring, we will use a network of acoustic sensors that are mounted internally or externally on a structure to detect, locate, and analyze various defects. Data processing using acoustic sensors distributed along the structures differs substantially from conventional centralized processing methods. In conventional data processing, all the sensors transmit their measurements at every time step to the central unit for final processing. However, there are two main reasons why centralized processing is not preferred for pipeline monitoring:

- Operational civil structures such pipelines are subject to complex, often highly non-linear, and localized temporal and spatial processes. Hence we want to perform some local processing to collect information in the neighborhood of localized defects;
- The central node needs to handle matrix operations that increase in size as the number of sensors increases.

We may want the sensors to shoulder some of the computational burden. Therefore, data processing by sensor networks requires integrated methods and methodologies including conventional distributed systems, distributed control, distributed estimation and detection, and distributed statistical signal processing. Our basic approach is to develop a general framework based on a ubiquitous network of acoustic sensors and controllers that provides continuous monitoring and inspection of structure damage. Although the problem is complex, we focus on using signal processing techniques to detect, analyze, and locate structure defects.

A. Survey of Detection Methods Using Ultrasonic Signals

The discrimination between noise and signals (from defects) is essential for structure health monitoring. The operational environment of a typical structure such as pipelines is usually very noisy. A noise analysis must be conducted to characterize the frequency bands of noise at different sections of a pipeline. We apply denoising procedures to reduce or remove electronic and other noise that contaminate the signature signals from pipeline defects. The denoising techniques including band-pass filtering and more sophisticated wavelet based filtering that reduce the noise level in the received acoustic signals.

Signals generated by acoustic sensors that propagate along the structure can be used to infer defects. For example, for pipelines that do not contain defects, their propagation characteristics can be calculated from modeling. When defects, for example, corrosions, occur, the acoustic signals may reflect and scatter due to the defects. Hence, the received signals differ from those propagating in the normal condition. We use simple discrimination techniques such as signal cross-correlation to discrimate defects. We discover that the cross-correlation of signals originating from similar parts of a structure shows a high correlation. Based on detailed knowledge of the structure, certain regions can be monitored directly by storing in memory the values of cross correlation between the actually recorded signal and a reference signal, yielding a simple map of signal similarities. Only the correlation coefficient, the event time and the "name" of the sensor node recording it have to be transmitted to the local processing unit. Finally, once the defect is detected and identified, an alarm message can be sent to the human operator through communication links.

Detection of burst signals caused by accidental heavy equipment impact is challenging. This is because burst signals can be very short in duration and may also be much lower in amplitude than the normal background acoustic signals. In order to detect third party damage signals, it becomes necessary to continually compare new acoustic signals to the background acoustic signal at that location. Fourier transform analysis is a power tool to achieve this goal. Fourier transform provides the synchronized signal characteristics required to properly remove background signal characteristics from new acoustic signals so that unique frequency variations caused by pipeline impacts can be revealed.

B. LabView Based Ultrasonic Transducer Network for Target Localization

To demonstrate the feasibility of a ultrasonic transducer network for damage localization to our students, we conduct experiments using LabVolt transducer circuit boards, Oscilloscope, multimeter, and LabView software in our educational laboratory of the engineering department. The experiment is carried out in three steps: 1) understand the principle of ultrasonic; 2) conduct distance measurement and data acquisition using three transducers; and 3) data analysis and processing using LabView and Matlab.

The first step for students to carry out the experiments is to explain and demonstrate the principles of transmission and reception of ultrasonic sound waves. The principles of ultrasonic wave propagation are summarized as follows:

- Ultrasonic transducers (ceramic piezoelectric transducer) transmit and receive sound waves;
- The basic principle lies on measuring the length of time from transmission to reception of the sound wave;
- When a sound wave hits a solid surface, it reflects off it; this reflected sound is called an echo;
- If we know the speed of sound in the air, we can calculate the distance to the obstacle. To do this we must measure the time taken for a pulse of sound to travel to the object and back again;
- The distance to the object and back is given as "distance=speed $\times$ time." As this is the total distance that the sound has travelled to the object and back, we must divide by 2 to find the one-way distance.

The second step is to collect ultrasonic data for processing. The measurement process includes the following components:

- LabVolt transducer fundamentals circuit board (91000-30);
- National Instruments USB 6251 data acquisition device;
- Quanser M-series terminal board;
- Computer with Daqmx and LabView signal express software.

The procedure for signal transmission and reception is summarized below:

- A ultrasonic Transducer circuit block contains a clock circuit which generates a 109 Hz pulse signal;
- A clock pulse modulates a 40 kHz square wave oscillator;
- The output at this point is a 180 μs burst of 40 KHz pulses every 9.0ms;
- A band pass filter converts this signal into sine wave bursts, which is seen at the transmitter output;
- An ultrasonic receiver boosts the signal amplitude it receives from the transmitter. A detector circuit demodulates the tone burst;
- The detector output drives a voltage comparator that inverts the pulses, squares the edges and removes the effect of ringing.

The final step of the experiment is to analyze the data. The data processing and analysis is carried out as follows:

- The transmitter and receiver outputs are combined together;
- By measuring the delay, distance to the object is calculated;

- The delay is the time taken for the transmitted to come back to the receiver;
- The distance calculation is "distance= velocity × time / 2," where the pulse is travelling an equal distance to and from the object; therefore time calculated is twice the distance;
- Signal analysis is performed in LabView 8.5. The delay measurement is shown in Figure 1;
- In LabView, block diagram code is developed to automatically calculate the delay and the distance.

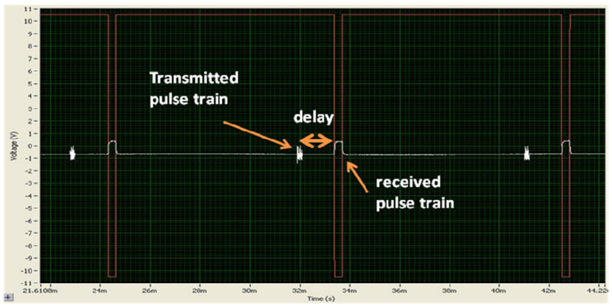

Figure 1. Delay measurement in LabView

Defect localization is an important task for sensor networks. Various localization methods have been proposed in the framework of sensor networks. Depending on the operational environment and assumptions, the localization techniques possess varying degrees of complexity and accuracy. Once the distance measure is completed using a single transducer, we will rely on multiple transducers to locate the target in a two-dimensional plane. The localization geometry is depicted in Figure 2.

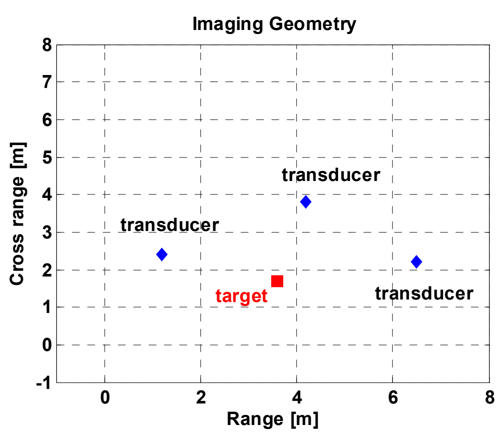

Figure 2. Imaging geometry using three transducers

We note that the propagation velocity for ultrasonic waves that propagate along a solid medium is very complicated. In general, we shall employ different velocity profiles of Lamb waves to compensate for the dispersion and to tune one or several propagation modes for localization. In our educational laboratory, we do not have sophisticated equipment to conduct the experiments to measure guided Lamb waves. To simplify the implementation, we use a simple experimental setup to demonstrate the proof of concept. Using multiple LabVolt transducer circuit blocks, we demonstrate how to detect and locate a defect by simple triangulation methods based on time-of-arrival of the propagating sound waves. The procedure is described as follows:

- We let (x_1, y_1), (x_2, y_2), and (x_3, y_3) denote the co-ordinates of the three sensors, respectively. t_1, t_2 and t_3 are the times calculated for the transmitted wave to reach the receiver.
- We first calculate the distance between each sensor and the object using the ultrasonic principle for distance measure.
- Let v denote the sound speed in the medium (here is the air), and (x, y) denote the position of the unknown object; the generalized equations are:

$$vt_1 = \sqrt{(x - x_1)^2 + (y - y_1)^2}$$
$$vt_2 = \sqrt{(x - x_2)^2 + (y - y_2)^2}$$
$$vt_3 = \sqrt{(x - x_3)^2 + (y - y_3)^2}$$

- By solving the above equations we get the co-ordinates of the unknown object at (x, y).

To further test our approach, we vary the positions of the transducers and the target and repeat the experiments. The measured target position in (x, y) is compared with the actual position. The relative error is calculated using:

$$\varepsilon_r = \frac{(x - \hat{x})^2 + (y - \hat{y})^2}{x^2 + y^2},$$

where $(\hat{x}, \hat{y})$ is the measured position. The results are summarized in Table 1. The results demonstrate that the proposed approach produces relative errors that are within the acceptable range given by the LabVolt transducer circuit board specifications.

Table 1. Experimental results on localization

Measured position	Actual position	Relative error
(3.84, 1.89)	(3.60, 1.70)	1.98%
(2.12, 1.48)	(2.08, 4.35)	2.51%

To streamline the data measurement process, we have developed a set of LabView virtual interface (VI) codes to collect, display, and process the measurement data. The front panel for data processing and display is shown in Figure 3. In this figure, both the transmitted data and the received data are plotted for comparison. The front panel is essentially the user interface. The commands for displaying and processing data are executed by clicking the buttons on the front panel.

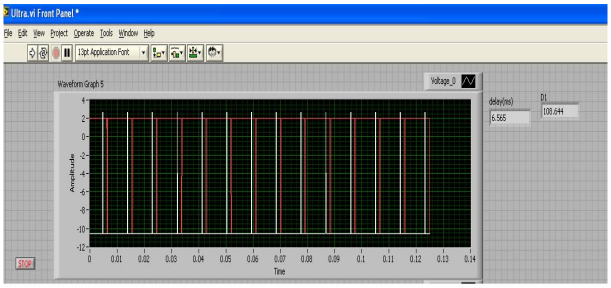

Figure 3. Front panel of the developed LabView virtual interface

Integrating SHM into an Undergraduate Engineering Curriculum

A complete SHM system using wireless sensor networks consists of three major components, i.e., data acquisition, data processing, and data communication. Data acquisition refers to the process of sensing the structures and collecting data from various sensor readings. Data processing is a process that analyzes the data to make a decision and to report whether the structure is damaged or needs further inspection. Finally, the decision information will be transmitted to the human operator through communication links.

To integrate the state of the art SHM research into an undergraduate engineering curriculum, we considered the following approaches:

- Utilize appropriate simulation tools in courses. As we discussed earlier in this paper, Lamb wave based defect detection and inspection is a promising approach in realizing structure monitoring such as bridges, pipelines, and dams. To help our students understand the mechanic principles of Lamb wave propagation, we decided to use ABAQUS simulation software in our ENAE/ENME 430 Finite Element Analysis. The ABAQUS software can simulate guided ultrasonic waves propagating on various civil and mechanical structures. This provides the first-hand experience for our students to become familiar with the basic inspection method and principles for structure health monitoring.
- Provide extensive data processing experience as it is indispensible for SHM. We enhanced the ENGE 460 Digital Signal Processing class by using Matlab and LabView software. Through many hands-on programming projects using Matlab and LabView, our students learn the principles of digital signal processing and their relation to SHM.
- Develop embedded system experiments for sensor networks. Wireless sensor networks include wireless communications, low-power embedded systems, sensor design, and instrumentation, etc. From a hardware perspective, sensors are becoming very inexpensive, which makes it possible to use them in various instrumentation and process control systems or deploy them in large networks. From a software perspective, extensive and sophisticated data gathering and data processing techniques designed specifically for sensor networks applications have been developed. These recent advances in sensor network technologies enable us to develop new experiments for use by undergraduate engineering students. The ENEE 464 Embedded System Design Lab in our curriculum covers the topic of sensor design and applications using HCS12 development board. The objectives of this course are: 1) To provide students with a better understanding of the electrical, computer, aerospace, and mechanical engineering disciplines; 2) To help students develop hands-on skills through self-motivating, team-based design activities; 3) To stress the importance of problem solving skills and critical thinking; and 4) To provide students a systematic view of sensor networks technologies at the component level, network level, and application level. This course combines lecture modules and laboratory projects. The lecturer components are focused on topics related to the engineering profession, engineering design, electrical and mechanical systems, and wireless sensor networks. The comprehensive laboratory projects are developed using popular data acquisition and simulation platforms such as LabView, Matlab/Simulink and sensor network platforms such as TinyOS and Java to provide students hands-on experience with the hardware.

Conclusion

The research and educational activities of this work were focused on developing a general acoustic sensor networks framework to provide continuous monitoring and inspection of structure health systems. The sensor networks detection, localization, and quantification of bursts, leaks and other anomalies in complex structures such as pipelines were considered. The integration of sensor networks based structure health monitoring into an undergraduate curriculum was presented. We demonstrated the feasibility of SHM in our educational laboratory.

Identifying a series of key courses in engineering curricula for implementing various concepts of sensor networks enabled us to develop a new research and education Signal Processing and Intelligent Sensing Lab (SPIS-Lab) that advances state of the art data processing methods and promotes student learning in engineering curricula.

Acknowledgments

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